COMPULSORY LICENSING AND INNOVATION

– HISTORICAL EVIDENCE FROM GERMAN PATENTS AFTER WWI*

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Compulsory licensing allows governments to license patented inventions without the consent of patent owners. Intended to mitigate the potential welfare losses from enforcing foreign-owned patents, many developing countries use this policy to improve access to drugs that are covered by foreign-owned patents. The effects of compulsory licensing on access to *new* drugs, however, are theoretically ambiguous: Compulsory licensing may encourage innovation by increasing competition or discourage innovation by reducing expected returns to R&D. Empirical evidence is rare, primarily because contemporary settings offer little exogenous variation in compulsory licensing. We address this empirical challenge by exploiting an event of compulsory licensing as a result of World War I when the US Trading with the Enemy Act made all German-owned patents available for licensing to US firms. Firm-level data on German patents indicate that compulsory licensing was associated with a 30 percent *increase* in invention by German firms whose inventions were licensed.

Keywords: Innovation, patents, compulsory licensing, TRIPS, intellectual property, economic history.

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In recent years, many developing countries have used compulsory licensing to improve access to patented drugs. Intended to mitigate the welfare costs from enforcing foreign-owned patent rights, compulsory licensing allows governments to license patents to domestic firms - without the consent of foreign patent owners.¹ For example, Brazil, Malaysia, Zimbabwe, Mozambique, Zambia, Ghana, Indonesia, Thailand, Rwanda, and Ecuador have used compulsory licensing to provide affordable HIV drugs to domestic consumers (Beall and Kuhn 2012), and Thailand and India have used compulsory licensing to improve access to cancer drugs. The welfare effects of this policy are a subject of intense international debates. A model of intellectual property rights in developing countries predicts that compulsory licensing can raise welfare by improving access to patented products (Bond and Saggi 2014).²

The dynamic effects of compulsory licensing on access to *new* innovations are, however, theoretically ambiguous and empirical evidence is rare.³ Notably, compulsory licensing may discourage long-run innovation by reducing the expected effectiveness of patents, and thereby lowering the expected returns from investments in R&D. For example, a basic model of intellectual property rights (e.g., in Scotchmer 2004, pp. 35-39) implies that secure patents can encourage innovation by improving inventors' ability to capture the returns from R&D.⁴

¹ With the 1995 TRIPS (Trade-Related Aspects of Intellectual Property Rights) Agreement, signatories agreed to gradually switch towards enforcing foreign-owned patents (which had not typically been enforced until then).

² A structural analysis of antibiotics in India shows that enforcing foreign patents can increase price by 100 to 400 percent (Chaudhuri, Goldberg, and Jia 2006). Duggan, Garthwaite and Goyal (2016) find that patents for pharmaceutical molecules have raised the price of molecules by less than 6 percent, suggesting that compulsory licensing and other regulatory tools have reduced upward pressures on price.

³ In the 1950s, F.M. Scherer and his co-authors interviewed 22 US companies, including 10 who had been subject to consent decrees requiring compulsory licensing. Their analysis indicates that the majority of companies judged patent protection to be unimportant in their decisions to invest in research and development (Scherer 1977). Chien (2003) examines six case studies of consent decrees with compulsory licensing in the United States between 1980 and 1997, and shows that five of six patent-owners did not reduce patenting after compulsory licensing.

⁴ A complementary view, reaching back to Schumpeter (1934 and 1942) argues that large firms, which are typically the owners of licensed patents, have greater incentives to innovate because they are better able to appropriate returns from investments in R&D. Goettler and Gordon (2011) confirm these predictions with estimates of a dynamic oligopoly model for the durable goods microprocessor industry; their estimates imply that the rate of innovation in product quality would be 4.2 percent higher if IBM was a monopolist.

Yet, theoretical models of competition and innovation also imply that compulsory licensing can also *encourage* innovation by increasing the threat of competition, and thereby motivating market leaders to invest in increasing the size of their lead. For example, Arrow (1962) shows that, if patents create exclusive monopoly rights to inventions, incentives to innovate are smaller for a monopolist who faces no (actual or potential) competition, compared with a competitive firm. For the monopolist, the stream of rents from an invention replaces an existing stream of rents. For a competitive firm, there are no existing streams of rents, so that incentives to innovate are higher for the competitive firm.⁵

Aghion et al. (2001, 2005) reconcile the positive and negative effects of competition on innovation to predict an inverted U-shaped relationship. At low levels of competition, an increase in competition encourages invention by encouraging incumbents to invest in R&D to “escape” competition. At high levels of competition, an increase in (“neck-and-neck”) competition discourages invention by further reducing post-invention rents.⁶

To examine the effects of compulsory licensing on the inventors whose patents were licensed, this paper examines the effects of an arguably exogenous event of compulsory licensing as a result of World War I. Under the 1917 Trading with the Enemy Act, US authorities confiscated all US patents by German inventors and made 4,706 German-owned US patents available for compulsory licensing. US authorities then issued non-exclusive licenses for 1,246 of these patents “upon equal terms and a royalty basis, to any bona fide American individual or corporation” (Haynes 1945, p. 260). Although the exact timing of licensing is unknown, most

⁵ Consistent with this view antitrust policy in a domestic setting has used compulsory licensing as a mechanism to encourage competition (Chien 2003). In 2013, for example, the US Department of Justice and the US Patent and Trademark Office issued a joint statement to call for compulsory licenses on thousands of patents (Policy Statement on Remedies for Standards-Essential Patents Subject to Voluntary F/RAND Commitments, January 8, 2013.)

⁶ Schmidt (1997) predicts an inverted U by incorporating bankruptcy: Competition increases the risk of bankruptcy, which encourages managers to innovate to preserve their jobs, but also reduces returns from cost-saving inventions by reducing demand for each firm.

licenses were issued between 1919 and 1922 (Steen 2001). Moser and Voena (2012) have shown that access to German patents helped trigger an increase in US invention in organic chemistry; in fields with licensing, US patents by domestic inventors increased by an additional 20 percent after 1918 compared with other fields of chemical research. This paper extends the research to investigate the effects of compulsory licensing on *inventors whose patents were licensed*.

To examine effects of the US TWEA on German inventors, we have constructed new historical firm-level data on German patents for chemicals.⁷ These data cover 79,591 patents issued by the German Patent Office (GPO) across 212 research fields of chemicals between 1900 and 1930; 101 of these fields were affected by compulsory licensing. To investigate firm-level changes, we match patents with information on 4,814 German firms. 30,499 patents were assigned to 4,814 firms; 50 of them saw at least one of their patents licensed under the TWEA.

Baseline specifications compare changes in German patents after 1918 across fields of chemical patenting that were differentially affected by compulsory licensing. This approach allows us to investigate the effects of compulsory licensing on invention, controlling for unobservable factors, such as war reparations and punitive tariffs, which influenced German invention in chemicals after the war.⁸

Consistent with the predictions of Arrow (1962), we find that German inventors began to patent *more* after 1918 in research fields in which their patents had been licensed. German inventors applied for 3.19 additional patents per year after 1918 in fields with licensing compared with other fields of chemical invention. Relative to a pre-1918 average of 10.77, this result implies a 30 percent increase.

⁷ We focus on chemicals and pharmaceuticals because these industries are important targets for compulsory licensing, and patents are exceptionally effective as a mechanism to protect chemicals and pharmaceuticals (Levin et al. 1987, Harhoff et al. 1999, Cohen, Nelson, and Walsh 2000), so that patent data are a useful proxy for invention.

⁸ We also control for patents by foreign inventors as a proxy for changes in demand, scientific breakthroughs, or other factors that may have encouraged patenting in Germany, irrespective of compulsory licensing.

A key concern with the baseline OLS regressions is that US firms may have been more likely to license German-owned US patents in fields in which US demand for invention was high, and German demand for invention may have increased in the same fields. Then, OLS estimates overstate the increase in invention that is due to licensing. Historical evidence, however, indicates that US firms were most likely to license German-owned patents in war-related research fields, such as dyestuffs and explosives, which faced severe problems of *excess capacity* after the war (Haber 1971, p. 251). Then, OLS under- rather than overestimates the increase in patenting that is due to licensing.

To investigate the direction and severity of selection, we exploit the fact that the US Alien Property Custodian confiscated all German-owned patents - irrespective of variation in demand - and that only confiscated patents were available for licensing to estimate instrumental variable regressions with confiscated patents as an instrument for licensed patents. Consistent with historical evidence on excess capacity, IV regressions indicate that OLS estimates are downward biased. We also repeat IV regressions with a matched sample of research fields, using the number of German patents by foreign inventors and the average patent length before 1918 as matching variables. IV estimates for the matched sample confirm that German inventors patented *more* after 1918 in research fields in which their patents had been licensed.

Additional tests control for the quality of patents, using data on inventors' decisions to pay renewal fees. This analysis suggests that part of the observed increase in patenting may have been due to an increase in lower-quality, strategic patents. Even for high-quality patents, however, our estimates indicate an additional 20 percent increase in invention in fields with licensing after 1918.

Firm-level analyses suggest that firms whose patents were licensed *increased* their R&D efforts in fields with licensing. On average, firms whose patents were licensed patented 89 percent *more* after 1919 in fields with licensing. These results are robust to excluding all patent applications after 1925, when six major chemical firms formed the conglomerate IG Farben. Firm level data also reveal a substantial increase in entry by new firms without previous patents into fields with compulsory licensing. Taken together, these results suggest that compulsory licensing may have *encouraged* innovation by increasing the threat of entry.

I. DATA

This paper examines a new historical data set of 79,591 patents for chemicals in Germany between 1900 and 1930. Our data expand on existing aggregate-level data on German patents (for example, Richter and Streb 2011) by including data on inventors' countries of residence, renewal decisions, and firm-level identifiers. This section presents a brief overview of the data; a data appendix provides more detail.

A. Patents across Research Fields, 1900-1930

Our data start with patent applications in 1900, the first year in which the GPO systematically assigned all patents to fine-grained subclasses, which allow us to define research fields.⁹ Data include patent applications until 1930, the last cohort of patent applications that were issued before 1933, when the Nazi government dismissed Jewish scientists from universities and other types of public sector jobs.¹⁰

⁹ An 1891 reform introduced product patents for chemicals; until 1891 Germany only granted process patents for chemicals (Haber 1971, p. 218). Until 1900, patents were assigned to 89 numerical classes; in 1900, the German Patent Office reformed this classification to create 513 alphanumeric subclasses.

¹⁰ The April 7, 1933 *Law for the Restoration of Public Service* dismissed all professors with a Jewish grandparent. Analyses of US patents indicate that dismissed German-Jewish scientists who moved to the United States created substantial benefits for US invention (Moser, Voena, and Waldinger 2014).

Among 212 subclasses of chemical invention, 167 include at least one confiscated patent, and 101 include at least one licensed patent.¹¹ The average subclass with at least one licensed patent includes 18 licensed and 38 confiscated patents (with a standard deviation of 53.65 and 64.33, respectively, Appendix Table A2). Five subclasses include more than 100 licensed patents: 22a *azo dyes* (436 licensed patents), 12o *hydrocarbons* (242), 12i *metalloids* (146), 12q *aminophenol* (110), and 12k *ammonia* (108).

To assign inventor nationalities to all German patents, we extract text strings with the inventor's city of origin from each patent. 58,691 of 79,591 German patents are by German inventors. The other 20,900 German patents are by foreign inventors, including 4,133 by inventors from the United States, 3,162 from Great Britain, 3,041 from France, 2,984 from Switzerland, and 1,458 from Austria.¹² Data on German patents by US inventors allow us to check whether compulsory licensing led to an increase in US invention (Moser and Voena 2012, pp. 404-5). These data confirm that US invention increased significantly more in fields with licensing (Figure 1). Between 1900 and 1918, US firms applied for 0.67 patents per year in fields with licensing, compared with 0.56 in other fields. After 1918, US firms applied for 0.91 additional patents per year in fields with licensing compared with 0.37 in other fields.

B. Renewal Decisions to Proxy Patent Value

Griliches (1990, p. 1669) observes that patents “differ greatly in ‘quality,’ in the magnitude of inventive output associated with them.” To measure such variation, Schankerman and Pakes (1986) propose to use inventors' decisions to pay renewal fees to capture variation in

¹¹ Based on the classification of patents in the Systematische Übersicht der vom 1. Januar bis 31. Dezember 1912 in die Patentrolle eingetragenen Patente (1912).

¹² A small number of Austrian-owned US patents, 32 patents, were subject to compulsory licensing under the TWEA. To be conservative, we exclude these patents from the treatment variable, and assign German patents by Austrian inventors to the control variable *patents by other foreign inventors*.

the private value of patents. Harhoff et al. (1999) document a positive correlation between inventors' reported valuation of patents and the number of years for which inventors renewed their patents. Lanjouw et al. (1998), however, caution that researchers cannot observe the true valuation of patents that are renewed for the full term, if renewal fees are low.¹³

In Germany, renewal fees were high, so that renewal decisions were economically meaningful. In the first two years, renewal fees were 50 $\mathcal{M}$ per year (Appendix Figure A2); this is equivalent to \$243 in 2012 using purchasing power (the most conservative conversion) and \$1,340 using income value (the largest estimate, Williamson 2014).¹⁴ After the second year, renewal fees increased by 50 $\mathcal{M}$ each year, reaching 700 $\mathcal{M}$ in the 15th year, which was the end of the statutory term. To renew a patent for five years, inventors had to pay 550 $\mathcal{M}$, between \$2,670 and \$14,700 in 2012.¹⁵

To construct renewal data, we followed all 79,591 GPO patents for chemicals through renewal records in the *Annual Reports of the German Patent Office*, 1901-1942. Half of all patents - 39,682 (49.86 percent) - were renewed for five years or more; we use these patents as a proxy for high-value patents.¹⁶ 14,605 patents were not renewed in the first year (18.35 percent), 18,319 (23.02 percent) were renewed for 10 years or more, and 6,089 (7.65 percent) were renewed for the full 15-year term (Appendix Figure A3).

¹³ Patent citations, as an alternative measure of patent quality, are not available for German patents because references to prior art were not recorded. Trajtenberg (1990) shows that counts of citation are correlated with the estimated social surplus of 456 patented improvements in CT scanners. Moser, Ohmstedt, and Rhode (2014) link patents with field trial data for hybrid corn, and show that citations are correlated with improvements in yields, as an objective measure for the size of patented inventions. They do, however, also find that citation counts for early patents may overstate their value because these patents are cited to establish patentability.

¹⁴ In 1915, 50 $\mathcal{M}$ were equal to \$10.31 (Bidwell, 1970).

¹⁵ By comparison, US renewal fees were only \$1,600 in 2012 and 2014, due 3.5 years after the issue date. <http://www.uspto.gov/web/offices/ac/qs/ope/fee010114.htm>; accessed March 2, 2014.

¹⁶ Another benefit of using five years as a cut-off is that our quality measure is unlikely to be affected by a September 19, 1914 decision of Germany's Federal Council (*Bundesrat*) to suspend renewal fees; this suspension lasted nine months. In 1918, the German Patent Office announced that patentees had to pay fees for the last four years to keep their patents active (*Blatt* 1918, p. 98). As a result, any patent that was renewed for five years or more has been subject to the full fees. In the main analysis we address the issue of this suspension and other war-related disruptions through robustness checks that exclude the war years (1914-1919) from the sample.

C. Firm-level Changes in Patenting

To investigate firm-level changes in patenting, we extract firm names from patent applications. 4,814 unique German firms own 30,499 GPO patents with application years between 1900 and 1930. Most of these firms (58.5 percent) own a single patent (Appendix Figure A4); another 22.9 percent own two or three patents. The average firm owns 6.3 patents. Only 14.8 percent own five or more patents. The remaining 49,092 German-owned patents were issued to individual inventors or foreign firms; in firm-level regressions, we use these patents as a control for scientific breakthroughs, changes in demand, or other unobservable factors that may influence changes in patenting across fields.

Firm-level patent data allow us to investigate changes in patenting for firms that were differentially affected by compulsory licensing. 1,017 of 1,246 licensed patents were owned by a total of 50 German firms (using records from Haynes 1945 and the Alien Property Custodian 1919, see Data Appendix). Another 229 licensed patents list the US Chemical Foundation (created for the purpose of licensing German-owned patents to US firms) as an assignee owner. The remaining 208 patents are owned by individuals, including 53 patents by co-assignees of a German firm. For example, Dr. Richard Herz from Frankfurt is listed as an inventor for US patents 956348, 960919, and 966092 of the German firm Cassella, and we assign one remaining US patent by Dr. Herz (US patent 1243171) to the same firm.

The firms that were most affected by licensing were the German Bayer AG (551 licensed patents), the Badische Anilin und Soda Fabrik (BASF, 308 licensed patents), Meister Lucius (104 licensed patents), Griesheim-Elektron (57), AGFA (38), Cassella (22), and the Berlin-Anhaltische Maschinenbau AG (BAMAG, 17). Another 43 firms saw between 1 and 12 of their

US patents licensed under the TWEA. 12,531 patents by these 50 German firms cover 123 subclasses in the German patent system, and 17,968 patents by 4,764 firms without licensed patents cover 202 subclasses.¹⁷

II. RESULTS

Comparisons of means indicate that German inventors began to patent *more* in research fields with licensing after 1918. In 101 fields with licensing, patent applications by German inventors increased by 53 percent from 10.77 per year until 1918 to 16.49 afterwards (Table 1, Panel A). By comparison, in 111 fields without licensing, patenting increased by less than 10 percent from 5.05 until 1918 to 5.54 afterwards.

Annual patent data show fields with licensing produced more patents per year in the pre-war period (Appendix Figure A5, Panel A). These data also suggest that patenting may have begun to increase at a slightly higher rate for fields with licensing before 1918. In the regressions, we will address this issue through alternative controls for pre-trends; results are robust to controlling for these trends.

Most notably, German inventors began to patent significantly more in fields with licensing after 1919, while patenting stayed flat in other fields. To investigate these changes systematically with controls, we estimate:

$$(1) \text{ patents}_{ct} = \beta_0 + \beta_1 \cdot \text{field with licensed patents}_c \cdot \text{post}_t + \beta_2 \cdot \text{patents by non-US foreign inventors}_{ct} + \delta_t + \theta_c + \varepsilon_{ct}$$

where the dependent variable patents_{ct} measures the number of successful applications for German patents by German inventors in field c and year t between 1900 and 1930. The variable

¹⁷ Another 28,192 patents by individual inventors cover 208 research fields. Although individual inventors were less likely to patent in the United States than German firms, some individual inventors may have been affected by compulsory licensing. Analyses at the firm level exclude these data.

field with licensed patents_c equals 1 for research fields in which at least one German-owned patent was licensed under the US TWEA. The variable *post_t* indicates years after 1918. Under the assumption that – in the absence of compulsory licensing - changes in patenting would have been comparable in fields with and without licensing, the coefficient β_l measures the effect of compulsory licensing on German invention.

The variable *patents by non-US foreign inventors_{ct}* controls for idiosyncratic variation in German patents by foreign inventors across fields and over time. We exclude US inventors from this control variable because patents by US inventors increased in response to the TWEA (Figure 1, as well as Moser and Voena 2012), so that *patents by US inventor* is an endogenous control.¹⁸ Field fixed effects θ_c control for variation across fields that is constant over time. Year fixed effects δ_t control for variation in patenting over time that affects all fields. Standard errors are clustered at the level of research fields.

OLS estimates indicate that German inventors applied for 3.19 additional patents per year after 1918 in research fields with licensing (Table 2, column 1, p-value 0.001). Compared with an average of 10.77 patents per year until 1918 for these fields, this implies a 30 percent increase. Excluding controls for GPO patents by foreign inventors increases the coefficient to 5.22 (Table 2, column 2, p-value 0.001).

Until 1918, changes in patenting were similar in fields with small and large numbers of licensed patents (Appendix Figure A5, Panel B). After 1918, patenting accelerated disproportionately in research fields with 10 or more licensed patents. In 1928, inventors applied for an average of 38.4 patents per year in fields with 10 or more licenses, compared with 17.41 in fields with 3 to 10 licenses, 11.92 in fields with 2 licenses and 6.17 patents in fields with fewer than 2 licenses.

¹⁸ Results are, however, robust to controlling for *patents by US inventors* (Appendix Table A4).

Intensity regressions with the number of *licensed patents_c* indicate that German inventors applied for 0.20 additional patents per year after 1918 for each additional patent that was licensed in field *c* (Table 2, column 6, p-value 0.004). For the average field with at least one licensed patent, which includes 18.04 licensed patents, this implies a 31 percent increase.

A. Controlling for Differential Pre-Trends

As a robustness check, we re-estimate the baseline specification allowing for separate linear pre-trends in patenting for each research field:

$$(2) \text{ patents}_{ct} = \beta_0 + \beta_1 \cdot \text{field with licensed patents}_c \cdot \text{post}_t \\ + \beta_2 \cdot \text{patents by non-US foreign inventors}_{ct} + \sum_c \phi_c \cdot \text{field}_c \cdot \text{preTWEA}_t \cdot t \\ + \delta_t + \theta_c + \varepsilon_{ct}$$

where *field_c* is a vector that distinguishes 212 research fields within chemicals, the indicator variable *preTWEA_t* equals 1 for years before 1919, and the variable *t* denotes a linear time trend. Estimates with these field-specific pre-trends indicate that German inventors applied for 5.54 additional patents per year after 1918 in fields with licensing (Table 2, column 3, p-value <0.001), which implies a 51 percent increase.

Results are also robust to including field-specific linear trends for the pre- and post-TWEA period, allowing for a trend break in 1918. These estimates indicate that German inventors applied for 4.54 additional patents per year after 1918 in fields with licensing (Table 2, column 4, p-value 0.022).

We also estimate the difference-in-differences coefficient of *field with licensed patents_c* • *post_t* separately for each year, with 1918 to 1921 as the omitted category (Figure 2, Panel A). Until 1917, effects are negative and statistically significant only for 5 of 18 years. After 1918 effects are positive and statistically significant for 5 of 12 years. Estimates increase after 1923,

with 3.47 additional patents in 1924 and 3.54 in 1925, implying a 32 and 33 percent increase, respectively (with p-values of 0.008 and 0.017).

An alternative test allows for a separate linear pre-trend for fields with licensing:

$$(3) \text{ patents}_{ct} = \beta_0 + \beta_1 \cdot \text{field with licensed patents}_c \cdot \text{post}_t \\ + \beta_2 \cdot \text{patents by non-US foreign inventors}_{ct} \\ + \beta_3 \cdot \text{field with licensed patents}_c \cdot \text{preTWEA}_t \cdot t + \delta_t + \theta_c + \varepsilon_{ct}$$

These regressions indicate an increase by 5.27 additional patents per year after 1918 (Table 2, column 5, p-value <0.001), which is larger than the baseline estimate of 3.19.¹⁹

B. Excluding the War Years

An additional robustness check excludes the war years (1915-1918). For example, patenting during these years may have been influenced by changes in the demand for war-related chemicals, such as explosives and dyes. These estimates are slightly larger than the baseline estimate of 3.19 additional patents (Table 2, column 1). OLS estimates indicate that German inventors applied for 3.48 additional patents in fields with licensing per year after 1918 (Appendix Table A5, column 1, p-value 0.001). Excluding controls for patents by foreign inventors increases the size of this estimate to 5.36 (Appendix Table A5, column 2, p-value 0.001). Intensity specifications indicate that German inventors applied for 0.20 additional patents per year after 1918 for each additional licensed patent (Appendix Table A5, column 5, p-value 0.006), which implies a 31 percent increase for the average field with at least 1 licensed patent.

C. Instrumental Variable Regressions

A key challenge to investigating the effects of compulsory licensing is that the research fields in which firms chose to license foreign-owned patents are unlikely to be exogenous. In

¹⁹ The coefficient of the linear trend for fields with licensing is small (0.207, p-value 0.006).

cases of compulsory licensing today, developing countries are more likely to license foreign-owned inventions in which domestic demand is high. During World War I, US firms may also have been more likely to license German-owned US patents in which demand for invention was high, so that OLS estimate would overstate the increase in invention in both contemporary and historical setting.

The historical setting allows us to address this issue empirically because –as a response to Germany’s military aggression - the confiscation of German-owned property was credibly exogenous to changes in patenting after 1918. We exploit this set-up to estimate intent-to-treat (ITT) and instrumental variable (IV) regressions with *fields with confiscated patents* as an instrument for fields with licensed patents. These regressions exploit the fact that only confiscated patents were available for licensing (so that fields with confiscated patents were more likely to become fields with licensing), and that changes in patenting after 1918 did not influence the choice of confiscated fields (because all German-owned US patents were confiscated in 1918.) ITT (or reduced form) regressions estimate:

$$(4) \text{ patents}_{ct} = \beta_0 + \beta_1 \cdot \text{field with confiscated patents}_c \cdot \text{post}_t + \beta_2 \cdot \text{patents by non-US foreign inventors}_{ct} + \delta_t + \theta_c + \varepsilon_{ct}$$

where *field with confiscated patents_c* equals 1 if field *c* includes at least 1 confiscated German-owned US patent. Among 212 research fields of chemical inventions, 167 fields include at least 1 confiscated patent; 101 of these 167 fields with confiscated patents include at least 1 licensed patent (60 percent). ITT estimates imply that German inventors applied for 2.50 additional patents per year after 1918 in fields with confiscated patents (Table 3, column 1, p-value 0.003). Compared with an average of 10.77 patents per field and year until 1918, this result implies a 23 percent increase.

ITT estimates of this regression indicate that OLS may *underestimate* the effects of compulsory licensing during WWII. At 2.50 (Table 3, column 1), ITT estimates are 31 percent larger than 1.91, the product of the OLS estimate of 3.19 (Table 2, column 1) and 0.60, the probability that at least one patent in a field with confiscated patents was licensed.²⁰

IV regressions that use *fields with confiscated patents_c* as an instrument for *fields with licensed patents_c* confirm that OLS is downward biased. First stage regressions indicate that a *field with confiscated patents* is 58 percent more likely to be a *field with licensed patents* (Table 3, column 4, p-value < 0.001). IV estimates indicate that German inventors applied for 4.28 additional patents per year after 1918 in fields with licensing (Table 3, column 6, p-value 0.002), compared with 3.19 for OLS (Table 2, column 1). The local average treatment effect (LATE) of 4.28 measures the effect of making German-owned US patents available for compulsory licensing by US firms in fields in which German inventors applied for US patents between 1900 and 1918. Inventions in these fields are geared towards the US market, and (due to the costs of patenting abroad) they are more likely to be owned by larger German firms.

These results are consistent with the fact that US firms were more likely to license German-owned patents for war-related chemicals, such as dyes or explosives. In these fields, German firms were affected by a dramatic *decline* in demand after 1919. Haber (1971, p. 251), for example, explains that:

“Without demand for war-related chemicals, the worst problem that German dye producers...faced turned out to be excess capacity.”

In fact, the field with the largest number of licensed patents was subclass 22a for azo dyes (436 licensed patents, Appendix Table A6), a dye that was dramatically affected by excess supply

²⁰ ITT estimates with patents that were renewed for at least 5 years imply a 15 percent increase in patenting in GPO research fields with confiscated patents (Appendix Table A7, column 1).

after World War I. In this field, patents by German inventors declined from 28.79 per year until 1918 to 24.17 afterwards. Thus, the sum of the historical evidence on selection indicates that selection based on war-related demands may have resulted in *negative* selection during World War I, while selection today is primarily positive.

D. Matching Estimates

An alternative estimation approach creates a subsample of comparable research fields with and without licensing using a nearest neighbor propensity score matching algorithm (Rosenbaum and Rubin, 1983). Specifically, we match research fields with and without licensing using 1) the level and yearly percentage change of foreign-owned German patents between 1900 and 1917 to control for trends in the pre-TWEA fecundity of research fields and 2) the level and yearly percentage change in the average renewal duration of patents to control for pre-TWEA trends in patent quality.²¹ In the matched sample, annual patents by German inventors increased by 58 percent from 8.66 until 1918 to 13.05 afterwards for fields with licensing, compared with 19 percent from 6.14 to 7.31 for matched fields without licensing (Appendix Figure A6).

OLS estimates for the matched sample indicate that German inventors applied for 2.13 additional patents per year after 1918 in research fields with licensing (Appendix Table A8, column 1, p-value 0.065). Compared with a pre-licensing average of 8.66 patents in the matched fields with licensing, these results imply a 25 percent increase (compared with a 30 percent increase for the full sample, Table 2, column 1). Including field-specific pre-trends increases the size of this estimate to 3.06 (Appendix Table A8, column 3, p-value 0.064). With a single linear

²¹ A matching algorithm estimates propensity scores with the probit regression: $\Pr(\text{field with licensed patents}_{ct} = 1 \mid X) = \Phi(\beta_0 + \sum_t \beta_{1t} \cdot \text{patents by non-US foreign inventors}_{ct} + \sum_t \beta_{2t} \cdot \% \Delta \text{ patents by non-US foreign inventors}_{ct} + \sum_t \beta_{3t} \cdot \text{average renewal duration}_{ct} + \sum_t \beta_{4t} \cdot \% \Delta \text{ average renewal duration}_{ct})$, where Φ is cumulative distribution function of the standard normal distribution, $\% \Delta$ denotes a yearly percentage change, and t ranges from 1900 to 1917.

pre-trend for fields with licensing, OLS estimates indicate that German inventors applied for 32.81 additional patents in fields with licensing (Appendix Table A8, column 4, p-value 0.081). The coefficient for the pre-trend is small (0.067) and not statistically significant (p-value 0.361). Time-varying estimates are similar to the baseline OLS estimates (Figure 2, Panel B).

E. Excluding Years after the Creation of IG Farben

An additional robustness check excludes application years after 1924, the last year before the creation of the IG Farben. The cartel-like “community of interest” (in German Interessengemeinschaft, or IG) formed on December 25, 1924. It included the largest firms in the German chemical industry: AGFA, Bayer, BASF, Hoechst, Griesheim-Elektron, and Chemische Fabrik (vorm. Weiler Ter Meer). Haber (1971, pp. 290-91) explains: “In the latter half of the 1920s, the German chemical industry employed nearly 0.3 million people, and on this reckoning IG Farben accounted for over a third.”²² To mitigate competition, members of the IG Farben specialized in specific chemicals. After the creation of IG Farben,

“the Leverkusen works of Bayer increased their make of dyes by over a quarter, ...Hoechst was assigned responsibility for all chemicals from acetylene, and in this connexion (sic) took over the Griesheim patents and technique for polyvinyl acetate manufacture... Bayer became the concern’s principal manufacturer of the azo-group of dyes...Badische became the specialist in high-pressure synthesis in all its aspects” (Haber 1971, pp. 285-86).²³

Estimates with the restricted sample of patents until 1924 confirm that patenting increased in research fields with licensing after 1918. Baseline estimates indicate that German inventors applied for 2.87 additional patents per year after 1918 in research fields with licensing

²² Also see Aftalion (2001, p. 138): “The new giant had a workforce of 67,000 people including 1,000 chemists, and accounted for one third of Germany’s chemical industry sales.”

²³ In the main specifications, we assign patents by IG Farben to the original six firms according to the pre-existing distribution of patents between 1910 and 1914 across firms and technology fields (Appendix Table A9). This approach allows us to include IG Farben in the inventor-level analysis but it assumes that the distribution of patenting remained stable after the 1924.

(Appendix Table A10, column 1, p-value 0.012). Compared with an average of 10.77 patents per year until 1918 in fields with licensing, this implies a 27 percent increase. Regressions with field-specific pre-trends indicate a larger increase of 5.07 additional patents per year after 1918 (Appendix Table A10, column 3, p-value 0.002), which implies a 47 percent increase.

Excluding data after 1924 may, however, lead us to underestimate firms' response to compulsory licensing, if compulsory licensing influences invention with some delay. For US inventors, the strongest increase in patenting occurred six years after the first licenses were issued, which is consistent with a prolonged period of learning (Moser and Voena 2012, p. 409). For example, Du Pont's early runs of indigo blue turned out green (Hounshell and Smith 1988, p.90). If German inventors also responded to compulsory licensing with some delay, regressions that drop years after 1924 underestimate the effects of compulsory licensing.

F. Renewals as a Control for Patent Value

We also examine whether the observed increase in patenting may be due to lower quality, strategic patents. Following Schankerman and Pakes (1986), we use information that we collect on inventors' decisions to pay renewal fees as a measure of variation in inventors' valuation of patents. Patents that inventors renewed for at least 5 years (the median renewal year) serve as a proxy for high-value patents. Estimates with renewed patents imply a large and statistically significant increase in high-value patents.²⁴ Renewed patents follow a similar trend for fields with and without licensing until 1918 (Appendix Figure A7, Panel A). After 1918, renewed patents increased in fields with licensing but not in other fields. In 1927, German inventors

²⁴ For example, inventors may have responded to the loss of their US patents by building a "patent thicket," which Shapiro (2001, p. 120) defines as a "dense web of overlapping intellectual property rights that a company must hack its way through in order to actually commercialize a new technology." For a sample of 95 semiconductor firms between 1979 and 1995, Hall and Ziedonis (2001) show that firms build portfolios of strategic patents to use against each other in case of litigation.

applied for 9.63 renewed patents in fields with licensing, more than three times compared with 2.29 patents in other fields. In fields with licensing, counts of renewed patents increased by 28 percent from 6.28 per year until 1918 to 8.05 after 1918 (Table 1, Panel A). In fields without licensing, renewed patents declined by 12 percent from 2.56 per year until 1918 to 2.28 afterwards.

Estimating the baseline specification (equation 1) with renewed patents as an outcome variable indicates that German inventors applied for 1.25 additional renewed patents per year after 1918 in fields with licensing (Table 2, column 8, p-value 0.011). Compared with an average of 6.28 renewed patents per field and year until 1918, this implies a 20 percent increase. Estimates with field-specific pre-trends indicate that German inventors applied for 2.55 additional renewed patents (Table 2, column 9, p-value 0.001), implying a 41 percent increase. Regressions with a separate trend in patenting for fields with licensing indicate that German inventors applied for 2.48 additional renewed patents per field and year, implying a 39 percent increase (not reported). Intensity regressions indicate that German inventors applied for 0.08 additional renewed patents per year after 1918 for each additional *licensed patent_c*; this implies a 23 percent increase for the average field with at least one licensed patent. Estimates of annual treatment effects (Appendix Figure A8) are insignificant for 14 of 18 years in the pre-period, but become positive and statistically significant after 1922.

III. FIRM-LEVEL CHANGES IN PATENTING

In this section, we investigate whether firms reduced their patenting activity in research fields with compulsory licensing. Specifically, we estimate triple difference regressions:

$$(5) \text{ patents}_{fct} = \gamma_0 + \gamma_1 \cdot \text{field w licensed patents}_c \cdot \text{firm w licensed patent}_f \cdot \text{post}_t \\ + \gamma_2 \cdot \text{field w licensed patents}_c \cdot \text{post}_t + \gamma_3 \cdot \text{firm w licensed patent}_f \cdot \text{post}_t$$

$$\begin{aligned}
& + \gamma_4 \cdot \text{field } w \text{ licensed patents}_c \cdot \text{firm } w \text{ licensed patent}_f \\
& + \gamma_5 \cdot \text{patents by non-US foreign inventors}_{ct} \\
& + \gamma_6 \cdot \text{patents by individuals}_{ct} + \delta_t + \theta_c + \lambda_f + \varepsilon_{fct}
\end{aligned}$$

where the outcome variable patents_{fct} counts patents by firm f in field c and application year t .

The variable $\text{firm } w \text{ licensed patent}_f$ equals 1 if at least one of firm f 's patents was licensed. The variable $\text{patents by individuals}_{ct}$ counts patents in field c and year t by individual German inventors; all other control variables are as defined above. The triple difference coefficient γ_l measures the effect of compulsory licensing on firms whose patents were licensed in fields with licensing, compared with other German firms and other fields of invention.

A. Baseline Firm-Level Estimates

OLS estimates indicate that firms whose patents had been licensed began to patent *more* in fields with licensing after 1918. German firms with licensed patents applied for 0.41 additional patents per year after 1918 in fields with licensing (Table 4, column 1, p-value 0.002). Compared with a mean of 0.46 patents per field and year until 1918 for firms with licensed patents, this implies an 89 percent increase. These results are robust to the inclusion of field-specific pre-trends (Table 4, column 2). Estimates of annual treatment effects (Figure 3, Panel A) are insignificant for 12 of 18 years in the pre-period, and begin to increase after 1922, reaching 0.64 in 1925 and 0.82 in 1927.

B. Restricting the Sample to Firms with Confiscated US Patents

We then examine whether the selection of firms into compulsory licensing may drive the observed increase in patenting. Intuitively, only firms who were large enough to enter the US market and patent their inventions abroad could hold US patents that were available for

confiscation. Larger firms with licensing could have been exposed to different shocks to their innovative activity, compared with smaller firms without licensing. The baseline results, then, could attribute to compulsory licensing unrelated changes in patenting over time across firms with different size.

Data on firm size, which we draw from a registry of publicly traded joint stock companies (*Handbuch der Deutschen Aktiengesellschaften* 1911 and 1912) indicate that firms with licensed patents were large compared with other German firms. A total of 4,814 firms applied for at least one chemical patent in Germany between 1900 and 1930; 193 of them (3.6 percent) are listed in the registries of *Aktiengesellschaften* (AGs). Eighteen of 50 firms with licensed patents were AGs, compared with 175 of 4,764 other firms (Appendix Table A3). On average, 18 AGs with licensed patents had a nominal capital stock of \$101,000, compared with \$50,800 for 175 other AGs in our sample (from *Handbuch* 1911 and 1912, in year 2012 dollars).²⁵ Data on employees are available for 18 AGs with licensed patents and 170 other AGs. On average, AGs with licensed patents had 1,425 employees in 1911 and 1912, compared with 1,165 employees for the other 170 German AGs. In terms of firm age, firms with licensed patents are older than other AGs: The average AG with licensed patents had been incorporated as a joint stock company in 1885. By comparison, the average AG without licensed patents had been incorporated as a joint stock company in 1893.

To investigate the potential effects of selection, we re-estimate firm-level regressions (in equation 5) for the restricted sample of 204 German firms who held US patents that were

²⁵ Firms with and without licensed US patents report comparable valuations of patents on their balance sheets. Haber (1971, p. 254), however, warns, "...when we look at the finance of chemical companies just before and just after the war, we have a woefully small sample, the information is inadequate and the conclusions must necessarily be tentative." Four of 18 firms with licensed patents reported patents among the assets on their balance sheets; two of them listed a positive value; two reported a symbolic 1 *Mark* for devalued patented assets. By comparison, 72 of 175 firms without licensed patents reported patents among their assets; 23 (31.9 percent) of them listed a positive value, 49 (68.1 percent) listed a symbolic value of 1 *Mark*.

confiscated under the TWEA. Fifty of these 204 firms held at least one patent that was *licensed*. The estimate for $field\ w\ licensed\ patents_c \cdot firm\ w\ licensed\ patent_f \cdot post_t$ indicates that, in this sample, German firms with licensed patents applied for 0.46 additional patents per year after 1918 (Appendix Table A11, column 1, p-value 0.001). The estimated coefficient is close to the baseline result of 0.41 additional patents per year after 1918. Results are robust to the inclusion of field-specific pre-trends (Appendix Table A11, column 2).

C. Instrumental Variable Regressions

We also estimate instrumental variable regressions using the research fields with *confiscated patents* as an instrument for research fields with *licensed patents*, and the German firms with *confiscated patents* as an instrument for the German firms with *licensed patents*. Fields and firms with confiscated patents are a good predictor for fields and firms with licensed patents because only confiscated patents were available for licensing. First-stage estimates imply that a *firm with confiscated patents* is 48 percent more likely to be a *firm with licensed patents*. Confiscations, however, were plausibly not influenced by changes in firm-level patenting for German firms after 1919, because US authorities confiscated all German-owned US patents. An IV estimate of $field\ w\ licensed\ patents_c \cdot firm\ w\ licensed\ patent_f \cdot post_t$ indicates that German firms with licensed patents applied for 0.61 additional patents per year after 1918 in fields with licensing (Appendix Table A11, column 3, p-value <0.001).

D. Matching Firms with and without Licensing

We then use a nearest neighbor matching algorithm (analogous to the procedure in section II.D) to create a subsample of comparable firms with and without licensed patents. Data

on the log capital stock, firm age, and the number of employees in 1911/12 from the German registry of joint stock companies enable us to match firms based on their size and age.²⁶ The matched sample includes 14 firms with licensed patents (with an average log capital stock of 2.2, an age of 26, and 1,428 employees in 1911/12) and 10 firms without licensed patents (with an average log capital stock of 2.5, an age of 25, and 1,268 employees in 1911/12).

OLS estimates indicate that German firms with licensed patents applied for 0.28 additional patents per year after 1918 in fields with licensing (Appendix Table A11, column 5, p-value 0.033). These results are robust to the inclusion of field-specific pre-trends (Appendix Table A11, column 6). We also re-estimate time-varying effects on the sample of matched firms with and without licensing. Time-varying estimates indicate no significant pre-trends until 1918, and show a significant increase in patenting after 1923, with 0.48 additional patents in 1924 and 0.54 in 1925 (Figure 3, Panel B).

As an additional test for selection on observables, we compute propensity score weights that match the average observable characteristics (nominal capital stock, age, and employees in 1911 and 1912) of firms with and without licensed patents (Di Nardo et al. 1996). This sample includes all the patents issued to the 193 German firms listed in the registry of publicly traded joint stock companies. The weighted OLS estimate of the triple difference coefficient γ_l indicates that German firms with licensed patents applied for 0.75 additional patents per year after 1918 in fields with licensing, relative to other German firms (Appendix Table A11, column 7, p-value < 0.001).

E. Excluding Years after the Creation of IG Farben

²⁶ For the firm level results, however, we cannot match on pre-trends because the data on joint stock companies are only available for one fiscal year (1911/12).

Regressions that exclude observations after 1924 confirm that firms whose patents had been licensed patented more in fields with licensing after 1918. Baseline estimates indicate that firms whose patents had been licensed applied for 0.15 additional patents after 1918 in fields with licensing (Table 4, column 3, p-value 0.002). Compared with an average of 0.46 patents per field and year until 1918 for firms with licensed patents, this implies a 33 percent increase. Regressions with field-specific pre-trends indicate a slightly larger increase of 0.17 additional patents per year after 1918 (Table 4, column 4, p-value 0.002), which implies a 37 percent increase.

F. Renewal Decisions to Proxy for Patent Quality

Regressions with renewal data imply a smaller, albeit substantial increase. German firms applied for 0.29 additional renewed patents after 1918 in fields in which their patents had been licensed (Table 4, column 5, p-value < 0.001). Relative to an average of 0.39 renewed patents per field and year until 1918 for firms with licensed patents, this implies a 74 percent increase. Estimates with field-specific pre-trends indicate that German firms applied for 0.30 additional renewed patents in fields with licensing (Table 4, column 6, p-value < 0.001), which implies a 77 percent increase. Regressions with a separate trend for firms with licensing indicate that German firms applied for 0.29 additional renewed patents per year in fields with licensing (not reported).

IV. MECHANISM

Why did firms whose patents had been licensed begin to patent more in fields with licensing after 1918? One potential mechanism is a response to an increase in the threat of competition in fields with compulsory licensing.

A. An Increase in the Threat of Entry

Our analysis of German patents reveals a significant differential increase of patents by US inventors in research fields with licensing (Figure 1). These results are consistent with US patent data, which indicate that US inventors began to patent more in fields with licensing after 1918 (Moser and Voena 2012). This increased presence of US inventors may have increased the threat of competition, which – according to Arrow (1962) – may have encouraged incumbent patentees to invent more.

Inventor-level analyses of changes in patenting also reveal a large – 70 percent - increase after 1918 in the number of *German* firms that were active in fields with licensing. Until 1918, an average of 2.29 German firms without licensed patents produced patents in fields with licensing; after 1918, an average of 3.90 German firms without licensed patents produced patents in fields with licensing (Table 5). By comparison, the average number of German firms in fields without licensing increased by only 23 percent, from 1.22 to 1.50 firms.

One example of a firm that entered fields with licensing is the Deutsche Gold und Silber-Scheide-Anstalt (Degussa). Until 1918, Degussa applied for a total of 58 patents across 10 fields of chemical inventions, including 54 patents in 8 fields with licensing. After 1918, Degussa applied for a total of 147 patents, including 83 patents in the same 8 fields with licensing, 24 in fields without licensing, and 50 patents in 12 fields with licensing, in which Degussa had not patented until 1918.

To investigate whether the observed increase in patenting in fields with licensing was driven by firms that *switched* into fields with licensing from other fields of chemical research, we measure the share of patents in fields with licensing by firms with previous patents in other fields

of chemicals (switchers) and firms without previous patents (entrants into chemical research).

This analysis shows that the increase in patenting by entrants in fields with licensing was driven primarily by entrants *without* previous patents for chemicals. Entrants without previous patents *in any field of chemical research* account for 2,898 of 5,065 patents (57 percent).²⁷

B. Larger Effects on Fields that were Less Competitive Before

Individual-level patent data also enable us to perform a basic test of the relationship between competition and innovation. Although market share data are not available at the fine-grained level of 212 research fields that we use in our analysis, we can create an alternative measure of competition through a Herfindahl-Hirshman index (HHI) of patents per technology field and year:

$$HHI_{ct} = \frac{(\sum_i p_{ict}^2)^{-1}/F_{ct}}{1^{-1}/F_{ct}}$$

where p_{ict} is firm i 's share of total patents in field c and year t , and F_{ct} measures the number of patent-active firms in field c and year t . Comparisons of patent counts for 3,265 field-year pairs show that most research fields are relatively competitive: Two-thirds of all field-year pairs have an HHI of 0.1 or less (Appendix Figure A10).²⁸

²⁷ Patents per year by firms *without* pre-1919 patents in other fields of chemical research increased from 1.45 in 1919 to 2.96 in 1924 and 2.91 in 1929 (Appendix Figure A9). By comparison, the average number of patents by entrants *with* pre-1919 patents increased from 1.28 in 1919 to 1.85 in 1924 and 1.82 in 1929.

²⁸ Similar to plots of patent counts across UK industries in Aghion et al. (2005), the data are also broadly consistent with an inverted U-shaped relationship between competition and invention. Appendix Figure A10 is most similar to Figure 1 in Aghion et al. 2005, which plots patents per industry and year against (1-) the Lerner index as a measure for the intensity of competition. Estimates with the HHI and the concentration ratio (C4, not reported) are also consistent with Levin, Cohen, and Mowery's (1985) findings that competition and invention are positively correlated up to the 5th and 6th decile of the C4 in FTC line of business data. Levin et al. (1985) find that this correlation disappears with controls for variation across industries in the effectiveness of mechanisms to appropriate the returns from R&D. Our analysis investigates variation in competition *within* chemicals in the early 20th century, when patents had become an effective mechanism to appropriate the returns from R&D in chemicals (Moser 2012).

To compare the effect of compulsory licensing across fields with low and high levels of *pre-existing* competition, we re-estimate the baseline specification (equation 2) with an additional interaction term between the difference-in-differences estimator and a set of indicator variables for deciles of the HHI across all years until 1918:

$$(6) \text{ patents}_{ct} = \alpha + \sum_d \beta_d \cdot \text{field w licensed patents}_c \cdot \text{pre-1919 HHI decile}_d \cdot \text{post}_t \\ + \sum_d \gamma_d \cdot \text{pre-1919 HHI decile}_d \cdot \text{post}_t + \zeta_1 \cdot \text{field w licensed patents}_c \cdot \text{post}_t \\ + \zeta_2 \cdot \text{patents by non-US foreign inventors}_{ct} + \delta_t \\ + \theta_c + \sum_c \phi_c \cdot \text{field}_c \cdot \text{preTWEA}_t \cdot t + \varepsilon_{ct}$$

where the 5th and 6th decile of the HHI are the omitted categories. Estimates increase from 8.41 *fewer* patents for the 10th decile (Appendix Figure A11, p-value of 0.25) to 14.90 *additional* patents for the 7th decile (p-value of 0.11). Estimates are close to zero for the 4th to the 1st decile of the HHI. These estimates suggest that the observed increase in patenting was driven by technologies in which patenting was relatively concentrated before 1919.

IV. CONCLUSIONS

This paper has used a new data set of 79,591 chemical patents in Germany between 1900 and 1930 to examine the effects of compulsory licensing under the WWI Trading with the Enemy Act on German invention. Under the TWEA, all German-owned US patents became subject to compulsory licensing in 1919. We find that compulsory licensing encouraged, rather than discouraged invention in Germany. German inventors produced 30 percent more patents after 1918 in research fields with licensing. Intent-to-treat regressions and instrumental variable regressions, which use fields with confiscations as an instrument for fields with licensing, suggest that OLS estimates underestimate the effect of compulsory licensing on German patents.

An analysis of high-quality patents indicates a slightly smaller increase in patenting. This suggests that some of the observed increase in patenting may have been due to an increase in

lower quality strategic patents. Estimates, however, remain large and statistically significant and imply a 20 percent increase in high-quality patents.

Firm-level analyses of patent data reveal a significant increase in the number of research-active firms in research fields with licensing. Nearly 40 percent of all patents after 1918 in fields with licensing were by firms without pre-1918 patents in these fields. Among entrants into fields with licensing, firms without previous patents in any other fields of chemicals produced more patents in fields with licensing after 1918 compared with firms that had been active in other fields of chemical research before 1918. We also find that German firms whose patents had been licensed produced more patents after 1918 in fields in which their patents had been licensed.

These results confirm the findings of Moser and Voena (2012), which have shown that US invention increased in response to the compulsory licensing of German-owned patents. Yet, the current paper can go further in examining the effects of compulsory licensing on inventors *whose patents were licensed*. The most basic models of intellectual property rights suggest that compulsory licensing reduce incentives to invest in R&D for patent owners. Incorporating cumulative invention and competition, however, yields the opposite prediction. Our findings indicate that compulsory licensing can promote invention by encouraging competitors to enter fields with licensing, which increases the threat of competition for incumbent inventors and motivates them to invest more in R&D.

In the early 20th century and today, industries that are most affected by compulsory licensing tend to be relatively concentrated. In 2013, for example, therapies by Gilead, Johnson & Johnson, and Bristol Myers dominated the market for HIV drugs. Gilead's *Truvada* and related drugs accounted for \$9 billion in sales, Bristol-Myers *Sustiva* generated \$3.6 billion, and *Ruveda*, which combines Gilead's drug *Viread* and *Emtriva*, recorded \$3.1 billion in sales, while

other drugs sold substantially less (Campbell 2014). Our findings suggest that compulsory licensing can encourage invention in these industries. In fact, we find that compulsory licensing was particularly effective at promoting invention in fields that were *ex ante* more concentrated, and less effective in fields that were competitive already.

It is, however, important to note that the benefits of compulsory licensing depend on the credibility with which national governments can commit to invoke it exclusively in cases of emergencies. Triggered by Germany's military aggression, the 1917 Trading with the Enemy Act was at the time perceived as a one-shot event. We find that incumbent inventors responded by investing heavily in R&D to escape competition with new entrants. Similar to other types of public policies, such as flood control measures, monetary policy, and capital taxation (Kydland and Prescott 1977, Fischer 1980), compulsory licensing is subject to dynamic inconsistency, and firms may invest less in R&D if they expect repeated episodes of compulsory licensing.²⁹ We conclude that compulsory licensing can *promote* innovation - if governments can credibly commit to using it only in exceptional cases of emergencies.

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²⁹ In fact, Kydland and Prescott (1977, p. 477) cite patent policy as an example for dynamic inconsistency: "Given that resources have been allocated to inventive activity which resulted in a new product or process, the efficient policy is not to permit patent protection. For this example, few would consider this optimal-control theory solution as being reasonable. Rather, the question would be posed in terms of the optimal patent life (Nordhaus 1969), which takes into consideration both the incentive for inventive activity provided by patent protection and the loss in consumer surplus that results when someone realizes monopoly rents."

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