Compulsory Licensing
Evidence from the *Trading with the Enemy Act*[*]

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February 18, 2009

Compulsory licensing, which is permissible under the Trade Related Intellectual Property Rights (TRIPS) agreement, allows domestic firms to produce inventions that are patented by foreign nationals, without the consent of patent owners. As an emergency measure, compulsory licensing offers clear benefits: It helps deliver life-saving drugs to millions of patients. The long run effects of compulsory licensing, however, are unclear. This paper uses an exogenous event of compulsory licensing after World War I to measure the long-run effects of compulsory licensing on domestic invention. Specifically, the analysis compares changes in patents by domestic inventors across technologies that were differentially affected by compulsory licensing under the Trading with the Enemy Act (TWEA). Our data suggest that compulsory licensing has a large positive effect on domestic invention. Firm-level analyses indicate that most of the increase in domestic invention results from learning-by-doing, as compulsory licensing enables a new set of firms to produce an invention. Our data also show that the full effects of compulsory licensing take up to ten years to materialize, suggesting that they will be missed in analyses of contemporary data.

[*] We thank Giacomo De Giorgi, Christina Gathmann, Eric Hilt, Andrea Pozzi and seminar participants at Arizona, Berkeley, Chicago, and Stanford for helpful comments. We owe special thanks to Ryan Lampe for helping us collect the U.S. patent data and Kathryn Steen for sharing her copies of archival records from the Chemical Foundation that are no longer publicly available. Adam Tarhouni, Emily Rains, Leah Karlin, Luke Brennan, Marina Kutyavina, and Stephanie Lee provided excellent research assistance. We thank the NBER's Group on *Innovation Policy and the Economy* and the Kauffman Foundation for financial support.

Compulsory licensing allows governments to grant domestic firms the right to license patented inventions, without the consent of patent owners. Permissible under TRIPS and the WTO's Doha Round of 2001,[1] compulsory licensing offers clear short term benefits; it creates access to life-saving drugs to millions of patients in developing countries (Kremer 2002, Galvão 2002, Gostin 2006). Most recently, Thailand and Brazil have used compulsory licenses for Merck's antiretroviral drug efavirenz to provide AIDS patients with much needed treatments. Despite these obvious short-term benefits, however, the long run effects of compulsory licensing are unclear.

This paper examines the long-run effects of compulsory licensing. Specifically, it tests, whether compulsory licensing encourages or discourages domestic invention in the long run. On the one hand, compulsory licensing might discourage invention, as it weakens the property rights of original inventors.[2] On the other hand, compulsory licensing might encourage invention as it allows a new set of firms to produce an invention, which creates opportunities for learning by doing (e.g., Arrow 1962, Irwin and Klenow 1994).[3]

This paper uses an exogenous event of compulsory licensing as a result of World War I to identify the long run effects of compulsory licensing. Specifically, it examines changes in the number of domestic inventors across subfields of chemical inventions that were differentially affected by the *Trading with the Enemy Act* (TWEA). Passed by Congress in November 1917, section 10 of this Act permitted U.S. firms to violate enemy-owned patents if they contributed to the war effort. As the war dragged on, the Act

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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] Pharmaceutical companies, especially in the United States and Europe, argue that compulsory licensing reduces their incentives to invest in R&D. Merck, for example, called Brazil's licensing of efavirenz 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).

[3] Compulsory licensing may also increase invention indirectly as it encourages investments in scientific training and other skills, which in turn facilitate invention (e.g., Landau and Rosenberg, 1992). Previous work on compulsory licensing has focused on compulsory licensing as a mechanism to address anti-competitive patenting behavior in domestic markets. In such settings, the policy is thought to be primarily welfare-enhancing. Thus compulsory licenses can 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). Case studies suggest that court-ordered compulsory licenses lower neither the research efforts (as measured in R&D dollars) nor the number of inventions (as measured in patents) of firms whose patents were subjected to compulsory licensing (Chien 2003).

became more and more punitive (Steen 2001, p. 99). One week before the Armistice at Compiègne on November 11, 1918, Congress passed an amendment to the TWEA, confiscating all enemy-owned patents, and by February 1919, German-owned patents were systematically licensed to U.S. firms.

To measure the policy's effects, it is necessary to control for other factors that may also encourage domestic invention. Most importantly, improvements in education and in scientific training, as well as an increase in the demand for domestically produced chemicals may also have encouraged domestic rates of invention. To address this issue, our empirical strategy relies on a difference-in-differences estimation, which compares changes in patents by domestic inventors across USPTO subclasses that were differentially affected by the TWEA. Inventions in all of these subclasses were affected by improvements in education, demand shocks, and other factors, while only some subclasses were affected by compulsory licensing. We extend the basic difference-in-differences estimates to account for differences in the intensity of treatment. Specifically, we repeat all tests using alternative measures of treatment which control for variation in the number and in the novelty of licensed patents.

To measure the intensity of treatment we have collected detailed information on 699 enemy-owned chemical patents that were licensed to U.S. firms. We use the distribution of these licenses across USPTO classes, along with the distribution of the total remaining years of patent life for all licensed patents across subclasses to construct three alternative measures of treatment.

Our outcome variable consists of nearly 170,000 chemical patents between 1875 and 1939. To construct these data, we have collected information on all USPTO (main) classes of organic chemicals that contained at least one license under the TWEA. Twenty-one main classes were affected by the TWEA; they produced a total of 165,400 patents between 1875 and 1939, which covered 8,422 subclasses; 336 of these subclasses were affected by compulsory licensing. Our estimation uses differences in the number of domestic patentees across treated and untreated subclasses to identify the effects of compulsory licensing.

OLS regressions indicate that compulsory licensing led to a large increase in the number of patents by domestic inventors. After 1919, when the average subclass produced

0.7 patents per year, subclasses that were affected by compulsory licensing generated an average of 0.12 additional domestic patents per year. Controlling for the intensity of treatment shows that each additional license increased domestic invention by about 0.1 patents per year; adding 10 years of patent life (as a measure of novelty) to a patent, increased domestic patents by 0.07 patents in the treated subclass.

Our historical analysis has the additional benefit that it examines a much longer time series than is available to contemporary studies. We use these data to examine the timing of a potential effect of compulsory licensing on domestic invention. This analysis reveals that the full effects of compulsory licensing set in after about 10 years, even though some effects occur as early as 5 years after licensing. These results are robust to controlling for the intensity of treatment: subclasses that received a larger number of licenses or a larger total number of remaining years of patent life on their licenses experienced a larger and statistically significant increase in patenting. The lag between compulsory licensing and the increase in domestic invention is intuitive. Compulsory licensing allows domestic firms to produce foreign technologies, but the ability to invent new technologies develops only gradually.

We examine the mechanisms by which compulsory licensing encourages domestic invention in a firm-level analysis of Du Pont de Nemours & Co. Specifically we measure differences in the effects of patents that were licensed to Du Pont and patents that were licensed to other firms under the TWEA. Data for Du Pont indicates that patents that were licensed directly to a firm accounted for most of the effects of compulsory licensing. In USPTO subclasses where Du Pont received a license under the TWEA, Du Pont generated about 0.09 additional patents per year after the TWEA. This effect is almost identical to the aggregate effect of the TWEA on all U.S. firms. In comparison, in subclasses where other firms received a license under the TWEA (and Du Pont itself received no license), Du Pont also produced more patents, but this effect was less than one quarter of the "own-patent" effect.

These results suggest that learning by producing is the key mechanism by which compulsory licensing encouraged domestic invention. The ability to produce foreign inventions based on patent records, however, is likely to take several years to acquire, consistent with a long lag between licensing and increases in domestic inventions. First, patent records may be incomplete, because firms have limited incentives to disclose more than they are required by the law. This feature will delay production especially even more if skill levels in the receiving industries are relatively low. Thus Du Pont and other U.S. firms struggled for years to produce German inventions based on technical information in the patents that they had licensed under the TWEA. In fact, a court case established in 1923, that a skilled U.S. chemist could not reproduce synthetic organic chemicals based on technical descriptions in the confiscated German patents.[4]

Although our results suggest a significant long-run effect of compulsory licensing, they may be compromised if not all aspects of the TWEA were exogenous. The timing of the TWEA was caused by World War I, which is exogenous to our outcome variable. Which technologies were confiscated is also exogenous, because the United States confiscated all enemy-owned property. Which technologies were licensed, however, may not be exogenous. For example, U.S. inventors may have been more likely to license technologies in technological fields where the domestic capacity for invention was low. If these classes experience a weaker increase in invention after the TWEA, because domestic inventors first had to bridge the knowledge gap that separated them from inventors in other countries, OLS will underestimate the effects of compulsory licensing. If on the other hand, invention grew more quickly in these classes, because demand for domestic inventions was great, OLS will overestimate the effects of compulsory licensing.

We address this issue by a triple differences estimation. Specifically, we account for unobservable characteristics that may have encouraged patenting by *all* non-German inventors by comparing patents by U.S. and foreign (non-German) inventors across more or less treated subclasses before and after the TWEA. Results from triple differences estimation suggest a slightly smaller positive effect on domestic invention, but they confirm that the TWEA led to a substantial increase in patenting by domestic inventors, and that this effect took about a decade to fully materialize.

Our results are robust to a broad range of alternative robustness checks. First, we control for subclass-specific time trends and find that the results are robust to including such trends. Second, to address the potential of serial correlation in the outcome variable

[4] Louis Freedman, who had earned degrees from Yale and Columbia, and was granted to a well-stocked lab at Brown, proved unable to produce cincophen, a drug to treat gout, based on confiscated German patents (Steen 2001 pp.91-92, 114-115).

patents within subclasses, we perform a block bootstrap; it confirms that the estimation coefficients are highly significant. Third, we restrict our sample to primary subclasses, excluding all secondary subclasses, which the USPTO adds to cross-reference inventions across related fields; restricting the sample to primary subclasses has no significant effect on the coefficients. Fourth, to control for a potential shift in demand as a result of World War I, we examine variation across treated and untreated subclasses within a specific chemical - indigo - that was most affected by a shock in demand. Even with a strong demand shock, patenting by domestic inventors increased substantially more in subclasses that were (more) affected by compulsory licensing. Finally, to check whether our results might be due to random variation, we repeat the estimation with a variety of placebo treatments; none of the placebos replicate the observed increase in domestic patents.

The remainder of this paper is structured as follows. Section I describes why the TWEA offers a useful experiment to examine the effects of compulsory licensing, section II presents our empirical strategy. Section III details our data collection and discusses potential sources of bias. Section IV presents our results, Section V presents robustness checks, and Section VI 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(e) 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 can not eventually yield aid or comfort to the enemy" (Alien Property Custodian 1919, p. 13). [5]

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

[5] 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. I would help to make that an absolute certainty by refusing to permit Germany to prosecute a war after the war. The military arm of her war machine has been palsied by the tremendous hammering of the allied powers. But her territory was not invaded, and 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, but with the same purpose that moved her on that fateful day in July when she set out to conquer the world." (Alien Property Custodian, 1919, p.16)

thereof" (Alien Property Custodian 1919, p.22). Thus, the Alien Property Custodian began to take over 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 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). At that time, 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 (Alien Property Custodian 1919, p.9).[6]

We focus our analysis on the early 20th century U.S. chemical industry, because this industry closely resembles modern-day settings of compulsory licensing. Even though the United States was one of the most developed economies of the early 20th century, its chemical industry was immature. In the early 1910s, Germany produced three quarters of the world's supply of coal-tar dyes (USTC, 1918). Large companies like Badische, Bayer and Hoechst captured most of this market. Between 1900 and 1910, 70 percent of all U.S. patents for synthetic organic compounds were granted to German firms (USTC 1918, Haynes 1945 p.214, Steen 2001). Imports from Germany provided up to 90 percent of dyes for the flourishing U.S. textile industry (Haynes, 1945 p.214).

Compulsory licensing under the TWEA allowed the U.S. government to grant U.S. firms access to German patents. By 1919, the Chemical Foundation began to license enemy-owned patents to U.S. firms. In 1921 the foundation possessed 4,764 patents, 874 trademarks, and 492 copyrights. From 1919 to 1922, during which it licensed 103 manufacturers to use its patents; about half of the licensees were manufacturers of synthetic organic chemicals. The foundation collected an income of $700,000, primarily from royalties (Steen 2001, p.100).

[6] Using the GDP deflator as a conservative measure. Using the relative share of GDP, the 2008 equivalent would be 88 billion dollars (Williamson 2008)

II. Empirical Strategy

Our empirical strategy compares changes in invention by U.S. nationals across chemicals that were differentially affected by the TWEA. Our dependent variable is the number of patents by U.S. inventors in a USPTO subclass for each year between 1875 and 1939.[7] This yields a basic regression equation of the following form:

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

where TREAT is a vector of treatment variables, *Z* is a vector of control variables, δ indicates year fixed effects and *f* subclass fixed effects.[8] In its simplest form, 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 to capture factors, such as changes in the attractiveness of U.S. markets or in the strength of patent rights for foreign nationals that may affect patenting by all foreign inventors.

A. Comparing Pre-Treatment Trends for Treated and Untreated Subclasses

A potential challenge to our identification strategy is that differences between treated and untreated subclasses in post- compared with pre-TWEA numbers of domestic patents may be driven by pre-existing differences in the time trends of patenting across treated and untreated subclasses. Then, an increase in the number of domestic patents in treated subclasses after the TWEA may be driven by a pre-existing trend towards more domestic patents in the treated subclasses.

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[7] The USPTO classifies patents according to technology fields. A (main) class generally distinguishes one technology from another. Subclasses, which are uniquely defined by alphanumeric symbols, differentiate technologies more finely according to specific characteristics and functional features. Each patent is assigned to one primary subclass and can be assigned to one or more secondary subclasses, which serve to cross-reference the patent to related technology fields. For a detailed description of the USPTO classification system see http://www.uspto.gov/web/offices/opc/documents/overview.pdf.

[8] Fixed effects include estimates for α_1 and α_2, from the standard difference-in-differences equation

$$\text{Patents by U.S. inventors}_{c,t} = \alpha_0 + \alpha_1' TREAT_c + \alpha_2 postTWEA_c + \beta' \cdot TREAT_c \cdot postTWEA_t + \gamma \cdot Z_{c,t} + \delta_t + f_c + \varepsilon_{c,t}$$

where, in our simplest specification, TREAT is a singleton that equals 1 if the subclass includes at least one licensed patent and 0 otherwise and post-TWEA equals 1 for every year between 1919 and 1939. In specifications that include measures for the intensity of treatment *TREAT* is a vector of these measures that enter linearly and non-linearly in the specification.

To check this, we compare the pre-TWEA trends of patenting by domestic inventors in treated and untreated subclasses. This test allows the coefficient β_t to vary across treated and untreated subclasses to vary prior to the TWEA. More formally, we estimate, for years between 1875 and 1919, using 1900 as the omitted year variable:

$$\text{Patents by U.S. inventors}_{c,t} = \alpha_0 + \beta_t \cdot YEAR_t \cdot TREAT_c \cdot pre1919_t + \gamma' Z_{c,t} + \delta_t + f_c + \varepsilon_{c,t}$$

A comparison of pre-trends for treated and untreated subclasses reveals no systematic differences in the pre-trend for treated and untreated subclasses (Figure 1).

B. Controlling for Differences in the Intensity of Treatment

We extend this basic difference-in-differences analysis to include two additional treatment variables which account for the intensity of treatment. First, we control for the number of patents that were licensed in each subclass (Figure 2). In most subclasses only one patent was licensed, but in a small number of subclasses many patents were licensed. For instance, a total of 8 patents were licensed in the subclass 106/402, which contains "compositions: coating or plastic – lakes".

The intensity of treatment may have also varied across old and new patents. For example, consider two patents that were both licensed in 1919; the *Old* patent was granted in 1903 and the *New* patent was granted in 1915. A compulsory license for *New* provides a stronger treatment because *New* was more novel than *Old* at the time it was licensed, which, assuming that technology improves over time makes *Old* more obsolete. To account for such variation, our second alternative treatment variable measures the total years of remaining patent life across all patents that were licensed within a given subclass (Figure 3)

$$\sum_{i=1}^{I} (\text{years of life of patent } i \text{ in class } c \text{ in 1918}).$$

C. Measuring Year-Specific Treatment Effects

To assess the timing of effects, we allow the treatment coefficient β to vary across years. This yields the regression equation

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

where β_t measures the difference in domestic patents for more intensely treated subclasses in year *t* between 1919 and 1939 post-TWEA compared with less intensely treated subclasses prior to the TWEA.

D. Triple Differences

One potential concern with our estimation strategy is that subclasses that were affected by compulsory licensing experienced an increase in innovation due to unobservable characteristics that are correlated with licensing decisions.[9] In other words, although the timing of compulsory licensing is exogenous, the choice of technologies in which U.S. firms chose to license enemy-owned patents may not be exogenous. Specifically, U.S. firms may have been more likely to license German patents in subclasses where U.S. domestic invention was weak (Figure 4).

This creates omitted variable bias, which implies that our results could either over- or underestimate the true effects of compulsory licensing. On the one hand, a lack of domestic competitors may have encouraged domestic inventors to patent more; OLS would wrongly attribute this effect to compulsory licensing. On the other hand, domestic firms may have lacked the necessary skills to invent in subclasses where U.S. invention was weak; then OLS underestimates the real effects of compulsory licensing.

To address this omitted variable bias, we propose to apply a triple difference estimation. The triple differences estimator compares changes in patents by U.S. inventors with changes in patents by non-German foreign inventors across more and less intensely treated subclasses before and after the TWEA:

$$\text{Patents by U.S. inventors}_{n,c,t} = \alpha_0 + \alpha_1 USA_n + \alpha_4 TREAT_c \cdot YEARpostTWEA_t + \alpha_5 USA_n \cdot TREAT_c + \alpha_6 USA_n \cdot YEARpostTWEA_t$$
$$+ \beta_t \cdot USA_n \cdot TREAT_c \cdot YEARpostTWEA_t + \delta_t + f_c + \varepsilon_{c,t}$$

[9] For example, U.S. firms may have been more likely to license enemy-owned patents in subclasses where U.S. invention lagged behind the technological frontier. In such subclasses, domestic invention may have increased as a result of compulsory licensing, as domestic firms learned by producing foreign inventions. But domestic inventors may have also learned through other channels that were independent of compulsory licensing, even though they affected the same subclasses. If this is true, our estimation attributes to compulsory licensing what is in fact a result of independent learning of U.S. inventors.

where USA counts the number of U.S. patents, *TREAT* is a vector of dummy variables that equal 1 for treated subclasses and 0 for untreated classes, and *YEARpostTWEA* is a dummy that equals 1 for years after 1919 and 0 for years up to 1919.[10]

The coefficient β_t is similar to a triple differences estimator, which measures the additional effect of compulsory licensing that affected patents by U.S. inventors compared with patents by other non-German inventors. In contrast to standard triple differences estimators, however, our estimation allows β_t to vary over time.

D. Placebo Treatments

Another potential threat to our identification strategy is that unobservables, such as the absence of German competitors in specific subclasses or demand shocks differentially affected treated subclasses, may have caused the increase in domestic patenting in treated subclasses independent of the treatment. To address this issue, we repeat our regressions by artificially exposing French inventors to the treatment that U.S. inventors received under the TWEA. In other words, we re-estimate our regressions under the counter-factual assumption that French inventors could take advantage of licensing enemy-owned U.S. under the TWEA and chose to license in the same subclasses as U.S. inventors. If factors other than the TWEA, such as the absence of German competition or unobservable demand shocks, caused the increase in domestic patenting in treated subclasses, we should observe a similar increase to the effect that we observe for U.S. inventors (who were affected by the TWEA) for French inventors (who were not).[11]

We also perform a number of more general placebo regressions to test whether our results may be driven by random correlation between explanatory variables other than the treatment. Specifically, we create a placebo treatment which randomly assigns subclasses to be "treated" (e.g., Di Giorgi 2007). The share of subclasses that are randomly assigned to the placebo treatment is equal to the share of subclasses that are treated under the TWEA (4.00 percent).

[10] As above, and *X* is a vector of treatment variables and *Z* is a vector of controls, in our case patents by foreign inventors. The variable *f* measures subclass-fixed effects and δ measures year-fixed effects.
[11] We examine French inventors because, similar to the United States, France did not have a strong presence in organic chemistry, although French industry was well developed in other sectors.

III. The Data

Our data include 699 enemy-owned chemical patents that were licensed to U.S. firms, as well as 165,400 patents in 21 classes that contained at least one patent that was licensed under the TWEA.

A. Data on the Treatment: Licensed Enemy-Owned 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 between 1919 and 1926 to one or more of 326 U.S. firms (Haynes, 1945, Steen 2001). Licensed patents belong to 21 USPTO classes and 335 primary and secondary subclasses (Table 1). We use the distribution of licensed patents across subclasses (Figure 2), along with the distribution of the total remaining years of patent life across subclasses (Figure 3) to construct three complementary measures of treatment.

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

Our outcome variable is the number of patents by domestic inventors per subclass and year. We have collected these data for all 21 USPTO main classes of chemicals that included at least one patent that was licensed under the TWEA. Between 1875 and 1945, these 21 classes included 165,400 patents, which we collect from the USPTO's official website (www.uspto.gov). These patents covered 8,422 subclasses of chemical inventions, of which 336 were affected by the TWEA.

To be consistent with the literature, we measure patents at their grant instead of application dates. Granted patents are a better measure of inventions because they exclude patent applications that are denied by patent examiners. For example, an application that duplicates an invention that has already been patented is denied, and thus excluded. We are, nevertheless, interested in the average lag between applications and grant because we would like to know when inventions that benefitted from compulsory licensing were made.

To estimate the average lag between application and grant dates, we have constructed a sample of 493 patents between 1930 and 1933 that contain the word "dye." In this sample, the average patent is granted 3 years after the application date, with a 25 percentile of 2, a mode of 3, and a 75th percentile 4 years.[12] This implies that the average invention that was granted a patent in 1932 was made approximately 3 years earlier, in 1929.

Patents by domestic inventors are measured as the difference between all patents and foreign patents in a subclass. Foreign patents are U.S. patents by inventors that reside in 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.

To examine the effects of compulsory licensing at the levels of individual U.S. firms, we collect additional data on the number of patents per year in each subclass for Du Pont de Nemours & Co. The Du Pont Company licensed a total of 234 enemy-owned patents under the TWEA. For example, it licensed R. Herz's 1910 patent for a blue vat dye (USPTO No. 956,348, R. Herz, Cassella, primary subclass 548/442). We identify the company's patents through a key word search of U.S. patents between 1875 and 1939 for "Du Pont;" this search yields a total of 3,150 patents, which we assign to primary and secondary subclasses.[13]

C. Measurement Error

Our data may be subject to measurement error in the way we assign patents to inventor nationalities. Specifically, our matching may overestimate the number of domestic inventors because we miss inventors from any country that is not included in our search. Another type of measurement error results from using Optical Character

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[12] To construct this sample, we searched www.patents.google.com for patents that contain the word "dye" anywhere in the patent. Google caps the result of this search at 600 patents and records application dates for 536 patents; 493 of the 536 patents with application dates belong to our sample.

[13] We search for all known variation of the DuPont 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.

Recognition (OCR) to identify patents by foreign inventors. OCR is worse at recognizing misspelled names or untidy script than the human eye, which will also lead us to overestimate the number of U.S. inventors.[14]

There is however, no reason to believe that these errors vary systematically across treated and untreated subclasses. To check for systematic errors, we hand-collected inventor nationalities of 625 patents of alizarin, indigo, azo dyes and aniline that were granted between 1900 and 1943. For these patents we identify the inventor's nationality 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 2 and Figure 7). Improvements in the quality of OCR will be captured by annual fixed effects.

Our data are also subject to some measurement error regarding the timing of the licensing. Publicly available archival records do not specify the exact date of licensing, and the archival records of the Chemical Foundation are not currently available. The Chemical Foundation continued to license enemy-owned patents until 1926, though the majority of licenses were granted between 1919 and 1921 (Steen 2001, p.100).

Another type of measurement error results from our use of the USPTO system of classification, which offers an independent mechanism of classifying patents. The range (or breadth) of patents that are included in a USPTO subclass may, however, vary across subclasses, which will lead us to underestimate patenting in subclasses that are narrowly defined. Moreover, inventors' propensity to patent may vary across subclasses and technology fields (Lerner 1995, Moser 2007), which could also bias our results. We address these issues by using class-subclass-specific fixed effects in all regressions.

D. Attenuation Bias

Most importantly, the USPTO classification system may cause us to underestimate the true effects of compulsory licensing. Specifically, our estimation approach assumes that the effects of compulsory licensing are limited to inventors in the same subclass.

[14] 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.

Given the relatively narrow definition of USPTO subclasses, however, it is likely that licensing in one subclass may also affect inventors in other classes.[15] Then treatment could also affect our control group, which will lead us to underestimate the true effects of licensing.[16]

IV. Results

A. Least Squares with Subclass- and Year- Fixed Effects

Preliminary results of for our most basic equation

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

show that the correlation between compulsory licensing and patenting by domestic inventors is high and statistically significant (Table 3).[17] In treated subclasses, which received at least one license under the TWEA, U.S. inventors produced on average 0.1 to 0.2 patents more per year between 1918 and 1939 (columns I to III). Controlling for the number of patents by all foreign inventors has a measurable influence on the treatment coefficient; these results are robust to alternative lag structures. This is a substantial

[15] 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). If SUTVA were satisfied, our empirical estimation would measure the difference between a world where some subclasses are treated by compulsory licensing and another where compulsory licensing does not exist. Even though this would be a cleaner test, its implications are far less interesting and relevant than what we can do with our data. Our estimation measures a causal effect as the difference in the actual number of domestic inventors in a treated subclass and the counterfactual number of domestic inventors in that subclass if it had not been treated by compulsory licensing. Thus the estimated effect is the difference between the observed number of domestic inventors for every treated subclass and the number of domestic inventors that would have been observed in each subclass without compulsory licensing. We define the average effect for the treated (ATT) to be the average of these estimated subclass-level effects. It is important to keep in mind, however, that this ATT does not measure the average difference in potential outcomes that would have been observed if all selected subclasses had been subject to compulsory licensing and all others had not (as it would under SUTVA). Most importantly, our empirical strategy requires additional assumptions about how subclasses are assigned to treatment, which we describe in more detail in the text.

[16] We could capture some of these spillover effects by combining subclasses that cover similar technologies, which would, however, be subjective. Instead, we plan to measure spillovers across subclasses by matching our data set of licensed patents with the NBER Patent Citation Data File (Hall, Jaffe, and Trajtenberg 2001), which includes all citations to U.S. patents that were granted between 1975 and 2002. If the subclasses of citing patents differ from the subclasses of licensed patents, our analysis underestimates the effect of compulsory licensing.

[17] As above, X is a vector of treatment variables and Z is a vector of controls, here contemporary and lagged patents obtained by foreign inventors. The variable f indicates subclass fixed effects, δ year fixed effects. Standard errors are clustered at the level of subclasses.

increase, especially compared with the average number of patents per subclasses and year, which is 0.68 between 1918 and 1939. All effects are significant at the 1 percent level.

B. Controlling for the Intensity of Treatment

Controlling for the intensity of treatment confirms that compulsory licensing encourages domestic invention. An additional license raises the annual number of patents by domestic inventors by an average of 0.06 to 0.1 patents per year (Table 3), column V-VI).[18] An additional year of patent life raises the number of annual patents in the treated subclass by 0.006 to 0.01 patents per year (column VIII-IX). This implies that licensing a new patent in 1918, which had 17 years of life left, increases patenting by nearly 0.102 patents per year, while an older patent, which had just one year of life left, only increases patenting by 0.006 patents per year. Again all effects are significant at the 1 percent level.[19]

B. Year-Specific Treatment Effects

We take advantage of the long run nature of our historical data to identify the timing of the impact of compulsory licensing. Specifically, we estimate year-specific treatment effects, where β_t measures the effect of compulsory licensing on patents by domestic inventors in year *t*

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

Regressions with year-specific treatment effects suggest that the effect of compulsory licensing on domestic inventors may take up to 10 years to fully materialize. For treated subclasses, the effect of licensing on the number of patents by domestic

[18] Consistent with a learning process where the marginal effect of additional knowledge is positive but decreasing, OLS results indicate that the marginal effect of additional patents is decreasing. A negative coefficient on the squared number of licensed patents suggests that the effect of additional patents may become negative when more than 18 patents are licensed in a subclass (compared with an average of 0.7 annual patents per subclass). This effect, however, is dependent on the functional form of our estimation equation. Moreover, none of more than 8,000 subclasses had more than 15 licensed patents.

[19] Marginal effects are decreasing both for additional licenses and for additional patent years. The effect of an additional year of remaining patent life becomes negative when more than 187 years of patent life are added to the remaining lifetime of all licensed patents in a subclass. This number corresponds to roughly 11 new patents in 1918, consistent with the results when treatment is defined as the number of licensed patents. These results are robust to the inclusion of linear and quadratic subclass-specific time trends.

inventors becomes statistically significant around 1932 (at 5 percent, Figure 8). Accounting for an average lag between patent applications and grants of three years, these results implied that U.S. nationals began to patent significantly more in treated subclasses in 1929, approximately 10 years after the TWEA, and 8 to 9 years after most patents had been granted. Regression results also suggest that a small effect was already present in the late 1920s; the year-specific treatment coefficient β_t is first significant in 1927.

The data also show that the effect on compulsory licensing is persistent throughout the 1930s. After 1932, treated subclasses produce between 0.4 and 0.6 additional patents per year. At the end of our sampling period, in 1939, subclasses that were affected by compulsory licensing continue to generate approximately 0.5 additional patents per year compared with untreated subclasses.

Adjusting for the intensity of treatment through the number of licenses per subclass confirms that the full effects of compulsory licensing materialized in the early 1930s, although year-specific treatment effects are positive and statistically significant as early as 1927. Point estimates suggest that an additional license under the TWEA generates between 0.2 and 0.3 additional domestic patents in the early 1930s compared with 0.05 in second half of the 1920s (Figure 9). Adjusting for the intensity of treatment by accounting for years of remaining patent life also confirms that the full effect of licensing occurs in the early 1930s; a less precisely estimated effect already occurs in the late 1920s (Figure 10).[20]

C. Triple Differences

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[20] We have repeated these regressions including both the simplest specification of treatment (where *TREAT = 1* if a subclass receives at least one license) and one of the two intensity-adjusted specifications. Specifically, we include controls for the number of licenses per subclass (in addition to our simplest measure of treatment that a subclass was affected by compulsory licensing), which yields the estimation equation

$$\text{Patents by U.S. inventors}_{c,t} =$$

$$\alpha_0 + \alpha_1 TREAT_c + \alpha_2 postTWEA_c + \beta \cdot (Dummy_c = 1 \text{ if subclass received at least one license}) \cdot postTWEA_t$$
$$+ \xi_t \text{Number of licenses}_c \cdot YEARpostTWEA_t + \gamma \cdot Z_{c,t} + \delta_t + f_c + \varepsilon_{c,t}$$

The equivalent regression with our second intensity-adjusted treatment variable as a control (remaining lifetime of all licensed patents) yields the equation

$$\text{Patents by U.S. inventors}_{c,t} =$$

$$\alpha_0 + \alpha_1 TREAT_c + \alpha_2 postTWEA_c + \beta \cdot (Dummy_c = 1 \text{ if subclass received at least one license}) \cdot postTWEA_t$$
$$+ \xi_t \text{Remaining lifetime of all licensed patents}_c \cdot YEARpostTWEA_t + \gamma \cdot Z_{c,t} + \delta_t + f_c + \varepsilon_{c,t}$$

Estimating time-varying treatment coefficients confirms that patenting was responsive to the intensity of treatment and that the effect of compulsory licensing was particularly large in the early 1930s.

Triple differences account for omitted variables that affect all non-German inventors by comparing changes in treated and untreated classes before and after the TWEA across U.S. and other non-German inventors. Triple difference estimates confirm that compulsory licensing had a significant positive effect on domestic invention (Figure 11). Subclasses that received at least one license during the TWEA began to produce more patents by domestic inventors around 1927, and had consistently larger number of domestic invention in the 1930s. Compared with patents by other non-German inventors, U.S. inventors produced 0.2 to 0.4 more patents in the 1930s (significant at 5 percent since 1933, Figure 11) in subclasses that were affected by the TWEA. This effect is especially significant compared with the average 0.7 patents per subclass and year. Equivalent regressions for intensity-adjusted measures of treatment (number of licenses and remaining patent years for all licensed patents) yield similar results.[21]

D. Placebo Treatments

An alternative check for the importance of other factors, such as the absence of German competitors during the war, is to examine whether changes in patenting after the TWEA also occurred for inventors that did not benefit from the TWEA. Specifically, we estimate a placebo treatment for French inventors, allowing them to be "treated" by the TWEA, as if they were U.S. firms. Any observed effects of the TWEA on French inventors (who could not benefit from the TWEA) would be a strong indication that other factors caused the observed increase in domestic patents by U.S. inventors after the TWEA.

In our data, 3,000 patents, approximately 1.7 percent, were granted to French inventors. Estimating year-specific treatment effects as in the equation

$$\text{Patents by French inventors}_{c,t} = \alpha_0 + \beta_t \cdot YEAR_t \cdot TREAT_c \cdot postTWEA_t + \gamma' Z_{c,t} + \delta_t + f_c + \varepsilon_{c,t}$$

[21] In evaluating this coefficient it is important to keep in mind that British inventors, which contributed the second larges number of foreign patents, may have been affected by compulsory licensing in the same way as U.S. inventors. Britain had passed an early version of its TWEA in September 1914 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 American 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). This implies that triple differences estimate a lower bound for the true effect of compulsory licensing.

shows no clear effect of this pre-TWEA placebo treatment on patenting by French inventors (Figure 12).

A set of more general placebo test rejects the hypothesis that random correlation across explanatory variables may cause the observed effects on U.S. invention. Specifically, we randomly assign 4 percent of all subclasses to be treated, and re-estimate the most basic regression 51 times with a randomly selected placebo treatment. In these tests, the hypothesis that the placebo treatment is significant is rejected for 45 of 50 placebos at the 5 percent level (Table 8).

V. Robustness checks

This section presents a series of robustness checks for our results, including controls for subclass-specific time trends, a block bootstrap to account for serial correlation, an analysis of compulsory licensing at the level of primary subclasses, and at the level of an individual dye (indigo), and several tests of placebo treatments.

A. Controlling for Subclass-Specific 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 subclass-specific linear and quadratic time trends:

$$\text{Patents by U.S. inventors}_{c,t} = \alpha_0 + \beta_t \cdot TREAT_c \cdot YEARpostTWEA_t + \gamma' Z_{c,t} + \delta_t + f_c + \phi_{1c} \cdot t + \phi_{2c} \cdot t^2 + \varepsilon_{c,t}$$

where β_t measures treatment effects in year *t* and δ_t captures year fixed effect controlling for subclass-specific time trends $\phi_{1c} \cdot t$ and $\phi_{2c} \cdot t^2$.[22]

Given the large number of subclasses, we cannot estimate the expanded regression for the entire data set; this would require to estimate about 20,000 coefficients, including 8,422 class fixed effects, 8,422 linear time trends, and 8,422 quadratic time trends in

[22] This methodology follows Wolfers (2007), who uses it to separate the dynamic effects of a shift towards no-fault divorce on divorce rates from pre-existing differences in time trends in divorce rates across states.

addition to time dummies, treatment variables, and controls. To address this issue, we restrict the sample to subclasses in two main classes that include the largest number of licenses (classes 8 and 534, Table 1). These two (main) classes span a total of 776 subclasses.

Results show that even after controlling for subclass-specific time trends, the number of domestic patents increased significantly more in treated subclasses than in untreated subclasses after the TWEA. Year-specific treatment coefficients are significant at the 5 percent or 1 percent level between 1919 and 1939.

To repeat this test on the entire data set, we introduce *treatment-specific* time trends. Specifically, we re-estimate the above equation that includes subclass-specific time trends, allowing time trends to vary only between treated and untreated classes, estimating a single time trend for all treated classes.

$$\text{Patents by U.S. inventors}_{c,t} = \alpha_0 + \beta_t' \cdot TREAT_c \cdot YEARpostTWEA_t + \gamma \cdot Z_{c,t} + \delta_t + f_c + \phi \cdot TREAT_c \cdot t + \varepsilon_{c,t}$$

Even controlling for treatment-specific time trends, year-specific treatment coefficients β_t are significant at the 1 percent level (Figure 13).[23]

B. Block Bootstrap to Account for Serial Correlation

Given the long time series of our data we also want to account for serial correlation in the outcome variable (the number of patents by domestic inventors per subclass and year), which could lead us to understate the standard error of the treatment coefficient β. In estimations with a large number of groups a block bootstrap, which maintain the autocorrelation structure within groups by keeping observations in the same group together, has been shown to perform best (Bertrand, Duflo, Mullainathan 2004).[24] Applied

[23] We have estimated this equation with and without quadratic time trends. Specifications without quadratic time trends fit the data better, but the year-specific treatment coefficients β_t are very similar with and without quadratic time trends, although standard errors are smaller without the quadratic trends.

[24] With low standard errors due to serial correlation in the dependent variables, OLS could lead to significant differences-in-differences estimates of a treatment effect, even if the treatment is artificial and assigned as a placebo. Even when standard errors are clustered at the level of groups, serial correlation may produce significant coefficients with placebo treatments. This problem seems to be less severe when the number of groups is large (as is true in our case). In simulations, the block bootstrap is least likely to produce

to our specific case, the block bootstrap maintains the structure of correlations at the level of subclasses, as it samples subclasses instead of observations (the number of patents per subclass and year). Specifically, we randomly draw subclasses with replacement, estimate OLS on each boot-strapped sample, and record coefficients and standard errors to compute the absolute t-statistic $t_r = abs\,(\hat{\beta}_r - \hat{\beta})/SE(\hat{\beta}_r)$. We draw a large number (79) bootstrapped samples, and reject the hypothesis that $\beta = 0$ at a 99 percent confidence interval if the 99 percent of the t_r are smaller than the t-statistic of our original regression.[25] The results of this block bootstrap estimation confirm that all treatment coefficients are significant at the 1 percent level (Table 4).

C. Restricting the Sample to Primary Subclasses

We also check our regressions by restricting the sample to primary subclasses. As described in the data section, patents may be assigned to one or more secondary subclasses, in addition to their primary subclass. Because a compulsory license affects both primary and secondary subclasses, we include secondary subclasses in all tests. As a robustness check, however, we restrict our sample to primary subclasses. If including secondary subclasses puts a lot of weight on patents that belong to many subclasses, the coefficients from this restricted sample (which includes 6,740 subclasses instead of 8,422) should differ substantially from the coefficients of the full sample.[26]

Results from the restricted sample of primary subclasses confirm results from the full sample. In primary subclasses that received at least one license under the TWEA, patenting increased by about 0.03 patents per year after the TWEA (Table 5, column I), compared with an average of 0.2 annual patents per primary subclass. Controlling for the intensity of treatment suggests that an additional license generated an additional 0.025 patents per treated primary subclass and year (Table 5, column II). An additional year of

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significant coefficients for placebo treatments (Bertrand, Duflo, and Mullainathan (2004), which is why we perform the block bootstrap sampling as a robustness check.

[25] 79 repetitions were set at random when our computer crashed. The sampling distribution of t_r is random and changing in N (the number of subclasses). As the number of groups increases, the difference between the distribution of t_r and the distribution of the t-statistic for the original regression tend to zero.

[26] Eliminating secondary subclasses - which cross-reference related technology areas - may also reduce correlation across subclasses; this is important because both clustering at the level of subclasses and the block bootstrap at the level of subclasses assume that the number of patents is independent across subclasses.

patent life generated 0.002 additional patents per primary subclass and year. These results are significant at the 1 percent level.[27]

D. Effects of Tariffs and Demand Shocks

Another potential concern with our identification strategy is that the increase in domestic invention may be caused by an increase in tariffs or in the demand for domestically produced chemicals as a result of World War I. A series of tariff acts began to protect the U.S. chemical industry as early as 1916 (the Emergency Tariff Act). In 1922 the Fordney McCumber Act imposed ad valorem tariffs of nearly 30 percent on imports of chemicals into the United States; it protected Protects indigo, alizarin and all vat dyes. In 1930, the Smoot Hawley tariff further increased these rates to 36 percent (Table 6, U.S. Tariff Commission, 1930, p.196, Eichengreen 1989, Irwin 1998). At the same time, Britain's naval blockade cut the U.S. textile industry off from German imports, creating severe shortages of dyes (e.g., Genesove 2006).

Interestingly, price data indicate that the main effects on demand for domestically produced dyes occurred prior to 1919 (Figure 14). A comparison of the wholesale price of chemicals with the general price index between 1890 and 1939 reveals that prices for chemicals responded significantly more strongly than other prices to the war. Chemical prices began to increase relative to the general price index in 1915, and the distance peaked in 1916. By the end of the war, however, chemical prices had returned to pre-war levels.

To assess the potential effects of a demand shock empirically, we examine inventions for indigo, which was one of the most affected products. Given the narrow definition of subclasses, it is not unreasonable to assume that the demand shock affected

[27] As an additional robustness check we have also re-estimated our main equations separately for each of the 21 USPTO (main) classes in our sample. Each of these classes is affected by compulsory licensing, but they may be differentially affected by unobservable factors that are unrelated to compulsory licensing. To compare treatment effects across main classes we estimate the following equation for each of the 21 classes: Patents by U.S. inventors in class $A_{c,t}$ =

$$\alpha_0 + \delta_t' \cdot TREAT_c \cdot YEARpostTWEA_t + \vartheta_t \cdot UNTREAT_c \cdot YEARpostTWEA_t + \gamma \cdot Z_{c,t} + \delta_t + f_c + \varepsilon_{c,t}$$

and compare changes in the coefficients δ_t and θ_t across classes. Results of class-specific regressions confirm that patenting in treated compared with untreated subclasses increased significantly after the TWEA. Year-specific treatment effects also confirm the timing of the effect of compulsory licensing in the late 1920s and early 1930s. Four of 21 classes were affected by at least 20 licenses: class 534 (organic compounds containing a noble gas, Table 1), class 8 (bleaching and dyeing: fluid treatments and chemical modifications of textiles and fibers), class 522 (organic compounds – azides), and class 548 (organic compounds containing 5 membered hetero rings). In classes 534 and 548, the most significant treatment effect occurred in the early 1930s; in classes 8 and 552, year-specific treatment effects are largest in the late 1920s.

both treated and untreated subclasses *within* indigo; we examine such variation as a robustness check.

World War I greatly increased demand for domestically produced indigo, which was needed to create the blue shade of Navy uniforms (e.g., Navy Department, 1917). Already before the war the United States had consumed 8 million pounds of indigo per year; 90 percent of which were imported from Germany.[28] 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 (Haynes 1945, Haber 1971, p.185). As a result, the price of indigo increased from less than 20 cents per pound (in real prices) before World War I to almost 70 cents in 1917.[29] By 1919, the price of indigo had dropped back to approximately 40 cents (Figure 15, Haynes 1945, p. 231).

To create a subsample of indigo patents, we first identified all U.S. patents of indigo between 1875 and 1939. In practice, this meant searching *Lexis Nexis Chronological Patent Files, 1790-1970* for the keyword "indigo." Merging this list with our data set on U.S. patents yields 749 patents of indigo between 1875 and 1940; these indigo patents cover a total of 718 subclasses.

OLS regressions of the indigo sample confirm that treated subclasses were significantly more likely to experience an increase in domestic patents (Table 6). Analyses of year-specific treatment effect show that year-specific treatment effects become stable and statistically significant around 1931, even though there are positive and statistically significant effects in the late 1920s (Figure 16). Partly because of the small number of observations in this subsample, the treatment effect ceases to be statistically significant in the late 1930s.

In sum, our empirical analysis and robustness checks indicate that compulsory licensing under the TWEA resulted in a large and persistent increase in domestic invention.

VII. Firm-level Analysis

In this section, we examine firm-level data on licensing and changes in patenting activity for Du Pont de Nemours & Co., to shed light on the mechanisms by which

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[28] The remaining 10 percent of U.S. indigo consumption were imported from Switzerland, England and India.

[29] Once the British blockade prevented imports from Germany, the U.S. sourced its indigo from China (52 percent), Japan, Hong Kong, British India (21 percent) and the U.K (20 percent); total imports, however dropped to 6,600,000 in 1916 (Haynes 1945, p. 231).

compulsory licensing encouraged invention. Specifically, we examine differences in the effects of licenses that were issued to Du Pont with the effects of licenses that were issued to other U.S. firms under the TWEA. Licenses that were issued to Du Pont enabled this firm to produce enemy-owned inventions, and may have thereby created opportunities for learning by doing. On the contrary, licenses that were issued to other firms may be an indicator of spillovers across firms, including knowledge spillovers, but also effects of compulsory licensing on incentives to invest in scientific training.

To capture these effects, we distinguish two types of treatments: licenses that were issued to Du Pont and licenses that were issued to other U.S. firms – but not Du Pont – under the TWEA. This yields the following modification of our most basic regression:

$$\begin{aligned}\text{Du Pont Patents}_{c,t} &= \alpha_0 + \beta_1 \cdot TREATDuPont_c \cdot postTWEA_t \\ &+ \beta_2 \cdot TREATnotDuPont_c \cdot postTWEA_t + \gamma' Z_{c,t} + \delta_t + f_c + \varepsilon_{c,t}\end{aligned}$$

To examine whether own licenses (and thereby learning-by-doing) affect firms differently from other firm licenses we test whether $\beta_1 = \beta_2$.

This firm-level analysis reveals that both own licenses and other firms' licenses have significant positive effects on invention in the long run; effects of own licenses are significantly stronger. In the Du Pont data, invention increased by 0.09 to 0.1 patents per subclass and year in subclasses where Du Pont received at least one license under the TWEA, compared with 0.03 patents per year in subclasses where any U.S. firm (but not Du Pont) received a license (Table 9, Columns I and II). Thus, the effects of both own and other firm licenses are significant, though the effect of own firm licenses is more than 4 times stronger. Interestingly, the effect of own licenses is almost identical to the general effect across all firms (Table 3).

Controlling for the intensity of treatment confirms these effects. An additional license granted to Du Pont increased Du Pont's patents per year by 0.05, compared to an effect of 0.01 for other firm's licenses (Table 9, III and IV). Again, both effects are significant, but the effect of own firm licenses is about four times larger. Regressions that control for the novelty of patents further strengthen these results (Table 9, V and VI). For all regressions, the Wald test on the null $\beta_1 = \beta_2$ rejects it at the 0.01 percent level.

VII. 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, U.S. inventors produced an average of 0.1 additional patents per year 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); they are also robust to controlling for subclass- and treatment-specific time trends, and a series of alternative tests.

The long-run nature of the analysis allows us to examine the timing of effects on domestic invention. Estimates of annual treatment effects suggest that the full effects of compulsory licensing set took up to 10 years to materialize. This lag is intuitive; in nascent industries, a country's domestic capacity to invent is limited. Compulsory licensing enables domestic firms to produce inventions that were invented abroad (and are in fact owned by foreign nationals). This creates opportunities for learning-by-doing, but learning occurs gradually; in the case of the U.S. chemical industry, up to a decade. Such long-term effects will be missed in most analyses of contemporary data.

Firm-level data confirm that learning-by-doing, and more specifically, experience that firms gain as they produce foreign inventions, is the most important driver for invention. An analysis of changes in patenting by the U.S. chemical firm Du Pont after the TWEA reveals that the company generated a substantial number of additional patents in USPTO subclasses where it received a license under the TWEA. In treated subclasses, Du Pont produced 0.09 additional patents per year, nearly equal the effect in the overall data. Interestingly, patenting also increased in licensing where other firms received a license under the TWEA, though this effect is substantially smaller, at approximately one quarter of the effects of licenses that were granted to Du Pont. This effect of other firms' licenses may be interpreted as an indicator for factors that affected the entire industry, including improvements in scientific training and human capital. Firm-level data also confirm the approximate lag of 10 years between licensing and the increase in invention.

A key factor in determining the lag between licensing and the increase in domestic invention lies in incomplete patent specifications. In the early 20th century United States, domestic firms struggled for many years to decipher patent specifications that German firms had, perhaps intentionally, left unclear. For example, "Acting under a license issued under the Trading-with-the-Enemy Act, Du Pont wrestled with the obscure descriptions in the German patents to work out a practical process (to produce indigo) only after long experimentation" (Haynes 1945, p.245). Incomplete patent specifications are likely to delay the benefits of compulsory licensing for domestic firms.[30]

Interestingly, the development of the U.S. chemical industry after the TWEA closely mirrors current experiences with compulsory licensing. India, for example permitted the compulsory of pharmaceuticals under its Patent Act of 1970. Under this Act, domestic firms were able to produce generic versions of foreign-owned pharmaceuticals until January 1, 2005, when India complied with the WTO requirements to respect foreign patents. Thus, Indian firms enjoyed a 35 year period of compulsory licensing. 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.

Finally, the delays that U.S. firms experienced with using foreign-owned patents suggest that human capital and tacit knowledge are essential to rapid technology transfers across countries. World War II provides an opportunity to measure the importance of human capital as a complement to patent grants. Only 14 years after the TWEA, on April

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[30] See Haynes (1945) for other example of how incomplete patent specifications slowed production. For example, Mark Weisberg, owner of the Providence, RI, Textile Chemical Company remembers: "…in the early days we purified alpha-naphthol by following the book, dissolving it in caustic soda and filtering. The filtration was arduous….Yields were poor…and the resultant compound was not entirely satisfactory…To remove this isomer, a problem that was not mentioned in the German patents, a concentrated solution of caustic potash was used. The above serve to illustrate the know-how, not in the patent literature, that was required to make success in the dyestuff field" (Haynes 1948, p. 230. . Alpha-napthol is an isomeric form of naphthol, $C_{10}H_7OH$; it typically takes the form of colorless or yellow prisms. In addition to making dyes, alpha-napthol is used to make perfumes and in organic synthesis.)

7th, 1933, the Nazi's "Law for the Restoration of the Professional Civil Service" led to the dismissal of 1,100 professors from German universities (Harthorne, 1937). Many of these scientists moved to the United States, and although they arrived after compulsory licensing increased domestic invention, their effects on domestic invention deserve further study.

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TABLE 1 – USPTO CLASSES

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 product thereof	1
568	Organic Compounds—Containing boron	1
570	Organic Compounds—Containing halogen	1

Notes: Data from Haynes (1939) and *www.uspto.gov*. Licenses refer to the total number of enemy-owned patents that were licensed to U.S. firms by the Chemical Foundation. Class numbers and class names refer to (main) classes within the USPTO system of classifying patents. Classes are divided into subclasses, which are the unit of observation for this analysis. Our data include all USPTO classes that received at least one compulsory license under the TWEA.

TABLE 2 – INVENTOR NATIONALITY ASSIGNED BY HAND VERSUS SEARCH

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

Notes: Based on a sample of 649 patents between 1900 and 1943. Data from Haynes (1939), www.uspto.gov, the *Lexis Nexis Chronological Patent Files (1790-1970)*, and www.patents.google.com. Our matching algorithm performs keyword searches on LexisNexis. Our hand-collected data include all 625 patents of dyes in what Delamare and Guineau (1999) consider the most important dyes in the early 20th century: alizarin, indigo, azo dyes, and aniline. In the hand-collected sample, all inventors come from one of the following countries: Argentina, Australia, Austria, Belgium, Brazil, China, England, France, Germany, India, Italy, the Netherlands, Russia, Scotland, Spain, and Switzerland.

Table 3 - OLS, dependent variable is patents by U.S. inventors per USPTO Subclass and Year (1875-1939)

	I	II	III	IV	V	VI	VII	VIII	IX
Subclass has at least one license	0.144***	0.118***	0.234***						
	(0.0395)	(0.0394)	(0.0415)						
Number of licenses				0.0881***	0.0622***	0.111***			
				(0.0259)	(0.0181)	(0.024)			
Number of licenses squared				-0.0048**					
				(0.0023)					
Remaining lifetime of licensed patents							0.0069***	0.006***	0.009***
							(0.0022)	(0.002)	(0.002)
Remaining lifetime of licensed patents squared							-0.00002		
							(0.00002)		
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***	
		(0.02)		(0.02)	(0.02)		(0.02)	(0.02)	
Subclass fixed effects			Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects			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 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 drop the first two years of data (column I).

TABLE 4 – 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 of the Lexis Nexis. Confidence interval obtained by running OLS regressions on 79 block bootstrap samples of the original dataset as in Bertrand *et al.* (2004), that draw entire subclasses to maintain the structure of correlation constant.

TABLE 5 – OLS PRIMARY SUBCLASSES, DEPENDENT VARIABLE IS PATENTS BY U.S. INVENTORS PER USPTO SUBCLASS AND YEAR

	I	**II**	**III**
Subclass has at least one license	0.031***		
	(0.019)		
Number of licenses		0.025***	
		(0.009)	
Remaining lifetime of licensed patents			0.002***
			(0.0007)
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
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: Each patent is assigned to one primary subclass, and may be assigned to one or more secondary subclasses. While other regressions include all subclasses that appear on a patent document, this regression includes only primary subclasses. This restricts the data to 7,513 subclasses in the 21 main classes. Primary subclasses in this sample produce an average of 0.2 patents per year. 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. Data on inventor nationality are based on a key word search of the *Lexis Nexi*s.

TABLE 6 TARIFFS ON CHEMICALSUNDER FORDNEY-MCCUMBER AND SMOOTH HAWLEY

	Fordney McCumber (1922)	Smoot-Hawley (1930)
Equivalent ad valorem rates	29.72%	36.02%

Note: U.S. Tariff Commission, *The Tariff Review*, July 1930, Table II, p. 196. Ad valorem rates are calculated as rates that would have prevailed on actual U.S. imports in 1928, if the Smoot-Hawley rates been in effect then. Rates are for total dutiable imports.

TABLE 7 - OLS DEPENDENT VARIABLE IS PATENTS BY U.S. INVENTORS PER USPTO SUBCLASS AND YEAR (1875-1939) – INDIGO PATENTS

	I	II	III
Subclass has at least one license	0.044***		
	(0.015)		
Number of licenses		0.027**	
		(0.0102)	
Remaining lifetime of licensed patents			0.002***
			(0.001)
Number of patents by foreign inventors	.004	.004	.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 from www.uspto.gov and the *Lexis Nexis Chronological Patent Files (1790-1970)*. Our data consist of all patents between 1875 and 1939 in 21 USPTO main classes that contained at least one licensed enemy patent. In those classes, we identify all 843 patents that contain the word "indigo" in the description of the invention and record the subclasses to which each patent belongs. Data on inventor nationality are based on a key word search of the *Lexis Nexi*s. The average number of indigo patents in each subclass-cell is 0.035.

TABLE 8 - OLS RESULTS WITH PLACEBO TREATMENT

DISTRIBUTION of the t-statistic	t-statistic
5th percentile	-1.68
Median	0.10
95th percentile	1.68

EXAMPLE	
Placebo (randomly assigning 4% of subclasses to treatment)	-0.007
	0.0144
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 treatment group has been created by randomly assigning treatment to 3.65% of subclasses, which is proportion of subclasses in our sample that included at least one license under the TWEA. Our data consist of all patents between 1875 and 1939 in 21 USPTO main classes that contained at least one licensed enemy patent. Data on inventor nationality are based on a key word search of the *Lexis Nexi*s.

TABLE 9 – OLS FOR DU PONT PATENTS, DEPENDENT VARIABLE IS DU PONT PATENTS BY USPTO SUBCLASS AND YEAR

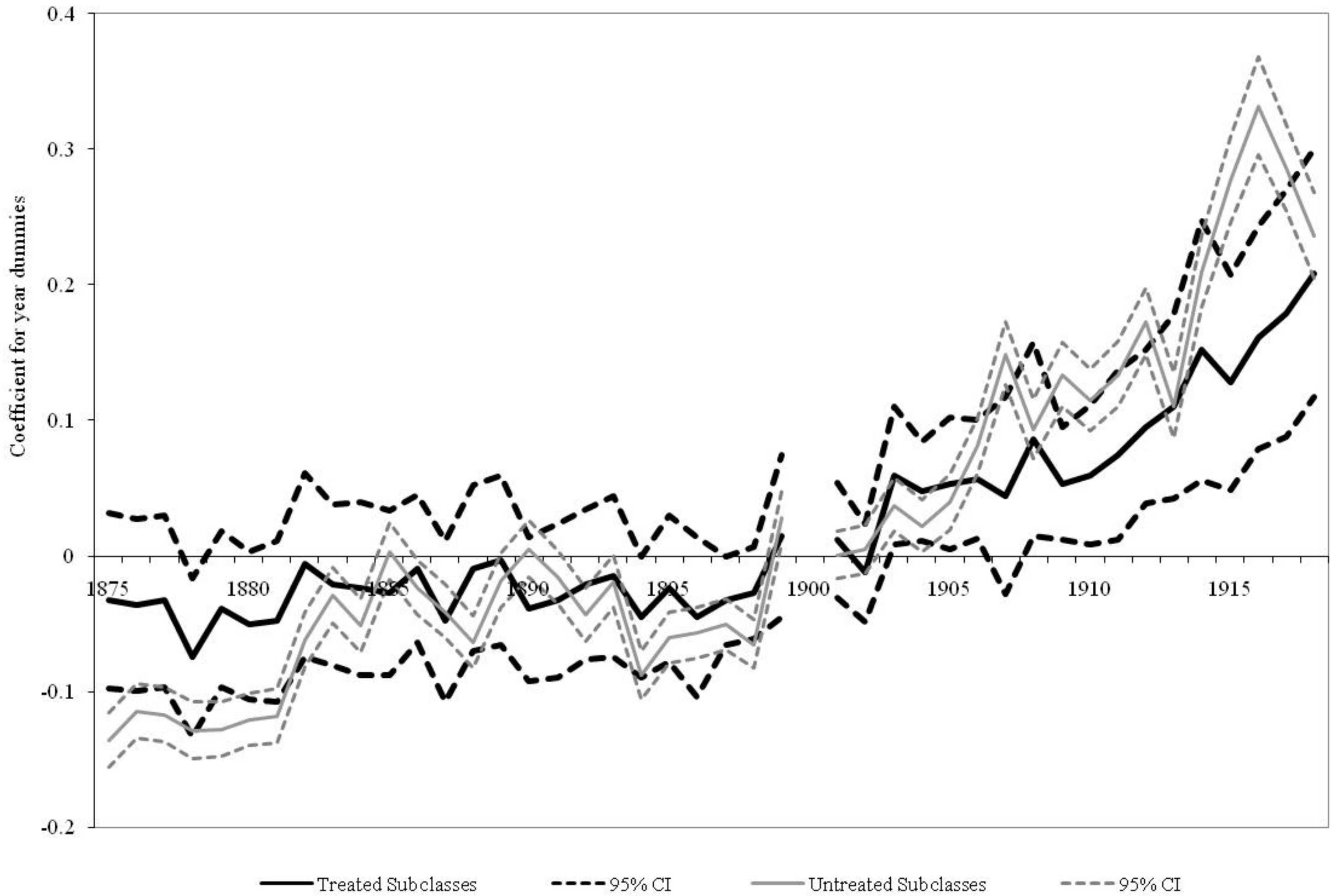
	I	**II**	**III**	**IV**	**V**	**VI**
Subclass has at least one license to Du Pont	0.0943***	0.0975***				
	0.0144	0.0119				
Subclass has at least one license to other firms	0.0213	0.0252***				
	0.0155	0.0095				
Licenses to Du Pont			0.0510***	0.0593***		
			0.0085	0.0075		
Licenses to other U.S. firms			0.0141*	0.0087*		
			0.0084	0.0048		
Remaining lifetime of Du Pont Licenses					0.004***	0.004***
					0.0006	0.0005
Remaining lifetime of other licenses					0.001*	0.001*
					0.0006	0.0005
Patents by foreign inventors	0.0295***		0.0295***		0.029***	
	0.0047		0.0047		0.0040	
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	222,924	222,924
Number of subclasses	1,913	5,716	1,913	5,716	5,716	5,716

Robust standard errors clustered at the subclass level in parentheses

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

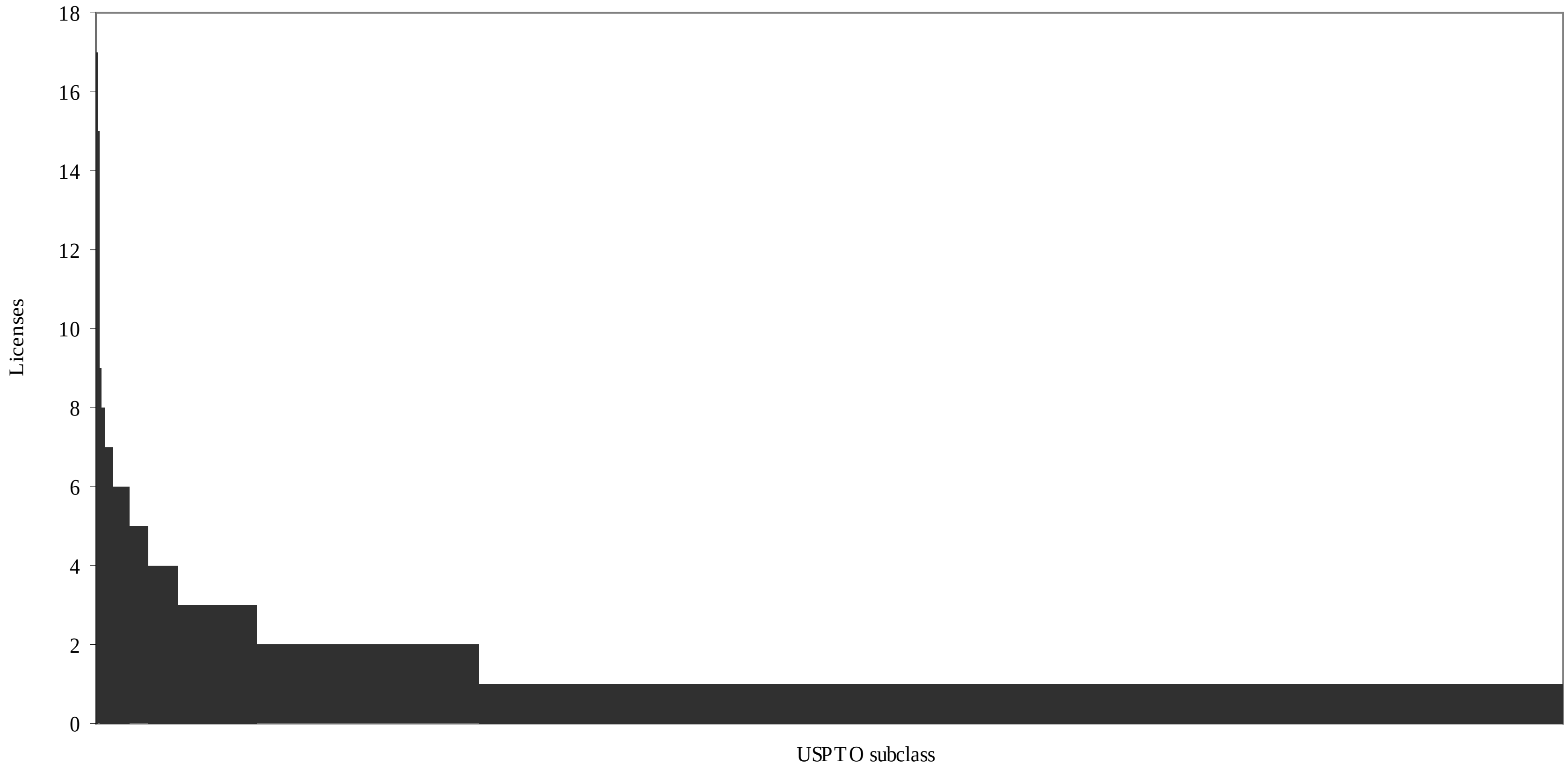
Note: Data from www.uspto.gov and the *Lexis Nexis Chronological Patent Files (1790-1970)*. Data consist of all 165,400 patents between 1875 and 1939 in 21 USPTO main classes that contained at least one license under the TWEA. These 21 main classes are subdivided into 8,422 subclasses. Data on inventor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

FIGURE 1 – PRE-TWEA TIME TRENDS IN PATENTS BY DOMESTIC INVENTORS: TREATED VS. UNTREATED SUBCLASSES



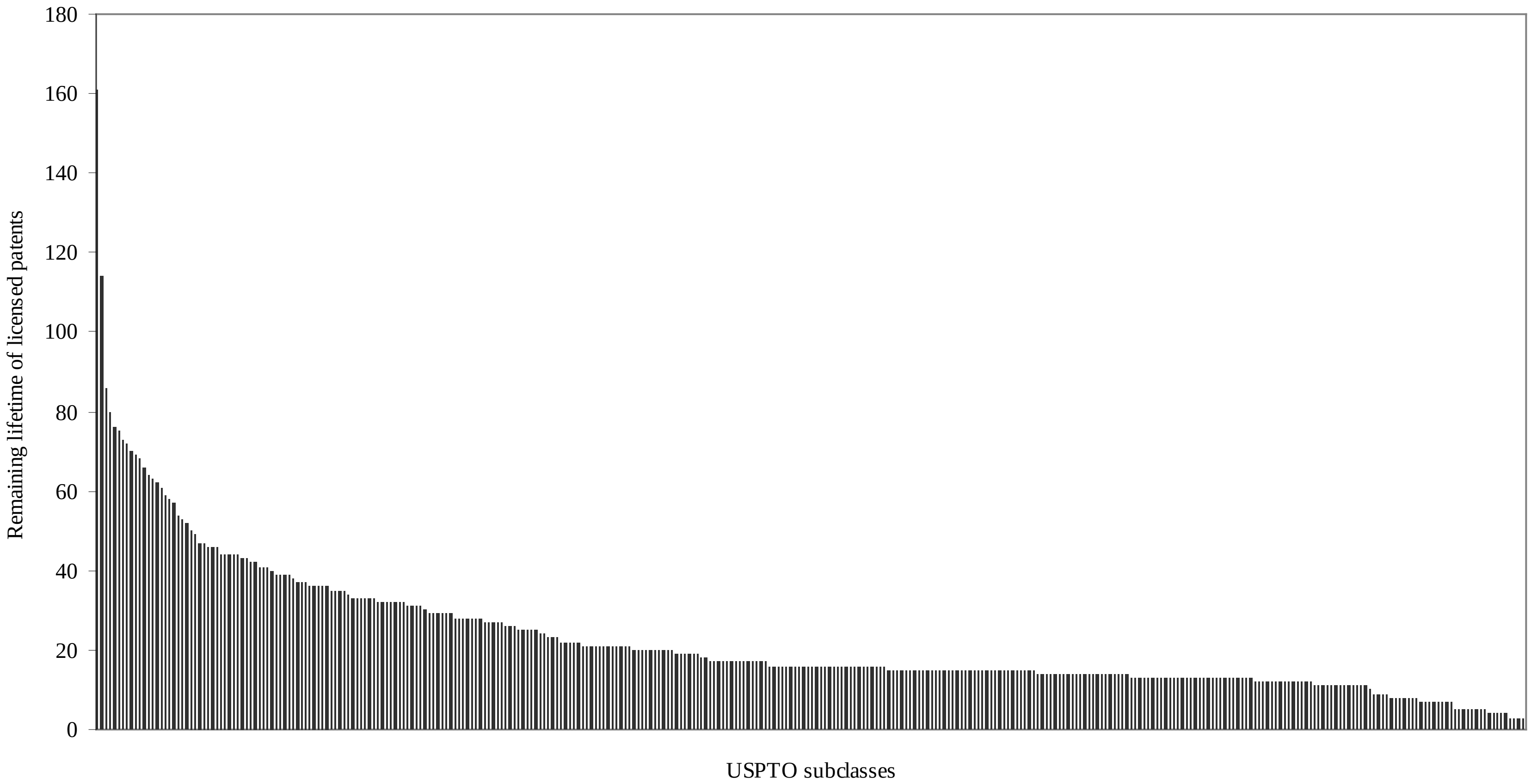
Notes: Data for 1900 serve as the omitted category. Data from www.uspto.gov and the *Lexis Nexis Chronological Patent Files (1790-1970)*. Our data consist of all 165,400 patents between 1875 and 1939 in 21 USPTO main classes that contained at least one licensed enemy patent. These 21 main classes are subdivided into 8,422 subclasses. Data on inventor nationality are based on a key word search for country names in *Lexis Nexi*s.

FIGURE 2 - NUMBER OF LICENSED PATENTS PER SUBCLASS



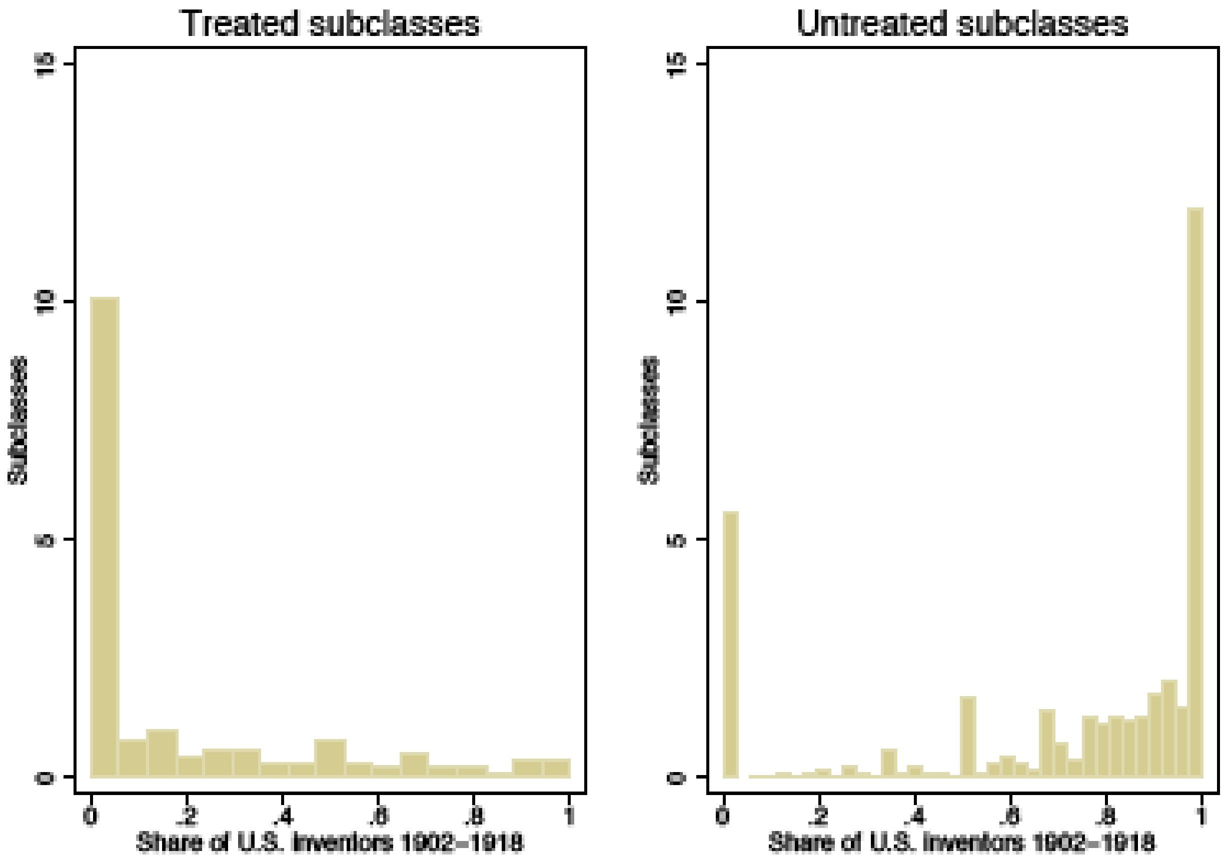
Notes: Data from Haynes (1945) and *www.uspto.gov*. Licenses refer to the total number of enemy-owned patents that were licensed to U.S. firms by the Chemical Foundation. Classes and subclasses refer to main classes and subclasses within the USPTO system of classifying patents. Main classes are divided into subclasses, which are the unit of observation for this analysis.

FIGURE 3 - REMAINING LIFETIME OF LICENSED PATENTS PER SUBCLASS



Source: Data from Haynes (1945) and www.uspto.gov. Licenses refer to the total number of enemy-owned patents that were licensed to U.S. firms by the Chemical Foundation Classes and subclasses refer to main classes and subclasses within the USPTO system of classifying patents. Main classes are divided into subclasses, which are the unit of observation for this analysis. The remaining lifetime of licensed patents is calculated adding 17 years to the year of granting and subtracting 1918, which is the year of initial licensing.

FIGURE 4 – NUMBER OF SUBCLASSES WITH AND WITHOUT LICENSE BY PRE-TWEA SHARE OF DOMESTIC INVENTORS



Notes: 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*.

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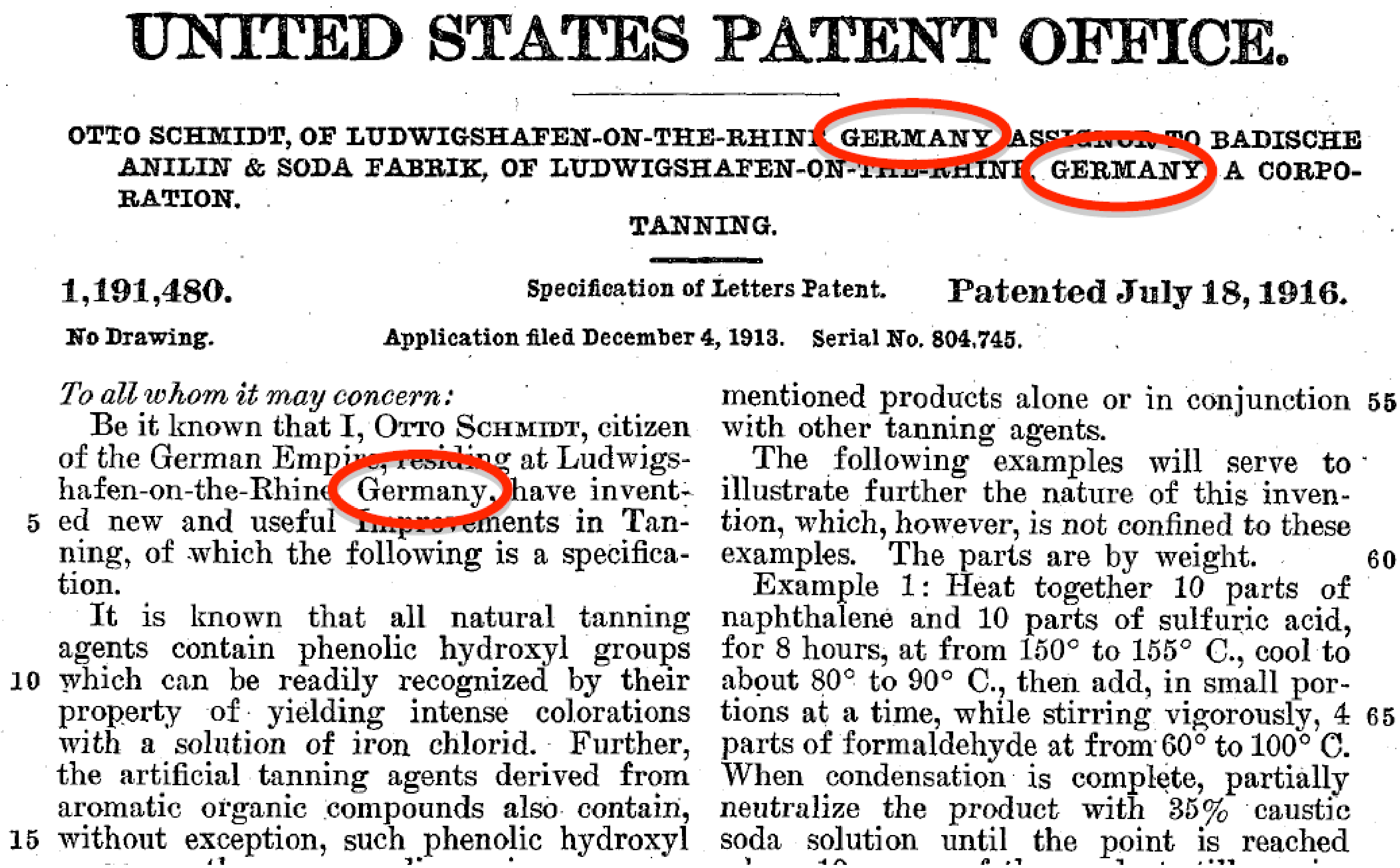
FIGURE 5 – SAMPLE U.S. PATENT OF DYESTUFF



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

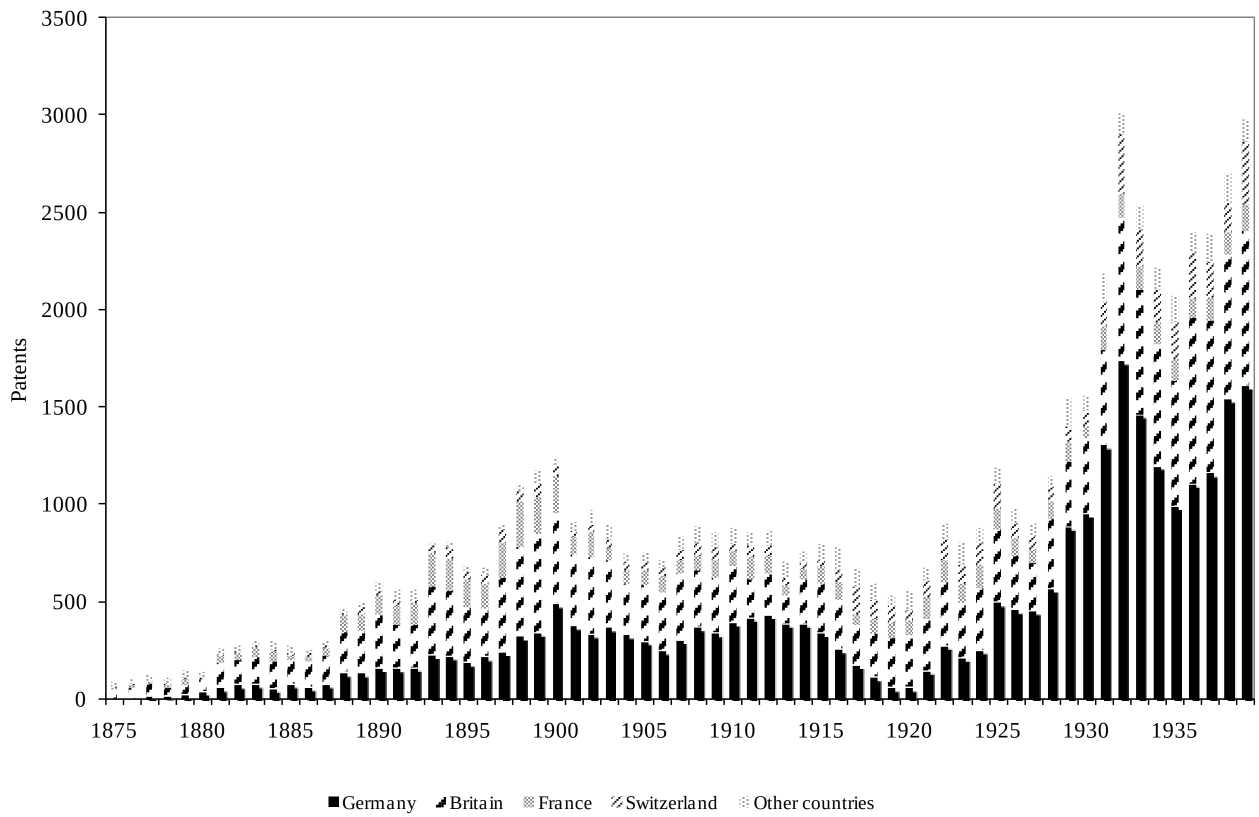
mentioned products alone or in conjunction with other tanning agents.

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

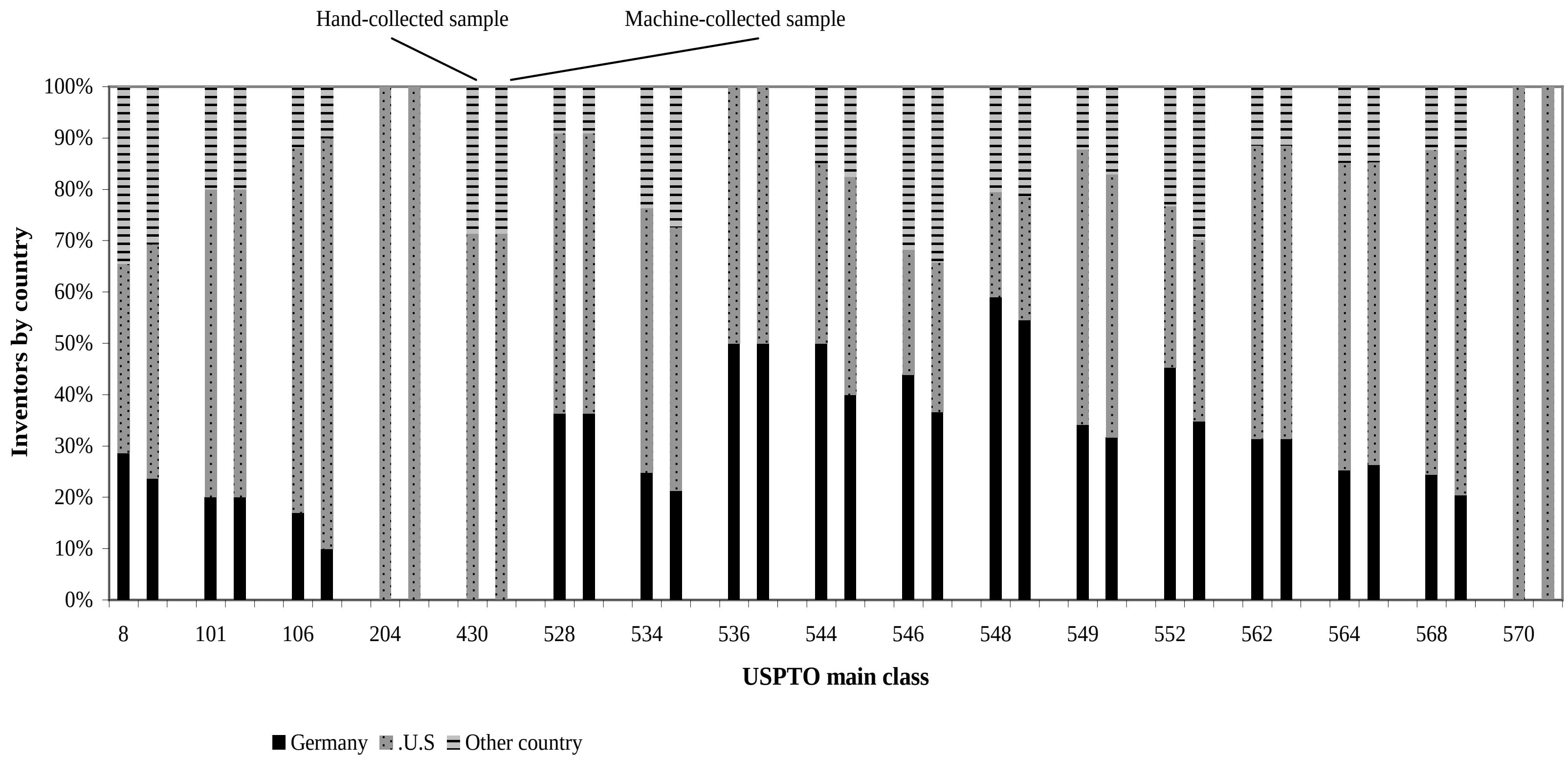
Notes: This patents illustrates the process by which optical character recognition assigns patents to inventor nationality. Our algorithm searches both the title and the full text of the patent in *Lexis Nexis*.

FIGURE 6 – U.S. CHEMICAL PATENTS BY FOREIGN INVENTORS (1875-1939)



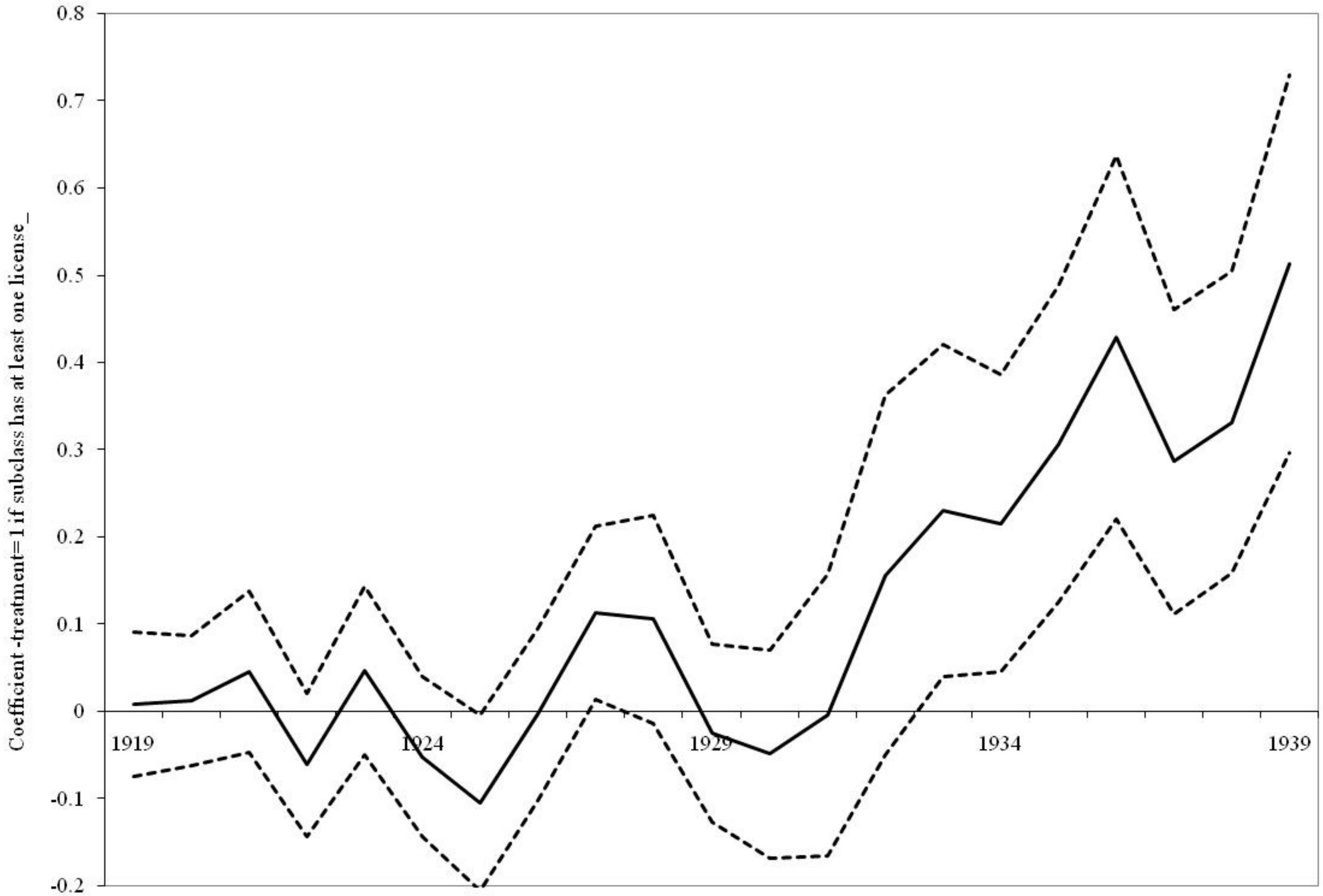
Notes: Data from www.uspto.gov and the *Lexis Nexis Chronological Patent Files (1790-1970)*. Our data consist of all 165,400 patents between 1875 and 1939 in 21 USPTO classes that received at least one license under the TWEA. Inventors' nationalities are identified by searching patent documents for names of foreign countries.. We search for any country that occurs as a country of origin in a hand-collected sample of 625 early 20th century dye patents and augment this list to include all countries exported dyes prior to 1945 (Haynes, 1945). Thus, we distinguish patents by inventors from Argentina, Australia, Austria, Belgium, Brazil, China, England, France, Germany, India, Italy, the Netherlands, Russia, Scotland, Spain, and Switzerland.

FIGURE 7 – HAND-CHECKED AND ALGORITM ASSIGNED NATIONALITES BY USPTO CLASS (1900-1943)



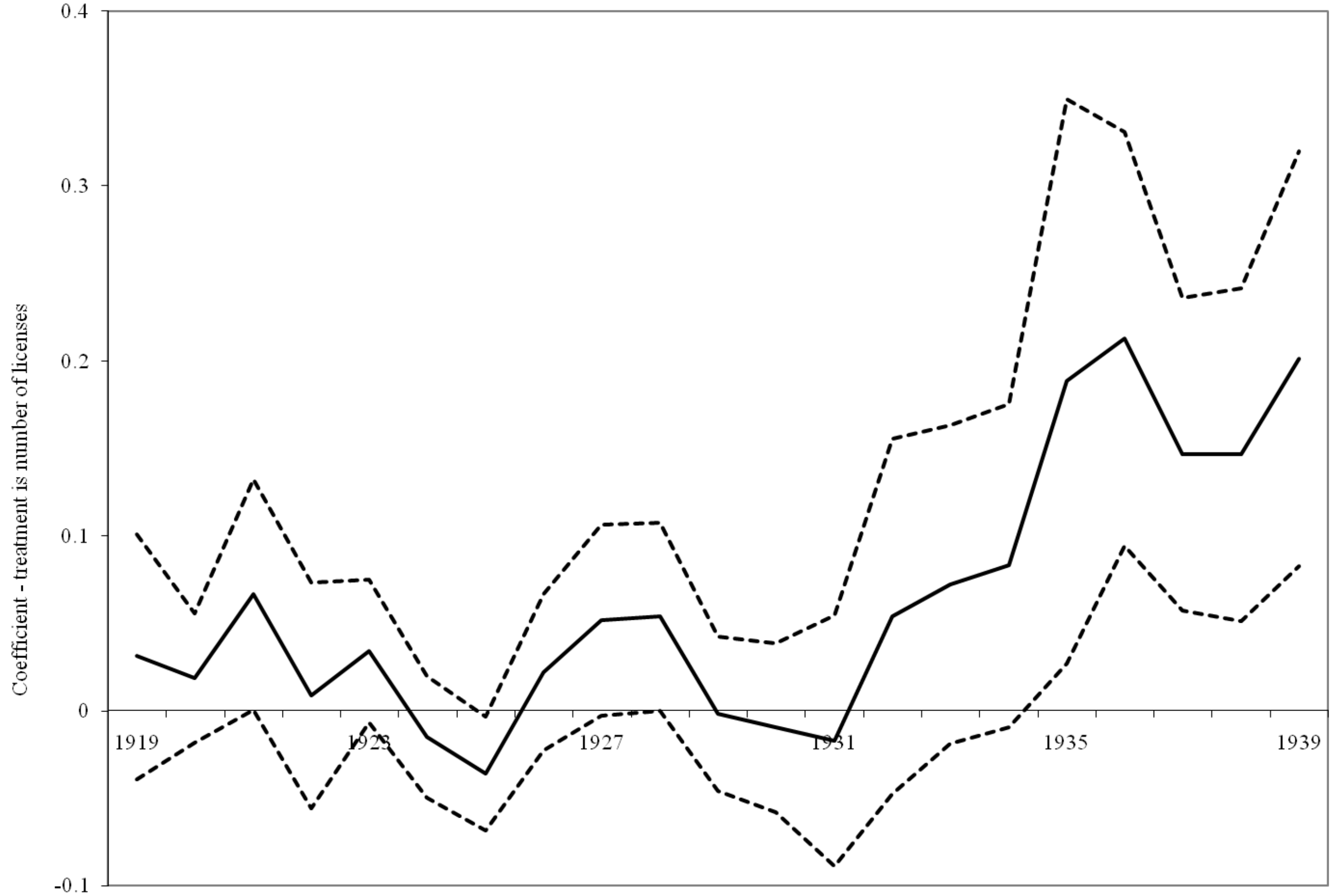
Notes: Data from Haynes (1945), www.uspto.gov and www.lexisnexis.com. To collect data on inventor nationality, we create an algorithm that performs keyword searches on LexisNexis. This algorithm relies on Optical Character Recognition (OCR), which is worse at recognizing misspelled names or untidy script 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 20th-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.

FIGURE 8 – YEAR-SPECIFIC TREATMENT EFFECT (1919-1939), DIFFERENCE-IN-DIFFERENCES ESTIMATION



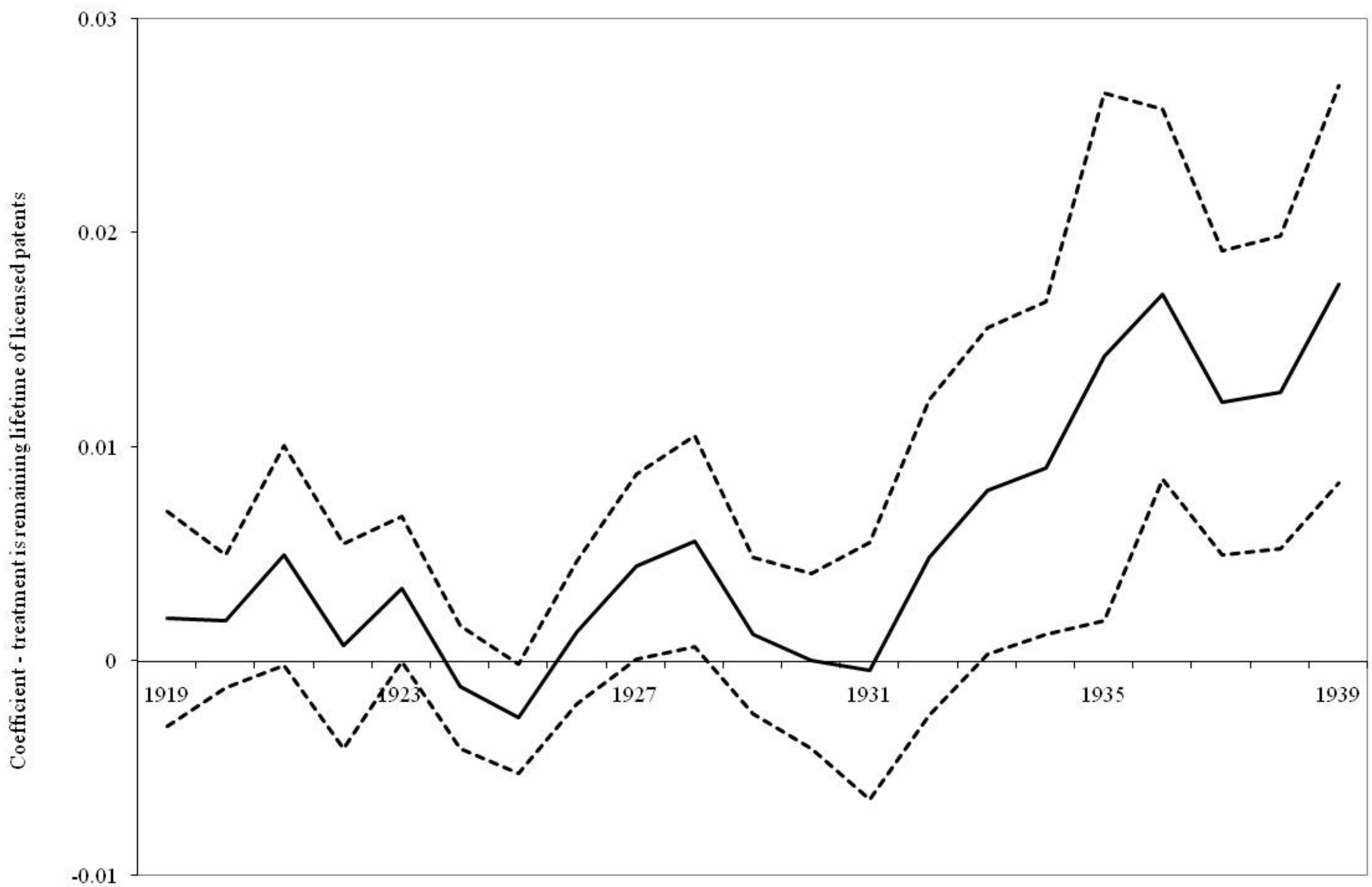
Notes: For a 95-percent confidence interval. Data from www.uspto.gov and www.lexisnexis.com. The data include all 165,400 patents between 1875 and 1939 in 21 USPTO main classes that received at least one license under the TWEA; data cover 8,422 subclasses, including 336 treated subclasses.

FIGURE 9 – YEAR-SPECIFIC TREATMENT EFFECT OF AN ADDITIONAL LICENSE UNDER THE TWEA (1919-1939), DIFFERENCE-IN-DIFFERENCES ESTIMATION



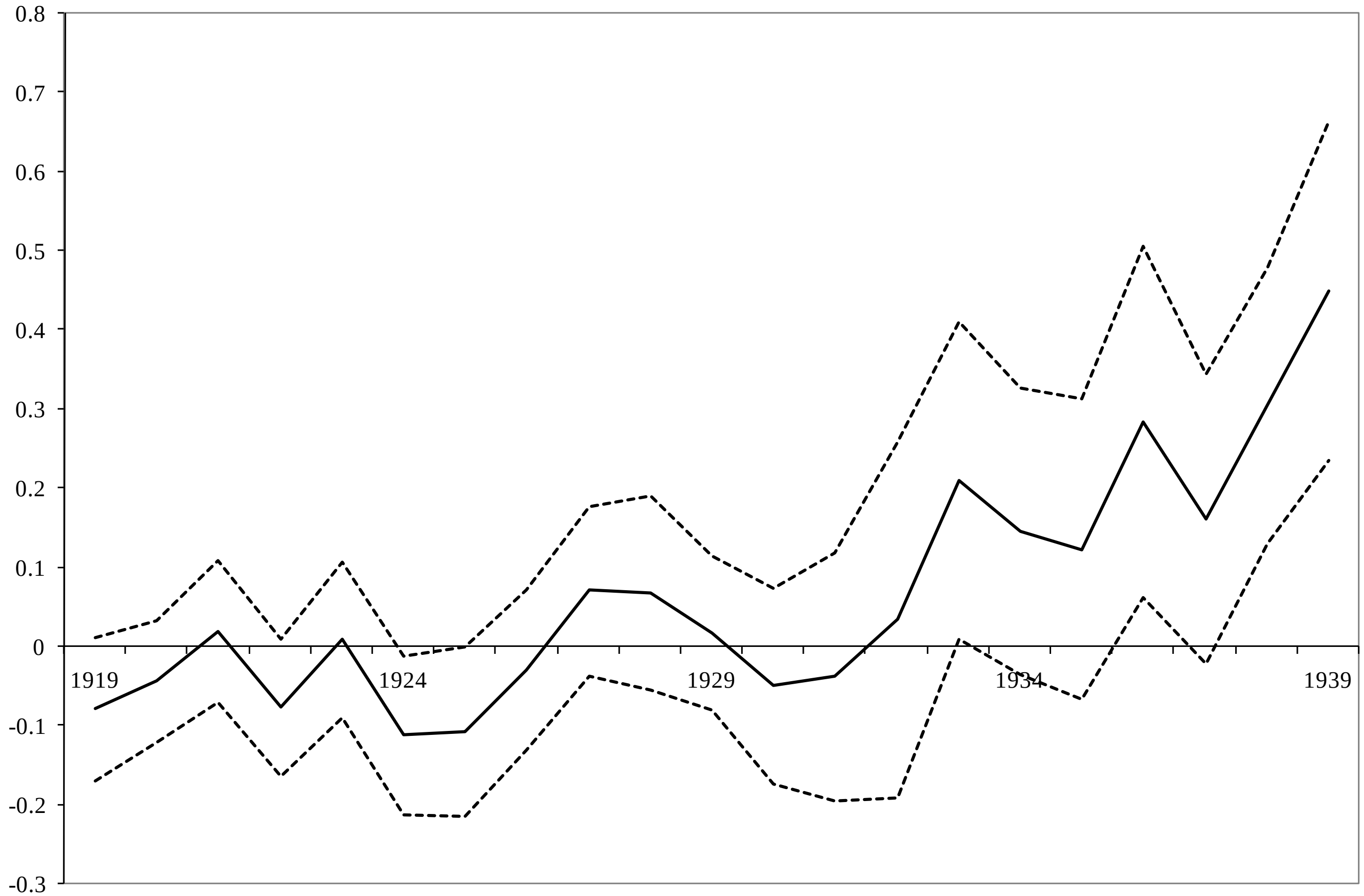
Notes: For a 95-percent confidence interval. Data from www.uspto.gov and www.lexisnexis.com. The data include all 165,400 patents between 1875 and 1939 in 21 USPTO main classes that received at least one license under the TWEA; data cover 8,422 subclasses, including 336 treated subclasses.

FIGURE 10 – YEAR-SPECIFIC TREATMENT EFFECT OF NOVELTY (ADDITIONAL YEARS OF PATENT LIFE), DIFFERENCE-IN-DIFFERENCES ESTIMATION



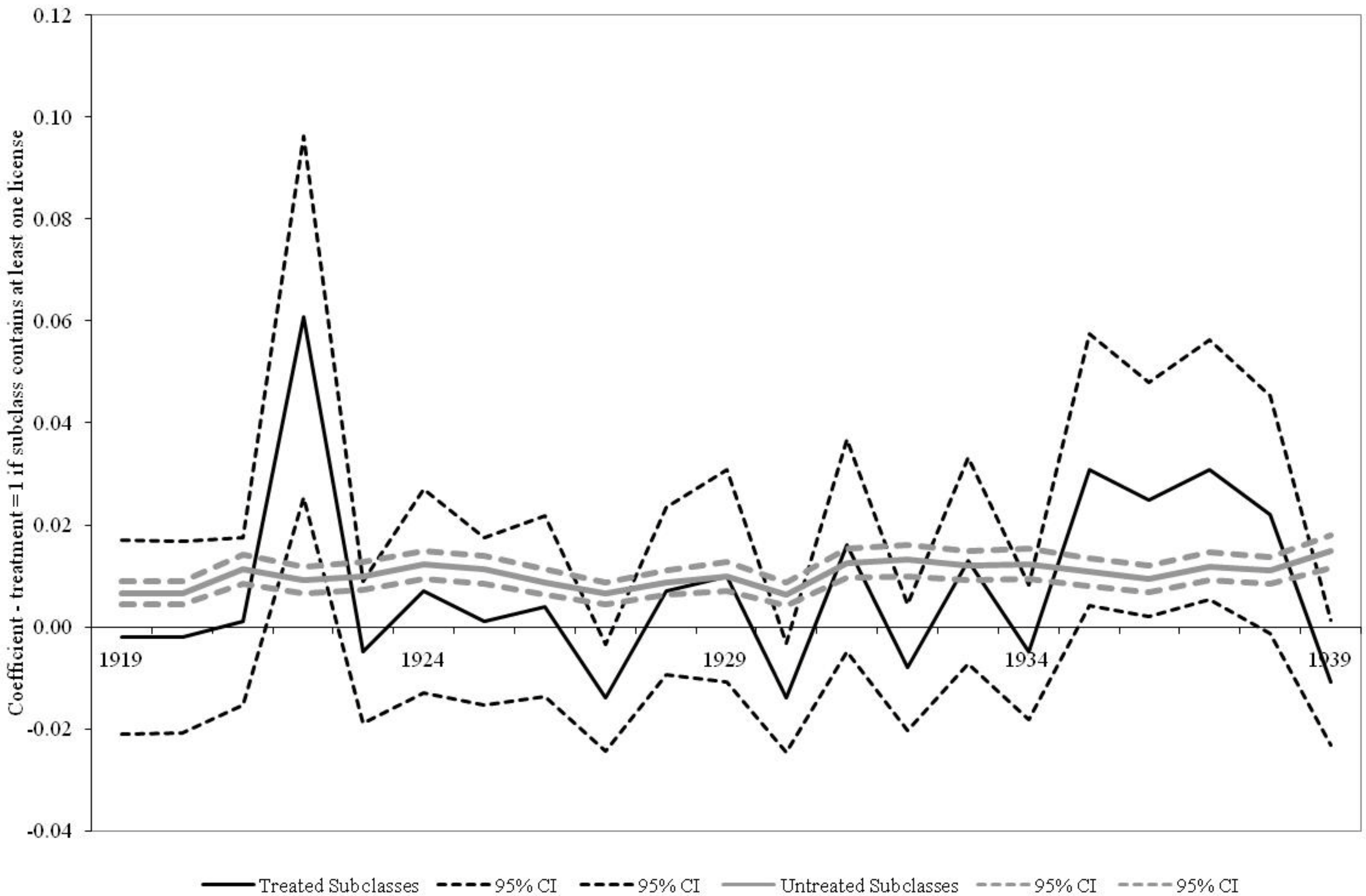
Notes: For a 95-percent confidence interval. Data from www.uspto.gov and www.lexisnexis.com. The data include all 165,400 patents between 1875 and 1939 in 21 USPTO main classes that received at least one license under the TWEA; data cover 8,422 subclasses, including 336 treated subclasses.

FIGURE 11 – YEAR-SPECIFIC TREATMENT EFFECT OF THE TWEA, TRIPLE DIFFERENCES



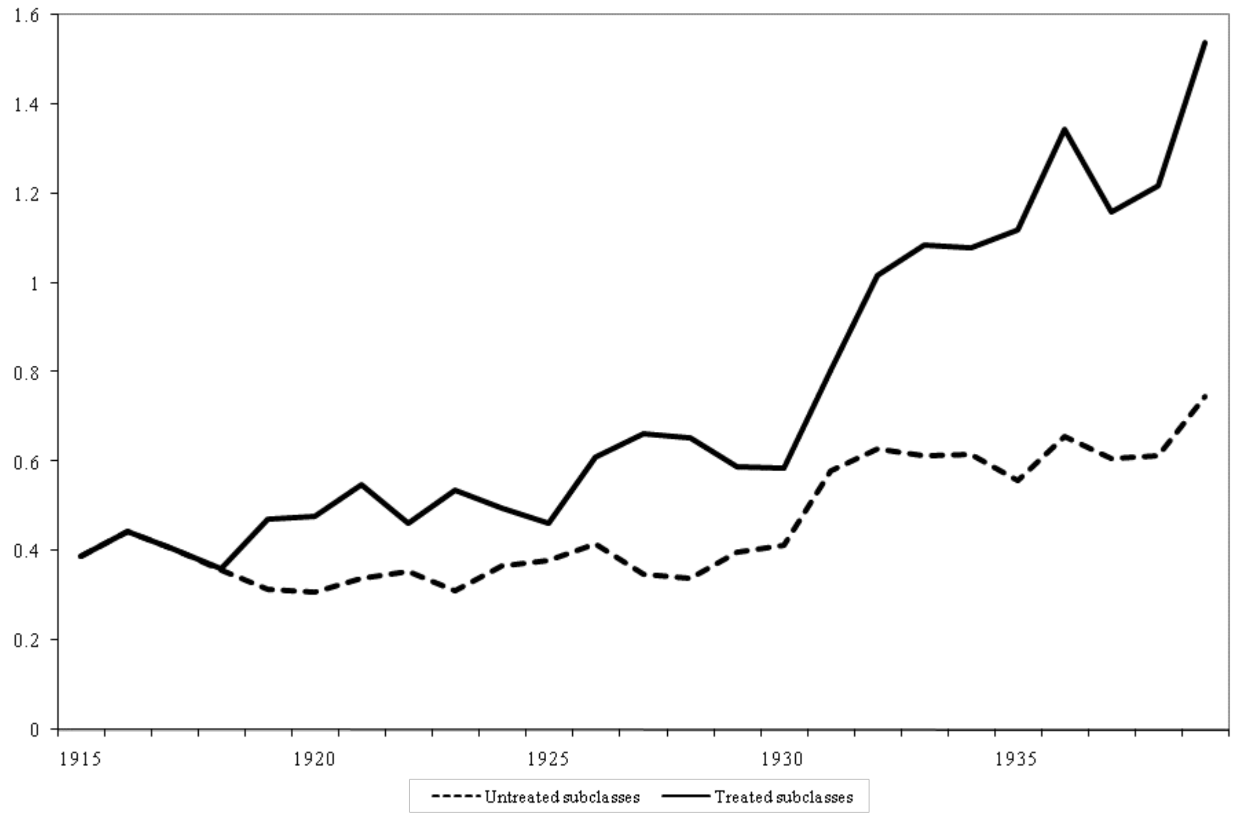
Notes: For a 95-percent confidence interval. Data from www.uspto.gov and www.lexisnexis.com. The data include all 165,400 patents between 1875 and 1939 in 21 USPTO main classes that received at least one license under the TWEA; this covers 8,422 subclasses, including 336 treated subclasses. The triple differences estimator compares U.S. patents by U.S. inventors with U.S. patents by other non-German inventors.

FIGURE 12 - PLACEBO TREATMENT ON PATENTS BY FRENCH INVENTORS (1919-1939)



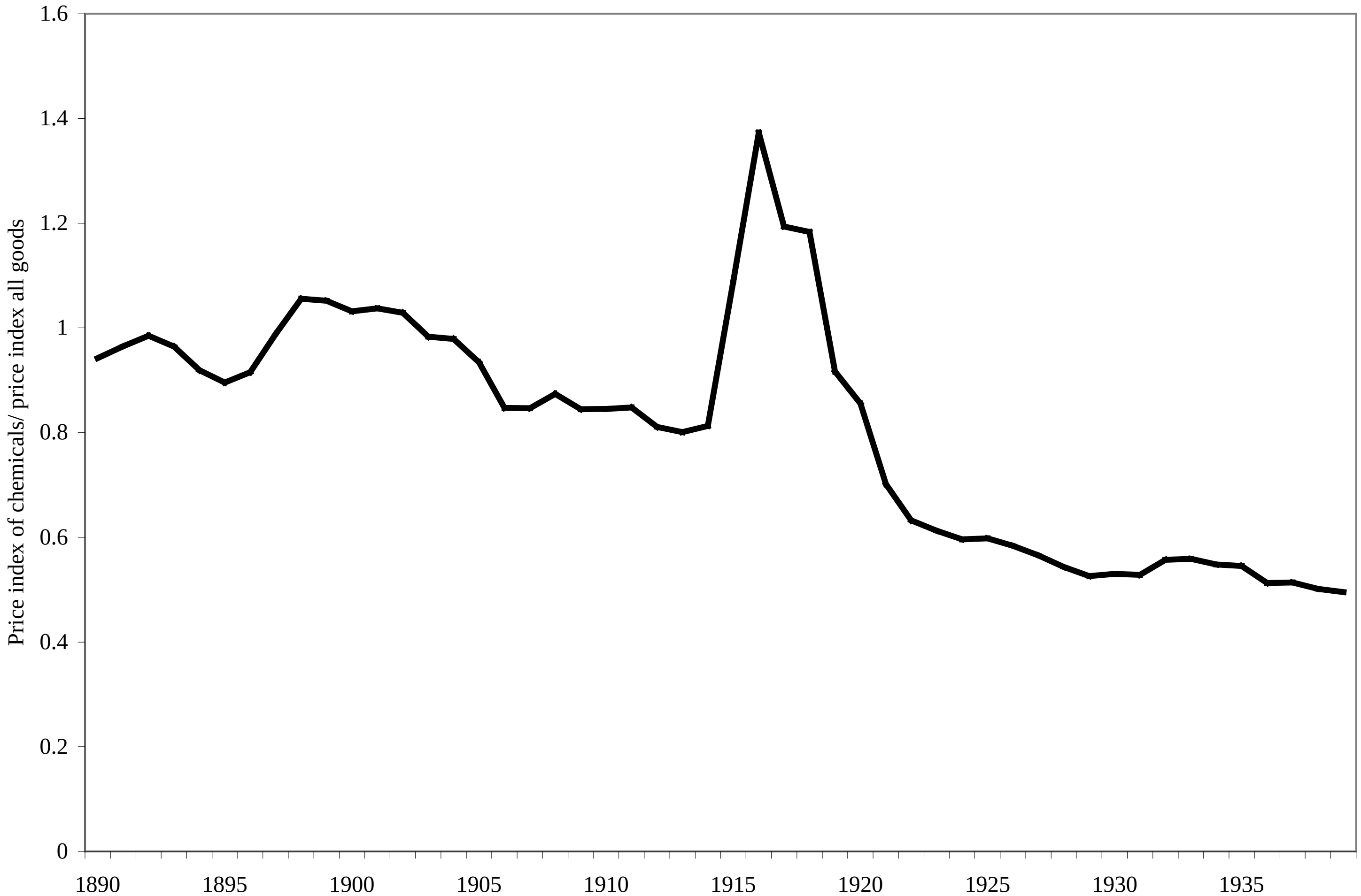
Notes: For a 95-percent confidence interval. Data from www.uspto.gov and www.lexisnexis.com. The data include all 165,400 patents between 1875 and 1939 in 21 USPTO main classes that received at least one license under the TWEA; this covers 8,422 subclasses, including 336 treated subclasses. The figure plots the coefficients of the year-specific effect of treatment on the number of patents from a French inventor.

FIGURE 13 – YEAR-SPECIFIC TREATMENT EFFECTS, DIFFERENCE-IN-DIFFERENCES, CONTROLLING FOR LINEAR TIME TRENDS



Notes: For a 95-percent confidence interval. Data from www.uspto.gov and www.lexisnexis.com. The data include all 165,400 patents between 1875 and 1939 in 21 USPTO main classes that received at least one license under the TWEA; this covers 8,422 subclasses, including 336 treated subclasses. The y-axis plots coefficients for the year-specific treatment $\beta_{t,}$ where a subclass is defined as treated if it received at least one license under the TWEA. The regression includes controls for linear time trends for treated subclasses.

FIGURE 14- RATIO OF THE PRICE INDEX OF CHEMICALS AND DRUGS OVER THE GENERAL LEVEL OF PRICES (1890-1940)

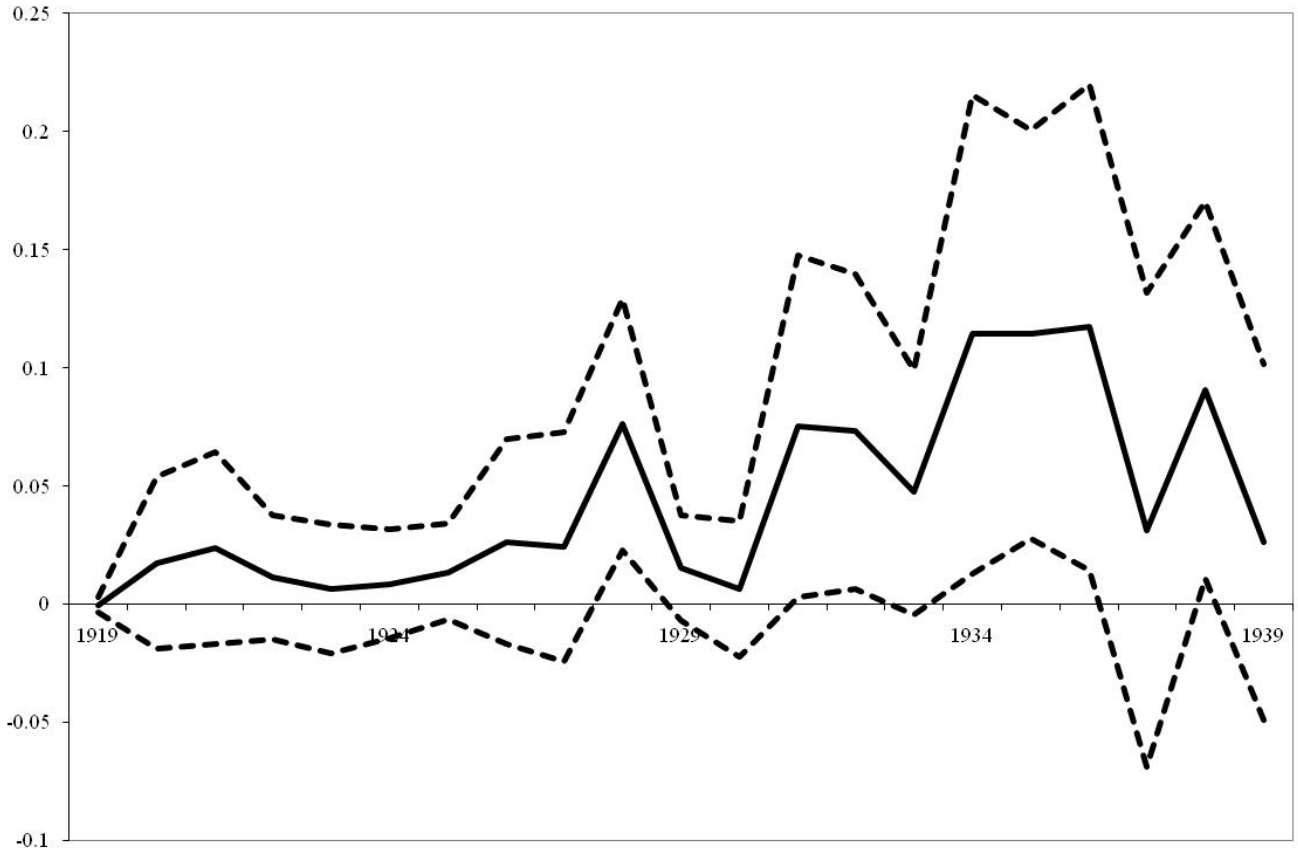


Notes: Price data from the NBER Macrohistory series 2007: "U.S. Index of the General Price Level 01/1860-11/1939" and "U.S. Index of Wholesale Price of Chemicals and Drugs, Bureau of Labor Statistics 01/1890-12/1951."

FIGURE 15 – INDIGO PRICE PER POUND

Notes: Price data from Haynes 1945, Haber 1971, p.185.

FIGURE 16 - YEAR-SPECIFIC TREATMENT EFFECT S DIFFERENCES IN DIFFERENCES (1919-1939) – PATENTS OF INDIGO DYES



Notes: For a 95-percent confidence interval. 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*. The average number of indigo patents in each subclass-cell is 0.035.