The Diffusion of Scientific Innovations: A Role Typology

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Abstract

How do scientific innovations spread within and across scientific communities? In this paper, we propose a general account of the diffusion of scientific innovations. This account acknowledges that novel ideas must be elaborated on and conceptually translated before they can be adopted and applied to field-specific problems. We motivate our account by examining an exemplary case of knowledge diffusion, namely, the early spread of theories of rational decision-making. These theories were grounded in a set of novel mathematical tools and concepts that originated in John von Neumann and Oskar Morgenstern's *Theory of Games and Economic Behavior* (1944, 1947) and subsequently spread widely across the social and behavioral sciences. Introducing a network-based diffusion measure, we trace the spread of those tools and concepts into distinct research areas. We furthermore present an analytically tractable typology for classifying publications according to their roles in the diffusion process. The proposed framework allows for a systematic examination of the conditions under which scientific innovations spread within and across both preexisting and newly emerging scientific communities.

1. Introduction

The development and dissemination of new ideas lie at the heart of scientific inquiry, and drawing upon such novel ideas is a constitutive element of scholarly activity. Scientific innovations - be they new theories, models, methods, techniques, or concepts - can diffuse widely and systematically, over long periods of time, and across a broad range of contexts. Such diffusion processes, which can be understood as instances of knowledge transfer, have

[1] Authors are listed in alphabetical order. We thank the audiences of the workshops *Decisions, Groups, and Networks* held in 2014 at the Center for Advanced Studies at Ludwig-Maximilians-University, Munich and of the workshop on *Social Simulation* held 2015 at the University of Bayreuth. We are particularly grateful to Jeff Biddle, Nicola Giocoli, Stephan Hartmann, Rainer Hegselmann, Paul Humphreys, Chiara Lisciandra, Thomas Sturm, Paul Teller, and two anonymous referees for their feedback on earlier drafts of this paper. This project was funded by the Alexander von Humboldt Foundation.

long been of interest in the history and philosophy of science (e.g., Ash 2006, Howlett/Morgan 2011, Kaiser 2004, Morgan 2014).[2] But to date, philosophers and historians of science have rarely drawn on the literature from innovation studies to further analyze processes of knowledge diffusion in science, nor have they made extensive use of quantitative-empirical methods to systematically analyze how particular scientific innovations spread.

In this paper, we address this gap in the literature by offering a novel account of the diffusion of knowledge in general and of scientific innovations in particular. We combine concepts and methods from contemporary innovation studies and empirical network analysis with a set of philosophical ideas derived from Thomas Kuhn's study of the emergence of innovations in science. Innovation scholars have long argued that the diffusion of innovations takes place in networks of actors who engage with the innovation in virtue of the different roles they play in the networks of which they are a part (Coleman et al. 1966, Valente 1995, Rogers 2003). In developing this argument, they have generally taken the innovation itself to remain unchanged as it spreads from one adopter to the next. Although that premise may hold true for innovations in general, it does not hold true, we argue, for scientific innovations. As Kuhn notes, novel ideas in science must be elaborated upon and conceptually translated before scientists can adopt and apply them to field-specific problems (1977 [1959]). The framework presented in this paper acknowledges this aspect as a precondition for the diffusion of scientific innovations, not only within but across preexisting and newly-forming fields.

Our aim is to identify and further characterize the roles played by network actors by combining the insights of both bodies of literature - innovation studies and Kuhn - that have so far been worked out separately. Specifically, we take Kuhn's idea of translation to be

[2] See, e.g., the special issues on interdisciplinarity in *Synthese* (2013), Vol. 190, and on model transfer in *Studies in History and Philosophy of Science* (2014), Vol. 48.

essential for the adoption of scientific innovations. We assume that this translation process is undertaken step-wise by scientists engaging in different ways with the scientific innovation in their written contributions. Those contributions actively promote the diffusion of a novel idea in virtue of different roles they play in the modification of the scientific innovation. In particular, we identify four different roles that scientific contributions (either published and unpublished) can play in extending upon and modifying the scientific innovation and thereby facilitating its spread: innovator, elaborator, translator, and specialist. Beyond the scientific innovation itself, contributions can take the role of elaborating on and experimenting with the innovation to better understand its potentials and limitations for their field. Contributions can then take the role of translating the innovation - often in its elaborated form - for new fields of enquiry. Translation aligns a scientific innovation with previous research traditions. It reveals the innovation's potential for particular disciplinary problems and establishes the basis for its application in specialist research, the fourth role that contributions can occupy.

Against this background, the contribution of this paper is twofold. First, we introduce a network-based diffusion measure that is empirically tractable and that allows researchers to reconstruct the extent to which a given scientific innovation has spread across preexisting and newly forming academic disciplines and fields. Specifically, we use co-citation analysis to identify topical overlaps among scholarly contributions that relate to the scientific innovation and were published in the years following its initial publication. The network of topical overlaps among these publications yields an empirical basis for measuring the spread of the scientific innovation into different domains. Second, we present a rule-based typology for classifying academic contributions in terms of their roles in facilitating the diffusion of the innovation. More specifically, we identify publications whose content was related to, and that were published in the wake of, the initial innovation and we classify these publications according to their role in facilitating stepwise modifications of the scientific innovation. Our classification distinguishes between 'innovator'-, 'elaborator'-, 'translator'-, and 'specialist'-

roles, each of which have distinct parts in promoting the adoption and modification of the scientific innovation. We characterize those roles systematically in terms of salient positions in the co-citation network that represents the diffusion outcome. This typology allows us to formulate general conjectures about the conditions under which scientific innovations diffuse across research fields.

We illustrate our approach by applying it to the well-documented case of axiomatic theories of rational decision-making, which originated in a set of highly innovative concepts and mathematical tools introduced by the mathematician John von Neumann and the economist Oskar Morgenstern in the mid-1940s. While these concepts and tools were initially considered to be too challenging mathematically by social scientists, they spread widely throughout the second half of the 20th century, both within and beyond the behavioral and social sciences. In this process, those innovative tools and concepts were extended, elaborated upon, sometimes transformed, and ultimately applied to a variety of problems across a wide range of fields. The application of our framework to the spread of rational choice theories (hereafter: RCTs) showcases its usefulness for addressing questions about knowledge diffusion within and across scientific communities more generally.

2. Thomas Kuhn on Scientific Innovations

While many core contributions to the philosophy of science have been concerned with questions of rational theory choice, scientific discovery, and progress in science, this literature has largely sought to develop theories of scientific rationality and the formulation of demarcation criteria for scientific knowledge (Lakatos 1978, Popper 1963, 2002 [1935]). In so doing, this literature has generally neglected how scientists actually come to accept and adopt a scientific innovation, and has tended to focus on logical and epistemological or, more broadly, rational features of theory choice and scientific change.[3] However, since Thomas Kuhn (1962), we know that non-rational factors can lead to the emergence of new paradigms and influence theory choice. While Kuhn is most well-known for his account of how science proceeds by way of alternations between normal science and scientific revolutions (Kuhn 1962), he offered an important insight on this matter in a lecture entitled 'The Essential Tension: Tradition and Innovation in Scientific Research' (Kuhn 1977 [1959]), which predated his *Structure of Scientific Revolutions* (1962). In this lecture, which predated his *Structure of Scientific Revolutions* (1962), Kuhn offers an important insight into how scientific innovations emerge and diffuse within and across scientific communities.

According to Kuhn, before a scientific innovation can take hold, the innovator confronts an 'essential tension' that originates in the need to play the roles of both iconoclast and traditionalist (Kuhn 1977 [1959]). As the constitutive characteristic of a scientific innovation is novelty, that is, a breaking with established conventions, the originator of a scientific innovation must on the one hand be a divergent thinker who questions old ideas and formulates new ones. On the other hand, he or she must also be a convergent thinker who can align his or her new ideas with prior knowledge (Kuhn 1977 [1959], 139 f.). In the sense that a scientific innovation resembles a theory that belongs to a different paradigm, proponents of both competing theories can be compared with two native speakers of different languages. While the vocabulary of two theories can be identical and most words might function in the same way, some relevant words in the basic and theoretical vocabulary function very differently. Scientists discover the existence of such differences when they experience repeated communication breakdowns between one another. Therefore, the need to bridge the gap between a novel idea and the established framework is particularly pressing in the case of

[3] Lakatos' criticized Popper's demarcation criterion for science from non-science as being too restrictive and ruling out many examples from scientific practice. Kuhn, however, came one step closer towards considering also the social context to be essential in his account of scientific knowledge production, which fits with our empirical approach.

scientific innovations. If scientific innovations are not adapted to and aligned with existing conceptual and theoretical frameworks, they might not become widely adopted across different fields.

Given Kuhn's more general picture of the existence of incommensurable paradigms in science (Kuhn 1962), translation overcomes potential communication breakdowns between scientists who adhere to different paradigms (Kuhn 1977 [1973]: 338). This idea can also be applied to scientific innovations: Translating a scientific innovation into the language of a particular field or subfield dissolves the tension between novelty and tradition and thereby facilitates its adoption.[4] Translation takes place by "treating already published papers as a Rosetta stone or, often more effective, by visiting the innovator, talking with him, watching him and his students at work" (Kuhn 1977 [1973]: 339), and then communicating this new piece of knowledge to specialist scientists in a language that they understand. This way, a scientific innovation is made valuable for field-specific purposes. As the original innovation is adapted, extended, or even transformed in the process of translation, the outcome may differ conceptually and/or methodologically from the original idea.

Translation of a scientific innovation does not guarantee adoption, and as such is not a sufficient condition for successful diffusion. However, in the following, we draw on Kuhn's insight that it is a necessary and thus integral precondition for the wide spread of scientific innovations. Before we outline our approach, we will introduce RCTs as one prominent example of a scientific innovation that has spread extensively across the social and behavioral sciences.

[4] In the following, we focus on scientific innovations because we take them to be the prime example of a piece of knowledge that undergoes such a translation process. Note, however, that already established theories can also require translation to apply them to new problems.

3. Theories of Rational Choice: An Example of a Scientific Innovation

Today, theories of rational decision-making are used in various disciplines and encompass a large number of approaches to human behavior within but also beyond the social sciences, including for instance biology and philosophy. RCTs come in many guises, are conceptually distinct, and have been applied to fundamentally different problems (Herfeld 2014, Thomas 2015, esp. ch. 5). However, they share several constitutive ingredients. First, they hold that human action should be conceptualized as rational action. Second, they are often grounded in a formal-axiomatic representation of rational action in set-theoretic terms. Preferences of an agent are represented by a binary relation whose structure is constrained by a set of consistency requirements, such as the transitivity and completeness axioms, which ensure the rationality of an agent's preferences. Those axioms furthermore allow for the deduction of such theorems as the principle of expected utility (Anand et al. 2009, Fishburn 1968). Examples of RCTs include game and decision theory, (subjective) expected utility theory, consumer choice theory in microeconomics, as well as approaches to conceptualizing human behavior in social choice theory, public choice theory, etc.

A natural starting point for studying the diffusion of RCTs is the *Theory of Games and Economic Behavior* (hereafter TGEB), published in 1944 by John von Neumann and Oskar Morgenstern. The novel contribution of the book is to formally represent human behavior by a set of formal-mathematical tools and concepts taken from mathematical logic, probability theory, axiomatic set theory, and topology (Boumans/Davis 2010, Debreu 1986, Isaac 2010).[5] Prior to the publication of the TGEB, those tools were unknown or hardly familiar to

[5] RCTs had numerous intellectual precursors (e.g., Bernoulli 1954 [1738]), De Finetti 1937, Frisch 1971 [1926], Pareto 1972 [1927], Ramsey 1931), including previous contributions by von Neumann to the analysis of strategic games (Dimand/Dimand 1992). While it could be argued that these were the true innovators behind RCTs, the TGEB was the first contribution to fuse those ideas to formulate what became two accounts of rational behavior that would prove fruitful for the behavioral and social sciences.

social and behavioral scientists. As such, the tools were highly innovative. In economics, they would replace calculus techniques that had traditionally been used to represent human decision-making as an optimization problem. Among its many contributions, the TGEB, by drawing on those formal-mathematical tools, contained two innovative formulations of rational decision-making that would become extremely important: (1) an axiomatic representation of the long-standing principle of expected utility, and (2) the minimax theorem as a 'rule' for rational action in situations of strategic uncertainty, which von Neumann and Morgenstern modeled by introducing the concept of a two-person zero-sum game.[6] Those concepts, together with the mathematical tools they were grounded in, would come to be adopted, elaborated upon, and modified, and would find extensive applications within and across the social and behavioral sciences.

The reviews following its publication show that from the beginning, the TGEB was received by scholars from various disciplines, ranging from mathematics and mathematical statistics to economics, sociology, and philosophy (Leonard 2010). Yet, while scholars acknowledged the path-breaking achievement of the book, the tools and concepts contained therein were not taken up immediately (Giocoli 2003, Weintraub 1992). In part, this was due to their relative inaccessibility to social scientists without extensive mathematical training, particularly in mathematical logic and topology. The major contributions contained in the TGEB were due to von Neumann, who was strongly influenced by the formal-axiomatic program of David Hilbert (e.g., Giocoli 2003a, Weintraub 2002). For social scientists, including Morgenstern, the effort of becoming acquainted with this new kind of mathematics initially set a substantial barrier to adoption (Leonard 1995). Initially, the most innovative ideas contained in the TGEB were only accessible to mathematically versed scholars, who

[6] Note that von Neumann and Morgenstern did not intend the principle of expected utility as a decision theory. Its popularization as a decision theory was fostered only later by economists such as Jacob Marschak (e.g., Giocoli 2006).

drew upon the TGEB as a useful "tool-box" (Giocoli 2003a), but beyond that small circle, scholars had serious difficulties with the work (e.g., Koopmans 1957: 171). Additional scientific contributions were needed that would make those new concepts and tools accessible and that would illustrate their relevance for field-specific applications.

Once social scientists overcame those initial barriers, the mathematical tools and concepts contained in the TGEB were taken up across a remarkably diverse range of scholarly enquiry, including mathematics, mathematical statistics, measurement theory, and mathematical psychology, applied behavioral decision research, social choice theory and sociology, political science, organization theory, as well as biology and philosophy, among others.[7] Moreover, by the 1970s they had laid the ground for entirely new subfields of enquiry, including public choice theory, mathematical finance, and operations research, including linear programming, as well as game and decision theory. Table 1 offers only a partial list of fields that have been directly influenced by the concepts and tools contained in the TGEB and that are commonly identified in the major historical accounts of those fields to which RCTs spread (see Amadae 2003, Debreu 1983, Dimand/Dimand 1992, Dimand 2000, Düppe/Weintraub 2014a, Erickson 2010, Erickson et al. 2013, Giocoli 2003 and 2012, Heukelom 2014 and 2010, Erickson 2015, Weintraub 2002).

--- Table 1 here ---

A full explanation of how the innovative mathematical tools and concepts contained in the TGEB spread to these different fields would require the identification of a complex set of interdependent factors that are furthermore particular to each field. As historical accounts

[7] While it can be said that social choice traces back to Condorcet's famous 'jury theorem', published by Marquis de Condorcet in 1785, modern social choice theory clearly has its roots in Kenneth Arrow's *Social Choice and Individual Values* published in 1951 and was as such equally affected by RCTs.

have established, the unique context of the Cold War profoundly shaped the political, social, and scientific conditions under which the TGEB and its conceptual successors were adopted.[8] While we hint at these contextual factors, they are not generalizable to all processes of knowledge diffusion. Central to our analysis, instead, is the observation that the innovation could only spread to those fields by being modified in various ways that enabled their applications to problems in those fields in the first place. Our primary aim is to capture this dimension of the diffusion process more generally. We do that by systematically analyzing the role of particular contributions that proved crucial in the adoption of the tools and concepts in the TGEB. We look especially at the role those contributions played in engaging with and modifying those tools and concepts and thereby enabling their spread. As will become clear in subsequent sections, our analysis offers a bird's-eye view of the outcome of the diffusion of the TGEB - one that is remarkably consistent with existing historical accounts and may thus be seen as a systematic way to trace diffusion processes that complements historical narratives.

4. A Network Representation of the Diffusion of a Scientific Innovation

Pioneering studies of the diffusion of innovations have investigated how innovations spread within networks of actual and potential adopters (Rogers 2003, Coleman et al. 1966, Strang/Tuma 1993, Valente 1995). We take up this idea insofar as we consider scientific innovations to spread through a network of loosely interrelated scholarly contributions that engage with, and extend upon, the innovation in question. Innovation studies generally conceptualize an innovation as a good whose essential properties remain unchanged in the process of its diffusion; yet this premise arguably does not hold for scientific innovations. As

[8] For an account of the history of von Neumann and Morgenstern's contribution, see Leonard (2010). For accounts on the history of rational choice theories, see Amadae (2003), Düppe/Weintraub (2014b), Erickson et al. (2013), Giocoli (2003), Heukelom (2010, 2014), Isaac (2010), Thomas (2015), and Weintraub (1992, 2002), among others.

mentioned above, to resolve the essential tension between developing a new idea and grounding it in contemporary scientific tradition (Kuhn 1977 [1959]), early adopters have to adapt, extend, re-combine, and even transform the initial scientific innovation in order to align it with disciplinary standards and existing theoretical frameworks and concepts. An effective analysis of the diffusion of scientific innovations must therefore not only track the temporal dimension of the spread of the scientific innovation into different domains. It must also acknowledge the substantive dimension of modification in the diffusion process and capture how the innovation's modification dynamically shapes and reconfigures the possibilities for its subsequent adoption and its extensive application beyond the problem for which it was invented.

To account for both the temporal and the substantive dimensions of the diffusion process, we model the spread of a scientific innovation as the emergence of a network of loosely related scholarly contributions that relate to, engage with, and extend the scientific innovation. We represent the outcome of this process as a network of relevant contributions that are connected (a) to one another and (b) to the scientific innovation itself via topical overlaps. We label this the network representation of the "epistemic domain" of a scientific innovation. With methods from network analysis, we then identify and characterize different roles that scientific contributions can play in the diffusion process and classify them in terms of those roles by examining their salient positions in this network representation. The resulting typology captures the idea that a scientific innovation can be applied extensively beyond the problem for which it was invented only because it is adapted, extended, or modified by subsequent scholarly contributions that take up different roles in the diffusion process.

The underlying rationale of constructing our network is straightforward and builds on the basic principle that new research acknowledges relevant prior knowledge by way of citations. Citations (1) attribute contributions to a particular publication and (2) convince a scientific community of the validity and novelty of one's own research (Gilbert 1977, Kaplan 1965). Our basic premise is that if a publication cites the innovative contribution, this reference acknowledges the innovation along with the other references that it cites. Those other references that are cited together with the innovative contribution signal an acknowledgement of potentially numerous additional literatures that were informed by the innovation and have in turn informed the publication. As such, whenever research repeatedly cites a particular scientific innovation together with specific other contributions, this indicates a basic - possibly latent - topical overlap between the innovation and those other contributions. For example, the fact that two publications are cited together with the TGEB in one and the same publication suggests that both may be related to the tools and concepts contained in the TGEB. By considering only co-citations that appear recurrently in contributions that also cite a particular scientific innovation (such as the TGEB), it is possible to establish the epistemic domain into which the innovation subsequently spread.[9]

This approach is an application of co-citation analysis, a well-established bibliometric method for analyzing such conjoint references that has been used to capture and measure the similarity in content between fields of research at the level of journals and disciplines (Small 1973, Small/Griffith 1974, McCain 1991, White/McCain 1998, Boyack et al., 2005). Co-citation analysis builds on the assumption that two publications exhibit topical overlap if they are often cited together in subsequent publications. Thus, by identifying works that are frequently cited a) together and b) along with the work containing the scientific innovation, we capture the intuition that the innovation spreads between contributions.

In the following we apply our approach to the diffusion of RCTs. We identify relevant contributions published between 1944 and 1970 from present-day publications, that is, from publications that were published between 1984 and 2014 that cite the TGEB. There are four

[9] Because it is already published, the innovation itself cannot establish such connections.

basic benefits to drawing on present-day publications. First, existing citation databases that we are aware of offer only an incomplete coverage of the period before the late 1980s, thereby effectively precluding a direct citation analysis. For example, coverage in both Web of Science and Scopus is limited for the period before the 1980s and surely inadequate for the period that is of interest to us, i.e. 1944-1970. Second, the nuanced developments accompanying the diffusion of scientific innovations are not captured in direct citations, i.e., of who cites whom. This can occur in contexts and times in which knowledge diffusion proceeds through working papers and other formats that are not systematically included in citation databases. Such nuances are thus not immediately reflected in publications. As will become more apparent in the following application, only a small number of observations are needed to ensure that a particular intellectual contribution will become part of the epistemic domain and will thereby be subject to subsequent analyses.

Third, attempts to reconstruct diffusion processes from direct citations confront the challenge that citation practices differ both qualitatively and quantitatively across disciplines and in time, and that citations may be made in response to skewed incentive structures of academic publishing (Crespo et al. 2013, Garfield 1979, Wilhite/Fong 2012). By reconstructing the epistemic domain from the citations made by present-day authors who are writing many years after the fact, we effectively circumvent this problem. Finally, co-citation analysis ensures that connections between papers with topical overlap are established even if those connections are not made explicit in the papers themselves. For example, many papers published in the 1950s refer indirectly to “von Neumann Morgenstern utility functions” without citing the TGEB explicitly. To the extent that the scientific innovation is modified in the process of its diffusion, co-citation of two contributions and with the publication containing the scientific innovation can also signal critical engagement and even rejection of an original innovation in order to justify a new formulation.[10] Finally, even if direct citation data were available for the time period of our study, research has found that co-citation analysis generates markedly better representations of ongoing research frontiers than do direct citations (Boyack/Klavans 2010).

5. Data Source and Collection

Our analysis is based on citation data that we collected from all 3,677 journal articles, 1,061 conference proceedings, and 167 book chapters that cite the TGEB according to Scopus, an online database for academic literature as of September 2014. As coverage in Scopus only goes back to the 1980s, the earliest publications in our database were published in 1984 and the most recent ones were published in 2014.[11]

As most of the 4,905 publications were written by more than one individual, the dataset contains contributions by 7,818 individuals, 1,700 of whom were (co-)authors of more than one publication. The 3,677 articles were published in 1,551 journals covering a broad range of disciplines, including economics, sociology, psychology, computational science, and mathematics, among many others. We extracted all references contained in the bibliographies of each of the 4,905 publications that cite the TGEB according to Scopus. This yielded 193,685 citations in total (39.5 on average), ranging from references to Aristotle's *Politics* to present-day publications such as Daniel Kahneman's *Thinking, Fast and Slow* of 2011 along with the TGEB. Table 2 lists the number of contributions from which bibliographic data has

[10] One example is Kenneth Arrow's adoption of Tarskian logic to formulate his choice theory, which he justified in reference to von Neumann and Morgenstern's axiomatic representation of behavior but which was conceptually different von Neumann and Morgenstern's theory in crucial respects (Arrow 1951, ch. 2).

[11] Scopus was chosen because it includes citation data on selected monographs, including the TGEB. We accessed the database on July 23, 2014, and downloaded the bibliographic data on all 4,905 publications that cited TGEB as of that date. As the criteria for inclusion in the Scopus database are restrictive, Scopus contains about a fifth of the citations to TGEB found on Google Scholar. However, as our analysis is based on co-occurrences of citations in publications, we do not need the comprehensive set of all publications citing TGEB - a large and representative sample of publications suffices (and is contained in our dataset).

been collected by period. The first period contains only fifteen articles, the first of which was published in 1984.

--- Table 2 here ---

As Scopus provides bibliographic information in free-text format, the data had to be pre-processed manually. Given our ulterior interest in the early spread of the TGEB following its initial publication, we limited our analysis to references of contributions that were originally published between 1944 and 1970.[12] We manually linked each recorded reference to a unique identifier and thereby ensured that different editions of the same text, as well as spelling variants, were aggregated to a single scientific contribution.[13] We thereby identified 1,967 unique texts that had been published in the period 1944-1970 and were cited 27,414 times in our 4,905 present-day publications, including 4,905 citations to the TGEB. This is the empirical basis for the following analyses.

6. Representing the Epistemic Domain of Rational Choice Theories

Our aim is to construct a network representation of the epistemic domain into which RCTs spread in the 25 years following the publication of the TGEB in 1944. In this network, a publication that was originally written between 1944 and 1970 is called a *node*. An inferred topical overlap between two or more publications connected because they have been co-cited is called an *edge* (or *tie*). These relationships between nodes and edges capture the structure of the epistemic domain. We have chosen the period between 1944 and 1970 because by the

[12] As most present-day publications cite work that was published after the period of interest, this eliminated 166,271 citations. While we cannot rule out the possibility of missing some observations due to transposed digits in the year of publication, exploratory analysis of the data indicates that this is not the case. Therefore, we do not expect a systematic bias to our findings.
[13] A workflow that is generalizable across research settings can be made available upon request.

early 1970s, the process of diffusion of RCTs was largely complete insofar as they had reached all of the fields and were subsequently applied in day-to-day research.

One complication arising for our analysis is that the bibliometric data available is taken from contributions that were published many years after the period that is of interest to us (cf. Table 1) and relates to our aim of using this data to examine the period following the initial publication of the scientific innovation. The absolute frequency of co-citations in our data is a function not (only) of how important a contribution became shortly after it was made, but also on how many citations it received in publications that were published after 1980. We must define criteria by which to identify and remove connections that are due to the data compilation strategy rather than any intrinsic feature of the diffusion process. We define these criteria with three aspects in mind: first, we must compensate for the fact that the co-citation data is taken from publications that were written many years after the fact; second, we must eliminate spurious connections; and third, the final network topology should be broadly interpretable in light of existing historical accounts of the spread of the TGEB. These criteria are met by a simple two-step procedure that consists of a) imposing a minimal threshold on the number of co-citations, and b) limiting the maximal number of years that two co-cited publications can be apart for a meaningful topical overlap to be in place. Given the novelty of our approach, we present and discuss each step in greater detail and illustrate the effects of each manipulation on the network in Figure 1.

First, we eliminated very weak connections by imposing a minimal threshold on how often two publications must be cited together for a tie to connect the nodes representing them. Without such a threshold, the mere fact that any one of the 4,905 publications in our database cited two publications would result in their being inextricably connected. For example, both Jean Piaget's 1969 classic *The Psychology of the Child* (Piaget/Inhelder 1969) and Max Planck's *Scientific Autobiography* of 1968 would become part of the epistemic domain of TGEB and would be connected to each other merely because they were both cited in a publication in 2005 that also cited the TGEB, discussing scientific revolutions from the vantage point of chaos theory.[14] Both publications arguably have little bearing on the TGEB and should therefore not become part of its epistemic domain. At the same time, imposing too high a threshold would eliminate smaller subfields of enquiry into which the TGEB spread. For example, setting a threshold higher than four would result in the elimination of Raiffa and Schlaifer's seminal *Applied Statistical Decision Theory* from the epistemic domain, a core contribution that established the foundations for applied Bayesian analysis at the intersection of game theory and statistical decision theory (Keeney 2016).[15]

We find that a threshold of three or more co-citations best balances the requirements of eliminating spurious connections while keeping small yet crucial subfields of enquiry in the network.[16] A threshold of three co-citations eliminates 24,278 edges as spurious, such as the example of Piaget and Planck given above. After removing isolates, i.e., nodes which are not connected to any other nodes by at least three co-citations, this reduces the size of our network from 1,967 to 936 nodes and the number of edges from 27,414 to 3,136.[17] The resultant network is depicted in Panel a of Figure 1. By definition, each contribution is connected to the TGEB, identified as the enlarged node at the center of the network. To reconstruct the epistemic domain into which the TGEB spread, we remove the TGEB from the network, allowing us to focus on the 2,201 connections among the remaining publications. After removing isolate nodes, this leaves all contributions made between 1944 and 1970 that are cited in present-day articles that cite the TGEB, and the topical overlaps among them (see Figure 1, Panel b).

[14] The authors cite Planck's text as an illustration of scientists' (in)ability to accommodate changes in their cognitive schemas (Perla/Carifio 2005, 4).
[15] In a personal reconstruction of early influences, Raiffa himself acknowledged the importance of TGEB in motivating his own work that would combine game theory with statistical decision theory (Raiffa 2002).
[16] We have calculated all variables for a variety of thresholds (cf. the robustness checks in footnote 29).
[17] By this criterion, any two publications must be cited together in three of 4,905 contributions, including lesser-known discussion papers (e.g., Hurwicz 1951) and dissertations (e.g., Leiserson 1966).

--- Figure 1 here ---

Panel c of Figure 1 presents the same co-citation network as Panel b, but with an updated layout. It reveals an important implication of the fact that our data stems from publications that were written many years after the period that is of interest to us: with the benefit of hindsight, authors writing today can establish connections among any and all publications that were written in the years following the initial publication of the scientific innovation. As it stands, this obscures a crucial temporal aspect of the spread of scientific innovations, namely, that publications should be connected not merely because they are cited together today, but because they addressed overlapping topics in a similar stage in the diffusion process and thereby directly or indirectly informed one another. For example, although 50 present-day publications in our database cite Pratt's article *Risk Aversion in the Small and Large* of 1964 together with Nash's classic article *The Bargaining Problem* of 1950, we would contend that this high number of co-citations is primarily due to the strong engagement of present-day authors with either of the two works rather than their inherent topical overlap. In other words, focusing on high co-citation rates alone obscures the vast differences in intellectual context in which both authors' respective engagement with the scientific innovation took place.

To address this matter, we limit the maximal number of years that any two publications can be apart for an identified topical overlap between them to be meaningful in terms of the diffusion process. In our case, we remove all edges between contributions that were published more than five years apart. While this implies that a paper published in 1951 cannot be connected directly to a paper published in 1957, even if both are cited together three or more times in present-day publications, they may still be connected through indirect links.[18] We take this to capture a reasonable assumption about progress in science, namely, that an active field of research brings forth at least one significant contribution within at most five years.[19]

Eliminating all edges between publications that were either co-cited fewer than three times or were published more than five years apart and removing isolates leaves 442 publications connected by 971 edges (panel d of Figure 1).[20] The following analysis is of this network, which we take to be an adequate representation of the epistemic domain into which the scientific innovations contained in the TGEB spread in the 25 years following its publication.

7. Analyzing the Epistemic Domain of Rational Choice Theories

The network representation of the epistemic domain of RCTs reflects the outcome of intellectual engagement with the mathematical tools and concepts contained in the TGEB between 1944 and 1970 as we have inferred it from co-citation patterns in present-day publications.[21] We propose that a careful analysis of the topology of this network can

[18] In the aforementioned example, Nash's classic *The Bargaining Problem* of 1951, in which he cast classical problems of bilateral exchange in terms of non-zero-sum two-person games, is connected to his 1953 article on two-person cooperative games, in which he extends the bargaining problem to cases in which the involved parties can enforce agreed-upon plans of (rational) action (Nash 1953). In turn, this paper is connected to Luce and Raiffa's well-known textbook *Games and Decisions* (1957) in which an entire chapter is devoted to Nash's work (chapter 6). Luce and Raiffa's textbook is in turn connected to Daniel Ellsberg's classic *Risk, Ambiguity and the Savage Axioms* (1961), in which Ellsberg rejects the use of von Neumann-Morgenstern utility functions when ambiguity precludes the assignment of meaningful probabilities to outcomes, and which, finally, is connected to Pratt's (1964) article that presents an economist's measure of risk aversion which builds on the curvature of von Neumann-Morgenstern utility functions.

[19] The requirement of 'significance' is that three or more present-day publications cite a publication together with one other publication of that field. Furthermore, as co-citations are taken from publications that have been written many years after the period of interest, this identifies topical overlaps that may not have been recognized at the time. With the benefit of hindsight, our network representation of the epistemic domain includes so-called 'sleeping beauty' publications, i.e., contributions whose significance only becomes apparent years after their publication. One example is Ellsberg (1961), which has been identified as one of the 30 most prominent 'sleeping beauty' publications of the social sciences and humanities (Qing et al. 2015), and is assigned a prominent role by our approach.

[20] While grounded in substantive deliberation, these thresholds could always be chosen differently. Less restrictive thresholds might identify even more fine-grained niches into which the TGEB spread, but (due to the source of our data) would come at the expense of overemphasizing the importance of fields that are of relevance to authors writing today. As a robustness check, we calculated all network variables for a variety of thresholds and compared their stability across specifications. We report on these checks in footnote 29.

[21] This network representation is ultimately of course an empirical artifact and as such does not and cannot capture intellectual engagement with the TGEB in its entirety. For example, 'mathematical game theory' seems curiously underrepresented in our network. This may be because of an underrepresentation of relevant publication outlets for mathematical game theorists in the Scopus database, or it may be because contributions

improve our understanding of the factors that contributed to the spread of RCTs. More specifically, network analysis allows us to identify particular publications that played salient roles in diffusing RCTs by engaging with and modifying them for field-specific purposes. Our aim in the following is to identify such publications analytically from their positions in the co-citation network and to assess the roles they had in the early diffusion of RCTs. Our analysis proceeds in three steps. First, we identify what we call the 'epistemic core' of RCTs as that set of contributions that are most closely connected with one other. Second, we establish the multiple sub-domains into which RCTs would come to spread as clusters in the periphery of the epistemic domain as per 1970. And third, we classify individual contributions contained in the epistemic domain in terms of different roles they had in facilitating the spread of the innovation. Our focus on particular clusters as well as on specific publications and the roles they played showcases the complementarity of our empirical approach to existing historical accounts.

The Epistemic Core of the Network

With the network representation of the epistemic domain established, the first step is to identify publications that elaborated upon the concepts and tools contained in the TGEB. By engaging directly with RCTs, these publications form the backbone of the epistemic domain. In their attempt to develop the scientific innovation further and make it useful, such early adopter publications will be cited broadly across existing specializations in the present-day literature and will therefore exhibit a high level of interconnectedness within the co-citation network. We identify the set of contributions belonging to the epistemic core, i.e., the subset of densely interconnected publications, as the 'epistemic core' of the scientific innovation. We thereby proceed by using a recursive graph-partitioning algorithm known as k-shell

made to this field after 1980 do not commonly cite the TGEB anymore and therefore do not show up in our database. While regrettable, we see no reason that this omission has a substantial impact on the composition and topology of the epistemic domain our approach *has* identified.

decomposition.[22] This algorithm groups the nodes of a network based on the number of connections they share with the other members of their respective shell. The more embedded a contribution is in the epistemic domain, the greater its number of connections to other highly-connected publications, and the higher its shell value will be. We define the epistemic core of the network as those publications that are part of the highest k-shell, in this case, the 29 publications that are connected to at least seven other publications in the epistemic core.

--- Figure 2 here ---

The epistemic core is depicted in the inset of Figure 2. In our example, it includes seminal contributions by Kenneth Arrow, Milton Friedman, Herbert Simon, John Nash, Harry Markowitz, Duncan Luce, and Abraham Wald, and others. From the start, these authors attempted to establish the potential of, and further develop, the tools and concepts contained in the TGEB and to make them fruitful for problems in their respective fields of interest. Most of them were less concerned with traditional disciplinary boundaries and established practices and frameworks. Their work crossed the borders of traditional fields of research, was interdisciplinary, and would come to have a profound impact on disciplines as diverse as economics, psychology, organization theory, statistics, mathematics, and finance. Frequently it even reshaped the theoretical foundations of specific fields (e.g., Arrow in social choice theory) and motivated fundamentally new research areas (e.g., Markowitz in mathematical finance). To better understand which publications were particularly important in fostering the spread of RCTs into the specialized research areas identified from historical accounts (recall

[22] K-shell decomposition has been successfully applied to identify network positions that are important for diffusion processes in general (Kempe et al. 2003, Kitsak et al. 2010). Technically, it involves identifying the maximal subgraph in which each node shares at least k connections with other nodes in the subgraph, or shell (Batagelj/Zaversnik 2011). For our analyses, we drew upon implementations in the *igraph*-package of the statistical programming framework *R* (Csardi/Nepusz 2006).

Table 1), it is instructive to consider how each publication relates to those fields. In a next step, we therefore analyze our network topology for salient positions in the network that indicate particular roles played by individual publications in the early stages of diffusion. Before we can assign such roles, however, we must first identify the different research areas into which the tools and concepts contained in the TGEB would finally spread.

Specialized Research Areas as Clusters of Contributions

The division of cognitive labor in knowledge production leads us to expect that successful scientific innovations spread into and across multiple research areas (Abbott 2001, Crane 1972, Kitcher 1990). In co-citation networks, such specialized fields manifest themselves as multiple interconnected clusters that can be understood as the outcome of academic knowledge production (Adams/Light 2014, Kronegger et al. 2011, Moody 2004, Moody/Light 2006). As clusters represent distinct research areas, they contain contributions with high topical overlap within clusters and low topical overlap between clusters. With the network topology established, we can identify such specialized fields inductively using an edge-based clustering algorithm.[23] This revealed fifteen clusters of interconnected contributions ranging in size from 4 to 86 contributions (Figure 3).

--- Figure 3 here ---

Figure 3 captures the division of the epistemic domain of RCTs into 15 specialist research areas that existed or emerged between 1944 and 1970.[24] Each node represents one of the 442

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[23] We used a betweenness-based algorithm to identify clusters consisting of nodes with many connections within-cluster and few connections between clusters (Newman/Girvan 2004). This algorithm resonates with our expectation that distinct research areas consist of publications that exhibit topical overlaps among themselves but not with neighboring fields of enquiry. A modularity score of Q =.59 for the partition indicates that the ratio of edges observed within-cluster relative to edges observed between-cluster well exceeds that which is to be expected by chance.

[24] For example, reducing the minimal number of co-citations from three to two yields a network of 874 publications and 25 publication clusters of size 4 or greater. Upon closer inspection, however, seven of those 25 clusters are disconnected from the overall network, leaving only 18 clusters directly connected to the core of the

publications in the domain, and its label and coloring denote the cluster it is part of. The layout places nodes which share many connections close to each other and thereby highlights the topical overlaps among contributions. This layout offers a visual indication of the extent to which clusters overlap, with several publications that have been assigned to cluster 07 (theories of conflict and cooperation) locating towards the top of Figure 3 in the region of cluster 03 (cooperative game theory), whereas cluster 10 on the right-hand side of figure 3 is almost completely separated from the rest of the network. Each cluster contains classic contributions of those fields into which the innovations contained in the TGEB spread. Table 3 offers a summary overview of each of the fifteen clusters. We have labeled the clusters according to the research area that the publications they contain contributed to. We focused on those contributions that were most cited within each cluster (cf. the rightmost column).

--- Table 3 here ---

With 86 publications, cluster 01 is the largest cluster. It occupies a central position in the overall network. Other clusters emerge from it and it contains groundbreaking contributions that would prove seminal for the development of different fields in the second half of the 20th century. For example, it contains elaborations on von Neumann and Morgenstern's axiomatic representation of the expected utility principle, including Leonard Savage's *The Foundations of Statistics* (1972 [1954]), Jacob Marschak's extension of von Neumann and Morgenstern's axiom set (Marschak 1950),[25] and Israel N. Herstein and John Milnor's (1953)

epistemic domain (compared with 14 of 15 clusters in the analysed network). On the other hand, setting a threshold of four co-citations reduces the epistemic domain to 294 publications in 14 clusters (the cluster of evolutionary biology is eliminated). Given our purpose of constructing a coherent network representation of the epistemic domain, setting the threshold at three therefore balances the goals of cohesiveness (i.e., identifying a large connected component) and granularity (i.e., preserving relevant publications and clusters).

[25] To preserve space, we do not list contributions that are only referred to as part of the epistemic domain of TGEB in the bibliography of this paper. Such references are indicated by square brackets. A complete list of the 442 publications that are identified as part of the epistemic domain is available from the authors.

axiomatic treatment of expected utility. It also contains early attempts to measure utility in economics, such as Milton Friedman and Savage (1948, 1952), William Baumol (1951), Paul Samuelson (1952), and Frederick Mosteller and Philip Nogee (1951), and early contributions to decision-making under uncertainty (e.g., Hurwicz 1951, Shackle 1949). Cluster 01 also contains Duncan Luce and Howard Raiffa's *Games and Decisions: Introduction and Critical Survey* (1957), the first accessible introduction and highly influential textbook containing the main tools and concepts of game and decision theory that facilitated their spread across the behavioral and social sciences (O'Rand 1992: 189). Finally, the cluster contains several publications that would prove seminal for new sub-disciplines, including Kenneth Arrow's *Social Choice and Individual Values* [1951] for the field of social choice theory, and Abraham Wald's monograph on *Statistical Decision Functions* [1950], which, together with David Blackwell and M. Abe Girshick's *Theory of Games and Statistical Decisions* [1954], established foundations for statistical decision analysis (e.g., Dimand/Dimand 1990).[26]

By comparison, clusters 02 to 15 are more consistent in terms of topical overlap and focus. For example, cluster 02 contains major contributions to non-cooperative games and bargaining theory, most notably the seminal contributions by John Nash (1950, 1950b, 1951, 1953). Nash's contribution laid the ground for bargaining theory and for non-cooperative game theory to spread into economics by introducing most famously the Nash equilibrium. The cluster also contains early work on stochastic learning models by Bush and Mosteller (1955) and Shapley [1953], both major contributions to the field of stochastic games, a subfield of non-cooperative game and bargaining theory.[27] Cluster 03 contains seminal contributions to cooperative game theory and coalition formation, including work by Robert Aumann (1964), Michael Maschler (1964), Martin Shubik (1959), and Lloyd Shapley

[26] That cluster '01' contains contributions of evident importance for decision-, game-, and social choice theory, suggesting that the cluster poses a residual category that could be analyzed further for sub-structures.
[27] See Leonard (1994, 2010) for a history of Nash's contribution to game theory.

(Shapley 1959, Shapley/Shubik 1966, 1969) on market games. And cluster 08 contains contributions that would prove central in establishing mathematical finance and the theory of portfolio selection, notably the work of Harry Markowitz (1959), William Sharpe (1963, 1964), and Francesco Modigliani together with Merton H. Miller (1958, 1961). The publications contained in the clusters and the clusters themselves are representative of the respective fields into which the tools and concepts contained in the TGEB spread.

Exemplary for applications of RCTs outside of economics, cluster 04 is dominated by Herbert Simon's work on behavioral models of rational choice (Simon 1955, 1956, 1957) and artificial intelligence [Simon 1960], and by contributions by Ward Edwards (1953, 1954a, 1954b, 1954c) laying the grounds for behavioral decision research in psychology. The cluster also contains contributions that introduced probability theory, mathematical learning theory, and expected utility theory into psychology (Davidson et al. 1957, Siegel 1957). Cluster 09 contains core contributions to measurement theory (e.g., Ellis 1966, Scott/Suppes 1958, Suppes/Zinnes 1963) and optimal statistical decision-making (e.g., DeGroot 1970). And cluster 10 contains classics by Slovic and Lichtenstein (1968), Tversky (1969, Edwards/Tversky 1967, Tversky/Russo 1969) and other seminal contributions that introduced formal decision theory into mathematical psychology (e.g., Becker/DeGroot/Marschak 1964).[28]

The clusters we identified and how they map onto distinct specialized research areas lend validity to our approach to reconstruct the epistemic domain of the scientific innovation from topical overlaps expressed in co-citation networks. While it would be interesting to examine in detail the connections among individual publications within each cluster in terms of content and the historical context of their production, our aim in this paper is more analytical. In the following section, we identify and interpret four roles that contributions can occupy in

[28] For a historical account of the early years of for example Clyde Coombs' mathematical psychology program and Edwards' program of behavioral decision research, see Heukelom (2010).

the diffusion process on the basis of our network representation of the epistemic domain of RCTs, according to which we can classify individual contributions in terms of the function they had in the diffusion of RCTs. Thereby, we lay a particular focus on those contributions that bridged the gap between the epistemic core and the different clusters, thereby enabling their spread across specialized fields.

Four Roles Identified from Salient Network Positions

In the preceding sections, we have constructed a network-topological representation of the epistemic domain of the TGEB and have distinguished between an epistemic core and a periphery of specialized research areas, including disciplines and sub-disciplines. In this section, we identify and further characterize four distinct roles that individual contributions can occupy in the diffusion of a scientific innovation. We identify those roles from the salient positions of contributions in the network. In addition to (1) the *innovator*, we distinguish between (2) *elaborators*, i.e., contributions that are part of the epistemic core but not connected to the periphery, (3) *specialists*, i.e., contributions that relate (only) to subfields located in the peripheral clusters, and (4) *translators*, i.e., contributions that connect the clusters to the epistemic core. Drawing on historical accounts of the spread of the TGEB, we argue that what we identify and interpret as translator contributions in particular had a central role in facilitating the diffusion of the tools and concepts contained in the TGEB by making them accessible to further work in both preexisting and newly emerging research areas.

--- Table 4 here ---

Table 4 summarizes this typology and offers criteria for classifying each contribution in the epistemic domain based on its salient position in the network topology. We will discuss each of the four roles in turn. First, there is the innovator, which establishes the basis for analysis. Rather than inferring this role from its network position, the innovator contribution is identified exogenously by drawing upon some information about the innovation in question. In our case, existing histories of RCTs in the social and behavioral sciences (e.g., Dimand/Dimand 1995, Giocoli 2003, Leonard 2010, Weintraub 2002) as well as review articles (e.g., Hurwicz 1945, Marschak 1946, Simon 1945) have pointed out the highly innovative mathematical contributions of von Neumann and Morgenstern's TGEB, which contains important concepts and mathematical tools that would later become identified as ingredients of modern RCTs (Anand et al. 2009).

Second, the role of elaborator is assigned to contributions that are part of the epistemic core without being connected to a distinct subfield of enquiry. This role captures the idea that after a fundamentally innovative contribution has been made, it often takes time until it has been supported by further evidence or until other scholars have been convinced of its conceptual, theoretical or empirical usefulness. Elaborators contribute to the innovation's establishment by clarifying, adapting and sometimes thereby extending its conceptual, theoretical, or empirical scope. By engaging with the innovation, elaborator contributions align the innovation with field-specific theoretical frameworks and methodological standards, modify it in ways that its usefulness for solving field-specific problems becomes apparent, or offer a commonly shared framework for the innovation to be used in specialist research. Analytically, we identify elaborators as publications that are part of the epistemic core, i.e., that share a strong topical overlap with other elaborators, but do not connect to a distinct research area.

Third, specialist publications exhibit topical overlap with contributions in their respective subfield (i.e., cluster of publications) but are not connected with the epistemic core. As the cluster structure of the epistemic domain captures the increasing specialization that is characteristic of modern science (Leahey et al. 2008), specialist contributions take on the role of working on problems within defined research agendas that tackle highly specialized rather than innovative topics in their respective field. They draw indirectly on the already established and modified innovation to address specific problems of interest within a particular scientific community. We expect specialist contributions to often be outcomes of what Kuhn (1970) has described as normal science. Analytically, we identify specialist contributions as being part of a cluster but not connected to the epistemic core.

While the identification of specialists offers an entry point for studying the cluster-internal structure of the epistemic domain, we consider the fourth role, the translator publications, crucial for examining the conditions under which scientific innovations spread. The translator's role is to establish a connection between the epistemic core and one or more clusters of specialist activity in the periphery of the epistemic domain. Translators differ from elaborators and specialists in that they have a bridging role in facilitating the spread of a scientific innovation from its elaboration in the epistemic core into specialized fields. Particularly in the incipient stage of the diffusion process, translators make the scientific innovation accessible and applicable to discipline-specific or even new problems that lie outside the innovation's direct domain of applications. They align the scientific innovation with more traditional research practices and make its epistemic value apparent for problems in their specialized fields. As such, they connect the core to an interrelated subset of specialists. Translator contributions modify a scientific innovation in such a way that they align with already established frameworks and concepts so that specialist contributions can draw on them. Thereby, translators facilitate the adoption of the scientific innovation across initially remote or even into new domains of enquiry, introduce it into distinct fields, and effectively resolve Kuhn's essential tension between tradition and novelty.

These four roles capture two important ideas that we have hinted at already. Scientific contributions must balance the essential tension between innovativeness on the one hand, and specialization and alignment on the other (see also De Langhe 2014, Uzzi, Mukherjee, Stringer, and Jones 2013). Translators balance this tension by drawing on the innovation to make a substantially novel contribution to problems in a specific research area. The authors of translator publications are able and willing to adopt the scientific innovation, a non-trivial precondition when considering that scientists are trained to use a limited set of established methods and concepts that often do not align with the scientific innovation. On the other hand, they ensure compatibility of their contribution with the epistemic core, which in turn has to inform the research undertaken in the clusters so that the innovation becomes accepted. In bridging the gap between the scientific innovation and a specific field of research, translators must have the rare characteristic of being novel enough to lay the ground for future progress while being sufficiently aligned with the disciplinary culture, accepted conceptual and theoretical frameworks, and traditional techniques in specialist fields.

Analytically, translators broker between the innovation and specialized fields in that they are part of the epistemic core but at the same time highly connected to at least one distinct cluster of specialist publications. In the following, we report on our analysis. Drawing on the taxonomy and respective definitions summarized in Table 3, we identify 15 translator publications in our example from our network representation that are listed in Table 5. They bridged between the scientific innovation of the TGEB and the sub-disciplines.[29]

--- Table 5 here ---

[29] To assess the robustness of our findings, we constructed networks while varying both the maximal number of years between publications by {4,5,6,7} and the minimal co-citation threshold by {2,3,4,5}, and assigned roles to each publication based on their position in the resultant networks. 24 of the 29 publications that we have identified as part of the epistemic core are also identified in 13 or more of the 16 networks. For those 180 publications that appeared in all 16 networks, we then compared role-assignments for each pair of constructed networks using the *Adjusted Rand Index* (*ARI*). This index ranges symmetrically between -1 and 1, with positive values indicating a greater-than-chance correspondence between classifications (Hubert/Arabie 1985). The proposed methodology yields outcomes that are reasonably robust to variations in the network construction, with an *ARI* of between 0.55 and 0.69 indicating a high degree of robustness relative to variations in the maximal number of years between publications and an *ARI* of between 0.12 and 0.3 indicating a moderate but still greater-than-chance robustness to variations in the co-citation threshold. The latter finding reinforces our expectation that increasing the co-citation threshold above three eliminates connections, publications, and research fields that were no longer pursued or that are no longer recognized in chronicles written since the early 1980s (see also footnote 24). Choosing a low threshold mitigates this effect.

In the case of the TGEB, eight of the 15 identified translators belong to the epistemic core. One cluster, that of non-cooperative game theory, has two translators, both of which were authored by Nash (1950, 1951), and both making essentially the same contribution, i.e., the Nash equilibrium. Four clusters (03, 07, 12, and 14) are not themselves directly connected to the epistemic core. In such cases, we assign that contribution the role of translator of a cluster, which has the most connections to contributions that are part of the epistemic core. For example, cluster 03 is not connected to the epistemic core directly, but Riker (1962) is connected to the epistemic core via Luce and Raiffa's classic textbook, and is therefore identified as the translator that made RCTs fruitful for political science. For cluster 07, Schelling (1960) is not in the epistemic core either, but is also connected to Luce and Raiffa (1957), to Simon (1955), and to Pratt (1964). Schelling (1960) has the strongest connection to the epistemic core and is therefore also identified as translator. By this logic, 13 of the 15 previously identified clusters have one translator (see Table 5). In the following section, we interpret and discuss how the translators facilitated the spread of RCTs across the social and behavioral sciences.

8. The Diffusion of Rational Choice Theories in Historical Context

In the previous sections, we have presented a novel approach to identifying the epistemic domain of the TGEB as an indicator for the diffusion process of RCTs and the tools and concepts they were grounded upon. We have identified four salient roles that contributions may have in fostering the diffusion process. With this role typology, we can identify elaborator, specialist, and translator publications on the basis of their network positions. We have claimed that translator publications have a particularly important role in that they link contributions that elaborated upon the TGEB with specialized research areas into which RCTs spread. In this section, we examine the role of translator publications in the diffusion of the tools and concepts contained in the TGEB in more detail and relate our rule-based analysis of bibliometric data back to historical accounts of the social context within which RCTs began to diffuse.

It is generally recognized that the TGEB had an important part in introducing RCTs into the social and behavioral sciences during the early Cold War era (Isaac 2010). While the axiomatic representation of the expected utility principle and the concept of a two-person zero-sum game did not readily match conceptually and methodologically with the traditional utility theory that was predominant at the time (ibid.), they inspired new measurement and data generation techniques, influenced theory-building, motivated the formulation of new formal-mathematical theories of decision-making, and legitimized applications of probability theory, the axiomatic method, and advanced statistical methods in the social and behavioral sciences, among many other issues (Erickson et al. 2013, esp. ch. 4). But before the mathematical tools and concepts contained in the TGEB could transcend intellectual and disciplinary boundaries and be adopted widely, they first had to enter the conceptual toolbox of the scientists. As their application required a substantially new skill set, they could transcend existing disciplinary and intellectual boundaries only by way of being translated. Translator contributions played a significant role in this process.

Existing accounts of the history of von Neumann and Morgenstern's contribution in the TGEB suggest that the spread of tools and concepts contained in it was enabled by contributions made by a small group of scholars who adopted them from early on and elaborated upon them in such a way that they became subsequently applicable to field-specific or new problems. Most of those scholars were considered pioneers and innovators in their field. Their work was interdisciplinary in that they bridged the gap between the highly mathematical contribution primarily von Neumann had made in the TGEB and more traditional theoretical frameworks used and problems tackled in specific areas. Scholars such as Herbert Simon, Kenneth Arrow, John Nash, Harry Markowitz, and Ward Edwards - whose contributions we identified as part of the epistemic core - were young and highly promising and had training in mathematics, mathematical statistics, probability theory, and/or later on in formal decision theory. At the same time, they were less concerned about disciplinary boundaries and more with innovative ways to address problems they considered important and pressing in their research area. Leonard Savage, not yet in his 40s, was an example: In formulating subjective expected utility theory, he fused the axiomatic theory of preferences of von Neumann and Morgenstern with the theory of subjective probability in the tradition of Frank Ramsey and Bruno De Finetti to arrive at a decision theory in risky situations (e.g., Giocoli 2003: 320, Kadane/Larkey 1982: 114). Subjective expected utility theory has been the most influential RCT in economics, statistics, and psychology (Giocoli 2003: 346, Heukelom 2010), as it enabled important applications in various subfields of economics, by serving as a basis for decision and game theoretic models, and by laying the foundations for modern Bayesian statistics and econometrics.[30]

While we cannot discuss the historical narrative in detail here, take Ward Edwards as an example. Edwards became "the father of behavioral decision making" in psychology (Weiss/Weiss 2009). In 1952, he finished his PhD thesis at Harvard, where Frederick Mosteller had introduced him to the TGEB. The outcome of his dissertation work was at least two core publications that laid the grounds for behavioral decision research in psychology (Edwards 1954, 1961). Edwards showed that people have different preferences for probabilities in choices under uncertainty and furthermore that subjective modifications had to be made to von Neumann and Morgenstern's objective probability scales (Shanteau et al. 1999, 408). Published in psychology journals and thus with psychologists as a target audience, those contributions offered an extensive survey of the research in economics on decision making under certainty and risk, including ordinal and cardinal utility theory and indifference curve analysis, and von Neumann and Morgenstern's contribution. In those

[30] For a historical overview, see Savage (1972 [1954]: 91 ff.). For a historical explanation of the success of Savage's subjective expected utility theory in economics, see Giocoli (2003).

publications, Edwards elaborated on how economic theories of decision making could connect to psychological theories as well as existing empirical research and where topical as well as conceptual overlaps between the two areas existed (e.g., Edwards 1954). Apart from expected utility theory, Edwards would eventually establish Bayesian statistics and Savage's 1954 contribution in psychology, which in turn was heavily influenced by the TGEB.

Besides the fact that the TGEB was taken up by these highly innovative and mathematically skilled scholars, another important observation stressed in historical narratives is that intense and cross-disciplinary collaborations between this rather small group were crucial in fostering this kind of novel research.[31] Regular meetings in research seminars, summer workshops, and informal sabbaticals at institutions including the *RAND Corporation* and the *Center for Advanced Studies in the Behavioral Sciences* at Stanford University (hereafter *CASBS*) led to the formation of closely-knit networks of those scholars exchanging ideas on how to work with the new tools and concepts (e.g., Düppe/Weintraub 2014a, Isaac 2010, Backhouse/Backhouse 2010: 11, Erickson 2010, O'Rand 1992). This close interaction between many early adopters of the TGEB is reflected in our analysis. While a co-citation analysis does not capture the social interaction structure of scientists and thus does not allow for inferences about the personal social networks of scientists, co-citation networks, at least in part, result from social network phenomena involving scientists (Mali et al. 2012: 214).

As an example, consider the early adoption of the TGEB in economics. The community of mathematical economists was still rather small in the late 1940s. Their work was not yet widely established, but they were among the first to adopt topology, the axiomatic method, and set theory to theorize about decision-making under risk and uncertainty. Many of the scholars that were part of this community, including Kenneth Arrow, Leonid Hurwicz,

[31] The term "cross-disciplinary research" is often used interchangeably with interdisciplinary or multidisciplinary collaboration and refers to the collaboration that involves the integration of knowledge from two or more disciplines (Klenk et al. 2010: 933).

Tjalling Koopmans, Herbert Simon, Gérard Debreu, and Harry Markowitz, were directly or indirectly affiliated with *RAND*, the *Cowles Commission for Research in Economics*, and the *CASBS* (e.g., Debreu 1983, Erickson et al. 2013). Their collaboration was arguably fostered by the institutional setup of short information channels, informal meetings, regular seminars and workshops with internal and external speakers, and a vivid feedback culture at *Cowles* and the *CASBS* (ibid.). Those kinds of hybrid research environments between a social science lab and a university (Düppe/Weintraub 2014a) allowed scholars to engage more naturally with highly innovative concepts such as the two-person, zero-sum game and the axiomatic representation of the expected utility principle. The key contributions made by these authors are identified as translators (cf. Table 5). They engaged with new mathematical tools and concepts largely collaboratively in those specific research environments. By modifying and subsequently applying the concepts they could find in the TGEB, their work published in the 1950s and 1960s turned into seminal contributions, translating the TGEB for decision theory, social choice theory, mathematical psychology and organizational theory, general equilibrium analysis, mathematical finance, activity analysis, measurement theory, and linear programming, among others. Placing the results of our analysis into the social context at the time partly explains how those translator contributions could be made and allows us to better understand under which conditions scientific innovations become adopted.

Some scholars also made seminal contributions that gave to a field a conceptual or methodological turn or even proved foundational for entirely new fields. For example, Herbert Simon's contributions initiated major research programs in organization theory, business administration, and artificial intelligence and led to his core concept of 'bounded rationality'. William F. Sharpe's work proved foundational for mathematical finance, and Richard E. Bellman's *Dynamic Programming* offered what would become a classic in the field, containing his mathematical theory of multistage decision processes as well as an introduction to mathematical methods and core concepts of mathematical economics and game theory. While these scholars made first steps towards adopting the innovative tools, they at the same time also remained representatives of their own fields, aligning their research with discipline-specific questions and roughly following discipline-specific conventions (Erickson et al. 2013: 12). As such, the positions of these authors' contributions within our network show that their role in the spread of RCTs is best understood as bridging a gap between authors elaborating on, and partly translating, the scientific innovation and specialists applying it to problems of their concern. By fulfilling this bridging function, translators contributed to the spread of the innovative ideas contained in the TGEB towards their modification and their application within and across old and new fields in the behavioral and social sciences.[32]

As they produce novel research while at the same time establishing compatibility with previous research, we suggest that authors of translator contributions can be understood in terms of what Collins and Evans (2007) have called 'interactional experts'. Interactional experts have acquired the ability—by engaging with experts of a particular area of expertise—to converse in a language that extends beyond the accustomed conceptual, methodical, and/or theoretical skill set of their research area. They are thereby able to engage with other specialized fields without themselves being part of that field. In our case, scholars such as Simon, Nash, Savage, Arrow, Debreu, and Markowitz were well-versed in mathematical logic, mathematical statistics, mathematical psychology, and economics without working themselves in mathematics, mathematical statistics, or mathematical economics respectively. Arguably, this enabled them to adopt a scientific innovation that had primarily been mathematical in nature and then translate it so that it could be taken up and used by others. They could occupy a bridging role between their own specialized field and

[32] We can only pick out some examples to illustrate the match between our findings and existing historical narratives. A substantial support of the results of our analysis with existing historical narratives or even historical research exceeds the scope of this paper.

other elaborators, which was demonstrated by the fact that subsequent publications would take up their contributions.

While a detailed discussion of the historical context remains to be undertaken in a different paper, we suggest that the concept of an ‘interactional expert’ could in combination with our role typology motivate further research that examines the social interaction among, and disciplinary backgrounds of, the authors of each type of contribution. It allows for making an inference from those publications to their authors. In our example, two innovative concepts—the axiomatic representation of the expected utility principle and the minimax theorem—together with a set of mathematical tools and concepts not used previously in the social and behavioral sciences first had to be comprehended, elaborated upon, and translated in such a way that they would become epistemically useful for a wide range of specialized research areas. This process was largely enabled by the translator contributions written by mathematically-skilled social or behavioral scientists, who with their work bridged the gap between elaborator and specialist contributions and thereby integrated the scientific innovation into normal science practice.

9. Conclusion

In this paper, we have addressed the question of how scientific innovations diffuse within and across scientific communities. We have introduced a novel diffusion measure based upon a co-citation network analysis and, using it, have traced the early spread of RCTs in the second half of the 20th century as an exemplary case. By applying our framework, we have investigated how the innovative mathematical tools and concepts as well as the two accounts of rational behavior contained in John von Neumann and Oskar Morgenstern’s *Theory of Games and Economic Behavior* led to the spread of axiomatic RCTs within and beyond the behavioral and social sciences. We have shown that translator publications facilitated the diffusion of new ideas by modifying a scientific innovation in ways that bridge the gap between the epistemic core of the innovation and specialized fields. As authors of translator publications must have the ability to communicate across fields, they can be understood as 'interactional experts' who allow for the innovation to enter pre-existing research areas and lay the grounds for new ones.

While illuminating the example of the diffusion of RCTs, our framework allows for some general conclusions about the roles that scientific contributions occupy in the diffusion of scientific innovations and as such about one instance of how knowledge becomes transferred across distinct contexts. Our approach and role typology can be applied to other representative cases for knowledge diffusion to identify and classify key contributions that modify a scientific innovation by way of their salient positions in the network. Furthermore, our analysis has methodological implications for the study of scientific innovation in particular and for the production of knowledge more generally. We see the usefulness of empirical network analysis for studying knowledge diffusion in science in the extent to which it allows to examine historical cases in systematic ways. The increasing availability of bibliometric data makes empirical network analysis a promising method to address questions about knowledge transfer in general.

Furthermore, systematic empirical studies such as ours complement detailed studies undertaken by historians and philosophers of science and thereby establish connections between historical research and more systematic analyses. While historical accounts, for instance of RCTs, can examine details of the social, political, cultural, and institutional context, elaborate extensively on professional biographies of the scientists, and trace the nature and intensity of personal relationships between scholars, such research may be constrained by confirmation biases, the limited availability of historical sources, and the specific focus a historian takes. A quantitative-empirical analysis - where appropriate - can complement detailed historical research, offer a broad and temporal perspective on diffusion processes, systematically identify all relevant actors or contributions according to a plausible set of rules, and mitigate potential biases originating in personal interest or a one-sided research emphasis.

The proposed framework offers a bird's-eye view of the spread of scientific innovations that complements more detailed historical studies. As such, it stands to be further substantiated by detailed historical studies of actual modification processes, of the conceptual and methodological implications that the scientific innovation in question has had for particular fields of inquiry, and of the human actors and the institutions they are a part of. With the overarching epistemic domain of the scientific innovation established, local sites of the diffusion can be reconstructed and interpreted against the backdrop of a historical context that is only partially amenable to applications of algorithmically and/or rule-based methods. For example, as a set of interrelating scholarly contributions, the epistemic domain of the TGEB offers ample opportunity for enriched reconstructions of reasons for an observed topical overlap or lack thereof. Each of the contributions that form part of the epistemic domain was made by particular authors who were working in specific institutional contexts and at particular times. Further research could zoom into the links between individual contributions, their authors and the multifaceted contexts within which they produced their work, focus more closely on one or more clusters, or study the interconnectedness of clusters.

By combining historical narrative and empirical network analysis, our case demonstrates how methods of network analysis can integrate and inform history and philosophy of science. By bringing more nuanced perspectives on the idiosyncrasies of particular diffusion settings, further research stands to identify points of similarity and divergence with the rule-based account that we have laid out in this paper and can thereby provoke fresh perspectives on the processes in question. In the belief that an overall account of the diffusion of particular scientific innovations is best rendered at the intersection between quantitative methods and qualitative accounts, further historical studies could examine the plausibility of the connections that emerge when applying our rule-based method to bibliometric data that has been collected many years after the fact.

Figures

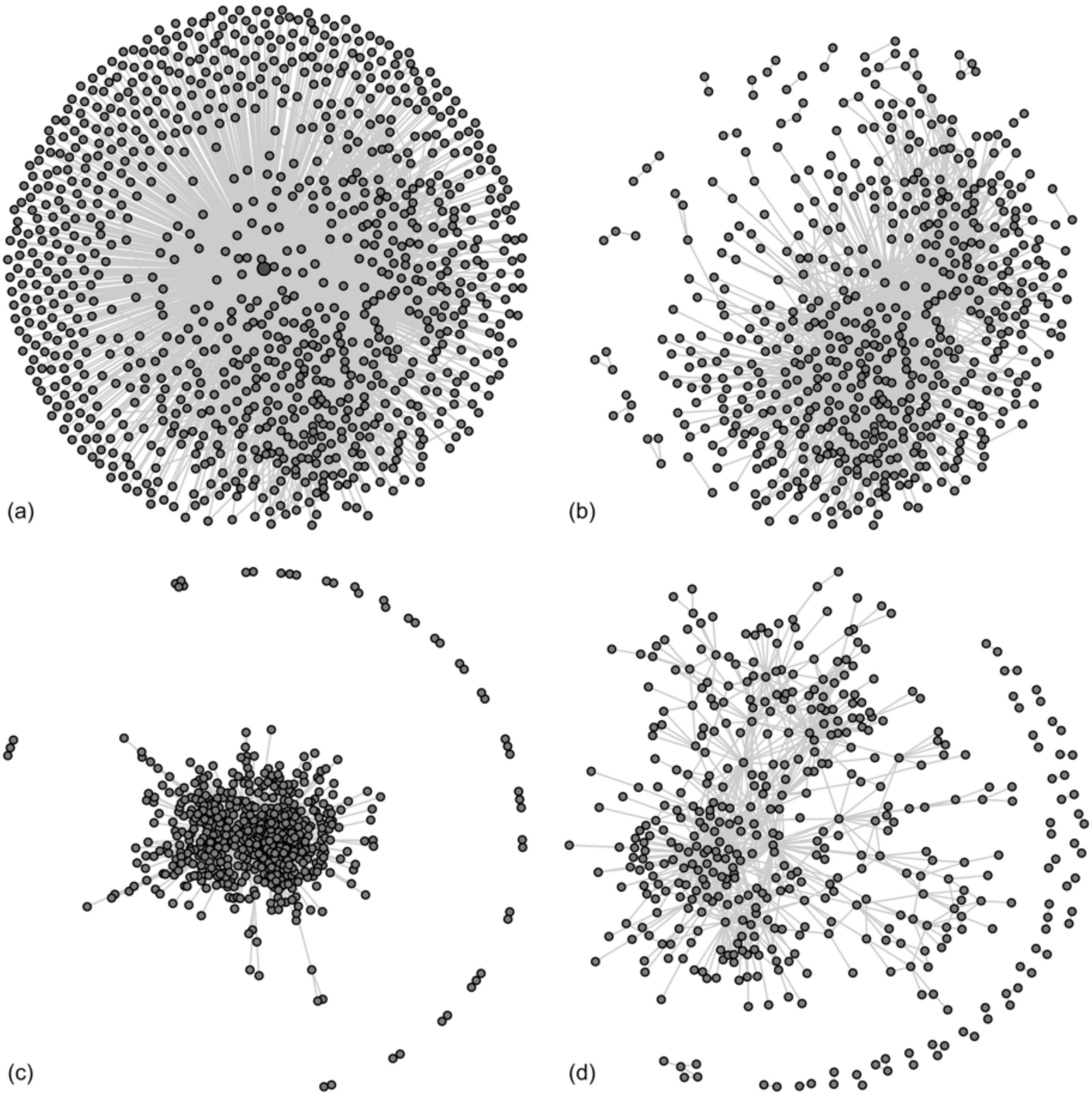


Figure 1: Constructing the network topology of the epistemic domain of the TGEB: Panel (a) shows all 936 contributions that are cited at least three times in 4,905 present-day publications that also cite the TGEB, the enlarged, darker node at the center of the network. Every node is connected to the TGEB. (b) depicts the network after removing the TGEB and isolate nodes (N=535). The updated layout of the same network in (c) reveals a dense clustering of co-citations in present-day publications. Eliminating all edges between publications that lie more than 5 years apart yields (d), the network topology (N=442). The layouts of (a), (c) and (d) are defined by the same algorithm (Fruchterman/Reingold 1991).

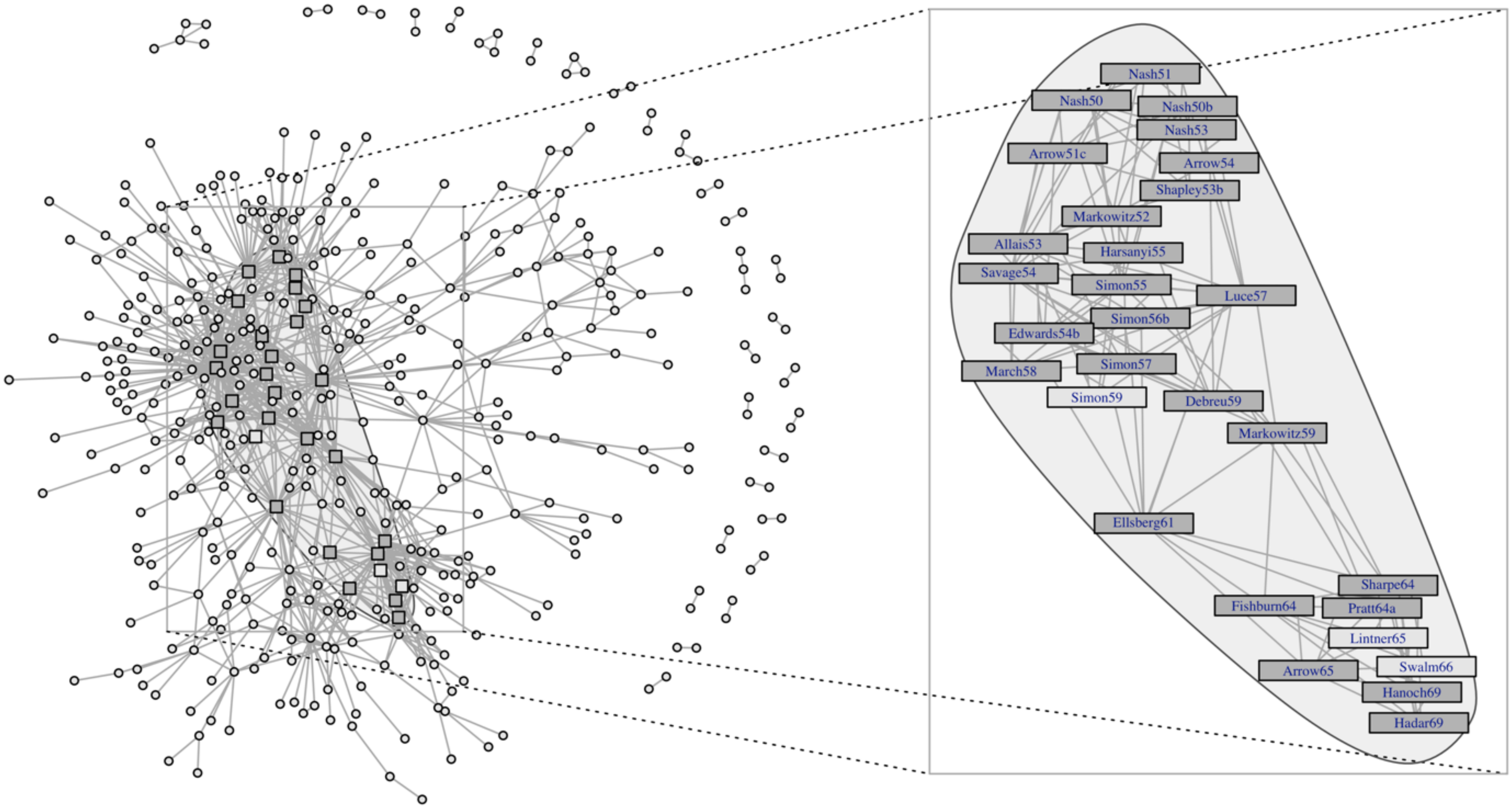


Figure 2 The core of the epistemic domain of the TGEB. The inset depicts topical overlaps within the epistemic core. Publications in dark gray shading are robust to moderate variations in network construction, i.e., they are identified as part of the epistemic core in at least 80% of tested variants (cf. footnote 29).

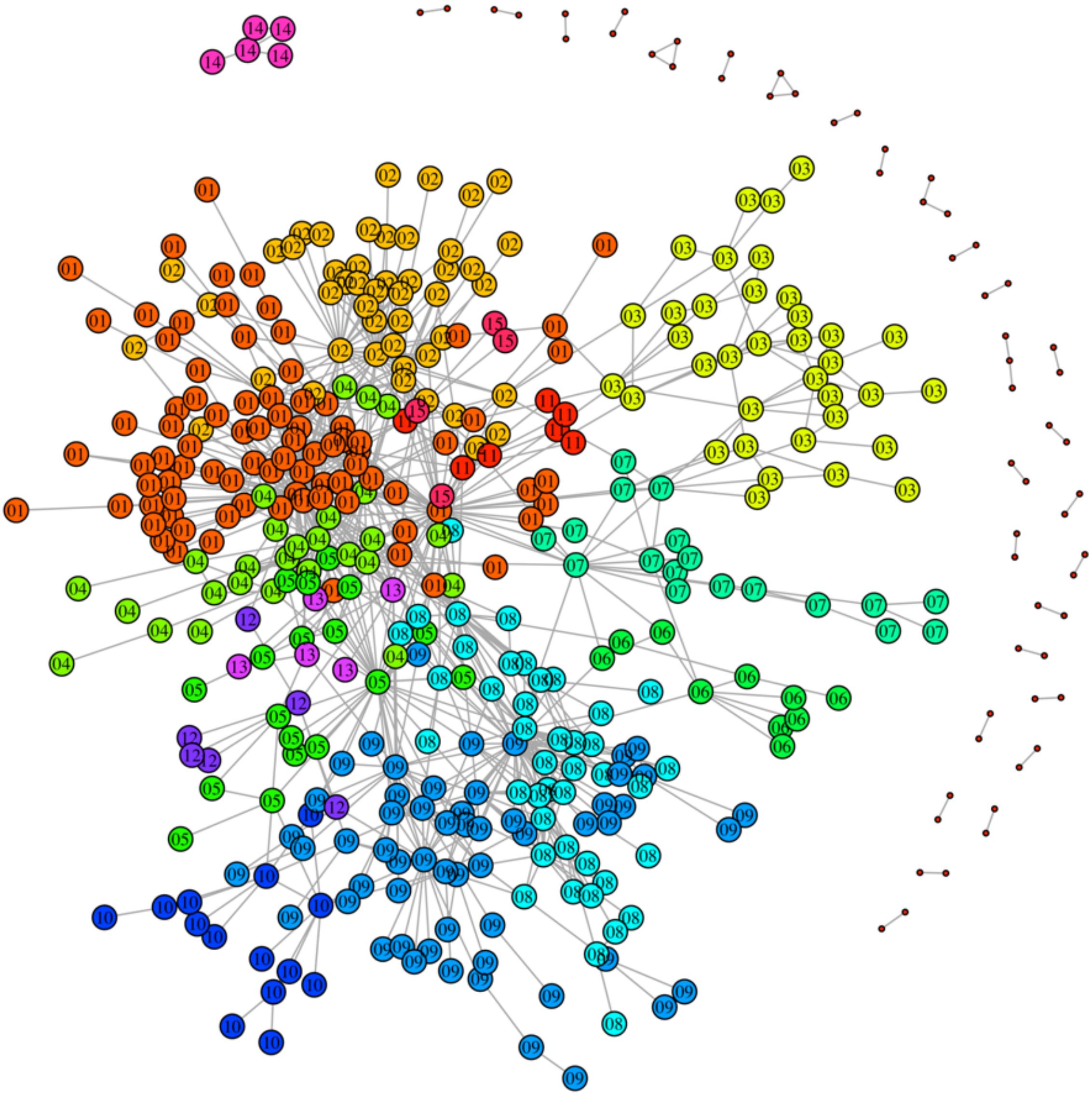


Figure 3: Clustering of the epistemic domain into which RCTs finally diffused.

Tables

Fields of academic enquiry
• General Equilibrium Analysis • Operations Research, Linear Programming, Activity Analysis • Behavioral Decision Research • Public Choice Theory • Social Choice Theory, Welfare Economics • Formal decision Theory • Mathematical statistics, statistical decision theory, Bayesianism • Artificial intelligence research • Cooperative / non-cooperative game theory, bargaining theory, theories of conflict • Mathematical psychology • Measurement theory • Theories of organization • Mathematical finance, portfolio selection theory • Evolutionary biology • Microeconomics, information theory, industrial organization • Philosophy, logic, computer science • Mechanism design theory

Table 1: Fields in the behavioral and social sciences that were influenced by the TGEB around 1970.

Period	Articles	Conference Papers	Book Chapters	Total
[1980,1995]	15 (46.0)	0 (0.0)	0 (0.0)	15 (46.0)
(1995,2000]	544 (44.0)	15 (32.3)	0 (0.0)	559 (38.0)
(2000,2005]	726 (44.9)	231 (26.2)	14 (39.2)	971 (36.1)
(2005,2010]	1,234 (49.3)	491 (26.1)	95 (52.8)	1,820 (38.5)
(2010,2014]	1,158 (58.8)	324 (25.5)	58 (56.3)	1,540 (43.4)
Total	3,677 (50.6)	1,061 (26.0)	167 (52.9)	4,905 (39.5)

Table 2: Data collected from 4,905 publications that cite TGEB according to Scopus; grouped by period and type of source. Numbers in parentheses denote average references for each source type and period.

ID	Research areas	Size	citations av. (s.d.)	year av. (s.d.)	Most cited within cluster
01	Theories of decision-making, broadly cited classics	86	32.3 (74.78)	1953.0 (3.7)	Savage54, Allais53, Luce57, Markowitz52, Arrow51c
02	Non-cooperative game theory, bargaining theory, cybernetics	47	29.4 (61.23)	1951.8 (3.1)	Nash51, Nash50, Nash50b, Nash53, Shapley54
03	Cooperative game theory, coalition formation	36	15.4 (13.07)	1964.0 (3.3)	Schmeidler69, Riker62, Banzhaf65, Shapley67, Davis65
04	Behavioral models of decision-making, math. psychology	27	22.3 (31.80)	1956.6 (3.8)	Simon55, Simon57, Edwards54b, Simon56b, March58
05	Stochastic decision theory, foundations of decision theory	18	28.1 (59.68)	1960.9 (2.7)	Ellsberg61, Cyert63, Simon59, Friedman66, Strotz56
06	Linear programming, incompl. information, Bayesianism	10	24.6 (24.94)	1965.2 (3.0)	Harsanyi67, Selten65, Akerlof70, Lewis69, Lemke64
07	Theories of conflict and cooperation	18	21.9 (23.24)	1962.9 (3.9)	Schelling60, Hardin68, Gillies59, Aumann59, Rapoport65
08	Mathematical finance, portfolio selection, asset pricing	42	17.1 (21.49)	1965.3 (3.8)	Markowitz59, Rothschild70, Sharpe64, Hadar69, Hanoch69
09	Statistical decision theory, measurement theory	57	22.5 (34.98)	1966.1 (3.0)	Pratt64a, Fishburn70c, Raiffa68, Anscombe63, Arrow65
10	Behavioral decision science	14	18.1 (20.14)	1967.6 (2.1)	Luce69, Tversky69, Slovic68, Becker64, Lancaster66
11	Linear programming, operations research	7	34.7 (54.90)	1958.6 (3.2)	Shapley53b, Bellman57a, Howard60, Pontryagin62, Bellman62
12	Applied statistical decision theory	6	11.7 (10.76)	1963.5 (3.0)	Raiffa61a, Howard66a, Edwards63a, Schlaifer59, Phillips66a
13	Economic theory of value	5	15.8 (17.28)	1959.6 (2.9)	Debreu59, Debreu60a, Kraft59, Scott64, Patinkin56
14	Evolutionary biology	5	10.6 (12.60)	1965.4 (2.4)	Hamilton64, Williams66, Hamilton67, WynnEdwards62, Lee68
15	General equilibrium analysis	4	11.5 (13.18)	1957.0 (2.2)	Arrow54, Koopmans57a, Arrow58a, McKenzie59

Table 3: Fifteen clusters of contributions representing distinct fields into which the conceptual innovations contained in the TGEB spread between 1944 and 1970.

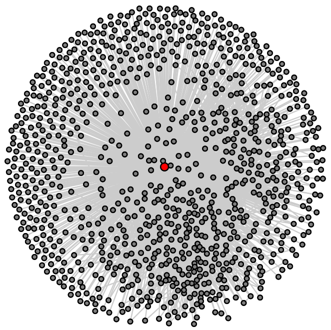
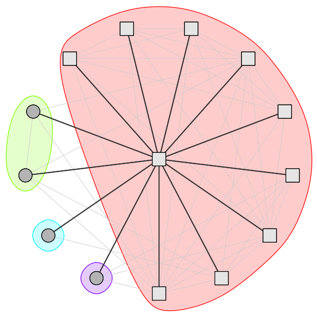
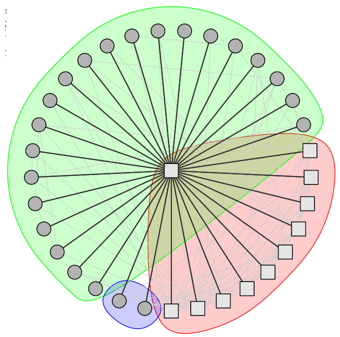
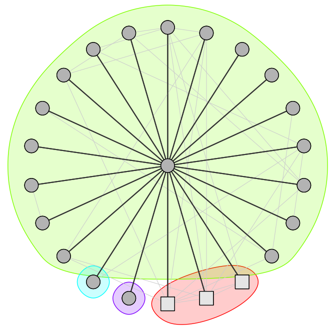
Role	Innovator	Elaborator	Translator	Specialist
Function	• Formulates innovation in a way that motivates subsequent engagement and elaboration.	• Adopts innovation and develops it further without establishing a separate sub-field of enquiry	• Makes innovation fruitful for applications in a separate (novel) field of enquiry. • Connects elaborators and specialists.	• Applies translated innovation to ‘normal science’ problems in a distinct subfield of enquiry.
Technical Criterion	• Is identified model-exogenously. • Starting point for data collection.	• Part of the epistemic core. • Low degree centrality in any cluster.	• Connects epistemic core to its cluster. • High(est) degree centrality within cluster.	• Not in the epistemic core. • Well-connected (only) to other contributions in its cluster.
Network Position				
N	1	13	16	82

Table 4: Four roles that publications can take on in the diffusion of a scientific innovation. Roles are assigned by identifying each publication’s position in the network representation of the epistemic domain of the epistemic domain. Publications that are part of the epistemic core are identified as squares.

Cluster	Translator publication	Times Cited
01	Savage, L.J., (1954): *The Foundations of Statistics*, New York: John Wiley and Sons	542
02	Nash, J.F. (1950): Equilibrium Points in n-Person Games, *PNAS*, 36, 48-49	274
02	Nash, J. (1951): Non-cooperative Games, *Annals of Mathematics*, 54, 286-295	295
03	Riker, W.H. (1962): *The Theory of Political Coalitions*, New Haven: Yale University Press	46
04	Simon, H.A. (1957): *Models of Man. Social and Rational: Mathematical Essays on Rational Human Behavior in a Social Setting*, Chapman & Hall Ltd., London	79
05	Ellsberg, D. (1961): Risk, Ambiguity and the Savage Axioms, *Quarterly Journal of Economics*, 75, 643-669	265
06	Harsanyi, J.C. (1967): Games with Incomplete Information Played by Bayesian Players (I, II and III), *Management Science*, 14, 159-182, 320-334, 486-502	90
07	Schelling, T.C. (1960): *The Strategy of Conflict*, Harvard University Press	93
08	Sharpe, W.F. (1964): Capital Asset Prices: A Theory of Market Equilibrium Under Conditions of Risk, *Journal of Finance*, 19, 425-442	64
09	Pratt, J.W. (1964): Risk Aversion in the Small and in the Large, *Econometrica*, 32 (1-2), 122-136	190
10	Becker, G.M., Degroot, M.H., Marschak, J. (1964): Measuring Utility by a Single-response Sequential Method, *Behavioural Science*, 9 (3), 226-232	20
11	Bellman, R. (1957): *Dynamic Programming*, Princeton, NJ: Princeton Univerity Press	46
12	Raiffa, H., Schlaifer, R. (1961): *Applied Statistical Decision Theory*, Cambridge, MA: MIT Press	32
13	Debreu, G. (1959): *Theory of Value: An Axiomatic Analysis of Economic Equilibrium*, New York: Wiley	46
15	Arrow, K.J., Debreu, G. (1954): Existence of an Equilibrium for a Competitive Economy, *Econometrica*, 22, 265-290	31

Table 5: Translator publications identified from their positions in the co-citation network.

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