Introduction

How quickly does know-how diffuse to firms outside an industry? Measuring knowledge directly is typically infeasible, but the speed of entry or market share erosion might indirectly measure its diffusion. Unfortunately, there is a confounding effect: increasing dominance, the perpetuation of market dominance through the complementarity of investment and market presence, which advantages incumbents or leading firms over rivals.[1] Incumbents may remain dominant, and entry not even occur, even as outside firms learn, since an entrant's success depends not only upon absolute ability but also on ability relative to that of the incumbent. Outsiders' absolute ability may improve over time due to knowledge diffusion but their relative ability deteriorate if the increasing dominance effect is stronger.

Were incumbents suddenly removed from an industry, however, entry would depend on absolute ability alone. Knowledge diffusion could then be inferred from the effect of a product's age on entry, as the older the product, the more time there would have been for knowledge of its composition and manufacture to have diffused to outside firms. An industry suddenly bereft of its incumbents is rare, but the US synthetic dye industry during World War I and its aftermath allows us to observe precisely that. This industry was heavily dominated by German firms before the war, which was to cut off many countries from that supply. The resulting Dye Famine, as it was called, induced domestic firms to enter the industry.

In this paper we ask which previously imported dyes US firms succeeded in producing when German imports were cut off. The knowledge diffusion rate is given by the ratio of the effect on production incidence of a dye's age to that of the log 1914 import quantity, proxying for prospective profits. More precisely, this measures the rate at which the development cost necessary to compensate for the lack of complete knowledge declines with the dye's age. As using

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[1] The simplest mechanism is larger firms' greater cost saving from variable cost reducing investments, as in Klepper (1996). Complementarity can arise for strategic reasons also, e.g., Gilbert and Newbery (1982), Cabral and Riordan (1994), and Athey and Schmutzler (2001). The source of increasing dominance is unimportant for our purposes.

import quantity to proxy for profit ignores variation in the price-cost margin, and newer dyes may be more or less complicated to develop than older ones, the analysis is conditioned on demand and technical attributes. We find a high annual rate of knowledge diffusion of about seventeen percent, implying a halving of the necessary investment with every four years of product age. Semi-parametric regression, however, suggests that the diffusion begins only after a two decade lag.

German firms returned to exporting to the US a couple of years after hostilities ended, by which time US firms had established a sufficient foothold in the industry, made surer by extremely high tariffs. We also consider the set of dyes the US continued to produce after this re-entry in order to determine which factors are relevant to post-entry competition.

The dye industry is an attractive industry to study, apart from the Dye Famine itself. The chemical industry as a whole is a striking example of the ability to recover a dominant position despite massive harm to physical capital and intellectual property. Cantwell's (1995, 2000) documentation of Germany's continued dominance in US chemical patenting despite patent confiscation, seizure of its firms' internal documents and destruction of many chemical factories during the second world war points to the centrality of human and organizational capital in firms' success. Arora (1995a, b) has used this industry to show the limited value of intellectual property without the accompanying human capital, even when knowledge is highly codifiable.

There are more prosaic reasons for studying this industry. From early on, dyes, as chemical compounds, were thoroughly categorized, first by Gustav Schultz, the fifth edition (Schultz, 1914) of whose work is used here. The Schultz category corresponds to a unique chemical compound, facilitating the analysis.[2] Also, comprehensive data on US production and imports are available. In aid of the 1916 tariff legislation deliberations, the Commerce Department collected and published detailed figures on the pre-war quantity of dye imports (and their value,

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[2] Differences in physical concentration make it not always a single product, but rather a set of very nearly perfect substitutes. As noted later, concentration differences can be controlled for by including price as a regressor.

for a subset of dyes), by the Schultz category (Norton, 1916).[3] Then from 1917 on, the Tariff Commission annually collected and reported production and imports, by the Schultz number. Finally, since dyes is generally regarded as the first high tech industry, with scientist managed firms (Liebenau, 1992, Marsch, 1994), dedicated R&D labs, and academic-industry collaboration, and given its close connection to the important explosives and pharmaceuticals industries, it boasts a vast business history literature.

Like all case studies, this one presents a singular example, and one might thus wonder how it might teach us about knowledge diffusion in other industries. Fortunately, the case is an extreme one, in which a number of factors combined to make entry hard / diffused knowledge hard to use / passive accumulation. Essentially, the US firms were on their own. Any attempt to learn from our findings about other industries requires that we locate this industry in technological-contractual space. This is characterized by three attributes. First, entry was de novo, and not that of incumbents from one sub-market entering another one. Although entrants came from neighbouring industries, such as input producers, end users and intermediaries, their knowledge base of dye production was limited. Second, although the information was highly codifiable (this was chemistry, after all) and much of the diffusion was in that form, it was often deficient. Third, during the period of entry there was no opportunity for human capital to flow from the incumbents to the entrants though hiring, since Germany and the US were at war. Fourth, there was no scope for market mediated technology transfer. During the period of information diffusion (before the war), US firms were not yet in the market, and saw no possibility of entry and had no incentive to purchase the information. During the period of entry, purchasing information from the incumbents was impossible because of the war. The last point bears repeating. Alfonso, Gambardella and ** have argued that much of what is deemed a spillover by studies such as Jaffee etc. actually is

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[3] Steen (1995a, p. 118) notes that Norton "assembled the data from confidential [customs] invoices … Norton's method generally gave the statistics veracity, although manufacturers mistrusted his figures for the dyes … which the tariff laws excluded." We supplement the Norton (1916) data with additional price figures from Norton (November 1916) for about 30 dyes, and for calculation of the HHI, Norton (1922), which provides firm level quantities.

transacted through the market. This thus isolates an extreme case of how quickly learn outside firms learns. We would expect entrants to be ablet o acquire faster

Like all case studies, this presents a singular case, but it has the advantage of also presenting an extreme situation in which entry was difficult, because entrants were de novo, and Fully deliminating the will require additional case studies.

Indeed, this is an extreme case, in that the knowledge is (relatively) highly codifiable, but there was no opportunity for the transfer of complementary tacit knowledge from the incumbents.

Section II: The History of Synthetic Dyes up to World War I

Synthetic dyes are produced from intermediates, themselves by-products of tar-crudes from coal ovens. The 1856 UK discovery and profitable commercialization of the first aniline dye prompted discoveries of other dyes and manufacturing processes there and elsewhere. The industry was initially chiefly based in the UK and France, but within fifteen years Germany clearly dominated it. This shift was embodied in the homeward migration of a number of influential German chemists. Furthermore, those firms that were at all successful elsewhere, particularly in the UK and the US, were generally founded by German emigrants.

Most economic historians (e.g., Beer, 1959, and most recently Murmann, 2003) attribute Germany's comparative advantage in dyes to its universities, which dominated organic chemistry, and their close working relationship with industry. Also stressed is the relatively greater esteem given industrial research (Hohenberg, 1967, in particular), and the greater access to primary and secondary education there (Murmann, 2003), as well as the inadequacies of other patent systems. The French system provided a very broad patent that covered the product, whatever the process, while the British provided little prior examination, and so led to massive patent litigation. The pre-unification German states, in contrast, had essentially no patent law,[4] allowing its firms to

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[4] Certain German states did have patent law, but lacked protection for imports from other ones (Murmann, 2003).

grow by copying the British and French innovations (Beer, 1959 and Travis, 2004). Both Marsch (1994) and Murmann (2003) argue that by 1877, when patent law was introduced in the newly formed Germany, German firms were themselves developing new dyes, and that the very stringent conditions for patents (granted in chemicals to processes only) helped protect them and stimulate industry research. The industry was sufficiently developed in Germany by then that it did not shift elsewhere, not even across the border to patent law-less Switzerland, which had a smaller dye industry itself. Note that demand and factor resources alone suggest that the industry would be dominated by the UK, which boasted both the world's greatest textile industry and abundant coal.

Of particular interest here is the failure of the industry to develop in the US. Taussig (1922) blamed the lack of scale economies, so central to US industrial success, and the abundance of skilled factory-level labour in Germany, but his is a minority view. Arora and Rosenberg (1998) note the US use of beehive ovens, which fail to provide coal-tar by-products. In any case, the major proximate cause, at the very least, was surely the dearth of trained organic chemists in the US (e.g., Murmann, 2003 and Thackray, 1985).

By 1913, Germany was producing between 83 to 88 percent of the world's dyes. The only other net exporter was Switzerland, with about six percent. In contrast, US dye firms produced only about two percent, or about 13% of US dye consumption (Reader, 1970, p. 252 and 258). Germany's dominance is also evident in its share of dye patents. Eighty one percent of the 1444 US dye patents issued between 1900 and 1917 and listed in Doyle (1926) was assigned to German firms. Another 10½% was assigned to Swiss firms. A mere 4½% went to US firms.

Of the 922 dyes listed by Schultz and the over 500 imported from abroad, US firms produced only 130. This number vastly overstates US capabilities, however, for its firms were essentially "assemblers"[5] and not "producers". According to Haynes (1945, Vol. 3, p. 213), of the

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[5] The Chemical Foundation counsel deemed the US industry "a mere assembling industry operating … on German intermediates. We imported things almost finished from Germany and turned them into finished dyes here by final processes which are often very simple." (*Dyestuff Hearings*, 1919, p. 90.) Norton (November 1916) writes, "The

seven US dye producers, only Schoellkopf, with 106 dyes by far the largest,[6] made any of its own intermediates, and "[o]nly one [US] chemical company …made any pretense of being a real producer of coal-tar intermediates and its claims were not very impressive." Indeed, when German imports were cut off, Schoellkopf was forced to cut back its dye production to fifteen categories only, most black or blue (Steen, 1995a, p. 124).

Examining the determinants of pre-war imports provides a baseline for analysing US production after the Dye Famine. Figure 1 shows the fraction of dyes imported in fiscal year 1914 (July 1, 1913- June 30, 1914) by the year of discovery, taken from Norton (1916), overlaid by the regression line. Its slope is only a statistically insignificant one tenth of a percent annual decline. Thus there was no differential tendency for earlier or later dyes to be imported.

Table 2's first column reports that regression, while the remaining columns add demand and cost proxies. Column (2) includes, as a profitability indicator, the count of countries among Germany, the US, the U.K. and France, for which Schultz (1914) reports at least one patent in the dye category. It is significant, but its inclusion does not affect the discovery year coefficient. Column (3) includes technical attributes. Dummy variables for the 16 dye classes, which indicate a shared common tar-crude or basic intermediate and so constitute the fundamental technological dye groupings, are jointly significant (p =.002). The Schultz Number (normalized to between 0 and 1) has a significant negative effect. The number of intermediates used in production and a measure of economies of scope, defined below, are insignificant. Column (4) includes demand attributes: fifteen (non-exclusive) dummy variables for the dye's colours and three (non-exclusive) dummies for the material (cotton, wool and silk) to which the dye may be applied. Both sets of variables are highly significant. Finally, column (5) includes all the control variables, each (set) of

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American manufacture was confined almost entirely to the "assembling" into finished dyes of [imported] coal-tar intermediate …." Little (March 1915) and Hesse (November 1915) also use this term.

[6] No other firm, including Bayer, the only German subsidiary operating in the US, produced more than fifteen.

which maintains its approximate significance level. Throughout, the coefficient on discovery year remains insignificant and essentially unchanged.[7]

These results aid in interpreting the discovery year's effect on 1917 US production. 1914 imports should be a function of US demand and cost, and, as we see in the highly significant F-statistics for colour, application material, patents and dye classes, is. In contrast, imports clearly do not depend on the discovery year, indicating that it proxies for neither demand nor cost.

Section III: The Dye Famine, US Entry and Technology Transfer

Soon after hostilities began, Britain's navy blockaded Germany.[8] This did not immediately cut off dye supply to the US, as there was a few months' worth of domestic stocks to draw on.[9] With foreign stocks available as well and a general impression that the war would not last long, investments in dye production were not immediately seen as profitable.

The stocks eventually ran out, however. In 1915, indigo continued to be imported at prewar levels, although the German share, previously never less than 92 percent, fell to 86 percent. But by 1916, indigo imports had fallen by nearly a fifth, with none originating in Germany: half now came from German produced stocks in China; the U.K., where a German plant had been confiscated, and India made up the rest. In 1917, the foreign stocks were depleted, and indigo imports fell to six percent of prewar levels. For other dyes, the shortage came earlier. Imports of alizarin from Germany, which had previously supplied 94 percent of these dyes, fell to zero already in 1916, and there being no substitute stocks, alizarin imports were not to rise above one percent of the 1915 level during the remaining war years.[10]

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[7] For the use of the country count see, for example, Putnam (1997). The largest class, Azo dyes, is omitted. Altering dyes slightly in application can produce different colours. The source for colours and materials is Rowe, 1924.

[8] A self-imposed German embargo that began a week before the war even begun (Haynes) was quickly removed.

[9] Two months, according to one importer; five (at textile mills) according to Little (March 1915).

[10] U. S. Tariff Commission, 1918b. Norton (February 1916) states that no dyes were imported from Germany past March 15 1915, and only small amounts imported from Switzerland.

The Dye Famine was characterized not only by low imports but, not surprisingly, high prices, and substitution to natural dyes. Figure 2 shows a price index for synthetic dyes. Relatively stable before the war, it doubles at the start of 1915 and peaks at more than ten times its pre-war real value somewhat more than a year later, before falling to about four times its real pre-war value at the end of 1918. The same figure shows natural dye prices, made chiefly from plants and some insects and the only substitute to synthetic dyes, following a similar but more moderate pattern. The profit opportunities were obvious, and many US firms entered the dye industry. By December 1915, fourteen firms were operating, by February 1916, sixteen, by May 1916, twenty-four; and by the time of the 1917 Census, some 81 firms overall were manufacturing synthetic dyes. [11] These firms originated in parallel (explosives), upstream (coal-tar), downstream (principally textile but also dyehouses, carbon paper, typewriter ribbon, printing ink and varnish producers) and intermediary (importers and sales agencies) industries (Haynes, p. 215-7, 235-6).

US production was made possible by the existing knowledge base – the accumulation of the know-how that had passively diffused outside of the industry since each dye's discovery – and the entrants' investment. The first was partly codified in the chemical literature and partly embodied in fragmentary tacit knowledge of individuals resident in the US. German textbooks, academic and trade journals, and patents were the first and obvious starting point, but insufficient in and of themselves. According to Haynes, cited by Travis (2004, p. 41), the textbooks were "ten years behind current chemical plant practises", and the journals never described the chemical processes exactly. The literature was by no means valueless,[12] but alone it did not give the firms the capability to produce the dyes.

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[11] See Norton (February 1916, March 1916, May 1916). For the synthetic dyes price index see Panel B of Table VIII, Jones and Cassebeer, 1919; that for natural dyes is constructed from manufactured product prices on pages 9-13 and commodity weights from Section V, both Carlton, 1919. Figures presented in United States, 1918a (p. 8) are broadly consistent but more moderate, showing an increase of 3.5 times of the (weighted) average price in 1916 over 1913.

[12] A journal footnote helped DuPont substantially improve an explosive intermediate plant (Hounshell and Smith, 1988).

Patent descriptions, which lacked vital information on catalysts, optimal temperatures, pressures and timing, were particularly problematic.[13] According to the admittedly pro-US bias of Haynes (Vol. 3, p. 214), the patents "had deliberate gaps and were deceitfully misleading". Nor was it always clear which patents corresponded to which dyes. So called 'evasion patents' may have been taken out only to mislead competitors, and one Du Pont executive went so far as to assert that it took almost as long to determine the match between a patent and a dye as to discover the dye in the first place (Hounshell and Smith, 1988) – surely an exaggeration, yet still indicative of the patent literature's limitations.[14]

Human capital was available as well, to a limited degree, most importantly in the form of the small pool of American chemists who had trained or worked in Germany (some many years before), such as the Yale chemistry professor that Calco hired (Travis, 2004). Other skills were important as well. US firms hired the German firms' local marketing agents for their knowledge about domestic demand and buyers (Hounshell and Smith, 1988, p. 82; Steen, 1995a, p. 25, 1995b); those hired by Du Pont brought with them samples of all of the dyes that Badische, a leading German dye manufacturer, had exported to the US. Manufacturing skill was also important; Calco's plant manager had worked in Hoffman-La Roche (Travis, 2004).

Developing a dye required additional investment beyond this initial knowledge base, however. One (limited) mode of investment was buying knowledge from elsewhere. At the end of 1916 DuPoint agreed to pay £25,000 annually for 10 years to the UK firm Levinstein in return for all its knowledge on dye production. A pre-war dye firm founded by a German émigré, Levinstein had learned more about dye production upon acquiring the Hoechst plant that the UK government had earlier confiscated from its German owners. Du Pont sent several employees to England for two months, who returned to codify the information in several reports, including 400

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[13] These difficulties were demonstrated dramatically in the *Chemical Foundation* case, when the judge instructed a young chemist, on his wedding eve, to use a patent description to produce a dye overnight. The chemist failed to do so with sufficient purity (Steen, 2001). How long it would have taken to get it right, if at all, cannot be known.

[14] Japanese firms were also unable to replicate the German dyes based on the patent descriptions (Kudo, 1994). On the limitation of technical information without accompanying human capital, see Arora (1995a and 1995b).

pages of ‘recipes’ for azo dyes and intermediates in February 1917. There were at least two more trips in the following two years. Du Pont also built an indigo plant based on the Hoechst plant.

Experimentation necessarily complemented these sources. As Cohen and Levinthal (1989) argue, absorbing others’ R&D advances requires in house capabilities, and so US firms established large R&D labs. Chemists and engineers constituted nine percent of employees of the 190 firms producing either dyes or their intermediates in 1917. Of these firms, 104 reported having a lab for solving both manufacturing and development problems and spending nearly two and a half million dollars (3.6% of dye sales) on them.[15] More firms may have conducted research but lacked accounting practices that separated out research costs. In 1918, reported R&D expenditure rose to slightly over 4.5 million dollars (US Tariff Commission, 1918a, 1919).

Notwithstanding these efforts, US firms clearly failed to fully replace the German dyes. Of the 835 dye categories in Schultz (1914) with an 1875 or later discovery date, 515 were imported in 1914; US firms succeeded in producing only 125 of those in 1917. Of those not imported in 1914, only 20 were subsequently produced in the US. These figures demonstrate a temporally stable demand, thus justifying pre-war imports as a demand proxy during the Dye Famine and later.

Once the war ended, transferring more up to date German human and organizational capital became possible. Du Pont’s 1919 attempt to hire the leading German expert, René Bohn (discoverer in 1901 of the indathrene dye class) was rebuffed, but ten more junior German chemists were hired the next year. One received the tremendously large salary of $25,000/year, $275,000 in 2004 dollars and about 50 percent more than the highest earning Bayer chemist before the war.[16] But German researchers alone were still not enough to fully replace the foreign made dyes, or fully compete with the German firms, who returned to the US market in 1922 under a 60 percent tariff. This led to the last type of technology transfer: buyouts. In 1924, the three major

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[15] By comparison, the NSF estimate of the R&D to sales ratio for the much larger category of Industrial Chemicals (1967 SIC codes 281-282), to which the dyes, crudes and intermediates (1967 SIC code 2815) belonged, falls from 5.1 in 1963 to 3.2 in 1974, more or less linearly.

[16] Murmann (2003, p. 154., citing Meyer-Thurow). We use the 1913 exchange rate of 4.2 marks/dollar (Officer, 2005).

Swiss dye firms jointly purchased a major US dye manufacturer, while Bayer entered into a joint venture with the same US firm that had purchased its government confiscated dye patents and plants in 1917; Bayer's main contribution in the agreement was its technical knowledge, without which the patents and plants had proved to be of little value to the US firm. A few years later, IG Farben, the merger of Bayer and all the other major German firms, bought the joint venture outright (Schröter, 1986). We emphasize that these methods of accessing the up to date tacit knowledge of the incumbents were not available in 1917, the period of analysis.

Section IV: A Model for the US Development Decision

This section justifies our inferring the knowledge diffusion rate from a probability model of 1917 US production. First consider the case in which all that US firms had on which to project a dye's profitability was the information on imports. At first, fragmentary quantity and price information would have been available from import agencies, whose employees went to work for the new dye firms, and buyers (textile mills and finishers). Some of the new firms had been importers or buyers themselves. With the publication of Norton (1916), all the import quantity and price figures used here would have become available to them.[17] In contrast, only limited cost information would have been at hand. Imported dyes were made outside of the US, and their production costs were surely trade secrets.

It is thus reasonable to suppose that the US firms would have projected potential monopoly profits to be proportional to import quantity ($\exp(q_i^D)$), if that was the only information available. If, further, log US development costs, F_i, depend linearly on the discovery year, Y_i, and an independent error term f_i, so that $F_i = f_0 + \beta Y_i + f_i$, then following Bresnahan and Reiss (1990), at least one US firm will supply the dye in 1917 if and only if monopoly profits exceed

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[17] An early, more detailed draft was shown at the Chemical Exhibition in September 1916 (Steen, 1995a, p. 118). A second draft was published in the *Journal of Industrial and Engineering Chemistry* two months later (Norton, November 1916), with some additional price information, but lacking the smaller dyes, compared to Norton (1916). DuPont was shown galleys sometime before August 1916 (Hounshell and Smith, 1988, p. 91).

development costs, i.e., $f_i \leq -f_0 - \beta Y_i + q_i^D$. Thus US production in 1917 occurs with probability $H(-f_0 - \beta Y_i + q_i^D)$, where H is the distribution of f_i. If we assume H is known up to a scale parameter σ, then β/σ and $1/\sigma$ are identified, and thus so is β, the rate at which the development cost necessary to compensate for the lack of complete knowledge declines with the dye's age, i.e., the knowledge diffusion rate.

Of course, US firms might have had additional cost and demand information beyond what we have, and if so would have had the incentive it to use it to incorporate the monopoly price cost margin and the shift in the level of demand since 1914 into their projected profits. Deviations in the latter across dyes would lead to a downward bias on the imports coefficient if the dye specific demand shifts were mean reverting over time; however, the Web appendix shows the dye specific production in the post-war period was actually highly persistent over time, indicating a small bias. Deviations in the price cost margin across dyes are also likely to cause a bias, since they are driven by differences in costs and non-proportional demand shifters, which also affect quantity (and so 1914 imports); the Web appendix show that this will lead to positive (negative) bias on the imports coefficient if demand is concave or not too convex (sufficiently convex). [18]

To remedy this, we include product attributes to proxy for non-proportional variations in demand, and technical attributes for cost. Demand is determined primarily by a dye's colour, the material to which it may be applied (wool, cotton, silk, etc.), its fastness and the method of application. We have indicators for the first two. Production cost is determined by the intermediates and the chemical procedures used. Log price is a function of both non-proportional demand shifters and costs, so we include its 1914 value where available. It perfectly proxies for the 1914 price-cost margin if either demand shifts only proportionally or marginal cost does not

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[18] These arguments are based on a log demand function of the form $s_i + \gamma \ln[sign(\gamma)(\alpha_i - P)]$, which encompasses several common specifications (Genesove and Mullin, 1998) and requires either $\alpha_i,\ \gamma > 0$ or $\alpha_i, \gamma + 1 < 0$. $k(\gamma) \equiv \ln[\gamma^{-1} sign(\gamma\ (\gamma/1+\gamma)^{\gamma+1}]$. Here e s_i is market size, γ demand concavity and α_i a vertical demand shifter.

vary.[19] Since the value of a dye should be approximately invariant to its physical concentration, including price controls for differences in that as well.

Section V: American Production in 1917

Table 3 presents a linear probability regression of US production in 1917. The sample is the 515 dyes imported in 1914 with a post 1875 discovery year.[20] The regression in Column (1) estimates that a one year older dye is 1.7 percentage points more likely to have been produced; the effect is highly significant. Figure 3 is the corresponding scatter diagram of the fraction of dyes produced in 1917 for each discovery year cohort, with the regression line overlaid.

Column (2) adds log imports. Its estimated coefficient associates a hundredfold difference in imports with a 29 percent increase in the likelihood of US production.[21] Including log imports has a negligible effect on the coefficient on the discovery year.

It is $\hat{\beta}$, minus the ratio of the coefficients on the discovery year to log imports that is of central interest, however. At 0.25, as reported in the second to last row, its value implies that a dye discovered one year later will cost 1-exp(.25) = 28 percent more to develop, or that it was more than 13,000 times more expensive to develop the very latest dyes, from 1913, than the earliest ones in our sample, from 1875. We will be revising the estimate downwards, but it is still worth noting that these large numbers are not so unreasonable. Conceivably, the 1875 dye cohort was so well understood that development consisted of little more than a simple run through, but development of the 1913 cohort was akin to discovering the dyes from scratch. So it is instructive to compare Gambardella (1999), who cites rates of marketed to total synthesized compounds from

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[19] For example, $\alpha_i = 0$ for iso-elastic demand. The dummy variables will also control for dependence among the dyes, so long as demand is separable in nests that correspond to these categories and firms ignore their effect on the sub-utility index function, a la Dixit and Stiglitz (1977). See the web appendix.

[20] Confidentiality requirements mean that quantity is available only for dyes produced by a sufficient number of firms, which helps explain why this work is concerned only with the incidence of production, and not its extent.

[21] In the deterministic model in which success is guaranteed by paying F_i, the inverse of the coefficient on log imports times $\sqrt{1/12}$ (the standard deviation of the standard uniform distribution) has the interpretation of the standard deviation of pre-development log expected profits. Here it is 4.6 (a factor about 100 in levels),

one in 3000 to one in 6000 in the closely allied pharmaceutical industry in the 1980s. Nonetheless, Beer (1959) cites for Bayer in the late 1800s a rate of marketed to total synthesized dyes of 37 in 2378, at least an order of magnitude lower than those in Gambardella and here.

Column (3) adds patent indicators. Since recent dyes are more likely to be covered by a patent, and as the vast majority of US dye patents were held by the Germans, one might think that the discovery year merely proxies for patent protection.[22] "US patent in force" indicates a still in force US patent listed in Schultz. Since a patent may indicate profitability, the count of countries with at least one issued patent in the category is also added. Both variables are insignificant, both singly and jointly (p=.20), indicating that, not withstanding US firms' claims, which were to lead a year later to patent confiscation, German owned patents were not an impediment to US development.[23] Recall that the country count predicted 1914 importation. Its insignificance here suggests that imports capture most of its effect on profitability.

To address the alternative explanation that development or production of newer dyes was intrinsically more difficult, column (4) includes technical attributes. The first is the number of intermediates used in production of the dye (Shreve, 1922).[24] Presumably the more intermediates used, the more difficult its development, as a firm (or its domestic supplier) had to determine how to produce more intermediates and there were more chemical steps involved. The estimates show that an additional intermediate reduced the probability of production by four percent.

The second variable, scope, is the log of the mean number of dyes for which an intermediate used in production of the given dye is used. Its level varies from 1 to 128, with a mean of 22. This measure of the commonness of the dye's inputs captures economies of scope in development and is highly significant and positive – doubling the mean number of dyes common

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[22] German patents were confiscated only after the November 1918 amendment to the Trading with the Enemy Act empowered the US government to do so. Although protecting German patents might have been difficult once the US entered the war, much of the development decisions reflected in the 1917 census would have preceded the amendment.

[23] Hesse (November 1915) also notes that but a fifth of the dye categories were in any way covered by US patents.

[24] Only 12 percent of dyes required a single intermediate, nearly half required two, a quarter required three, while very few required more than four.

to an intermediate increases the production probability by seven percent. This is hardly surprising. A dye requiring unique intermediates would obviously be more difficult and costly to produce.[25]

The third is the normalized Schultz number. Its coefficient is negative and highly significant, both statistically and economically. One can only guess why. The ordering is by class; within a class, the ordering is strongly correlated with discovery year, but hardly perfectly. Some dyes are derivatives of others, and are thus ordered; that these dyes can be produced only if their antecedents are must generate some negative correlation. But there are few such dyes. The Schultz number might reflect some other type of complexity, or the order in which the compilers became aware of the dye. In any case, higher order terms of the Schultz number, when added, are never significant. Dummy variables for the sixteen dye classes, also included, are highly significant, and their estimated coefficients positively related to those in Table 2

As a group, the technical attributes are highly significant. Their inclusion decreases the magnitude of both the discovery year and imports coefficients, but of the former more, so that $\hat{\beta}$ decreases to .17, implying a development cost for the 1913 cohort 430 times greater than that for 1875 – a factor much more in line with the rates from Beer and Gambaredella - or a halving of the necessary investment with every 4.1 years of product age.

Column (5) adds demand attributes: dummy variables for colour and materials. Colours are insignificant, but materials highly so (overwhelmingly due to the negative effect of cotton –for reasons that are unclear). Together, they are significant, although their inclusion does not materially affect $\hat{\beta}$. But when in Column (6) we add the technical attributes back in, all the demand attributes are jointly insignificant (p=.34). As the demand variables were highly

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[25] Data are missing for both these variables for 13 dyes. The mean values are used instead. The results are substantially the same if those observations are dropped instead. The numbers of chemical reactions and inputs used in the production of a given dye's intermediates were also considered, but were always found to be insignificant.

significant in predicting 1914 imports, with or without conditioning on the technical attributes, this result suggests that log-imports captures most of the demand variation.[26]

Table 4 adds the log import price (the log of the import value minus the log of the import quantity). That cuts down the sample by a third, as the value is not always reported in either of Norton (1916, November 1916). To recall, price is a perfect proxy for the physical composition, if the markup does not vary, and a very good proxy for the markup, if only $\alpha_i$or c_i varies across dyes, but not both. It is an excellent proxy if US firms had no information on cost but needed to infer it from price; it should also capture the complexity of development, if that is correlated with production cost. The estimated coefficient on log price is always negative, and significant so long as technical attributes are not included; when they are, the absolute coefficient falls by a third, and is no longer significant. The negative sign, reduced magnitude and insignificance when controlling for technical attributes, and the lesser sensitivity to the presence of demand attributes is consistent with price proxying mainly for costs. $\hat{\beta}$ is not appreciably affected by including price.

Our model has assumed a single German exporter in 1914, although often there were more. The Web appendix corrects imports for multiple German exporters, assuming Cournot behaviour, and shows that $\hat{\beta}$ is robust to the choice of concentration measure and across a reasonable degree of demand convexity (γ). Extremely convex demand implies a $\hat{\beta}$ greater by half as much. The appendix also offers an ordered logit analysis, a la Bresnahan and Reiss (1990), of the number of US dye producers as an alternative to the discrete choice analysis based on US entry or non-entry, This approach exploits the additional information in firm numbers, but at the cost of additional

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[26] When included, the 1914 market share of Swiss firms, the source of almost all non-German pre-war imports, is insignificant and its inclusion has negligible effect on the other coefficients. Swiss exports to the U.S. were also impeded during this period, by a cut-off of German intermediates, Atlantic warfare, and restrictions on Swiss exports Inputs to production of German intermediates were diverted to chemical warfare. By late 1916 Switzerland permitted dye exports only in proportion to raw material imports (*Journal of Industrial and Engineering Chemistry,* 1916); only the UK received licenses.

assumptions about the relationship of US monopoly to oligopoly profits.[27] The estimated diffusion rate estimated there is always larger than in the incidence regressions, by between one to six percentage points, but it follows the same pattern. There is no precision gain in estimating β.

Finally, as Figure 3 suggests a non-linear relationship between production incidence and discovery year, we re-estimate the model with discovery year fixed effects. The estimated effects are shown in Figure 4, overlaid by a lowess estimator, using a 19 year (half the data's range) bandwidth. The figure suggests that knowledge begins to diffuse only after about a two decade lag, and even after some four decades is not completely diffused.[28]

Both the long diffusion period and the lag are striking. The first seems at odds with survey evidence, such as Mansfield (1985), whose respondents claim that half of all chemical innovations leak out in a year and a half, or Levin et al. (1987), where at least 87 percent of all innovations could be duplicated in less than five, typically three, years. But such evidence is relevant to knowledge diffusion among competitors with more or less equal knowledge bases, and not between outside firms and foreign incumbents, as here. Nor can the reasonableness of our estimates be assessed by reference to the entry rate of outsiders in this or other industries: as the model stresses, the entry rate depends not only on the knowledge diffusion rate, but also on post-entry anticipated profits and the product age, even with incumbents removed.

One tempting explanation for the lag is that knowledge diffusion only begins after patent protection ends, perhaps because at that point more firms begin producing the dye, thus increasing the opportunity for knowledge diffusion. This interpretation is not contradicted by Table 3's result that patent protection in the US did not impede US development, if it is the patent protection in the

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[27] These additional restrictions are equal coefficients on regressors for the deterministic part of profits, and a common shock to profits, independent of potential firm numbers. The restrictions can be relaxed, but presumably at the cost of a lesser precision. The web appendix presents additional estimates for a poisson model.

[28] The coefficient on imports is .053 (s.e. = .01). The regressors from column (6) of Table 3 are included. As there are only 38 different discovery year values, Yatchew's partial linear model (2003) produces very similar results. The Web appendix shows that these results are not an artefact of a linear probability model, and that similar results are obtained with nonlinear probability models.

innovating country that impedes diffusion first among competitors in that country. The estimated lag is, however, five years longer than the fifteen year German patent duration.

Section VI: Post-Entry Competition: 1923 Production & Imports

Post-1923 competition, after German firms were allowed back into the market (albeit under very high tariffs, Versailles dye reparations, and French occupation and taxation of their main dye producing area), affords an opportunity to uncover the pattern of US firms' relative disadvantage in production, without the confounding factor of development costs. So as to concentrate on production, rather than development, this section considers the incidence of 1923 US production, on the sample of dyes US firms succeeded in developing during 1917-19.[29]

This restriction introduces two selection biases. The first stems from demand persistence: dyes developed during the earlier period are likely to have had high 1917-19 demand, relative to 1914 imports, and so high relative 1923 demand as well. To deal with it, we further restrict the sample to dyes either produced or imported (but not both) in 1923. This eliminates the bias if demand shocks increase foreign and US monopoly profits in the same proportion, and competition is strong.[30] The second selection bias stems from the low un-observable development costs that developed dyes are likely to have had. This generates a selection bias if development costs are correlated with productive efficiency. Olsen's (1980) result indicates that the bias on a coefficient will be proportional to the product of that correlation and the corresponding coefficient in Table 3's regressions. The development cost – productive efficiency correlation is likely to be negative

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[29] German dyes returned in 1920 under a license system that ended only in March 1922 (Steen 1995a, p. 312-318). All sources make clear that US production costs were much greater than German. Schröter (1986, p. 180) writes that specialized dyes cost 2 to 3 times as much when produced in a post-war German subsidiary in the US than in Germany. Schoelkopf's detailed 1908 congressional testimony put US labor, building, material and overall costs at 89, 50, 25 and 35 percent more than German costs (Hesse, August 1915). Taussig (1922) also notes the cost differential.

[30] Write 1923 log monopoly profits for the most efficient US and foreign firm as $X\gamma^j + \eta + \varepsilon^j$, $j = U, D$, with η a common shock, ϵ^D and ϵ^U cost shocks, X observable determinants of profitability, and η, $\epsilon^D - \epsilon^U$ and X mutually independent and assume sufficiently strong competition that only the most efficient firm can operate. Then, given a firm in the market, the probability that it is American is, conditional on (X, η), an increasing function of $X(\gamma^U - \gamma^D)$ only. η is thus eliminated.

(hard to develop dyes are also hard to produce at the current technological frontier), so that this bias should be positive (negative) for variables with a negative (positive) coefficient in Table 3. [31]

Table 6 shows linear probability estimates of the incidence of US production on the sample of the 95 dyes developed in 1917-19 and either produced or imported in 1923. No matter what variables are included, the discovery year coefficient is always small and insignificant. Perhaps US firms' relative disadvantage in young dyes was in development only, and not production. However, as the discovery year coefficient in Table 3 is negative, it is possible that the true coefficient is negative but is masked by a positive selection bias. Imports are also insignificant. This is consistent with imports proxying for a common proportional demand shock, which, as we have just argued, should be eliminated by restricting the sample to dyes either domestically produced or imported. But the estimated standard error is large, indicating little power to the test.

The technical attributes estimates have a clear interpretation. Dyes that use more intermediates are relatively less likely to be domestically produced than imported. That in 1917 such dyes were more likely to be produced implies that the estimated coefficient here is biased towards zero, strengthening the conclusion. A similar argument indicates that the positive coefficient on Scope is also biased towards zero. Thus, complexity and uniqueness seem to have relatively disadvantaged the US firms. The Schultz number is now insignificant, however. When price is added (cutting the sample to 75 dyes), its estimated coefficient is negative (although insignificant), consistent with higher priced dyes being more complex and so relatively more difficult for US firms to produce. It thus seems clear that technical attributes that made development difficult are also likely to have competitively disadvantaged entrants post-entry.

Section VII: Conclusion

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[31] We do not use a Heckman (1976) correction, as of candidates for an instrument, two – high wartime demand colours, such as olive-green, khaki and navy blue, and non-German 1914 exports – have already been shown not to predict 1917 production. The third, dyes based on intermediates used for wartime explosives, is co-linear with the dye classes.

Copying foreign dyes rested on two elements – the accumulated ‘common knowledge of educated men’ (Hohenberg, 1967) that had diffused from the incumbents in un-abetted fashion over four decades, and the subsequent, complementary investment of US firms, which entailed absorbing this knowledge, and then experimenting and conducting initial production runs. That older dyes were more likely to be produced in 1917 indicates that more accumulated knowledge required less complementary investment. Dividing the discovery year coefficient in the 1917 production regression by the log imports coefficient yields an annual knowledge diffusion rate of 17 percent (our best estimate), where knowledge is measured in terms of the additional investment necessary for development. However, non-linear estimation implies that diffusion begins only about two decades after the discovery, but then proceeded rapidly. This is consistent with the absence of development of the very youngest dyes. Complexity and uniqueness made dyes more difficult to develop and also more difficult to produce, relative to incumbents.

That incumbents get better at what they do over time makes them a moving target for outsiders and so makes inferring the knowledge diffusion rate among the latter difficult, if not typically impossible. However, if incumbents are barred from the industry, then the rate can be inferred, since then outsiders’ absolute ability and not that relative to the incumbents determines entry. There are undoubtedly other cases in which incumbents are suddenly removed, whether due to conflict, protectionism or some other cause. If the product space is sufficiently delineated, and product age and a proxy for profits available, the diffusion rate can be estimated for those industries as well. The Dye Famine case is one of a high degree of codifiability, zero mobility of human and organizational mobility and a very low starting point for the outside firms. Comparing knowledge diffusion rates across industries and relating them to these parameters would be a useful extension to this work, and would help further our understanding of the determinants of entry and the limits of incumbency.

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Figure 1. Frac. of Dyes Imported in 1914 by Discovery Year

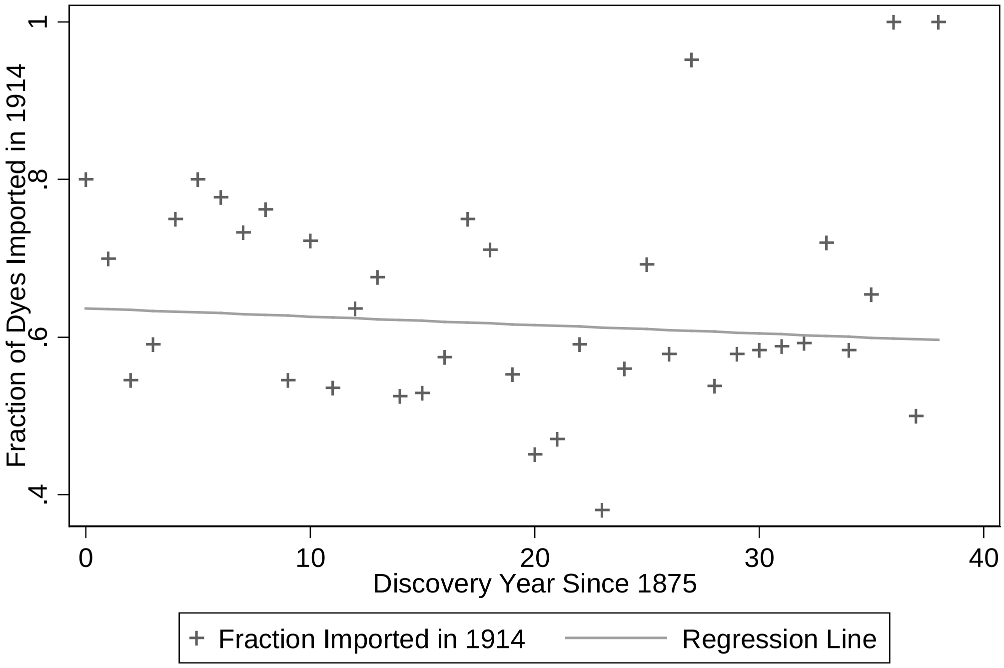


FIGURE 2

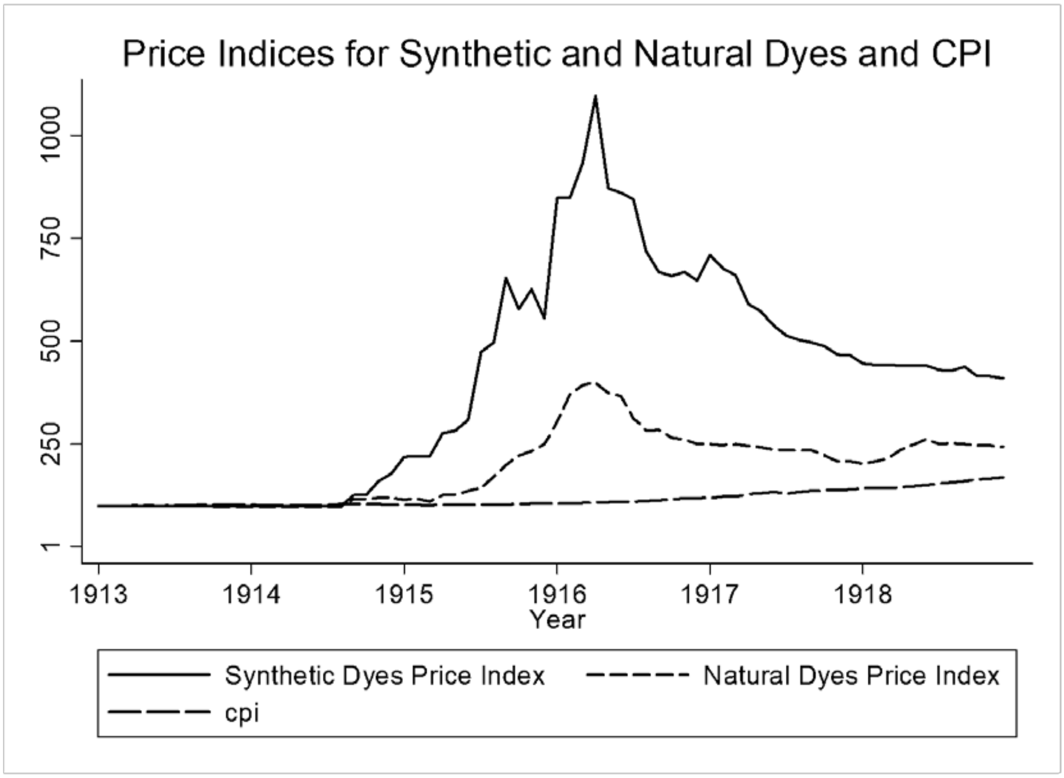


Figure 3. Fraction of Dyes Produced in 1917
(of dyes imported in 1914) by Discovery Year

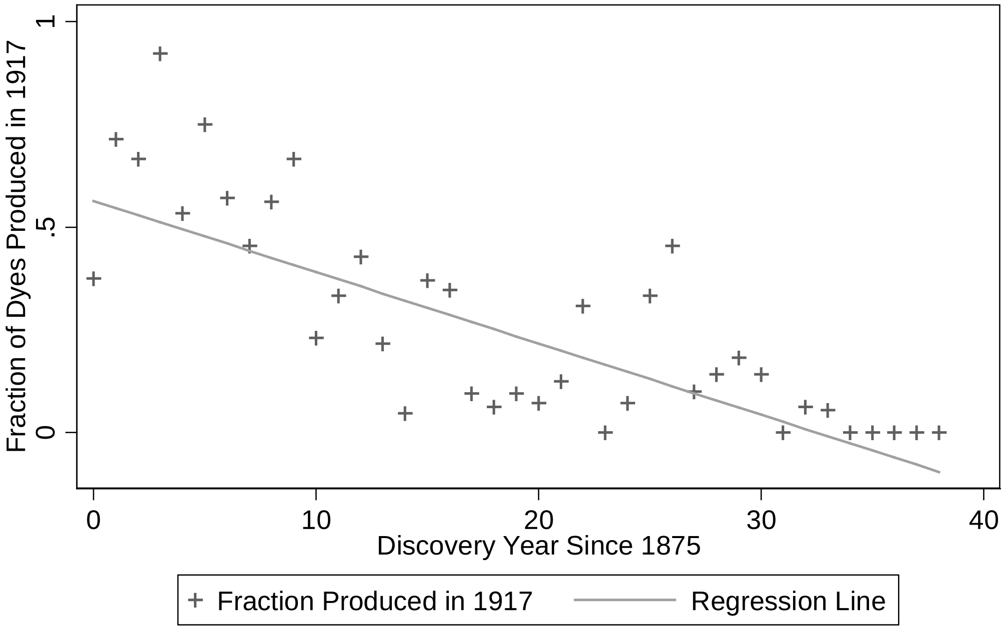
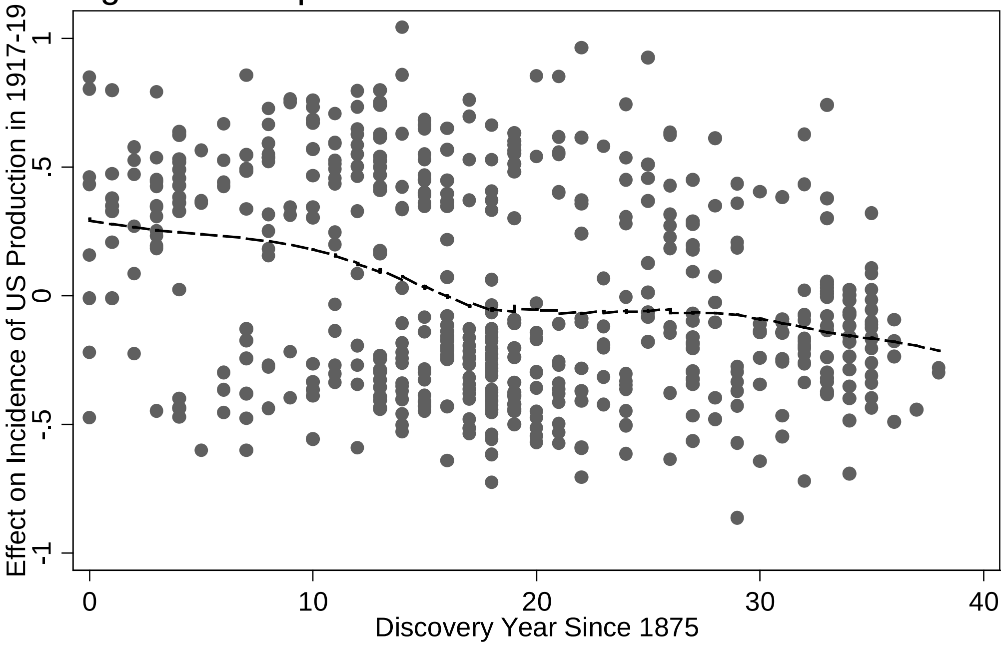


Figure 4 Non-parametric Estimate in Partial Linear Model



bandwidth = .5

Table 1: Summary Statistics

	All post 1875 (N=835)		Imported in 1914 (N=515)		Imported in 1914 & Price reported (N=345)	
	Mean	S.D.	Mean	S.D.	Mean	S.D.
Discovery Year - 1875	18.67	9.24	18.53	9.57	17.39	9.62
Ln (Import Quantity)			8.85	2.09	9.74	1.74
Import Quantity (tonnes)			39.2	93. 0	56.3	108.6
Ln Import Price					-1.42	0.73
Price (dollars)					0.32	0.33
Schultz Number	0.50	0.29	0.50	0.29	0.47	0.29
No. of Intermediates	2.36	1.01	2.36	1.03	2.37	1.00
	Number	%	Number	%	Number	%
MATERIALS						
Cotton	501	*61.0*	304	*60.2*	185	*57.8*
Silk	188	*22.9*	138	*27.3*	105	*32.8*
Wool	391	*47.6*	254	*50.3*	183	*57.2*

Table 2: Incidence of American Importation in 1914

	(1)	(2)	(3)	(4)	(5)
Discovery Year – 1875	-.001	-.001	-.002	-.001	-.002
	(.002)	(.002)	(.002)	(.002)	(.002)
# Countries w/ Patents		.02			.02
		(.01)			(.01)
Schultz Number			-.33		-.44
(Norm. on [0,1])			(.17)		(.19)
No. of Intermediates			.02		.02
			(.02)		(.02)
Scope			-.02		-.01
			(.02)		(.02)
16 Dye Class (p-value)			(.0003)		(.009)
15 Colours (p-value)				(.0000)	(.0000)
3 Materials (p-value)				(.006)	(.060)
Constant	.64	.60	.77	.44	.49
	(.04)	(.05)	(.08)	(.06)	(.11)
Technical (p-value)			(.0016)		(.011)
Demand (p-value)				(.0000)	(.0000)
R-squared	.0004	.004	.049	.072	.121

Linear regression estimates, with a dependent variable equal to one if the dye was imported in 1914, zero otherwise. Regression coefficients with standard errors in parentheses below are reported, except in the case of a set of dummy variables, for which the p-value, is reported. The number of observations is 835.

Table 3: Incidence of American Production in 1917

	(1)	(2)	(4)	(5)	(6)	(7)
Discovery Year – 1875	-.017	-.016	-.010	-.014	-.011	
	(.002)	(.002)	(.002)	(.002)	(.002)	
Ln(Import Quantity)		.063	.065	.063	.065	
		(.008)	(.008)	(.008)	(.008)	
No. Countries w/ Patents					.015	
					(.01)	
US Patent in Force					.06	
					(.06)	
Number of Intermediates			-.04		-.04	
			(.02)		(.02)	
Scope			.10		.10	
			(.02)		(.02)	
Schultz Number			-.85		-.64	
			(.16)		(.19)	
16 Dye Classes (p-value)			(.0015)		(.03)	
15 Colours (p-value)				(.14)	(.44)	
3 Materials (p-value)				(.0005)	(.12)	
Technical (p-value)			*(.0000)*		*(.0000)*	
Demand (p-value)				*(.004)*	*(.34)*	
Swiss Market Share						
R-squared	.15	.24	.35	.30	.38	
Ratio of Coefficients ($\hat{\beta}$)	---	.25	.16	.22	.17	
	(---)	(.04)	(.04)	(.04)	(.04)	

Linear regression estimates, with dependent variable equal to one if dye produced by at least one US firm in 1917, zero otherwise. The sample is all dyes imported in 1914 with a reported discovery year of 1875 or later. Ratio of Coefficients ($\hat{\beta}$) is minus that on discovery year to that on ln(Import Quantity). Its standard error is calculated by the delta method, as implemented in Stata's nlcom command. Regression coefficients with standard errors in parentheses are reported, except for a set of dummy variables, for which the p-value is reported. The joint test for more than one set of variables is shown in italics. The number of observations is 515.

Table 4: Incidence of American Production in 1917 (with log-Price)

	(1)	(2)	(3)	(4)	(5)	(6)
Discovery Year – 1875	-.020	-.018	-.020	-.012	-.017	
	(.002)	(.002)	(.003)	(.003)	(.003)	
Ln(Import Quantity)		.064	.063	.078	.066	
		(.013)	(.013)	(.013)	(.014)	
Ln(Import Price)		-.074	-.078	-.039	-.066	-.036
		(.032)	(.031)	(.035)	(.035)	(.038)
No. Countries w/ Patents			-.004			.01
			(.01)			(.02)
US Patent in Force			.08			.01
			(.08)			(.08)
Number of Intermediates				-.041		-.041
				(.024)		(.026)
Scope				.12		.12
				(.03)		(.03)
Schultz Number				-.94		-.83
				(.21)		(.27)
16 Dye Classes (p-value)				(.006)		(.03)
15 Colours (p-value)					(.72)	(.71)
3 Materials (p-value)					(.06)	(.38)
Technical (p-value)				*(.0000)*		*(.0001)*
Demand (p-value)					*(.41)*	*(.69)*
R-squared	.17	.26	.26	.38	.30	.38
Ratio of Coefficients ($\hat{\beta}$)	---	.27	.31	.15	.25	.17
	(---)	(.07)	(.09)	(.05)	(.07)	(.06)

See notes for Table 3, except that there is an additional sample inclusion condition that the 1914 import value be available. The number of observations is 345.

Table 4: US Production in 1923, among dyes produced in 1917-19 & produced or imported in 1923

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Discovery Year – 1875	-.002	-.002	-.0003	-.002	.002	.004	-.003	.010
	(.004)	(.004)	(.004)	(.004)	(.005)	(.005)	(.005)	(.006)
Ln(Import Quantity)		.018	.014	.025	.007	.005	.004	.011
		(.016)	(.016)	(.016)	(.018)	(.018)	(.022)	(.023)
Ln(Import Price)							-.107	-.106
							(.060)	(.082)
Countries w/ Patents			.02			.02		.02
			(.02)			(.02)		(.03)
# of Intermediates				-.11		-.14		-.15
				(.05)		(.05)		(.06)
Scope				.06		.14		.15
				(.05)		(.05)		(.06)
Schultz Number				.19		.57		.49
				(.29)		(.35)		(.41)
12 Dye Classes (p-value)				(.07)		(.016)		(.19)
12 Colours (p-values)					(.27)	(.03)		(.21)
3 Materials (p-value)					(.08)	(.002)		(.03)
Technical (p-value)				(.004)		(.001)		(.01)
Demand (p-value)					(.05)	(.002)		(.04)
R-squared	.002	.016	.03	.34	.27	.58	.08	.65
Number of Observations	95	95	95	95	95	95	75	75

Regression coefficients with standard errors in parentheses below are reported, except in the case of a set of dummy variables, for which the p-value, is reported. The joint test for more than one set of variables is shown in italics.