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ABSTRACT

The Coevolution of Industries and National Institutions: Theory and Evidence

by J. Peter Murmann[*]

A survey across space and time reveals that leading firms operating in global industries often cluster in one or a few countries. The paper argues that nations differ in how successful they are in a particular industry because coevolutionary processes linking a particular industry and national institutions powerfully shape the path of an industry's development. Across a wide range of contexts, scientific progress and industrial leadership reinforce each other in spirals of cumulative national advantage. A historical case study of synthetic dyes from 1857 to 1914 provides a dramatic example of how these positive feedback processes gave German organic chemistry and German dye firms a dominant position in the world. Over time, the relative strength of a nation in a particular industry and the capability of the country in a relevant scientific or engineering discipline display a strong positive correlation. Additional shorter case studies of agriculture, packaged software, and biotechnology support this induced hypothesis. We argue that the exchange of personnel between industry and academic institutions, the formation of commercial ties between them, lobbying on each other's behalf and direct support from state agencies constitute causal mechanisms that can explain why successful firms often cluster in particular countries.

Keywords: Industry evolution, national institution, science-industry interface
JEL classification: L10, O30

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ZUSAMMENFASSUNG

Dominanz durch spezifische Koevolution von Industrien und nationalen Institutionen

Die führenden Unternehmen eines Industriezweiges konzentrieren sich, obwohl sie auf einem internationalen oder globalen Markt agieren, oft nur in einer eng begrenzten Anzahl von Ländern – oder in nur einem Land. Auf der Grundlage verschiedener Fallstudien werden in diesem Artikel spezifische Verknüpfungen von Industrie und national geprägter Wissenschaftslandschaft aufgezeigt, die in einem Prozess enger gegenseitiger Einflussnahme zu einer jeweils herausragenden – dominanten – wirtschaftlichen Position führten. Die Untersuchung der internationalen Dominanz Deutschlands auf dem Gebiet der Herstellung synthetischer Farbstoffe vor dem Ersten Weltkrieg zeigt eine starke positive Wechselwirkung zwischen der Forschung auf dem Gebiet der organischen Chemie und der Marktstellung der farbstoffproduzierenden Unternehmen. Der Aufstieg bedeutender Unternehmen wie Bayer, BASF und Hoechst steht dabei über personellen Austausch, kommerzielle Beziehungen und gemeinsames Lobbying in so enger Verbindung zu den relevanten akademischen Institutionen und ihrer Entwicklung, daß von einem koevolutionären Prozess gesprochen werden kann. Eine derartige positive Korrelation und ein daraus entstehender spezifischer Vorteil wird durch die Betrachtung des Marktes für Computer-Software oder des derzeit vieldiskutierten Bereichs der Biotechnologie untermauert.

1. Introduction: Wealth and the Passions

There are few things – perhaps only one – that can arouse the passions of human beings as much as wealth. As social creatures human beings desire wealth often not in an absolute sense of possessing more than before but in the relative sense of possessing more than one's neighbor. Veblen (1899, p. 290) called this passion 'the emulative predatory impulse' which he regarded as an evolved cultural modification of the basic instinct of workmanship that gave human being a predilection for worthwhile achievement. It is not a coincidence that Adam Smith's classic text *The Wealth of Nations* (1937, 1776) was preceded by his *Theory of Moral Sentiments* (1761) in which he inquired into the passions that were necessary for creating a society that could generate wealth. A close reading of Smith reveals that understanding economic inequality – a topic that became a key issue a century later in the development of sociology – was for him quite essential in identifying wealth-generating processes (see, for example, *The Wealth of Nations*, Book V, Chapter 1). Despite this longstanding human passion for wealth and the almost equally long-standing fear of destabilizing inequalities in modern societies (Hirschman, 1997), economics and sociology have not yet provided a complete understanding of how nations generate wealth and how they can distribute it relatively evenly. Even when we narrow the question considerably and inquire why nations differ dramatically in the performance of a particular branch of industry, existing theories do not provide us with an adequate explanation (Mowery and Nelson, 1999; Porter, 1990). Consider this intriguing puzzle.

For thousands of years before the discovery of the first synthetic dye in 1856, human beings all over the world dyed textiles, using coloring materials derived mainly from plants and to a much smaller extent from such animals as mollusks. To extract, for example, one gram of the natural dye Tyrian Purple from a tiny gland of the body of a mollusk, 12000 animals were required. Because brilliant dyes that were resistant to wear and tear were very expensive, the color of a person's clothing would typically reveal one's socioeconomic status: common people tended to walk around either in undyed or in dark single color linens whereas Kings and Queens at the apex of the social hierarchy would show themselves in the most beautiful colors that the light spectrum has to offer. The subsequent "democratization of colors" was set in motion by the 18-year old William Henry Perkin, who had enrolled as a student at the Royal College of Chemistry in London and serendipitously discovered a purple coloring material in his test tube while he was trying to synthesize quinine – a substance that many an Englishman consumed as a medicine to fight malaria on trips to the tropical possessions of the British empire.

Perkin abandoned his university career and together with his father and brother opened up a year later the first plant that produced a synthetic dye in the world. They had to overcome many production and marketing hurdles to commercialize William Henry's discovery. On the marketing side, Perkin & Sons was assisted greatly by the young French Empress Eugénie who had been encouraged by the French court to wear the newest patterns of the Lyon silk industry and the Parisian haute couture. In the second half of 1857, the empress had become particularly fond of a new purple shade that had been introduced by Lyon silk dyers. She created an haute couture fashion craze that, with a season's delay, spilled also into Great Britain and prompted British dyers and colorists to overcome their resistance and use Perkin's novel synthetic dye. Protected by a British patent, Perkin & Sons made handsome monopoly profits. And within a few years, British and French firms had introduced synthetic dyes spanning the entire color spectrum.

Contemporary observers were convinced that Britain was predestined to dominate the global synthetic dye industry for decades. August Wilhelm Hofmann, for example, who was the most distinguished organic chemist working in London at the time and under whom Perkin had studied at the Royal College of Chemistry, wrote in his *Report* (1863, p. 120) *on the Chemical Section of the International Exhibition of 1862*: "[A]t no distant date … [Britain will be] the greatest colour producing country in the world; nay, by the strangest revolutions, she may, ere long, send her coal-derived blues to indigo growing India, her tar-distilled crimson to cochineal-producing Mexico and her fossil substitutes for quercitron and safflower to China and Japan, and the other countries whence these articles are now derived." Although Britain and France were the leading producers for the first decade of the synthetic dye industry, it was not Britain but Germany that came to dominate the global market before World War I (WW I). Initially copying British and French synthetic dyes, the German dye industry possessed by 1870 a world market share of about 50% that continued to climb to about 85% at the outbreak of World War I. At that point, the British and French global market shares had been reduced to 3.1% and 1.2% respectively. Switzerland had become the second largest producer in the world with 6.2% and the United States produced 1.9% of the world total (Reader, 1970, p. 258). In the year before World War I, synthetic dyes were Germany's largest export item (80% of domestic production was shipped abroad) and their production had created a large amount of wealth for Germany because synthetic dyes, despite large price decreases, remained a very profitable business for the large Germany producers. So where is the puzzle?

The puzzle about this economic success story arises the moment one tries to explain why Germany and not Britain came to dominate the industry. Presented with the fact of this long German dominance, one may simply jump to the conclusion that Germany must have had a large cost advantage in raw materials or a much greater local demand for dyes. But surprisingly neither a supply nor a demand explanation works. The most basic raw material for synthetic dyes was coal. Germany produced a lot more coal compared to France: almost twice as much as in 1859 and six times as much in 1913. But Britain started out producing about six times as much coal than Germany in 1859 and was still ahead by 1913. The U.S. produced 25 percent more coal than Germany in 1859 and twice as much in 1913. And Switzerland had no coal at all. If one examines the raw material supply at an even greater level of detail, one learns that the most immediate raw material for dye production – coal tar – was largely imported by Germany from Britain because British cities generated it in huge quantities as an unwanted byproduct of making illumination gas for lighting the streets before electrification. If raw materials were a decisive advantage, Britain should have developed the largest dye industry and not Germany and Switzerland. And the U.S. should have at least matched Germany's performance. Better raw material supplies, then, clearly cannot explain how Germany and Switzerland came to outperform all the other countries. A demand side explanation does not work either. If one examines the relative sizes of the textile industry in the five countries, one finds that in 1852 the largest textile industry in the world was Britain's. Britain had a capacity of cotton spindles that was 23 times larger than Germany's, five times larger than the capacity of France, four times larger than the capacity of the U.S., and 23 times larger than the capacity of Switzerland (Landes, 1969). While most countries improved their relative position until 1913, British spindle capacity at this later date was still five times larger than that of Germany, almost twice as large as that of the U.S., seven times larger than that of France and now 40 times larger than that of Switzerland. If it was not quantity but the quality of demand that played the decisive role, France with the leading high fashion industry in the world would have had a clear advantage over Germany. Given that neither the obvious supply or demand explanations work in this context, we are left with the intriguing puzzle of why Germany was able to catch up with Britain and France in the synthetic dye industry and gradually built a dominant position that remained unchallenged before World War I.

Using a variety of organizational theory perspectives – the resource-based theory (Wernerfeld, 1984; Barney, 1991), organizational ecology (Hannan and Freeman, 1989), institutional theory (Meyer and Rowan, 1977; DiMaggio and Powell, 1983; Oliver, 1991; Scott, 1991) resource-dependence (Pfeffer and Salancik, 1978), network theory (Burt, 1992; Tilly, 1998) and evolutionary theory (Nelson and Winter, 1982; Aldrich, 1999; Langton, 1984) – as investigative tools, we articulate in this paper a model that can explain the initially puzzling German dominance in this sector. Extending Nelson & Winter (1982), we argue that a coevolutionary process that links national firm populations and national institutions is able to explain the dramatic differences in economic performance of the five main synthetic dye producing countries.[1] This coevolutionary model that we derive from a detailed historical study of the synthetic dye industry between 1857 and 1914 is also tested against the empirical record of three other

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[1] We are not the first ones to notice the remarkable dominance of German firms in the synthetic dye industry before World War I. Historians such as Beer (1959), Hohenberg (1967), Landes (1969), Lindert & Trace (1971) have linked the performance of the industry to the superior research and teaching system in Germany. But because they have not collected a systematic database of all the firms in the industry, they did not see the coevolutionary process that created the German dominance. Furthermore, our database shows that France was not trailing Britain at all in the first years of the industry. These findings call for a reevaluation of the early period in the synthetic dye industry as it is currently presented in the historiography of the industry.

industries. Given the space constraints of an article, we focus on the most important national institution in the early dye industry – the research and teaching system in which colleges and universities played a key role.

2. Theoretical Puzzles and Methods

The puzzle about the German dominance in the synthetic dye industry before World War I becomes even more intriguing when one examines it through the lens of existing paradigms in organization theory and economics. The resource-based theory, for example, argues that firms achieve a sustainable competitive advantage when they possess difficult to trade or replicate resources (Barney, 1986). The resourced-based view would offer a complete explanation of this puzzle if a single German firm produced virtually all German dyes. But this was not the case. In 1914, 25 dye firms operated in Germany. Three of them – Bayer, Hoechst and BASF – each had about a 22 percent market share. Because organizational ecologists regard firms as severely limited in their ability to successfully change their strategies and core structural features, ecological theorists often attribute differences in survival rates – which are seen as a key indicator of good performance – to being born during the right period of the population life cycle (Hannan and Freeman, 1989). A standard ecological model would offer a compelling explanation of German dominance if the three major German firms had been born during a period when no foreign competitors had also entered the industry. But during the first half of the 1860s when Bayer (1863), Hoechst (1962), and BASF (1965) entered the industry, there were more entries in France than in Germany. Nonetheless the French market share started to decline by the mid 1860s and reached an insignificant 1.2 percent by 1914.

In many models of neoclassical economics all firms are treated as homogenous and they are viewed as constrained only by technological and market conditions. We have already shown that market conditions cannot explain German dominance. But perhaps German firms had access to technology that French, British and American firms could not acquire. In this scenario, all Germans firms should have been homogeneously advantaged by having access to superior technology. The historical record, however, disconfirms this hypothesis. German firms in the early years of the industry copied French and British synthetic dye inventions. Furthermore, German firms were very heterogeneous as our detailed case study of two of the 116 German companies in our database reveals. To hold all environmental variables as constant as possible, we selected two German firms that entered dye industry in the same town of Barmen. The two firms – Jäger and Bayer – were also born in the early phase of the industry, 1858 and 1863 respectively; and both had previously traded in natural dyes. In the course of the next 50 years Bayer developed into a large Chandlerian firm with formal R&D laboratories and professional management, selling dyes all over the world, while Jäger remained a small family run organization that possessed less than one percent of the German market in 1914. Although both firms were started in the same environment, they developed into organizations with very heterogeneous capabilities for developing new dyes, for producing them efficiently, and for marketing them effectively to dyers all over the world. As this matched comparison reveals, a standard neoclassical model of the firm is also not able to give a satisfactory explanation of German dominance in synthetic dyes.

To explain the shift in industrial leadership from Britain and France to Germany and to solve the puzzle of the 40-year dominance of German producers in the industry, it appears necessary to refine existing theories. The goal of this paper is to investigate in detail the strategies that were pursued by players in the different national context and induce causal processes that produce such vast differences in performance of the national industries. We follow Eisenhardt's approach to build theories from case studies (Eisenhardt, 1989). We also recognize that every empirical investigation presupposes a classification methodology that implicitly contains non-empirical concepts about what counts as similar and what counts as different (Hodgson, 2001). Even inductive research is based on implicit theories about how the social world operates. To allow other scholars to verify our findings in different settings, it is important to articulate as much as possible our a priori theoretical orientation toward the research question at hand. In our quest to solve the puzzle of how Germany acquired this dominant position, we examined the historical dynamics in the synthetic dye industry through the lens of existing frameworks in organization theory such as the resource-based theory of the firm, organizational ecology, and evolutionary theories à la Nelson and Winter (1982) and Langton (1984). This methodology offered the advantage that it would be possible to build on those aspects of the existing theories that illuminated the historical dynamics in the synthetic dye industry. But even more importantly, holding existing theories against the historical record of the synthetic dye industry would bring into focus the explanatory gaps that existed within and between the different theoretical approaches. In the next section, we offer not a mere description of the events that transpired, but instead a theorized history that we have constructed to lay open the causal processes that can explain the puzzle of how German firms came to dominate the synthetic dye industry.

Historical case studies are not entirely new to organization theory. Langton (1984) studied the entrepreneur Josiah Wedgwood and the British pottery industry to develop an evolutionary theory for the rise of bureaucratic firms. Leblebici et al. (1991) in turn investigated the history of the U.S. broadcasting industry to construct an empirically grounded account of how institutional practices change. In both cases the motivation for the histories was to refine existing theories. In the case of Langton (1984), the aim was to specify causal processes that could bring about the dominance of bureaucratic organizations that Max Weber described in great detail. In the case of Leblebici et al. the goal was to fill an explanatory gap in neo-institutional theory, namely, of how organizational fields could change after they had been institutionalized.

The first part of our research methodology was to learn about the existing theories of industrial change. The second major task was to study in fine detail the actual dynamics and events in the synthetic dye industry. We began by reading all existing histories of the dye industry. The appendix lists the most important studies on which we relied. Third, we visited the German dye plants of Bayer in Leverkusen and BASF in Ludwigshafen to familiarize ourselves with how dye production is organized. Fourth, borrowing from the organizational ecologists, we collected data on all firms in all dye-producing countries before World War I. Because it became apparent very early on that frequently dye firms went out of existence while their plants continued to be operated by another firm, we also constructed a related database on dye plants and the various types of products they made.

Our database of firms and plants was designed to contain numerical as well as relevant qualitative data. Because we pulled together information from a wide variety of sources – histories of the dye and chemical industries, histories of firms, trade directories of various kinds, reports on firms exhibiting at world exhibitions, trade association membership lists, and biographies of leading industrialists and chemists – our database is considerably richer than any hitherto amassed. We constructed our database of firms and plants after we had already acquired a considerable understanding of the dynamics that marked the industry. Our knowledge of this industry allowed us to design the database with an eye toward potentially key micro-variables that influenced the development of the industry. For instance, we tracked products such as synthetic alizarin, which has been identified as an important innovation in the historiography of the synthetic dye industry. These data would make it possible to examine hypotheses advanced in the historiography of the industry in a more systematic fashion. A case in point is the idea that a new wave of entry occurred in the industry because of the development of synthetic alizarin.

In sum, we used both quantitative and qualitative methods in our study. By combining the method of collecting data on all firms in the industry – a method that was pioneered by organizational ecologists – with the methods of business and economic history that examine fine details of an empirical context, we were able to construct an empirically grounded model of coevolution that extends considerably the resource-based theory of the firm.

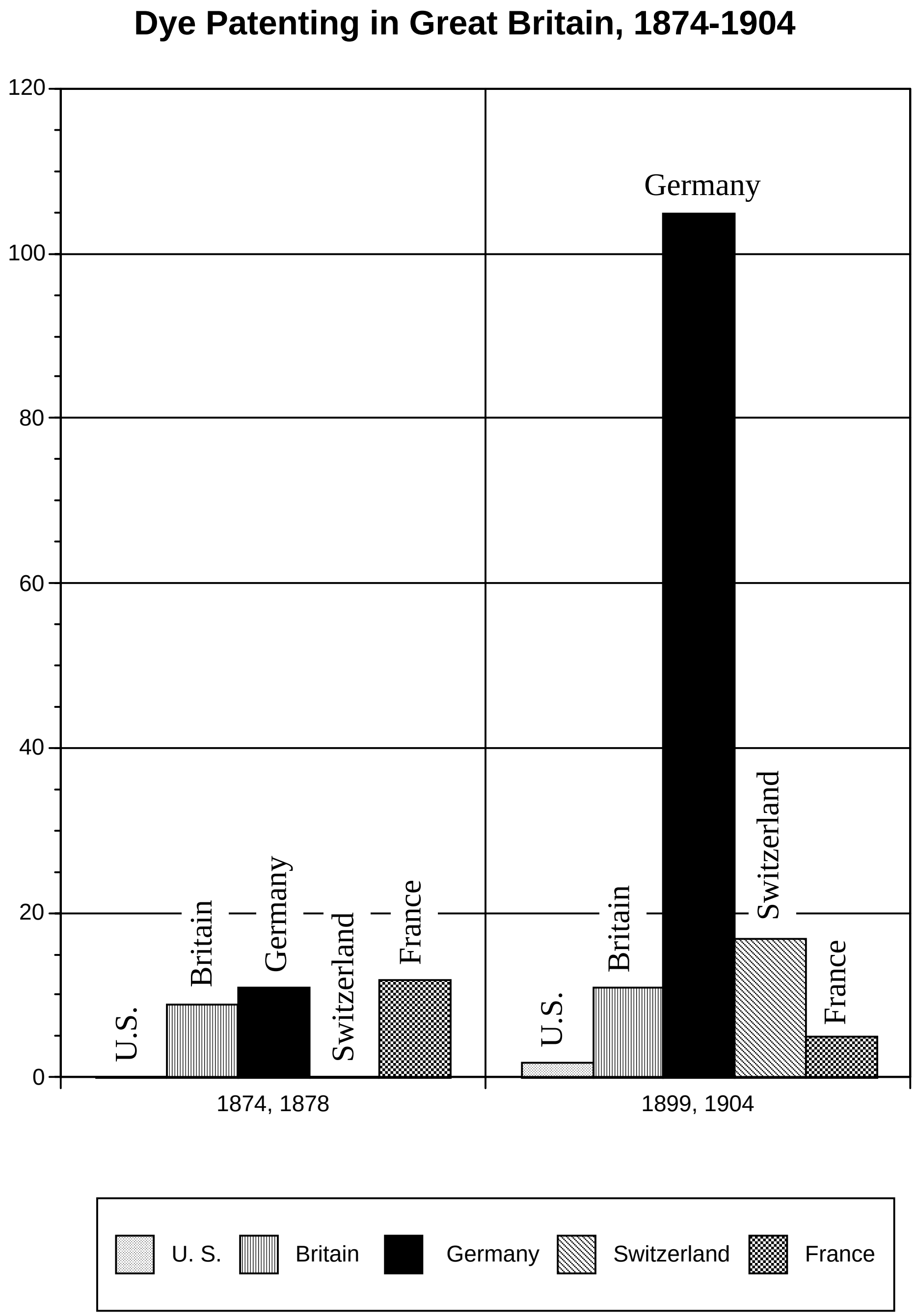
3. A Theorized History of the Synthetic Dye Industry

In setting out to identify the factors that explain how Germany acquired such a powerful competitive advantage in the synthetic dye industry, it is useful to recall that in the final analysis all competitive advantages are based on being able to offer a product at a lower cost or higher quality. To put it a bit differently, any factor that is presumed to confer a competitive advantage must in the end pass the test of translating into lower cost or higher quality or both. In this theorized history, we are tracing back the causal chain from these most proximate reasons of a competitive advantage to more distant ones that explain how Germany came to dominate the synthetic dye market all over the world. One of the most striking features of the synthetic dye industry before WW I was the very high rate of innovation. Perkin's discovery of the first synthetic dye in 1856 was only the beginning of a long stream of product and process innovations that turned the dye industry into a very dynamic field with large opportunities for new firms to offer novel colors.

By conservative estimates, dyers and printers could choose from 900 distinct synthetic dyes on the eve of World War I. From the very beginning of the industry, a frenzied search broke out to find synthetic routes to the commercially most significant natural dyes, alizarin and indigo. Perkin in Britain and the team of Carl Graebe and Carl Liebermann in Germany invented synthetic alizarin concurrently in 1869. Within a few years, farmers in Europe had to give up planting madder, the crop from which alizarin was made. But synthetic dyes not only competed with their natural counterparts. They also competed with one another: new synthetic dyes often made older ones obsolete, as was the case with the first synthetic dye, aniline purple, which only had a commercial life of a few years. Firms in the 1860s already made more than one particular dye. As the number of distinct synthetic dyes proliferated, some firms offered their customers a full spectrum of synthetic dyes. From 1862 (the first year for which data are available) to 1913, output increased by 3800% in terms of value. Because of price decreases, the increase in terms of volume was substantially higher. The expansion in production from 1871 (the first year for which an estimate is available) to 1913 was 4000% (from 3,500 to 160,000 tons). This immense increase in output was made possible in part by the large proliferation of dyes that were sold in the market.

Continuous product and process innovations were both crucial for building and maintaining a competitive advantage in the synthetic dye industry. Britain and France initially prospered in this industry because these two countries produced all the product innovations during the first five years of the industry while German and Swiss firms copied foreign products and focused on process innovations to reduce production costs. In the middle of the 1870s Germany had become an innovator herself, and by the turn of the century she had come to dominate dye innovations. Patent filings in Great Britain are one clear indicator of the how severely other countries had fallen behind.

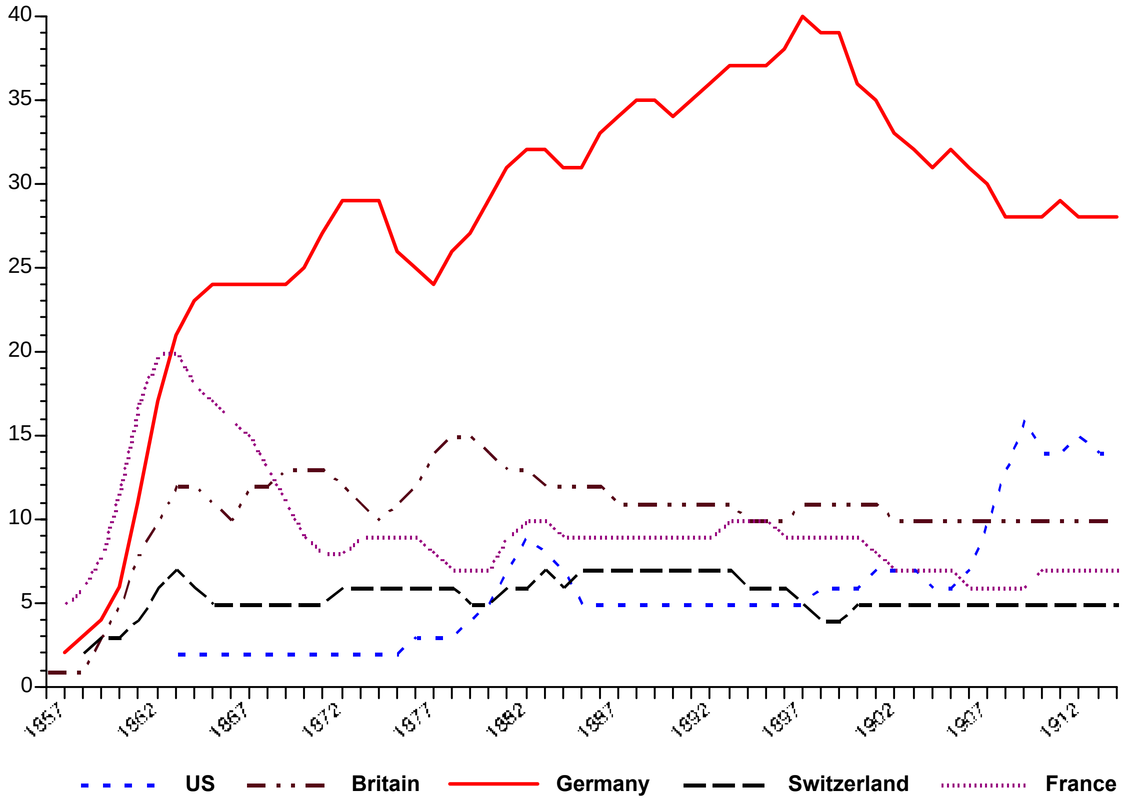
Figure 1: Number of Patent per Country



Note: Absence of a bar for a country indicates zero patents.

Evolutionary economics (Nelson & Winter, 1982) maintains that firms are limited in their ability to implement new strategies. Given this constraint on exploring novel forms of behavior, it is possible that the initial high rate of product innovations in France and the high rate of process improvement innovations in Germany was due to a large number of competing firms trying out alternative business models. Our dataset of all firms in the synthetic dye industry confirms this theoretically grounded speculation. Already in the second year of the industry (1858), France had five entries in the industry while Perkin & Sons remained the only firm in Britain and two imitator firms commenced production in Germany (see Figure 2). Between 1858 and 1862, France had become the leading innovator in the global synthetic dye industry; but the industry experienced a sharp decline in innovation because one firm, La Fuchsine, convinced the courts to grant it a master patent for synthetic dyes, and based on this legal title called upon the police to close down a large number of French firms. The French patent ruling was responsible for the shakeout that occurred in France. At least seven firms (Feer, Durand, Dollfus, Guinon/Monnet, Gerber-Keller, and Poirrier[2]) closed down production and set up shop across the border in Switzerland (which had no patent law). Other French firms had to focus on minor dyes.

Figure 2: Number of Dye Firms by Country



After 1862, however, Germany always had the largest share in the global population of dye firms. When entirely new dye classes such as azo dyes were discovered, more new

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[2] Poirier did not close down its entire firm in France but transferred its fuchsine dye production to Switzerland.

German firms entered the industry than from any other country when new dye technologies became available.

Our investigation of the population densities and the organization of the industry revealed some very interesting clues about why Germany came to dominate the industry by the 1870s with a market share of about 50%. At the global level (i.e. the sum of all producer countries) 284 firm entered the industry and 226 firms exited the industry between 1857 and 1914. The global failure rate stood at 79%, which suggests that most firms had pursued an inadequate business model or had developed standard operating procedures that were not competitive in the medium run. In Germany, 91 of the 116 entrants before 1914 went out of business. The figures for Britain were 36 out of 47 firms and for the U.S. 25 out of 35 firms. The fact that the failure rate in the three countries was very similar (Germany 78.4%, Britain 76.5%, and the U.S. 71.4%) highlights that the absolute numbers of entry and exit are very important for understanding the competitiveness of an industry. The most successful country also experienced the highest number of firm failures! Our data on dye innovations and industry demography paint a very clear picture. German firms caught up with French and British firms because they began to innovate themselves and because there was simply a larger population of German firms that could explore alternative strategies for competing technologically in the synthetic dye industry.

But why were there so many more entries in Germany? The key reason was that more skilled chemists were available in Germany than in any other country.[3] Before the birth of the synthetic dye industry, Germany was the home of a small, by later standards, but nonetheless very good research and teaching system in organic chemistry. The Napoleonic conquest of German lands had convinced many a ruler of the 39 German states to invest larger sums into medical and pharmaceutical education in the hope of being able to draft more soldiers from a healthier population. Because chemistry was part of the curriculum of students in medicines and pharmacy, universities started to appoint more professors in chemistry. By around 1830 the demand for chemistry teachers allowed professors to offer courses designed specifically for students who majored in chemistry. In this context, Justus von Liebig developed a very innovative chemistry curriculum on German soil in which students would conduct original research that gave them considerable skills in synthetic chemistry. The German training system grew substantially over time and provided German firms with highly qualified scientists not available to the same degree in Britain, the U.S. and France before 1914. For as long as the necessary financial resources were available, a self-sustaining capability in organic German chemistry developed because chemists wanted to train more chemists to help them advance chemical knowledge. Because most of the new chemists could not find

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[3] Another important reason that led to more firm entries in Germany was the absence of an effective patent protection before 1877. We will take up the relationship between national patent practices and national firm populations in a separate paper.

academic positions, they were willing to work for state agencies or private firms. Swiss firms enjoyed a similar advantage over British, French, and American rivals. Switzerland, whose university system was integrated with that of Germany because personnel and students moved across borders at high frequencies, had two first rate centers of organic chemistry in Zurich and in Geneva. Given that knowledge in synthetic organic chemistry was a critical, hard-to-imitate resource, German firms enjoyed a substantial advantage that they were able to translate into a domination of world dye markets. Possessing no institutions that offered graduate training in science and engineering in 1850, the U.S. experienced a dramatic growth of universities that provided training in engineering and to a smaller extent in science after the Land Grant act of 1862. But until World War I, American universities offered almost no advanced training in *synthetic* organic chemistry, which formed the key knowledge base for the dye industry. This made it difficult for American firms to build up the necessary capabilities to compete in the international dye industry. In France the dye industry had lost its competitive edge just as its science capability in organic chemistry had become weak because one of the two French professors in organic chemistry had died and a successor was not appointed for a couple of years. The French dye industry never recovered. In essence, the German dye industry developed its global dominance by residing in a social context that provided a small, but undeniably, better university system in chemistry at the start of the industry and that later provided even larger numbers of highly trained science and engineering students that could give local firms a competitive advantage.

The innovative capabilities of the German dye industry rested to a large extent on the human capital that was embodied in the highly skilled organic chemists and engineers who were employed in corporate R&D labs that were created after 1877 by all larger German dye firms to create new products and processes. (The dye industry was the cradle of corporate R&D labs that today are commonplace among large firms in technologically dynamic industries.) Neither the German nor the British dye industry would train their scientists and engineers fully in-house. They would rely rather on universities, polytechnics, and trade schools to provide their scientific and technical personnel with fundamental education. Firms then hired these well-educated individuals and taught them the skills that were peculiar to the specific tasks required in the industrial context of the synthetic dye industry. The key point is that dye firms in both countries relied (as they still do today) on their social environment for the training of their scientific and technical human resources. Probably because empirical work on the resource-based theory of the firm has only analyzed industries in one particular nation to date, it has not realized that hard to replicate and trade assets not only reside in individual firms but also in the larger social environment (Maijoor and van Witteloostuijn, 1996; Brush and Artz, 1999; Kraatz and Zajac, 2000). After the early period that lasted from 1857 until around 1865, the German synthetic dye industry enjoyed substantial competitive advantages over that of

Britainbecause it was geographically and culturally closer to valuable human resources that were produced by a superior educational system.

To be sure, Britain had a significant number of scientists with international reputations in the nineteenth century. But such eminent figures as Michael Faraday, Humphry Davy, John Dalton and William Wollaston did not create research schools as Justus von Liebig, Friedrich Wöhler, Hermann Kolbe, Robert Wilhelm Bunsen, August Wilhelm Hofmann, Adolf Baeyer and others did in Germany. Britain excelled in producing a large number of world class "private" scientists, who were often associated with learned societies and academies, but did not develop the institutional framework for producing a large number of qualified students who could be employed by industry. German universities, in contrast, were often educating more chemists than society needed (Titze, 1987; Flechtner, 1959). Men like Heinrich Caro, Carl Alexander von Martius, Johann Peter Griess, and Otto Witt – to name a few – in part went to Britain not because it was an excellent industrial training ground for any aspiring young man but rather because jobs for chemists in Germany were scarcer than qualified applicants. The overproduction of chemists in Germany was of course a good fortune to Britain, as she could make up for the lack of local training by hiring Germans. However, when the expansion of the German dye industry and academic chemistry created excellent opportunities for German chemists at home, it was increasingly difficult for British firms to hire German talent.

While powerful people in government, industry, and the academy resisted the expansion of science and technology teaching in Germany as well as in Britain, Britain's misfortune was that these forces were much stronger at home than on German soil. Although the overall British student population increased 20 percent between 1900 and 1913, Germany's climbed 60 per cent in the same period. Between 1893 and 1911 the numbers of students at the civic universities in Britain (excluding Oxford and Cambridge) rose only from around 6400 to 9000 or by 40%. Of those 9000 only 1000 were engineering students and 1700 science students (Haber, 1971, p. 51). If one adds to the figure of about 11,000 technology and science full-time students at the technical universities the number of science students educated at the regular German universities, it is evident how much larger was the output of scientifically literate manpower in Germany. These differences in university output became reflected at the highest echelons of industrial leadership. Recent research on successful British and German businessmen in the period from 1870-1914 has shown that in the case of Britain, 13% of them were academically trained versus 24% in the case of Germany (Berghoff and Möller, 1994). One important reason why the German system of higher technical and scientific education was superior to the British one lies in the higher level of financial support by German governments. At the end of the 19th century, the British government paid £26,000 to universities for all purposes. Prussia alone, though the largest German state, supported her universities with £476,000. The corresponding figures for the academic year 1911/12 amount to £123,000 and £700,000 (Haber, 1971, p. 45 and p. 51).

Ben David's (1977) analysis of the scientific literature reveals that France had been the leading country in chemistry until Germany surpassed it in the 1830s. By the time the dye industry started there were two centers of organic chemistry in France (Chevreul, 1866). The most influential teacher in the field of industrial organic chemistry in France, Th.-J. Pelouze, died in 1867 (Fox, 1992). His private laboratory had been a breeding ground for dozens of young industrial chemists, several of whom went into the dye industry. When Pelouze passed away there was no one to continue his successful teaching laboratory, and the production of highly qualified organic chemists who could start new dye ventures virtually ended for many years (Leprieur, 1979). As a result, the number of potential entrepreneurs decreased dramatically in France. At this particular time, the structural differences in the French and German university systems made the supply of entrepreneurs in France much less robust than in Germany. The centralized French academic system, which had one major chemical research center in Paris and one more in Lyon, was much more vulnerable to a temporary dramatic loss in quality and output than the decentralized German system. Altogether there were about 30 university and technical university departments in organic chemistry in Germany at the time. If one German center declined for some time, there were still about 7 major centers of organic chemistry research and teaching left. France never recovered when its dye industry and its academic capability in organic chemistry both had become weak in the early 1870s.

The relative failure of the U.S. synthetic dye industry before 1914 can be traced in large measure to the lack of research and teaching in synthetic organic chemistry available in the country. The American system of higher education made great advances in the late 19th century. A close examination of the system reveals, however, that it became strong in many disciplines but not in the one crucial for the dye industry – synthetic organic chemistry. In 1850, the U.S. had no universities that offered graduate training in science or engineering. To compensate for this deficiency, about 10,000 Americans went to Germany to receive graduate training in the 19th century (Stern, 1987, p. 248). Among them were many people who went to places like Giessen to obtain advanced training in organic chemistry. In the middle of the century there were attempts to create rigorous science research and education at Yale and Harvard, but these attempts invariably met with little success because of a lack of support by society at large (Rossiter, 1975).

Education statistics for the entire U.S. show the explosive growth of the American system of higher education after 1862. Starting at a lower enrollment level than Germany, the increase in the United States is even higher than in Germany for the same period. Because U.S. degree statistics for the period before World War I are already broken down by subject, it is possible to gain a quantitative picture about the growth of individual disciplines. The yearly number of U.S. bachelor's degrees in all fields and in chemistry increased by over 400% in the period from 1890 until 1914 (7,228 to 31,540 and 631 to 2573 respectively). During the same period, the yearly number of doctorates in chemistry increased by about the same percentage from 28 to 107 (Thackray, 1985).

Virtually none of these Ph.D.s, however, was in synthetic organic chemistry. Thus the entrepreneurs that started dye firms in the U.S. had to cope with a total absence of domestically-trained talent. Entering the dye business required that entrepreneurs had either themselves received chemical training in Germany (as was the case with Schoellkopf) or that they relied on talent that was educated in Germany or Switzerland (as was the case with Heller & Merz). Firms such as American Aniline Works who tried to acquire the necessary chemical skills by reading German textbooks stood no chance of replicating the capabilities of rivals who had synthetic organic chemists on their staff.[4] But, of course, the number of people who would go to Germany to receive an education and the number of German chemists who would come to the U.S. at the same salary level as in Germany was limited. Unlike in Britain where the Royal College of Chemistry (under Hofmann's leadership until 1865) educated students who could staff the new synthetic dye industry, the U.S. did not possess a center of organic chemistry that would educate potential entrepreneurs. By international standards, organic chemistry and the synthetic dye industry in the U.S. were weak for the entire period before 1914.

The Interface Between Scientific Education and the Dye Industry

Industrial leadership passed into the hands of the German industry since firms could not only draw on a larger body of talented chemists and engineers but also were able to join forces with German professors in their quest for developing new products. In Germany and Switzerland the interface between scientific education and the dye industry was much more developed than in other countries. A very large number of contacts between academia and industry were initiated and cemented through teacher-student relationships. When Hofmann was lured back to Germany in 1865 to head a large new university laboratory in Berlin, the British dye industry lost one of her most important academic partners. After his student Perkin had synthesized aniline purple and launched the synthetic dye industry, Hofmann used his laboratory in London to discover other dyes.[5] He consulted widely and channeled students into British dye firms. When he moved to Berlin, he continued this pattern. In addition to becoming the most important consultant

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[4] Williams Haynes (1954, p. 310) tells the following delightful anecdote about the entry strategy of American Aniline Works: "Being quite ignorant of any color-making process, they advertised in English and German trade papers for formulas and directions. The English replies proved valueless and none came from Germany, for the publisher of their advertisement was promptly arrested, charged with aiding a surreptitious attempt to steal German trade secrets."

[5] Hofmann received a British patent for a violet aniline in May of 1863. He licensed the dye to Simpson, Maule & Nicholson, Knosp of Stuttgart (Germany), and later Renard Frères in France (Travis, 1993, p. 79).

to the AGFA (there is evidence that he held stock in the company), he also became a tireless organizer of German academic chemistry and its relationship to industry.

Hofmann was by no means an exception. Firms could draw on a large number of university researchers who were willing to interact in a variety of ways with industrial firms. The most famous episodes are the alliance Carl Graebe and Carl Liebermann formed in 1869 with Heinrich Caro, the research director of BASF, to pool their discoveries and jointly file a patent for alizarin in Britain (Travis, 1993). Even before Bayer had established its own central research laboratory, the firm made use of the superior research facilities that existed at many German universities. The first assignment Bayer handed to newly hired chemist Carl Duisberg was to work for six months (1883-1884) in the organic chemistry laboratory at the University of Strasbourg and research basic problems of interest to the company (Duisberg, 1933).[6] When Bayer had difficulty getting high yields in their newly set-up acid plant in Leverkusen in the 1890s, the firm could call upon the advice of the leading expert for inorganic chemical technology and famous textbook author, Georg Lunge, a German chemist who was for many years on the faculty of the Zurich Technical University (Flechtner, 1959, p. 151).

British firms, of course, also interacted with institutions of science in addition to their traditional reliance on the chemical consultants who traveled from one firm to the next.[7] Levinstein, for example, relied on universities for human talent just as the German firms did. But at the same salary level, British firms could not recruit German talent because on average they would prefer to work in their homeland if they were offered a good position there. British firms thus had a decisive cost disadvantage in hiring superior organic chemists. As industrial firms are primarily profit-oriented institutions, the level of involvement of academic scientists and their support of public research activities depends largely on the perceived benefits that will flow from this activity. Since the German academic system in this period had a larger number of leading chemistry professors and educated more well-trained chemists with skills that were of use to industry than the British one, it is not surprising that German industry cultivated the interface with academia more extensively than British industry. German entrepreneurs simply had more to gain from interacting with their local university system (Gulati, 1998).

If one begins to map out the contacts between academic organic chemists, dye chemists in industry, and dye entrepreneurs, some striking network patterns emerge that helps explain the embedded action (Uzzi, 1997) that took place between firms and universities. A number of leading academic chemists were at the center of the network: Hofmann (in London until 1865, then Berlin until 1892), Baeyer (Berlin, Strasbourg,

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[6] Duisberg later developed into a towering figure in the German chemical industry. He became CEO of Bayer, the principal architect of the German dye cartel, leader of the German Association of Chemists, the Chemical Industry Association, and, after his retirement from executive duty at I. G. Farbenindustrie Aktiengesellschaft, the representative of the Association of German Employers (Flechtner, 1959).

[7] One of these traveling consultants, George E. Davis, became a cofounder of the Society of Chemical Industry and was author of the first (1901) English-language handbook on chemical engineering.

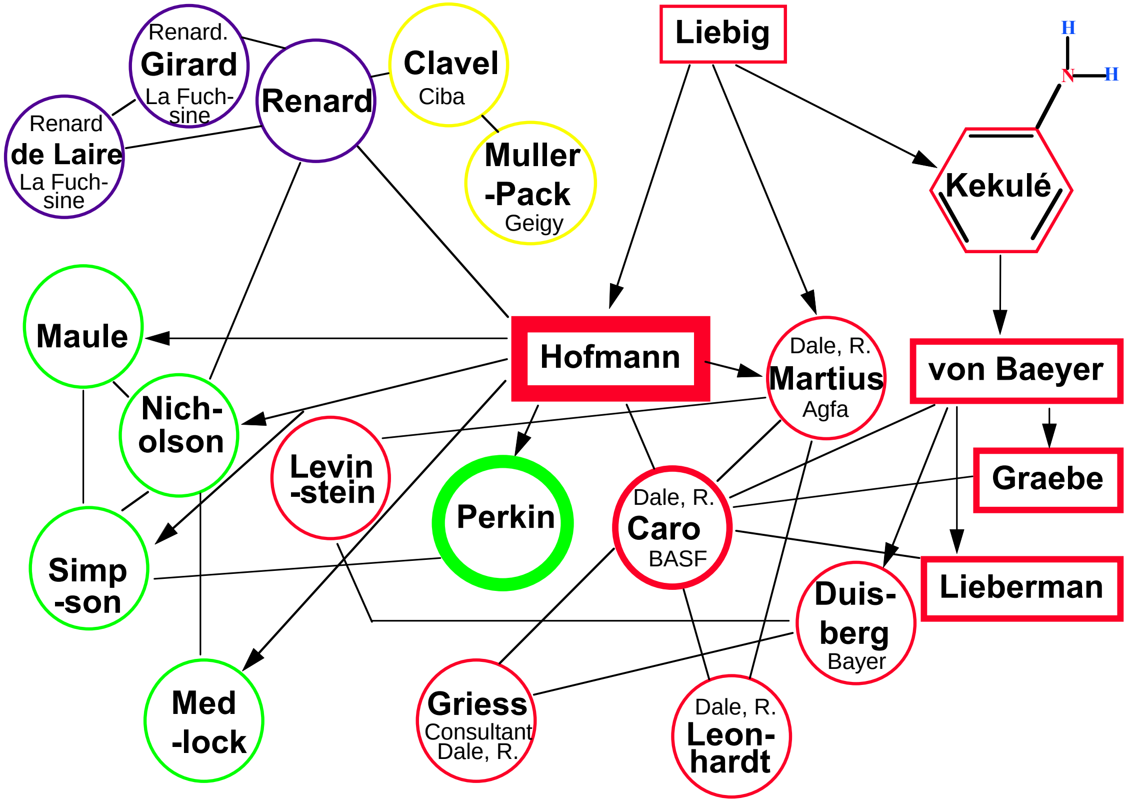
Munich), and Witt (first in private industry in Britain, France and Germany, then Professor of Chemical Technology at the *Technische Hochschule* in Berlin). Similarly, among the industrial members of the network some players such as Caro at BASF and Martius at AGFA and later Duisberg at Bayer acquired a central position.

The origin of the network can be traced to Liebig, who trained a generation of leading chemists (among them Hofmann, Kekulé [who in turn was the teacher of Baeyer] and many British and some American chemists). Figure 3 tries to represent the early industrial-academic network that connected entrepreneurs with academic sources of knowledge. The early British entrepreneurs in the dye industry almost exclusively came out of Hofmann's laboratory at the Royal College of Chemistry in London (see Travis, 1993, and Fox, 1987 for biographical details). Later Baeyer, Hofmann, and Kekulé trained in Germany many of the chemists who would develop the new dyes.

The center of the academic-industrial network became located in Germany because the laboratories of Hofmann (Berlin), Baeyer (Berlin, Strasbourg, Munich), and later Emil Fischer (Strasbourg , Munich, Berlin) became leading centers of organic chemistry where new knowledge was created at a faster rate than in British laboratories. Students from the United States and Britain would very frequently come to Germany to receive advanced training in organic chemistry. A good example is Dan Dawson. After founding a dye firm in Great Britain, Dawson, at age thirty-eight, decided to let his brothers run the business while he went to the University of Berlin in 1874 to study with Hofmann (Fox, 1987, p. 141). But a reverse flow did not take place after Hofmann left London for Berlin in 1865. Britain attracted a substantial number of German chemists because the British pioneers of the dye industry as well as the large dyeing and brewing industries provided an excellent training ground as well as jobs that were often hard to come by in Germany where chemists were typically in oversupply. While the network branched across all the major dye producing and consuming countries, the strongest links existed in Germany. Because German academics had a stronger incentive to help German firms rather than their British or American rivals, German firms had less difficulty in establishing a strong relationship to academics.

Dissecting the anatomy of the academic-industrial network shows that its centers were located in Germany. The academic-industrial network expanded much faster in Germany and Switzerland than in Britain, France and the United States. The student-teacher relationship was the most important mechanism that created the strong links in the network. Spending long hours together in the lab, making joint scientific discoveries, and publishing papers under joint authorship not only transferred the knowledge (often tacit) of how to do organic chemistry but also created strong emotional ties between teachers and students.

Figure 3: The Early Academic Industrial Dye Network[8]



The Role of Dye Firms in Forging a National Science Capability

A look behind the scenes of how research and training systems were funded reveals that in all five major dye producing countries the size and quality of the higher education system was in part a result of industrialists taking actions. The five countries, however, differed enormously in the degree to which dye industry leaders became involved and were successful in building a strong research and training system. We saw earlier that

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[8] The figure is a simplified representation of the early dye network. It does not contain all relationships and is meant to be suggestive rather than exhaustive. Circles represent individuals in industry (the words in small letters identifies firm[s] the individual is affiliated with if not evident from his name), squares (or the benzene ring in the case of Kekulé) represent academics. Lines with arrows on one end represent student-teacher relationships. Graebe, for example, is the student of von Baeyer. Individuals on the right side (dark grey: Levinstein, Griess, Caro, Leonhardt, Duisburg, Martius) of the figure are Germans; individuals in the southwest corner (grey: Maule, Nicholson, Simpson, Medlock, Perkin) are British; individuals in the northwest corner (dark grey: De Laire, Girard, Renard) are French; and Clavel and Muller-Pack in the upper middle (very light grey) are Swiss. Thicker lines indicate that the individual is relatively more important. Hofmann is positioned in the middle of the figure because he assumed the central role in the early period of the industrial-academic network.

enrollments in science and engineering grew much faster in Germany than in Britain. Germany trained the vast majority of organic chemists in the world before World War I. At the turn of the century Prussia, the largest of the German states, spent almost 20 times more on universities than all of Britain. Although Britain was trying to catch up with Germany's superior research and training system, it was still far behind Germany in 1914.

The expansion of the research and teaching system required large sums of money. Unlike the United States, where many private universities existed, German universities and research institutes were public entities, funded almost entirely by public monies. This meant that increased contributions to universities had to pass through the political process. Even though the German economy was expanding at unprecedented speed from 1857-1914 and making it economically feasible to spend more on education, government officials and parliaments still had to be convinced to spend more money on education rather than on other politically popular programs.

Instead of examining the influence of the dye industry on science and education policy in every single German state, I will restrict myself to the case of Prussia. Because it was the largest state, but even more importantly, because it was a laggard in its support for science and technical education compared (on a per capita basis) to such states as Baden and Bavaria (Borscheid, 1976), Prussia presents the most appropriate state for examining why spending on universities and *Technische Hochschulen* (technical colleges) increased rapidly in the period from 1857 to 1914. The enormous expansion of universities, technical universities *(Technische Hochschulen)*, as well as the many research institutes formed after the 1880s was orchestrated from the desk of Friedrich Althoff, who all handled professorial appointments at Prussian universities and *Technische Hochschulen,* between 1882 and 1907, serving under five successive ministers. Because he shared the vision that broad scientific and technological research and education would be of immense benefit to society, he was a key ally in the efforts of the dye industry to expand educational facilities. Furthermore, given his unique control over the direction of the Prussian university system and Prussia's trend-setting role for other German states, the dye industry would have to form an alliance with him if they wanted to be successful at all during his long tenure. The German dye industry employed three strategies to upgrade its supply of scientific and engineering talent that could staff its firms: 1) use collective organizations to mobilize support, 2) lobby parliament directly, 3) create private-public academic partnerships.

Strategy One: While individual contacts between firm leaders in some instances played a role, for example the close personal relationship between Böttinger (Bayer) and Althoff (Brocke, 1980, p. 77), collective bodies were the main tools through which the dye industry marshalled the necessary political support for expanding the training of chemists and chemical technologists that were so crucial for their business. Carl Duisberg's (Bayer) draft of a petition, written in the name of the *Verein deutscher*

Chemiker (Club of German Chemists) to convince Prussian authorities to appoint more professors in chemistry, is a good example of how dye firms engaged in collective action. (The petition is reprinted in Duisberg, 1923, pp. 153-154.)

Strategy Two: When Henry Böttinger (one of Bayer's directors) won a seat in the Prussian parliament as a member of the National-Liberal Party, he used this public platform to advance the educational goals of the dye industry directly (Duisberg, 1923, p. 181). Because he was a very close friend of Althoff (Brocke, 1980, p. 17) and the Prussian finance minister, Baron Georg von Rheinhaben (Johnson, 1992, p. 79), he could coordinate his parliamentary proposals with the key players inside the Prussian government to increase educational spending.

Strategy Three: Böttinger and Althoff worked together on numerous projects to upgrade German science and engineering education. At the turn of the century, they created a new organizational form in the German research and teaching landscape, a public and private partnership to sponsor industrially relevant applied research. The *Göttinger Vereinigung zur Förderung der angewandten Physik* (Göttinger Association for the Advancement of Applied Physics) was financed in large part by private firms (Burchardt, 1992, p. 20). The success of this partnership paved the way for a large effort that began in 1905 to improve chemical research in Germany.

The collective efforts that lay behind the formation of a German Research Institute in Chemistry are very instructive about the collective processes that made the growth of the German research and teaching system possible. Dye-industry representatives formed the largest contingent of industrialists on the board of directors of the *Kaiser Wilhelm Institute for Chemistry* and made substantial financial contributions. Every large dye firm was involved: von Brünning (Hoechst), Oppenheim (AGFA), von Böttinger (Bayer), von Brunck (BASF), Duisberg (Bayer), ter Meer (ter Meer) joined leading academics like Emil Fischer and Carl Liebermann as well as government officials on the board (Ungewitter, 1927, p. 436; Johnson, 1992, pp. 99-101). Emil Fischer could rely on Althoff's and Böttinger's help in getting the state government of Prussia to donate the land upon which the first two institutes (the *Kaiser Wilhelm Institutes for Chemistry and Physical Chemistry*) were to be built in Berlin Dahlem (Ungewitter, 1927, p. 434).

Just as in Germany, industrialists actively shaped the research and training system in Britain.[9] A coalition between academics and firm leaders was successful in expanding research and training opportunities, but not nearly to the same extent as in Germany. A survey held in 1902 by the British Association for the Advancement of Science found that in a sample of 502 chemists employed in the British chemical industry only 59 were graduates of schools of higher education (Morrell, 1993, p. 108). This means that, unlike in Germany, even by 1902 only a small fraction of British chemists were trained at

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[9] Sanderson's *The British Universities and British Industry, 1850-1970* remains the most valuable book on the subject of how business participated in creating and upgrading universities.

institutions that were at the forefront of research in chemistry. The remainder continued to be educated by polytechnics, local colleges, evening classes, and the like.

A number of factors were responsible for the British inability to catch up with Germany. Most importantly, a strong bureaucracy championing higher education was missing (Wrigley, 1987, p. 163). The alliance between civic-minded industrialists and academics was dramatically weakened by not having this third element that made the German lobbying alliance so successful. Since the British industry had been the world leader for many decades, the awareness of the link between education and industrial progress was much weaker in British society and its ruling classes than in Germany. This made it more difficult to bring society's spending up to the same level as in Germany. Furthermore, the British dye industry was collectively not as organized as the German industry. Because the dye industry fell far behind that of Germany in terms of size, the British alliance between industrialists and academics did not enjoy nearly as many resources and as much political clout as the German one.

Professor Roscoe undoubtedly was to Britain what Hofmann was to Germany, with the only, and perhaps crucial, difference that Hofmann was an organic chemist who ventured fully into dye chemistry while Roscoe was a general chemist. (For the German dye industry it was clearly an advantage to have an organic dye chemist at the center of the link between science and industry.) Sanderson observes that "it is quite impossible to do justice to or exaggerate the importance of Roscoe as the new model of the English industrially oriented scientific professor, as a conceiver of the idea of a civic university serving local industry, and as a founder of modern chemical education in this country" (1972, p. 84). As the first professor-consultant in the British chemical industry, Roscoe organized with Ludwig Mond and George Davis the Society of Chemical Industry (SCI) and served as the first president of the society. Furthermore, he helped turn Owens College in Manchester into a full-fledged university with a Royal Charter.

An industry that was falling behind its foreign competitors, an industry where some of the most important leaders were retiring early and did not systematically lobby for better educational facilities (e.g. Perkin and Nicholson) was not a fertile ground for stimulating the build-up of a strong scientific and technological base that would support the industry. Between 1857 and 1914, scientific and technical training programs expanded significantly in Britain. But they did not expand at the same rate as in Germany. A chief cause lay in the resistance of British firms to hire many university graduates when at the same time Germans firms were staffing large R&D laboratories with many chemists and were hiring engineers to build efficient production processes. This underlines how coming relatively late into the era of industry was a blessing for Germany because firm managers were not encumbered by an outdated model that saw university graduates as an inappropriate tool for improving the efficiency of production (Wrigley, 1987, pp. 173-175). A relatively small domestic demand for organic chemists did not allow British universities to build up large research and teaching programs in organic chemistry.

This created a vicious cycle. When progressive firms such as Levinstein wanted to hire academic organic chemists and production engineers, they typically had to import German and Swiss talent before 1900 because British universities did not produce the same quality of graduates. Unless British firms paid these foreigners more than they would make at home, they would not be able to hire the best talent away from Germany and Switzerland. Both paying more or having lesser talent would put them at a competitive disadvantage with German firms. When British industry then lost more and more market share to the German firms, it did not have the resources to support universities and lobby for expansion of the system to the same degree as in Germany. While in Germany success bred the resources for more success, in Britain the relative decline caused a lack of resources that led to further decline. In Germany's case the process of expanding universities was self-multiplying; in the British case it was self-limiting.[10]

Because the U.S. did not possess a significant domestic dye industry, dye firms had very little clout either to induce the rapidly growing state universities to create programs in organic chemistry and dye chemistry in particular or to collect large private donations to establish such programs. The case of the U.S. illustrates the strong mutual dependency between economic and academic development. In those sectors where American firms were strong, academic strength would develop rather quickly, and in turn help foster technologically advanced industries. This positive feedback set in motion a virtuous cycle. The oil and steel industries were the sectors that first made use of academic chemists. In the synthetic dye industry the situation only changed during and after World War I when the build-up of an organic chemicals industry became a national concern. Firms such as Du Pont then became active in helping to create a strong U.S. research and teaching base in organic chemicals.

4. The Nature and Mechanisms of a Coevolutionary Explanation

As part of the open-systems revolution in organization theory, evolutionary models of organizational phenomena began to blossom in the late 1970s and early 1980s. Despite significant differences in some key concepts and assumptions, the contributions of Hannan & Freeman (1977; 1984), Aldrich (1979), Nelson & Winter (1982), McKelvey

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[10] Consider the counterfactual scenario of Britain training more chemists than jobs available before the rise of the dye industry. Under these circumstances many chemists would have been "forced to become entrepreneurs" as in the case of Germany. In this scenario it would have been less difficult to expand educational offerings because more firms would have been around to hire graduates. Instead of such a positive cycle, Britain was caught in the reverse process. The fact that educational facilities expanded at all is testimony of the persistent efforts by progressive industrialists and typically German-trained scientists.

(1982), McKelvey & Aldrich (1983) and Langton (1984) have in common that they focus on selection processes rather than agent's intentions in explaining organizational outcomes. The fact that 91 of the 100 German dye industry entrants had ceased to exist by 1914 underlines that intentions of entrepreneurs and managers of building a successful business are not sufficient for a firm to prosper. Despite having all the best intentions, the vast majority of start-ups were not sufficiently well adapted to survive in a competitive environment. Given the high failure rate of firms, a selection-based evolutionary model seems particularly appropriate to explain the dynamics in the synthetic dye industry before 1914.

There are three requirements for a rigorous evolutionary explanation of industrial development.

(1) To introduce novelty into the economic system, it has to specify a mechanism that creates variations of the existing structures, for example, innovations in firm strategies and organizational routines. Without a constant source of novelty, a selection process cannot create new economic structures that are better adapted to the economic requirements of society.

(2) It needs to articulate consistent selection pressures. Or to put it more precisely, new variants must be created at a higher frequency than new selection criteria because otherwise the evolutionary process cannot act as a "blind watchmaker" that brings about better adapted structures through trial and error. The "evolutionary system" would degenerate into a random walk that on average could not be expected to lead to structures that are better adapted to their environment.

(3) It has to specify to be a retention mechanism that transmits economic structures from the present into the future. Without such a retention mechanism new developments could not build on previous adaptive achievements, but would have to start from scratch. Complex non-random structures would not be possible. It is important to remember that any evolutionary analysis requires at least two levels, a level which identifies particular individuals that reproduce at differential rates and a level which specifies a particular population that is the locus of evolutionary change.

Starting with Campbell (1969) scholars have rediscovered several times that evolutionary explanations apply to all phenomena that can be conceptualized as a variation and selective retention system. Already in *On the Origin of Species* (1964, p. 422) Darwin appealed to the work of linguists to illustrate his ideas of a biological genealogy. Richard Dawkins (1976) referred to the general nature of selection processes with the unfortunate term *Universal Darwinism*. Recently the interdisciplinary team of Hull, Langman & Glenn (2001) has articulated a *General Account of Selection* processes (GAS) from a comparative study of biology, immunology, and human behavior. A historical study of national university systems reveals that the development of such systems can also be conceptualized as an evolutionary process. The changes in national populations of universities clearly meet the criteria of an "evolutionary system" a la Campbell. If one goes back in time, the record shows that a sizable number of universities were abandoned, leading to change in the population of national universities. Of the 1990 four-year colleges that were founded in the U.S. between 1636 and 1973, 515 had gone out of existence by 1973 (Marshall, 1995). A map of German universities in 1900 by Franz Eulenberg (1904) shows a surprisingly large number of universities that existed for some time and then were abandoned.

An evolutionary analysis of national university populations can track, for instance, the relative frequencies of private versus public universities. Or, as Aldrich (1999, pp. 177-180) points out, one could examine over time the relative frequencies of single sex versus coeducational colleges in the United States. An evolutionary analysis can pick out any trait or characteristic and then trace how the frequency of that particular trait or characteristic changes over time in the population. Instead of tracking changes in the population of individual universities, one can track the frequency of professor appointments in a particular field, the share of publications of a discipline in the entire scientific literature and so on. Given that we wanted to solve the puzzle surrounding the German dominance in the synthetic dye industry, we examined over time the relative importance of research and teaching in organic chemistry in the British, German, and U.S., French and Swiss university populations. We showed that the frequencies of chemistry professors, students in chemistry, and funding provided for chemistry research grew much more dramatically in Germany than in Great Britain or France.

The central hypothesis derived from the case of the synthetic dye industry is that the evolution of each national firm population and each national university population was causally linked. Because of this causal link it is appropriate to speak of coevolution. Biological ecologists have thought extensively about the relationship between two different populations and they have identified six possible kinds of pairwise interactions (see Table 1). Only three of these six types of relationships qualify as an example of coevolution because only in the cases of (1) competition, (2) predation, parasitism, Batesian mimicry, (3) mutualism and Müllerian mimicry the causation runs both ways between the two populations.

Table 1: Summary of the Various Sorts of Direct Pairwise Interactions that May Occur Between Two Populations (adapted from Pianka, 1994, p. 230)

	Population		
Type of Interaction	**A**	**B**	**Nature of the Interaction**
Competition	-	-	Each population inhibits the other
Predation, Parasitism Batesian mimicry	+	-	Population A – the predator, parasite or mimic – kills or exploits members of a population B – the prey, host or model
Neutralism	0	0	Neither populations affects the other
Mutualism, Müllerian mimicry	+	+	Interaction is favorable to both (can be obligatory or faculative)
Commensalism	+	0	Population A, the commensal, benefits, whereas B, the host is not affected
Amensalism	-	0	Population A is inhibited, but B is unaffected

Coevolutionary arguments are beginning to receive more attention in organization and management theory (Eisenhardt and Galunic, 2000; McKelvey, 1999; Lewin and Volberda, 1999; Baum and McKelvey, 1999; Lewin, Long and Carroll, 1999; Koza and Lewin, 1998; McKelvey, 1997; Barnett and Hansen, 1996; Levinthal and Myatt, 1995; March, 1994; Baum and Singh, 1994; Yates, 1993); but because researchers are using coevolutionary language often in an imprecise or inconsistent manner they have invited unnecessary criticism. Some observers of the present state of coevolutionary scholarship in organization theory jump to the unwarranted conclusion that in coevolutionary explanations everything seems to be coevolving with everything else and hence cannot provide a parsimonious explanation. In biology it is not the case that every species is coevolving with every other species in the world. In many cases, coevolution takes place between two species, for example a particular plant and a particular insect, the former serving as food and the latter as an instrument for spreading the pollen (Thompson, 1994). Coevolutionary relationships frequently also exist between a predator and its prey (Nitecki, 1983). Similarly, a particular industry coevolves to a significant extent only with a very restricted number of other industries and surrounding social institutions. Often a coevolutionary relationship exists between producers and user populations as in the case of the tabulating industry and the life insurance industry documented by Yates (1993). At other times a coevolutionary relationship exists between two populations of competing technologies such as propellers and jet engines that power airplanes.

Because of the ambiguities in the existing organization theory literature, we want to provide a precise definition of our use of the term "coevolution." *Two evolving* *populations coevolve if and only if they have a significant causal impact on each other's ability to replicate.*[11] Such causal influence can proceed through two avenues, 1) by altering the selection criteria or 2) by changing the replicative capacity of individuals in the population without necessarily altering the selection criteria. Stuart Kauffman (1993) uses the idea of coupled fitness landscapes[12] to express this conception of coevolution. In coevolution à la Kauffman one partner deforms the fitness landscape of the second partner and vice versa. As a result, a coevolutionary relationship between entities can increase the average fitness of both populations (mutualism), decrease the average fitness of both (competition), or have a negative or positive impact on the average fitness of one but not the other (predation & parasitism). Whether a coevolutionary process is beneficial or harmful for the parties involved depends on the particular causal relationship that links the parties and, therefore, needs to be specified in the empirical analysis.

Having articulated the most abstract level of coevolutionary relationship between any two populations, we want to return to the case of the coevolution between national industries and institutions. Based on the historical case study of the synthetic dye industry and the field of organic chemistry, it is possible to induce the following general proposition.

Hypothesis: *The relative strength of a national industry which has a significant input of science or engineering knowledge is causally related to the strength of the relevant science or engineering discipline in the nation and vice versa. Over longer periods, a nation cannot remain weak in one domain and strong in the other. Both domains will either become both strong or both weak.*

The meaning of this hypothesis can be illustrated by showing how a randomly distributed population of academic industrial (AI) complexes (an industry and its associated academic discipline constitute a complex) evolves over time to a state that is predicted by the hypothesis.

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[11] Our definition of coevolution is very similar to Nitecki's (1983, p.1): "Coevolution occurs when the direct or indirect interaction of two or more evolving units produces an evolutionary response in each."

[12] Borrowing from Wright (1931; 1932) Kauffman (1993, pp. 33-34) defines a fitness landscape as the distribution of fitness values over the space of possible genotypes for individuals in a population. According to Kauffman, each possible genotype has a particular fitness value. The population on this view is a tight or loose cluster of individuals located at different points in the landscape. In this model, adaptive evolution in a population amounts to a hill-climbing process. When a population evolves, selection will lead to the reduction of some genotypes and the proliferation of others. As a result, over time the cluster of individuals representing the population will "flow" over the fitness landscape.

Figure 4: Coevolution at the National Level at Time T1

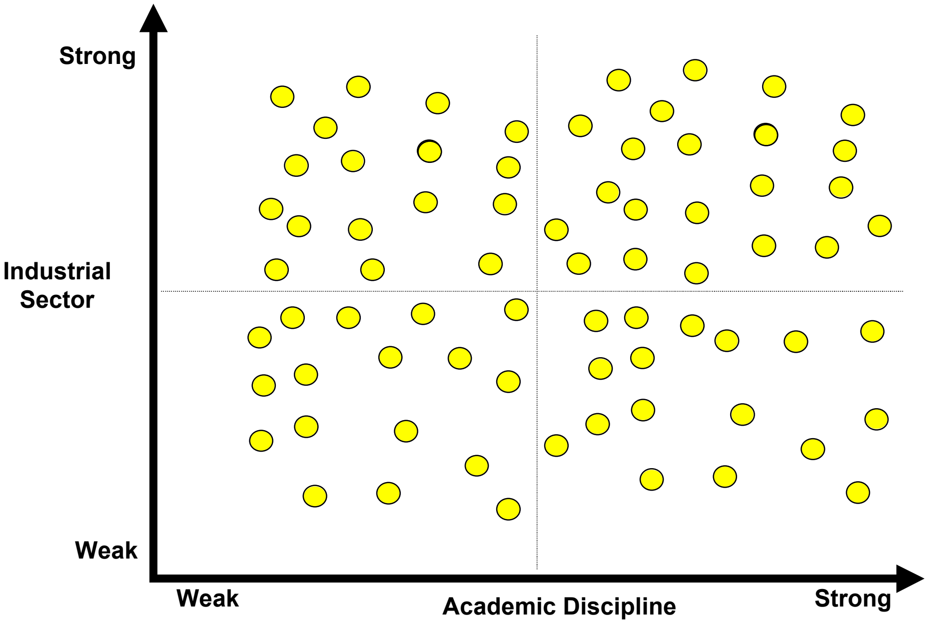


Figure 4, of course, does not represent an actual historical case. It rather constitutes a thought experiment to illustrate what would happen to such a hypothetical random distribution of AI complexes.

Figure 5: Coevolution at the National Level at Time T2

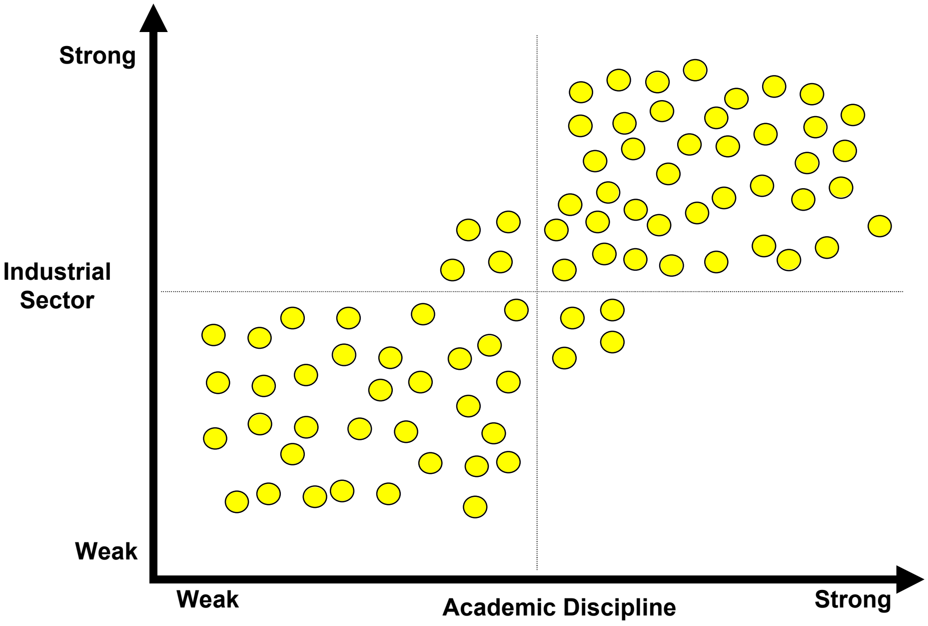
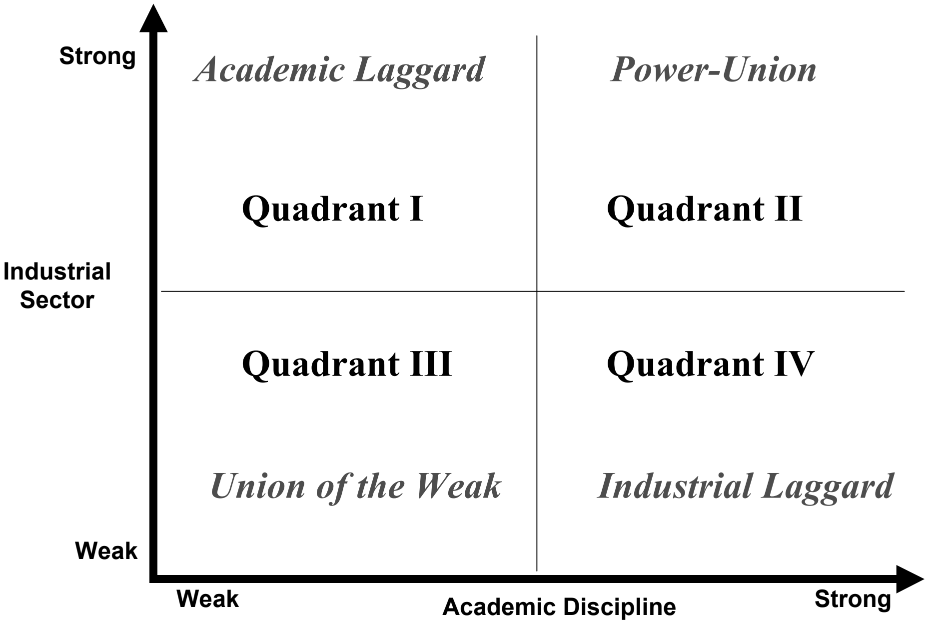


Figure 6: Typology of Academic Industrial (AI) Complexes



The hypothesis predicts that Quadrant I and Quadrant IV are unstable positions. A-I complexes tend to gravitate toward Quadrant II and Quadrant III.[13] But how? Good social science identifies robust causal processes that explain how social outcomes are produced from a given set of social conditions (Tilly, 1998). Because environments (inputs) differ, the same causal process can produce very different outcomes. Evolutionary theory is a concatenation of three general causal processes (variation, selection and retention) that can account for how well designed social structures come into existence without a designer. Evolutionary theory is abstract enough to apply to a diverse set of phenomena studied by the social and natural sciences. Similarly, the processes (competition, mutualism, etc.) that link two populations to form a coevolutionary relationship are articulated on a very abstract level. To explain change in a particular phenomenon as a coevolutionary process it is therefore necessary to identify in more empirical detail how the two populations are causally linked to produce the observed outcome. The case study of the synthetic dye industry and its relationship with organic chemistry has brought into focus a set of causal processes that may more generally form the link between national industries and relevant academic disciplines.

Exchange of Personnel. The most important causal process linking industry and the academy was the exchange of personnel between these two social domains. Leading professors in the academic field trained students, many of whom later became leading chemists in industrial firms. Exchange also occurred in the opposite direction. Chemists

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[13] Our argument does not require that no scientists and entrepreneurs can move across borders. It merely requires that the transfer of personnel is costly and does not happen instantaneously.

working in firms were also recruited to join the faculty of universities. The flow of personnel between the two social domains created a mutualistic relationship in which both sides benefited.

Formation of Commercial Ties. Academics, who were responsible for the majority of the most important dye innovations before the development of corporate R&D labs, sold their innovations to firms. Since academics were closer in social space to firms in the national environment, they were more likely to enter into a commercial relationship with a domestic firm. Firms, in turn, provided academics with royalties as well as equipment and materials to conduct research. These commercial ties also created a mutualistic relationship between the two spheres.

Lobbying on behalf of the other social domain. Industries compete with other industries for favorable regulation, tax treatment, and other forms of support from governments (Hirsch, 1975). Science and education budgets are limited in every country. As a consequence academic disciplines compete with other disciplines for resources. Given the possible joint benefits that can accrue to academic disciplines and their related industries, academics and industrialists have an incentive to lobby governments to increase their support for their partner's social domain or they can form coalitions on issues that concern both. Forming such a coalition creates a mutualistic relationship between the academic and industrial partners, but at the same time it can create a competitive relationship between different academic disciplines (or between different industries) by pitting them against one another.

Direct Support of State Agencies. A final causal process that creates an indirect link between industries and academic disciplines is the state, which can take actions to strengthen both the industry and the relevant academic discipline. In this case the causal relationship does not directly connect an industry and an academic discipline and hence does not qualify as coevolution. The actions of the state may play a significant role in determining whether *Academic Laggard* or an *Industrial Laggard* AI complex is transformed into a *Union of the Weak* or a *Power Union*. Our central hypothesis predicts that an AI complex in the *Academic Laggard* or *Industrial Laggard* categories is unstable, but it does predict what category the AI complex will turn into.

5. Support for the Coevolutionary Hypothesis in other Settings

Supporting Case 1: While the discipline of organic chemistry was very weak in the U. S. during the period from 1850 to 1914, the American university system became quite strong in those disciplines that related to industries in which the country had become a world leader. One such industry was agriculture. With the completion of railroads all across the continent and the cultivation of the western regions, land used for agricultural production almost quadrupled in the U.S., while increasing just slightly in Germany, stagnating in France, and even declining in Britain (Mitchell, 1992). Since the American population only tripled in the same period, a big food surplus allowed the U.S. to become the largest agricultural exporter in the world (Mitchell, 1998). The leadership position in agriculture did not come "natural" but rather involved a lot of human ingenuity and careful experimentation. Because the climatic and topographical conditions in the west were so different from the eastern United States, a large amount of biological and chemical knowledge had to be developed to grow wheat, cotton, and other staples successfully in different parts of the country (Olmstead and Rhode, 2000). Formal agricultural research made a big contribution to learning what crop to plant in a particular area and how to protect it from parasites. As mentioned earlier, the United States in 1850 had no graduate training in any discipline. By international standards the AI complex in agriculture started out mid-nineteenth century in the *Academic Laggard* category, but moved in the course of next 65 years into the *Power Union* category, confirming the prediction that AI complexes in the *Academic Laggard* category are not stable.

Beginning with the Morrill Act of 1862 through which Congress appropriated to each State funds from the sale of federal land, the U.S. began to build a very large system of higher education, creating many new campuses and upgrading existing ones (Nelson and Rosenberg, 1994; Rosenberg and Nelson, 1994). The U.S. had approximately 750, often small, private colleges in 1860, but their teaching in the practical arts was extremely limited. For over a decade before the passage of the Morrill Act, agricultural interests in many regions lobbied heavily to develop colleges that would offer training in soil analyses, fertilizer chemistry, crop evaluation, and other scientific research that would make American agriculture more effective (Noble, 1977). The Morrill Act had the explicit goal of setting up "colleges for the benefit of agriculture and the mechanic arts" but left it up to each state legislature to determine specifically how the federal grants were to be spent and what courses were to be offered.[14] This provision made the existing colleges and 75 newly created Land Grant schools very receptive to local political pressures. The Massachusetts legislature, for example, divided the grant between MIT, which would teach the engineering courses, and a newly founded Massachusetts Agricultural College in Amherst (1864),[15] which would teach the agricultural courses, as stipulated by the Morrill Act (Ferleger and Lazonick, 1994, p. 118). By contrast, in Connecticut agricultural interests prevented Yale from receiving Land Grant funds and pushed through their plan to create a University of Connecticut that would focus on teaching practical subjects. In New York, Ezra Cornell obtained the land grant from the

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[14] Section 4 of the Morrill Act articulates its focus on practical education: "… each State which may take and claim the benefit of this act, to the endowment, support, and maintenance of at least one college where the leading object shall be, without excluding other scientific and classical studies, and including military tactics, to teach such branches of learning as are related to agriculture and the mechanic arts, in such manner as the legislatures of the States may respectively prescribe, in order to promote the liberal and practical education of the industrial classes in the several pursuits and professions in life."

[15] The Massachusetts Agricultural College was renamed "University of Massachusetts Amherst" in 1924. Its annual reports starting in 1864 are conveniently available on the web at http://clio.fivecolleges.edu/umass.

legislature by matching it with $500,000 of his own money and founded a university in his name. As part of its Land Grant legacy, Cornell to this day operates some of its schools as public and some of its schools as private institutions. Because diseases and pests would not stop at the borders of individual states, the Federal government created also in 1862 the U.S. Department of Agriculture, which was elevated to cabinet status in 1889 (USDA, 2002). President Lincoln called it the "people department" because 50 percent of all Americans were farmers (today two percent) who needed good seeds and useful information on how to grow their crops. In response to growing concerns about the spread of contagious pleuropneumonia, hog cholera, and other diseases, *The Bureau of Animal Industry* was founded in 1884 as a division of the USDA (Olmstead and Rhode, 2000).

Between 1870 and 1887, 15 states set up agricultural experimentation stations to develop more systematic biological knowledge about productive farming techniques in the region (USDA, 2002). Pest and other diseases continually threatened plants and animal stocks throughout the nation. This provided strong incentives to develop and disseminate knowledge about how to combat pests, how to use chemicals against them, and how to develop new crop varieties that might be resistant to parasites and better adapted to the different soil and climatic conditions around the country. Take cotton as representative example. While at the end of the colonial period only a few cotton varieties existed, 442 varieties of cotton were available in the U.S. by 1918 (Olmstead and Rhode, 2000). Of the 58 varieties of cotton named in the Census of 1880, only six were common in 1895 and none were grown to any extent by the mid-1930s. Individual states set up agricultural boards to act as a clearinghouse for information and to conduct research. But the threats to farms loomed so large that agricultural interests wanted to Federal government to become even more active than it already had been through the activities of the USDA. They argued that there was insufficient coordination between individual states in attacking the problems of American agriculture. Another round of lobbying led Congress to pass the Hatch Act of 1887 in which the Federal Government agreed to provide funds for one agricultural experimentation station in each state (Ferleger and Lazonick, 1994). The wording of the act leaves little doubt that more agricultural research was perceived to be very important for the country.[16] The Secretary

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[16] Section 2 of the Hatch Act makes clear that it was intended to create and disseminate scientific knowledge about agriculture: "It is further the policy of the Congress to promote the efficient production, marketing, distribution, and utilization of products of the farm as essential to the health and welfare of our peoples and to promote a sound and prosperous agriculture and rural life as indispensable to the maintenance of maximum employment and national prosperity and security. It is also the intent of Congress to assure agriculture a position in research equal to that of industry, which will aid in maintaining an equitable balance between agriculture and other segments of our economy. It shall be the object and duty of the State agricultural experiment stations through expenditure of the appropriations hereinafter authorized to conduct original and other researches, investigations, and experiments bearing directly on and contributing to the establishment and maintenance of a permanent and effective agricultural industry of the United States, including researches basic to the problems of agriculture in its broadest aspects, and such investigations as have for their purpose the development

of the USDA was assigned the task to administer the act, to facilitate joint research projects between experimentation stations in different states and the USDA scientists, but above all to ensure the dissemination of knowledge. By the 1890s, 49 experimentation stations, which were all affiliated with the original Land Grant colleges, received Hatch Act funding (USDA, 2002).[17] Some of these experimentation stations were later converted into full-fledged university campuses, as for example in the case of the University of Massachusetts at Amherst, the University of California at Davis, and Texas A&M at College Station. The efforts to put agricultural practice on a more scientific footing had already paid off nicely before World War I. Between 1850 and 1910 the national average milk yield per cow increased from 2,371 pounds to 3,570 pounds, or by about 51 percent. In the important dairy states of Wisconsin and Illinois, yields rose by about 60 and 85 percent respectively (Olmstead and Rhode, 2000). In part due to the Babcock butterfat test developed in 1890 at the University of Wisconsin, the quality of milk improved dramatically in this period, paving the way for a large food industry based on dairy products.

The new colleges and universities that were created in the second half of the 19th century were clearly designed to produce a workforce that could serve the important sectors of the American economy at that time such as agriculture, light machinery, steel, and mining. Between 1902 and 1913 enrollments in agricultural undergraduate programs at the Land Grant colleges increased swiftly from 2,471 to 14,844 in part because a sufficient scientific base had been established to design an effective curriculum (Ferleger and Lazonick, 1994, p. 123). Enrollments in mechanic arts courses grew much more slowly in this period from 10,535 to in 1902 to 16,125 in1913.[18] It was much more difficult for a physical science such as chemistry to take off. Johns Hopkins dominated the training of Ph.D.s in chemistry until the turn of the century. One hundred of the 251 chemistry Ph.D.s granted in the U.S. between 1860 and 1899 were granted by Johns Hopkins (Thackray, Sturchio, Carroll and Bud, 1985). But it is important to recognize that this research was driven by practical concerns. The Ph.Ds. in chemistry were virtually all in analytical chemistry that could support U.S. agriculture, the rapidly growing inorganic chemicals industry, the steel industry, and the powerful mining industries in the U.S. The U.S. university system did not develop strength in pure science that was in any way comparable to what was achieved in Germany before the First World War (Rosenberg, 1998).

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and improvement of the rural home and rural life and the maximum contribution by agriculture to the welfare of the consumer, as may be deemed advisable, having due regard to the varying conditions and needs of the respective States."

[17] The Hatch Act funds agricultural research to this day: in 1990 Congress appropriated $170,539,616. For a current list of agricultural experimentation stations and their activities, go to http://www.agnr.umd.edu/users/nera/usamapl.htm.

[18] All bachelor degrees granted at American colleges and universities increased by 436%, from 7,228 in 1890 to 31,540 in 1914.

In the case of the German dye industry, science was strong first, and the superiority of academic research in the country later allowed the industry to become a world leader. An "Industrial Laggard" AI complex was transformed into a "Power Union." The American case was different. A number of "Academic Laggards" AI complexes were transformed into "Power Unions." Agriculture, oil and steel had become leading industries without a very strong national capability in the related sciences (Skolnik and Reese, 1976). American expenditure per university had quadrupled between 1895 and 1910, growing at twice the rate of Germany, leaving Britain a distant third. Since the mid 1890s, American spending per student nearly doubled in this period (Johnson, 1990, p. 18). Confirming our hypothesis, spending increases were proportionately larger in those disciplines that were related to industries where American firms were world leaders, such as in agriculture.

Supporting Case II. Another industry in which one country has come to dominate the global market is packaged software. In 1987 U.S. firms sold prepackaged software in value of $ 5.9 billion. For over a decade, computer software sales increased much faster than hardware sales and this trend seems to continue. In 1988 they were 50% of total computer related sales and by 1993 they were already 75% (Steinmueller, 1996, p. 20). In the same year, the U.S. dominated most markets by a wide margin (**Table 2** provides detailed figures).

Table 2: Market Share of U.S. Firms in Packaged Software
by Region and Product Category, 1993 (percent)

Consuming Region	Tools	Applications
United States	83.5	87.9
Western Europe	74.6	41.3
Japan	64.7	35.3

Source: Mowery (1996, p. 8)

Back in the 1930s Germany and Britain were as advanced as the United States in the theory of computers (Malerba and Torrisi, 1996, pp.168-169). But today Germany and Britain are not nearly as strong in computer science as in the U.S. A ranking of countries in terms of the number of citations per published computer science paper in each country (a good measure of the quality of a discipline) for the period from 1994-1998 shows the U.S. to be the leader with an average of 1.4 citations, Great Britain to be number eight with 1.1, France and Germany with 1.0 in position 13 and 14 respectively, and Japan to be number 18 with 0.4 (Salter, D'Este, Martin, Guena, Scott, Pavitt, Patel and Nightgale, 2000, Table 49).[19] The symmetric relative specialization index[20] for computer science in the period from 1981-1998 shows the U.S. (+.10) to be leading), followed by Great Britain (+.06), Japan (+.04) , Germany, (-.05) and France (-.14). In this period the trend was downward for Britain and Germany but upward for Japan (Salter et al., 2000, Tables 55-59). Japan's weakness in computer science is particularly surprising because unlike Britain and France the country still has a very large and successful hardware industry.

The history of computing AI complexes around the world reveals that *Direct Support of State Agencies* and *Exchange of Personnel* were the key causal mechanisms behind the coevolution of the discipline of computer science and the software industry that established a "Power Union" complex in the U.S. The Cold War prompted the U.S. military to fund the development of computers and software such as the SAGE air defense system in the 1950s. As a result, the Pentagon provided significant support for the industry by creating a higher demand for computer software than in any other country. By one estimate, even in the early 1980s military demand accounted for 50 percent of total software industry revenues in the U.S. (Langlois and Mowery, 1996, p. 68). This steady early demand allowed strong firms such as IBM to emerge, which because of its first mover advantage came to dominate world markets in the mainframe era. At the same time the Pentagon and the National Science Foundation (NSF) were eager to help develop computer science departments in the U.S. By establishing a separate discipline of computer science, the goal was to advance software languages and tools, and train a large number of programmers that were needed for defense purposes. Langlois and Mowery (1996, p. 58) report that "in 1963 about half of the $97 million spent by universities on computer equipment came from the federal government, while the universities themselves paid 34 percent and computer makers picket up the remaining 16 percent." To endow the newly established computer science departments with the best hardware, the NSF gave 200 universities $85 million between 1957 and 1972.

American universities acted as important sites for the quick dissemination of new programming techniques to industry because students would carry the newest knowledge with them. Unlike in Japan, where software engineers received most of the training in-

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[19] Without additional corroborating evidence, any single indicator of the strength of an academic discipline in a particular country has to be used with caution. The numbers of Salter et al. (2000) are based on information provided by the Institute for Scientific Information (ISI) and the NSF. The figures are probably biased by the fact that the ISI database used in the analysis covers a relatively small number of journals and has an English language bias. This means that the European countries that are too small to afford publishing in their native language appear stronger than they actually are. All that said, the data appear largely consistent with other reports of the relative strength of the various countries in computer science.

[20] The Relative Specialization Index (RSI) is calculated as follows. For a given country (i) and scientific field (j), this indicator is defined as the share of publications in scientific field (j) in relation to the total number of publications by that country "i", divided by the share of that field "j" in the total world publications (values greater than one indicate relative specialization). The Symmetric Relative Specialization Index (SRSI) that we report here is defined as: (RSI-1)/(RSI+1). This SRSI is bounded between –1 and +1.

house (Baba, Takai and Mizuta, 1996 pp. 111-112), U.S. computer science departments created a highly trained cadre of people who could be hired by the military and by industry to write cutting edge programs. They also created Ph.D.s who would become the faculty of this new discipline. To increase the productivity of software design, federal agencies sponsored the creation of new programming tools and languages to be diffused as widely as possible both in the military as well as in the civilian sector. The department of defense, for example, sponsored in 1960 the creation of a new language for business applications, COBOL (common business-oriented language). Two years later IBM offered COBOL for several of its 1401 models. This illustrates how tight a link had been formed between military, industry and academia in the U.S. In Britain the links between these different social spheres were not nearly as strong (Grindley, 1996).

There were huge defense-to-civilian spillovers in the U.S. The vast majority of software innovations between 1950 and 1975 were federally funded and universities such as MIT played a large role in their creation (for details see Langlois & Mowery, 1996, p. 67). In Britain, Germany, France, Italy and Japan, computer science as an applied discipline developed much later. Because American firms now dominate world markets, the industries in the other countries are much smaller and do not have the resources to support their local universities as much as is the case in the U.S. Despite efforts in the European countries and Japan to upgrade computer science teaching and the output of software engineers, the government programs have not met their goals in part because the U.S. academic-industrial interface is now so well developed that it draws the best talent from everywhere. Trying to catch up with the U.S. in software, computer science departments have been created at national universities (Baba et al., 1996). But because of a lack of Ph.D. programs, Japanese universities had difficulties hiring qualified staff. In 1992 a committee formed by the Japanese Ministry of education proposed to transplant the core American computer science curriculum. Although the difficulty of finding qualified faculty continued, there is some evidence that the concerted actions helped to upgrade the discipline computer of science somewhat in Japan. The discipline's Science Specialization Score changed from -.20 in the period from 1986-1990 to 0.08 for the period 1994-1998 (Salter et al., 2000, Table 49). The packaged software case illustrates how difficult it is to dislodge an AI complex in the "Power Union" category once it has been established.

Supporting Case III. Although pharmaceutical biotechnology has not existed long enough to observe fully whether AI complexes develop according to our prediction, there is some emerging evidence that the industry and its supporting academic disciplines are coevolving. After World War II the funding for U.S. universities shifted dramatically from state and private sources to the Federal government. With the beginning of the Cold War, the Federal government became very active for the first time in the nation's history in funding science and engineering. A decision was made not to follow the German model and create federal institutes in every scientific discipline but rather to support science through generous grants given to existing universities. Through the NSF, the National Institute of Health (NIH), and the various military agencies, the United States began to fund a large amount of basic research in molecular biology. By late 1960s the United States had surpassed Germany in basic and biomedical research in the life sciences. In 1972, Stanley Cohen, a professor at Stanford University, and Herbert Boyer, a professor at the University of California at San Francisco, discovered an enzyme that could insert foreign DNA into bacteria that would then go on to replicate at very high rates and produce proteins by design. This innovation opened up vast possibilities for creating new pharmaceutical and biochemical substances through the use of recombinant DNA technology (McKelvey, 1996). The next thirty years of the biotech industry resembles in many details the pattern of the synthetic dye industry in the second half of the 19th century. American firms became the world leaders in the new pharmaceutical biotech industry because they had easier access to the leading researchers in the world, who were located in the main at American universities and research institutes (Zucker, Darby and Brewer, 1998). Having access to the centers of innovations and the centers of academic training proved absolutely crucial in developing successful commercial products (Powell, Koput and Smith-Doerr, 1996). Often time professors would found their own firms to exploit an innovation they had made in the university laboratory (Liebeskind, Oliver, Zucker and Brewer, 1996). Frequently professors would sit on boards of firms and channel students to firms with whom they had established collaborative ties. Firms would provide university research with funding in return for privileged access to the professor's findings.

In Germany the new field of recombinant DNA did not nearly develop at the same speed because German law prohibited the manipulation of genetic materials in response to the euthanasia legacy of the Nazi era. As a result Germany was not at the forefront of the new science. Starting in the middle 1980s German pharmaceutical giants such as Hoechst and Bayer were forced to locate much of their biotech research in the U.S. and fund collaborative research with U.S.-based research institutions if they did not want to lose out completely in this new industry. This strengthened the U.S. industry even more. The giant pharmaceutical firms also started to buy U.S. biotech firms because they were not able to replicate the same innovative capabilities back at home. The biotech industry is yet another example of how the "academic leader" nation is often able to also become an industrial leader if an academic field suddenly opens up the possibility of a new class of products. The strength of the industry in turn made affiliated academic discipline stronger. The Symmetric Relative Specialization Index for the field of Molecular Biology & Genetics shows that the discipline became more important in the U.S. from 1981 to 1998. The score increased from 0.04 (1981-85), to 0.07 (1986-1990), 0.11 (1991-1995) to 0.14 (1994-1998) (Salter et al., 2000, Table 58). The same causal processes (exchange of personnel, commercial ties, support of state agencies) that turned Germany into the dominant producer of synthetic dyes accounts for the leadership role of the U.S. in the biotech industry for the last 30 years. The fields of molecular biology and genetics coevolved with the pharmaceutical biotech industry.

6. Discussion and Future Research

These three shorter case studies of agriculture, packaged software and pharmaceutical biotechnology have provided preliminary support for our general hypothesis about the coevolution of national industries and relevant scientific and engineering disciplines. The important task, however, of verifying the hypothesis with a large sample remains to be done. Given the space constraints of an article, we focused on the research and training system to spell out how the development of national industries and national institutions can be conceptualized as coevolutionary process. We have done some preliminary analyses (not reported here) that suggest that national patent laws and practices also coevolved with the synthetic dye industry, lending further support to the proposition that coevolutionary models are a fruitful way to theorize about industrial development. We took nations to be the unit of analysis to trace coevolutionary processes. But a priori there is no reason why nations should be the only object of analysis that display positive feedback processes that lead to the kind clustering of successful industrial activity that we observed in the case of the synthetic dye industry. The computer industries of Silicon Valley and Route 128 in Boston also seem to have coevolved with their academic institutions in the vicinity (Saxenian, 1994). Coevolutionary processes very well may account for patterns of regional specialization and regional advantage within a nation (Sorenson and Audia, 2000).

In addition to testing the coevolutionary hypothesis with larger samples, an important task for future research is to establish the boundary conditions of the model. Under what conditions do AI complexes tend not to gravitate toward the categories of the "Union of the Weak" or "Power Union"? To put it slightly differently, when are AI complexes in "Academic Laggard" and "Industrial Laggard" categories stable configurations? There may be national contexts in which the causal processes that we have identified may not be operational because laws or national traditions prevent strong interactions between the industrial and academic social system. Japan, for example, by law prohibits university professors from engaging in consulting relationships with industry. As far as we know, professors are not allowed to sit on corporate boards and receive any compensation from industry. These legal rules clearly make it more difficult to establish close interactions between the academy and industry.

Another task in developing the scope conditions of the theory is to examine variables that may mediate between the coevolutionary processes (Ocasio, 1999). We have begun to investigate the relationship between science and industry in the former Soviet Union. Anecdotal evidence suggests that the central hypothesis is even true for a socialist economy because the Soviet Union tended to be weak in biology as well as in agricultural products, weak in engineering discipline that had to do with high volume consumer products, but very good in military technology and the related disciplines of physics and propulsion engineering. Our preliminary research on the former Soviet Union suggests that it may be a particularly fertile research site to discover key variables that may mediate a simple coevolutionary relationship. Similarly, France in the post-World War II era on first glance appears to be a promising country to search for variables that may mediate our model. Preliminary discussions with experts of the French academic industrial interface have provided some evidence that the administrative heritage of France creates a mutualistic relationship between industry and academic fields in those industrial arenas that can be administered on a military model. Although France had a superb research capability in molecular biology in the 1960s, France has not been nearly as successful in biotechnology (which seems to require decentralized planning) compared to the nuclear industry and high speed trains.

In investigating the puzzle that motivated our paper, we were particularly surprised by the importance of the academic-industrial knowledge network for the development of competitive advantages. Those firms that had better access to a central university professor in organic chemistry possessed a crucial advantage compared to their rivals. With more systematic data that is available today in such industries as biotechnology, one could examine more formally the relationship between competitive advantage and access to central university researchers in the academic-industrial knowledge network. Our findings suggest that there may be considerable opportunities in exploring more extensively possible links between network analysis and evolutionary theory.

Our cross-national research design and our coevolutionary model allowed us to offer an important refinement the resource-based theory of the firm. It was not one firm's possessing a hard to imitate and trade competitive advantage that explains the German dominance in the synthetic dye industry but rather a national environment that was difficult to replicate in the short run. Britain and the U.S. developed a much more successful dye industry after World War I because the two nations would have almost lost the war because of their weak manufacturing capability in organic chemistry. Today, after Du Pont, Dow and other large American chemical firms sold their dye plants that they started in the wake of World War I, all dye plants in the U.S. are once again owned by German and Swiss manufacturers long after dye chemistry ceased to be at the forefront of the field of organic chemistry. German and Swiss firms continue to be the largest dye firms in the world although there are now hundreds of firms in India and China. How it is possible for firms to hold on to some competitive advantage for 140 years strikes us as yet another big puzzle that deserves to be investigated in its own right.

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Appendix 1: Most Important Sources on the History of the Synthetic Dye Industry

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