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# COMPULSORY LICENSING - EVIDENCE FROM THE TRADING WITH THE ENEMY ACT

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**ABSTRACT**

Compulsory licensing allows firms in developing countries to produce foreign-owned inventions without the consent of foreign patent owners. This paper uses an exogenous event of compulsory licensing after World War I under the Trading with the Enemy Act to examine the long run effects of compulsory licensing on domestic invention. Difference-in-differences analyses of nearly 200,000 chemical inventions suggest that compulsory licensing increased domestic invention by at least 20 percent.

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Compulsory licensing allows firms in developing country to produce foreign inventions without the consent of foreign patent owners.[1] Countries such as Brazil, Thailand and India have used the policy to procure life-saving drugs for millions of patients and are proposing it as a means to access foreign technologies to combat climate change.[2] Opponents of compulsory licensing, however, fear that the policy may reduce long-run access to critical innovations, as it weakens incentives to invent and transfer new technologies abroad.[3]

This paper examines an important aspect of compulsory licensing, which has been neglected in the policy debate: What are the long-run effects on domestic invention in countries that use compulsory licensing to access foreign technologies? On the one hand, the ability to license foreign inventions at below-market rates may weaken incentives for domestic innovation. On the other hand, experience with producing foreign innovations may enable developing countries to build up their own domestic industries and in the long run increase domestic invention through learning by doing (e.g., Arrow 1962, Stokey 1995, Irwin and Klenow 1994) and other mechanisms.

To identify the long-run effects of compulsory licensing on domestic invention, this paper takes advantage of an exogenous episode of compulsory licensing as a result of World War I. In November 1917, Congress passed the *Trading with the Enemy Act* (TWEA). Section 10 of the Act permitted U.S. firms to violate enemy-owned patents if they contributed to the war effort.[4] As the war dragged on, the TWEA became more and more punitive (Steen 2001, p.99). One week before the Armistice at Compiègne on November 11, 1918, Congress amended the TWEA to confiscate all enemy-owned patents; by February 1919, German-owned patents were systematically licensed to U.S. firms.

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[1] In general, TRIPS Art.31 allows compulsory licenses after negotiations for voluntary licenses have failed. In cases of emergency, TRIPS allows governments to grant compulsory licenses without first trying to negotiate. The World Trade Organization (WTO) Doha Declaration of 2001 emphasized developing countries' rights to issue compulsory licenses: "Each member has the right to grant compulsory licenses and the freedom to determine the grounds upon which such licenses are granted." (WT/MIN(01)/DEC/1, Art. 5.b)

[2] Thailand and Brazil have used compulsory licenses to produce antiretrovirals for AIDS patients and India has indicated its plans to use compulsory licensing to combat swine flu (Kremer 2002, Galvão 2002, Gostin 2006, Steinbrook, 2007).

[3] The U.S. pharmaceutical company Merck criticized Brazil's licensing of its HIV drug efavirenz as an "expropriation of intellectual property" that may in the long run "hurt patients who require new life-saving therapies" (*Intellectual Property Watch*, May 7, 2007). Survey results and case studies, however, suggest that compulsory licensing does not provoke drastic reactions by affected firms (e.g., Scherer 1977, Chien 2003). As a mechanism to address anti-competitive patenting behavior in domestic markets, compulsory licensing is expected to increase overall welfare by encouraging the optimal trade-off between incentives for R&D and the dead weight loss of long-lived patents (Tandon 1982, Gilbert and Shapiro 1990).

[4] 12 U.S.C. § 95a. Today, Cuba is the only country still affected by the TWEA.

To measure the effects of compulsory licensing, this paper compares changes in annual patents for chemical inventions by domestic inventors across technologies that were differentially affected by the TWEA. This strategy allows us to control for alternative factors that may have encouraged domestic invention, such as improvements in education and scientific training (e.g., Landau and Rosenberg, 1992) or tariff barriers intended to protect the U.S. chemical industry (e.g., Eichengreen 1989, Irwin 1998). Technologies are measured at the level of narrowly-defined subclasses of United States Patent Office (USPTO) patents. Chemical inventions in all of these subclasses were affected by more general factors, such as tariffs and improvements in education, but only some subclasses were affected by compulsory licensing. Specifically, subclasses are defined as treated if a domestic firm was issued a compulsory license for one of 699 enemy-owned chemical patents under the TWEA.

In addition to distinguishing subclasses with and without treatment, we measure the effects of variation in the intensity of treatment. Specifically, we control for differences in the number of licensed patents across subclasses and in the novelty of licensed patents.

Changes in the domestic invention are measured by the number of U.S. patents granted to domestic inventors per subclass and year. To construct the data, we collected information on all 21 USPTO classes of organic chemicals that received at least one license under the TWEA. These 21 classes produced a total of 165,400 patents between 1875 and 1939 and covered 8,422 subclasses; 335 of these subclasses received at least one license under the TWEA.

OLS regressions reveal substantial increases in domestic invention in subclasses that were affected by compulsory licensing relative to other subclasses after the TWEA. In subclasses that received at least one license, domestic inventors produced an average of 0.118 additional patents per year after the TWEA, implying an increase of nearly 20 percent, compared with an average of 0.684 patents per subclass between 1919 and 1939. Each additional license generated 0.062 additional patents per subclass and year; in subclasses where U.S. firms licensed patents that were 10 years younger (i.e., more novel), domestic inventors produced 0.060 additional patents per year.

In addition to estimating the overall impact of compulsory licensing, we also examine the timing of these effects. This is important because, among other things, it may help shed some light on the mechanisms by which licensing encourages invention. If licensing increases invention through learning by doing, effects may take several years to materialize, as domestic firms learn to produce foreign inventions and build their own production capacities. This process might be especially slow if domestic inventors need "time to learn," as Arora and Rosenberg (1998, p.79) suggest to have been the case for organic chemicals in the United States, where initial levels of domestic invention were low.[5] In fact, we find that pre-TWEA levels of domestic invention were especially low in treated subclasses.

Estimates of annual treatment effects confirm that the full impact of compulsory licensing took several years to materialize. Enemy-owned patents were licensed from 1919 and 1924, with most licenses being granted in 1920 and 1921 (Steen 2001, p.100). Although annual treatment effects become significant as early as 1927, the strongest effects occur for patents that were granted after 1931. Given that patent applications occur two to three years before grants in our data, this implies that the largest effects on applications began in 1929 – eight to nine years after most patents had been licensed. Once the effects were established, they remained large and significant (at nearly 60 percent additional patents per subclass and year) throughout the 1930s.

One caveat with these results is that the licensing decisions of U.S. firms may not have been exogenous, even though the timing of the TWEA and the types of technologies that were available for licensing were exogenous. For example, U.S. patent data for the pre-period indicate that U.S. inventors were most likely to license in subclasses where levels of domestic invention were initially low. In those subclasses domestic invention is likely to have increased more slowly because U.S. firms had more catching up to do before they could create their own inventions. As a result, OLS estimates may underestimate the true effects of compulsory licensing. On the other hand, U.S. inventors may have been more likely to license in subclasses where the demand for domestic invention was high, and invention in those subclasses may have increased more quickly (independent of the TWEA). In that case, OLS would overestimate the true effects of compulsory licensing.

To test for these potential problems, we subject the data to a series of robustness checks. Triple difference regressions account for unobservable characteristics that may have encouraged

[5]Also see Haber 1971, pp.205-206, Aftalion 1991, p.144, Mowery and Rosenberg 1998, p.75. In 1923 chemical trials during a court case established that a skilled U.S. chemist could not reproduce synthetic organic chemicals based on confiscated German patents: Louis Freedman, who had earned degrees from Yale and Columbia proved unable to produce cincophen, a drug to treat gout (Steen 2001 pp.91-92, 114-115). Additional delays may result from incomplete information in patent documents. The German firm BASF, for example, withheld critical information about the Haber-Bosch process from its patent application and U.S. firms took nearly a decade to replicate its process (Haynes 1945, pp.86-87). We discuss these factors in more detail in the section on the historical background of the TWEA.

patenting by *all* non-German inventors in treated subclasses. Specifically, we compare changes in patenting by domestic inventors with changes in patenting by other non-German inventors before and after the TWEA. Triple difference estimates confirm that licensing encouraged patenting by domestic inventors, even relative to other non-German inventors. An alternative placebo test artificially exposes French inventors, who could not license enemy patents under the TWEA to "treatment" by compulsory licensing. In this placebo test, compulsory licensing has no effect.

To assess the direction and size of selection bias, we estimate intent-to-treat (ITT) and instrumental variable (IV) regressions, where the number of enemy-owned patents that U.S. firms could have licensed under the TWEA measures the ITT and IV variables. ITT estimates are slightly smaller than OLS estimates, while IV estimates are somewhat larger, which indicates that selection bias (such as the concentration of licensing in subclasses with low initial skill levels) may indeed lead us to underestimate the true effects of compulsory licensing.

Additional robustness checks include regressions that control for pre-existing time trends, regressions that control for variation above the subclass level, regressions on a restricted sample of primary subclasses, regressions for changes in patenting within a specific chemical (indigo dyes), and placebo tests to check for random correlation.

In a final section of the paper, we perform a firm level analysis to shed some light on the mechanism by which compulsory licensing encourages invention. Specifically, we distinguish the effects of patents that were licensed to a specific U.S. firm (Du Pont) from the effects of patents that were licensed to other firms. Effects of own licenses are more likely to result from learning that occurs when a firm produces foreign inventions, while other licenses capture factors that benefit the industry more broadly, such as improvements in skills and knowledge spillovers across firms. Our results suggest that both types of mechanisms were important, but effects of own licenses were roughly four times as large as effects of other firms' licenses. These estimates are comparable to results for the late 20$^{th}$-century, which find that within-firm learning effects are about three times as large as effects of knowledge spillovers across firms (Irwin and Klenow 1994).

The remainder of this paper is structured as follows. Section I summarizes basic features of the TWEA. Section II presents our empirical strategy. Section III details the data collection and discusses potential sources of bias and measurement error. Section IV presents estimation results, Section V robustness checks, and section VI summarizes results of our firm-level analysis. Section VII concludes.

## I. The TWEA as a Natural Experiment of Compulsory Licensing

Created by an Act of Congress on October 6, 1917, the TWEA was intended to "dislodge the hostile Hun within our gates" (Alien Property Custodian 1919, p.17) to destroy "Germany's great industrial army on American soil," its "spy centers," and "nests of sedition" (Alien Property Custodian 1919, p.14). To this end, the TWEA placed all enemy property "beyond the control of influence of its former owners, where it cannot eventually yield aid or comfort to the enemy" (Alien Property Custodian 1919, p. 13).[6]

On March 28, 1918, the TWEA was amended to give the Custodian the power to sell enemy property, including all enemy-owned patents "as though he were the owner thereof" (Alien Property Custodian 1919, p.22). Thus, the Alien Property Custodian began to appropriate any patent owned by "enemy persons" and corporations doing business in Germany, Austria-Hungary, Bulgaria, and Turkey, as well as the occupied parts of Belgium, France, Russia, and the Balkans (Alien Property Custodian 1919, p.7), administering these properties as a trust.

By February 22, 1919, Mitchell Palmer, the Alien Property Custodian and President of the Bureau of Investigation (today's FBI) felt comfortable to say that "practically all known enemy property in the United States has been taken over by me and is administered according to the provisions of the trading with the enemy act" (Alien Property Custodian 1919, p.7); 35,400 reports of alien property had been received, and 32,296 trusts had been created, with a total value exceeding $500 million in 1919, equivalent to 4.7 billion in 2008 (Appendix Table A1).[7]

At the time of the TWEA, the U.S. organic chemical industry was largely based on natural, wood-based products, and lagged behind in more complex processes, including organic synthesis (e.g., Aftalion 1991, pp.117-119, Arora and Rosenberg 1998, p.74). In these areas,

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[6] The destruction of German property was also intended to prevent Germany from starting another war: "…the great overshadowing result which has come from this war is the assurance of peace almost everlasting amongst the peoples of the earth. It would help to make that an absolute certainty by refusing to permit Germany to prosecute a war after the war... if she can get out of the war with her home territory intact, rebuild a stable government and still have her foreign markets subject to her exploitation, by means no less foul and unfair than those which she has employed on the field of battle, we shall not be safe from future onslaughts different in methods…." (Alien Property Custodian 1919, p.16)

[7] Using the GDP deflator as a conservative measure; based on relative shares of GDP, the 2008 equivalent would be $88 billion (Williamson 2008).

foreign patentees dominated U.S. markets. For example, 70 percent of all U.S. patents for synthetic organic compounds between 1900 and 1910 were granted to German firms (USTC 1918, Haynes 1945 p.214, Steen 2001). World War I temporarily suspended German competition, but German firms swiftly returned to their U.S. markets and resumed patenting in the 1920s (Figure 1).

The TWEA granted U.S. firms access to all patents that had been owned by enemies during the war. On behalf of the U.S. government, the Chemical Foundation began to issue non-exclusive licenses of enemy patents in 1919.[8] Licensing continued until 1926 though most licenses were granted in 1920 and 1921 (Steen 2001, p.100).

## II. Empirical Strategy

Our empirical strategy compares changes in domestic invention between 1875 and 1939 across chemicals that were differentially affected by the TWEA. The dependent variable is the number of patents by U.S. inventors per USPTO subclass and year:

$$\textit{Patents by U.S. inventors}_{c,t} = \alpha_0 + \beta' \, \textit{TREAT}_c \cdot \textit{postTWEA}_t + \gamma \cdot Z_{c,t} + \delta_t + f_c + \varepsilon_{c,t}$$

where *TREAT* is a vector of treatment variables and *postTWEA* equals 1 for every year after 1918. In our most basic specification, we define a subclass as treated if it contained at least one enemy-owned patent that was licensed to a U.S. firm. The control variable *Z* measures the total number of foreign patents; it controls for unobservable factors, such as technological progress within subclasses; $\delta$ indicates year fixed effects and *f* subclass fixed effects.[9]

### *A. Controlling for Differences in the Intensity of Treatment*

We extend the basic difference-in-differences framework to include two additional variables to measure the intensity of treatment. First, we control for the number of patents that were licensed in each subclass. Most subclasses received only one license under the TWEA, but

[8] In 1921 the Chemical Foundation owned 4,764 patents, 874 trademarks, and 492 copyrights. Although licenses were sold below market rates, the foundation collected nearly $700,000 in royalties (ca. 7 million 2008$, using the GDP deflator).

[9] Fixed effects include estimates for $\alpha_1$ and $\alpha_2$, from the standard difference-in-differences equation $\textit{Patents by U.S. inventors}_{c,t} = \alpha_0 + \alpha_1' \textit{TREAT}_c + \alpha_2 \cdot \textit{postTWEA}_c + \beta' \, \textit{TREAT}_c \cdot \textit{postTWEA}_t + \gamma \cdot Z_{c,t} + \delta_t + f_c + \varepsilon_{c,t}$ In our simplest specification *TREAT* equals 1 if the subclass includes at least one licensed patent. In specifications that control for the intensity of treatment *TREAT* is a vector of the number of licensed patents per subclass and the total years of remaining patent life of all licensed patents; these measures enter linearly and non-linearly in alternative specifications.

a small number of subclasses received many licenses (Figure 2). Subclass 106/402 "compositions: coating or plastic – lakes," for example, received eight licenses. Second, we control for the total remaining lifetime across all licensed patents to measure differences in the novelty of licensed patents across subclasses (Figure 3). To illustrate such differences, compare an old patent that was granted in 1903 with a new patent that was granted 12 years later, in 1915. If both patents were licensed under the TWEA and if technologies improve over time, the old patent would become obsolete more quickly, and a license for the new patent conveys greater benefits to licensees.

*B. Measuring Annual Treatment Effects*

In addition to average effects we estimate annual treatment effects to examine the timing of changes in domestic invention. If compulsory licensing encourages invention through experience and learning-by-doing (e.g., Arrow 1967) the most significant changes should occur with some delay. Low initial skill levels in licensing countries (which, as we will show below, may disproportionately affect treated technologies) and incomplete information in patent documents may create further delays. At the time of the TWEA, the German chemical company BASF, for example, had "effectively bulwarked its discovery (of the Haber-Bosch process) with strong, broad patents which detailed meticulously the apparatus, temperatures and pressures, but cleverly avoided particulars as to the catalysts employed or their preparation" (Haynes 1945, pp.86-87). As a result, a "prolonged learning experience was necessary to understand the two sides of catalysis, the chemical side and the engineering and design side."[10] To measure the extent of such potential delays, we estimate annual treatment effects $\beta_t$

$$\textit{Patents by U.S. inventors}_{c,t} = \alpha_0 + \beta_t \cdot TREAT_c \cdot YEARpostTWEA_t + \gamma \cdot Z_{c,t} + \delta_t + f_c + \varepsilon_{c,t}$$

where $\beta_t$ measures the differential change in domestic patenting between treated and untreated subclasses in year $t$ after the TWEA.

[10] Mowery and Rosenberg 1998, p.75 (citing Haber 1971, pp.205-206). Additional delays may result from variation in business cycles, which constrain investments in R&D. For example, personnel cuts during the recession of 1920 deeply affected DuPont's research team on dyestuffs, which already "had already been struggling with the burden of catching up with chemists in the German dye industry" (Hounshell and Smith 1988, p.89). Between mid and end 1920, the team's salary roll fell from 565 to 217, so that "(r)esearch chemists washed their own dishes, ran their own errands and did all of the experimental work" (Hounshell and Smith 1988, p.89).

*C. Comparing Pre-Treatment Trends for Treated and Untreated Subclasses*

A potential challenge to the difference-in-differences strategy is that differential changes between treated and untreated subclasses may be driven by pre-existing differences in the time trends of patenting. To address this issue, we allow $\beta_t$ to vary across treated and untreated subclasses prior to the TWEA, using 1900 as the baseline and restricting the sample to pre-TWEA years.

$$\textit{Patents by U.S. inventors}_{c,t} = \alpha_0 + \beta_t \cdot YEAR_t \cdot TREAT_c \cdot pre1919_t + \gamma \cdot Z_{c,t} + \delta_t + f_c + \varepsilon_{c,t}$$

This test reveals no systematic differences in pre-trends across treated and untreated subclasses (Figure 4).

*D. Triple Differences and Placebo Treatments for French Inventors*

Another concern is that unobservable factors such as the temporary absence of German competitors from U.S. markets may have encouraged invention independently of the TWEA.[11] If such increases differentially affected domestic invention in treated subclasses, they would lead us to overestimate the true effects of compulsory licensing. To address this, we estimate triple difference regressions, which compare changes in annual patents by U.S. inventors with changes in annual patents by all other non-German inventors across treated and untreated subclasses before and after the TWEA:

$$\begin{aligned} Patents_{n,c,t} = \; & \alpha_0 + \alpha_1 USA_n + \alpha_2 TREAT_c \cdot YEARpostTWEA_t + \alpha_3 USA_n \cdot TREAT_c \\ & + \alpha_4 USA_n \cdot YEARpostTWEA_t \\ & + \beta_t \cdot USA_n \cdot TREAT_c \cdot YEARpostTWEA_t + \delta_t + f_c + \varepsilon_{c,t} \end{aligned}$$

where the subscript *n* distinguishes U.S. and other non-German inventors, USA distinguishes patents by U.S. inventors, and $\beta_t$ measures the additional effect of compulsory licensing on U.S. inventors relative to other non-German inventors.

An alternative test artificially exposes French inventors, who were also lagging behind in organic chemistry (e.g., Aftalion 1991), to a placebo treatment under the U.S. TWEA. Specifically, we re-estimate the basic specification with annual treatment effects under the

[11] For example, historical accounts suggest that the absence of German competitors from overseas markets opened the field to integrated producers of dyestuffs from England, the United States, France, Japan, and Switzerland (Aftalion 1991, p.125).

counter-factual that French inventors, who could not take advantage of compulsory licensing provisions, did in fact benefit from them.

$$\textit{Patents by French inventors}_{c,t} = \alpha_0 + \beta_t \cdot TREAT_c \cdot YEARpostTWEA_t + \gamma \cdot Z_{c,t} + \delta_t + f_c + \varepsilon_{c,t}$$

If unobservables, such as the absence of German competitors during the war, caused U.S. inventors to patent more after 1919, French inventors should experience a similar increase.

*E. Intent to Treat and Instrumental Variable Regressions*

Perhaps the most important threat to our identification strategy is that the licensing decisions of U.S. firms may not have been exogenous, even though the TWEA itself and the technologies that U.S. firms could license were exogenous. In fact, patent data indicate that subclasses where U.S. inventors chose to license were substantially different from other subclasses: U.S. firms were more likely to license in subclasses where initial levels of domestic invention were weak (Figure 5). Under the TWEA, enemy-owned patents became available for licensing in 1,341 subclasses; the pre-TWEA share of domestic invention in these subclasses was 85 percent. U.S. firms chose to license in 335 of these subclasses; the pre-TWEA share of domestic inventions in these (treated) subclasses was 50 percent. Thus, the data suggest that U.S. firms were more likely to license in subclasses where their pre-TWEA inventive capacity was weak. As a result, the effects of compulsory licensing may have been delayed (which is consistent with the historical evidence), and OLS may underestimate the true effects of compulsory licensing.

Intent to treat (ITT) regressions allow us to identify the direction of this selection bias (e.g., Imbens and Wooldridge 2009). We define intent to treat as the number of enemy patents that were available for licensing under the TWEA.[12]

$$\textit{Patents by U.S. inventors}_{c,t} = \alpha_0 + \beta \cdot \textit{Enemy patents}_c \cdot postTWEA_t + \gamma \cdot Z_{c,t} + \delta_t + f_c + \varepsilon_{c,t}$$

[12] Specifically, we construct a list of all 4,767 enemy-owned patents that the Chemical Foundation had made available for licensing by 1922 (Alien Property Custodian 1922, pp.884-960). The alternative, binary, definition of ITT as a subclass that included at least one enemy patent would assign nearly 50 percent of subclasses to the ITT. In the IV regressions, this binary treatment variable would consistently estimate the sign of the average per-unit treatment effect but over-estimate the size of the effect if treatment is continuous (Angrist and Imbens 1995; Angrist, Imbens, and Rubin 1996).

An alternative test uses the number of enemy patents as an instrument for licensed patents. *Enemy patents* is highly correlated with the *number of licenses* that were granted to U.S. firms, but variation in *enemy patents* (other than those that were licensed) should not by itself increase domestic invention.

First stage: $\textit{Number of licenses}_{c,t} = \eta_0 + \phi \cdot \textit{Enemy patents}_c \cdot \textit{postTWEA}_t + \mu_t + g_c + \omega_{ct}$

Second stage: $\textit{Patents by U.S. inventors}_{c,t} = \alpha_0 + \beta \cdot \textit{Number of licenses}_c \cdot \textit{postTWEA}_t + \delta_t + f_c + \varepsilon_{c,t}$

*F. Robustness Checks*

In addition, we perform a number of alternative robustness checks, including regressions that control for pre-existing time trends, regressions that control for variation at the level above the subclass level, regressions on a restricted sample of primary subclasses, regressions within a specific type of chemicals (indigo dyes) and a series of placebo tests.

## III. The Data

Our treatment variable consists of 699 enemy-owned chemical patents that were licensed to U.S. firms; the outcome variable includes all 165,400 U.S. patents in 21 USPTO (main) classes that received at least one compulsory license under the TWEA.

*A. Data on the Treatment: Licensed Enemy Patents*

Under the TWEA, the United States confiscated over 4,500 enemy-owned patents for chemical inventions. Of these patents, 699 were licensed by the Chemical Foundation to one or more of 326 U.S. firms from 1919 to 1926 (Haynes 1945). Exact data on the grant dates of licenses are unavailable, although we know that most licenses occurred in 1920 and 1921 (Steen 2001, p.100). Licensed patents belong to 335 primary and secondary subclasses, which we define as treated. Variation in the number of licensed patents across treated subclasses (Figure 2) and in the novelty of licensed patents (measured as the total remaining years of patent life for all licensed patents in a given subclass, Figure 3) allow us to control for the intensity of treatment.

*B. Data on the Outcome: U.S. Patents 1875-1945*

Domestic invention is measured as the number of U.S. patents by domestic inventors per subclass and year. We have collected these data for all 21 USPTO classes of chemicals that received at least one dyestuff license under the TWEA (Appendix Table A2). Between 1875 and 1945, these 21 classes generated 165,400 patents, which we collect from the USPTO official website (www.uspto.gov). These patents cover 8,422 subclasses, 335 of which are treated.

Ideally we would measure changes in domestic invention based on the application (rather than grant) dates of U.S. patents. Because data limitations only allow us to measure grant dates, we estimate the length of the lag between patent applications and grants. In a sample of 493 dyestuff patents between 1930 and 1933, the median patent is granted three years after the application (with a $25^{th}$ percentile of two and a $75^{th}$ percentile of four years).[13]

Patents by domestic inventors are measured by subtracting foreign patents from the total number of U.S. patents per year. Foreign patents are U.S. patents by inventors from Argentina, Australia, Austria, Belgium, Brazil, China, England, France, Germany, India, Italy, the Netherlands, Russia, Scotland, Spain and Switzerland. This list includes the nationalities of all inventors that we found by hand-checking 625 patents of alizarin, indigo, azo dyes, and aniline, which Delamare and Guineau (1999) consider the most important dyes in the early 20th century. Inventors' country of origins are identified through keyword searches for country names in the *Lexis Nexis Chronological Patent Files, 1790-1970* (Figure 6). For example, we assign a patent to be of a German inventor if it contains the word "Germany" anywhere in title or in the description of the invention.

Data on inventor nationality reveal that German firms quickly re-entered the United States after the war, despite the potential incentive effects of the TWEA (Figure 1).[14]

*C. Measurement Error and Attenuation Bias*

[13] More generally, the lag between applications and grants has been shown to vary over time and across technologies, depending, among other factors, on the complexity of patent applications and the workload of examiners (Popp, Juhl, and Johnson 2004). To measure the size of the lag in our sample, we searched the site www.google.com/patents for patents that include the word "dye." Google capped our search at 600 patents; 536 of these patents included application dates, and 493 belong to our sample.

[14] German discoveries in the 1920s and 30s include the production of insulin in 1922 (using pancreas glands from slaughterhouses), estradiol (progynone) in 1928, and Raschig's phenol synthesis via the catalytic chlorination of benzene in 1935 (Aftalion 1991, pp.187-188). According to contemporary accounts, Germany's quick re-entry to chemical research was partly fuelled by war-time profits from the production of combat gases and explosives (Aftalion 1991, pp.138-139).

Our data may be subject to measurement error in the way we assign patents to inventor nationalities. Specifically, we may overestimate the number of patents by domestic inventors if countries that are not included in our search patented a significant number of inventions; this error, however, is likely to be small. Another type of measurement error results from using Optical Character Recognition (OCR) to identify patents by foreign inventors, because OCR is worse at recognizing misspelled names or untidy script than the human eye.[15]

Although there is no reason to believe that these errors vary systematically across treated and untreated subclasses, we hand-collected inventor nationalities of 625 patents of alizarin, indigo, azo dyes and aniline to check for systematic bias. For these patents we identify inventors' nationalities by carefully reading the full text of each patent. A comparison of the hand-collected and machine-collected data reveals no significant differences in inventor nationalities across subclasses (Table 1 and Figure A1).

Another type of measurement error results from our use of the USPTO classification system. Specifically, inventors' propensity to patent may vary across subclasses (Scherer 1971, Lerner 1995, and Moser 2009) and we may underestimate patenting in subclasses that are narrowly defined. To address these issues, all regressions include subclass-specific fixed effects.

Most importantly, however, the narrow definition of treated technologies at the level of USPTO subclasses may lead us to underestimate the effects of compulsory licensing: Our estimation assumes that treatment effects are limited to inventors in a specific subclass. Given the narrow definition of USPTO subclasses it is, however, likely that some effects of compulsory licensing spill over to other subclasses that are included in our control.[16]

## IV. Results

Results for our most basic regression

$$\textit{Patents by U.S. inventors}_{c,t} = \alpha_0 + \beta'\, TREAT_c \cdot postTWEA_t + \gamma \cdot Z_{c,t} + \delta_t + f_c + \varepsilon_{c,t}$$

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[15] To identify as many foreign inventors as possible, we search for the name of a foreign country anywhere in the document. This overestimates the number of foreign inventors, if patent applications use the country name in a different context. For example, we wrongly assign USPTO patent 1,674,085 to Great Britain, because its inventors (who came from Massachusetts) also applied for a patent in Britain and mentioned this in their patent document. Several cross-checks of our data, however, indicate that such errors are rare. Improvements in the quality of OCR over time will be captured by annual fixed effects.

[16] More formally, our estimation violates the stable unit treatment value assumption (SUTVA) because there is some interference between treated and untreated units (Rubin 1990, p.282).

suggest a high and statistically significant correlation between compulsory licensing and patenting by domestic inventors: In subclasses where domestic firms benefitted from compulsory licensing, domestic inventors produced between 0.118 and 0.234 additional patents per year after 1919 (Table 2, columns 1-3, significant at 1 percent). Compared with an average of 0.684 annual patents in the average subclass after 1919, this implies a 15 to 30 percent increase in domestic invention. Coefficients stay highly significant when standard errors are computed by a block bootstrap clustered at the subclass level to account for serial correlation in domestic patenting (Appendix Table A3).[17] Controls for patents by foreign inventors have a measurable influence on treatment effects, but treatment effects remain large and statistically significant.

*A. Controlling for the Intensity of Treatment*

Regressions with controls for the intensity of treatment indicate that effects on domestic inventions increase both with the number and the novelty of licensed patents. An additional license increases domestic patents by 0.062 to 0.111 per year, equivalent to a 9 to 14 percent increase (Table 2, columns 5-6, significant at 1 percent).[18] An additional year of patent life increases the number of patents by 0.006 to 0.009 per year (Table 2, columns 8-9, significant at 1 percent), which implies that licensing a *new* patent in 1918 (with 17 years of remaining patent life) adds 0.102 to 0.153 patents per year (17 years * 0.006 to 0.009 patents per year), while licensing an *old* patent (with just one year of remaining patent life) adds less than 0.010 (1 year * 0.006 to 0.009 patents per year).[19]

*B. Annual Treatment Effects*

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[17] A potential problem with difference-in-differences estimation is that, in the presence of serial correlation in the dependent variable, standard errors may be underestimated even with clustering. For difference-in-differences estimations with a large number of groups a block bootstrap, which maintains the autocorrelation structure within groups by keeping observations that belong to the same group together in a "block', has been shown to perform best (Bertrand, Duflo, and Mullainathan 2004). Applied to our specific case, the block bootstrap maintains the structure of autocorrelations within subclasses, as it samples subclasses instead of observations. We draw a large number of (79) bootstrapped samples (the computer crashed at 79), and reject the hypothesis that $\beta = 0$ at a 99 percent confidence interval (Appendix Table A3).

[18] Consistent with the idea that the marginal benefits of additional knowledge are decreasing, coefficients on the square of licensed patents are negative. Taken to the extreme, this implies that, in subclasses which had already received more than 18 licenses, an additional license may discourage domestic invention. In practice, however, none of the 335 treated subclasses in our data received more than 15 licenses.

[19] To control for differences in the quality of licensed patents, we also match our data with citations in U.S. patents between 1975 and 2002 (Hall, Jaffe, and Trajtenberg 2001); 154 of our 699 licensed patents were cited at least once. Adjusting treatment variables for citations has no significant effect on estimated effects.

Consistent with the idea that compulsory licensing enables domestic firms to learn by producing, estimates of annual treatment effects suggest that the effects of compulsory licensing took several years to materialize. In the regression

$$\textit{Patents by U.S. inventors}_{c,t} = \alpha_0 + \beta_t \cdot TREAT_c \cdot YEARpostTWEA_t + \gamma \cdot Z_{c,t} + \delta_t + f_c + \varepsilon_{c,t}$$

where $\beta_t$ measures the effect of compulsory licensing in year $t$, annual treatment effects for patent grants become statistically significant in 1927 (Figure 7, significant at 5 percent), implying an increase in patent *applications* around 1924, three to four years after most licenses had been granted.[20] The full effects of licensing, however, set in about five years later, in 1932, implying an effect on applications in 1929, eight to nine years after most licenses had been granted.

These results match up with historical evidence suggesting that U.S. firms needed "time to learn" (Arora and Rosenberg 1998, p.79). For example, the Winthrop Chemical Company, which had acquired all of Bayer's patents and production machinery

> "could not figure out how to make the sixty-three drugs that were supposed to be (its) stock-in-trade…The former German supervisors having been jailed or deported, nobody knew how to run the machines; …the patents, which were supposed to specify manufacturing processes, were marvels of obfuscation" (Mann and Plummer 1991, pp.52-53).[21]

Once such obstacles had been overcome, the TWEA's effects on domestic invention remained strong and significant throughout the 1930s. After 1932, treated subclasses generated from 0.216 to 0.513 additional patents per year, implying an increase of 59 to 88 percent in treated subclasses. In 1939, for example, domestic inventors produced an additional 0.513 patents in subclasses where they had received a license under the TWEA.

Controlling for the intensity of treatment further strengthens these results. Regressions that control for the number of licenses confirm that the full effects of licensing materialized in the early 1930s, although effects were statistically significant as early as 1927. In the 1930s, an additional license increased domestic patents by up to 0.213 patents per year (Figure 8). Regressions that control for the novelty of licensed patents confirm that the strongest effects of

[20] For patents in our data, grants occur with a three year lag. See the data section for a detailed description.

[21] The quick re-entry of German firms into the U.S. market, which dealt a powerful blow to U.S. production (Arora and Rosenberg 1998, p.78, Haynes 1945, p.521), may also have contributed to this delay.

licensing occurred in the early 1930s, although less precisely estimated treatment effects are observable by 1928 (Figure 9).[22]

*C. Triple Differences and Placebo "Treatment" for French Inventors*

Triple difference regressions, which compare changes in patenting by domestic inventors with changes in patenting by all other non-German inventors allow us to control for unobservable heterogeneity across subclasses, such as the temporary absence of German competitors, which may have encouraged patenting by all non-German inventors, regardless of the TWEA.

$$Patents_{n,c,t} = \alpha_0 + \alpha_3 USA_n + \alpha_4 TREAT_c \cdot YEARpostTWEA_t + \alpha_5 USA_n \cdot TREAT_c + \alpha_6 USA_n \cdot YEARpostTWEA_t + \beta_t \cdot USA_n \cdot TREAT_c \cdot YEARpostTWEA_t + \delta_t + f_c + \varepsilon_{c,t}$$

Triple difference estimates confirm that licensing encouraged patenting by U.S inventors, even relative to other non-German inventors. In treated subclasses, domestic inventors produced an additional 0.065 patents per year after 1919 compared with other non-German inventors (significant at 10 percent), which implies a 10 percent increase. The timing of effects also closely matches the results from our basic specifications. Beginning in 1933, domestic inventors produced an additional 0.123 to 0.449 patents per year in treated subclasses (Figure 10, significant at 1 percent), which implies an 18 to 66 percent increase. The true effects of compulsory licensing may be even higher, because the control includes a large number of British inventors who were affected by their own version of the TWEA.[23] Triple difference regressions that account for the intensity of treatment (not reported) further strengthen these results.

An alternative (Placebo) test allows French inventors, who could not license patents under the TWEA, to benefit from the TWEA.[24] It estimates

[22] We also estimate regressions with both binary and intensity-adjusted measures of treatment. For example, we estimate $Patents\ by\ U.S.\ inventors_{c,t} = \alpha_0 + \beta \cdot TREAT_c \cdot postTWEA_t + \xi\ Number\ of\ licenses_c \cdot YEARpostTWEA_t + \gamma \cdot Z_{c,t} + \delta_t + f_c + \varepsilon_{c,t}$, which confirms the results in Figures 8 and 9.

[23] In September 1914, the House of Commons passed an Act forbidding all transactions "that would improve the financial or commercial position of a person trading or residing in an enemy country" (*House of Commons Debate 08 August 1916 vol. 85 column 871*). In parallel with the TWEA, the British Act was extended in 1919 to allow for compulsory licensing. The amended Act required "the Comptroller to grant a compulsory license under a food or medicine patent to anyone who seemed competent to work the invention" (Davenport 1979, p.81). We include British inventors in the triple difference control to be conservative.

[24] Exactly 3,000 of the 164,500 U.S. patents in our data were granted to French inventors.

$$\textit{Patents by French inventors}_{c,t} = \alpha_0 + \beta_t \cdot TREAT_c \cdot YEARpostTWEA_t + \gamma \cdot Z_{c,t} + \delta_t + f_c + \varepsilon_{c,t}$$

Results from this counterfactual regression reveal no measurable changes in annual patents by French inventors for treated subclasses (Figure 11), confirming that the effects of the TWEA were limited to U.S. firms.

*E. Intent to Treat and Instrumental Variables*

To test for bias based on selection into treatment, we estimate ITT regressions where "treatment" is defined as the number of enemy patents that were available for licensing under the TWEA.

$$\textit{Patents by U.S. inventors}_{c,t} = \alpha_0 + \beta \cdot \textit{Enemy patents}_c \cdot postTWEA_t + \gamma \cdot Z_{c,t} + \delta_t + f_c + \varepsilon_{c,t}$$

Results from this regression confirm the findings of OLS: Each additional enemy patent that was available for licensing increased the number of domestic patents per year by 0.054 (Table 3, column 1, significant at 1 percent), implying an 8 percent increase for each additional patent. Similarly, each additional year of patent life increased the number of domestic patents by 0.006 (Table 3, column 3, significant at 1 percent) implying a 0.9 percent increase for each additional year of patent life. These estimates are only slightly smaller than OLS (0.062 for an additional license and 0.006 for an additional year of patent life), suggesting that selection bias may lead OLS to under- rather than overestimate the true effects of licensing.[25]

IV regressions with *enemy patents* as an instrument for *licensed patents* confirm that OLS estimates are downward biased. In IV regressions, an additional license adds 0.332 domestic patents per year, while an additional year of patent life adds 0.025 domestic patents (Table 4, columns 3-4, significant at 1 percent).[26]

## V. Robustness checks

[25] For binary treatment variables, ITT = TOT * P(treatment), where TOT represents unbiased estimates of treatment on the treated (Angrist and Imbens 1995, Wooldridge 2002, p.636). Here P(treatment) equals 335/1341 (subclasses where U.S. firms licensed enemy patents/ subclasses where enemy patents were available for licensing), implying that unbiased TOT estimates would be 0.273 * 226/1,341= 1.089. Because estimating binary treatment variables may yield inflated IV estimates if the "real" treatment is continuous (Angrist, Imbens, and Rubin 1996), we perform IV and ITT with continuous treatment variables.

[26] For a binary ITT variable that is uncorrelated with the error term in the second stage of the IV regression, the IV coefficient consistently estimates TOT as TOT= ITT/P(treatment). In our data, this implies TOT= 0.0714/0.215= 0.322= IV. A Hausman specification test rejects consistency for OLS estimates at the 1 percent level under the assumption that IV estimates are consistent.

This section presents a series of robustness checks, including controls for pre-existing time trends in patenting, broader class-specific effects, placebo treatments to control for random correlation in explanatory variables, and changes in the USPTO classification system.

*A. Controlling for Pre-Existing Time Trends*

One potential problem with difference-in-differences is that it may confound the dynamic effects of compulsory licensing with pre-existing differences in time trends across treated and untreated subclasses. In other words, subclasses that were affected by compulsory licensing may have experienced an increase in domestic patenting after the TWEA due to differences in time trends that *preceded* the TWEA. To address this issue, we extend our regressions to include a linear time trend for all treated subclasses for the pre-TWEA period:

$$\textit{Patents by U.S. inventors}_{c,t} = \alpha_0 + \beta_t \cdot TREAT_c \cdot YEARpostTWEA_t + \gamma \cdot Z_{c,t} + \delta_t + f_c + \phi \cdot TREAT_c \cdot t + \varepsilon_{c,t}$$

where $\beta_t$ measures treatment effects in year $t$ and $\delta_t$ captures year fixed effect controlling for a pre-existing time trend $\phi \cdot TREAT_c \cdot t$. Results of this regression confirm that patenting by domestic inventors increased significantly more for treated than for untreated subclasses after the TWEA, even controlling for pre-existing time trends (Figure 12).[27]

An alternative test controls for *subclass*-specific linear and quadratic time trends:

$$\textit{Patents by U.S. inventors}_{c,t} = \alpha_0 + \beta_t \cdot TREAT_c \cdot YEARpostTWEA_t + \gamma Z_{c,t} + \delta_t + f_c + \phi_{1c} \cdot t + \phi_{2c} \cdot t^2 + \varepsilon_{c,t}$$

In these regressions (not reported) treatment effects are also positive and statistically significant, further strengthening the results.[28]

*B. Controlling for Time Trends at the Level of Main Classes*

[27] Regressions with quadratic time trends yield larger standard errors but nearly identical coefficients $\beta_t$.

[28] To limit the number of parameters, we restrict the sample to 776 subclasses for the two classes with the largest number of licenses (8:bleaching and dyeing and 534:organic compounds containing a noble gas).
An equivalent regression on the entire sample would require estimating 8,422 subclass fixed effects, 8,422 linear time trends, and 8,422 quadratic time trends in addition to treatment variables and controls.

As an alternative way to account for the potential of differential growth paths across treated and untreated subclasses, we include interaction terms between year dummies and each of the broader 21 USPTO main classes.

$$\textit{Patents by U.S. inventors}_{c,t} = \alpha_0 + \beta_t \cdot TREAT_c \cdot postTWEA_t + \gamma \cdot Z_{c,t} + \delta_t + f_c + \lambda_{mt} Year_t \cdot Class_c + \varepsilon_{c,t}$$

where $\lambda_{mt}$ represents a fixed effect for USPTO class *m* and year *t*. Due to the large number of variables and interaction terms, computational constraints only allow us to estimate this regression for a 10 percent random sample of the data. Results from this sample, however, indicate that estimates are robust to controlling for class-specific time trends (Table 5).[29]

*C. Placebo Treatments*

We also perform more general placebo regressions to check whether our results might be driven by random correlation between explanatory variables other than the treatment. Specifically, we create a placebo treatment where the same share of subclasses (4 percent) is randomly assigned to treatment and re-estimate the most basic regression 50 times. These tests indicate that random correlation across explanatory variables cannot explain the estimated effects; the hypothesis that the placebo treatment is significant is rejected for 45 of 50 placebos at the 5 percent level (Table 6).

*D. Dropping Newly-Created Subclasses and Secondary Subclasses*

Two additional tests address potential problems with the USPTO classification system. Most importantly, we account for the fact that the USPTO periodically adds new subclasses to accommodate new areas of invention. In our data 2,737 new subclasses were added after 1919. Because domestic inventors could not patent in these subclasses prior to 1919, patenting increases mechanically in new subclasses after 1919, which may lead us to underestimate the true effects of licensing.

[29] We also estimate regressions separately for all 21 main classes; class-specific regressions confirm that domestic patenting increased in treated subclasses after the TWEA. In two of four classes with more than 20 licenses treatment effects were strongest in the late 1920s (8:bleaching and dyeing and 552:azides); in the two other classes with more than 20 licenses treatment effects were strongest in the early 1930s (534:organic compounds containing a noble gas and 548:organic compounds containing 5-membered hetero rings).

Regressions with a restricted sample of pre-existing subclasses confirm that including newly-created subclasses lead us to underestimate the true effects of licensing. In subclasses that received at least one license under the TWEA domestic inventors produced 0.190 additional patents per year (Table 7, column 2 significant at 1 percent). Compared with a mean of 0.310 patents per subclass and year in the restricted sample this implies a 61 percent increase in domestic invention. Regressions that control for the intensity of treatment further strengthen these results. Each additional license increases domestic patents by 0.078 per year (Table 7, column 5, significant at 1 percent), and each additional year of patent life increased domestic patents by 0.007 per year (Table 7, column 8, significant at 1 percent).

This increase in estimated effects may be due to the fact that U.S. inventors were lagging behind for much of the period and less able to generate inventions in new fields without access to foreign technologies. U.S. chemists E.F. Hitch and I.E. Knapp concede

> "No matter how much we may dislike to be followers and not pioneers, we must, in the first few years, confine our efforts in this field largely to the manufacture of colors that have already been produced by foreign manufacturers" (cited in Hounshell and Smith 1988, p.90)

Another potential concern is that the USPTO assigns patents to several secondary subclasses (in addition to primary subclasses) to cross-reference related technologies. Our analysis includes secondary subclasses because they are affected by compulsory licensing. Their inclusion may, however, give too much weight to patents that were assigned to many subclasses. For example, 25 percent of patents in our data where assigned to at least four secondary subclasses. To address this issue, we restrict the sample to the 6,740 primary subclasses in the data.

Regressions for the restricted sample confirm results from the full sample. In primary subclasses that received at least one license under the TWEA, domestic inventors produced 0.031 additional patents per year after 1919 (Table 8, column 1). This implies a 17 percent increase in patenting compared with an average of 0.183 of patents per year and primary subclass after 1919. Controlling for the intensity of treatment further strengthens these results: Each additional license increased domestic patents by 0.025 per year, and each additional year of patent life increased domestic patents by 0.002 patents (Table 8, columns 2-3, significant at 1 percent).

*F. Treatment Effects within Indigo*

A final robustness check measures treatment effects within a specific group of chemicals - indigo dyes - which were disproportionately affected by increases in tariffs and the demand for domestic production. In 1914, 90 percent of the U.S. demand for indigo was imported from Germany. In 1915, Britain's naval blockade cut U.S. markets off from German imports so effectively, that the last shipment of German dyes arrived in March 1915 (Haber 1971, p.185). At the same time, the United States' entry into the war increased demand for domestically produced indigo to create the blue shade of Navy uniforms (e.g., Navy Department 1917). To encourage domestic production, Congress established a five-year tariff barrier in September 1916 (Aftalion 1991, pp.123-124).[30] As a result, the price of indigo rose from 20 cents per pound in 1914 to nearly 70 cents in 1917. While prices for other dyes recovered quickly to their pre-war levels, indigo remained expensive at 40 cents in 1919, double its pre-war (Appendix Figures A2 and A3, Haynes 1945, p. 231).[31]

This relatively persistent price increase may have encouraged innovation; if such innovation occurred disproportionately in treated subclasses, it will lead us to over-estimate the true effects of licensing. Then, treatment effects within indigo should be much smaller than treatment effects for the full sample, because indigo was more affected by the demand shock than were other chemicals.

Regressions within a restricted sample of indigo patents, however, confirm that licensing encouraged domestic inventions. In treated subclasses domestic inventors produced 0.027 additional patents per year and subclass (Table 9, column 2, significant at 1 percent). Compared with an average of 0.684 patents per subclass and year, this implies a 4 percent increase in domestic patenting within indigo, roughly comparable to the effects in the overall sample. Regressions that control for the intensity of treatment confirm these effects (Table 9, columns 1-

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[30] Tariff protection continued throughout the 1920s and 1930s. In 1922 the Fordney McCumber Act imposed ad valorem tariffs of nearly 30 percent on chemical imports; it covered indigo, alizarin and vat dyes. In 1930, the Smoot Hawley Act raised tariff rates to 36 percent (U.S. Tariff Commission 1930, p.196, Eichengreen 1989, Irwin 1998).

[31] Another reason to examine indigo separately is that indigo was subject to a technology sharing agreement, which may have transferred knowledge of German production processes to U.S. firms. In November 1916, the British chemical firm Herbert Levinstein agreed to share with Du Pont its secrets of producing synthetic indigo dyes, which included knowledge that Levinstein had acquired when it purchased a confiscated British plant of the German company Hoechst (Hounshell and Smith 1988, pp.81-85). Historical records, however, suggest that Du Pont wrestled with the problem of producing indigo for several years and succeeded "only after long experimentation" (Haynes 1945, p.245). In addition to the within indigo test we also restrict the sample to non-Du Pont firms, which leaves results qualitatively unchanged.

3). The timing of effects also closely mirrors the effects in the overall sample. Annual treatment effects become stable and statistically significant in 1931 though there are some statistically significant effects as early as 1928 (Figure 13).

**VI. Firm-level analysis**

As a final test, we analyze firm-level data for Du Pont de Nemours & Co. to shed some light on the mechanisms by which compulsory licensing encouraged domestic invention.[32] Keeping in mind that our identification strategy is much weaker at the firm level, we compare the effects of Du Pont's own licenses with the effects of licenses that were issued to other U.S. firms. Licenses that were issued to Du Pont created learning opportunities for Du Pont, while licenses to other firms benefitted the U.S. industry more broadly. For example, other licenses may capture changes in incentives to invest in skills and education or knowledge spillovers across firms.

$$Du\ Pont\ Patents_{c,t} = \alpha_0 + \beta_1 \cdot TREATDuPont_c \cdot postTWEA_t + \beta_2 \cdot TREATotherFirms_c \cdot postTWEA_t + \gamma \cdot Z_{c,t} + \delta_t + f_c + \varepsilon_{c,t}$$

Firm-level regressions indicate that both own and other firms' licenses encouraged patenting, though own licenses had substantially stronger effects. In subclasses where DuPont received a license under the TWEA, the company's annual patents increased by 0.094 to 0.098 patents after 1919 (Table 10, columns 1-2, significant at 1 percent). In subclasses where other U.S. firm received a license, Du Pont's annual patents increased by 0.021 to 0.025 patents roughly one third this effect (Table 10, columns 1-2).

Although these results are subject to selection bias, which may lead us to over-estimate the own-license effects, they match up closely with empirical estimates on learning-by-doing and knowledge spillovers in the late 20th-century. Such estimates suggest that firms benefit about three times as much from own production than from production of other U.S. firms (Irwin and Klenow 1994).

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[32] The data for this firm-level analysis consist of all 234 licenses and 1,618 chemical patents that were granted to Du Pont between 1875 and 1939. We identify these patents by searching Lexis Nexis for all known variants of the company's name, including E. I. Du Pont de Nemours & Co., Du Pont Ammonia Corp., Du Pont Cellophane Co, Du Pont Everdur Co, Du Pont Fibersilk Co, Du Pont Film & Picture Co, and Du Pont Rayon Co. This search yields a total of 3,571 patents in 241 classes and 5,716 subclasses; 1,618 of these patents are in one of the 21 classes that were affected by the TWEA.

Controlling for the intensity of treatment further strengthens these results. An additional license granted to Du Pont increased Du Pont's patents per year by 0.051, compared to an effect of 0.014 for other firm's licenses (Table 10, column 3). Again, both effects are significant, but the effects of a firm's own licenses are about four times larger. Regressions that control for the novelty of patents further strengthen these results (Table 10, columns 5-6). For all regressions, Wald tests reject the hypothesis that treatment effects of own and other licenses are equal at 0.01 percent significance. Estimates of annual treatment effects confirm results at the industry level. The most significant effects of licensing set in around 1933, although effects set in as early as 1927 (Figure 14, significant at 5 percent). In terms of patent application, this implies that the full effects of licensing on set in 3 to 9 years after most licenses had been granted.

**VI. Conclusions**

This paper has used the TWEA as a natural experiment to examine whether compulsory licensing encourages invention by nationals in nascent industries. Data on chemical patents by U.S. inventors after the TWEA indicate that compulsory licensing has a strong and persistent positive effect on domestic invention. In USPTO subclasses, where at least one enemy-owned patent was licensed to a domestic firm under the TWEA, domestic patenting increased by about 20 percent after the TWEA (compared with subclasses that were not affected). These results are robust to controlling for the intensity of treatment by accounting for the number of licenses that were granted and by accounting for the novelty of licensed patents. Results are also robust to a variety of alternative tests, including triple differences (comparing changes in the number of patents by U.S. inventors before and after the TWEA with changes in the number of patents by other, non-German inventors), controls for subclass- and treatment-specific time trends, and placebo tests for other non-German inventors.[33] Intent-to-treat and instrumental variable regressions further suggest that the analysis may under-, rather than over-estimate the true effects of licensing.

[33] Even without any effects on innovation, compulsory licensing may create significant positive welfare effects on consumers in developing countries as a mechanism to maintain product variety. For example, welfare losses of extending patent protection to pharmaceuticals on Indian consumer have been shown to be substantially smaller under policies, such as compulsory licensing, that maintain product variety (Chaudhuri, Goldberg, and Jia 2006). As a mechanism to address anti-competitive patenting behavior in domestic markets, compulsory licensing is expected to increase overall welfare by encouraging the optimal trade-off between incentives for R&D and the dead weight loss of long-lived patents (Tandon 1982, Gilbert and Shapiro 1990).

The long-term nature of the data also allows us to examine the timing of such effects. Estimates of annual treatment effects indicate that the strongest effects of licensing set in around 1929 (measured in terms of patent applications) and persisted throughout the 1930s. These findings are consistent with evidence in aggregate data that total factor productivity increased during this period and that innovations that were developed between 1929 and 1941 set the stage for advances in productivity growth throughout the 1950s and 1960s (Field 2003). They are also mirrored in changing patterns of scientific citations (e.g., Thackeray et al. 1985, pp. 405-407), which indicate that the U.S. chemical industry gained prominence as an originator of knowledge in the 1930s.[34]

In addition the gradual nature of estimated effects, results from firm-level analyses suggest that learning-by-doing played an important role in encouraging domestic invention. After a painful period of experimentation, the U.S. firms benefitted from the ability to produce foreign inventions and were able to develop their own innovative capacity. Thus, measured effects of firm's own licenses are around three times larger than the effects of licenses that were granted to other U.S. firms (which may capture knowledge spillovers as well as more general effects, such as changes in incentives to invest in education).

Although our analysis falls short of estimating the overall welfare effects of compulsory licensing on innovation, it is interesting to note that the development of the U.S. chemical industry after the TWEA closely mirrors recent experiences with compulsory licensing. India, for example, permitted compulsory licensing for pharmaceuticals under its Patent Act of 1970. Under this Act, domestic firms had been able to produce generic versions of foreign-owned pharmaceuticals until January 1, 2005, when India complied with the WTO requirements to respect foreign patents. Although there has been no systematic study of the effects of compulsory licensing in India, anecdotal evidence is suggestive. Today, India ranks fourth in the production of pharmaceuticals and is the world's leading supplier of generic medicines, with two thirds of its exports going to developing countries.

To estimate the welfare effects of compulsory licensing, future projects should examine the incentive effects of compulsory licensing on invention in countries whose property rights are violated. The recent experience of the U.S. chemical industry in reaction to compulsory

[34] Based on citations in the top seven U.S. journals and the German journal *Chemische Berichte*.

licensing provisions in India and more recently under TRIPS offers a promising setting for such analyses.

Finally, the difficult learning process that U.S. firm experienced after the TWEA suggest that human capital and tacit knowledge are essential in facilitating rapid technology transfers across countries. World War II provides an opportunity to measure these effects: On April 7th 1933, Adolf Hitler's "Law for the Restoration of the Professional Civil Service" led to the dismissal of 1,100 scientists from German universities (Hartshorne 1937). Many of these scientists moved to the United States in the mid 1930s, several years after compulsory licensing had helped to jump-start the organic chemical industry. Their contributions to U.S. invention deserve further study.[35]

## REFERENCES


Aftalion, F., 1991. A History of the International Chemical Industry, O. Benfey. Trans. Philadelpia, Univeristy of Pennsylvania Press.

Alien Property Custodian. 1919. *A detailed report by the Alien Property Custodian of all proceedings had by him under the Trading with the Enemy Act during the calendar year 1918 and to the close of business on February 15, 1919.* Washington: Government Printing Office.

Angrist, Joshua, and Guido Imbens. 1995. "Two-Stage Least Squares Estimation of Average Causal Effects in Models with Variable Treatment Intensity." *Journal of the American Statistical Associations*, 90(430): 431-442.

Angrist, Joshua, Guido Imbens, and Donald Rubin. 1996. "Identification of Causal Effects Using Instrumental Variables." *Journal of Econometrics*, 71(1-2): 145-160

Arrow, Kenneth. 1962. "The Economic Implications of Learning by Doing." *Review of Economic Studies*, 29(3): 155-173.

Bertrand, Marianne, Esther Duflo, and Sendhil Mullainathan. 2004. "How Much Should We Trust Differences-in-Differences Estimates?" *Quarterly Journal of Economics*, 119(1): 249-275.

Chaudhuri, Shubham, Pinelopi K. Goldberg, and Panle Jia. 2006. "Estimating the Effects of Global Patent Protection in Pharmaceuticals: A Case Study of Quinolones in India." *American Economic Review*, 96(5): 1477–1514.

Chien, Colleen. 2003. "Cheap Drugs at What Price to Innovation: Does the Compulsory Licensing of Pharmaceuticals Hurt Innovation?" *Berkeley Technology Law Journal*


[35] Between 1933 and 1939, 129 scientists were dismissed from German universities (Deichman, 2001, pp.118-125). We have been able to collect emigration and employment histories for 62 of them from Strauss (1983); 32 eventually arrived in the United States, 5 as early as 1933, and another 16 throughout the 1930s.

Davenport, A. Neil. 1979. *The United Kingdom Patent System*, Homewell, UK: Kenneth Mason

Deichmann, Ute. 2001. *Flüchten, Mitmachen, Vergessen. Chemiker und Biochemiker im Nationalsozialismus*, Weinheim: Wiley.

Delamare François and Bernard Guineau. 1999. *Colors – The Story of Dyes and Pigments.* Harry N. Adams Inc.

Eichengreen, Barry. 1989. "The Political Economy of the Smoot-Hawley Tariff." *Research in Economic History*, 12: 1-43.

Field, Alexander. 2003. "The Most Technologically Progressive Decade of the Twentieth Century." *American Economic Review*, 93(4): 1399-1413.

Galvão, J. 2002. "Access to Antiretroviral Drugs in Brazil." *The Lancet,* 360(9348): 1862-1865.

Gilbert, Richard, and Carl Shapiro. 1990. "Optimal Patent Length and Breadth." *RAND Journal of Economics*, 21(1): 106-112.

Gostin, Lawrence O. 2006. "Medical Countermeasures for Pandemic Influenza: Ethics and the Law." *Journal of the American Medical Association*, 295(5): 554-556.

Haber, Ludwig Fritz. 1971. *The Chemical Industry, 1900-1930: International Growth and Technological Change*. Oxford: Clarendon Press

Hall, Bronwyn H., Adam B. Jaffe, and Manuel Tratjenberg. 2001. "The NBER Patent Citation Data File: Lessons, Insights and Methodological Tools." *NBER Working Paper* 8498.

Hartshorne, Edward Yarnall. 1937. *The German Universities and National Socialism*. Cambridge: Harvard University Press

Haynes, Williams. 1945. *American Chemical Industry – The World War I Period 1912-1922*. Vol.3. New York: D. Van Nostrand Company.

Imbens, Guido W. and Jeffrey M. Wooldridge . 2009. "Recent Developments in the Econometrics of Program Evaluation."*Journal of Economic Literature*, 47(1): 5-86

Irwin, Douglas. 1998. "The Smoot-Hawley Tariff: A Quantitative Assessment." *Review of Economics and Statistics,* 80(2): 326–334.

Irwin, Douglas A and Klenow, Peter J. 1994. "Learning-by-Doing Spillovers in the Semiconductor Industry." *Journal of Political Economy*, 102(6): 1200-1227.

Kremer, Michael. 2002. "Pharmaceuticals and the Developing World." *Journal of Economic Perspectives,* 16(4): 67-90.

Landau, Ralph and Rosenberg, Nathan. 1992. "Successful Commercialization in the Chemical Process Industries." In *Technology and the Wealth of Nations*, ed. N. Rosenberg, R. Landau, and D. C. Mowery, 73-120. Stanford: Stanford University Press.

Lerner, Joshua. 1995. "Patenting in the Shadow of Competitors." *Journal of Law and Economics,* 38(2): 463-495.

*Lexis Nexis Chronological Patent Files, 1790-1970*. Available at www.lexisnexis.com

Moser, Petra. 2009. "Why Don't Inventors Patent?" Available at http://ssrn.com/abstract=930241

Mowery, David C. and Nathan Rosenberg. 1998. *Paths of Innovation. Technological Change in 20th-century America*. Cambridge: University Press.

Navy Department. 1917. *Uniform Regulations, United States Navy, Together with Regulations Together with Regulations Common to both Navy and Marine Corps*, Washington, DC: Government Printing Office

Popp, David, Ted Juhl and Daniel Johnson. 2004."Time in Purgatory: Examining the Grant Lag for U.S. Patent Applications." *Topics in Economic Analysis & Policy*, 4(1): Article 29.

Rubin, Donald B. 1990. "Formal Modes of Statistical Inference for Causal Effects." *Journal of Statistical Planning and Inference*, 25: 279-292.

Steen, Kathryn. 2001. "Patents, Patriotism, and 'Skilled in the Art' USA v. The Chemical Foundation, Inc., 1923-1926." *Isis*, 92(1): 91-122.

Steinbrook, Robert. 2007. "Thailand and the Compulsory Licensing of Efavirenz." *New England Journal of Medicine*, 356(7): 544-546.

Stokey, Nancy L. 1988. "Learning by Doing and the Introduction of New Goods." *The Journal of Political Economy*, 96(4): 701-717.

Strauss, Herbert A, ed. 1983. *International Biographical Dictionary of Central European Emigrés 1933-1945*. Vol. 2, *The Arts, Sciences, and Literature*. New York: Research Foundation for Jewish Immigration

Thackeray, Arnold, Jeffrey L. Sturchio, P.Thomas Carroll and Robert Bud. 1985. *Chemistry in America, 1876-1976*. Reidler Publishing Company: p.564.

Tandon, Pankaj. 1982. "Optimal Patents with Compulsory Licensing." *Journal of Political Economy* 90(3): 470-486.

United States Tariff Commission, "Census of Dyes and Coal-tar Chemicals", several years, *Tariff Information Series No.11*, Government Printing Office, Washington, 1918-1923.

U.S. Tariff Commission, *The Tariff Review*, July 1930, Government Printing Office, Washington, 1918-1923.

Williamson, Samuel H. 2008. "Five Ways to Compute the Relative Value of a U.S. Dollar Amount, 1790 to Present." *MeasuringWorth*

Wooldridge Jeffrey. 2002. *Econometric Analysis of Cross Section and Panel Data*. Cambridge: The MIT Press.

World Trade Organization. 2001. *Ministerial Declaration*, November, 20,WT/MIN(01)/DEC/1.

TABLE 1 – HAND-COLLECTED VERSUS ALGORITHM-ASSIGNED NATIONALITIES

| **Inventor Nationality** | **Hand-collected** | **Algorithm-assigned** |
|---|---|---|
| United States | 241 | 290 |
| German | 226 | 197 |
| Other foreign | 159 | 138 |
| Total | 625 | 625 |

*Note*: Data from Haynes (1939), www.uspto.gov, the *Lexis Nexis Chronological Patent Files (1790-1970)* and www.google.com/patents. To collect data on inventor nationality, we create an algorithm that performs keyword searches on *LexisNexis*. This algorithm relies on Optical Character Recognition (OCR), which is worse at recognizing misspelled names or untidy script than the human eye. To check for measurement error, we hand-collected an alternative data set that includes all 625 patents for the most important dyes of the early 20$^{th}$-century (Delamare and Guineau, 1999): alizarin, indigo, azo dyes, and aniline. In the hand-collected sample, inventors come from Argentina, Australia, Austria, Belgium, Brazil, China, England, France, Germany, India, Italy, the Netherlands, Russia, Scotland, Spain, Switzerland, and the United States.

TABLE 2 – OLS REGRESSIONS, DEPENDENT VARIABLE IS PATENTS BY U.S. INVENTORS PER USPTO SUBCLASS AND YEAR (1875-1939)

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|---|
| Subclass has at least one license | 0.144*** | 0.118*** | 0.234*** | | | | | | |
| | (0.040) | (0.039) | (0.042) | | | | | | |
| Number of licenses | | | | 0.088*** | 0.062*** | 0.111*** | | | |
| | | | | (0.026) | (0.018) | (0.024) | | | |
| Number of licenses squared | | | | -0.005** | | | | | |
| | | | | (0.002) | | | | | |
| Remaining lifetime of licensed patents | | | | | | | 0.007*** | 0.006*** | 0.009*** |
| | | | | | | | (0.002) | (0.002) | (0.002) |
| Remaining lifetime of licensed patents squared (*100) | | | | | | | -0.002 | | |
| | | | | | | | (0.002) | | |
| Number of patents by foreign inventors (t-2) | 0.301*** | | | | | | | | |
| | (0.018) | | | | | | | | |
| Number of patents by foreign inventors | | 0.322*** | | 0.321*** | 0.322*** | | 0.321*** | 0.321*** | |
| | | (0.020) | | (0.020) | (0.020) | | (0.020) | (0.020) | |
| Subclass fixed effects | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Year fixed effects | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Observations | 530,587 | 547,430 | 547,430 | 547,430 | 547,430 | 547,430 | 547,430 | 547,430 | 547,430 |
| Number of subclasses | 8,422 | 8,422 | 8,422 | 8,422 | 8,422 | 8,422 | 8,422 | 8,422 | 8,422 |

Robust standard errors clustered at the subclass level in parentheses

*** p<0.01, ** p<0.05, * p<0.1

*Note*: Data from www.uspto.gov and the *Lexis Nexis Chronological Patent Files (1790-1970)*. Our data consist of all 165,400 patents between 1875 and 1939 in 21 USPTO main classes that contained at least one licensed enemy dyestuff patent. These 21 main classes are subdivided into 8,422 subclasses. Data on inventor nationality are based on a key word search for country names in *Lexis Nexis*. Regressions that include a two year lag for number of patents by foreign inventors drop the first two years of data.

TABLE 3– INTENT TO TREAT REGRESSIONS
DEPENDENT VARIABLE IS PATENTS BY U.S. INVENTORS PER USPTO SUBCLASS AND YEAR

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| Number of enemy patents | 0.054*** | 0.071*** | | |
| | (0.007) | (0.009) | | |
| Remaining lifetime of enemy patents | | | 0.006*** | 0.009*** |
| | | | (0.001) | (0.001) |
| Number of patents by foreign inventors | 0.317*** | | 0.317*** | |
| | (0.019) | | (0.019) | |
| Subclass fixed effects | Yes | Yes | Yes | Yes |
| Year fixed effects | Yes | Yes | Yes | Yes |
| Observations | 547,430 | 547,430 | 547,430 | 547,430 |
| Number of subclasses | 8,422 | 8,422 | 8,422 | 8,422 |

Robust standard errors clustered at the subclass level in parentheses
*** p<0.01, ** p<0.05, * p<0.1

*Note*: Data from www.uspto.gov and the *Lexis Nexis Chronological Patent Files (1790-1970*) consist of all 165,400 patents between 1875 and 1939 in 21 USPTO main classes that contained at least one licensed enemy dyestuff patent. These 21 main classes are subdivided into 8,422 subclasses.

TABLE 4 – INSTRUMENTAL VARIABLE REGRESSIONS,
DEPENDENT VARIABLE IS PATENTS BY U.S. INVENTORS PER USPTO SUBCLASS AND YEAR

| | First Stage | | Second Stage | |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| Number of enemy patents | 0.215*** | | | |
| | (0.000) | | | |
| Remaining lifetime of enemy patents | | 0.344*** | | |
| | | (0.001) | | |
| Number of licenses | | | 0.332*** | |
| | | | (0.010) | |
| Remaining lifetime of licensed patents | | | | 0.025*** |
| | | | | (0.001) |
| Subclass fixed effects | Yes | Yes | Yes | Yes |
| Year fixed effects | Yes | Yes | Yes | Yes |
| Observations | 547,430 | 547,430 | 547,430 | 547,430 |
| Number of subclasses | 8,422 | 8,422 | 8,422 | 8,422 |

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

*Note*: Data from www.uspto.gov and the *Lexis Nexis Chronological Patent Files (1790-1970*) consist of all 165,400 patents between 1875 and 1939 in 21 USPTO main classes that contained at least one licensed enemy dyestuff patent. These 21 main classes are subdivided into 8,422 subclasses.

TABLE 5 – OLS WITH INTERACTIONS BETWEEN USPTO MAIN CLASSES AND YEARS
DEPENDENT VARIABLE IS PATENTS BY U.S. INVENTORS PER USPTO SUBCLASS AND YEAR

| | (1) | (2) | (3) |
|---|---|---|---|
| Subclass has at least one license | 0.312** | | |
| | (0.134) | | |
| Number of licenses | | 0.132** | |
| | | (0.053) | |
| Remaining lifetime of licensed patents | | | 0.010** |
| | | | (0.004) |
| Number of patents by foreign inventors | 0.305*** | 0.303*** | 0.303*** |
| | (0.051) | (0.051) | (0.051) |
| Subclass fixed effects | Yes | Yes | Yes |
| Year fixed effects | Yes | Yes | Yes |
| Main class * year fixed effects | Yes | Yes | Yes |
| Observations | 54,795 | 54,795 | 54,795 |
| Number of subclasses | 843 | 843 | 843 |

Robust standard errors clustered at the subclass level in parentheses
*** p<0.01, ** p<0.05, * p<0.1

*Note*: Estimated for a 10 percent random sample of subclasses, stratified at the class level. In this sample, the average number of patents per year and subclass is 0.45.

TABLE 6 - OLS REGRESSIONS WITH PLACEBO TREATMENT

| DISTRIBUTION of the t-statistic | t-statistic |
|---|---|
| 5th percentile | -1.68 |
| Median | 0.10 |
| 95th percentile | 1.68 |
| | |
| SAMPLE REGRESSION: | |
| Placebo (randomly assigning 4% of subclasses to treatment) | -0.007 |
| | 0.014 |
| Number of patents by foreign inventors | 0.324*** |
| | (0.019) |
| Constant | 0.154*** |
| | (0.007) |
| Subclass fixed effects | Yes |
| Year fixed effects | Yes |
| Observations | 547,430 |
| Number of subclasses | 8,422 |

*Note:* The placebo randomly assigns the same share of subclasses that are treated under the TWEA (4 percent) to the treatment group..

TABLE 7 – OLS, RESTRICTING THE SAMPLE TO SUBCLASSES THAT EXISTED PRIOR TO THE TWEA
DEPENDENT VARIABLE IS PATENTS BY U.S. INVENTORS PER SUBCLASS AND YEAR

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|---|
| Subclass has at least one license | 0.206*** | 0.190*** | 0.276*** | | | | | | |
| | (0.052) | (0.052) | (0.055) | | | | | | |
| Number of licenses | | | | 0.145*** | 0.078*** | 0.111*** | | | |
| | | | | (0.032) | (0.025) | (0.030) | | | |
| Number of licenses squared | | | | -0.012*** | | | | | |
| | | | | (0.003) | | | | | |
| Remaining lifetime of licensed patents | | | | | | | 0.012*** | 0.007*** | 0.010*** |
| | | | | | | | (0.003) | (0.002) | (0.002) |
| Remaining lifetime of licensed patents squared (*100) | | | | | | | -0.008** | | |
| | | | | | | | (0.003) | | |
| Number of patents by foreign inventors (t-2) | 0.298*** | | | | | | | | |
| | (0.019) | | | | | | | | |
| Number of patents by foreign inventors | | 0.329*** | | 0.328*** | 0.329*** | | 0.328*** | 0.329*** | |
| | | (0.020) | | (0.020) | (0.020) | | (0.020) | (0.020) | |
| Subclass fixed effects | | | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Year fixed effects | | | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Observations | 283,450 | 283,450 | 283,450 | 283,450 | 283,450 | 283,450 | 283,450 | 283,450 | 283,450 |
| Number of subclasses | 5,685 | 5,685 | 5,685 | 5,685 | 5,685 | 5,685 | 5,685 | 5,685 | 5,685 |

Robust standard errors clustered at the subclass level in parentheses
*** p<0.01, ** p<0.05, * p<0.1

*Note*: Data from www.uspto.gov and the *Lexis Nexis Chronological Patent Files (1790-1970)*. Our data consist of all 165,400 patents between 1875 and 1939 in 21 USPTO main classes that contained at least one licensed enemy dyestuff patent. These 21 main classes are subdivided into 8,422 subclasses. Subclasses created after 1919 have been dropped and subclasses not yet created have been given a missing value in the years that preceded their creation. Regressions that include a two year lag drop the first two years of data.

TABLE 8 – OLS, RESTRICTING THE SAMPLE TO PRIMARY SUBCLASSES
DEPENDENT VARIABLE IS PATENTS BY U.S. INVENTORS PER SUBCLASS AND YEAR

| | (1) | (2) | (3) |
|---|---|---|---|
| Subclass has at least one license | 0.031*** | | |
| | (0.019) | | |
| Number of licenses | | 0.025*** | |
| | | (0.009) | |
| Remaining lifetime of licensed patents | | | 0.002*** |
| | | | (0.001) |
| Number of patents by foreign inventors | 0.188*** | 0.188*** | 0.188*** |
| | (0.015) | (0.015) | (0.015) |
| Subclass fixed effects | Yes | Yes | Yes |
| Year fixed effects | Yes | Yes | Yes |
| Main class * year fixed effects | No | No | No |
| Observations | 438,100 | 438,100 | 438,100 |
| Number of subclasses | 6,740 | 6,740 | 6,740 |

Robust standard errors clustered at the subclass level in parentheses
*** p<0.01, ** p<0.05, * p<0.1

*Note*: Data include all 7,513 primary subclasses in the 21 main classes treated by the TWEA. Primary subclasses in this sample include an average of 0.183 patents per year.

TABLE 9– OLS, RESTRICTING THE SAMPLE TO INDIGO PATENTS
DEPENDENT VARIABLE IS PATENTS BY U.S. INVENTORS PER SUBCLASS AND YEAR

| | (1) | (2) | (3) |
|---|---|---|---|
| Subclass has at least one license | 0.044*** | | |
| | (0.015) | | |
| Number of licenses | | 0.027*** | |
| | | (0.010) | |
| Remaining lifetime of licensed patents | | | 0.002*** |
| | | | (0.001) |
| Number of patents by foreign inventors | 0.004 | 0.004 | 0.004 |
| | (0.003) | (0.003) | (0.003) |
| Subclass fixed effects | Yes | Yes | Yes |
| Year fixed effects | Yes | Yes | Yes |
| Observations | 46,670 | 46,670 | 46,670 |
| Number of subclasses | 718 | 718 | 718 |

Robust standard errors clustered at the subclass level in parentheses
*** p<0.01, ** p<0.05, * p<0.1

*Note*: Data consist of all 843 patents in our data that contain the word "indigo." In the indigo sample, the average number of patents per subclass and year is 0.038.

TABLE 10 – OLS REGRESSIONS AT THE FIRM-LEVEL, DEPENDENT VARIABLE IS PATENTS BY DU PONT PER SUBCLASS AND YEAR

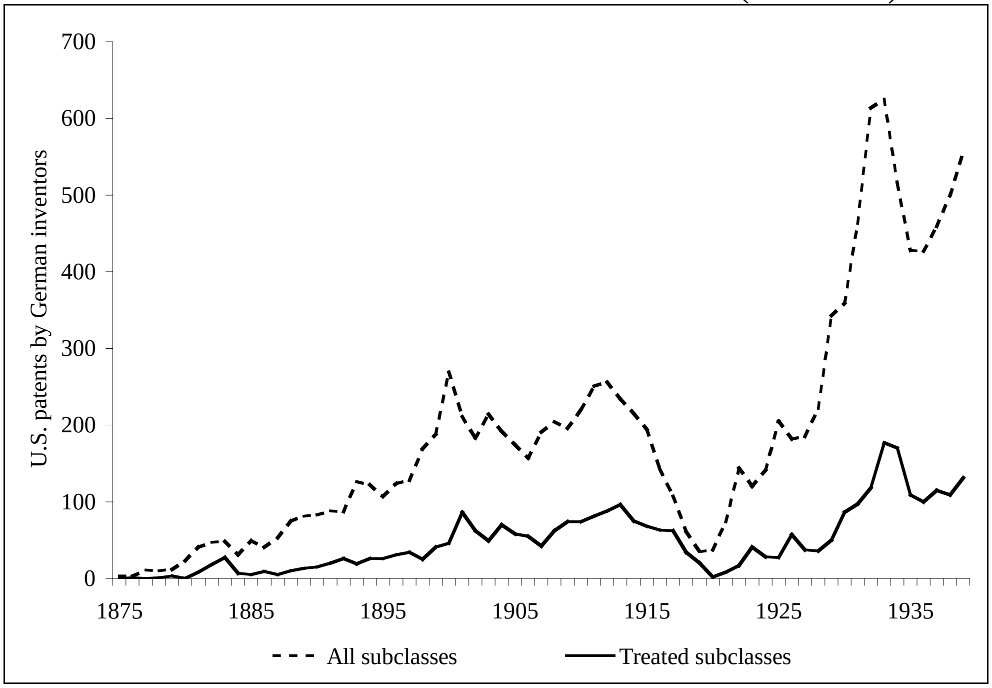
| | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| Subclass has at least one license to Du Pont | 0.094*** | 0.098*** | | | | |
| | (0.014) | (0.012) | | | | |
| Subclass has at least one license to other firms | 0.021 | 0.025*** | | | | |
| | (0.016) | (0.010) | | | | |
| Licenses to Du Pont | | | 0.051*** | 0.059*** | | |
| | | | (0.009) | (0.008) | | |
| Licenses to other U.S. firms | | | 0.014* | 0.009* | | |
| | | | (0.008) | (0.005) | | |
| Remaining lifetime of Du Pont licenses | | | | | 0.004*** | 0.004*** |
| | | | | | (0.001) | (0.001) |
| Remaining lifetime of other licenses | | | | | 0.001* | 0.001* |
| | | | | | (0.001) | (0.001) |
| Patents by foreign inventors | 0.030*** | | 0.030*** | | 0.029*** | |
| | (0.005) | | (0.005) | | (0.004) | |
| Subclass fixed effects | Yes | Yes | Yes | Yes | Yes | Yes |
| Year fixed effects | Yes | Yes | Yes | Yes | Yes | Yes |
| Observations | 72,694 | 222,924 | 72,694 | 222,924 | 72,694 | 222,924 |
| Number of subclasses | 1,913 | 5,716 | 1,913 | 5,716 | 1,913 | 5,716 |

Robust standard errors clustered at the subclass level in parentheses

*** p<0.01, ** p<0.05, * p<0.1

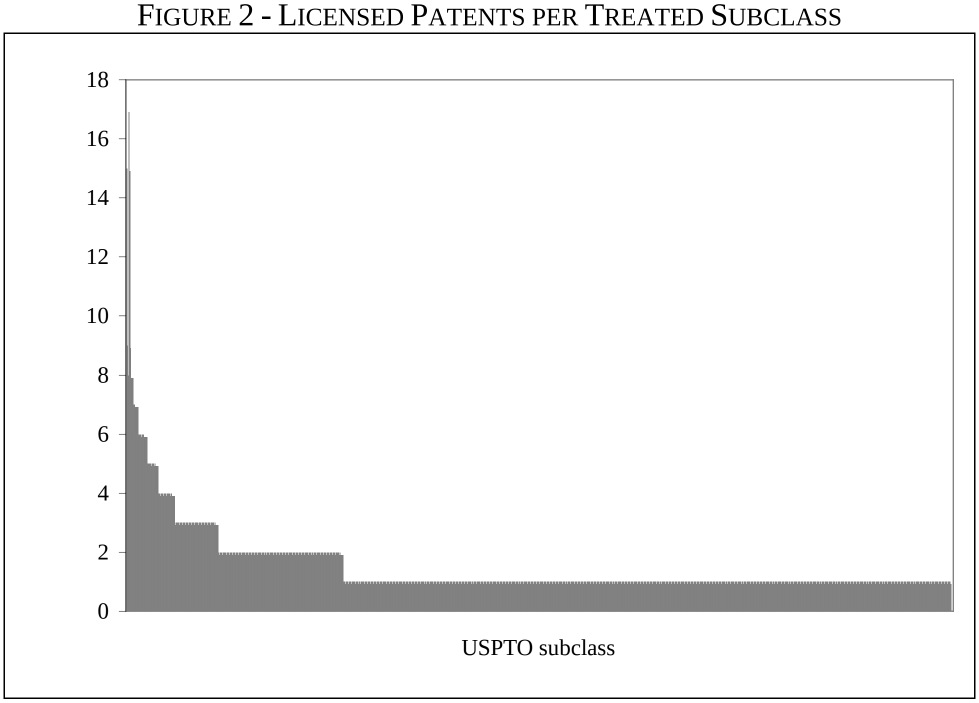
*Note*: The data consist of all 3,571 U.S. patent grants between 1875 and 1939 that include the word "Du Pont" or variations of the company's name. These patents cover a total of 5,716 subclasses; 1,618 of the 3,571 Du Pont patents belong to one of 21 treated USPTO main classes. Data on patents by foreign inventors are available for 1,913 subclasses.

FIGURE 1 – U.S. PATENTS BY GERMAN INVENTORS (1875-1939)



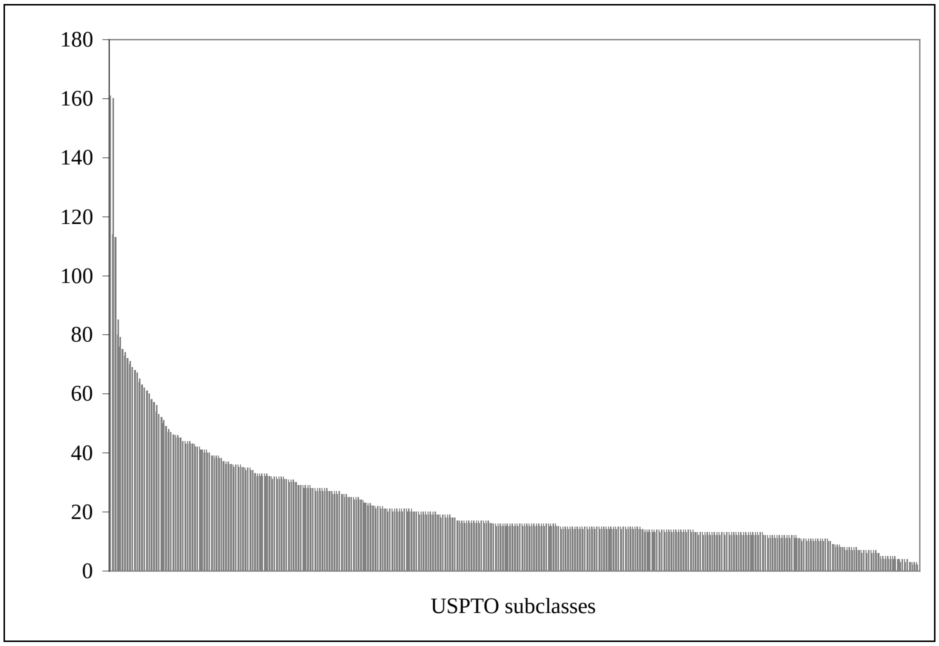

*Notes:* Data from www.uspto.gov and the *Lexis Nexis Chronological Patent Files (1790-1970)* include all 165,400 patents between 1875 and 1939 in 21 USPTO classes that received at least one license under the TWEA. These 21 main classes cover 8,422 subclasses, 335 of which are treated. Data on inventor nationality are based on a key word search for country names in *Lexis Nexis*.

FIGURE 2 - LICENSED PATENTS PER TREATED SUBCLASS



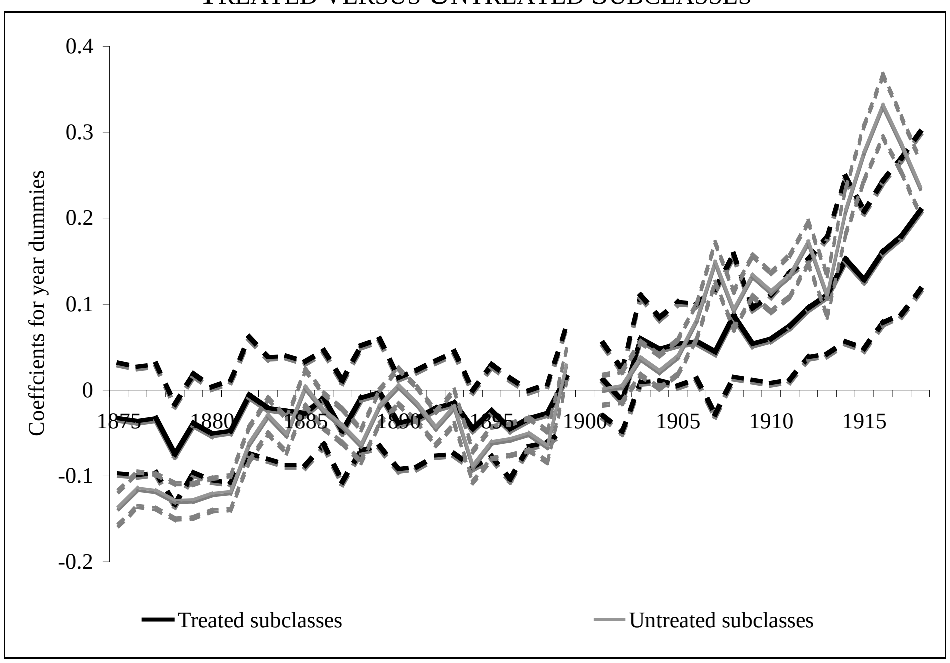

*Notes*: Data from Haynes (1945) and *www.uspto.gov*. The y-axis records the number of licensed patents in a treated subclass. Treated subclasses are defined as subclasses that received at least one license under the TWEA; 335 subclasses in our data where treated.

FIGURE 3 - REMAINING YEARS OF PATENT LIFE PER TREATED SUBCLASS



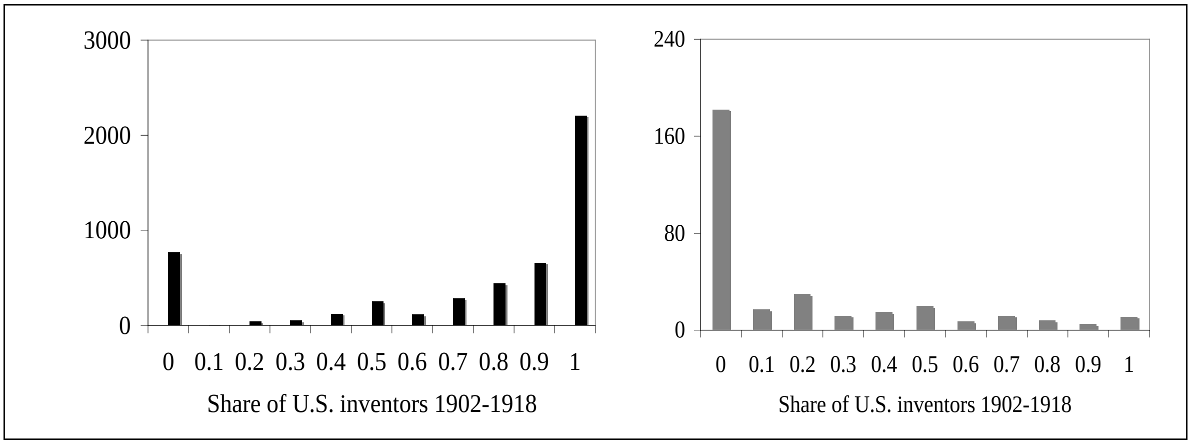

*Notes:* Data from Haynes (1945) and *www.uspto.gov*. The y-axis records the total years of remaining patent life for all licensed patents in a treated subclass. For each licensed patents, the remaining years of patent life are calculated by subtracting the patent's age in 1919 from 17 years (patent life in the United States in 1919). Treated subclasses are defined as subclasses that received at least one license under the TWEA; 335 subclasses in our data where treated.

FIGURE 4 – PRE-TWEA TIME TRENDS IN PATENTING BY DOMESTIC INVENTORS: TREATED VERSUS UNTREATED SUBCLASSES



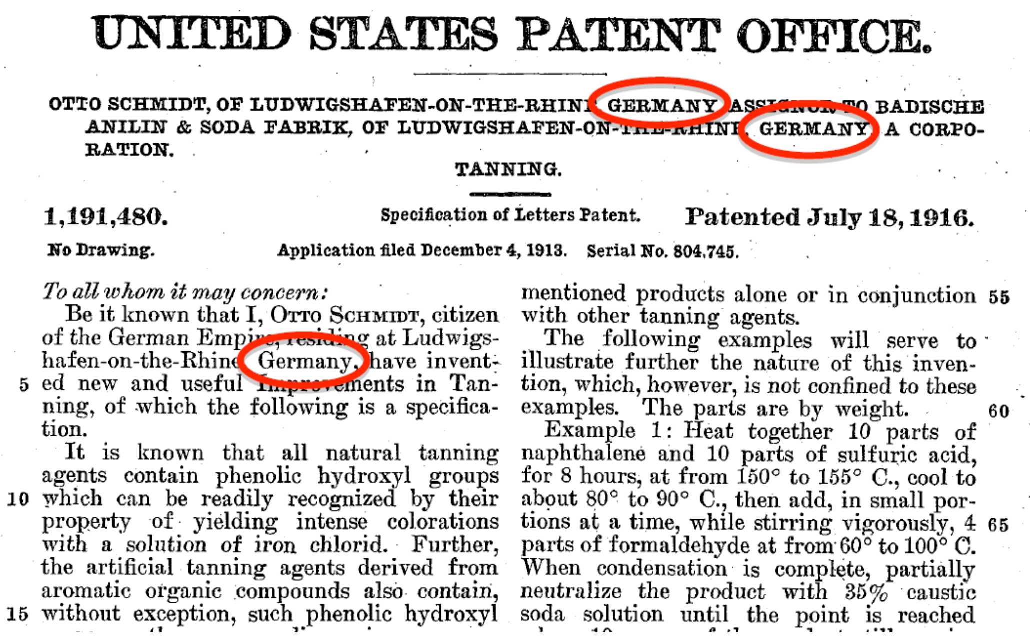

*Notes:* Data from www.uspto.gov and the *Lexis Nexis Chronological Patent Files (1790-1970)* include all 165,400 patents between 1875 and 1939 in 21 USPTO classes that received at least one license under the TWEA. These 21 classes cover 8,422 subclasses, 335 of which are treated; the omitted year is 1900.

FIGURE 5 – PRE-TWEA SHARES OF DOMESTIC INVENTORS:
TREATED VERSUS UNTREATED SUBCLASSES




*Notes:* Data on annual patents and inventor nationalities were constructed from www.uspto.gov and the *Lexis Nexis Chronological Patent Files (1790-1970)*. Treated subclasses received at least one license under the TWEA. Data include 8,422 subclasses, 335 of which are treated.

FIGURE 6 – EXAMPLE OF A U.S. PATENT IN OUR DATA



UNITED STATES PATENT OFFICE.

OTTO SCHMIDT, OF LUDWIGSHAFEN-ON-THE-RHINE, GERMANY, ASSIGNOR TO BADISCHE ANILIN & SODA FABRIK, OF LUDWIGSHAFEN-ON-THE-RHINE, GERMANY, A CORPORATION.

TANNING.

1,191,480. Specification of Letters Patent. Patented July 18, 1916.

No Drawing. Application filed December 4, 1913. Serial No. 804,745.

*To all whom it may concern:*

Be it known that I, OTTO SCHMIDT, citizen of the German Empire, residing at Ludwigshafen-on-the-Rhine, Germany, have invented new and useful Improvements in Tanning, of which the following is a specification.

It is known that all natural tanning agents contain phenolic hydroxyl groups which can be readily recognized by their property of yielding intense colorations with a solution of iron chlorid. Further, the artificial tanning agents derived from aromatic organic compounds also contain, without exception, such phenolic hydroxyl

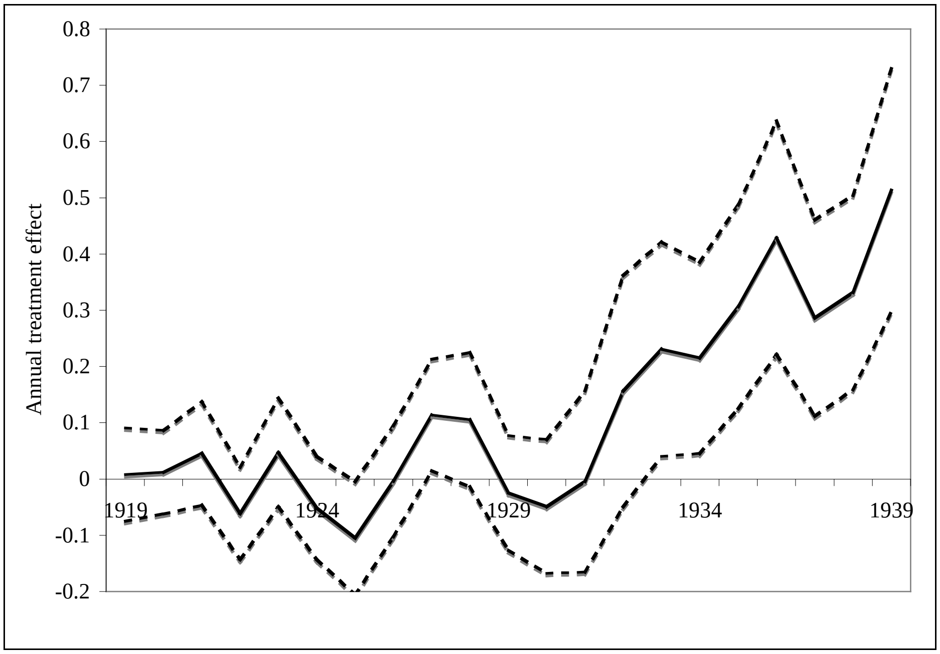
mentioned products alone or in conjunction with other tanning agents.

The following examples will serve to illustrate further the nature of this invention, which, however, is not confined to these examples. The parts are by weight.

Example 1: Heat together 10 parts of naphthalene and 10 parts of sulfuric acid, for 8 hours, at from 150° to 155° C., cool to about 80° to 90° C., then add, in small portions at a time, while stirring vigorously, 4 parts of formaldehyde at from 60° to 100° C. When condensation is complete, partially neutralize the product with 35% caustic soda solution until the point is reached

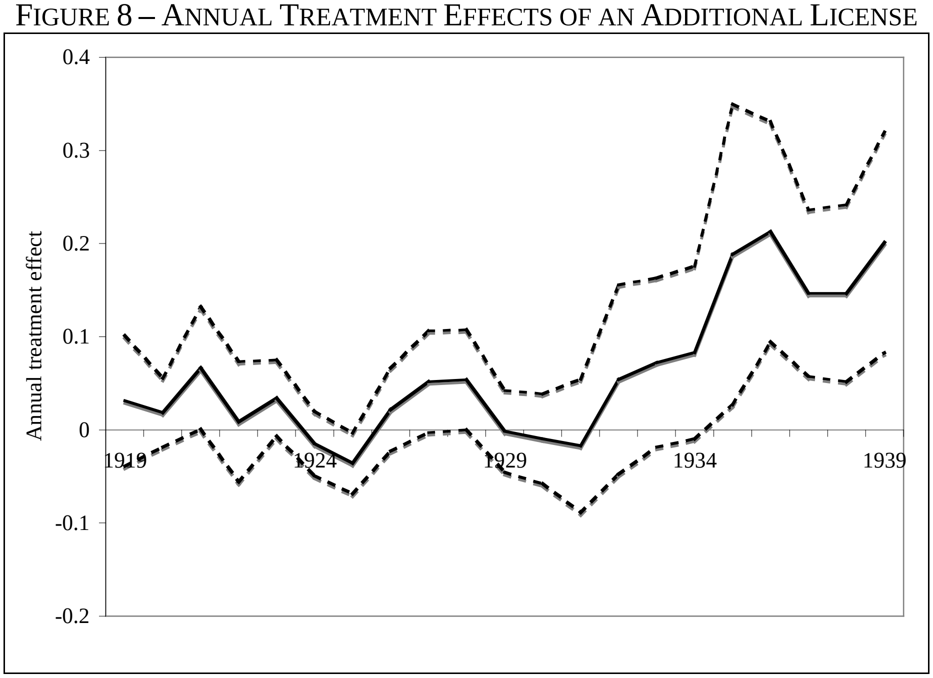
*Notes*: Optical character recognition is used to identify the inventor's nationality for each of the 165,400 patents in the data. The algorithm searches both the title and the full text of each patent the *Lexis Nexis Chronological Patent Files (1790-1970)*.

FIGURE 7 – ANNUAL TREATMENT EFFECTS: TREATMENT =1 FOR SUBCLASSES THAT RECEIVED AT LEAST ONE LICENSE UNDER THE TWEA



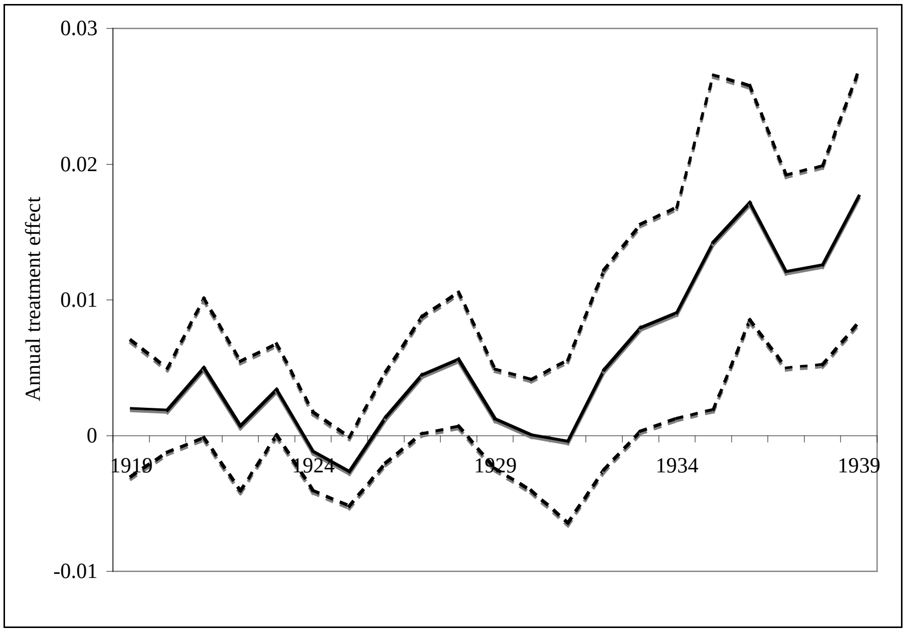

*Notes*: For a 95-percent confidence interval of the regression *Patents by U.S. inventors*$_{c,t}$ = $\alpha_0 + \beta_t \cdot TREAT_c \cdot YEARpostTWEA_t + \gamma \cdot Z_{c,t} + \delta_t + f_c + \varepsilon_{c,t}$ , where *TREAT* = 1 if a subclass received at least one license under the TWEA. Data include all 165,400 patents between 1875 and 1939 in 21 USPTO classes that received at least one license. These 21 classes cover 8,422 subclasses, 335 of which are treated.

FIGURE 8 – ANNUAL TREATMENT EFFECTS OF AN ADDITIONAL LICENSE



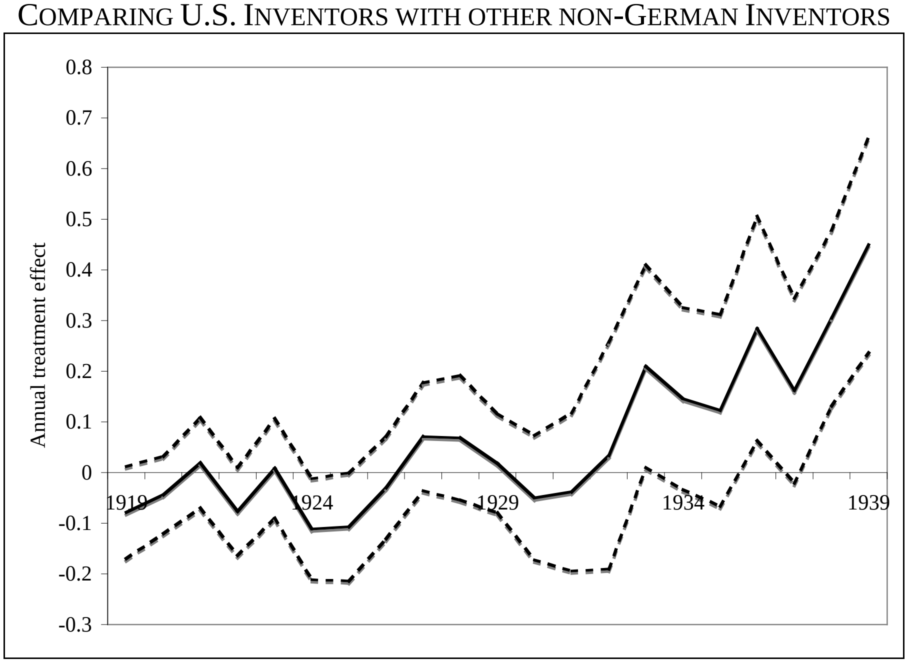

*Notes*: For a 95-percent confidence interval of the regression *Patents by U.S. inventors*$_{c,t}$ = $\alpha_0 + \beta_t \cdot TREAT_c \cdot YEARpostTWEA_t + \gamma \cdot Z_{c,t} + \delta_t + f_c + \varepsilon_{c,t}$ , where *TREAT* measures the number of licenses in one of 335 treated subclasses. Data include all 165,400 patents between 1875 and 1939 in 21 treated main classes.

FIGURE 9 – ANNUAL TREATMENT EFFECTS OF AN ADDITIONAL YEAR OF PATENT LIFE



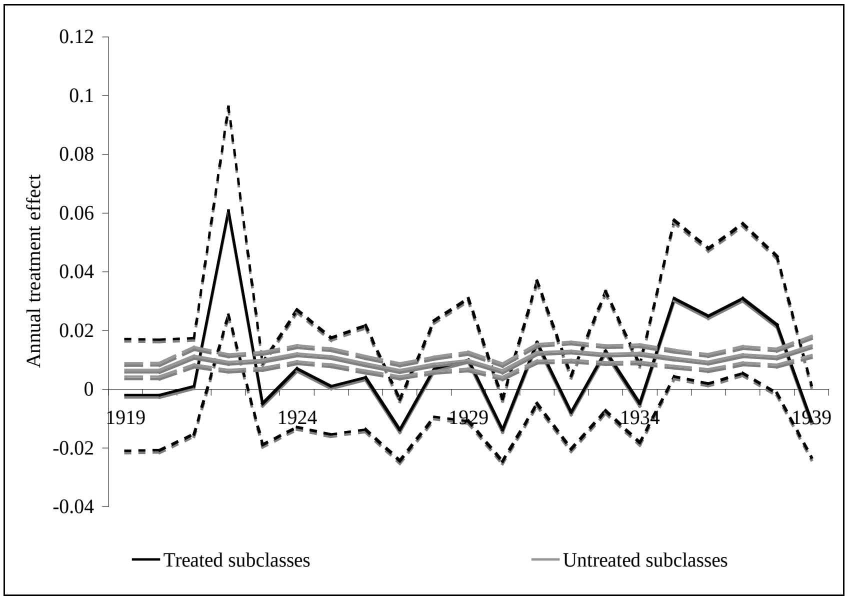

*Notes*: For a 95-percent confidence interval of the regression *Patents by U.S. inventors*$_{c,t}$ = $\alpha_0 + ß_t \cdot TREAT_c \cdot YEARpostTWEA_t + \gamma \cdot Z_{c,t} + \delta_t + f_c + \varepsilon_{c,t}$ , where *TREAT* measures the total remaining years of patent life for all licensed patents in a treated subclasses. Data include 165,400 patents between 1875 and 1939.

FIGURE 10 – ANNUAL TREATMENT EFFECTS: TRIPLE DIFFERENCES COMPARING U.S. INVENTORS WITH OTHER NON-GERMAN INVENTORS



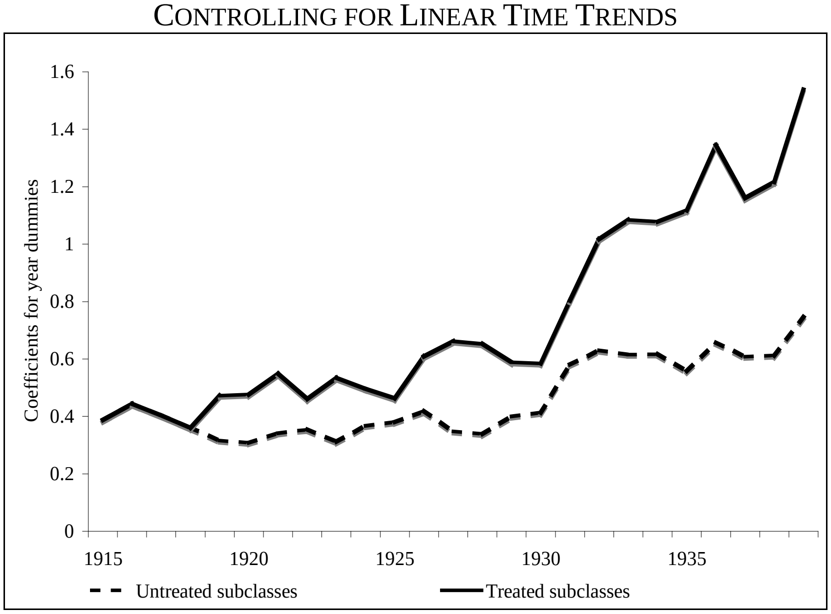

*Notes*: For a 95-percent confidence interval of the regression $Patents_{n,c,t} = \alpha_0 + \alpha_3 USA_n + \alpha_4 TREAT_c \cdot YEARpostTWEA_t + \alpha_5 USA_n \cdot TREAT_c + \alpha_6 USA_n \cdot YEARpostTWEA_t + ß_t \cdot USA_n \cdot TREAT_c \cdot YEARpostTWEA_t + \delta_t + f_c + \varepsilon_{c,t}$, where *TREAT* measures the total remaining years of patent life for all licensed patents in a treated subclasses. Data include 165,400 patents between 1875 and 1939.

FIGURE 11 – ANNUAL TREATMENT EFFECTS: PLACEBO ON FRENCH INVENTORS




*Notes*: For a 95-percent confidence interval of the regression *Patents by French inventors*$_{c,t} = \alpha_0 + \beta_t \cdot TREAT_c \cdot YEARpostTWEA_t + \gamma \cdot Z_{c,t} + \delta_t + f_c + \varepsilon_{c,t}$ where *TREAT*=1 for subclasses where U.S. firms received at least one license under the TWEA. Data include all 3,000 U.S. patents in treated subclasses between 1875 and 1939 that were granted to French inventors.

FIGURE 12 – ANNUAL TREATMENT EFFECTS,
CONTROLLING FOR LINEAR TIME TRENDS

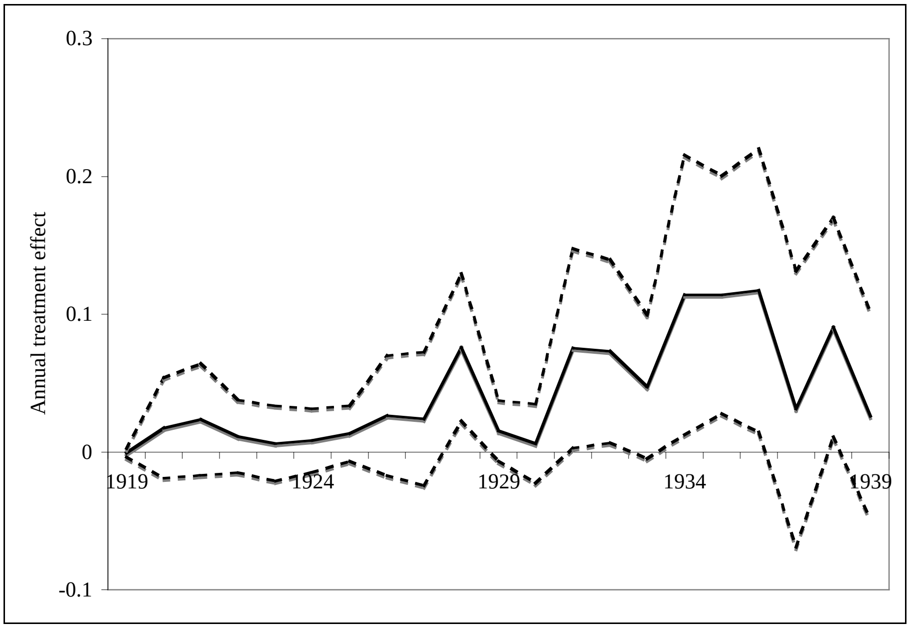



*Notes*: The regression equation is

*Patents by US inventors*$_{c,t} = \alpha_0 + \beta_t \cdot TREAT_c \cdot YEARpostTWEA_t + \gamma \cdot Z_{c,t} + \delta_t + f_c + \phi \cdot TREAT_c \cdot t + \varepsilon_{c,t}$

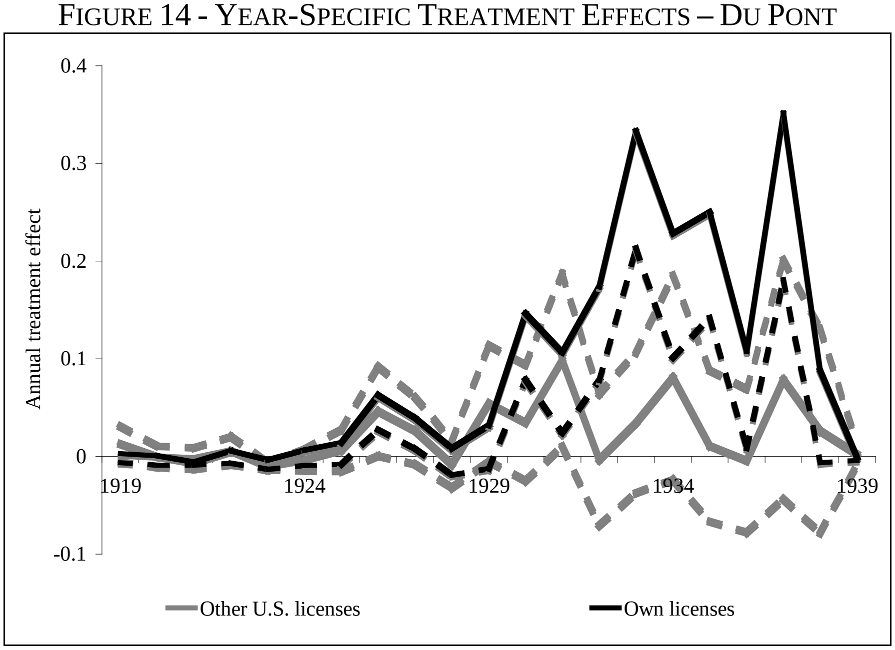
where *TREAT*=1 for subclasses where U.S. firms received at least one license under the TWEA. The y-axis plots coefficients for the year-specific treatment $\beta_t$, and the year fixed effects $\delta_t$ where a subclass is defined as treated if it received at least one license under the TWEA. Line for untreated subclasses represents $\delta_t$, line for treated subclasses represents $\beta_t + \delta_t$.

FIGURE 13 – ANNUAL TREATMENT EFFECTS: INDIGO PATENTS




*Notes*: For a 95-percent confidence interval of the regression *Indigo patents by U.S. inventors*$_{c,t}$ = $\alpha_0 + \beta_t \cdot TREAT_c \cdot YEARpostTWEA_t + \gamma \cdot Z_{c,t} + \delta_t + f_c + \varepsilon_{c,t}$ , where *TREAT* = 1 if a subclass received at least one license under the TWEA. Data include all x patents between 1875 and 1939 in 21 USPTO classes that received at least one license. These 21 classes cover 718 subclasses, 127 of which are treated. The average number of indigo patents in each subclass-cell is 0.035.

FIGURE 14 - YEAR-SPECIFIC TREATMENT EFFECTS – DU PONT




*Notes*: For a 95-percent confidence interval of the regression *Patents by U.S. inventors*$_{c,t}$ = $\alpha_0 + \beta_t \cdot TREAT_c \cdot YEARpostTWEA_t + \gamma \cdot Z_{c,t} + \delta_t + f_c + \varepsilon_{c,t}$ , where *TREAT* = 1 if Du Pont received at least one license in this subclass. Data include 3,571 U.S. patents between 1875 and 1939 that include variation of the company name. These patents cover x subclasses, y of which are treated.

# APPENDIX

TABLE A1 – TWEA TRUSTS BY NATIONALITY OF ENEMY

| ***Nationality*** | ***Number of trusts*** | ***Estimated value*** |
|---|---|---|
| German enemies | 17,339 | 326,855,090.39 |
| Austrian enemies | 7,580 | 39,555,557.34 |
| Interned enemies | 140 | 3,457,898.17 |
| American enemies | 648 | 91,866,053.40 |
| Other enemies | 1,567 | 40,371,354.63 |
| Net income from Treasury investments | - | 839,770.82 |
| **Total** | **27,274** | **502,945,724.75** |

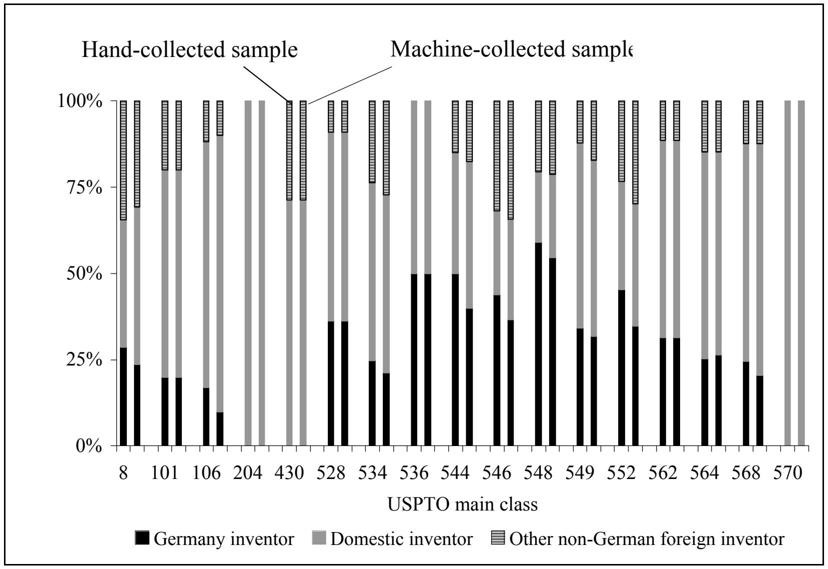
*Notes*: In nominal 1919 dollars; from *Custodian of Alien Property Report, 1919*.

TABLE A2 – USPTO CLASSES AFFECTED BY THE TWEA

| Class | Title | Licenses |
|---|---|---|
| 534 | Organic Compounds—Containing a noble gas | 133 |
| 8 | Bleaching and dyeing; fluid treatment and chemical modification of textiles and fibers | 47 |
| 552 | Organic Compounds—Azides | 27 |
| 548 | Organic Compounds—Containing 5-membered hetero rings | 23 |
| 544 | Organic Compounds—Containing 6-membered hetero rings with at least one nitrogen | 16 |
| 106 | Compositions: coating or plastic | 14 |
| 546 | Organic Compounds—Containing 6-membered hetero rings with 5 carbons and 1 nitrogen | 14 |
| 549 | Organic Compounds—Containing sulfur hetero rings | 11 |
| 528 | Synthetic resins or natural rubbers | 10 |
| 564 | Organic Compounds—Containing amino nitrogen | 7 |
| 562 | Organic Compounds—Persulphonic acids and salts | 6 |
| 536 | Organic Compounds—Carbohydrates and derivatives | 3 |
| 172 | Earth working | 2 |
| 74 | Machine element or mechanism | 1 |
| 101 | Printing | 1 |
| 192 | Clutches and power-stop control | 1 |
| 204 | Chemistry: electrical and wave energy | 1 |
| 416 | Fluid reaction surfaces (i.e., impellers) | 1 |
| 430 | Radiation imagery chemistry: process, composition, or products | 1 |
| 568 | Organic Compounds—Containing boron | 1 |
| 570 | Organic Compounds—Containing halogen | 1 |

*Note*: Data from Haynes (1939) and www.uspto.gov. Class numbers and class names refer to (main) classes within the USPTO classification system. Classes are divided into subclasses, which are the unit of observation for the empirical analysis. Licenses are the total number of enemy-owned patents that were licensed to U.S. firms in a given USPTO class under the TWEA.

FIGURE A1– HAND-COLLECTED VS. ALGORITHM-ASSIGNED NATIONALITIES BY USPTO CLASS



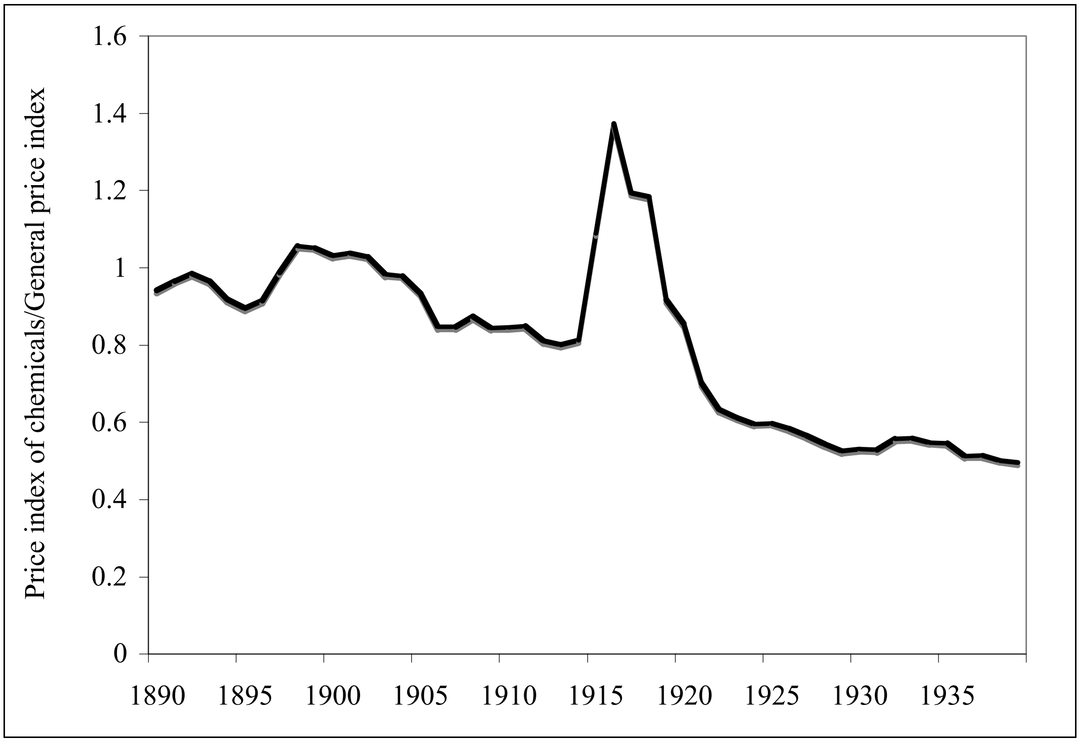

*Note*: Classes are 21 (main) USPTO classes that received at least one license under the TWEA (see Table A2 for class names). Data from Haynes (1939), www.uspto.gov, the *Lexis Nexis Chronological Patent Files (1790-1970),* and www.patents.google.com. To collect data on inventor nationality, we create an algorithm that performs keyword searches on *LexisNexis*. This algorithm relies on Optical Character Recognition (OCR), which is worse at recognizing misspelled names or untidy script than the human eye. To check for measurement error, we hand-collected an alternative data set that includes all 625 patents for the most important dyes of the early 20$^{th}$-century (Delamare and Guineau, 1999): alizarin, indigo, azo dyes, and aniline. In the hand-collected sample, inventors come from Argentina, Australia, Austria, Belgium, Brazil, China, England, France, Germany, India, Italy, the Netherlands, Russia, Scotland, Spain, Switzerland, and the United States.

TABLE A3 – CONFIDENCE INTERVAL OF THE BLOCK BOOTSTRAP COEFFICIENTS

| **Treatment coefficient** | **99% confidence interval** | | **BDM test** |
|---|---|---|---|
| Subclass includes at least one license | 0.0346864 | 0.1942624 | 99% |
| Number of licenses | 0.0203172 | 0.1149504 | 99% |
| Remaining lifetime of licensed patents | 0.0018647 | 0.0103889 | 99% |

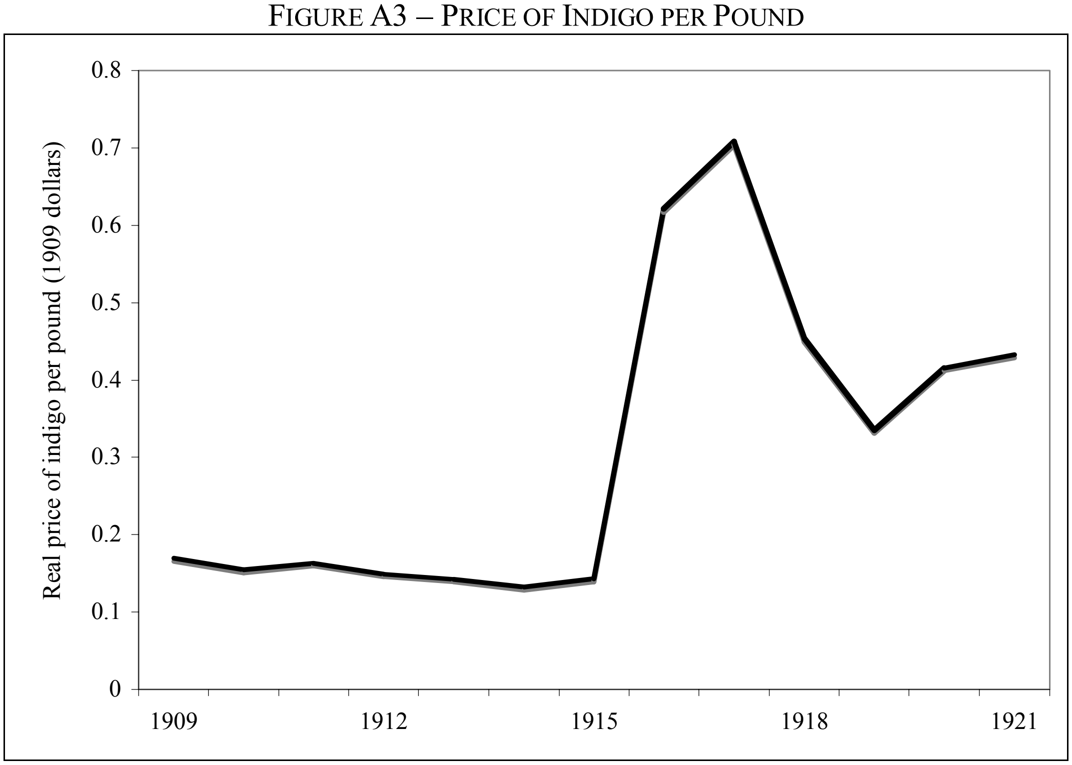
*Note*: Data from www.uspto.gov and the *Lexis Nexis Chronological Patent Files (1790-1970)*. Our data consist of all 165,400 patents between 1875 and 1939 in 21 USPTO main classes that contained at least one licensed enemy patent. These 21 main classes are subdivided into 8,422 subclasses. Data on inventor nationality are based on a key word search for country names in *Lexis Nexis*. Confidence intervals are based on OLS regressions for 79 block bootstrap samples of the full data, these samples draw entire subclasses to maintain the structure of correlations of the full sample (Bertrand, Duflo, and Mullainathan 2004).

FIGURE A2- PRICE OF CHEMICALS RELATIVE TO GENERAL PRICE INDEX




*Note*: This series plots the ratio of the Bureau of Labor Statistics *U.S. Index of Wholesale Price of Chemicals and Drugs* to the *U.S. Index of the General Price Level* (*NBER Macrohistory Series*, 2007).

FIGURE A3 – PRICE OF INDIGO PER POUND




*Note*: Price data from Haynes 1945 and Haber 1971, p.185.