New Patterns of Scientific Growth: How Research Expanded After the Invention of Scanning Tunneling Microscopy and the Discovery of Buckminsterfullerenes

Thomas Heinze and Richard Heidler
Lehrstuhl Organisationssoziologie, Gaussstraße 20, Bergische Universität Wuppertal, 42119 Wuppertal, Germany. E-mail: {theinze,heidler}@uni-wuppertal.de

Raphael Heiko Heiberger and Jan Riebling
Lehrstuhl Soziologie II, Lichtenhaidestraße 11, Otto-Friedrich-Universität Bamberg, 96045 Bamberg, Germany. E-mail: {raphael-heiko.heiberger,jan.riebling}@uni-bamberg.de

This article describes patterns of scientific growth that emerge in response to major research accomplishments in instrumentation and the discovery of new matter. Using two Nobel Prize-winning contributions, the scanning tunneling microscope (STM) and the discovery of Buckminsterfullerenes (BUF), we examine the growth of follow-up research via citation networks at the author and subdiscipline level. A longitudinal network analysis suggests that structure, cohesiveness, and interdisciplinarity vary considerably with the type of breakthrough and over time. Scientific progress appears to be multifaceted, including not only theoretical advances but also the discovery of new instrumentation and new matter. In addition, we argue that scientific growth does not necessarily lead to the formation of new specialties or new subdisciplines. Rather, we observe the emergence of a research community formed at the intersection of subdisciplinary boundaries.

Introduction

This article analyzes the impact of scientific contributions that were recognized as breakthroughs according to how they stimulated follow-up work both inside and outside their original disciplinary context. The first goal of our work is to better understand the scientific growth that originates from different types of scientific advances. While it is common practice to analyze disciplinary reconfigurations following major theoretical advances, our analysis includes often neglected types of scientific accomplishments: The development of a new research instrument and the discovery of new matter. Our second purpose is to investigate whether scientific growth following major research accomplishments leads to disciplinary reconfigurations other than subdisciplinary specialization. While the history and sociology of science typically interpret scientific growth as a process of disciplinary specialization and differentiation, we explore whether this conventional interpretation holds for the development of new research instrumentation and the discovery of new matter.

Conceptually, this article draws on two related arguments. First, there has been renewed attention to the question, what constitutes a major advance in research, and how such breakthroughs can be properly operationalized and identified (Aksnes, 2003; Sternberg, 2003; Hollingsworth, 2004; Guetzkow, Lamont, & Mallard, 2004; Heinze, Shapira, Senker, & Kuhlmann, 2007)? In this literature, there is a broad consensus that major scientific advances include not only new theories, but also new data or new approaches (Guetzkow et al., 2004), or new empirical phenomena and new instrumentation (Heinze et al., 2007). Major advances are often recognized by peers within a few years after their initial publication (Seglen, 1992; Aksnes, 2003), and they frequently receive major prizes (Zuckermann, 1977; Hollingsworth, 2004).

The second argument debates whether scientific growth typically leads to specialization and differentiation. In this debate, the central role of experimental systems in the generation of new knowledge has been pointed out (Hacking, 1983; Shapin & Schaffer, 1985; Heidelberger & Steinle, 1998; Meli 2006, Rheinberger, 1997, 2010). In particular, Rheinberger (1997, 2010) and Shinn and Jörges (2002) argue that the history and sociology of science have largely been written in the framework of a discipline-related science culture, and that the impacts of experimental systems and research instrumentation on the advancement of science

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have been overlooked. Because new instruments and experimental systems develop across disciplinary and institutional borders and do not constitute distinctive academic fields, they have almost disappeared from the discipline-tuned radar of science studies.

Drawing upon two recent breakthroughs in physics and chemistry, we discuss three interrelated questions. First, we examine the level of recognition attracted by these breakthroughs. Second, we investigate the spectrum and concentration of academic disciplines that are the focus of follow-up research. Third, we analyze the intellectual integration and connectedness of the academic disciplines that cite these breakthroughs. We address these questions by analyzing the structure and evolution of the citation networks composed of all Web of Science (Wos) Science Citation Index (SCI), and Social Sciences Citation Index (SSCI) publications that cited these breakthroughs. Data analysis is conducted at the levels of authors and subdisciplines. We find that scientific growth following a research breakthrough is a complex phenomenon that involves, for example, rapid or gradual growth/decline, single-peaked or multiple-peaked growth paths, intradisciplinary or interdisciplinary communication patterns, and highly concentrated or broadly distributed recognition. Furthermore, we find substantial differences between follow-up research of scanning tunneling microscope (STM) as an example of instrumentation and Buckminsterfullerenes (BUF) as an example of empirical discovery; these differences shed light on the intricate relationship between cognitive and social dynamics in science. Our results suggest that after these two breakthroughs, an international interdisciplinary research community emerged that is intellectually anchored in the representation and modification of matter at the nanoscale.

The structure of the paper is as follows: First, we outline two widely accepted models of scientific change: The theory model of scientific progress and the discipline model of scientific growth (next section). Then we introduce research questions to extend these two conventional beliefs. After describing the two breakthroughs and their selection, we present data sources and variables. Next we discuss and interpret empirical findings (Results section), and finally we summarize the results, discuss limitations of the paper, and point to further research possibilities (Conclusion and Discussion).

Two Conventional Models of Scientific Progress and Growth

Two positions regarding scientific growth contribute to the fundamental tenets of the philosophy, the history, and the sociology of science. First, it is commonly believed that the formulation of new theories represents the major route to the advancement of knowledge. For example, Popper (1959) defines scientific progress as a falsification of hypotheses through which there is a continuous exclusion of empirically unsubstantiated theoretical statements. Kuhn (1970, 1987), while criticizing Popper, also presents a similar position due to his focus on revolutionary theoretical changes. Lakatos (1970), in criticizing Kuhn's model of scientific revolutions, emphasizes the significance of research programs that have a theoretical core. Similarly, this common focus on theoretical advances has deeply influenced the sociology of science. For example, Merton (1968) argues that empirical findings, new data, and new methods are important in science insofar as they exercise pressure for the improvement and extension of theories. Regarding empirical findings, Merton identifies the serendipity pattern, that is, "observing an unanticipated, anomalous and strategic datum which becomes the occasion for developing a new theory or for extending an existing theory" (Merton, 1968, p. 507). In addition, he discusses the reformulation pattern that "centers in the hitherto neglected but relevant fact which presses for an extension of the conceptual scheme" (Merton, 1968, p. 511). Finally, the new method pattern involves "the invention of research procedures which tend to shift the foci of theoretic interest to the growing points of research" (Merton, 1968, p. 512). Merton does not conceive of the three patterns as independent categories of scientific accomplishments. Rather, he argues that all three have merely a "stimulating effect upon the further development of *theory"* (Merton, 1968, p. 512, emphasis added).

In the following discussion, the close connection between knowledge advancement and the formulation of new theories is called the *theory model of scientific progress*. Since the 1980s, this model has been criticized as understating the role of experimental settings in advancing knowledge. Today, the central role of experimental systems, both in generating new knowledge and in renewing established doctrine, is widely acknowledged in science history (Hacking, 1983; Shapin & Schaffer, 1985; Rheinberger, 1997, 2010; Heidelberger & Steinle, 1998; Meli, 2006). For example, Hacking (1983) argues that experiments generate new scientific entities and facts independently from theories; thus, "experimentation has a life of its own" (Hacking, 1983, p. 250). According to Rheinberger (1997, 2010), the function of sophisticated experimental systems is not limited to theory testing, but is to continuously generate new empirical facts that may or may not have implications for theory development. In line with this experimental turn, there has been a lively debate about what constitutes major advances in science, and how such breakthroughs can be properly operationalized and identified (Aksnes, 2003; Sternberg, 2003; Hollingsworth, 2004; Guetzkow et al., 2004; Heinze et al., 2007). For example, Guetzkow et al. (2004) found that original contributions to the social sciences and humanities include new data, new approaches, and understudied topics. Heinze et al. (2007) identified new methods, new empirical phenomena, and advances in instruments as important aspects of scientific creativity in the natural and technical sciences. This literature suggests that the theory model tends to neglect other equally important accomplishments in research. In this paper, we apply the insights of these findings and study the intellectual impact of advances in research instrumentation and discoveries of new matter.

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The second position holds that scientific growth unfolds as a process of specialization or differentiation (Luhmann, 1992; Stichweh, 1994), similar to how physical chemistry gradually developed as a new branch of chemistry (Servos, 1990), or materials science emerged as a new discipline (Bensaude-Vincent, 2001). New specialties arise when breakthroughs attract a substantial number of peer scientists to work on related questions and problems (Felt & Nowotny, 1992; Jansen, 1998; Braun, 2012). New disciplines also arise when powerful societal actors support particular types of expertise. For example, governments and industry have sponsored various research activities that in turn spurred the formation of disciplines, such as physical chemistry or earth sciences (Hounshell & Smith, 1988; Doel, 2003; Hamblin, 2005).

In the following discussion, we refer to the close connection between scientific growth and specialty formation or the emergence of new subdisciplines as the *disciplinary model of scientific growth*. Following recent findings about the emergence of research technologies, we argue that this model tends to neglect other equally important responses to breakthroughs, and therefore it eclipses an immense amount of science that occurs outside the disciplinary matrix. For example, Shinn and Jörges (2002) show that research technologies have often been overlooked, because they typically develop across disciplinary and institutional borders, and they often do not constitute academic fields. An example of a typical research technologist is engineer Ernst Ruska, who developed electron microscopy in the 1930s. Ruska's career started at the Technical University of Berlin and he worked for two companies, including Siemens. Later he was appointed director at the Fritz-Haber-Institut of the Max-Planck Society (Lambert & Mulvay, 1996). Within these three institutional contexts, Ruska continuously improved the electron microscope. His invention was neither inspired by theory, nor did it have major theoretical implications. Ruska did not know about de Broglie's wave theory when developing his first prototype. Despite its wide applicability across various disciplines, including structural biology, virology, and materials science, the new microscopy did not establish a new subdiscipline; thus, the electron microscope is barely visible on the discipline-tuned radar of traditional history and sociology of science. In this paper, we apply insights from the literature on research technologies and study how more recent discoveries of new instrumentation and new matter have led to follow-up research across disciplinary boundaries.

It follows from earlier discussion that the theory model of scientific progress and the discipline model of scientific growth are related to each other. In their simplest and perhaps crudest forms, both models claim that knowledge advances predominantly via new theories, and that new theories are the essential element in the establishment of academic disciplines. Thus, one type of scientific progress (theoretical advances) is regarded as a precondition for one type of scientific growth (specialty/subdiscipline formation).

To be sure, there are more elaborated versions of these two models. For example, Law (1973) argues that, depending on the problem definitions used within scientific communities, specialties may be based on theory, methods, or subject matter. Knorr-Cetina (1999) discusses the considerable cultural differences between specialties, such as high-energy physics and molecular biology. Whitley (2000) argues that physics is more hierarchical and integrated than either chemistry, biology, or the social sciences. Although these elaborated versions improve upon the original two models, they are mostly based on anecdotal evidence and do not consider how cultural or social differences between specialties or disciplines influence growth patterns once major intellectual advances have occurred. Even more elaborated models assume similarity in growth patterns across different disciplines. In this paper, we explore the follow-up research that emerged after two major nontheoretical breakthroughs. Our exploration is based on quantitative and longitudinal data, and we compare the intellectual responses to breakthroughs having anchors in quite different disciplinary settings: physics (instrumentation) and chemistry (new matter). The next section introduces the research questions guiding our analysis.

Research Questions

Our purpose is to extend both the theory model and the discipline model in an exploratory fashion. We address three sets of questions to accomplish this. First, we determine the growth of research following certain research breakthroughs. (Q-a) How quickly are breakthrough papers taken up by peers? (Q-b) Does the amount of follow-up research reach a peak and then decrease over time? Second, we measure the spectrum and concentration of academic disciplines in follow-up research. (Q-c) How many subdisciplines are active in follow-up research? (Q-d) Is follow-up research broadly distributed among all or concentrated in a few subdisciplines? (Q-e) How interdisciplinary is the communication within follow-up research? Third, we explore the intellectual connectivity of follow-up research. (Q-f) How often do citing scientists recognize each other? (Q-g) How interconnected is the network of citing scientists?

According to the theory model and the disciplinary model, we would expect the following stylized answers. (Q-a) Growth of follow-up research is instant and rapid because the theoretical claim has high scientific value leading many scientists to migrate into the emerging field. (Q-b) Follow-up research reaches a peak once all knowledge claims from the breakthrough are harvested. At that point, the scientists' attention increasingly shifts to new theoretical claims. (Q-c) Few subdisciplines follow the breakthrough because its scientific value applies to a limited intellectual territory. (Q-d) Follow-up research is highly concentrated in few subdisciplines for which the breakthrough is particularly relevant. (Q-e) Although the level of interdisciplinary communication grows initially, it remains low as theoretical advances are integrated into disciplinary knowledge. (Q-f)

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Scientists engaged in follow-up work often cite each other because they share a common disciplinary base. (Q-g) The network of citing scientists is cohesive and interconnected because of their common disciplinary base.

These stylized responses refer primarily to theoretical advances within a paradigm. According to Kuhn (1970, pp. 23–35), theoretical advances within a paradigm include the derivation of new laws from existing laws or the identification of inconsistencies in theoretical statements. Although Kuhn (1970) is famous for distinguishing between normal science and scientific revolutions, he addressed the issue of nonparadigmatic theoretical advances as well. This point is important because if we referred primarily to paradigmatic theoretical shifts, then several of our stylized responses would require revision. For example, in the case of paradigmatic shifts, (Q-f) could be stated as follows: "Scientists engaged in follow-up work after the fracture of disciplines often do not cite each other because they are no longer within the same paradigm."

Clearly, the stylized responses have not been tested empirically, and they are one possible interpretation of the result of theory and discipline models of scientific change: they are by no means exhaustive. Thus, one could argue that disconfirming Q-a to Q-g would not disconfirm the two models, but merely this paper's interpretation of the resulting effects of those models. Still, we believe that our stylized responses are plausible because they capture important, although perhaps not all aspects of the two conventional models that have been so influential in the philosophy and history of science.

Moving beyond the theory model and the disciplinary model requires an exploratory empirical approach. Therefore, we study the result of breakthroughs in research instrumentation and the discovery of new matter using large-scale longitudinal publication and citation data sets. The next section describes the selection of these breakthroughs, and the corresponding data sets and variables are then introduced. Once comprehensive empirical observation data have been obtained, they can be compared and contrasted with the above responses based on the two conventional models (Results).

Selection of Scientific Breakthroughs

Several bibliometric studies have suggested that a 10-year time window is appropriate for the analysis of scientific growth, although some studies considered shorter periods of 3–5 years (van Dalen & Henkens, 2004; Glänzel, Schlemmer, & Thijs, 2003; Sengupta & Henzler, 1991; Stern, 1990). Furthermore, studies of stratification in science show that, despite a global trend of awarding prestigious prizes to older scientists (in particular for their lifetime accomplishments), a considerable number of such prizes, among them the Nobel Prize, are awarded a few years after publication (Jones & Weinberg, 2011; Hollingsworth, 2002; Zuckerman, 1992). On this basis, we consider scientific contributions that, in the decade following their publication, received both an unusually high number of citations as well as a Nobel Prize. High numbers of citations typically indicate scientific relevance. In addition, the Nobel Prize indicates that a contribution is regarded as ground-breaking by the scientific community. We believe that these two indicators in combination, select scientific breakthroughs in a reliable and robust way. Clearly, our selection tends to exclude contributions that did not resonate well with peers during the first years after their publication: So-called premature discoveries that have been either ignored or even resisted (Campanario, 2009; van Raan, 2004; Stent 2002; Shadish et al., 1995). However, our focus is on scientific breakthroughs that have been incorporated relatively swiftly in ongoing research.

Using the two criteria mentioned earlier, we identified two breakthroughs that meet the qualifications of being highly cited in the 10 years after their publication, as well as leading to a Nobel Prize in that period. First, we select the invention of a new research instrument, the scanning tunneling microscope (STM). This was a major advance in spectroscopy, and its inventors, Gerd Binnig and Heinrich Rohrer, subsequently received the Nobel Prize in physics. The principle of the STM is that a precisely constructed tip is moved line-wise over a surface to measure the tunneling current. In contrast to classic microscopy, STM is based both on contact free scanning and on the well-known tunneling effect, under which tiny objects like electrons are able to pass through solid objects. While the theoretical principle of STM was well understood, technical obstacles to its development needed to be overcome, such as how to construct a nondeforming tip and protect the measuring unit from vibrations (Mody, 2011; Choi & Mody, 2009; Hessenbruch, 2004; Bai, 2000; Chen, 1993).

Second, we selected the discovery of Buckminsterfullerenes (BUF), a soccer ball-like carbon structure. For this discovery, Harold Kroto, Richard Smalley, and Robert Curl received the Nobel Prize in chemistry. BUF is an aromatic molecule consisting of 60 carbon atoms made up of 20 hexagons and 12 pentagons. BUF is part of the larger fullerene molecule family, members of which all share a closed ball-like shape. This shape makes it possible to imprison various other atoms and molecules inside the carbon cage. Several years after its discovery, it was still not possible to obtain sufficient quantities of BUF to enable a study of both its chemical properties and its hypothesized structure. It was not until the development of a heating process that mass production of carbon fullerenes was possible, thereby enabling BUF to develop into a global research field (Aldersey-Williams, 1995; Baggot, 1994).

STM and BUF are adequate candidates for extending both the theory model and the discipline model. First, theory does not play a prominent role in either case, demonstrating that scientific progress may spring from accomplishments other than theoretical advances. In the case of STM, there were some initial reservations from quantum theorists because, according to Heisenberg's uncertainty principle, it was considered impossible to reduce the distance between the instrument's tip and the observation surface to merely an atom. However, it was soon discovered that the Heisenberg

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principle applies only to free atoms and not to atoms embedded in solid matter. In addition, the tunneling effect underlying STM was predicted in the 1920s, and its acceptance as a general phenomenon in physics occurred in the 1950s. Therefore, the preparatory theoretical work was completed long before the construction of the new research instrument in the 1980s. In the case of BUF, the aromatic molecule was theoretically well understood. As early as the 1960s, scientists theorized the possibility of a closed cage structure of carbon, a truncated icosahedron with 60 carbon atoms. Undoubtedly the new carbon configuration came as a surprise to the scientific community, but the preparatory theoretical work was completed long before the empirical discovery in the 1980s.

Second, the applicability of both STM and BUF to the extension of the two conventional models of scientific progress and growth is indicated as both breakthroughs shaped the emergence of the nanotech community. STM and BUF are two key events that spurred the global proliferation of research and development at the nanoscale. In support of Shinn and Jörges's argument (2002), there is strong evidence that this community spans the boundaries of several academic disciplines (Jansen, von Goertz, & Heidler, 2010; Rafols & Meyer, 2007; Baird & Shew, 2004). Although it initially formed around probe microscopy (and thus STM), this network of scientists continued to embrace more and more disciplines (including BUF) (Mody, 2011). As in the case of Ernst Ruska's electron microscope, the community included various types of organizations, including large companies such as IBM and AT&T, leading research universities, and smaller start-up companies. Therefore, BUF and STM are useful candidates for widening the scope of the theory model and the disciplinary model.

Both STM and BUF can be identified using so-called "flags" (Moed, 2005, pp. 38, 53, 86, 87); these are key papers representing the two breakthroughs. There are four articles in the case of STM (Binnig, Rohrer, Gerber, & Weibel, 1982a–c; Binnig & Rohrer, 1982), and one article in the case of BUF (Kroto, Heath, Obrien, Curl, & Smalley, 1985). Although the invention of STM is considered to have occurred in 1982, technical improvements made it necessary to publish a series of four papers. Binnig and Rohrer aimed to present the utility of STM by applying it to different surfaces, and thereby addressed audiences in different journals. Typically, each of the four STM flags are cited as a stand-alone reference.

There are differences between STM and BUF regarding the two selection criteria (Table 1). While Binnig and Rohrer received the Nobel Prize 4 years after STM development, BUF discoverers Kroto, Smalley, and Curl had to wait 10 years for the Nobel Prize. This delay was probably caused by lack of availability of carbon fullerenes in sizeable quantities for other researchers in the 1980s. Therefore, it took longer to establish BUF's scientific value compared to STM. In contrast, BUF received twice as many citations as STM in the first 10 years after the initial publication, and BUF's annual citation number is twice as high as that of STM. Before we examine these different patterns in more detail (Results), we introduce the data sets and variables.

Data sets and Variables

Our investigation draws on three data sets. First, the publication data set (PUB) contains all WoS (SCI, SSCI) publications that cited either STM or BUF (articles, notes, reviews, letters, and proceedings). Second, we use two network data sets based on citations. The nodes are authors (NW-A) and subdisciplines (NW-D) in the first and second network data sets, respectively. All data sets contain longitudinal data covering 29 years for STM (1982–2010) and 26 years for BUF (1985–2010).

Figure 1 illustrates the network delineation. The basic idea is to take all publications citing the breakthrough and to build year-wise networks of citations between authors (NW-A) and subdiscplines (NW-D). In our example, two papers, both published in 2010, each cite the flag publications. The first has two authors (A, B) and the second is a single-author publication (C) cited by the first. Because the first cites the second, there is a citation tie from both A and B to C. There is also a reciprocal tie from author C to both A and B because C has papers from both A and B in its list of references. Please note that references are included only if they cite the flag publications, other references are excluded. NW-A shows an author-based network graph and a reachability matrix derived from this graph. NW-D shows the tie between applied physics and organic chemistry, the two WoS subject codes that are carried by the two paper's host journal (Moed, 2005). In Figure 1 the first article is assigned to applied physics and the second article to organic chemistry. This constitutes a tie from applied physics to organic chemistry. Articles with multiple subject categories constitute citation ties between every category, analogous to multiple authors. All networks were analyzed with Pajek (de Nooy, Mrvar, & Batagelj, 2012), and the visualizations are prepared using Gephi (www.gephi.org).

TABLE 1. Scanning Tunneling Microscope (STM) and Buckminsterfullerene (BUF).

	Publication year	Nobel Prize year	Citing articles ten years after first publication	Citing articles by end of 2010	Average annual number of citing articles by end of 2010
STM	1982	1986	1,077	3,764	135
BUF	1985	1995	2,030	6,985	279

Source: Web of Science (SCI, SSCI).

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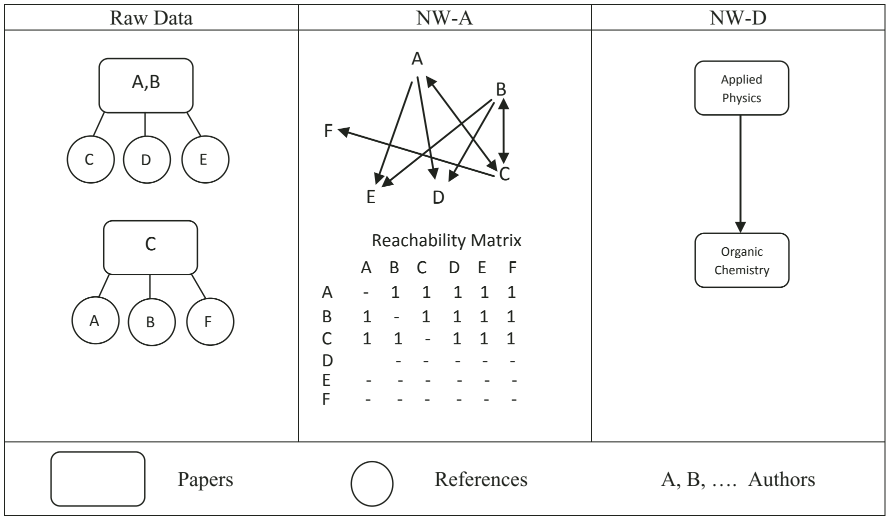

FIG. 1. Delineation of citation networks (NW-A, NW-D).

The citation analysis in this paper neither aims at analyzing research fronts nor entire fields. Compared to cocitation analysis or bibliographic coupling, which have been found useful tools for representing research fronts (Boyack & Klavans, 2010), and compared to analyses of interrelations between journal clusters to study the structure and evolution of entire scientific fields like chemistry (Boyack, Börner, & Klavans, 2007), we focus on direct citation ties when examining the growth of follow-up work in both STM and BUF. While cocitation analysis and bibliographic coupling focus primarily on the cognitive side of citation relations, including the proper representation of entire research fields, we are interested in how breakthrough research became socially disseminated. This perspective can be addressed using both a social network methodology including author–author ties (NW-A) and a perspective using subdisciplinary networks (NW-D). More generally, direct citation ties are particularly useful for examining the social structure of scientific growth, including core, semiperiphery, and periphery (Tables 3, 4).

Several variables are used to answer our research questions (Table 2). First, regarding growth of follow-up research (Q-a, Q-b), we measure how many articles cited either STM or BUF. An increasing number of articles citing STM or BUF indicates growth (I_1). In contrast, the number of author citations measures the growth of intellectual relations among follow-up publications (I_2). Furthermore, we measure the number of authors who recognize each other via citations (I_3). Second, regarding the spectrum and concentration of subdisciplines (Q-c, Q-d, Q-e), we measure the number of WoS subject codes citing STM or BUF. The more subject codes, the higher the disciplinary spectrum of follow-up research (I_4). Furthermore, we measure the interdisciplinarity and concentration of citation flows. As the share of citations between subject codes increases, the follow-up research becomes more interdisciplinary (I_5), the Herfindahl index increases for ingoing citations, and the intellectual ties become more concentrated (I_6). Third, regarding the intellectual connectivity (Q-f, Q-g), we examine the connectedness of author pairs using the density of the reachability matrix (I_7), and we measure thematic fragmentation using the modularity index (I_8). Finally, we inspect visualizations of the citation networks (NW-D) to determine the degree of internal differentiation and integration (I_9). These visualizations add important structural information at the level of discipline-related citation networks (NW-D) to our time series data of I_7 and I_8, which are based on author-related citation networks (NW-A).

Results

Growth of Follow-up Research

Our data do not support the stylized answers of the theory model that suggest that scientific recognition is instant and grows rapidly (Q-a), but we find some support that follow-up research reaches a peak and then gradually declines (Q-b). In our investigation, growth in the number of STM publications is steady and linear (plus 18 articles per year) and reaches its maximum 12 years after the breakthrough (Figure 2). Then the number of follow-up publications continuously declines but at a lower rate than the initial growth (minus 6 articles per year). In contrast, after a few years of no growth there is almost an explosion of interest in BUF; within 3 years, follow-up work grows by a factor of 6 (plus 130 articles per year). This initial growth is too steep to continue, hence there is an 8-year decline (minus 22 articles per year) followed by a renewed growth period (plus 14 articles per year).

Both STM and BUF show growth patterns that diverge from the stylized answers derived from the theory model, in

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TABLE 2. Data sets and variables.

Variable	Theoretical range	Empirical range	Formula	Explanation of formula	Interpretation of variable	Data set
I. Growth of follow-up research						
Number of citing articles	0 to ∞	STM (15–217) BUF (44–461)	$I_1 = P$	P = Number of articles citing flag articles.	Growth of follow-up research	PUB
Number of author citations	0 to ∞	STM (72–8657) BUF (517–60241)	$I_2 = C$	C = Number of author citations including self-citations.	Growth of intellectual connections in follow-up research	NW-A
Number of authors	0 to ∞	STM (14–1273) BUF (57–3961)	$I_3 = A$	A = Number of authors that can reach each other without considering the direction of citation ties.	Growth of research population size	NW-A
II. Spectrum and concentration of sub-disciplines in follow-up research						
Number of subdisciplines	0 to 225	STM (8–61) BUF (14–85)	$I_4 = D$	D = Number of WoS subject codes citing the breakthrough.	Disciplinary spectrum of follow-up research	PUB
Share of inter-disciplinary citation flows	0 to 1	STM (0,67–0,89) BUF (0,65–0,87)	$I_5 = \frac{C_{inter}}{C_{all}}$	C_{inter} = Number of citations between WoS subject codes. C_{all} = Number of all citations.	Interdisciplinarity of follow-up research	NW-D
Herfindahl index for ingoing citations	0 to 1/D	STM (0,08–0,39) BUF (0,08–0,37)	$I_6 = \sum_{i=1}^{D} c_{in}^2$	D = Number of WoS subject codes citing breakthrough. C_{in} = Share of ingoing ties to i[th] WoS subject code.	Concentration of knowledge flows	NW-D
III. Intellectual connectivity of follow-up research						
Connectedness index	0 to 1	STM (0,00–0,29) BUF (0,05–0,43)	$I_7 = \frac{V_A}{n(n-1)/2}$	V_A = Number of reachable author pairs (considering direction of ties); Denominator = Number of possible pairs.	Reachability in follow-up research	NW-A
Modularity index	−1 to +1	STM (−0,04–0,75) BUF (0,21–0,68)	$I_8 = \frac{1}{2m}\sum_{ij}\left[A_{ij} - \frac{d_i d_j}{2m}\right]\delta(g_i, g_j)$	A_{ij} = Number of ties between vertices i and j; $d_i d_j/2m$ = Expected ties in random network; $\delta(g_i g_j) = 1$ if two authors belong to the same group ($g_i g_j$), 0 otherwise.	Differentiation of follow-up research	NW-A
Weighted degree distribution	–	–	I_9 = Center-(Semiperiphery) -Periphery structure	–	Structuration of follow-up research	NW-D

Note: STM = Scanning Tunneling Microscope; BUF = Buckminsterfullerene.

particular (Q-a). STM grew steadily but not rapidly, since the follow-up work was constrained both by the implicit knowledge necessary to interpret STM data, and by the particular skills needed to adapt materials and the experimental setting. This made instant and widespread use of STM impossible. As Mody (2004) argues, early adopters visited labs with proper STM facilities for a few weeks in order to learn probe microscopy, taught their students some of their own techniques and knowledge, wrote a few articles, and then left to set up their own STM group elsewhere. This situation did not change until the mid-1990s, when user-friendly STM versions became commercially available. But even after the peak in the mid 1990s, interest in STM decreased very gradually. This shows that many scientists tinkered with and probed the limits of STM during the time when atomic force microscopy (AFM) and other novel spectroscopy instruments, all building on the STM breakthrough, were being developed (Meyer, Hug, & Bennewitz, 2006, p. 127; Kalinin & Gruverman, 2007, p. 9). There was continued follow-up research, which suggested that harvesting all knowledge claims in research instrumentation takes much longer than predicted by the theory model.

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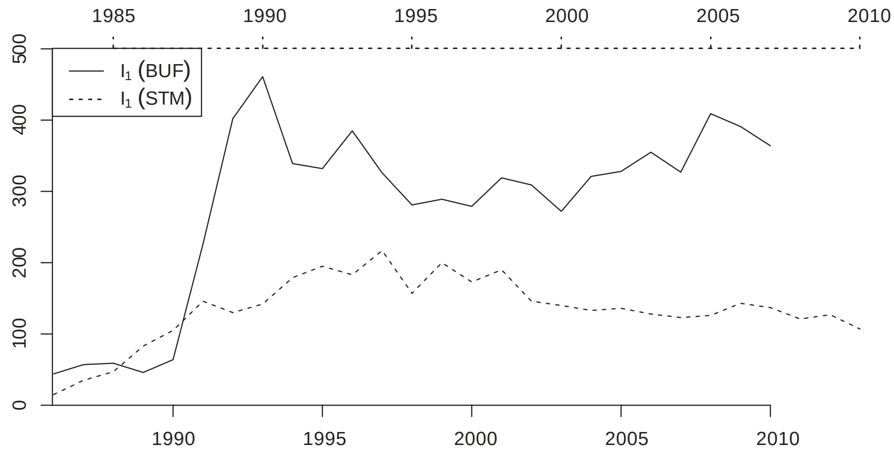

FIG. 2. Growth of follow-up research (I_1).

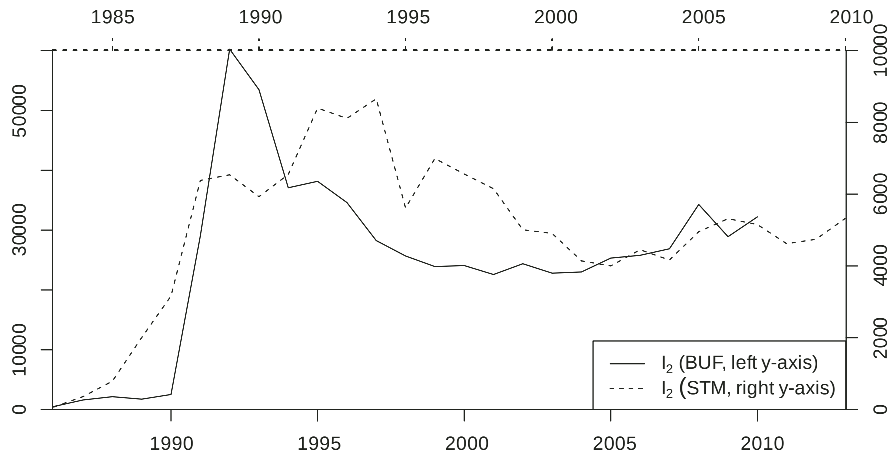

FIG. 3. Growth of intellectual connections in follow-up research (I_2).

BUF follow-up work did not take off initially because sizeable quantities of BUF could not be produced. Therefore, most scientists were precluded from entering this new research area. This situation changed when Krätschmer, Lamb, Fostiropoulos, and Huffman (1990) developed a simple evaporation method for BUF production which made large-scale follow-up research possible. Due to the accumulated interest, the number of follow-up publications almost exploded. It seems plausible to assume that if BUF could have been produced in large quantities right from the start, a major citation peak would have occurred before 1993. Likewise, it seems plausible that follow-up work of conceptual or theoretical knowledge claims would not be delayed in a similar fashion, because even if these claims could not be empirically tested directly, they would still spark a debate among theorists. Therefore, although delays in the recognition of conceptual or theoretical claims are quite possible, they would still be less likely than in cases, such as BUF, where the availability of certain quantities of sophisticated materials determines whether or not one can participate in follow-up research. Furthermore, a new growth path since 2003 shows that the follow-up work did not have initial growth and then decline, as argued by the theory model. A similar picture emerges when the number of author citation ties is considered (Figure 3). Most interesting is the fact that the number of authors recognizing each other (Figure 4) has been on a growth path for BUF, while it reached a peak and then declined for STM. The size of the BUF population is much larger and growing (slightly below 4,000 in 2010) than that of STM (around 1,000 since the mid-2000s).

Spectrum and Concentration of Subdisciplines in Follow-up Research

Our data also does not support the following stylized answers for the discipline model: few subdisciplines build on scientific breakthroughs (Q-c), recognition is highly concentrated in a few subdisciplines for which the breakthrough is of particular value (Q-d), and the level of communication across disciplinary boundaries remains at a low level (Q-e).

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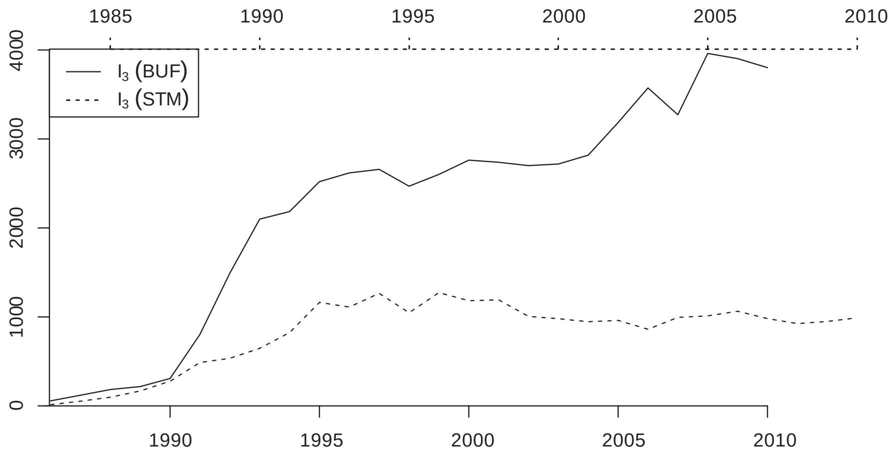

FIG. 4. Number of authors (I_3).

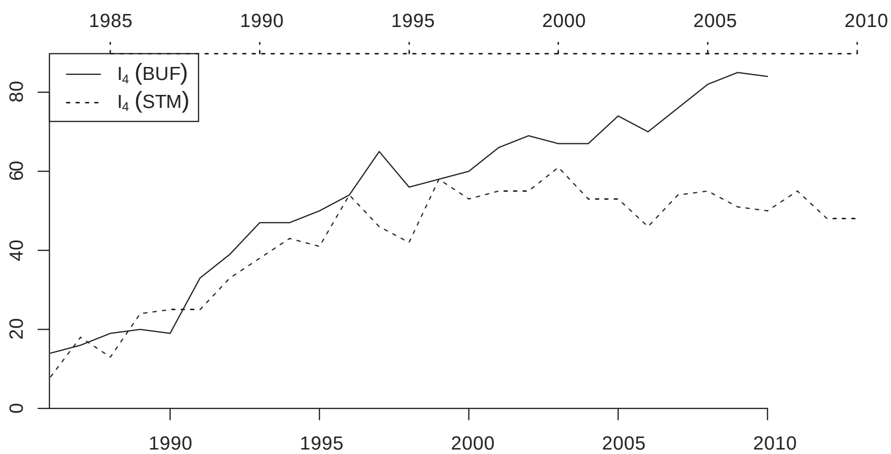

FIG. 5. Disciplinary spectrum of follow-up research (I_4).

There is a steep increase in the number of WoS subject codes both for STM and BUF (Figure 5). In the first decade after its publication, there were more than 50 (out of 225) subdisciplines that built on the work of STM, and more than 60 in BUF. STM reached its peak in 2000 and then stabilized around 50, while BUF continues to attract more and more subject codes, with a preliminary peak of 85 in 2009. These results are substantiated by the high share of interdisciplinary citation flows and the low concentration of citation ties (Figure 6). The Herfindahl values decreased considerably within the first few years and then stabilized for both STM and BUF around 0.1. This indicates that the follow-up work was not dominated by a few subdisciplines, but instead was spread out over a wide range of disciplinary settings. Correspondingly, the share of cross-field citations grew rapidly and then stabilized around 85%. This means that both STM and BUF initiated follow-up research that cut across established cognitive boundaries. The follow-up work in both STM and BUF is broadly distributed and not concentrated in a few fields, as advocated by the conventional discipline model.

Examining the longitudinal results on the spectrum and the concentration of subdisciplines in follow-up research (I_4, I_5, I_6), we conclude that although STM originated in applied physics, it became a broadly used instrument with considerable scientific value in many subdisciplines. Our data fit well with Mody's observation that "as more and more disciplines became interested in probe microscopy, the instruments started to be used in an astonishing variety of ways" (Mody, 2004, p. 124). However, there seems to be a limit of about 50 subdisciplines (WoS subject codes) that are capable of utilizing the microscopic techniques based on STM; thus, its interdisciplinarity has a clearly defined limit. In contrast, there seems to be no such clearly defined limit for interdisciplinarity in the BUF case. Although BUF was discovered more than two decades ago, the number of subdisciplines in follow-up research is still rising. Examples include the medical field with research on drug delivery, materials science and engineering using BUF to strengthen alloys or other materials, mathematics investigating BUF graph properties, information science with computational simulations of BUF-based molecules, toxicology and the

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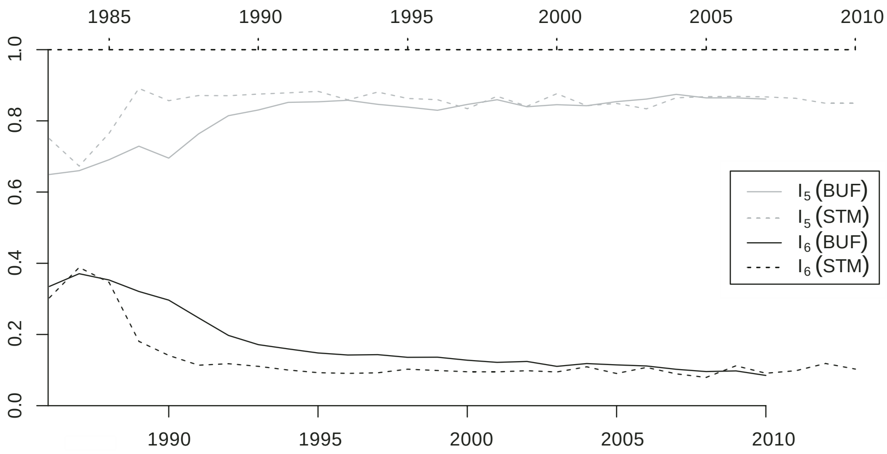

FIG. 6. Interdisciplinarity and concentration of follow-up research (I_5, I_6).

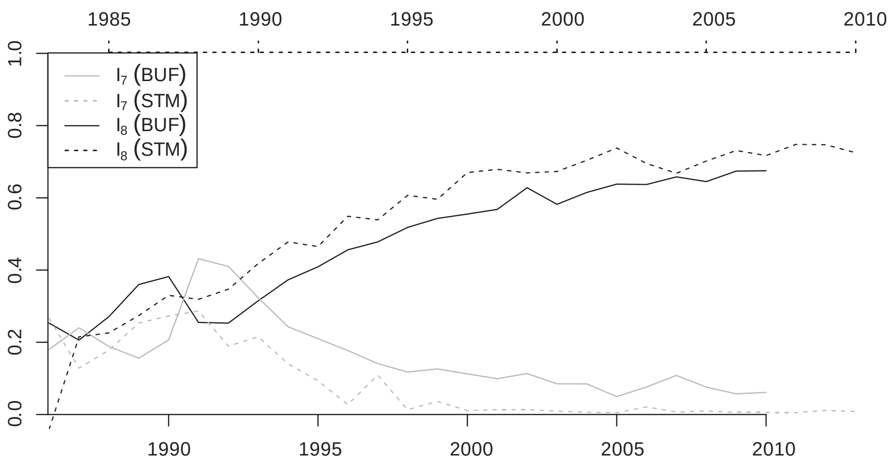

FIG. 7. Reachability and differentiation in follow-up research (I_7, I_8).

effects of BUF on fish, and astrophysics with a search for BUF in celestial objects. There appears to be no upper limit in the number of disciplines following up on the BUF breakthrough.

Intellectual Connectedness of Follow-up Research

Finally, we found that our data do not support the suggestion from the discipline model that the network of citing scientists is both dense and interconnected (Q-e, Q-f). Author reachability is relatively low and decreases for both STM and BUF. Therefore, citation networks as a whole do not make a strongly integrated nexus of cognitive relations. This finding is corroborated by the modularity indicator, which strongly increased for both breakthroughs and then became relatively stable around 0.7 for STM (Figure 7). High modularity indicates fragmentation of a network with clearly separable thematic cliques, while low values indicate a more compact and interconnected network. Clearly, the modularity index does not measure whether new subdisciplines have emerged in response to the publication of STM or BUF. Rather, it reveals to what degree the citation network can be subdivided into thematic cliques. In Selection of Scientific Breakthroughs, we argued that STM and BUF are meant to extend the theory/discipline model. Therefore, thematic rather than disciplinary fragmentation is our focus. In that respect, higher modularity values for STM than for BUF show that there are many thematic research groups that apply STM to various materials and topics. Our findings correspond to Mody's interpretation that probe microscopy "flowered into a thicket of 30 or 40 different kinds of instruments, and hundreds of different operating modes" (Mody, 2004, p. 124). In comparison, although the BUF citation networks are larger than those of STM, they are less fragmented (Figure 7).

We gain further insight into follow-up research by analyzing network visualizations at the subdiscipline level (NW-D). In contrast to the suggestion of the disciplinary model of

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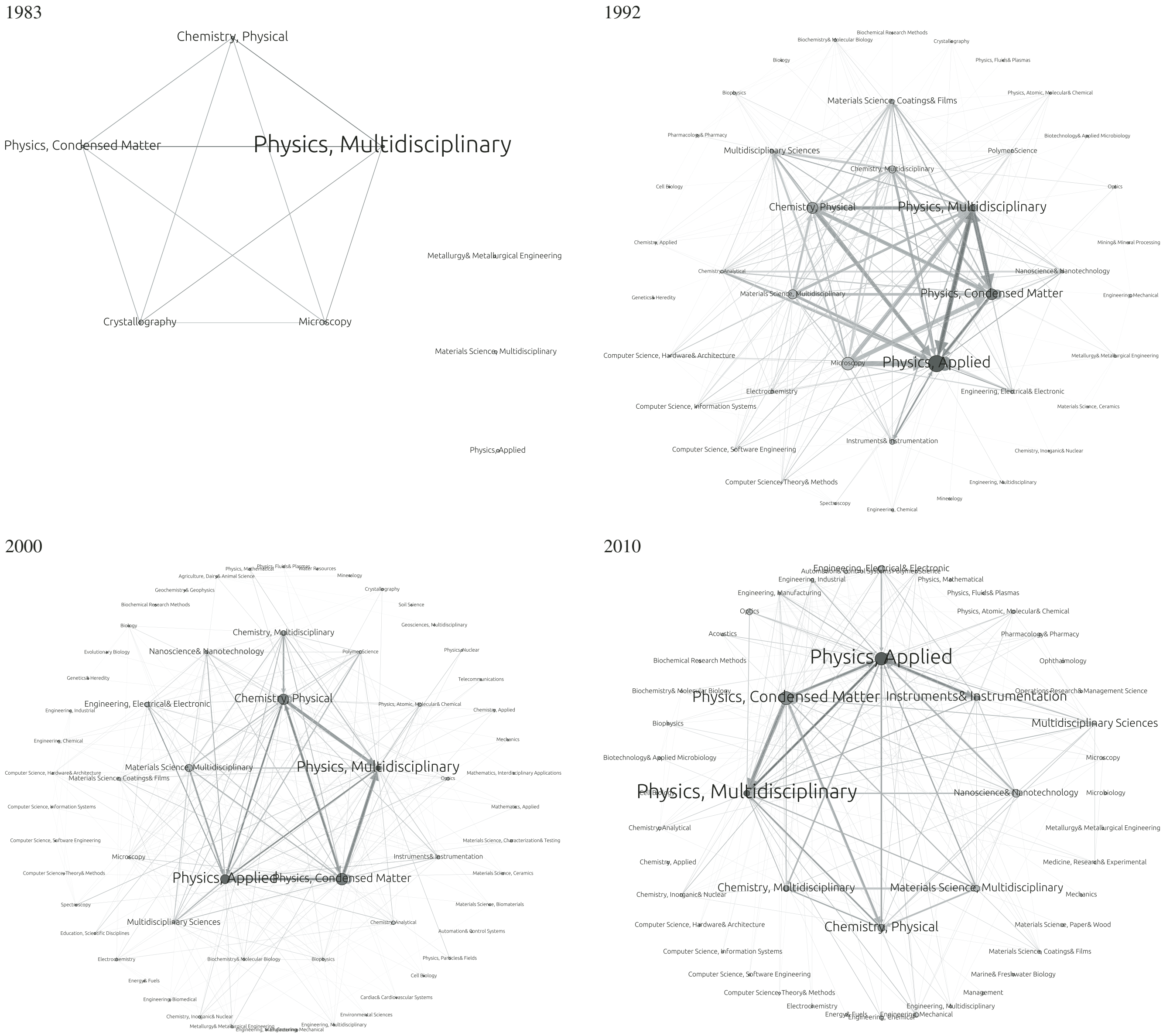
TABLE 3. STM citation network (NW-D).



Note: STM-based discipline-citation networks are based on WoS (SCI, SSCI) subject codes. Subdisciplines have circle shapes, circle size is proportional to the number of articles published in the respective subdiscipline. Arrows represent weighted citations from one subdiscipline to another, their thickness is proportional to the number of citations. Citations which stay inside a subdiscipline exist, hence there are arrows pointing back to the same subdiscipline. Label size represents the number of incoming citations. The division of disciplines into center-(semi)periphery is based on the degree distribution: subdisciplines in the center have a weighted degree of more than 300 and subdisciplines in the semiperiphery have a weighted degree of more than 40.

scientific growth, these citation networks are not tightly connected but are structured entities that display remarkable differences between STM and BUF (Tables 3, 4). The BUF network shows a stable and invariant core consisting of physical chemistry, atomic/molecular/chemical physics, multidisciplinary chemistry, and multidisciplinary sciences (1986–2010). Following mass synthesis in 1990, the network grew considerably, but at the same time a semiperiphery emerged that includes fields like applied physics, material sciences, analytical chemistry, organic chemistry, spectroscopy, and astronomy/astrophysics (Table 4, 1992). In the semiperiphery, subdisciplines like analytical chemistry, chemical engineering, or organic chemistry accompany the two core chemistry fields, whereas mathematical physics, applied physics, astrophysics, optics, and spectroscopy have stronger ties to the two core physics fields. BUF's semiperiphery is stable over time; however, the reciprocal citations in the core plummet, indicating that the network consolidates after its exceptional growth (2000, 2010). It is also interesting to observe that health-related

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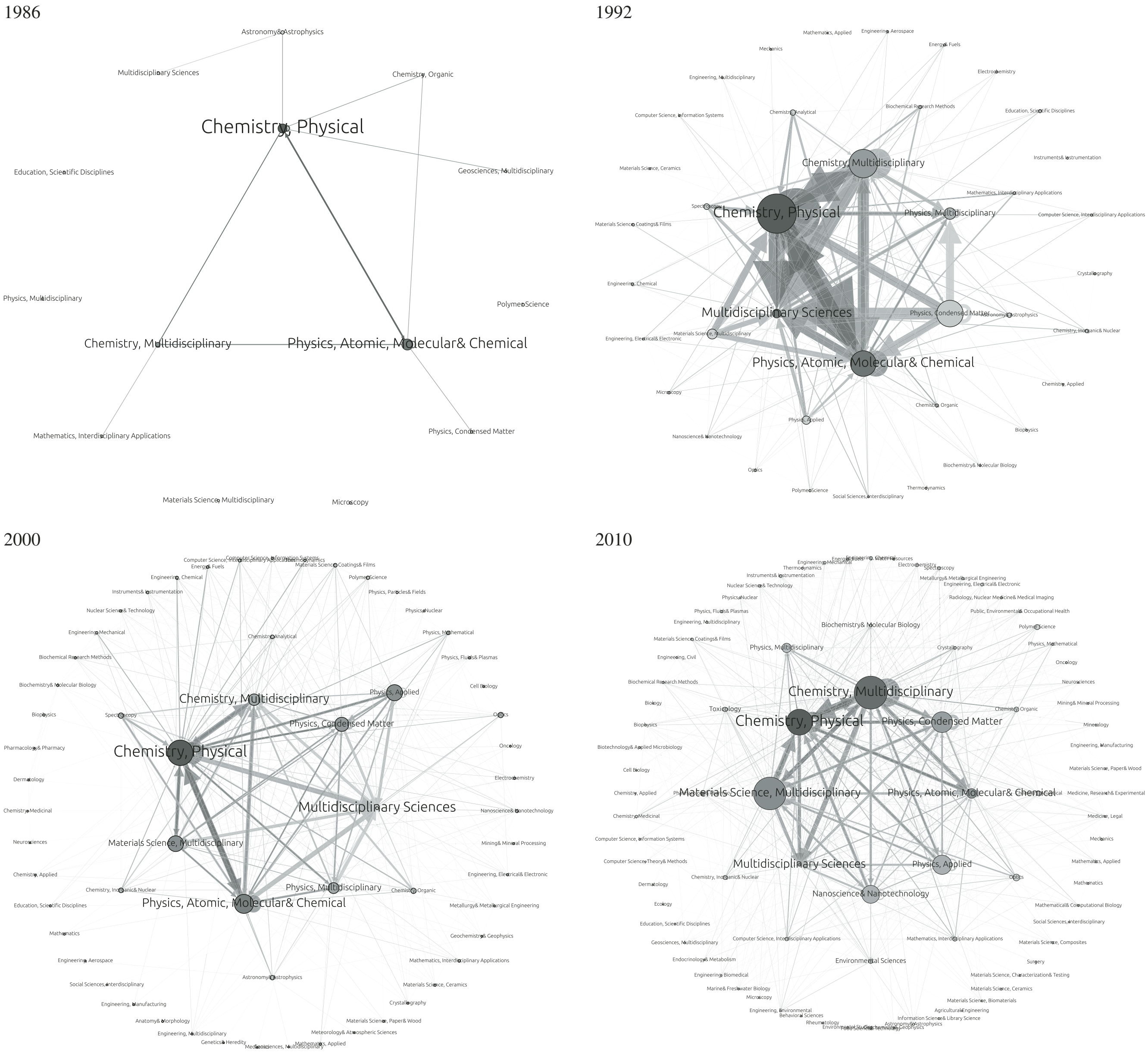
TABLE 4. BUF citation network (NW-D).



Note: See comments in Table 3. Due to a higher number of citations, BUF arrows represent twice as many citations as STM arrows. The same applies with respect to degree distribution: subdisciplines in the center have a weighted degree of more than 600 and subdisciplines in the semiperiphery have a weighted degree of more than 80.

subdisciplines, such as the environmental sciences, pharmacology/pharmacy, or toxicology, enter BUF's semi-periphery relatively late (2010).

Although the STM network grows more gradually than the BUF network (I_1, I_2, I_3), it develops a similar internal differentiation (core, semiperiphery, periphery). In the beginning the STM network is very small, but its core, which includes the physics of condensed matter, applied physics, physical chemistry, and multidisciplinary physics, remains stable over the entire observation period (1983–2010). After STM becomes commercially available, the number of users grows considerably and there emerges a semiperiphery that includes materials science/coating and films, multidisciplinary materials science, electrical/electronic engineering, microscopy, multidisciplinary and analytical chemistry, instruments/instrumentation, and multidisciplinary sciences (1992). In contrast to BUF, STM's semiperiphery is not stable but disappears once STM is established as a mainstream microscopic tool in various user communities. By 2010, the semiperiphery vanishes, indicating that relations between the various user communities and developers of STM and related probe microscopy became tenuous, and also indicating that STM's diffusion into the wider academic community was complete.

We conclude from the longitudinal results on intellectual connectedness in follow-up research (I_7, I_8, I_9) that the conventional interpretation of scientific growth as a process of disciplinary specialization seems inadequate for follow-up research in research instrumentation and the discovery of new matter. Scientific growth in both STM and BUF leads to differentiations into core, semiperiphery, and periphery. However, as our longitudinal data show, NW-D cores consist of (almost) the same subdisciplines (SCI subject codes) over the whole observation period. There are fluctuations in the intensity of intellectual ties between these core fields, and between the semiperipheral and peripheral fields. However, no sign could be found in the NW-A and NW-D citation networks that either STM or BUF constitute subdisciplines of their own. Intellectual innovations such as these have been absorbed and integrated by a growing number of scientists pursuing different themes and research lines, as indicated by the increasing modularity values (I_8). However, they are not the anchors from which densely and mutually connected network configurations emerged, as shown by the low and decreasing reachability in citation ties (I_7). In addition, our results show that the BUF and STM networks are formed not within disciplines, but at their intersections—a finding that corroborates Mody's (2011) qualitative findings.

Conclusion and Discussion

This paper assembles and discusses comprehensive quantitative evidence that demonstrates the inadequacy of conventional interpretations of scientific change as theoretical progress and disciplinary specialization, with respect to the growth patterns of follow-up research in empirical discovery and research instrumentation. We provide findings that are particularly complementary to Mody's (2004, 2011) qualitative analysis of the emergence of the nanotech community, first around probe microscopy (STM), and later around a broader set of research and development at the nanoscale, including BUF. Below, we summarize our results.

(Q-a, Q-b) Follow-up work in research instrumentation (STM) grows in a steady and linear fashion because it is bounded both by the particular skills needed to make sophisticated experimental settings work, and by the implicit knowledge necessary to interpret data with the new instrument. After the citation peak scientific interest begins to decline very gradually, suggesting that the new instrument has long-term scientific value. In comparison, newly discovered matter (BUF) diffuses into scientific praxis only if the new material is widely available. Follow-up research then grows rapidly and, despite some fluctuations, remains on a general growth path. In sum, both research instrumentation and newly discovered matter show patterns of follow-up work that differ markedly from those suggested by the theory model, in particular (Q-a).

(Q-c, Q-d, Q-e) Intellectual advances in research instrumentation (STM) and new matter (BUF) set in motion follow-up research that is broadly distributed across a wide range of disciplinary settings. Every breakthrough is anchored in (three or four) core subdisciplines, to which the follow-up publications are intellectually connected. It seems that instrumentation has an upper bound of interdisciplinary relations, whereas an upper limit was not found for research building on newly discovered matter. In sum, both instrumentation and new matter breakthroughs show patterns of follow-up work that are markedly different from those suggested by the discipline model.

(Q-f, Q-g) The intellectual connections between the authors of follow-up contributions are best described as modular and partly interconnected. High modularity for both instrumentation (STM) and new matter (BUF) indicate considerable intellectual differentiation within citation networks. This corresponds to a high degree of interdisciplinarity and suggests that there are subdisciplinary communities that independently build upon intellectual innovations. The internal structures of citation networks in instrumentation and new matter are similar (core, semiperiphery, periphery), but the semiperiphery is more stable in new matter follow-up research. In sum, the conventional interpretation of scientific growth as a process of disciplinary specialization is not supported with regard to instrumentation (STM) and new matter (BUF).

Taken together, our empirical findings suggest that scientific change is a complex phenomenon encompassing both different types of intellectual advances (including empirical discovery and instrumentation) and various patterns of scientific growth (including rapid or gradual growth/decline, single-peaked or multiple-peaked growth paths, intradisciplinary or interdisciplinary recognition, highly concentrated or broadly distributed recognition). Conventional beliefs about intellectual change and growth of research opportunities are based on simplified models that are not incorrect but tend to be narrow and exclusive. In contrast, this paper argues that a broad and inclusive perspective is more fruitful, both conceptually and empirically.

Admittedly, our work has several limitations. First, we do not analyze advances in theory. Rather, the theory model is our conceptual benchmark which is contrasted with quantitative evidence for STM (instrumentation) and BUF (new matter). One could argue that the theory model itself needs to be tested by an empirical example. We do agree and have done work in this direction: Early and preliminary evidence for a theoretical breakthrough in astrophysics (not presented in this paper) provides support to the theory model. In the future, more efforts are necessary to empirically validate the theory model. Second, we do not analyze scientific methods as a separate entity. Instead, we focus on instruments and empirical discovery. One might argue that instruments, empirical discovery, and methods together constitute experimental systems, as conceptualized by Rheinberger (1997, 2010) and Shinn and Jörges (2002). We do agree. If there are major advances in nanotechnology methods, we believe that

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comparing their follow-up research with that of STM and BUF could yield additional, valuable insights. Third, one might object to our case selection. Although we are confident that STM or BUF are good representatives of advances in instrumentation and empirical discovery, one might argue that more examples in each category would improve the robustness of the results. We also agree with this, and when adding new examples, one might consider domains similar to nanotechnology. Fourth, and perhaps most important, the discussion has touched upon the fundamental question of how the development of new instrumentation or the discovery of new matter then act to reconfigure disciplinary boundaries. Our analysis suggests that neither STM nor BUF has led to the formation of new specialties or subdisciplines as a consequence of scientific growth. Rather, network analysis shows densification of communication across disciplinary boundaries. Therefore, one might argue that the effects of this temporary interdisciplinarity are unknown. We believe that answering this fundamental question requires a systematic study of how breakthroughs like STM or BUF became institutionalized in universities and other (public or private) research institutes. There are interesting qualitative details in the works of Mody (2004, 2011) and Choi and Mody (2009) in this regard. However, there is a need for dedicated quantitative analyses that illuminate the complex interplay between intellectual dynamics and institutional renewal.

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References

Aksnes, D.W. (2003). Characteristics of highly cited papers. Research Evaluation, 12, 159–170.

Aldersey-Williams, H. (1995). The most beautiful molecule. An adventure in chemistry. London: Aurum Press.

Baggot, J. (1994). Perfect symmetry. The accidental discovery of Buckminsterfullerene. Oxford, UK: Oxford University Press.

Bai, C. (2000). Scanning tunneling microscopy and its applications. New York: Springer.

Baird, D., & Shew, A. (2004). Probing the history of scanning tunneling microscopy. In D. Baird, A. Nordmann, & J. Schummer (Eds.), Discovering the nanoscale (pp. 145–156). Amsterdam: IOS Press.

Bensaude-Vincent, B. (2001). The construction of a discipline: Materials science in the United States. Historical Studies in the Physical and the Biological Sciences, 31(2), 223–248.

Binnig, G., Rohrer, H., Gerber, C., & Weibel, E. (1982a). Surface studies by scanning tunneling microscopy. Physical Review Letters, 49, 57–61 [there is a typo in "Binning" in the original publication].

Binnig, G., & Rohrer, H. (1982). Scanning tunneling microscopy. Helvetica Physica Acta, 55, 726–735.

Binnig, G., Rohrer, H., Gerber, C., & Weibel, E. (1982b). Tunneling through a controllable vacuum gap. Appl. Phys. Lett. 40, 178.

Binnig, G., Rohrer, H., Gerber, C., & Weibel, E. (1982c). Vacuum tunneling. Physica B & C, 109, 2075–2077.

Boyack, K.W., Börner, K., & Klavans, R. (2007). Mapping the structure and evolution of chemistry research. Proceedings of the 11th International Conference on Scientometrics and Informetrics (ISSI 2007), Madrid, Spain, June 25–27, 112–123.

Boyack, K.W., & Klavans, R. (2010). Co-citation analysis, bibliogaphic coupling, and direct citation: Which citation approach represents the research front most accurately? Journal of the American Society for Information Science and Technology 61(12), 2389–2404.

Braun, D. (2012). Die Förderung wissenschaftlicher Innovation an Schweizer Universitäten. In T. Heinze & G. Krücken (Eds.), Institutionelle Erneuerungsfähigkeit der Forschung (pp. 65–100). Wiesbaden, Germany: VS Verlag für Sozialwissenschaften.

Campanario, J.M. (2009). Rejecting and resisting Nobel class discoveries: Accounts by Nobel Laureates. Scientometrics, 81, 549–565.

Chen, C.J. (1993). Introduction to scanning tunneling microscopy. New York: Oxford University Press.

Choi, H., & Mody, C.C.M. (2009). The long history of molecular electronics: Microelectronics origins of nanotechnology. Social Studies of Science, 39(1), 11–50.

de Nooy, W., Mrvar, A., & Bategelj, V. (2012). Exploratory social network analysis with Pajek. 2nd Ed. New York: Cambridge University Press.

Doel, R.E. (2003). Constituting the postwar earth sciences: The military's influence on the environmental sciences in the USA after 1945. Social Studies of Science, 33(5), 635–666.

Felt, U., & Nowotny, H. (1992). Striking gold in the 1990s: The discovery of high-temperature superconductivity and its impact on the science system. Science, Technology, & Human Values, 17, 506–531.

Glänzel, W., Schlemmer, B., & Thijs, B. (2003). Better late than never? On the chance to become highly cited only beyond the standard bibliometric time horizon. Scientometrics, 58, 571–586.

Guetzkow, J., Lamont, M., & Mallard, G. (2004). What is originality in the humanities and the social science? American Sociological Review, 69(2), 190–212.

Hacking, I. (1983). Representing and intervening. Cambridge, UK: Cambridge University Press.

Hamblin, J.D. (2005). Oceanography's greatest patron. In J.D. Hamblin (Ed.), Oceanographers and the cold war. Disciples of marine science (pp. 32–58). Seattle/London: University of Washington Press.

Heidelberger, M., & Steinle, F. (1998). Experimental essays. Versuche zum Experiment. Baden-Baden, Germany: Nomos

Heinze, T., Shapira, P., Senker, J., & Kuhlmann, S. (2007). Identifying creative research accomplishments: Methodology and results for nanotechnology and human genetics. Scientometrics, 70, 125–152.

Hessenbruch, A. (2004). Nanotechnology and the negotiation of novelty. In D. Baird, A. Nordmann, & J. Schummer (Eds), Discovering the nanoscale (pp. 135–144). Amsterdam: IOS Press.

Hollingsworth, R. (2002). Research organizations and major discoveries in twentieth-century science: A case of excellence in biomedical research. WZB Discussion Paper P02-003. Berlin: WZB.

Hollingsworth, R.J. (2004). Institutionalizing excellence in biomedical research: The case of Rockefeller University. Creating a tradition of biomedical research. In D.H. Stapleton (Ed.), Contributions to the history of the Rockefeller University (pp. 17–63). New York: Rockefeller University Press.

Hounshell, D.A., & Smith, J.K. (1988). Science and corporate strategy: Du Pont R & D 1902–1980. Cambridge, UK: Cambridge University Press.

Jansen, D. (1998). Hochtemperatursupraleitung — Herausforderungen für Forschung, Wirtschaft und Politik. Baden-Baden, Germany: Nomos.

Jansen, D., von Goertz, R., & Heidler, R. (2010). Knowledge production and the structure of collaboration networks in two scientific fields. Scientometrics, 83, 219–241.

Jones, B.F., & B.A. Weinberg (2011). Age dynamics in scientific creativity. Proceedings of the National Academy of Sciences, 108, 18910–18914.

Kalinin, S., & Gruverman, A. (Eds). (2007). Scanning probe microscopy. Electrical and electrochemical phenomena at the nanoscale. Vol. II. Heidelberg, Germany: Springer.

DOI: 10.1002/asi

Knorr-Cetina, K. (1999). Epistemic cultures. How the sciences make knowledge. Cambridge, MA: Harvard University Press.

Krätschmer, W., Lamb, L.D., Fostiropoulos, K., & Huffman, D.R. (1990). Solid C60: A new form of carbon. Nature, 347, 345.

Kroto, H.W., Heath, J.R., Obrien, S.C., Curl, R.F., & Smalley, R.E. (1985). C-60 — Buckminsterfullerene. Nature, 318, 162–163.

Kuhn, T. (1970). The structure of scientific revolutions, 2nd enlarged Edition. Chicago: Chicago University Press.

Kuhn, T. (1987). Black-body theory and the quantum discontinuity, 1894–1912. Chicago & London: Chicago University Press.

Lakatos, I. (1970). Falsification and the methodology of scientific research programmes. In I. Lakatos & A. Musgrave (Eds.), Criticism and the growth of knowledge (pp. 91–196). Cambridge, UK: Cambridge University Press.

Lambert, L., & Mulvey, T. (1996). Ernst Ruska (1906–1988): Inventor extraordinaire of the electron microscope: A memoir. Advances in Imaging and Electron Physics, 95, 2–62.

Law, J. (1973). The development of specialties in science: The case of x-ray protein crystallography. Social Studies of Science, 3, 275–303.

Luhmann, N. (1992). Die Wissenschaft der Gesellschaft. Frankfurt am Main, Germany: Suhrkamp.

Meli, D.B. (2006). Thinking with objects: The Transformation of mechanics in the seventeenth century. Baltimore: Johns Hopkins University Press.

Merton, R.K. (1968). The bearing of empirical research on sociological theory. In R.K. Merton (Ed.), Social theory and social structure (pp. 156–171). Glencoe, IL: Free Press.

Meyer, E., Hug, H.J., & Bennewitz, R. (2006). Scanning probe microscopy: The lab on a tip. Heidelberg, Germany: Springer.

Mody, C.C.M. (2004). How probe microscopists became nanotechnologists. In D. Baird, A. Nordmann, & J. Schummer (Eds.), Discovering the nanoscale (pp. 119–134). Amsterdam: IOS Press.

Mody, C.C.M. (2011). Instrumental community. Probe microscopy and the path to nanotechnology. Cambridge, MA: MIT Press

Moed, H.F. (2005). Citation analysis in research evaluation. Dordrecht, Netherlands: Springer.

Popper, K. (1959). The logic of scientific discovery. London: Hutchinson.

Rafols, I., & Meyer, M. (2007). How cross-disciplinary is bionanotechnology? Explorations in the specialty of molecular motors. Scientometrics, 70(3), 633–650.

Rheinberger, H.-J. (1997). Toward a history of epistemic things: Synthesizing proteins in the test tube. Stanford, CA: Stanford University Press

Rheinberger, H.-J. (2010). An epistemology of the concrete: Twentieth-century histories of life. Durham, NC: Duke University Press.

Seglen, P.O. (1992). The skewness of science. American Society for Information Science Journal, 43, 628–638.

Sengupta, I.N., & Henzler, R.G. (1991). Citedness and uncitedness of cancer articles. Scientometrics, 22, 283–296.

Servos, J.W. (1990). Physical chemistry from Ostwald to Pauling. The making of a science in America. Princeton, NJ: Princeton University Press.

Shadish, W.R., Tolliver, D., Gray, M., & Sen Gupta, S.K. (1995). Author judgements about works they cite: Three studies from psychology journals. Social Studies of Science 25, 477–499.

Shapin, S., & Schaffer, S. (1985). Leviathan and the air-pump: Hobbes, Boyle, and the experimental life. Princeton, NJ: Princeton University Press.

Shinn, T., & Joerges, B. (2002). The transverse science and technology culture: Dynamics and roles of research-technology. Social Science Information, 41(2), 207–251.

Stent, G.S. (2002). Prematurity of scientific discovery. In E. Hook (Ed.), Prematurity in scientific discovery. On resistance and neglect (pp. 22–33). Berkeley, CA: University of California Press.

Stern, R.E. (1990). Uncitedness in the biomedical literature. American Society for Information Science Journal, 41, 193–196.

Sternberg, R.J. (2003). Wisdom, intelligence, and creativity synthesized. Cambridge, UK: Cambridge University Press.

Stichweh, R. (1994). Wissenschaft, Universität, Professionen. Soziologische Analysen. Frankfurt am Main, Germany: Suhrkamp.

Van Dalen, H.P., & Henkens, K. (2004). Demographers and their journals: Who remains uncited after ten years? Population and Development Review, 30, 489–506.

Van Raan, A.F.J. (2004). Sleeping beauties in science. Scientometrics, 59, 467–472.

Whitley, R. (2000). The intellectual and social organization of the sciences. 2nd Ed. Oxford, UK: Oxford University Press.

Zuckerman, H. (1977). The sociology of the Nobel Prize. In H. Zuckerman (Ed.), Scientific elite: Nobel Laureates in the United States (pp. 16–58). New York: Free Press.

Zuckerman, H. (1992). The proliferation of prizes: Nobel complements and Nobel surrogates in the reward system of science. Theoretical Medicine and Bioethics, 13(2), 217–231.

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