Organization Science
Vol. 24, No. 1, January–February 2013, pp. 58–78
ISSN 1047-7039 (print) | ISSN 1526-5455 (online)
http://dx.doi.org/10.1287/orsc.1110.0718

The Coevolution of Industries and Important Features of Their Environments

Johann Peter Murmann
Australian School of Business, University of New South Wales, Sydney, New South Wales 2052, Australia,
os@professor-murmann.net

As the rate of innovation increases, organizational environments are becoming faster and more complex, posing greater challenges for organizations to adapt. This study argues that the concept of coevolution offers a bridge between the prescient adaptationist and ex post selectionist perspectives of organizational change to account for the increasing rates of change. The mutual causal influences in a coevolutionary relationship help explain why competing sets of firms or individual firms can capture dominant shares in product markets. Using a comparative historical method and drawing on evidence from five countries over a 60-year period, this paper inquires how precisely coevolutionary processes work in shaping the evolution of industries and important features of their environments. It identifies—in the context of the synthetic dye industry—three causal mechanisms (exchange of personnel, commercial ties, and lobbying) and suggests how they acted as levers on the fundamental mechanisms of evolution. Understanding the levers is important for managing change in a world that is increasingly becoming coevolutionary, requiring managers to focus more on the emergent, system-level properties of their environments.

Key words: evolutionary approaches; organizational evolution and change; technological change; coevolution; archival research
History: Published online in *Articles in Advance* February 15, 2012.

Introduction

Research on coevolution has gained importance since its initial formulation for organization theory and strategy by McKelvey (1997). One important reason scholars have been drawn to the idea of coevolution is the widespread perception that organizational environments are becoming faster (Wiggins and Ruefli 2005), more competitive (D'Aveni et al. 2010), and more turbulent (Lewin et al. 1999), creating a greater opportunity for influencing features of the macro environment. The idea that environments are changing more quickly already received systematic confirmation three decades ago. Qualls et al. (1981) demonstrated that in the preceding five decades, product life cycles were becoming rapidly shorter across 27 product categories. These trends have only continued (McGrath and Cliffe 2011). In their call for more coevolutionary research, Lewin et al. (1999) cited advances in information technology, globalization of product and labor markets, and the rise of global pools of capital among the many reasons why organizational environments have become more turbulent. In advanced economies, the recent entry of Chinese firms into markets has undermined the viability of many low-tech manufacturing sectors, forcing firms to locate production in lower-cost countries.

Even in high-tech industries where advanced industrial economies are less challenged by the new economic powers in the Far East, the dynamics connecting the development of technologies and industries are becoming faster and are increasingly seen as coevolutionary (Lewin et al. 1999). Biotech and nanotech industries are prominent examples where the fundamental technologies were developed in large measure by academic scientists but rapidly transferred to the commercial sector, leading to fast changes in the industrial landscape. In both cases, new start-up firms sprang up and quickly focused on using the new scientific knowledge to develop products. The commercial applicability and demand for talent in turn influenced the direction of how universities developed the discipline of molecular biology (Henderson et al. 1999) and nanotechnology (Zucker et al. 2007). Initially, it seemed that specialized biotech firms might cause the decline of incumbent pharmaceutical firms, but Rothaermel and Thursby (2007) have provided evidence for biotechnology and nanotechnology that incumbent firms learned how to adapt to this new technology through a variety of mechanisms. In the case of biotech, alliances with start-up firms or the outright purchase of biotech firms were key mechanisms of adaptation to a fast-moving technological frontier.

Although there is an emerging consensus that in high-tech sectors, firms, industries, technologies, and institutions like universities coevolve (Nelson 1995, Murmann 2003), we lack a detailed account of how these coevolutionary processes take place and how they influence basic variation–selection–retention processes that underlie the evolution of the two partners in the coevolutionary relationship. If we want to gain a deeper understanding of why rates of environmental change have been increasing over the past decades, and if we want to identify how managers can perhaps cope with these dynamics, we need to identify the causal levers that drive coevolution.

This paper makes three important contributions to literature. First, Maruyama (1968) has argued that there are two fundamental types of mutual causal systems: deviation-countering and deviation-amplifying structures. Building on Maruyama (1968) and McKelvey (1997), this paper shows how deviation-amplifying mutual causal processes can account for how particular industries and aspects of their environments can change more rapidly. This dynamic helps explain why industries in different countries, although initially performing similarly, can diverge quite dramatically over time (Dosi and Kogut 1993).

Second, after articulating the logic of coevolutionary explanation, the paper examines the case of the synthetic dye industry and the academic chemistry that was a key part of the industry's environment. In doing so, this paper illustrates what kind of data are required to show coevolution empirically, and it can serve as a template for studies in other contexts. Only by studying different contexts will we be able to assess the generalizability of the causal mechanisms we find in this context.

Third, going far beyond Murmann and Homburg (2001) and Murmann (2003), this paper advances the theory of coevolution by inductively identifying specific causal mechanisms that drive such coevolution and connects them to the fundamental processes—variation, selection, and retention (VSR)—that underpin the evolution of populations. This will identify general levers of intervention for actors. It will also allow researchers to design much more specific studies in the future to ascertain the relative contribution of intentional actions versus ex post selection processes as explanations of organizational adaptation.

The rest of this paper will proceed as follows. I will first provide a theoretical background and then lay out the historical case study methods I used to induce the mechanisms of coevolution. Next I will provide the empirical analysis that follows the two-step process articulated in the theory section for demonstrating coevolutionary dynamics. Finally, in the discussion section, I will identify the implications of this study for organization theory and strategy research more broadly.

Theoretical Background

Management scholars have developed two types of explanations for why an organization is well adapted to an altered environment. The first explanation locates the causal origin of the organization's successful alignment with environmental demands in the actions of individual managers (Andrews 1971, Child 1972) or top management teams (Hambrick and Mason 1984). Organization theorists introduced the evolutionary perspective in the 1970s to provide an alternative to the standard explanation for how organizations become well adapted to changes in their environment. Following Campbell (1969, 1974a), organizational scholars (Hannan and Freeman 1977, Aldrich 1979, Weick 1979, McKelvey 1982) realized that prescient intentional action (Andrews 1971, Child 1972) is not the only way to explain well-adapted organizations. As long as many different entities (variation) are created, whether these entities are simple actions of individuals or entire organizations, as long as consistent selection pressures eliminate ill-adapted entities (selection), and as long as the entities have stability across time (retention), the surviving entities will be well-adapted to their environments.

Coevolution Occurs at Multiple Levels of Social Organization

Coevolutionary ideas have been introduced into organization theory in part to bridge this simple dichotomy as well as to get a deeper understanding of how organizational change processes unfold (McKelvey 1997, Lewin and Volberda 1999). Many researchers have been drawn to the idea of coevolution because of the realization that different levels of social organization—groups, subunits, organizations, industries, institutions, and economies—often change together (McKelvey 1997, Murmann 2003). Sometimes this is framed in terms of part–whole coevolution (Baum 1999, Lewin et al. 1999, Rosenkopf and Nerkar 1999, Jacobides and Winter 2005), sometimes in terms of part–part coevolution explaining changes of the whole (Weeks and Galunic 2003), and other times in terms of multiple populations influencing each other's development and therefore coevolving (McKelvey 1997).

Partners in a coevolutionary relationship, therefore, can be on the same level (McKelvey 2002 calls this horizontal coevolution) or can be across different levels (McKelvey 2002 calls this vertical coevolution). Eisenhardt and Galunic (2000) carried out a coevolutionary analysis at the horizontal level by studying how business units within the same firms coevolved. Burgelman (2002) conducted a vertical analysis when he described how one company's (Intel) capabilities coevolved with the PC segment of the computer industry, thus becoming increasingly locked in to that segment. Ven de Ven and Grazman (1999) operated at three levels of analysis—the individual manager, the organization as a whole, and the entire industry—when they tried to explain the historical trajectory of health-care organizations in Minnesota from a coevolutionary perspective.

Scholars in recent years have realized that what sets coevolutionary theory apart from standard evolutionary explanations is that causality does not only run from the environment to the evolving entity but also runs from the entity to the environment (Murmann 2003). Coevolutionary researchers focusing on technology have highlighted that technologies change while the industry that is using or producing the technology undergoes change itself (Yates 1993, Nelson 1994, Rosenkopf and Tushman 1994, Murmann 2003, Henderson and Stern 2004, Funk 2009). As a consequence, at least part of the environment—a technology, for example—changes through this interaction. Consider the case of the now-ubiquitous Internet. Firms are not only dramatically affected by Internet technologies, but Microsoft, Apple, Google, and the like also have a dramatic impact on how Internet technologies develop.

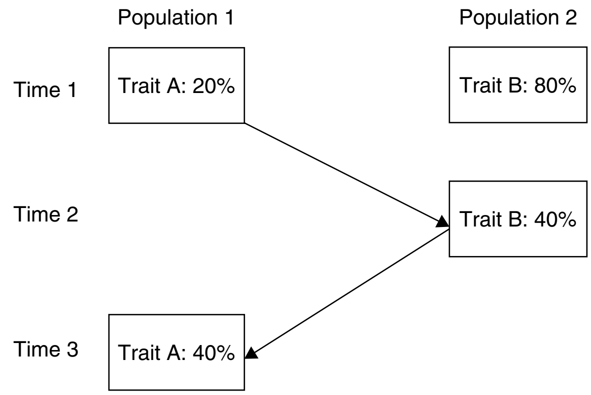
Although much work has pointed to coevolution and asserted its importance, there has been little work on its precise mechanisms and how coevolutionary mechanisms impact the VSR processes of evolutionary change. To gain a deeper understanding of what agents can do to shape their environments in such a coevolutionary framework, we need to know more about the different causal levers they can potentially utilize.

Maruyama (1968) pointed out that there are two types of mutual causal systems: deviation-countering and deviation-amplifying structures. Standard evolutionary explanations already have strong negative, deviating countering loops built into them. When reciprocal causal processes create stronger positive (deviation-amplifying) than negative (deviation-countering) feedback loops, small initial differences between firms or technologies can turn into large differences given sufficient time.

Coevolutionary Explanations Involve Two Steps

Providing a coevolutionary explanation for the evolution of an industry and an important feature of its environment involves two steps. First, one needs to show that the industry and the important feature of the environment can both be conceptualized as populations that undergo change through VSR processes. As part of this demonstration, one must spell out precisely how the variation, selection, and retention processes work in each social arena (this has been done many times for industrial evolution; see, e.g., Aldrich 1979). Second, the analysis needs to show that reciprocal (bidirectional) causal mechanisms exist that link the evolutionary trajectory of the two populations by causally affecting at least one of the three component VSR processes that constitute evolutionary change in each arena. As McKelvey (2002) pointed out, this means that some kind of mutation or adaptive change in population A causes a responsive adaptive change in population B; this change in population B, in turn, leads to a change in the first population, which is now A′. This again triggers a change in the second population, which then becomes B′, and this mutually causal adaptive response continues for as long as the coevolutionary relationship exists. See Figure 1.

Figure 1 Coevolution of Two Populations



Reciprocal causality can come about through two separate causal mechanisms that act in opposite directions or through one and the same causal mechanism acting in both directions.

Because high-tech industries are seen as particularly susceptible to coevolutionary processes, and science and technology are so important for these industries, in this paper I focus on analyzing the mutual causal influences between industries and academic disciplines. VSR explanations of industrial change (e.g., Aldrich 1979, Murmann 2003) are widely understood and need not be reviewed here. However, because organization theorists to date have not systematically studied academic development from an evolutionary perspective, it is necessary—before proceeding to the methods and setting of this study—to discuss in some detail the theoretical arguments as to how cognitive changes in the academy in general and individual disciplines in particular can be explained through the VSR model.

Evolution of Academic Disciplines

Toulmin (1972) and Hull (1988), both philosophers of science, developed an evolutionary model of conceptual change, breaking with the long-held notion dating back to Plato that scientific ideas constitute immutable, timeless entities. Instead, they provided considerable evidence in their arguments that the whole body of scientific knowledge is made up of populations of ideas. Each academic discipline, in turn, consists of a population of ideas that changes over time as scholars adopt new ideas and modify or drop existing ones. At the center of this approach is the notion that scientific disciplines are historical entities, forming genealogies of ideas.

To provide a compelling evolutionary explanation for cognitive change in academic disciplines, one must also specify concrete instances of variation, selection, and retention processes for this empirical arena. The processes that introduce new variations into the population of ideas are constituted by researchers who propose new scientific ideas without being fully prescient as to how successful their ideas will be (Campbell 1974b). The reasons researchers propose a particular idea (i.e., the intentions behind putting forward a certain concept) do not really matter in an evolutionary framework. What matters is the impact of the new idea among scientific workers (Campbell and Paller 1989). Most ideas proposed have little influence in a discipline because other researchers do not adopt them. The selection process comes about because members of an academic discipline adopt in their own work only a subset of the ideas available at a given moment in time (Campbell 1987). This means that each idea always competes with other ideas for the attention of researchers who are willing to incorporate particular ideas into their work. Productive and more readily testable ideas attract more researchers and gain influence. What evolves when an academic discipline changes is the frequency with which members of the discipline subscribe to particular ideas. The retention mechanisms in disciplinary change are constituted by the memories of individual researchers as well as in the scientific literature. The memories of individual researchers are connected not solely by writing and reading the disciplinary literature but also through direct interaction with one another. Scientific knowledge and know-how is frequently distributed across different human beings. This means that research programs often require groups of people who work together and combine different pieces of knowledge and know-how.

Especially in the empirical sciences, much of the know-how necessary to do scientific work is passed on from master to disciple (Latour and Woolgar 1986). This apprenticeship mode of teaching also has strong selective properties. The disciple does not learn all the ideas that have ever existed in a discipline but rather the ideas that the master subscribes to at that time. Hence, there is a strong correlation between the cognitive content of the mind of a particular master and that of a particular student. The novel ideas that a student discovers typically are variants or recombination of ideas that were already held by the master. Just as in the case of industrial change, an evolutionary account of disciplinary change is compelling because individual researchers need not have any significant foresight about which ideas will turn out to be particularly successful (Campbell 1974a). Having laid the theoretical background, I can now move to the methods and setting of this study before I present the empirical analysis.

Methods and Setting

Historical case studies are particularly well suited to close explanatory gaps and refine existing macro-organization theories (Langton 1984, Leblebici et al. 1991). I selected the synthetic dye industry and the discipline of chemistry from 1850 to 1914 as an historical case study for investigating how the mechanisms that drive coevolution shape the VSR processes of standard evolution. I had five key reasons for this choice:

1. As mentioned in the introduction, coevolutionary dynamics are widely seen to have become more important as organizational environments have become more turbulent in recent decades. If one can show that these dynamics played a significant role in 19th century, when they should have played a lesser role, the idea that they are particularly important in contemporary settings gains strong support.

2. The synthetic dye industry constitutes an extreme case in terms of a number of important dimensions. As described by Murmann and Homburg (2001) and Murmann (2003), Britain and France dominated the synthetic industry for the first eight years, and German firms and, to a lesser extent, their Swiss rivals came to dominate the industry for decades. In contrast, American firms played only a minor role in this important industrial development. This large variation in performance across the five countries makes it easier to detect key causal mechanisms. By representing an especially pure example of the social process under investigation (Ragin 1987, p. 23), this case study offers the prospect that one can more readily establish the key causal mechanisms driving coevolution and discover their effects on the component VSR processes.

3. The industry under study started at roughly the same time in several countries—Britain (1857), France (1858), Germany (1858), Switzerland (1859), and the United States (1864) (Murmann and Homburg 2001). This gives the comparisons across the different national dye industries more face validity because in a contemporaneous comparison many factors are held constant that would probably be variable in those comparisons across national industries, which started at different historical moments.

4. The industry was not in a competitive equilibrium during the first 60 years of its existence. From its early years, the industry experienced a continuous stream of innovations. To be able to observe that an industry is coevolving with something else, the industry itself must clearly be undergoing evolutionary change. Studying an industry that has become stationary will not allow one to detect the causal forces that drive coevolution and its impact on the VSR processes in the two coevolving populations.

5. The histories of both the synthetic dye industry and the discipline of chemistry from 1857 to 1914 are well documented for several reasons. Sufficient time passed for historians to write extensively about both social spheres. Because the major German companies went public in the early 1880s, there is a long trail of data in the form of annual reports and company histories. Historians of science and technology (Cardwell 1957, Furter 1982) have paid substantial attention to this industry because it was the setting in which industrial research and development (R&D) laboratories were first

created (in the 1870s). For their parts, historians of the synthetic industry (e.g., Beer 1959, van den Belt et al. 1984, Travis 1993) have long known the importance of organic chemistry in the development of synthetic dyes but have not constructed a coevolutionary explanation.

My data collection strategies combined the traditional methods of historians with social science methods. The historian tries to read every document that can help piece together the most accurate representation of what really happened. The social scientist strives to obtain representative samples and create numerical representations of the phenomenon. For the industry evolution analysis, I was able to draw on the Homburg–Murmann database that contains data on all firms in all dye-producing countries before World War I (Murmann 2003; Appendix B provides a description of the database).[1] The database of firms currently contains 379 distinct firm units. The database of firms and plants was designed to contain numerical as well as relevant qualitative data, allowing us to construct frequency measures as to how important features of national populations of firms evolved.

The data on the development of the discipline of chemistry came from the published works of a large number of historians of science. Again, I combined both qualitative and quantitative data to analyze how the discipline of chemistry developed in the five different countries over the 60-year period. A number of complementary ways can be used to measure empirically how scientific knowledge changes over time. One way is to analyze how the content of scientific publications develops over time. Another is to track the disciplinary affiliation of university professors and identify in what field or subfield they are appointed. A third way is to track the abstracts of doctoral dissertations and code them in terms of their key ideas and the field or subfield to which they belong.

Given the challenges encountered in obtaining comparable data for five countries in the 19th century, I found that it proved expedient to study cognitive changes in the discipline of chemistry in the five countries by analyzing the frequencies with which certain classes of ideas (inorganic chemistry, organic chemistry) appeared in articles published in scientific journals. In this analysis, all chemistry-related articles appearing in a country in a given year form the national population of ideas in chemistry. Because organic chemists developed synthetic dyes, I tracked the relative frequency of organic chemistry publications in each of the five countries when this was possible or provided a qualitative evaluation based on the historiography of chemistry for each country. To assess the relative importance of each national organic chemistry community, I obtained information analyzing chemical abstracts for the global literature on organic chemistry.

The comparative historical method (Stinchcombe 1978, Tilly 1984, Ragin 1987) used in this study overlaps to a considerable degree with the case study methodology articulated by Eisenhardt (1989). The hallmark of both methodologies is the engagement in a repeated dialogue between ideas and evidence to develop new theories. The research carried out for this paper had both deductive and inductive parts. Drawing on the work of philosophers of science who have already articulated an evolutionary perspective on the development of academic disciplines (Toulmin 1972, Hull 1988), I devised a framework for interpreting the development of the field of chemistry through the VSR model. Recall that coevolutionary explanations as defined in the theoretical background section involve two separable populations. Each is undergoing change to a significant degree through a selection process, but each also has a direct causal impact on the development path of the second population. I inferred from this that one or more coevolutionary processes are needed to affect at minimum one of the three component processes of evolutionary change (variation, selection, and retention). These steps were deductive. The second major inductive part involving a repeated dialogue between ideas and evidence concerned the establishment of actual causal mechanisms that could drive the coevolution of the industry and academic discipline; it also involved the identification of how these mechanisms would impact the VSR processes in each of the coevolving partners. I went to the historical data to determine how specific reciprocal causal mechanism(s) created a coevolutionary process linking the variation, selection, and retention processes that shaped the evolution of the synthetic dye industry and the field of chemistry. To qualify as a causal mechanism, the cause had to precede the effect temporally, and stronger causal mechanisms had to have stronger effects. I started by comparing the cases of Germany, Britain, and the United States to isolate the true causes from spurious ones. Later I examined whether any emerging causal constructs would hold up when compared with the evidence from the French and Swiss cases.

Empirical Analysis

As articulated in the theoretical discussion, the first step in a coevolutionary analysis is to show that the two partners in a relationship can be interpreted as populations that adapt through the VSR processes. In this section, I present the empirical evidence to support this interpretation. Then I move on to the second step of a coevolutionary analysis, in which I identify reciprocal causal mechanisms and how they connect to the VSR processes taking place in the two interacting populations.

The Evolution of the Synthetic Dye Industry

What evidence is available that the populations of firms constituting the five major national synthetic dye industries experienced substantial change during their first six decades brought about through the mechanisms of the

VSR model? The standard empirical procedure for determining whether a population has undergone evolutionary change is to trace the frequency of particular traits. The Homburg–Murmann database of synthetic dye firms contains information on a variety of traits that historians of the industry have found important. For the present purpose, I analyze the frequency of the following three traits that historians identified as the key features of how German firms came to dominate the world market.

1. *Possession of a Formal R&D Laboratory*: How many firms had a formal R&D laboratory that would routinely generate new products, and what was those firms' collective domestic market share? A formal R&D laboratory is one that is operationalized as a separate organizational unit (not part of production unit) and that has at least two chemists engaged in research and development.

2. *Ownership Structure*: How many firms had a particular ownership structure? For the present analytical purposes, it is expedient to track ownership type in terms of four possible categories: (a) single individual, family firm, or partnerships; (b) limited liability company; (c) public stock company; and (d) foreign-owned subsidiary. When the legal status of a firm is uncertain, it is classified as certain. Because the legal status of firms has a significant effect on many corporate governance issues, such as what kind of person will lead the firm (for example, owner versus salaried manager) and how the firm can finance growth, a change in the frequencies of ownership type offers insights into how the competitive pressures developed in the various national environments and how the character of each national industry changed over time.

3. *Global Sales Force*: How many firms had a global sales force (defined as salespeople on the company payroll working in at least three continents)? Firms initially started out selling locally and distributing over distance using independent sales agents. As Chandler (1990) pointed out, a company cannot afford to spend large amounts of capital on building large plants if it cannot count on a steady flow of orders. Building large marketing and distribution networks hence is an effective tool for ensuring relatively steady demand for a firm's products that made large plant investments economically viable. Tracking the frequency of firms in each country with a global sales force provides another important insight into the types of firms that populated the national industry at various points in time.

I used the Homburg–Murmann database to carry out a comparative analysis of industry evolution for each of the five leading producer nations: Britain, Germany, France, Switzerland, and the United States (see Table 1). Whenever possible, measures are reported four times—three years after the start of the industry in 1860, then in 1877, 1893, and finally once just before World War I (1913 or 1914). That war, an exogenous shock that completely disrupted the global market for synthetic dyes, constitutes a natural stopping point for the analysis. By measuring the frequencies of various traits of firms in the five national synthetic populations four times, it is possible to ascertain whether each country population experienced evolutionary change and whether the populations of the five countries evolved in different ways. Along with each frequency measure, Table 1 also reports the size of the sample (n) that went into calculating a particular frequency. What follows is an in-depth analysis of how the five national industries developed over six decades.

A comparison of the frequencies for each trait and each country at the four points in time supports the notion that each country to a considerable degree constituted different selection environments that forced local firm populations to evolve in dissimilar ways. In 1860, no firm had a formal R&D laboratory in any country; by 1914, 23% of German firms and 20% of Swiss firms had formal R&D laboratories, whereas only 9% of British firms, 10% of French firms, and no American firms had one. The contrast between Germany and Switzerland, on the one hand, and Britain, France, and the United States, on the other hand, is even more pronounced if one measures the domestic market share of the firms that had a local formal R&D department. In Germany and Switzerland, the share was 95% and 47%, respectively; in France, Britain, and the United States, the proportions were 2%, 1.5%, and 0%, respectively.

The data on firm entries, firm exits, and firm failure rates in each country from 1857 to 1914 support the notion that these changes in trait frequencies were brought about in large measure through selection processes. For three time periods between 1860 and 1914, I calculated the frequency of firm turnover in the different countries' populations by adding the number of entries and exits, and then dividing this number by the number of firms that existed in the population the year before. The turnover figures for specific periods and each country lie between 1 (the number of entries and exits equals the number of firms that comprised the population) and 12.33 (the number of entries and exits is more than 12 times the number of firms that formed the population). In all countries, at least 64% of all firms eventually exited the industry, altering the composition of the national firm populations (for the data, see rows 6, 7, and 8 in Table 1).

Rows 5 and 9 in Table 1 provide an overview of how competitive forces pushed the country populations in different directions. With respective global market shares in 1862 of 50% and 40%, the synthetic dye industries of Great Britain and France were operating on a much larger global scale than those of Germany, Switzerland, and the United States. When some German firms began to make innovation more routine in the late 1870s by

Table 1 Indicators for the Evolution of National Populations of Synthetic Dye Firms

	Great Britain	Germany	France	Switzerland	United States
1. Percentage of firms with local formal R&D department	1860: 0% ($n=7$) 1877: 0% ($n=14$) 1893: 7% ($n=15$) 1914: 9% ($n=12$)	1860: 0% ($n=6$) 1877: 4% ($n=25$) 1893: 20% ($n=34$) 1914: 23%[a] ($n=26$)	1860: 0% ($n=9$) 1877: 10% ($n=10$) 1893: 9% ($n=11$) 1914: 8% ($n=13$)	1860: 0% ($n=3$) 1877: 0% ($n=7$) 1893: 12% ($n=8$) 1914: 20%[b] ($n=5$)	1865: 0% ($n=2$) 1877: 0% ($n=3$) 1893: 0% ($n=6$) 1914: 0% ($n=11$)
2. Domestic market share of firms with local formal R&D department	1860: 0% 1914: 1.5%	1860: 0% 1914: 95%	1860: 0% 1914: 2%	1860: 0% 1914: 47%	1860: 0% 1914: 0%
3. Ownership structure[c]	1860: $n=7$ 86% F 14% S	1860: $n=6$ 83% F 17% U	1860: $n=9$ 100% F	1860: $n=3$ 100% F	1865: $n=2$ 50% S 50% U
	1877: $n=14$ 86% F 7% L 7% S	1877: $n=25$ 88% F 12% L	1877: $n=10$ 90% F 10% L	1877: $n=7$ 100% F	1877: $n=3$ 66% L 33% U
	1893: $n=15$ 40% F 47% L 13% P	1893: $n=34$ 82% F 3% L 3% S 12% P	1893: $n=11$ 45% F 18% L 27% S 9% P	1893: $n=8$ 87% F 13% L	1893: $n=6$ 83% L 17% S
	1914: $n=12$ 25% F 67% L 8% S	1914: $n=26$ 19% F 42% L 12% S 27% P	1914: $n=13$ 23% F 7% L 62% S 7% P	1914: $n=5$ 80% L 20% P	1914: $n=11$ 55% L 18% S 27% U[d]
4. Percentage of firms with their own sales force on at least three continents	1860: 0% ($n=7$) 1914: 0% ($n=12$)	1860: 0% ($n=6$) 1914: 14%[e] ($n=26$)	1860: 0% ($n=9$) 1914: 0% ($n=13$)	1860: 0% ($n=3$) 1914: 20% ($n=5$)	1860: 0% ($n=2$) 1914: 0% ($n=11$)
5. Share of all firms in the world	1860: 28% 1877: 22% 1893: 17% 1914: 14%	1860: 24% 1877: 38% 1893: 39% 1914: 31%	1860: 36% 1877: 15% 1893: 12% 1914: 15%	1860: 12% 1877: 11% 1893: 11% 1914: 8 %	1860: 0% 1877: 5% 1893: 7% 1914: 13%
6. Total firm entries Total firm exits Firm failure rate	53 43 81%	118 94 80%	68 57 83%	32 26 81%	28 18 64%
7. Firm entries + exits	1861–1877: 50 1878–1893: 24 1894–1914: 15	1861–1877: 74 1878–1893: 72 1894–1914: 59	1861–1877: 44 1878–1893: 24 1894–1914: 15	1861–1877: 25 1878–1893: 8 1894–1914: 21	1865–1877: 5 1878–1893: 13 1894–1914: 28
8. Firm turnover[f]	1861–1877: 7.14 1878–1893: 1.71 1894–1914: 1.00	1861–1877: 12.33 1878–1893: 2.88 1894–1914: 1.74	1861–1877: 7.11 1878–1893: 2.18 1894–1914: 2.36	1861–1877: 8.33 1878–1893: 1.14 1894–1914: 2.62	1865–1877: 2.50 1878–1893: 4.33 1894–1914: 4.67
9. Share global[g]	1862: 50.0% 1873: 18.0% 1893: 12.0% (est.) 1913: 6.5%	1862: 3.0%, 1873: 50.0% 1893: 70.0% 1913: 74.1%	1862: 40.0% 1873: 17.0% 1893: 11.8% (est.) 1913: 5.4%	1862: 2.5% 1873: 13.0% 1893: 10% (est.) 1913: 7.0%	1862: 0.0% 1873: 0.2% 1893: 1.8% (est.) 1913: 3.3%

[a]The six largest German firms controlling 95% of the German market had formal R&D departments. The comparable numbers for the other countries are two rows below.

[b]The other two larger firms, Sandoz and Geigy, unlike CIBA, had no formal R&D laboratory but contracted R&D out to university chemists.

[c]F = single individual, family firms, and partnerships; L = limited liability company; P = public stock company; S = foreign-owned subsidiary; U = status uncertain.

[d]The Yale database (http://icf.som.yale.edu/nyse/) shows that none of the American firms were listed on the New York Stock Exchange.

[e]The six largest German firms controlling at least 90% of the German market had a formal R&D department.

[f]Turnover is calculated by adding up the firm entries and exits in the period and dividing it by the number of firms in the year before the period.

[g]The 1862 figures are from Leprieur and Papon (1979, p. 207). The authors report that Germany and Switzerland together held 5% of the market. I estimate that Germany's share amounted to 3% and the Swiss share to 2%. The 1873 figures were put together by Ernst Homburg from Hofmann (1873, p. 108), Wurtz (1876, p. 235), and Kopp (1874, p. 153). The 1912 figures are from Thissen (1922). Except in the case of Germany, I did not have figures for the year 1893. I estimated the countries' market shares by assuming that market shares declined between 1877 and 1914 in a linear fashion.

creating formal R&D laboratories, they developed an enormous competitive advantage over their domestic and foreign rivals by continuously coming out with better and cheaper dye products. By 1885, "industrialization" of innovation in the form of formal R&D labs allowed German firms to push their collective market share up to 74%, a position they maintained for 30 years. The only firms that could still compete with Germany in producing high-quality dyes were the Swiss firms, whose global share of production increased from 2.5% in 1860 to 7.0% in 1913.

In 1914, the top three German producers accounted for 66% of domestic production. BASF, Bayer, and Hoechst were each responsible for about 22% of domestic production, and given Germany's world market share, each accounted for about 17% of world production. The competitive pressures that these three firms exerted with their large plants, R&D laboratories, and global marketing and distribution capabilities were felt not only in Germany but also in all other producer countries.

The German domination of global synthetic dye production had a profound impact on how both the German industry and the other national industries evolved. This is visible both in terms of the frequencies of ownership structure in the five countries and in terms of the frequencies with which firms in the different countries had their own global sales forces. In 1860, all firms across the five countries (except one foreign subsidiary in Britain) fell into the first ownership category of single individual, family, or partnership firms (for details, see row 3 in Table 1). Ownership structure changed dramatically in all countries, but in different ways. By 1914, 27% of German firms were public stock companies (category d), as were 29% of Swiss companies and 7% of French companies; no companies in the other two countries were public. The most frequent ownership type in the French firm population was the foreign-owned subsidiary (62%); in Britain and the United States, the limited liability company predominated (67% and 55%, respectively). In terms of having their own global sales force, the patterns for the five national populations are similar to those having a formal R&D laboratory. In 1860, no synthetic dye firm in the world had its own global sales force. By 1914, 20% of Swiss firms and 14% of German firms had one, but none in the three other countries had any. These data show clearly that the synthetic dye industry in all five countries experienced significant evolutionary change in the period from 1857 to 1914.

The Evolution of Academic Chemistry

To establish that the academic discipline of chemistry evolved in one or more of the five countries under study, one can track the relative frequency of organic chemistry ideas in the broader national literature on chemistry. Table 2 summarizes all the data I collected to compare the development of organic chemistry ideas in the scientific work of chemists in the five different countries for the period from 1850 to 1914. The broad patterns are very clear. In both Germany and Switzerland, organic chemistry gained in importance and came to totally dominate chemical research by the early 1890s (in the first half of the 1890s in Germany, 88% of all publications of chemistry institute directors concerned organic chemistry ideas). The share of organic chemistry publications later declined in Germany and Switzerland because a new subfield of physical chemistry opened many new research opportunities and scientific rewards, attracting the attention of a new generation of chemical workers. By contrast, in France and Britain, organic chemistry publications declined as a share of the national chemical literature. In France in 1850, organic chemistry represented 50% of the French chemical literature; by 1914, it was only 30%.

With the creation of land-grant colleges in the United States in 1862, academic chemistry grew faster there than in any other country (Thackray et al. 1985). But the U.S. chemical community devoted little attention to organic chemistry, especially aromatic organic chemistry, which is the basis of dye chemistry. In 1907, only 3.3% of all U.S. chemical publications were devoted to organic chemistry ideas. American chemical researchers instead devoted much attention to mineral and soil analysis, physical chemistry, and chemical engineering (Nye 1993, Rosenberg 1998).

The rise of organic chemistry ideas in general, and specifically of aromatic organic chemistry in the German chemical community, started in the mid-1860s. The later domination of the global chemical literature in these chemical subfields by German researchers is documented in detail in the lower half of Table 2. In the period 1850–1854, France had a larger world share (35%) than Germany (29%) and Britain (24%). In 1877, German researchers published 62% of all organic chemistry papers in the world, Swiss researchers 7%, French researchers 15.2%, British researchers 5.9%, and U.S. researchers 0.9%. In 1907, Germany still dominated organic chemistry, but its global share was reduced to 48%; Swiss researchers were now responsible for 5%, British researchers for 16.2%, French for 12.2%, and U.S. researchers for 3.6%. These data on the changes in frequency of types of publications support the notion that the national academic disciplines of chemistry evolved in terms of their cognitive content during the period from 1857 to 1914.

Coevolution of the Dye Industry and Academic Chemistry

Having presented evidence that both the five national populations of synthetic dye firms and the five national populations of chemistry ideas indeed evolved, the

Table 2 Indicators of Evolution of National Disciplines of Chemistry

	Great Britain	Germany	France	Switzerland	United States	Notes
Percentage of organic chemistry publications in the chemical literature	1850: 35% Declines after 1865 but increases somewhat after the 1890s.	1850: 50% 1871–75: 79%[a] 1891–95: 88% 1910–14: 57%	1850: 50% 1873: 30% 1895: 40% 1914: 30%	Organic chemistry is dominant in the field of chemistry in the 1890s.	1907: 3.3%[b]	Source for 1850 data is Ernst Homburg (personal communication).
Sources	Bud and Roberts 1984, Nye 1993	Johnson 1989, p. 239	Société de Chimique 1873, 1895, 1914	Simon 1997	*Chemical Abstracts* 1907	
Share of global organic chemistry publications	1850–54: 24% 1855–59: 17% 1860–64: 23% 1865–69: 9%	1850–54: 29% 1855–59: 31% 1860–64: 38% 1865–69: 61%	1850–54: 35% 1855–59: 40% 1860–64: 23% 1865–69: 14%			Source: van den Belt et al. 1984[c]
						Source: Boig and Howerton 1952, p. 30
	1877: 5.9%	1877: 62%[d]	1877: 15.2%	1877: 7%[d]	1877: 0.9%	$N = 904$[e] $C = 8$[f]
	1887: 8.5%	1887: 52%	1887: 10.9%	1887: 5%	1887: 2.7%	$N = 1{,}303$ $C = 12$
	1897: 8.5%	1897: 48%	1897: 16.2%	1897: 5%	1897: 4.9%	$N = 1{,}542$ $C = 15$
	1907: 16.2%	1907: 48%	1907: 12.2%	1907: 5%	1907: 3.6%	$N = 2{,}364$[g] $C = 15$

[a]The figures refer to share of organic chemistry papers in literature on pure chemistry.

[b]The United States at this time was weak in aromatic organic chemistry but strong in mineral soil, physical chemistry, and chemical engineering (Nye 1993, p. 114; Rosenberg 1998). *Chemical Abstracts*, a publication of the American Chemical Society, data are available at http://cas.org.

[c]Figures were calculated by Ernst Homburg, a leading scholar in the history of chemistry, and are published in Table 2 (p. 144) of van den Belt et al. (1984).

[d]Based on an independent evaluation of the data by Ernst Homburg, it became apparent that the source underestimates the Swiss and Austrian shares in the data, especially in 1877. Homburg provided me with corrected numbers for Germany and Switzerland between 1877 and 1907. In Homburg's analysis, Switzerland has a 2% higher share compared to simply taking the German and Swiss share in the source data and calculating the Swiss share based on the sizes of the German and Swiss populations respectively in 1850 (Germany 35,397,000; Switzerland 2,392,700) and 1880 (Germany 45,234,100; Switzerland 2,839,000). I did not use for this calculation the 1877 or 1907 populations because chemists would be at least in their 20s before writing journal articles in chemistry. The German Swiss estimates are rounded to the nearest percent.

[e]Figures for 1877 are derived from the *Chemisches Zentralblatt* (German abstracting service).

[f]The letter C stands for country. The number that follows is the number of countries involved in the sample. Since between 1877 and 1914 seven more countries (15 instead of 8) started producing articles in the chemical literature, the share of each country has to come down, everything being equal.

[g]The 1907 figures for *Chemical Abstracts* show the same country share patterns.

second step in making a coevolutionary argument is to identify significant causal mechanisms that link the evolutionary trajectory of the two distinct national populations by causally affecting each other. Identifying these causal mechanisms should provide additional explanatory power to account for why the five national populations of synthetic dye firms and the five national populations of chemical ideas evolved in the particular ways they did.

In Murmann (2003) I speculated inductively that the *exchange of personnel* between industrial firms and academic organizations, the *formation of commercial ties* between the two social arenas, and *lobbying* on each other's behalf linked the fate of each national pair of populations. For the present paper, I systematically collected evidence to examine this hypothesis. I constructed causal maps (see Tables 3 and 4) for two of the five countries—Britain, where the industry and organic chemistry became weak, and Germany, where the organic chemistry became strong—to show the temporal order of how these three causal mechanisms led to coevolution. In Germany, the strongest case, the synthetic dye industry and the academic discipline of chemistry immensely aided each other's development. However, to show that these causal mechanisms amount to coevolution and to make a novel theoretical contribution, it is also crucially necessary to articulate the implications of the direct causal links and their effects on the VSR processes in industry and academia. Discussion of the implications of indirect or second-order causal effects is left for another paper.

The Three Mechanisms of Coevolution and Their Implication for the VSR Model

Given that three causal processes (exchange of personnel, commercial ties, and lobbying) are impinging on two social arenas (industry and academia), which in turn are transformed by three population-level causal processes (VSR), we can make the deductive inference that there are 18 ($3 \times 2 \times 3$) possible coevolutionary effects. In the

Table 3 Causal Map of Coevolutionary Dynamics in Britain

Population 1: Industry		Population 2: Academia
		1856: Perkin, a student of Hofmann at the Royal College of Chemistry, invents the first synthetic dye, aniline purple
1857–1862: Perkin and other students of Hofmann start most synthetic dye firms as full liability companies, launching new dyes	← EP	
	CT →	1862: Receiving chemicals from his former students and other dye firms, Hofmann determines the structure of dyes more precisely and thereby advances organic chemistry
1863: Hofmann licenses the patents for his violet dyes to the firm Simpson, Maule and Nicholson, which becomes the largest dye firm in the world	← CT	
	CT →	1865: Hofmann leaves for Berlin, Germany, where he believes he will be able to have an even more intense and closer relationship with industry. Organic chemistry in Britain loses its leading figures and declines in subsequent years
1865–1874: The global market share of British firms declines because of stronger German competition. Ivan Levinstein lobbies and financially supports the creation of a second chair in chemistry (focusing on organic chemistry) at Owens College in Manchester	L →	1875: The German-trained chemist Carl Schorlemmer is appointed at Owens College to train organic chemists for the dye industry
1880: Levinstein is the only firm in the British dye industry to create a formal R&D laboratory. Because of the shortage of organic chemistry talent created in Britain, it hires German chemists	← EP	
1885–1894: British chemists are moving from the firm Brooke Simpson and Spiller to academic posts	EP →	1897–1907: Organic chemistry again becomes stronger in Britain
1880–1906: Industrialists lobby the government to increase funding for technical and scientific education so as not to fall further behind the Germany synthetic dye industry	L →	1907: To close the gap with Germany in technical higher education in Britain, Imperial College in London is created

Notes. The events and causes presented in these maps are a simplification of the actual causal structure leading to the coevolution of the dye industry and academic chemistry. Causes, for example, often act over long periods of time, which cannot appear on the map without rendering it useless as an instrument to represent that causes precede their effects. EP, exchange of personnel; CT, commercial ties; L, lobbying.

five-country historical case study of the synthetic dye industry and academic chemistry, 12 of the 18 possible effects are detectable based on inductive reasoning. In both social arenas, the exchange of personnel affected the variation, selection, and retention processes, whereas the formation of commercial ties affected only the variation and selection processes, and lobbying affected only the selection processes. The strength of the causal effects was not uniform across the five different countries but varied depending on the national conditions and the development stage of each social arena. In short, the causal processes remained the same but their effects varied depending on the time and place they occurred (for a metatheoretical treatment of this point, see Stinchcombe 1978, Tilly 1984). Besides drawing on evidence already encountered in the historical narrative, I will present evidence across the five countries on how the exchange of personnel affected the variation processes in the two social domains. In contrast, for the other 10 effects, I will focus primarily on their formulation and will be much more selective in the historical evidence I present. The three bidirectional causal processes had the following specific effects on the VSR processes in the two social arenas.

Table 4 Causal Map of Coevolutionary Dynamics in Germany

Population 1: Industry		Population 2: Academia
1858–1862: Entrepreneurs and chemists start synthetic dye companies as full liability companies	EP →	1863–1866: Chemists shift their focus to aromatic chemistry. Chemists with industry experience return to academia
German firms start introducing innovations.	← EP	1866: Kekulé's benzene ring theory improves understanding of chemical structure of synthetic dyes
Firms provide chemists with chemical samples for research	CT →	1868: Graebe and Lieberman synthesize artificial alizarin
1869: The firm BASF works with Graebe and Lieberman to commercialize synthetic alizarin	← CT	
1870–1873: The entry of 34 firms producing alizarin in Germany leads to the dominance of German firms on the world market		
1877: Passage of patent law: only process patents are granted for chemicals	← L	1876: The German Association of Chemists sends a petition to parliament in support of process patents for chemicals
1877–1886: Formal R&D emerges as a routine function at dye firms	← EP	1875–1877: The di-azo coupling reaction is fully understood by chemists, paving the way for creating hundreds of new dyestuffs
1881: BASF and Hoechst work with Baeyer on commercial indigo process	← CT	1880: Baeyer synthesizes the most important natural dye, indigo, on a laboratory scale
1883–1905: To fund growth, many German synthetic dye firms become public companies		
1897: BASF introduces synthetic indigo, displacing the last remaining natural dye	EP →	Because of the growing number of R&D labs in synthetic dye firms, demand for and training of organic chemists increases strongly. German chemical institutes are dominated by organic chemists who become the highest-paid academics across all fields
1905–1911: Representatives of leading dye firms lobby and make financial contributions to create a German Imperial Institute for Chemistry	L →	1911: Imperial Institute for Chemistry opened in Berlin
1905–1914: The largest dye firms develop global sales forces to distribute their portfolio of dye products throughout the entire world		

Notes. The events and causes presented in these maps are a simplification of the actual causal structure leading to the coevolution of the dye industry and academic chemistry. Causes, for example, often act over long periods of time, which cannot appear on the map without rendering it useless as an instrument to represent that causes precede their effects. EP, exchange of personnel; CT, commercial ties; L, lobbying.

Exchange of Personnel. Many individuals moved from academic institutions to industrial firms, and vice versa. This flow of personnel across the two social arenas had consequences for the VSR processes in each of them. As far as the variation processes are concerned, the effect was both qualitative and quantitative. *The evidence suggests that academically acquired knowledge allowed individuals to come up with novel business ideas and increased the rate at which firms were founded.* Upon graduation, most people trained in chemistry at academic institutions in the 19th century could not find employment at academic institutions but had to secure jobs somewhere else. When Perkin & Sons started production of the first synthetic dye in 1857, the firm demonstrated that organic chemistry could be the source of new dye products. In the ensuing years, many academically trained chemists tried to jump on the synthetic dye bandwagon, either by becoming lead entrepreneurs themselves (as in the case of Simpson, Maule and Nicholson in Britain and Kalle in Germany) or by partnering with businessmen (as in the case of Lucius at Hoechst and the Clemm brothers at BASF in Germany). Firms that employed many academically trained chemists were qualitatively different from those that employed few or none. In the former, academic knowledge guided what kind of variations in products, production processes, and business models were tried, thus producing more kinds of variants than in firms where the search process was less guided by academic chemical knowledge.

The flow of personnel from academic institutions to industrial firms also had important quantitative effects. Those national environments that trained a greater number of organic chemists produced a larger set of entrepreneurs who could start firms in the synthetic dye industry, thereby increasing the variety of business practices in the industry. Within a few years, Germany had a greater number of dye firms than any other country, largely because Germany produced more persons trained in synthetic organic chemistry than did any other country. In stark contrast, the United States had no start-ups before 1864 and only a few in later decades because U.S. academic institutions produced hardly any synthetic organic chemists in the 1850s and not many afterward. One of the reasons why the number of French firms never again increased was that the production of organic chemists was severely reduced after 1867 with the death of Pelouze, who had been one of the two key teachers in France. The list of early entrepreneurs in the British synthetic dye industry reads like an alumni directory of the Royal College of Chemistry in London, which, under the academic leadership of Hofmann, was almost the only place in Britain where one could learn advanced organic chemistry. After chemical theory had advanced to the point in the 1870s that academically trained chemists could substantially reduce the amount of trial and error necessary to develop a new dye, German and Swiss firms started to hire more and more Ph.D. chemists to staff their formal R&D laboratories. The product and process variations developed in these formal R&D laboratories were strongly influenced by the new theoretical developments in academic organic chemistry.

Personnel also flowed from industrial firms to academic institutions, influencing the variation processes that took place in academic chemistry. *The case study suggests that industry experience allowed academic researchers to come up with novel scientific ideas, applications, and methods.* From the 1830s on, chemists all over Europe began to synthesize naturally occurring compounds from scratch and to determine the exact composition of important substances. William Henry Perkin's invention of the first synthetic dye stimulated not only chemists and tinkerers in industry but also academic chemists to develop new ideas and hypotheses about the chemical composition and structure of dyes. One of the most important synthetic dyes, alizarin, was invented in 1868 by Graebe and Lieberman, a team of academic researchers who worked in the laboratory of Professor Baeyer in Berlin. Before joining Baeyer's team, Graebe had worked in 1864 as a chemist at the Hoechst synthetic dye company. Benefiting from Graebe's industrial experience, Baeyer himself began in 1865 to work on synthesizing indigo, considered the crown jewel of all natural dyes because of its unique hue and lucrative market. Baeyer won the 1905 Nobel Prize in chemistry for achieving indigo synthesis in 1878.

The same pattern existed on a smaller scale in Switzerland, Britain, and France. Robert Gehm, who worked at the Swiss dye firm CIBA from 1884 to 1894, was appointed professor to the newly created chair for organic chemical technology at the Technical University in Zurich. From 1875 to 1885, Raphael Meldola, and then in his place, Arthur Green from 1885 to 1894, occupied the position of research chemist at the British firm Brooke, Simpson & Spiller, where they made brilliant discoveries, such as Meldola Blue by Meldola and Primuline by Green, before they took academic positions at the London-based Finsbury Technical College and the University of Leeds, respectively. Charles Lauth worked as a chemist in the French dye industry in the 1860s; in 1882, he became founder of and professor at the School of Chemistry and Physics (Ecole de Chimie et de Physique) in Paris.

Besides transferring ideas, chemists working in industry frequently developed new methods of synthesis that were transferred to academic institutions, often very directly when the inventor of the method moved to an academic institution. While working in the dye industry for many years, Otto Witt developed a new method of synthesis that gave rise to thousands of organic compounds. Later, he joined the School of Chemistry in Mulhouse and then worked at another industrial firm before settling at the Technical University of Berlin in 1885, where he spent the rest of his career. This movement of personnel from industry back to academia happened in at least four of the five countries (no case has been documented for the United States). Once again, the size of the flows was greater in Germany than any other country because Germany had many more university laboratories where industry chemists could move. The differences in the sizes of these flows help explain why German chemistry (large flow) became dominated by organic chemistry ideas, whereas American chemistry (no flow) devoted very little attention to synthetic organic chemistry before World War I.

The transfer of personnel from academic institutions to industry had a second important effect on the national populations of firms by altering the selecting process, depending on the magnitude of the transfer. *The case study suggests that firms that were able to hire the best talent from an academic discipline were likely to flourish from this access to scarce resources.* Analysis of what distinguished the successful firms from the large number of failing firms in the synthetic dye industry reveals that access to advanced knowledge of organic chemistry was one of the crucial factors for firms that succeeded over the long run. Advanced knowledge of organic chemistry was not equally distributed across the five countries at the beginning of the industry (the United States, for example, possessed almost none); however, as the industry developed, the centers of synthetic organic chemistry research became increasingly located in Germany (see again Table 2). Even within Germany, the creation of new knowledge in organic chemistry was dominated by a few professors in chemistry such as Hofmann (Berlin) and Baeyer (Berlin and later Strasbourg and Munich), together with generations of their students. These professors needed to maintain close ties to industrial firms so that they could secure jobs in industry for many of their students, because jobs at academic institutions were relatively scarce. For individual firms, it was crucial to secure access to advanced knowledge by hiring academic chemists from the centers of academic research in synthetic organic chemistry. For German firms, it was easier (and, at the same level of quality, cheaper) to recruit personnel from the leading centers of synthetic organic chemistry research because German firms were closer in terms of both geographic and social distance. Between 1890 and 1914, the three German firms making synthetic dyes (BASF, Bayer, and Hoechst) increased the number of chemists recruited from universities from 350 to 930. However, compared with the flow of German and Swiss chemists to German and Swiss firms, the flow of academic chemists to synthetic dye firms in the other three countries was very small. In fact, because their domestic environments did not produce a sufficient number of organic chemists, the relatively successful firms in Britain (Levinstein) and the United States (Schoellkopf) hired German chemists, albeit on a much smaller scale, to improve their competitiveness.

The transfer of personnel from industry back to academic institutions also changed the selection process within the academy. *The case study provides evidence that academic researchers who were able to recruit talent with useful knowledge from industry increased their access to scarce resources and thus were more productive.* In Germany far more than in any other country, academic organic chemists recruited industrial chemists into their laboratories and were thereby able to increase their share of organic chemistry ideas in the discipline of chemistry. Robert Merton (1968) has documented that scientists who are successful receive a disproportionate share of resources during the next round of funding, which in turn gives them an advantage in coming up with the next scientific discovery. Most scientists, of course, are aware of this so-called Matthew effect in science. Therefore, they are eager to attract people to their research teams who appear to possess critical pieces of knowledge and critical skills for carrying out research projects.

Especially in the early decades of the synthetic dye industry, many chemists who worked at synthetic dye firms possessed knowledge and skills that were very useful for making advances in academic chemistry. Hofmann, for example, recruited in 1865 as his assistant Carl Alexander Martius, who had studied chemistry under Hofmann's own teacher (Liebig) in Munich but who had joined one of the leading British dye firms of the time, Dale Roberts, in the early 1860s. For the same reason, Lieberman, after having been promoted to professor of chemistry at the Technical University of Berlin, recruited Otto Witt, who had acquired extensive industrial knowledge. By recruiting chemists with industrial experience, academic leaders like Hofmann became more productive and increased their share of organic chemistry ideas in German chemistry. Hofmann and a bit later Baeyer became towering figures in chemistry. Between 1865 and his death, Hofmann had graduated 150 doctoral students and had published alone or with his students 899 pieces of chemical research. From 1875 to 1915, 560 people were associated with Baeyer's research group in Munich, which generated about 1,200 papers on organic chemistry. Of these 560 people, 395 received their Ph.D. degrees under Baeyer or one of his many lieutenants. In turn, 50 of these 395 Ph.D.'s became university professors. As these figures show, recruiting talent from industry was quite advantageous for Hofmann and Baeyer in competing for status and influence with other professors of chemistry. (They received other benefits that will be discussed later in the paper.)

The exchange of personnel affected also the retention processes in the two social domains. *The case study suggests that firms that recruited personnel from a particular academic discipline more readily retained knowledge related to the cognitive structure and methodologies of the disciplines.* Scholars of organization learning (Levitt and March 1988), researchers of absorptive capacity (Cohen and Levinthal 1990), and cognitive psychologists (Schacter 1996) have documented that learning is channeled by the cognitive structures agents already possess. This means that a firm is much more likely to display inertia when encountering knowledge very different from the kind of knowledge already embedded in the organization and that it will display more flexibility with regard to knowledge related to what is stored in the rules of the organization and the memory of its members. The firm will pay attention to threats and opportunities based on its existing knowledge structures (Ocasio 1997). Consequently, the frequency with which firms recruit people trained in a particular academic discipline influences the specific path and method in which firms acquire new practices.

One of the reasons the three firms (BASF, Bayer, and Hoechst) that emerged as the leading producers in Germany during the early 1870s were able to maintain their domestic market share (and increase their global market share) for the next 40 years was that they started to hire so many academic chemists, which allowed the firms to catch up with each other whenever one particular producer came out with a blockbuster new dye. By continually hiring freshly minted organic chemists from the leading academic centers, the three firms built sufficient absorptive capacities (Cohen and Levinthal 1990) to be able to understand the chemical basis for any new dye and then to copy it, or to create a dye having a technical effect similar to that of the new dye if direct copying was precluded by patents. Because German dye firms on average employed a greater proportion of chemists than British, French, and American dye firms, the rationalist outlook of organic chemistry in German firms, on average, permeated more aspects of the firms all the way down to the organization of the plants, contributing to their competitive advantage. Deep appreciation of advanced chemistry was deemed so important at the three leading German firms that when they made the transition to managerial firms in the early 1880s, only Ph.D. chemists were appointed to the CEO position for the next 100 years (Teltschik 1992, pp. 288–289).

The exchange of personnel also affected the retention processes in the academy. A comparison of the development of academic chemistry in the five countries from 1850 to 1914 suggests that *academic disciplines that recruited personnel from industrial firms more readily retained knowledge that was relevant for practical application.* Chemists with industrial experience were more likely to absorb new chemical insights generated in industry than were chemists who had worked only at academic laboratories. The greater flow in Germany (compared with France, Britain, and the United States) of industrial chemists back to academic institutions had the consequence of making German academic chemistry much more attuned to the advances made and the problems encountered by industrial organic chemists than did French, British, or American academic chemistry. Especially in France, commentators on the decline of the French dye industry and French chemistry blamed the lack of intensive interaction (and the resulting scarcity of cognitive and cultural overlap) between the two social arenas as one of the chief causes for the decline. On the other hand, in Germany, the large exchange of personnel between the two spheres made organic chemistry so entrenched in academic institutions for chemical research that the German field of chemistry had difficulty responding to new opportunities on physical chemistry, in which ideas and methods were quite different from those of synthetic organic chemistry. Over the period studied here (1857–1914), the exchange of personnel strengthened the retention processes in German chemistry but at the same time reduced the frequency of variations that differed greatly from existing ideas in organic chemistry. In the United States, personnel did not flow from the tiny synthetic dye industry to academic chemistry but instead from the large mining, steel, and agricultural industries, explaining in part why synthetic organic chemistry ideas had so much difficulty taking hold in the U.S. context before World War I.

Commercial Ties. The second important coevolutionary mechanism linking the development of industry and academia was the formation of commercial ties. I have already discussed some of the benefits that industries and academic disciplines received by exchanging personnel. Both social arenas also improved their viability by developing mutually advantageous commercial ties with each other. Once again, such mutually beneficial ties did not exist to the same extent between every firm and every academic researcher, nor did they form randomly. Rather, there was competition for links to the best industrial and academic partners, and a few players in both domains secured themselves the most lucrative connections. Most of the time, the commercial ties emerged from existing social links (previous student–teacher or student–student relationships). Because commercial ties were often embedded in preexisting direct or indirect relationships (Uzzi 1997), such commercial transactions were not renegotiated every year and frequently lasted for decades, as in the case of Hofmann with AGFA and Baeyer with BASF and Hoechst. The long-term nature of these commercial ties gave them even greater exclusionary power (Gulati 1998), making it difficult for other firms and professors to get access to or compete away the benefits of those commercial relationships.

The formation of commercial ties also affected the variation process in industry. The case evidence suggests that *firms with ties to academic researchers were more likely to get access to new product ideas that were developed at academic institutions.* Already in the first few years of the synthetic dye industry, firms had received new product ideas from people working at academic institutions. Hofmann's inventions helped Simpson, Maule and Nicholson become the largest firm in the world during the last part of the 1860s. Once Hofmann returned to Germany, BASF and then AGFA (which was founded in 1873 by Martius, Hofmann's first assistant in Berlin) were the two firms that received virtually all the new product ideas and innovations coming from Hofmann's academic laboratory. Academic researchers typically did not maintain concurrent commercial ties with more than two firms. BASF and Hoechst both benefited from their long-term ties to Baeyer, who gave them an exclusive license to his blockbuster indigo synthesis, allowing the two firms to capture most of the large market that existed for natural indigo. Because most new developments in organic chemistry after 1865 came from German academic institutions, German firms formed the majority of important ties to the leading academic innovators and, compared with the other countries, received a disproportionate share of the innovations developed at academic institutions.

As has already been mentioned, chemists working at firms developed new techniques and methods for organic syntheses that were useful for academic research as well as industrial purposes. A comparison of the relative success of chemists in the five countries suggests that *academic researchers with ties to firms were more likely to gain access to the new instruments and knowledge developed in firms that could stimulate new scientific ideas.* One of the most famous cases involves Hofmann and Peter Griess, a German who moved to Royal College of Chemistry where he was an assistant of Hofmann from 1858 to 1862. Griess then joined industry, where he stayed for the rest of his life. Early during his industrial career, he developed a new reaction method, the azo coupling reaction. Hofmann was the first person to fully realize the potential of making endless new organic compounds with this reaction, and in 1877, he published how one could create new molecules using what he called "Griess's method." Twenty years later, the reaction had become the cornerstone of the largest class of dyes developed before World War I. Because the synthetic dye industry spawned many more firms in Germany than in any other country (see rows 5–8 in Table 1), opportunities for academic chemists to form commercial ties and be the recipients of new chemical ideas and methodologies were greater in Germany than in Britain, France, or the United States.

The formation of commercial ties between industrial firms and academic researchers had two other important effects. It altered the selection process within both the national populations of firms and the population of chemical ideas, depending on how frequently commercial ties occurred in each of the five countries. Comparing successful firms with firms that were relative failures in all five countries suggests that *firms that obtained exclusive access to product ideas and other useful knowledge from academics were likely to flourish from this access to scarce resources.* Firms such as Bayer, BASF, Hoechst, AGFA, Casella, and Kalle in Germany; CIBA in Switzerland; Levinstein in England; and Schoellkopf in the United States all decreased the competition they faced by securing innovative products first developed by academic researchers. At the same time, the more successful firms increased the competitive pressures on those firms that were stuck with their old products and not able to secure access to important new product ideas developed by academics. Because such commercial ties were more frequent among German and Swiss firms than among British, French, and American firms, the German and Swiss firms were able to increase their respective market shares at the expense of the other three national populations of firms.

The formation of commercial ties also affected the selection process within the academic community, depending on the frequency with which these ties occurred in the five countries. Commercial ties relaxed selection pressures because *royalties from patents, student referral fees, consulting fees, and donations of materials created a more munificent environment for the academic researchers who received them.* Within the list of resources that academics could receive through commercial ties, donations of materials were extremely important because many of the organic chemicals that academic researchers needed for the experiments at that time were extremely expensive or not available on the market at all. Murmann (2003, p. 72) mapped out the key people in the industrial–academic knowledge network of 1856–1883. Among the 22 key people, 55% were German, 22% British, 18% French, 5% Swiss, and none were American. A central player in the early network was Hofmann, who worked at the Royal College of Chemistry in London from 1845 to 1865 and was the teacher of the inventor of the first synthetic dye, William Henry Perkin. One of the key reasons why Hofmann returned from London to his native Germany to take a university chair in Berlin in 1865, which he held until 1892, was his belief that he could have a closer relationship with industry in Germany (Martius 1918). He clearly believed that close ties to industrial firms could be very advantageous to advancing his standing as a chemist within the academic community.

By forming commercial ties, leading academic chemists such as Hofmann and Baeyer were also in a position to take on riskier projects, because not only were they able to finance larger laboratories, sometimes even a second private laboratory, but also because industry provided the support to carry out long-term projects. They would gain access to substances from their commercial partners that were not available elsewhere, analyze the substances, and publish scientific articles on them, thereby furthering their academic careers. The case study shows that these two academics are extreme examples of forming commercial ties with firms but clearly are not exceptions. Academics in all countries formed such commercial ties. However, because over time the frequency and the financial size of these ties were larger in Germany and Switzerland than in the three other countries, organic chemistry flourished within Germany and Switzerland to a much greater extent than in the United States, France, and Britain.

Lobbying. The third important coevolutionary mechanism linking the development of industry and academia was lobbying on each other's behalf. In contrast to the other two general mechanisms (exchange of personnel and formation of commercial ties), lobbying affected only the selection processes in both social arenas. Just as academic disciplines compete with other disciplines for talent and a share of the limited resources that society is willing to spend on scientific research at any given moment, particular industries also compete with other industries in the same country for a favorable set of laws, regulations, tax treatment, and many other forms of support. *The case study suggests that academics in specific disciplines could help particular industries obtain public policies and regulations that favored these industries over competing ones, creating a more munificent environment for the firms in the former.* In their standing relative to academics from other disciplines, organic chemists in Germany and Switzerland came to be more prominent than organic chemists in France, Britain, and the United States. In their joint lobbying campaigns with industrial firms, academics in Germany and Switzerland engaged in more successful collective action to secure favorable tax and tariff treatments, allowing German and Swiss dye firms to buy the materials for making synthetic dyes more cheaply than firms in Britain, France, and the United States. Similarly, the German dye industry, unlike the British one, was aided by prominent academics such as Hofmann and Witt in efforts to obtain a patent law that would help their competitive position in relation to foreign rivals. After overtaking all other national synthetic dye industries, the German dye industry secured its dominant position in large part because it could form a powerful lobbying coalition with organic chemists, who came to dominate the chemical discipline in Germany.

These joint lobbying efforts also affected the selection processes for ideas in academic chemistry. *The case study suggests that industrialists helped a particular discipline obtain a greater share of the limited public research monies, creating a more munificent environment for the ideas of the discipline.* Because the dye industry in Germany and Switzerland became economically so much more important than other branches of industry in those countries, the German and Swiss dye industries could help local professors of organic chemistry much more than the British, French, and American dye industries could help their respective academic groups. German synthetic dye firms individually—and later collectively through their trade association—lobbied the German government to increase the ability of German universities to do research and train students in organic chemistry. For example, large, new, state-of-the-art laboratories were built after 1864 in Bonn, Berlin, and Munich, with Hofmann and Baeyer recruited to head the

Figure 2 Three Mechanisms of Coevolution

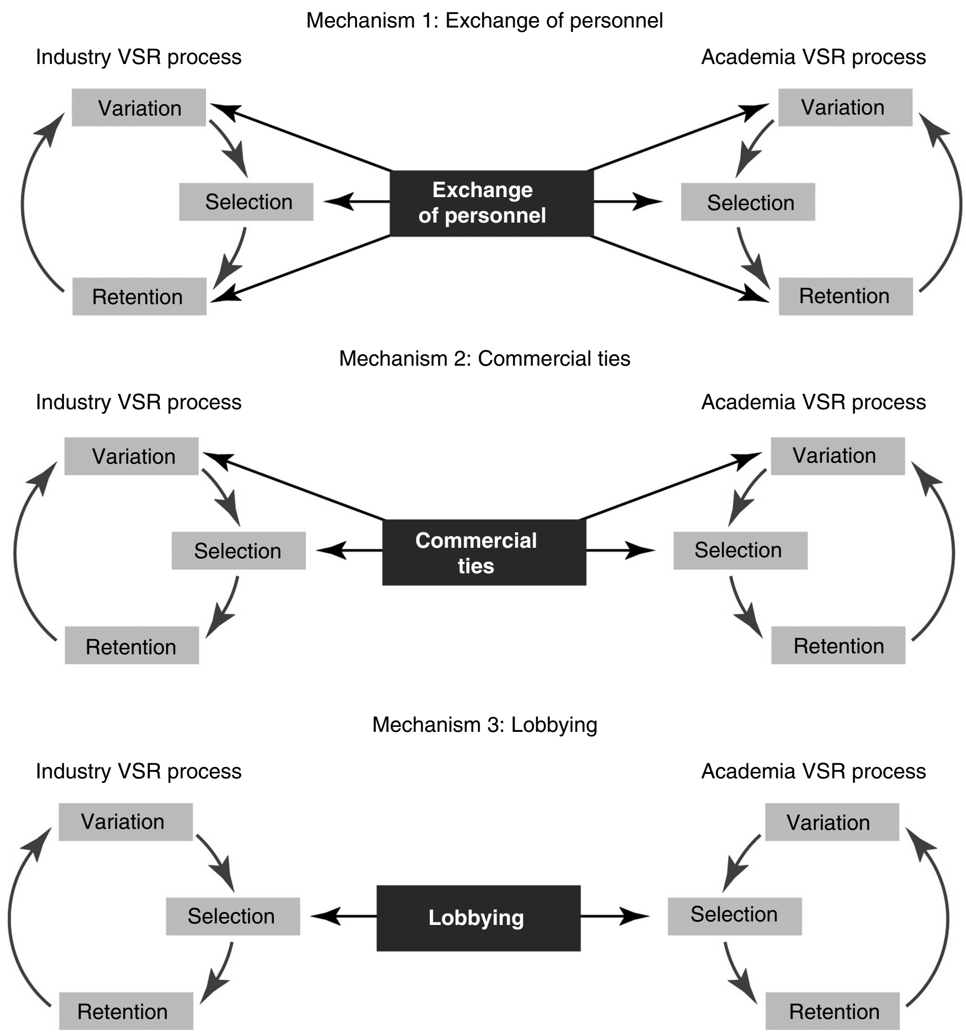


Table 5 Causal Mechanisms and Their Effects on the Evolution of Industries and Academic Disciplines

Exchange of personnel		Commercial ties		Lobbying	
Industry	Academia	Industry	Academia	Industry	Academia
Variation					
Academically acquired knowledge allows individuals to come up with novel business ideas and increase the founding rate of firms	Industry experience allows academic researchers to come up with novel scientific ideas, applications, and methods	Firms with ties to academic researchers are more likely to get access to new product ideas that are developed at academic institutions	Academic researchers with ties to firms are more likely to get access to new instruments and knowledge developed in firms that can stimulate new scientific ideas	*Not observed*	*Not observed*
Selection					
Firms that are able to hire the best talent from an academic discipline are likely to flourish from this access to scarce resources	Academic researchers who are able to recruit talent with useful knowledge from industry will increase their access to scarce resources and be more productive	Firms that obtain exclusive access to product ideas and other useful knowledge from academics are likely to flourish from this access to scarce resources	Royalties from patents, student referral fees, consulting fees, and donations of instruments and materials create a more munificent environment for the academic researchers who receive them	Academics in specific disciplines help particular industries obtain public policies and regulations that favor these industries over competing industries, creating a more munificent environment for the former	Industrialists help particular disciplines obtain a greater share of the limited public research monies, creating a more munificent environment for the ideas of the discipline
Retention					
Firms that recruit personnel from a particular academic discipline will more readily retain knowledge related to the cognitive structure and methodologies of the disciplines	Academic disciplines that recruit personnel from industrial firms will more readily retain knowledge that is relevant for practical application	*Not observed*	*Not observed*	*Not observed*	*Not observed*

latter two. As a result of their heading large laboratories, organic chemists in general became the most highly paid academics in Germany. To maintain the leadership position of German academic chemistry, the industry also lobbied the government to fund jointly with industry a chemical research institute (the Kaiser Wilhelm Institute for Chemistry in Berlin), which was better endowed than any university laboratory in Germany. As a result of these lobbying efforts, organic chemistry ideas could flourish much more easily in the German and Swiss contexts than in the French, British, and American ones. Figure 2 and Table 5 summarize the 12 effects of the three causal mechanisms discussed above.

Discussion and Conclusion

Organizational environments are becoming faster and more complex, especially in high-tech sectors. Although these dynamics pose greater challenges for organizations to adapt (Brown and Eisenhardt 1997, McKelvey and Boisot 2009), this historical case study shows how these same dynamics offer opportunities for agents to improve their chances for success by shaping important aspects of organizational environments in their favor. This notion differs from research performed within the standard evolutionary perspective, in which environments are typically treated as givens and beyond the causal reach of the agents. From a coevolutionary perspective, human agents can to some extent shape their own environment. German dye firms, which failed in larger numbers than in any other country, came from behind and overtook French and British players by a large margin before World War I in part by shaping their environment more successfully. The present paper makes two contributions to understanding these dynamic processes.

First, the paper illustrates what kind of data are required to demonstrate coevolution, providing researchers with a template for how to investigate in other contexts how industries and important features of their environments change through coevolutionary processes. Coevolution requires that the two partners in a coevolutionary relationship can be conceptualized as populations that experience significant entry and exit of individual entities making up the population. I provide evidence that important traits of each population (e.g., *the frequency of firms with formal R&D labs* in the case of the national synthetic dye industries and *the frequency of organic chemistry ideas* in the case of the national chemistry academic disciplines) changed through entry and exit dynamics brought about by selection forces. In this way, I show that coevolution drove the mutual adaptation processes between the dye industry and academic chemistry.

An exciting agenda for future research is to gain a more precise estimate of just how many changes are due to the turnover of firms in the industry versus top managers changing their firms to adapt to the environment. Mintzberg and McHugh (1985) already showed that within the history of one organization, periods where a CEO shaped the strategy of the entire organization were repeatedly followed by periods where strategy emerged from lower levels of the organization, often as a response to environmental pressures. To make progress on this question about the relative causal power of top management versus population-level selection process in bringing about organizational adaptation, future research efforts need to collect data on both the entries and exits of firms and document the changes among existing firms that survive, as Mintzberg and McHugh (1985) and Burgelman (2002) have done for individual organizations. The present study and the work of Chesbrough (1999) on the hard drive industry in Japan and the United States suggest that countries may differ somewhat in this respect.

Second, going far beyond Murmann and Homburg (2001) and Murmann (2003), I advance the theory of coevolution by identifying inductively how specific causal mechanisms (in this case study, they are *exchange of personnel*, *commercial ties,* and *lobbying*) connect to the fundamental VSR processes that drive the evolution of populations. To constitute a coevolutionary dynamic, identifying one causal mechanism with an effect both on the evolution of the industry and on the academic discipline would have been sufficient (*two* effects). Given that *three* distinct processes (VSR) within each of the two partner populations could have been affected, one bidirectional causal mechanism connecting the two population dynamics could have had a maximum of six (2×3) distinct effects. At minimum, the historical analysis needs to show six causal effects from a set of 18 possible ones.

The analysis identifies 12 effects on the VSR processes (see Figure 2 and Table 5). Each of the three bidirectional causal mechanisms had an effect on the selection processes in both populations (six effects), yet only the exchange of personnel and the formation of commercial ties had an effect on the variation processes in two populations (four effects), and only the exchange of personnel had an effect on the retention processes in both populations (two effects). Research in other settings is required to establish whether these findings are specific to this context or whether they generalize across many industries and other important features of their environments.

The large number of exits (see rows 6–8 in Table 1) in the national firm populations shows that many agents lacked anything close to perfect foresight. But clearly, big winners emerged in the German and Swiss dye populations, which outcompeted their British, French, and U.S. counterparts because of self-amplifying coevolutionary dynamics between sets of firms and aspects of their national environments. I want to highlight here how these successful agents activated coevolutionary levers to improve the odds of succeeding in a dynamic world or what McKelvey and Boisot (2009) refer to as improving the agent's *farsight*. Some German and Swiss firms recruited many students from leading academic chemists (*exchange of personnel*) to come up with novel dyes (variation) and/or acquired novel dyes from leading academics (*commercial ties*). Through these coevolutionary levers, some firms created technological discontinuities in the market that made it more turbulent for competitors without creating more turbulence for the firm itself that introduced the novel dye. Those firms that first started to create formal R&D laboratories (e.g., BASF, Bayer, Hoechst, CIBA, Geigy) and then scaled them up by hiring more and more graduate chemists from universities not only created more turbulence for competitors, but they also bought an insurance policy against innovative actions by competitors. Firms with large R&D labs could more readily match their competitors' new technologies than firms that lacked such labs.

Coevolutionary theory is a bridge between the prescient adaptationist and ex post selectionist perspectives of organizational change, countering the misperception that evolutionary arguments in management require human agents to act randomly, without intentions, when striving to develop new variations. Perkin, the inventor of the first synthetic dye, intended to synthesize a drug against malaria. He failed to develop the drug, but when, as an unintended by-product of his research he found a colored substance in his test tube, he adjusted his goals and created an entirely new industry based on synthetic dyes. Yet 17 years later, when the coevolutionary dynamics in Britain proved less favorable than those in Germany, and when Perkin faced what by then had become a formidable alliance between large German competitors and German academic chemists, he sold his firm and retired on his fortune. Coevolutionary theory brings into focus this interplay of environmental structure and agency.

Acknowledgments

The author has incurred many debts in writing and rewriting this paper. He wants to single out Ernst Homburg, without whose assistance this study would have not been possible. Aside from the anonymous reviewers and the senior editor, Deborah Dougherty, the author also thanks Joel Baum, Guido Buenstorf, Mauro Guillen, Elsa von Martius, Lea von Martius, Bill McKelvey, Joel Mokyr, Richard Nelson, Willie Ocasio, Salih Ozdemir, Huggy Rao, Charles Tilly (1929–2008), Michael Tushman, Brian Uzzi, Sid Winter, Ed Zajac, and Mark Zbaracki, who all helped improve this paper as it went through its many versions. Seminar participants from a long list of universities around the world prompted the author to sharpen his arguments. Now the article will take on a life independent of its author.

Endnote

[1]Murmann and Homburg described in their 2001 paper how the dye industry developed in the five countries. Their paper, dedicated to laying out national differences in patterns of evolution, was descriptive and not theoretical in purpose. They did not present evidence on the changes in frequency of the three traits of the national populations of firms (*possession of a formal R&D laboratory*, *ownership structure*, and *global sales force*), which I analyze in the empirical section of the present paper. In the last paragraph of their paper, Murmann and Homburg (2001) call specifically for the development of a theory of coevolution that I develop here. Furthermore, Murmann and Homburg (2001) did not present any of the data on the development of academic chemistry, which I have collected for this paper to inductively identify how the mechanisms of coevolution relate to the VSR processes.

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Johann Peter Murmann is an associate professor of strategy at the Australian School of Business, University of New South Wales. He received a B.A. in philosophy from the University of California, Berkeley, and a Ph.D. in management of organizations from Columbia University. His research interests focus on the evolution of firms, technologies, and national institutions. He is the editor of *Evolutionary Theories in the Social Sciences* (http://www.etss.net).