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IZA DP No. 15517

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AUGUST 2022

ISSN: 2365-9793

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ABSTRACT

Competition and Innovation: The Breakup of IG Farben*

The relationship between competition and innovation is difficult to disentangle, as exogenous variation in market structure is rare. The 1952 breakup of Germany's leading chemical company, IG Farben, represents such a disruption. After the Second World War, the Allies occupying Germany imposed the breakup because of IG Farben's importance for the German war economy instead of standard antitrust concerns. In technology areas where the breakup reduced concentration, patenting increased strongly, driven by domestic firms unrelated to IG Farben. An analysis of patent texts shows that an increased propensity to patent does not drive the effect. Descriptively, IG Farben's successors increased their patenting activities as well, and their patenting specialized relative to the pre-breakup period. The results are consistent with a breakup-induced innovation increase by the IG Farben successors, which then spilled over to the wider chemical industry.

JEL Classification: O31, L44, N44
Keywords: innovation, competition, merger, antitrust, IG Farben

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* I thank seminar participants at Boston University, University of Maryland, University of Mannheim, LMU Munich, DICE, EPFL, the CRC TRR 190 retreat 2021, the Economic History Association, and at countless internal Max Planck Institute for Innovation and Competition seminars for their comments. In particular, I thank Thilo Albers, Serguey Braguinsky, Florian Ederer, Jeff Furman, Walker Hanlon, Dietmar Harhoff, Tim Simcoe, and Fabian Waldinger. Part of this research was completed while visiting Boston University and University of Maryland. I gratefully acknowledge financial support from the DFG through Collaborative Research Center TRR 190 "Rationality and Competition."

1 Introduction

Innovation is a key driver of economic growth, as it allows firms to increase their productivity and grow by capturing and creating markets with new products or improved variants. Superior innovation performance by superstar firms has long been highlighted by Schumpeterian (1942) arguments and has recently been linked to modern concentration trends (e.g. Crouzet and Eberly, 2019; Autor, Dorn, Katz, et al., 2020). In contrast, overly large concentration may decrease incumbents' innovation incentives (Arrow, 1962; Aghion et al., 2005) and, with that, harm growth and societal welfare. A large theoretical literature discusses this possibility in the context of mergers (Federico, Scott Morton, and Shapiro, 2019) - which can cause important shifts in competition and receive regulatory scrutiny. Empirically, however, the effect of competition on innovation is difficult to determine, as both are highly endogenous, and exogenous variation in market structure is rare. However, observing the impact of cases in which governmental interventions reshaped the structure of an industry represents one way forward. Such cases - a list often headed by the breakups of Standard Oil and AT&T - are, however, few and far between (Lamoreaux, 2019) and have as of yet failed to include the breakup of IG Farben.

In this study, I exploit the 1952 breakup of Germany's largest chemical company by the Allied Powers outside of standard antitrust practice (Stokes, 1988). The breakup target, IG Farben, was one of the most innovative German companies. Three of its scientists won Nobel prizes - one for the world's first antibiotic. It played an outsized role in the German innovation system, responsible for 5.8% of all patents by German inventors, up to 16.5% in chemistry. IG Farben was also of crucial relevance for the German war machine (Hayes, 1987; Plumpe, 1990). The victorious Allies recognized this and IG Farben's economic influence as undue political potential. IG Farben's crimes, including its major involvement at the Auschwitz concentration camp, fueled this negative perception. After a year-long deliberation, the Allies decided on a breakup largely following their occupation zones in Germany. Three large successors - BASF, Bayer, and Hoechst[1] - were created, as well as a dozen smaller businesses (Stokes, 1994).

After the breakup, innovation in technologies exposed to the IG Farben breakup increased strongly and persistently compared to other chemical technologies. In this study, I proxy breakup exposure with the concentration change resulting from the breakup of IG Farben (Nocke and Whinston, 2022), whereby I focus on the hypothetical change if the breakup had been implemented before the war according to the eventual breakup structure. With this pre-war measure, I avoid contaminating the exposure measure with wartime events and post-breakup adjustments. Before 1952, patenting trends in exposed and unaffected technologies

[1] BASF and Bayer continue to exist as global corporations under the same names. After a series of mergers in the late 1990s, Hoechst is now part of Sanofi, Celanese, and others.

were parallel. After the breakup, however, patenting in exposed technologies increasingly diverged, indicating a sizeable positive innovation effect.

Identification relies on the assumption of parallel trends for continuous exposure variables (Callaway, Goodman-Bacon, and Sant'Anna, 2021), which is consistent with the data. A major concern is that exposure might reflect unobserved differences in technological potential, which could have led to larger exposure due to increased investments by IG Farben. However, the results are robust to alternative measures of breakup exposure that focus on the geographic distribution of pre-war patents within IG Farben. This focus reduces the influence of the absolute investment amount. A second assumption maintains that the IG Farben shock is separable from other contemporary changes. Reassuringly, the timing of the effect suggests that it was unrelated to war-related changes. Confounding factors would need to correlate closely to the geographic structure of IG Farben across occupation zones. Instead, most factors are large-scale developments and affect the entire chemical industry. Nonetheless, I test the impact of many parallel events and include control variables for war destruction, dismantlement, the German separation, among others. If factors are immeasurable, I discuss their potential impact based on the historical literature.

Conceptually, the IG Farben breakup can be understood from the perspective of a merger. Both a breakup and a merger constitute a change in control rights over production assets of the merged entity, but in the opposite direction.[2] Theoretically, a merger's innovation effect on the combined firms is ambiguous: it depends on the particular market structure and the presence of merger efficiencies (Marshall and Parra, 2019; Jullien and Lefouili, 2018; Gilbert, 2020).[3] For aggregate effects, other firms' reactions to the IG Farben breakup are important. These may be strategic substitutes or complements (Bulow, Geanakoplos, and Klemperer, 1985; Gilbert, 2020, p. 89). Assuming the breakup increases innovation output by the IG Farben successors, firms operating in the same technology space as IG Farben likely face both technology spillovers and product market competition (Bloom, Schankerman, and Van Reenen, 2013). Innovation by IG Farben's competitors may be a strategic substitute and decrease in response to increased competition due to the breakup, which would partially offset changes in innovation output by the IG Farben successors (e.g. Federico, Langus, and Valletti, 2017). On

[2]As an antitrust tool, a breakup would aim to induce long-lasting competition. In contrast, companies can also be broken up along business lines, as in corporate de-mergers, inducing little to no change in competition. In the case of IG Farben, the breakup induced considerable (horizontal) competition at the technology and product level (Poege, 2022).

[3]Marshall and Parra (2019) study innovation in response to an increase in the number of firms and argue that the sign of the innovation effect depends on the particular market structure. However, a breakup leaves R&D and production assets unchanged and increases competition by dividing control rights, which is conceptually close to a merger in reverse (Federico, Scott Morton, and Shapiro, 2019). For example, Federico, Langus, and Valletti (2017, 2018) argue that decreased innovation incentives likely dominate, inducing a negative competition-innovation relationship. In contrast, e.g., technology sharing between merging firms increases their innovation incentives by raising the value of a given innovation (Denicolò and Polo, 2021).

the other hand, competitor responses may be strategic complements and exacerbate IG Farben's changed innovation activities, for example, if technology spillovers are important, as suggested by Bloom, Schankerman, and Van Reenen (2013). Similarly, if IG Farben could exploit its monopoly position to prevent entry or collude with other incumbents to delineate markets (as Haber, 1971, p. 287 suggests), the breakup would increase incentives to innovate and enter for other firms.

To better understand the mechanisms, I decompose the effects by applicant groups and quality margins. First, results are similar when counting only patents without IG Farben association, indicating that non-IG Farben firms drive the main results. Descriptively, post-war patenting by the IG Farben successors begins at the pre-war level and increases after the breakup, both in absolute terms and in comparison with a synthetic control. Positive innovation effects of the breakup for both the IG Farben successors and affected technologies suggest that the innovation responses of IG Farben and other firms were strategic complements. Technology spillovers seem to outweigh the effects of product market competition. Second, increased competition could also increase the value of patents, thereby changing the propensity to patent a given invention. Indeed, raw patent counts increase immediately after the breakup, whereas the quality-weighted count rises gradually. Average quality decreases immediately after the breakup but normalizes within a few years. A quality-quantity trade-off is introduced, but only in the short run. Third, I test whether the effect is explained by domestic or foreign patenting. Patenting by foreign applicants in Germany increased after the war, but the increase occurred discretely and prior to the finalization of IG Farben's breakup. Therefore, the changes in foreign patenting are likely unrelated. Domestic applicants drive the majority of the increased patenting after 1952.

To find supporting evidence that technology spillovers, rather than product market interactions, drive the increase in innovation, I introduce fine-grained historical data on the suppliers of thousands of chemical products. With these, I identify which firms were exposed to potentially increased competition with IG Farben in the product market. For the analysis, I utilize a firm panel of pre-war incumbents. Innovation by incumbent firm is quantitatively important and is crucial for the main effect on the technology level. Through a difference in differences analysis on the firm-level but otherwise analogous to the technology-level analysis described above, I analyze chemical patent counts before and after the IG Farben breakup. In this analysis, both technological and product-market exposure indicators are associated with increased patenting by affected firms. The latter indicates that cessation of exclusionary conduct by IG Farben is not the primary mechanism, as otherwise, the main effect should stem from firms that were no direct competitors. However technological exposure seems to dominate in specifications including both exposure measures, and exposure to product market competition matters less. This finding is consistent with technology spillovers as a mechanism.

In addition to the effect of competition on innovation quantity, the breakup could have induced increased duplication of research within technologies. Project choice, diversity, and duplication of research have been discussed theoretically (Denicolò and Polo, 2018; Letina, 2016; Gilbert, 2019; Bryan, Lemus, and Marshall, 2022), but empirical analysis has been limited. In particular, measurement remains a challenge outside of specific sectors like pharmaceuticals. In the context of IG Farben's breakup, the successor companies competed in many fields, from the production of basic chemicals to the cutting-edge technologies of the time. For example, all three successors strongly invested in plastics and synthetic fiber research - which often yielded different approaches and, consequently, products (Teltschik, 1992).[4] In an extension, I propose indicators of technological overlap and dispersion based on patent text similarity. While IG Farben's successors continued to patent within the same technologies, their research specialized. On an aggregate level, the dispersion of research within affected technology classes increases.

The innovation analysis employs German patent data to measure innovation outputs in technologies and by firms, as well as fine-grained product-level data. Making this novel data available, either newly or much improved, is also a contribution of this study. I begin with scanned grant documents and historical product catalogs and apply image processing, pattern recognition, and machine learning methods to build relevant datasets. In the case of patents, I recover applicant, inventor, and technology class information so far unavailable at a comparable scale. I select technology classes relevant to the chemical industry based on contemporary classifications. As standard measures for heterogeneity between patents, such as forward citations (Harhoff et al., 1999), are unavailable, I introduce quality measures based on patent texts. Analogous to citations, these quality measures describe the importance of a patent for subsequent patents and relative to previous patents (cf. Kelly et al., 2021). Further, I use patent texts to build measures of technology-level specialization. With this, I contribute to the emerging literature on the usage of (patent) texts to better understand technological advances of firms and technologies (Kelly et al., 2021; Arts, Cassiman, and Gomez, 2018).

With this study, I contribute to the empirical literature on competition and innovation (Gilbert, 2006; Cohen, 2010; Gilbert, 2020). Research on competition and innovation enjoys a long tradition, going back at least to Schumpeter (1942) and Arrow (1962). The dynamic relationship between industry structure (competition) and industry outcomes complicates empirical work, especially reduced-form. Structure likely influences performance and vice versa. In the absence of direct shocks to market structure, authors have analyzed other interventions that imply competition changes, such as the removal of trade barriers, and found ambiguous

[4]At the same time, considerable specialization remained. So, while Bayer and Hoechst continued to excel in pharmaceutical research, BASF's entry into this field remained fraught with problems (Teltschik, 1992).

innovation results (Shu and Steinwender, 2018). By exploiting the IG Farben breakup, I provide more direct evidence.

The literature on mergers and innovation is closely related. Many arguments on the effect of mergers - such as the trade-off between potential efficiencies with disincentives arising from reduced competition - can be reversed and applied to breakups. When analyzing mergers, studies have relied on matching methods combined with difference in differences and sometimes instrumental variable analysis to estimate effects. The resulting evidence is mixed, with either no (Danzon, Epstein, and Nicholson, 2007) or negative innovation effects (Ornaghi, 2009; Szücs, 2014; Haucap, Rasch, and Stiebale, 2019) of mergers. However, the occurrence of mergers and litigation by antitrust authorities are selective (Carlton, 2009). In this study, I instead estimate effects within one event, which differentially affected a broad range of technologies. In particular, I highlight the importance of competitor responses induced through technology spillovers, which have received less attention from the literature (Haucap, Rasch, and Stiebale, 2019). Other studies descriptively identify important stylized features and consequences of mergers (Cassiman et al., 2005; Cunningham, Ederer, and Ma, 2021). A third strand relies on structural estimation to study competition and innovation surrounding mergers (Goettler and Gordon, 2011; Igami and Uetake, 2020).

This study contributes to the literature on the history of antitrust, particularly regarding breakups of large corporations. Such government actions are rare, and cases remain few and far between. The literature has focused on seminal US cases, such as Standard Oil or the Bell system (Lamoreaux, 2019). In terms of innovation, the latter is more relevant, and researchers have found increased productivity and innovation following the Bell breakup (Olley and Pakes, 1996; Watzinger and Schnitzer, 2020). The most important feature of the Bell breakup was the vertical separation between the research unit Bell Labs and various regional commercial distribution and operating units in 1984. In understanding breakups, the IG Farben case complements this case, due to its differing structure - a horizontal breakup between various innovative units of a company - and because it covers a new industry in which innovation is well and broadly quantifiable. Other studies exploiting important historical antitrust events include Baten, Bianchi, and Moser (2017), Moser and Voena (2012), and Watzinger, Fackler, et al. (2020), who analyze government-mandated compulsory licensing of patents and find positive innovation effects.

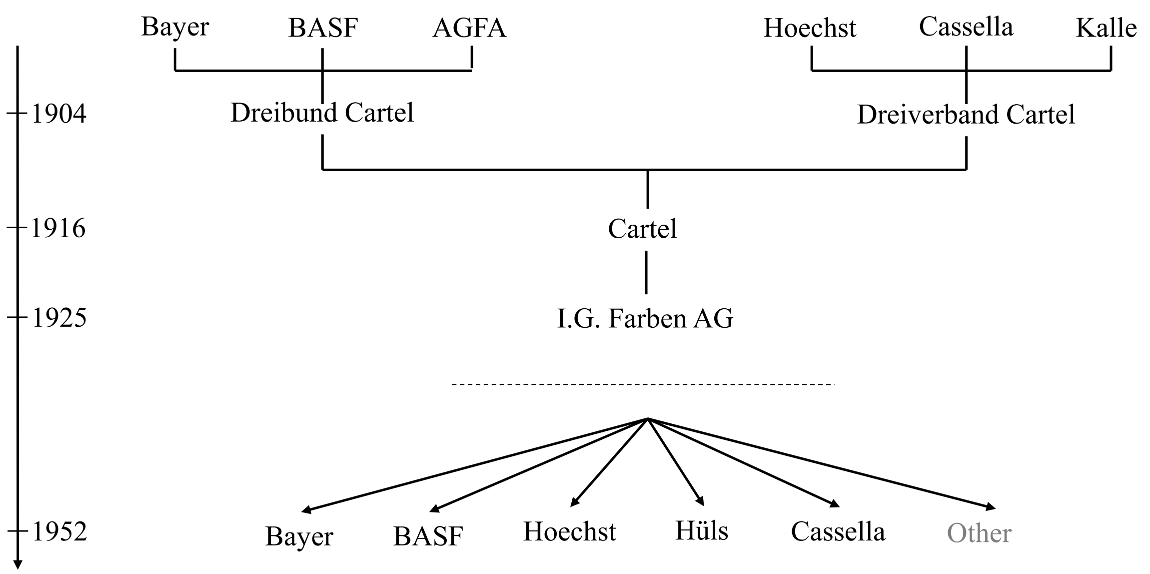
The remainder of the paper is organized as follows. Section 2 discusses the history of IG Farben, and Section 3 introduces data sources. Section 4 discusses the empirical strategy. Sections 5 and 6 introduce measures of the breakup in innovation space and then study innovation effects. Section 7 describes the subsequent development of the IG Farben successors, and Section 8 concludes.

2 Historical Background

IG Farben used to be the largest company in Germany and the largest chemical company in the world. It was also one of the most innovative German companies in history, with three of its scientists winning Nobel prizes. IG Farben played an outsized role in the German innovation system, responsible for 5.8% of all patents by German inventors, up to 16.5% in chemistry. For comparison, IG Farben's share of German-invented German patents was three times that of AT&T/Bell among US-invented US patents (2%, see Watzinger and Schnitzer, 2020). IG Farben's fate has attracted considerable interest from historians (Haber, 1971; Hayes, 1987; Plumpe, 1990; Kreikamp, 1977; Stokes, 1988, 1994, 1995; Jeffreys, 2010) due to its industry dominance and controversial history. This section provides a brief overview of IG Farben's rise and fall, to contextualize the economic analysis of its breakup.

2.1 Making IG Farben

Figure 1: The Development of I.G. Farbenindustrie A.G.



Notes: Shows the historical time-line of IG Farben, from preceding cartels, 1925 merger and subsequent breakup using stock transfers. Source: Stokes (1988, p. 12). Does not include smaller subsidiaries as well as close cartels of IG Farben in the explosives industry.

In 1925, IG Farben was formed by merging several of the largest German chemical companies into a single stock company. Figure 1 presents IG Farben's timeline and eventual split. Before the merger, the firms were part of an organized cartel of the same name. Cartels were widespread throughout the German economy at the time; however, German laws stipulated that each member could quit unilaterally. These regulations created hold-up problems among the cartel members:

If each member could leave and break the cartel, then forfeiting one's own sales division or name was inconceivable. To resolve these inefficiencies, cartel members merged, thereby relinquishing their outward profile to join the new *IG Farbenindustrie AG*. In addition to holdup problems (ter Meer, 1953, pp. 17–23), easier access to capital further incentivized the integration (Abelshauser, 2003, p. 228). Both factors are merger efficiencies in today's view.

IG Farben's internal organization was characterized both by specialization and redundancy. While a central administration took over important functions, production and research remained organized at a lower level (Haber, 1971, pp. 338–340), a practice called "centralized decentralization". For example, IG Farben maintained at least 25 research laboratories (Plumpe, 1990, p. 475) with wide geographical distribution across Germany (see Figure 2). Inventive activity occurred within in all major work units (Haber, 1971, p. 357; ter Meer, 1953, pp. 29–30), and many units maintained their own patent offices.[5] Nonetheless, IG Farben rationalized production and specialization increased (Haber, 1971, pp. 286–287). However, duplication remained, as "almost all of the central factories produced a broad range of basic chemicals, intermediates, and finished products" (Stokes, 1988, p. 18). Consequently, the IG Farben breakup would later create competition within technologies and product markets.

During the Second World War, IG Farben was instrumental to the German war effort and committed war crimes and crimes against humanity. During its 20 year existence, IG Farben retained or acquired a dominant position in much of the German organics, plastics, and explosives industry. Further, IG Farben was directly or indirectly responsible for producing much of the synthetic fuel and rubber from German coal as import substitutes. As part of a broader autarky strategy, the company was vital for the start and continuation of the war. IG Farben also conducted extensive acquisitions in the German-occupied territories and was later accused of plundering. Like many German industries, IG Farben sourced forced and slave labor from concentration camps. The most infamous IG Farben investment was at Auschwitz, where IG Farben built one of its most advanced facilities. Furthermore, an IG Farben subsidiary supplied the Zyklon B pesticide used for murdering more than a million people at Auschwitz and other camps. IG's actions before and during the war fueled the company's reputation as "Hell's cartel" (Jeffreys, 2010).

[5] In supervising its complex structure, IG Farben created multiple internal groups ("Betriebsgemeinschaften", Stokes, 1988, pp. 14–19). Control over production remained with the production groups. A total of five such groups encompassed 33 major production complexes, of which Table F-2 in the appendix lists the main ones. The groups specialized in certain areas of chemistry, such as Upper Rhine (Ludwigshafen, later BASF) in high-pressure chemistry, Lower Rhine (Leverkusen, later Bayer) in pharmaceuticals, or Berlin in photographic paper, film, and artificial silk. Working committees within the wider IG Farben administration attempted coordination between the groups.

2.2 Breaking IG Farben

IG Farben's importance to the German war machine and its crimes drove the Allied powers to confiscate IG's property in 1945, leaving the administration in the hand of the respective zonal government. Meanwhile, the heightening cold war tensions complicated the Allies' attempts to coordinate their occupation policy (Stokes, 1994, p. 71). Their subsequent actions differed greatly. While the Soviets quickly began dismantling their IG plants, each Western Ally grew more hesitant and "became increasingly protective of the interests of the former IG group in its zone" (Stokes, 1994, p. 71). Even the US administration, initially set on separating IG Farben into small units, relented to the new economic and political realities. The Western integration of the US, British, and French occupation zones into the bizone and, later, trizone unified the Allied administration of IG Farben. As a result, Stedman (1950, p. 442) calls the 1945 breakup "largely theoretical" and states that "[t]he individual units today are in closer collaboration than they were then". While this claim is certainly exaggerated, it demonstrates some US officials' disappointment with the state of German deconcentration. The breakup question was resolved in earnest only in the early 1950s.

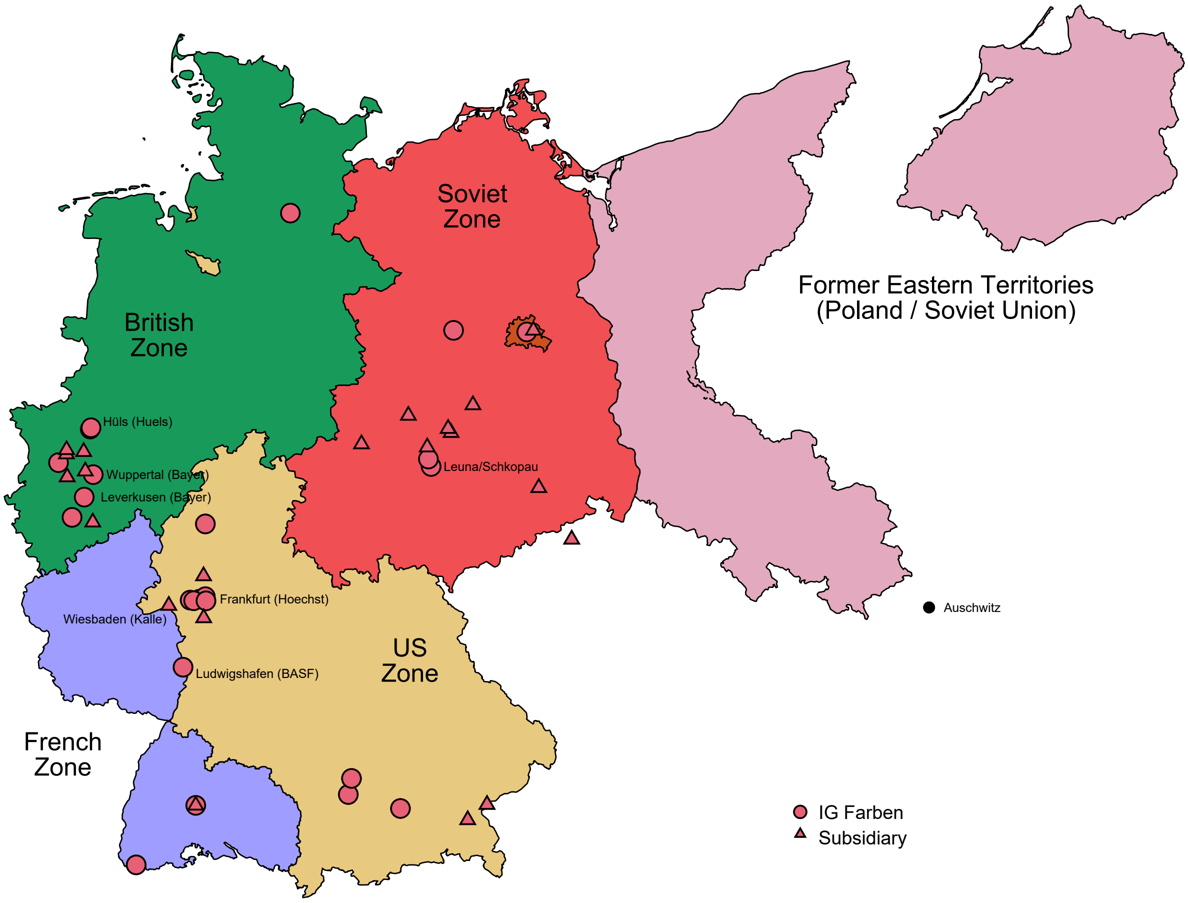
IG Farben's breakup was not expected or planned before the war, and its structure was only determined during the occupation period. IG Farben officials saw the writing on the wall, but eventually, preparation for the Allied victory remained rudimentary (Stokes, 1988, pp. 32–33).[6] Stokes, writes:

> Although the final outcome of the breakup was not predictable in 1945, zonal policies helped prejudice its general contours. Practically speaking, the major Western successors of IG Farben were going to be the three large works units of the old firm, the central factories of which lay in different zones. (Stokes, 1994, p. 71)

With this, the eventual breakup largely followed IG Farben's internal structure. This, however, was not the only possible outcome. Initially, US officials considered an arrangement with much smaller units. This idea was initially implemented in the US zone, but by 1952, Hoechst had largely reassembled its structure. Another Allied proposal would have grouped activities related to synthetic fibers and artificial silk into one successor, which would have bundled the plants Dormagen (later Bayer), Bobingen (later Hoechst), and Rottweil (later independent). However, this proposal was abandoned mainly due to British political support for Bayer (Stokes, 1994, pp. 73–75).

[6]Some attempts were made, however. IG officials attempted to transfer ownership of foreign assets to avoid confiscation. Ideas such as a legal separation of war-related factories from civilian production were considered but dropped. In the end, these decisions would be taken by others.

Figure 2: Locations of IG Farben manufacturing and research



Notes: Shows IG Farben locations in Germany's 1936 territory, by postwar situation. BASF formed around the Ludwigshafen facilities in the French occupation zone (blue). Bayer formed around facilities in the British occupation zones. Hoechst formed around the facilities in the United States occupation zone (yellow). Some locations (Troisdorf, Marl-Hüls, Wiesbaden) formed smaller successors. The large facilities the Soviet zone (red) in Leuna, Schkopau and Wolfen were restructured as publicly owned enterprises (Volkseigener Betrieb, VEB). The former German areas in the East became Polish or Soviet Union territories after 1945 and did not contain major research-active IG Farben facilities. The IG facilities near Auschwitz, in occupied territories, received large investments during the war, yet never reached completion. Source: Max Planck Institute for Demographic Research: MPIDR Population History GIS Collection, own calculations.

In 1951, the Allies announced the final breakup structure, and the major successors were legally incorporated by 1952. [7] The breakup was executed via stock transfers. Each owner of IG Farbenindustrie AG shares received successor shares according to their initial capitalization. IG Farben patents were redistributed among the successors, primarily according to the location of invention and occasionally according to current use. However, all successors were granted

[7]Between 1945 and the finalization of the breakup in 1952, IG Farben itself was in flux. Zonal structure divided effective control among the four Allied Powers in 1945. Then, the consolidation of the Western occupation zones consolidated the administration into the Western and Eastern zone by 1948. In August 1950, the Western Allies created the legal basis for separating IG Farben. The incorporation of the main successors (Hoechst on December 7, 1951; Bayer on December 19, 1951; BASF on January 30, 1952) concluded the most important part of the breakup.

non-exclusive royalty-free licenses.[8] In the years following the breakup, the successors thrived in separation. Although they began to acquire non-IG Farben competitors, especially in the early 1960s, the breakup structure was not majorly adjusted until 1970.

2.3 Historical context

IG Farben's breakup occurred during one of the most turbulent episodes of German history. Yet, the German economy and society were neither immediately nor fundamentally transformed. Historically, a core question is whether the end of the Second World War set off a complete renewal ("Hour Zero") or was rather characterized by societal and economic continuity. This question was the subject of intense debate in post-war German society. Both for society and for the economy, historians today emphasize continuity and reject notions of a radical divergence (e.g. Morsey, 2010). Overall, the German economy recovered quickly and returned to pre-war export levels by 1950.

Nonetheless, several historical factors were crucial for German industrial development. The war left German cities with varying degrees of damage. After the liberation by the Allied Powers, Germany was occupied and divided into occupation zones. With the occupation came industrial controls, including the dismantlement of industrial capacity to reduce the German war potential or to serve as reparations. Eventually, differing occupation policies would lead to economic and political division between East and West Germany.

In most cases, the aforementioned historical factors affected all sectors of German industry. However, insofar as effects are differential, they present limitations to this paper's generalizability. For many aspects, it is possible to introduce control variables for statistical robustness checks. For others, detailed discussions of the historical circumstance in Appendix F guide an appraisal of the limitations.

3 Data

As patents are most suitable to protect chemical and pharmaceutical innovations, they provide valid measures of innovative activities in these fields (e.g. Cohen, Nelson, and Walsh, 2000;

[8] For example, BASF received over 2200 patents invented in its own units, compared to 26 patents invented in other units, 76 jointly invented with another unit, and roughly 30 patents jointly invented with third parties. See HHStA/2092/14781, 17305, 17306. For patent licenses, see regulation No 2 under Law 35 of the Allies High Commission (AHK/98/2010-2012). Free licenses were available to fully owned IG Farben subsidiaries, discounted licenses to majority-owned ones.

Moser, 2012).[9] Based on this idea, I use patent data as a proxy for innovation. To generate this data, I digitize German patent grant documents ranging from the 1920s to the 1960s in order to obtain information on technology class and application year. This period starts five years before the IG Farben merger and ends ten years after the breakup, following Stokes (1994). The sample restriction also reflects data availability.[10] This data construction complements data provided by the German patent office and fills in unavailable or unreliable information. Appendix A discusses the data construction process in detail and assesses various quality aspects. Of special note, the German patent office ceased operations for most of 1945 and all of 1946 and 1947. I always exclude these years. I further exclude war-time applications in most analyses due to the circumstance of their application, but also because the patent office only processed them in the 1950s. Applicants will selectively pursue prosecution of patents still relevant 5-10 years after the original application.

For ease of access, patent offices have long classified patents by technology classes. While these are not congruent to individual markets or products, technological experts considered them relevant at the time. During the sample period, the German classification system contained more than 500 technology classes, a number comparable to the four-digit level of the present-day Cooperative Patent Classification (CPC). Of those, only a subset relates to chemistry. Inspired by Baten, Bianchi, and Moser (2017), I identify all classes related to chemistry based on descriptions of the group-level technological areas. In total, 135 relevant technology classes remain and form the basis for this study's analysis.[11]

As patent quality is heterogeneous, adjustments are advisable - most commonly via weighting with patent citation counts (Harhoff et al., 1999). However, patent citation information is unavailable in the historical German patent data. I adopt an alternative quality measure based on text similarity scores between patents (Kelly et al., 2021). Patents similar to future patents are called influential, while patents similar to past patents are called derivative. Kelly et al. define text-based patent quality as the ratio of future and past similarity and show that text-based and citation-based quality correlate well. I adopt Kelly et al.'s methodology for the German

[9]During the time of interest, the German patent law did not allow product patents in pharmaceuticals and chemistry. However, processes were patentable. These were effective in deterring entry, as a competitor producing the same product would have to prove that they employed a different process (Uhrich, 2010).

[10]After the sample period, the German technology classification and publication regime changed. As a result, many grant documents are unavailable for digitization, and the German technology classes are no longer reported on others. During the sample period studied here, patent grants, as observed in the data, track information from official statistics well, but this correlation breaks down during the mid-1960s.

[11]The CPC's four-digit level is a comparably high-level aggregation. Technology groups, the next-lower level of aggregation in the German classification, are not consistently available and undergo rapid change as technology evolves. The next-higher top-level grouping has 89 technologies, of which 34 at least partially refer to chemistry and closely related fields.

context.[12] I normalize the patent-level quality measures to mean three and standard deviation one so that quality-weighted patent counts are of comparable scale but also non-negative. I validate the quality measures and show that they correlate with indicators for important chemical patents as identified by contemporaneous publications.

For a subset of the analysis, I rely on a firm panel and information from product catalogs covering the German chemical industry. These product catalogs provided information to industrial purchasers about both a large number of chemical products and their supplying firms. These lists include both chemical substances and refined chemical products, such as industrial cleaners or paints. I digitize the firm and product lists from catalogs covering late 1939, mid-1952, and 1961 in addition to complementary lists of contemporary firms. Appendix C discusses this process in detail.

4 Empirical Strategy

My analysis is based on a difference in differences approach, comparing technologies with high exposure D_i to the IG Farben breakup to technologies with low or without exposure:

$$log(Y_{it}) = \alpha_i + \beta_t D_i + \gamma_t + \delta X_{it} + \epsilon_{it} \tag{1}$$

The regressions include technology class fixed effects α_i, time fixed effects γ_t, as well as additional controls X_{it}. Exposure to the IG Farben shock D_i is a continuous variable measuring the concentration change caused by the IG Farben breakup. The primary outcome variable is innovation (quality-weighted patent counts), and the units of observation are the technology class by application year. [13]

For display purposes in tables, I group the yearly coefficients as in equation 2.

$$log(Y_{it}) = \alpha_i + \beta_{1948-1951} D_i + \beta_{1952-1961} D_i + \gamma_t + \delta X_{it} + \epsilon_{it} \tag{2}$$

One long pre-period covers the time before the war, when IG Farben was one company. I normalize the coefficient $\beta_{1925-1939}$ to zero to provide a baseline for the long-run, pre-war patenting level. The post-war, pre-breakup period is grouped into $\beta_{1948-1951}$. This period informs about new post-war levels. Finally, in early 1952, most successors had incorporated

[12]Unlike the US context, institutional factors cause the total count of German patents to vary widely over time. To account for this, I use the average future/past similarity instead of the sum of future/past similarity scores. I further employ a modern text similarity algorithm that focuses not on word counts but on the text's overall structure (Doc2Vec, see Le and Mikolov, 2014). Appendix A discusses details.

[13]With, on average, only three technology classes per higher-level technology, the inclusion of technology×year FEs does not leave enough variation of exposure within classes.

and the breakup had taken effect. The post-period is covered by the coefficient $\beta_{1952-1961}$ continues until 1961, following Stokes (1994). For this analysis, the main interest is on the difference between the two post-war coefficients, $\beta_{1952-1961} - \beta_{1948-1951}$.

To characterize the breakup exposure D_i, I measure the technology-level concentration change induced by the IG Farben breakup (Nocke and Whinston, 2022). Using the Herfindahl-Hirschman index (HHI)[14] as the measure of concentration, I operationalize breakup exposure as the difference between HHI^{IG} of IG Farben as a single entity and $\text{HHI}^{\overline{IG}}$ of IG Farben divided into successors according to the eventual breakup structure, so that $D_i := \Delta\text{HHI} = \text{HHI}^{IG} - \text{HHI}^{\overline{IG}}$. Because of IG Farben's geographical dispersion, I can recover the breakup structure based on inventors' location and post-breakup employer. I use patent counts from the IG Farben successors to calculate both HHI and their difference, ΔHHI. In the main analysis, ΔHHI follows the literature by calculating HHI from shares of IG Farben successors towards the overall set of patents in a technology class. However, the class-level ΔHHI combines exposure to the breakup through the intensity of IG Farben investment in a particular technology class as well as the distribution of investment among successors within the class. While this represents the economically relevant measure, focusing on the specific breakup rule and its geography is advantageous for identification purposes. Reassuringly, the results are robust to measures solely focusing on the breakup within the set of IG Farben patents, thereby isolating variation introduced by the breakup across occupation zones.

Identification assumptions For causal inference, I rely on two different assumptions. First, I assume that without the breakup, classes with exposure $D_i = d$ would have developed as classes with exposure $D_i = 0$. This assumption is sufficient to identify level effects, specifically $ATT(d|d)$. Whenever ATEs or average causal responses are interpreted, a stronger version of this assumption is required (Callaway, Goodman-Bacon, and Sant'Anna, 2021). Second, I assume that the IG Farben shock can be separated from other contemporary changes, i.e., that exposure to the IG Farben breakup is independent of potentially confounding shocks.

The first assumption - parallel trends - stems the historical literature, which suggests that the IG Farben breakup was a previously unanticipated event. Investments in technology and production capacity were long-term and did not account for the subsequent breakup as it was unforeseeable. This argument motivates a comparison between technology classes affected

[14]To measure competition, measures such as markups would also be desirable. Yet, financial data of German firms are only available for a set of large, stock-listed companies and restricted to observations either before the war or after the breakup. As a closer alternative, the CR4 share, the share of patents by the four largest applicants, would be available. The CR4 share would be less sensitive to the incorrect disambiguation of small applicants. On the other hand, the IG breakup often replaced the largest applicant with three applicants, which are still the largest ones. The CR4 change is then entirely determined by the share of the two applicants shifted out of the top 4, which is not a good measure of the implied concentration change.

by the shock and those affected only slightly or not at all. While the variation of IG Farben investments across technology areas is not random, this variation is unrelated to the eventual breakup.

However, even if the breakup was unpredictable, IG Farben might still have invested in particularly promising technologies and markets. Breakup exposure ΔHHI is partially driven by the overall amount of IG Farben investment in a technology, which threatens the parallel trends assumption. I relax this assumption by focusing on the breakup structure across successors, particularly across geography. The breakup structure is predominantly determined by the geographic structure of the Allied occupation zones. Firstly, research and production were not randomly distributed across IG Farben facilities. However, the distribution is chosen independently from the Western occupation zones' geography, which historically strongly impacted the breakup structure. Without the zones' impact, alternative ideas such as a breakup into even smaller units would have been fathomable. On the other hand, IG Farben's re-organization into a unified structure could also have occurred. Further, different zonal structures could have yielded different outcomes. For example, had France not insisted on receiving its own area of influence, the successor BASF could have been part of the US zone, thereby changing the initial structure of breakup considerations. Furthermore, a breakup along production lines instead of geography was also a theoretical possibility. These factors facilitate a weaker version of the first identification assumption: technology areas with different research investment distributions across successors or occupation zones would have, absent the shock, developed in parallel.

The second assumption is that the IG Farben shock can be separated from other contemporary changes. I test the influence of many parallel events and test robustness by including control variables for war destruction, dismantlement, the German separation, among others. The timing of the IG Farben breakup further allows for a discussion of the influence of historical factors. I provide a detailed historical appraisal of these various factors in Appendix F. I also show robustness to historical factors in a firm-level specification, in which control variables are constructed differently.

5 Measurement of Competition in Innovation Space

In this study, I measure changes in technology-level concentration to characterize the impact of the IG Farben breakup. In general, technology-level concentration does not equate to traditional measures of competition in product markets, and such extrapolations should remain cautious. Technologies as defined by patent classifications likely encompass many products; thus, changes in technology concentration likely hide substantial variance in product-level change. In principle, it is even possible for a breakup to yield significant technology-level changes without product-level changes if the breakup happens between products, as in corporate de-mergers. In the IG Farben case, this is unlikely as (based on historical product catalogs) the breakup created substantial product-level competition as well (Poege, 2022). Similarly, a product can be subject to inputs from several technologies. Despite these caveats, the technological dimension itself is important (Bloom, Schankerman, and Van Reenen, 2013) and competition for technological capabilities can be a precursor to competition in product markets. In subsequent analyses, I use product-level data to discuss the distinction between product-level and technology-level competition.

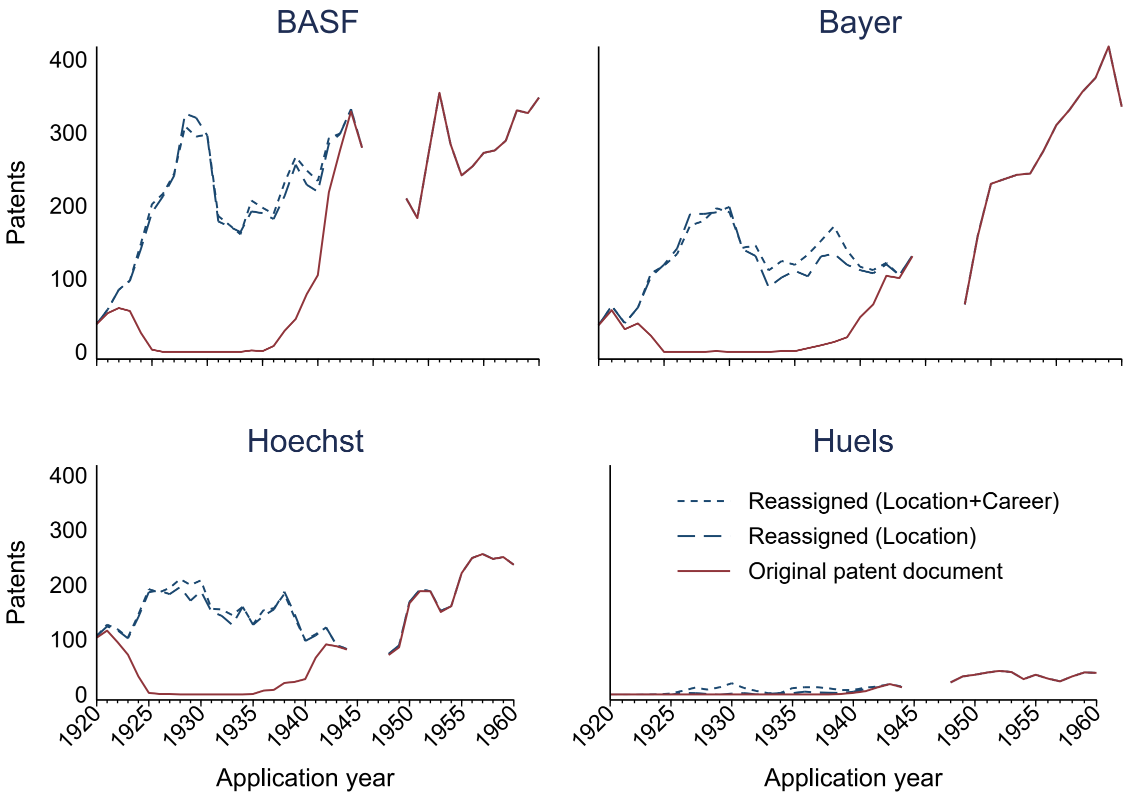
As introduced previously, I measure breakup exposure as the concentration change caused by the IG Farben breakup as $\Delta\text{HHI} = \text{HHI}^{IG} - \text{HHI}^{\overline{IG}}$. This equation captures the hypothetical difference in concentration either with IG Farben as one entity (HHI^{IG}) or when broken up into successors according to the eventual assignment rules ($\text{HHI}^{\overline{IG}}$). So defined, the concentration change ΔHHI is non-negative. Due to war-related changes and potential endogenous adjustments of the IG Farben's technology portfolio in the early post-war years, I measure ΔHHI in the pre-war period. However, $\text{HHI}^{\overline{IG}}$ is unobserved during IG Farben's lifespan as a unified corporation because the bulk of IG Farben-related patents was filed as applicant "IG Farben". The breakup structure needs to be reconstructed.

As the breakup had strong geographic components, I can reconstruct its structure based on R&D locations revealed through information about the patents' inventors. With the geographic dispersion of research facilities across Germany, the inventors' locations reveal an association with the eventual successors. Closely following the post-war patent reassignment (see Section 2.2), I assign inventor locations to the nearest research facility or, alternatively, according to the inventors' pre-merger or post-war employer. This process is successful for up to 90% of IG Farben patents.[15] I discuss details of the reassignment process in Appendix A.5. Figure 3 presents the results for the largest successors.

For the main results, I focus on ΔHHI as measured in the pre-war period (e.g., 1925-1939). However, the results are robust to the equivalent measure from the post-war, pre-breakup period (1948-1951). As post-war patents were primarily granted after the breakup, I can observe the post-breakup structure directly via applicant information. $\text{HHI}^{\overline{IG}}$ is observed, and HHI^{IG} can be recovered by considering all successors as one block, thereby excluding noise from the reassignment rules. For the main analysis, however, a focus on pre-war patents is preferable as the resulting exposure measures are unaffected by the effects of the war and potential anticipation.

[15]The 10% unassigned patents cannot be considered for calculations of ΔHHI. I assign them to the IG Farben successors while preserving shares. For example, if one patent was assigned to BASF and Bayer each, but one patent remained unassigned, I proceed as if 1.5 patents were assigned to BASF and Bayer. I apply the same procedure towards patents by East German IG Farben successors as they quickly become irrelevant for West German technological development.

Figure 3: Patents of successor companies, assigned by inventor locations



Notes: Subsidiaries aside, IG Farben's Frankfurt headquarter is the applicant listed on all IG Farben patents. However, unlike most companies at the time, almost all patents list inventors. Due to the geographic spread of IG Farben's research facilities, inventor locations allow the reassignment to eventual successors. Only in some cases are the inventor careers from deduplicated patent applications more informative. Here, inventors are reassigned to their post-war place of employment. The graph shows the yearly number of granted patent applications for the three large successor companies and the newly independent Huels. Numbers are as listed on the original patent documents (solid red line), as reassigned to eventual successors using location information (dashed blue line), and as reassigned to eventual successors using location information and inventor name disambiguation (solid blue line). For the smaller successors and East German patents, see Figure A-6.

In Table 1, I provide concentration (change) measures for selected technology classes in which IG Farben was strongly engaged. In technology classes traditionally associated with the dye manufacturing, IG Farben's traditional business, the breakup implied substantial changes exceeding 1000 points. However, there is substantial variance. For example, exposure is relatively weaker in ammonium and pharmaceuticals, despite the intensive engagement of plants such as those constituting the successors BASF and Bayer, respectively. To characterize the overall concentration change, I divide classes into high and low breakup exposure, splitting at the 75th percentile (cutoff 185).[16] In the top 25% of classes, ΔHHI is very large, on average almost 1,200. In contrast, in the remainder of chemistry (and outside of chemistry), the breakup

[16]For reference, a merger with an effect of $\Delta\text{HHI} > 100$ or > 200, depending on absolute HHI, would be above the FTC screening thresholds for product markets. However, direct comparisons between concentration in antitrust markets and technologies come with caveats, as discussed at the beginning of this section.

Table 1: ΔHHI implied by the breakup

Selected technology classes	Patents 1925-1939					48-52
	Count	IG %	HHI^{IG}	$\text{HHI}^{\overline{IG}}$	ΔHHI	ΔHHI
8M: Coloring	643	56.45	3323	944	2379	1717
12G: Processes (general)	400	25.75	713	311	402	174
12K: Ammonium, Cyanides	484	16.43	382	211	171	263
22E: Indigo-based dyes	377	76.39	5910	1582	4328	2592
29B: Chemical fibers	601	28.79	891	219	671	159
30H: Drug development	1050	14.67	253	107	146	70
39C: Synthetic plastics	325	50.77	2647	869	1778	783
45L: Pesticides	700	31.29	1078	380	698	245
Means for ΔHHI > p75 (N=33)	731	37.07	1820	625	1195	641
Means for ΔHHI ≤ p75 (N=102)	681	4.40	403	380	23	43
Means overall	693	12.38	750	440	310	190

Notes: Shows the concentration change implied by the IG Farben breakup for selected technology classes and by breakup exposure. The columns show the count of granted patents, the share of patents by IG Farben or subsidiaries (IG %), the Herfindahl-Hirschman index considering all as one block (HHI^{IG}) and split up according to the eventual successors ($\text{HHI}^{\overline{IG}}$) as well as the difference, ΔHHI. The first columns consider patents filed between 1925 and 1939, and the last column for 1948-1952. Patent counts are rounded from fractional counts. Statistics are calculated by technology class, means across exposed/comparison technology classes in the last two rows.

had almost no effect on technology-level concentration. Concentration changes measured based on the post-war pre-breakup period are generally smaller, although still substantial.

Finally, I calculate alternative measurements of ΔHHI that remove the effect of the amount of IG Farben investment and only focus on the distribution of investment across successors or occupation zones. The standard ΔHHI introduced above describes concentration changes within technology classes and relates to the previous literature. The change in HHI provides an intuitive description of the concentration change caused by the IG Farben breakup. However, HHI strongly depends on the share of IG Farben-related patents in each technology class, which may be endogenous to future technological potential. A set of alternative measures removes this dependence by considering only IG Farben-related patents. Starting from this set, alternative HHI can be computed, either by analyzing the breakup of IG Farben across successors or by exclusively analyzing geographical variation across occupation zones. To do so, I restrict attention to IG Farben-related patents. Consequently, $\text{HHI}^{IG} = 10000$ for all technology classes. $\text{HHI}^{\overline{IG}}$ either follows the structure of the eventual successors, determined as outlined above, leading to $\Delta\text{HHI}_{\text{Within}}$. Alternatively, $\text{HHI}^{\overline{IG}}$ follows only the geographical distribution of IG Farben across the occupation zones. This this case, instead of successor shares, shares in the British, French, and US occupation zones form the basis of $\text{HHI}^{\overline{IG}}$.[17] This removes variation introduced from subsidiary structures and leads to $\Delta\text{HHI}_{\text{Occ}}$.

[17] As the IG Farben successors lose access to the Eastern zone, I exclude patents invented there.

6 Effects of the Breakup on Innovation

The main outcome variables relate to the patenting activity in a technology class, either overall or restricted to non-IG Farben firms. While the theoretical literature, as well as antitrust litigation, focuses primarily on direct effects on the merging parties, an aggregate view is crucial for an economic analysis of the breakup.

I first present descriptive statistics of the estimation sample. This sample is a technology-year panel of chemical technology classes. To present summary statistics, I group technology classes into those with high and low breakup exposure, split at the 75th exposure percentile. The two sets of technology classes are comparable before the war. Table 2 demonstrates that the groups of technology classes exhibit similar pre-war patent counts; this is also true in terms of patenting by foreigners and by East German firms and inventors. Firm lists (see Appendix C) are more likely to contain applicants from classes with high breakup exposure. Exposed technologies were also more concentrated before the war; however the presence of IG Farben fully explains these differences. Nonetheless, wartime destruction equally affects patent applicants across the two groups. Finally, excluding from IG Farben, applicants are equally likely to be slated for post-war dismantlement.

Next, I analyze the effect of breakup exposure across technology classes on quality-weighted patent counts through difference in differences regressions. The subsequent results incorporate two-way fixed effects of patent class and application year; I also report interactions of application year dummies with breakup exposure. As discussed in the previous section, breakup exposure is the hypothetical change in HHI between IG Farben as one entity and broken up according to the eventual breakup structure. Empirically, the main breakup exposure variable is highly right-skewed. In the regressions, I use a log-transformed version of this variable so that $D_i = log(\Delta\text{HHI})$. I set $D_i = 0$ for $\Delta\text{HHI} \leq 1$. Results are robust to various alternative specifications, such as unadjusted logarithms or an inverse hyperbolic sine transformations (Table B-2). Throughout, I cluster standard errors at the technology class level (Bertrand, Duflo, and Mullainathan, 2004).

The first set of results shows specifications exposing the full dynamics of pre-trends and post-breakup differences. Figure 4 distinguishes four periods. First, during the pre-war period, IG Farben was one unified company. Then, the figure omits the patent applications during the Second World War. Wartime applications were only processed in the 1950s. As firms will only pursue applications still valuable post-breakup, patent counts are subject to selection bias. After the war follows the post-war pre-breakup period from 1948 to 1951. Finally, by 1952, most successors had incorporated and the breakup had taken effect. Using the baseline regressions with quality-weighted patent counts, Figure 4a shows flat pre-trends both before the war and

Table 2: Descriptive statistics for IG/non-IG exposed technology classes

Comparing 1925-1939 tech classes: High vs low breakup exposure					
N=33 (H) 102 (L)	High exp.	Low exp.	Difference	(SE)	p-value
Granted patents (p.a.)	49.85	46.59	−3.26	(22.20)	0.884
- Domestic	36.22	33.77	−2.45	(17.41)	0.888
- Foreign	10.18	8.95	−1.22	(3.43)	0.722
- Quality-weighted	147.80	140.12	−7.68	(64.95)	0.906
Matched to firm (%)	0.61	0.30	−0.31	(0.03)	0.000^{***}
- IG Farben (%)	0.37	0.04	−0.33	(0.02)	0.000^{***}
- Other (%)	0.24	0.26	0.01	(0.03)	0.604
HHI (IG together)	1819.88	403.26	−1416.62	(246.22)	0.000^{***}
HHI (IG separate)	624.57	379.94	−244.63	(185.68)	0.190
Domestic East (%)	0.17	0.18	0.01	(0.02)	0.614
Domestic East/Berlin (%)	0.23	0.30	0.07	(0.02)	0.000^{***}
War destruction (%)	0.33	0.33	−0.01	(0.01)	0.382
Dismantle (%)	0.39	0.13	−0.26	(0.02)	0.000^{***}
Dismantle (No IG, %)	0.08	0.09	0.01	(0.02)	0.445

Notes: Shows difference between technology classes with high and low breakup exposure. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. All data refers to patents applied for in 1925-1939. Patents counts are annual. Domestic and foreign patents are identified using inventor locations if available, applicant locations otherwise. Patents are weighted according to forward text similarity divided by backward text similarity, on patent-level normalized to mean three and standard deviation one. The share of matched patents refers to patents matched to the firm dataset described in Section F. HHI is calculated first assuming all IG Farben members to be one entity, then separately according to their post-1952 split-up. The location of patents is first described by the share applied for from the Eastern, Soviet sector. Berlin is handled separately due to its special, divided status. War destructions refers to the share of flats destroyed between 1939 and 1945, weighted by the patent locations in a technology class. Dismantlement on the technology class level is calculated as the share of patents by firms targeted by dismantlement. As the exposed group is strongly selected towards IG Farben patents, it is also shown considering only non-IG firms.

before the breakup as well as long-run increases in patent count after the breakup. Panel 4b plots the average quantity of granted patents per class for the high- and low-exposure groups as well as patents outside of chemistry. Before the war, the high- and low-exposure groups showed comparable trends and levels; even the non-chemistry classes only deviated in levels. Overall, the delayed start of the effect in both panels is characteristic of innovation processes, whereby R&D investments may take time to materialize as patents. The timing of the effects further suggests that they are not tied to changes in the overall postwar order.

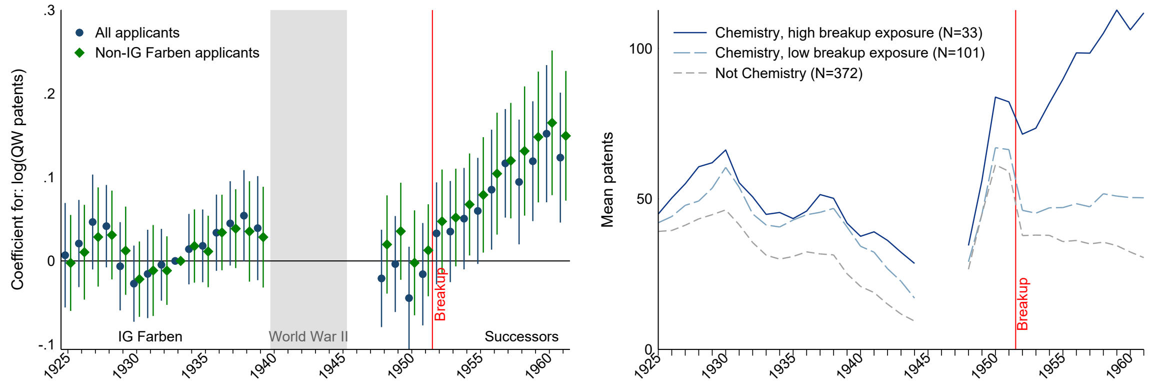
For some analyses, I report grouped difference in differences coefficients instead of detailed dynamics for a larger set of dependent variables. Starting from Table 3, $\beta_{1948-1951}$ and $\beta_{1952-1961}$ group the respective years, showing differences to the baseline period 1925-1944. The main coefficient of interest is $\beta_{1952-1961} - \beta_{1948-1951}$. While pre- and post-war outcome variable levels are often comparable (i.e. $\beta_{1948-1951} = 0$), the war could have resulted in level shifts, making the individual β comparisons uninformative about the breakup. Table 3 reports coefficients for alternative dependent or breakup exposure variables. Results are robust to estimation using Poisson regression.[18]

[18] See Figure B-2 and Table B-5 in the Appendix.

Figure 4: Technology class-level regressions: Quality-weighted counts

(a) Quality-weighted patent count: Regression

(b) Patent counts: Descriptives



Notes: Descriptives and regressions comparing technology classes with high and low exposure to the IG Farben breakup, as defined by the 75th percentile of ΔHHI (185). Exposure is measured using pre-war (1925-1939) data, but the breakup is finalized and effective around 1952. Shows quality-weighted counts of granted patents, with average patent quality winsorized and rescaled to have average three and standard deviation one to exclude negative values. 4a shows OLS regressions of log quality-weighted patent counts in technology classes with and without pre-war IG Farben breakup exposure. Shows 95% confidence intervals. 4b shows average quality-weighted patent counts in the two groups. The graphs correspond to mean(log y) (left) and mean(y) (right), explaining the difference. The German patent office closed from 1945 to 1947. Wartime patent applications are largely prosecuted post-war and hence omitted.

Robustness checks related to the historical context I test whether the main results are robust to the inclusion of control variables capturing historical factors. For each control variable, I discuss the specific historical context and the role of IG Farben itself in detail. Due to its length, this discussion is relegated to Appendix F. Table B-1 in the appendix summarizes the results of including the control variables; in these regressions, the main coefficients of interest remain similar to the baseline specification. As control variables, I first construct measures of exposure to war destruction based on city-level damage estimates (Kästner, 1949; Hohn, 1991). Second, I quantify the extent of Allied policies aimed at reducing the German war potential. For this, I digitize lists of firms slated for dismantlement in the occupation zones (Harmssen, 1951) and assign shares to technologies and dismantlement dummies to firms. I also test whether the results are robust to the exclusion of technological fields, particularly plastics - which were specifically targeted by postwar regulation. Third, I assign patents to the respective occupation zones and quantify the exposure of technologies or firms to the division of East and West Germany. Fourth, I employ the firm-level count of pre-war US patents to quantify the exposure to confiscation of foreign IP or the post-war expropriation of German IP (Gimbel, 1990).[19] In Appendix F, I also discuss unquantifiable historical evidence, including the wartime loss of life, technological opportunity, post-war growth, and IG Farben itself as a dismantlement target.

[19]In Poege (2022), I also reject the hypotheses that additional Allied competition policy - the 1947 dissolution of cartels - or policy related to internationalization - the 1951 entry into the General Agreement on Tariffs and Trade (GATT) - are confounding factors. Both require product-level analyses involving prices, which would require substantial additional discussion of data and literature and are ancillary in the context of this paper.

Effect sizes The estimated effects are substantial but not unrealistic relative to previous estimates, given the shock's immense size. The difference in differences coefficient is 0.107, which for a concentration change of ΔHHI = 200 corresponds to a 77% patenting increase relative to a technology without concentration change. This figure amounts to 36.3 additional patent grants per technology class and year. In comparison, Haucap, Rasch, and Stiebale (2019) analyze patent applications by merged entity and competitors relative to matched control firms after merger events. They find large decreases in innovation output for the merged entity (around 30% - up to 44% after propensity score matching) and more moderate reductions for competitors (around 7% - up to 25% after propensity score matching). However, recent mergers have - given more stringent antitrust enforcement - much smaller effects on market and technology structure compared to the IG Farben breakup. Similarly, Watzinger, Fackler, et al. (2020) find that compulsory licensing of Bell patents leads to 3.2 patent applications per year more for a mean dependent variable of 6.8. Focusing on the breakup of AT&T/Bell itself, Watzinger and Schnitzer (2020) find an increase of more than 70 patents per year for a mean of almost 120, an increase of 60%. As part of their counterfactual analysis, Igami and Uetake (2020) study the effect of increased or reduced merger thresholds according to the number of active firms in the market and find smaller effects. If mergers to monopoly were permitted, in their simulations, about 7% fewer innovations would occur relative to a baseline threshold of $N = 3$; 10% fewer relative to a $N = 6$ threshold.

Alternative exposure variables While intuitively appealing, ΔHHI does not directly conform to the identification justification of an idiosyncratic breakup of IG Farben along the occupation zones. ΔHHI, as used in the previous analysis, has the advantage of its close relationship to the prior industrial organization literature. On the other hand, ΔHHI is only partially driven by the breakup along the occupation zones, as it strongly depends on the share of IG Farben patents within a particular technology. Ideally, the statistical analysis would compare between technologies with similar involvement of IG Farben but with variation in breakup intensity driven by geographic structure.

With two alternative breakup measures, I focus on variation within IG Farben. As discussed in Section 5, $\Delta\text{HHI}_{\text{Within}}$ considers only patents associated with IG Farben and its subsidiaries for the calculation of the HHI. $\Delta\text{HHI}_{\text{Occ}}$ additionally disregards the subsidiary structure and considers only IG Farben's geographical structure across occupation zones. Both approaches remove the amount of IG Farben investment in a particular technology from the analysis. I standardize the measures to mean zero and standard deviation one.[20] Results based on these measures are consistent with prior results: Figure 5 shows that the dynamic effect follows a

[20] In contrast to the previously used ΔHHI, the alternative exposure measures are substantially less skewed. In fact, the log transformation increases the skewness, so I do not apply it. Note that the measures are only defined

Table 3: Effects in technology class-level regression: Main results

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Exposure: log(ΔHHI) 1925-1939				1930-1939	1925-1935	1948-1952
log(Patents)	All (Quality)	Non-IG (Quality)	All (Count)	Non-IG (Count)	Non-IG (Quality)	Non-IG (Quality)	Non-IG (Quality)
β_{48-51}	-0.039^{*}	0.003	-0.024	0.012	0.003	0.005	0.009
	(0.022)	(0.020)	(0.023)	(0.020)	(0.020)	(0.019)	(0.020)
β_{52-61}	0.069^{***}	0.092^{***}	0.073^{***}	0.093^{***}	0.092^{***}	0.087^{***}	0.091^{***}
	(0.025)	(0.023)	(0.024)	(0.023)	(0.024)	(0.022)	(0.024)
$\beta_{52-61} - \beta_{48-51}$	0.107^{***}	0.089^{***}	0.097^{***}	0.082^{***}	0.089^{***}	0.081^{***}	0.081^{***}
	(0.020)	(0.021)	(0.019)	(0.019)	(0.021)	(0.021)	(0.022)
Tech FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Classes	135	135	135	135	133	135	134
Dep. var. mean	4.169	4.044	3.060	2.937	4.055	4.044	4.051
Adj. R-Square	0.792	0.789	0.829	0.827	0.788	0.788	0.788
Observations	3757	3730	3777	3750	3715	3730	3721

Notes: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ Standard errors clustered on the technology class level in parentheses. ΔHHI is the difference between technology-level concentration, considering IG Farben as one block or as broken up according to the 1952 successors. Exposure is set to zero for $\Delta\text{HHI} \leq 1$. The difference in differences coefficients in turn compare patent counts in 1948-1951 and 1952-1961 with the pre-war period. The main effect is the difference between these two coefficients, tabulated in row {52-61}-{48-51}. The dependent variables are quality-weighted patent counts, except columns (3) and (4) with simple patent counts. Quality weights are normalized to mean three, standard deviation one. The columns restrict patents by applicants, either all (columns 1, 3) or applicants unconnected to IG Farben (columns 2, 4, 5-7). The number of observations differs if for some technologies, the ΔHHI or quality scores could not be computed or for some technology-year cells, no non-zero patent counts are available. In the appendix, Poisson regression results are available in Table B-5, estimates with control variables in Table B-1.

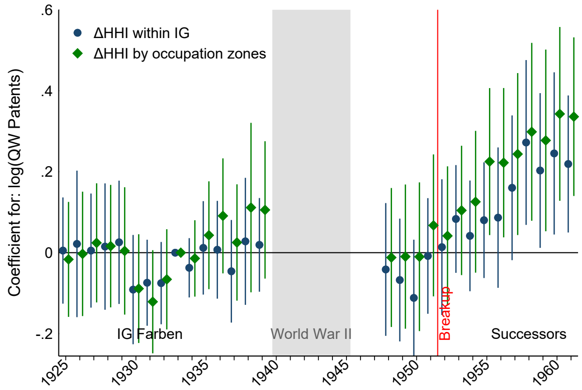
gradual increase without a pre-war trend. A concentration decrease by one standard deviation increases patenting by around 20% on average over the 1952-1961 period, relative to 1948-1951.

Quantity and quality of innovation IG Farben's breakup could have increased the propensity to patent among the company's successors and their competitors. After the breakup, the successors could no longer access each other's patents and research findings. Accordingly, the value of possessing patents increased. An increased propensity to patent among some market participants could have spilled over to other actors, as they faced an increased need to claim their stakes.

With an increased patenting propensity, differential effects across quality and quantity are possible. Raw patent counts, as well as average yearly patent quality, allow further investigation. Figure 6 presents the results of difference in differences regressions for both raw counts (Panel

for technology classes with non-zero IG Farben share. See Table B-4 in the appendix for detailed results in table format.

Figure 5: Technology class-level regressions: Alternative calculation of ΔHHI

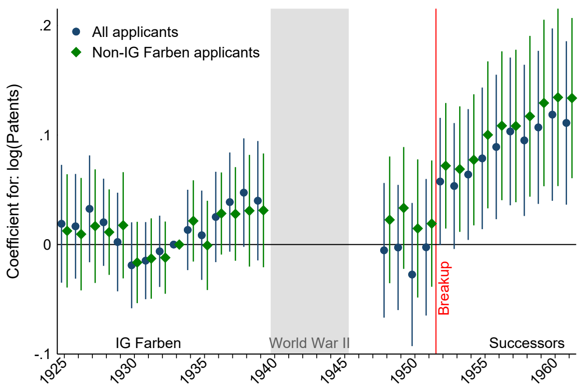


Notes: Technology-year panel regression with 95% confidence intervals. The dependent variables are quality-weighted, non-IG patents. Continuous exposure measures are interacted with year indicators. Exposure is measured using pre-war (1925-1939) data, but the breakup is finalized and effective around 1952. The explanatory variables as explained in Section 5 are standardized to mean zero an standard deviation one. The German patent office closed from 1945 to 1947. Wartime patent applications are largely prosecuted post-war and hence omitted.

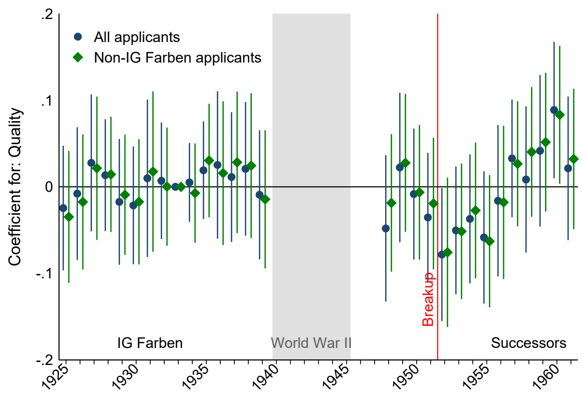
6a), and for average quality (Panel 6b). The sharp increase in the raw patent count after 1952, together with the drop in the average patent quality, suggests an initial quantity-quality trade-off. The sudden increase in patents is unlikely to reflect an increase in innovation but instead points to a change in the propensity to patent.[21] Adjusting for quality attenuates the initial increase, and the overall results are consistent between raw and quality-adjusted patent counts.

Figure 6: Technology class-level regressions: Count and Quality

(a) Patent count



(b) Average quality



Notes: Technology-year panel regression with 95% confidence intervals. 6a shows OLS regressions of log patent counts in technology classes with and without pre-war IG Farben exposure. 6b corresponding regressions for average patent quality within classes.

[21] Alternatively, strategic delay may play a role. Firms might hold back patent applications during 1948-1951 because of uncertainties over IG Farben's future. If the firms expected that some extent of compulsory licensing would be imposed between the successors, such behavior would be rational. However, this observation is inconsistent with the post-breakup drop in quality, as incentives to delay are larger for important patents. Further, there is no spike in patenting by the IG Farben successors compared to other firms. See Appendix D.

An analysis of inventor counts yields similar results. The number of inventors listed on a patent represents a classic but also an imprecise measure of investment in a particular project. Despite their higher cost, larger teams yield better results in scientific and technological endeavors (Wuchty, Jones, and Uzzi, 2007). Therefore, the number of distinct inventors active in a technology class and the average number of inventors listed on patents in a technology class present two corresponding dependent variables. Figure B-4 in the appendix reports results. The number of unique inventors in IG-exposed classes follows a similar pattern as the patent count: increases are driven by new inventors rather than by established ones. The average number of inventors per patent does not display an initial jump in 1952 but presents a slight, positive, long-run tendency. This evidence also suggests short-term increases in the propensity to patent and long-term increases in innovation effort.

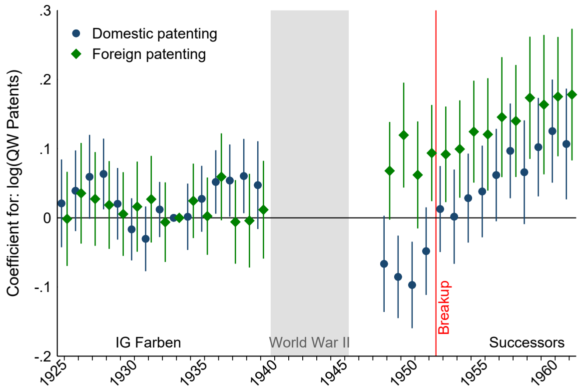
For an analysis of research specialization in the affected technologies, see Appendix E. There, I use patent texts to construct a technology-level measure of specialization, thereby showing that specialization increases after the breakup. I further discuss innovation specialization between the IG Farben successors in Section 7.

Domestic and foreign patenting Foreign competition and foreign entry can potentially negatively affect innovation and other economic outcomes (Autor, Dorn, and Hanson, 2013; Bloom, Draca, and Van Reenen, 2016; Autor, Dorn, Hanson, et al., 2020). These dynamics also present concerns in cases of mergers (Montag, 2021). When considering the breakup of a leading company, policymakers may question whether retaining a national champion is preferable to prevent foreign competition, even at the expense of welfare and innovation. In the context of IG Farben's breakup, this is a distinct possibility. The end of the Second World War brought the beginning of Germany's integration into the Western alliance system. However, whether the IG Farben breakup further facilitated this process is unclear.

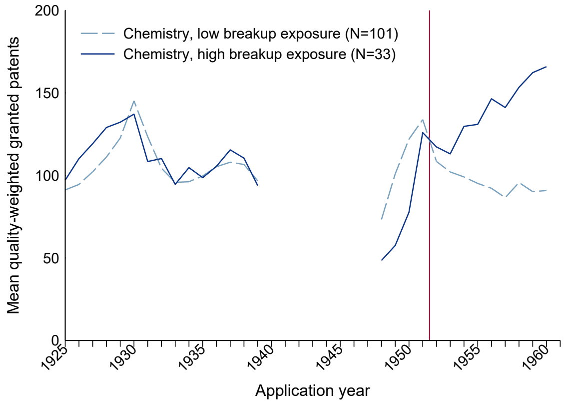
While increased foreign patenting played an important role after the Second World War, it is less important than changes in domestic patenting in the context of the IG Farben shock. Figure 7a shows that technology classes exposed to the IG Farben shock experience a specifically large increase in foreign patenting after the war. However, this increase occurs immediately and the timing appears unrelated to the IG Farben shock. This development occurs in the context of a long-run decline in foreign patenting before and during the war. Immediately after the war, the number of patents by foreign applicants and inventors increased distinctly in exposed and unaffected technologies, although to a smaller extent for the latter. Domestic patenting develops differently, with much larger relative increases for technologies exposed to the IG Farben shock. After the war, comparison group levels immediately increase relative to those of the breakup exposure group, so that in Figure 7a the coefficients in 1948-1951 are negative.

Figure 7: Domestic and foreign patenting

(a) Regression analysis



(b) Descriptive: Domestic patents



Notes: Shows quality-weighted counts of granted patents, where patent location is defined by inventor location if available, applicant location otherwise. Patent quality is normalized to mean three. Panel 7a presents results from a technology-year panel regression analysis (95% confidence intervals) with $D_i = log(\Delta\text{HHI})$ (with $D_i = 0$ for $\Delta\text{HHI} \leq 1$) interacted with application year. Panel 7b shows the quality-weighted quantity of domestic patents over time. For the corresponding graph on foreign patents, refer to Figure B-1 in the appendix. The German patent office closed from 1945 to 1947, so that no data is available for these years.

Visual inspection in Figure 7b indicates that this trend is not due to differential trends but differential levels. After 1952, the trends diverge, with the comparison group slowly decreasing and the breakup exposure group strongly increasing. Consequently, the difference between the early and late coefficients is very large.[22] Overall, as the quantity of domestic patenting is larger than foreign patenting, the estimated effects also reflect quantitatively more important increases.

Product market and technology spillovers The technology class level analysis conflates the effects of competition in technology space and product markets. Firms operating in the same technological areas are more likely to offer similar products. In the framework of Bloom, Schankerman, and Van Reenen (2013), the IG Farben breakup could have increased innovation outputs among IG Farben successors (see Section 7), which then, in turn, would have spilled over through technology and product market linkages. In this view, positive spillovers to technology competitors and (possibly moderate) negative spillovers to product market rivals are consistent with the previous analysis. Consequently, the analysis needs to shift to examine direct measures of product market competition in order to solidify this conjecture.

To address this perspective, I provide supporting evidence by taking the analysis to the firm level. In addition to technological exposure, I can classify firms by their exposure to IG Farben on the product level. For this, I use detailed product-level supplier catalogs to characterize the market structure of the German chemical industry before and after the breakup. Appendix C describes the data construction in detail. In the 1952 product catalog - the first published

[22]See also the comparison of the grouped coefficients in Table B-3 in the appendix.

after war and breakup - I can observe the number of products a firm offered in competition with IG Farben and, as a subset, the number of products offered by at least two IG Farben successors. In the 1939 product catalog, the main successors of IG Farben are listed as a single firm. Therefore, I focus only on the extensive margin of potential exposure to increased product market competition due to the breakup. While the shift to the firm level is necessary to explore additional insights, the focus on firms in the context of the IG Farben breakup is less desirable compared to the modern context. Since the measure for technological exposure to the breakup relies on pre-war data, I restrict to incumbents in this analysis.[23] For this population of firms, there was considerable turnover due to German wartime and post-war reorganization. Nonetheless, the core result of increased innovation by exposed firms remains consistent with the technology class-level analysis.

The estimation follows a similar logic as equation 2 with grouped the yearly coefficients, but now on the firm-level:

$$\begin{aligned} log(Y_{it}) = \beta^{Tech}_{1948-1951}\, D^{Tech}_i + \beta^{Tech}_{1952-1961}\, D^{Tech}_i + \beta^{Prod}_{1948-1951}\, D^{Prod}_i + \beta^{Prod}_{1952-1961}\, D^{Prod}_i \\ + \alpha_i + \gamma_t + \delta X_{it} + \epsilon_{it} \end{aligned} \tag{3}$$

$$\text{with} \quad D^{Tech}_i = log \sum_{j \in J} w^{Tech}_{ij} D^{Tech}_j \quad \text{and} \quad D^{Prod}_i = log \sum_{p \in P} w^{Prod}_{ip} D^{Prod}_p$$

where the technology-level exposure $D^{Tech}_j = \Delta\text{HHI}_j$, as used in the previous analysis, is aggregated to the firm-level with weights w^{Tech}_{ij} corresponding to the share of firm i's pre-war patenting in technology j. D^{Prod}_p takes value one in case of product-level exposure to IG Farben (or its breakup, respectively). The product catalogs do not provide information about the importance of a given product to a firm's overall product portfolio. Consequently, I set $w^{Prod}_{ip} = 1$. With this, a firm's product-level exposure, as applied in the regressions, is the number of products exposed to IG Farben (or its breakup). When a firm is not listed in a product catalog or not exposed to IG Farben, I set exposure D^{Prod}_i to zero. Different from the technology level, zero values are common for the dependent variable on the firm level, so I approximate $log(Y)$ with the inverse hyperbolic sine transformation.

I compare the effects of technology and product market exposure to the IG Farben breakup and find evidence consistent with technology spillovers. In Table 4, the baseline specification with only technology-level exposure is consistent with previous results, albeit smaller in magni-

[23]In Figure B-1b in the appendix, I show the share of patents by applicants who had already patented before the war. These applicants applied for the majority of patents, especially in technology classes with high exposure to the breakup. In the firm panel, I consider only firms that could be matched to entries from a set of sources of firm information with non-negligible pre-war patent grants.

tude.[24] Next, I employ product-level measures instead of technology-level exposure and tend to find positive effects as well. As the product-level exposure variables follow a different definition, their magnitude cannot be compared directly. Nonetheless, the positive effect on innovation suggests that the results are not driven by IG Farben's ability to exclude competitors from entry, which historically had been the case (Haber, 1971). In that case, the product-level exposure by itself - defined as being a competitor of IG Farben in the market - should not be linked to post-breakup innovation increases. Finally, I include measures for both technology-level and product-level exposure. The correlation between the two exposure measures is around 0.48, similar to the magnitudes reported in Bloom, Schankerman, and Van Reenen (2013).[25] I find that firms technologically exposed to the IG Farben breakup increase their innovation output; however, coefficient estimates for firms operating in the same product markets are reduced in magnitude and no longer statistically significant. This suggests that the effects work through the technological dimension, for example, as spillovers.

7 Innovation by IG Farben

The breakup's economic effect on IG Farben is difficult to study causally, as appropriate control groups are hard to find. Despite IG FArben's size, the number of successor companies is too small for statistical analysis. However, with descriptive analysis of financial and patent data, it is possible to contextualize the development of IG Farben and its successors. In this section, I further discuss the specialization of IG Farben's patent portfolio.

IG Farben and its successors were highly innovative companies with high R&D intensities, both before and after the breakup. At the peak of IG Farben's strength in the late 1920s, R&D spending reached 8-12% of revenue, over 50% of which was derived from exports (Figure 8). In the 1930s and 1940s, domestic turnover rose while export shrank in the context of the great depression and Nazi autarky policy. R&D continued to play an important role, though at more moderate levels than before. The immediate post-war statistics reflect the economic difficulties and the rapid return to pre-war levels (Figure 8). After the war, turnover collapsed, and export links were disrupted. However, as with the overall economy, recovery was quick enough that by the early 1950s, the Western IG Farben successors returned to mid-1930s turnover and export shares. Over the following decades, all successors became globally successful corporations. Successors' R&D intensities and patenting levels initially remained comparable to before the war, with large increases in patenting and high but constant R&D intensity thereafter. IG Farben's patenting also increased relative to a synthetic control group constructed from the

[24] I show the robustness of this result across various specifications and subsamples of firms, such as excluding foreign firms or IG Farben successors, in Appendix C.

[25] For scatter plots of the two exposure measures, see Figure C-2 in the appendix.

Table 4: Firm-level regressions with technology and product market exposure

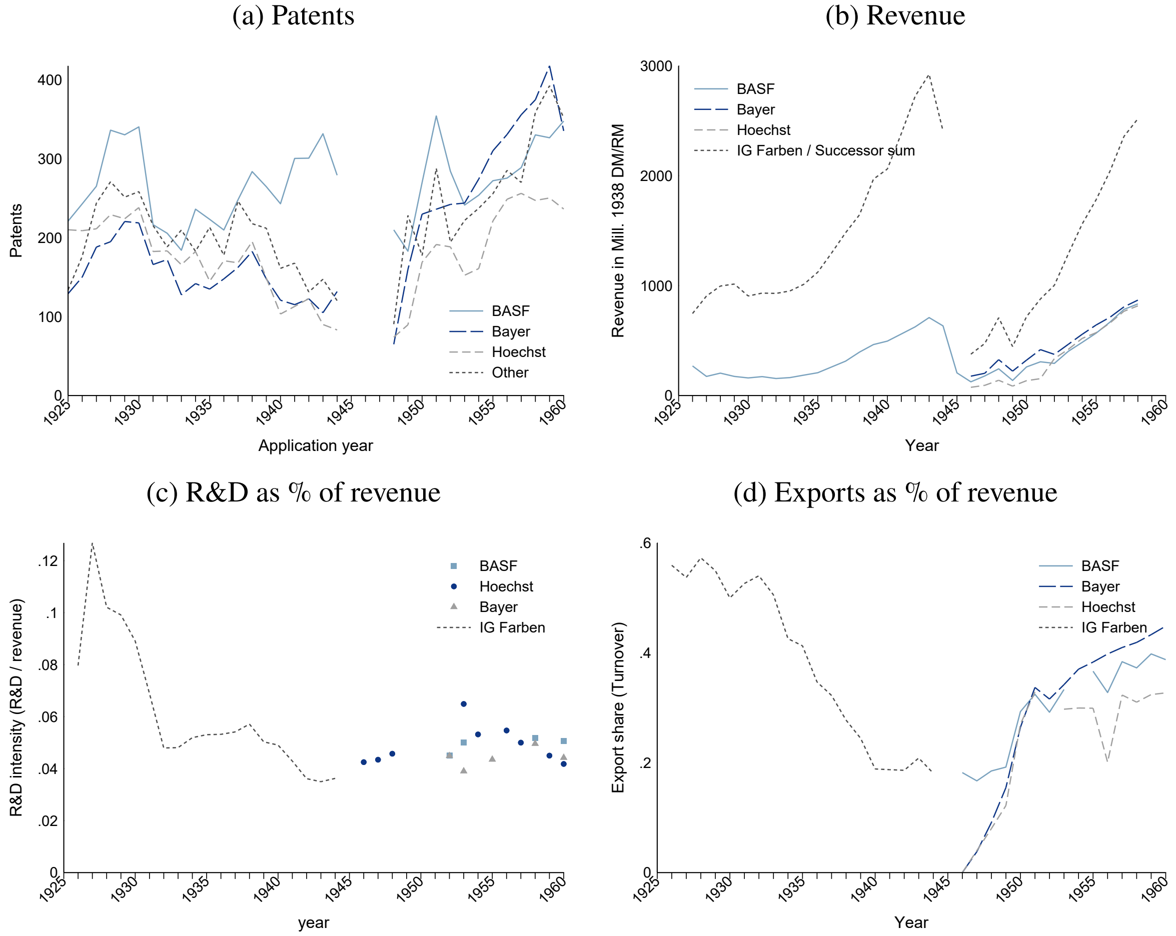
Product market exposure		IG Products 1939 (d)		IG Products 1952 (log)		Breakup exposure 1952 (log)	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
$\beta^{Technology}_{48-51}$	0.014		0.037		0.016		0.014
	(0.022)		(0.025)		(0.024)		(0.024)
$\beta^{Technology}_{52-61}$	0.067***		0.088***		0.060**		0.057*
	(0.025)		(0.031)		(0.030)		(0.030)
$\beta^{Product}_{52-61}$		−0.171	−0.279**	0.010	−0.006	0.014	−0.002
		(0.111)	(0.131)	(0.043)	(0.048)	(0.049)	(0.054)
$\beta^{Product}_{52-61}$		0.006	−0.247	0.093**	0.031	0.110**	0.046
		(0.130)	(0.159)	(0.045)	(0.055)	(0.051)	(0.060)
$\beta^{Tech}_{52-61} - \beta^{Tech}_{48-51}$	0.053***		0.051**		0.044*		0.043*
	(0.019)		(0.023)		(0.023)		(0.023)
$\beta^{Prod}_{52-61} - \beta^{Prod}_{48-51}$		0.178*	0.032	0.083**	0.037	0.095**	0.048
		(0.102)	(0.123)	(0.036)	(0.044)	(0.041)	(0.049)
Firm, Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N Firms	355	355	355	355	355	355	355
Adj. R-Square	0.621	0.619	0.622	0.620	0.621	0.620	0.621
Observations	12070	12070	12070	12070	12070	12070	12070

Notes: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ Standard errors clustered on the firm level in parentheses. The dependent variables are inverse hyperbolic sine transformed quality-weighted patents in technology classes related to the chemical industry. Technology exposure for β^{Tech}, ΔHHI, refers log pre-war-weighted exposure to ΔHHI in technology. Product market exposure for $\beta^{Product}$ varies across columns. In columns 2-3, it is an indicator variable for whether the firm is exposed to IG Farben according to the 1939 product catalog. In columns 4-5, it is the log number of products exposed to competition from IG Farben successors in the 1952 product catalog. In column 6-7, it is the log number of products exposed to the breakup, i.e. multiple IG Farben successors, in the 1952 product catalog. For control variables, see the legend of Table C-2 in the appendix (column 7).

German electronics industry. The electronics industry was dominated by a duopoly of AEG and Siemens (Feldenkirchen, 1987), who were spared from Allied breakups, yet similarly affected by war-related shocks. In fact, these two companies were the only two with comparable patenting amounts to those of IG Farben. Patenting by IG Farben and the synthetic control developed in parallel during the pre-war and pre-breakup years but increasingly diverged after 1952, when patenting among the IG Farben successors strongly increased. I report details of the analysis in Appendix D.

After the breakup, IG Farben's successors continued to patent in the same broad technology areas. Similarity and overlap can be defined based on technology class categories to describe the broad orientation of company technology portfolios. The calculation of the comparison score starts with the set of new patents applied for in a year, grouped by their technology class. This creates a vector of 135 elements, corresponding to the number of technology

Figure 8: IG Farben and its successors over time



Notes: Data as available from secondary sources. 8b: IG Farben after 1945 is the successors' sum. Source: ter Meer, 1953 (Data on IG Farben before 1945), Abelshauser, 2003 (BASF turnover), Stokes, 1988 (Exports, turnover), FAZ/ZEIT newspaper archives (Post-war R&D and turnover), Statistical yearbooks (Inflation), own calculations based on Section 7 (Patents).

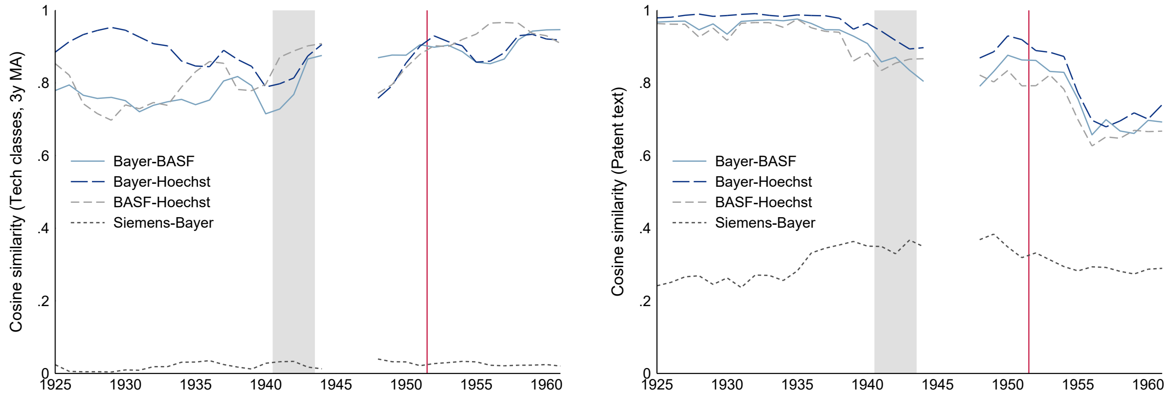
classes in chemistry. Each element contains the (normalized) number of patents in the class by, for example, successor BASF. Then, the comparison score is calculated by finding the cosine similarity between the companies' vectors. Recall that the cosine similarity between two vectors is $cos(\theta)$, where θ is the angle between the two vectors. With that, the cosine similarity lies on the interval $[-1, 1]$ (on $[0, 1]$ if all vector elements are non-negative), and similarity increases with declining θ; if $\theta = 0$ and the vectors have the same orientation, the cosine similarity reaches 1. Figure 9a plots the pairwise yearly similarity between the IG Farben successors. This descriptive plot shows that the eventual successors worked on very similar technology classes during IG Farben's existence and that the breakup did not reduce these similarities.

Although the successors continued to patent in the same technologies, their research content specialized relative to each other. I use text similarity measures based on patent full texts to look inside the technology classes (Arts, Cassiman, and Gomez, 2018). After applying the Doc2Vec

Figure 9: Technology similarity over time: IG Farben successors

(a) Tech classes of new patents

(b) Text content of new patents



Notes: 9a: Technology similarity between IG Farben successors based on new patents across technology classes. 9b: Technology similarity between IG Farben successors based on the text content of new patents. Both graphs show yearly cosine similarities between pairs of companies. Siemens is shown as third-party comparison.

algorithm (Le and Mikolov, 2014), each patent is represented as a vector v. To represent the technological orientation of a firm i, I calculate the average vector $\bar{v}_{it}$ within each year t, normalized to length one. Pairwise similarity between companies is then given by the cosine similarity between the company-year average vectors, $s_{ijt} = \bar{v}_{it} \cdot \bar{v}_{jt}$. Figure 9b plots the pairwise yearly similarity between the IG Farben successors. In contrast to class-based similarity, text-based similarity decreases after the breakup, implying that companies, on average, specialize within technologies. Appendix E shows that similar results hold for the aggregate change in research trajectories within technology classes following the IG Farben breakup.

8 Conclusion

In this paper, I study the effect of the IG Farben's 1952 breakup on innovation. The horizontal division of IG Farben's different R&D locations created competition within technology classes, which strongly increased innovation in affected technology classes. Innovation effects incorporate short-run quantity-quality trade-offs and are driven by changes in domestic patenting. Although foreign patenting in Germany increased, the differential increase in technologies with breakup exposure does not explain this increase overall.

Naturally, the historical context of the IG Farben breakup is fraught with potential confounding factors. As such, any analysis remains afflicted by limitations. However, it is possible to analyze the historical context to assess the strength of confounding factors. The impact of some factors can be quantified for robustness analyses, while others can be understood more clearly in the historical context. Robustness analyses, in turn, introduce control variables for the effects of war destruction, Allied occupation and competition policies, and the Soviet sector. Since the observed effects only materialize after the breakup and effects are driven by technologies where the IG separation increased competition, it is unlikely that a single factor from the historical context can explain the set of observed effects better than the IG Farben breakup itself.

The results might be lower bound estimates as IG Farben's successors did not engage in all-out competition. This was primarily due to the traditional production field specializations, but possibly also due to common ownership. Each IG Farben shareholder received stock of every successor and created latent incentives for the successors not to harm each other. Nevertheless, historically, the successors perceived each other as benchmarks and shied away from the temptation to fully re-cartelize (Abelshauser, 2003, pp. 457–478).

The historical setting of the IG Farben breakup is very relevant today. Large corporations with strong investments in in-house research continue to drive technological developments, both globally in the present time and historically in the German chemical industry of the early 1950s. Scale effects are key to success. Mergers such as ChemChina-Syngenta, Dow-DuPont, or Bayer-Monsanto have focused attention on competition and innovation. On the other hand, whether such findings apply to platform industries with their pronounced network effects requires future research.

Future research could study the effects of the IG Farben breakup on other domains of interest. Breakup-induced changes in competition could also affect product markets, for example, in terms of prices and changed entry dynamics. Further, the labor markets for skilled workers in the chemical industry and inventors likely did not remain unaffected. Beyond the case of IG Farben, empirical investigations into the effects of recent mergers on innovation should focus more closely on the role of technological spillovers and duplication of research.

The results in this paper highlight the importance of market and technology competition and a robust antitrust policy for innovation. Further, the history of IG Farben represents a successful government-mandated breakup and opens questions about the role of such breakups as a last-resort instrument in antitrust toolkits. However, while single breakups can have positive consequences, a *policy* of repeated breakups may reduce incentives to invest in innovation. In IG Farben's case, the German government would later introduce formal competition legislation following the US role model and was committed to a policy environment without further breakups (Murach-Brand, 2004). Future research should study how negative dynamic incentives of breakups as a policy tool can be avoided or mitigated.

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For Online Publication

A Patent Data

For the analyses in this paper, various parts of the information contained on individual patents are required. While some data could be acquired from the German patent office, much of the needed information has to be acquired through image processing or OCR and subsequent text processing. These are especially the technology class, applicant name, inventor location and application year. Here, a largely automated processing pipeline was designed which delivers highly accurate information for almost all patent documents.

Figure A-1: IG Farben patent

DEUTSCHES REICH

AUSGEGEBEN AM
11. MÄRZ 1941

REICHSPATENTAMT

PATENTSCHRIFT

№ 703 500

KLASSE 12o GRUPPE 14

I 56776 IVd/12 o

Dr. Karl Köberle † und Dr. Otto Schlichting in Ludwigshafen, Rhein,
sind als Erfinder genannt worden.

I. G. Farbenindustrie Akt.-Ges. in Frankfurt, Main

Herstellung von Perylencarbonsäureestern

Patentiert im Deutschen Reiche vom 1. Januar 1937 ab
Patenterteilung bekanntgemacht am 6. Februar 1941

Es wurde gefunden, daß man reine Perylencarbonsäureester erhält, wenn man Perylencarbonsäuren mit Phosphorhalogeniden oder Thionylchlorid erhitzt und nach Beendigung der Reaktion das Umsetzungsgemisch als sol-

Man führt die Umsetzung zweckmäßig in höhersiedenden Verdünnungsmitteln, wie Chlorbenzol, o-Dichlorbenzol, Trichlorbenzol oder Nitrobenzol durch, indem man die Perylencarbonsäure mit der entsprechenden Menge

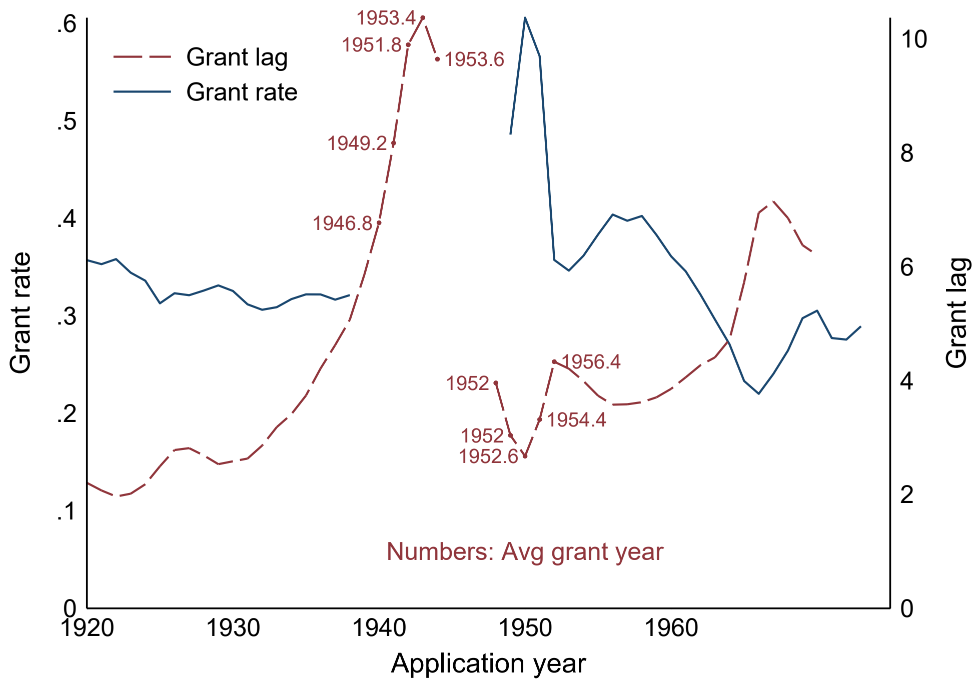
Notes: Example patent. Highlighted are technology class (12o) and group (14). Further, inventor location (Ludwigshafen) and application year (1937) are marked.

A.1 Year Information

The German patent office was first set up in 1877, although successors existed in the various German states. It handled German IP matters until mid-1945 when it closed. In 1948, when preliminary offices reopened. These accepted patent applications, but processing started only in 1950. By then, also wartime applications were processed. Therefore, patent statistics show a gap between 1946 and 1947, but are available from 1948 onwards. Figure A-2 shows the difference between application and grant year for patents where this information is available. Note the increased grant lag for wartime patents, implying that patents applied for during these years are typically granted when technological requirements have already changed. Consequently, applicants might have only selectively pursued these patents, leading to selection issues.

In historical patent records from before 1945, only granted patents ("Patentschriften") are available. To ensure a correct pre-post comparison, I disregard applications that were not ultimately granted, even when this data is available. Figure A-2 shows the grant rate by comparing the number of granted patents in the data with the number of applied patents from administrative publications. Comparing the number of granted patents (completeness of the data) is impossible as the administrative publications list granted patents by their grant year. In the long run, the grant rate remains roughly the same, although a policy of limited novelty checks at reopening yields a temporarily much higher grant rate.

Figure A-2: Patent grant lags



Notes: By application year, shows grant lag and grant rate of German patents. Grant lag is computed as difference between grant and application year, when both information is available. Grant rate is computed as a comparison of the annually filed patent applications as reported in the "Blatt für Patent-, Muster- und Zeichenwesen." 1948 and 1949 are jointly reported and thus collapsed.

A.2 Technology Class Information

The German patent office classified technologies into 89 technology sections and roughly 540 technology classes. Descriptions of these technology classes from 1910 and 1949 (*Taschenbuch des Patentwesens* 1910; Deutsches Patent- und Markenamt, 1949) show that at this level, the technology classes' content remains almost always the same.

The descriptions of the technology classes and the 1949 technology groups enable the classification of the technology classes into such that are directly relevant to the chemical industry. This classification includes classes from health care, photography, and agriculture relevant to the chemical industry and yields 135 classes. The paragraph on text quality measures below validates this definition with patent lists featuring significant advances in inorganic chemistry.

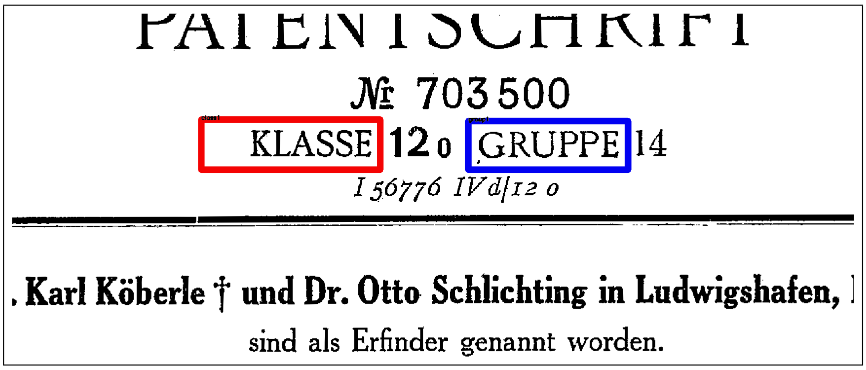
While the technology class information is printed on patent documents, making them available for data analysis presented a major challenge. Standard OCR (Tesseract) proved unreliable because the technology classes are numbers and letters without context in the middle of the document. Therefore, OCR had to be augmented with a pattern recognition algorithm designed directly for the font of the classification. Figure A-3 demonstrates the process. First, in the relevant subsection of the patent scan, the location of the technology class and group are identified. For this, image templates of the "KLASSE" and "GRUPPE" strings are matched to the scan. Over time, with the layout of the patents, the actual font and templates also change. Especially the processing of the letters is often incorrect so that they are matched to a set of templates based on problems identified in the training data. The letter font also changes over time, requiring multiple sets of templates. All areas known to be blank, for example, behind the matched latter, are painted white to remove manual markings and other noise. Finally, the remainder of the technology class string is processed using OCR. In addition to this general process, some automatic corrections are applied. For example, 3 and 8 are often confused. Also, rule-based automatic corrections remove technology class letters that do not occur in the technology class list. This process relies on OpenCV (https://opencv.org/) in combination with Tesseract (https://github.com/tesseract-ocr/tesseract).

Based on manual training data, it was possible to retrieve the technology class information with up to 95% accuracy. In most cases where the algorithm was unsuccessful, the underlying image quality is problematic, and manual processing is required. For example, many documents before 1900 were manually reclassified to a finer classification system. These manual additions lead to problems, as Table A-1 shows.

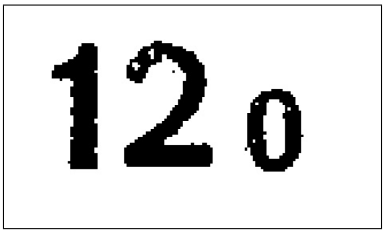
For the main analysis, I rely on data on the technology classes of patents between 1925 and 1961. For the calculation of quality weights, however, patent data for the preceding and

Figure A-3: Technology class extraction

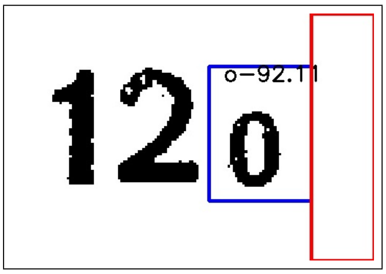
(a) Locate technology class using image templates



(b) Extracted technology class



(c) Match of letter ‘o’



Notes: Process of extracting the technology class, based of the example in Figure A-1. First, the locations of the technology class within the document is identified, to reduce variance from the input documents (A-3a). As a result, the technology class snippet is extracted (A-3b). Based on extracts, the correct letter is identified (A-3c). Standard OCR can identify the remaining numbers sufficiently well.

subsequent years is also required - see Section A.4. For an analysis until 1961, I extend the technology class data into the mid-1960s. Unfortunately, problems with the underlying data impede a further extension. Around 1970, the German patent office transitioned towards a new patent classification system. Many grant documents appear to be unavailable at this time - the number of available scanned documents and yearly grant counts from official statistics differ strongly. Because of grant lags, the data substantially under-reports patent grants throughout the mid-1960s. A second issue is that given the grant lag of patents, grants of applications in the late 1960s applications often became public during the 1970s when only the international classes are reported on the documents.

Table A-1: Quality indicators for technology class processing

	All		Excluding bad input	
	Count	Correct (%)	Count	Correct (%)
1877-1900	172	77.33	138	93.48
1901-1920	531	92.66	514	95.72
1921-1933	275	98.18	272	98.53
1934-1945	344	97.38	342	97.95
1948-1949	780	97.69	779	97.82
1950-1954	101	98.02	97	100.00
1955-1961	478	93.10	457	95.62
later	67	98.51	66	98.48
Total	2748	94.69	2665	97.00

Notes: Quality indicators by application years of patents, based on randomly selected patent documents. The two rightmost columns exclude patents where bad input data makes correct processing impossible. The predominant reason are manual, handwritten additions (before 1900) or changes of the technology class.

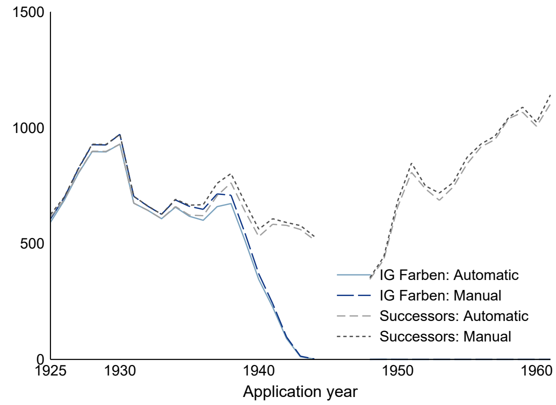
A.3 Applicant and Inventor Information

Applicant and inventor information is extracted from the OCR using machine learning. First, the precise location of applicant/inventor strings is ascertained using keywords. For example, "sind als Erfinder genannt worden" (were named as inventors) signifies that the inventors are named just before. The necessary keywords change over time as the layouts of the patents change.

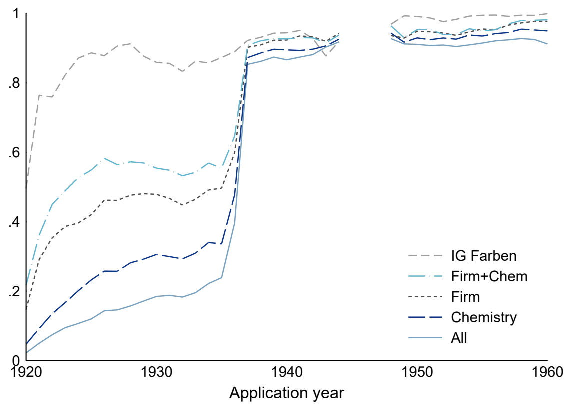
Before application year 1938, most patents do not have inventor information. Figure A-4b shows the share of patents with inventor information for different groups. For some time, supplying inventor information was voluntary, which only changed when the 1936 reform of the German patent law introduced the inventors' right to be named. Large firms often listed the inventor of their patents already before the form. In the case of IG Farben, this information is available for about 90% of all IG Farben patents. In the remainder, the inventor information was typically intentionally omitted from the document.

Figure A-4: Patent processing descriptives

(a) Patent matching algorithm: IG Farben patents based on automatic and manual processing.



(b) Share patents with inventor information



Notes: (A-4a) plots the patent counts of IG Farben and successor companies BASF, Bayer, Hoechst, Huels, Cassella and Agfa. Automatic refers to the processing pipeline above, manual to manual classification of company names based on the DPMA base data. (A-4b) plots the share of patents with inventor information, by groups. Before 1937, listing inventors was optional and was more likely done by large firms such as the IG Farben (top line). Matched firms in chemistry (second line) and matched firms overall (third line) list inventors with decreasing frequency. Patents in chemistry (fourth line) and patents overall (last line) are least likely to list inventors.

A.4 Text Analysis and Quality Measures

The first step of the text analysis is to find a numerical representation of the documents (patent full texts) to compute similarity scores between them. Text analysis is done based on Angelov (2020)'s wrapper of Doc2Vec (Le and Mikolov, 2014). Doc2Vec is advantageous compared to the bag of word (TF-IDF)-based numerical representations that are often used in the economic literature. For one, it is able to take the context of a word into account. Also, it is designed to incorporate the structure of documents. Finally, Doc2Vec has some ability to take into account different writing variants of the same word, which alleviates the necessity for stemming and lemmatization and makes it more robust against OCR errors. The calculation with Doc2Vec results in a set of document vectors v_i (normalized to unit length), between which the similarity is calculated as the cosine similarity. Note that with Doc2Vec, $\rho_{ij} \in [-1, 1]$. This differs from bag of word-based representations where all vector elements are non-negative and S_{ij} has lower bound zero.

$$\rho_{ij} = v_i \cdot v_j \tag{4}$$

Calculating a vector space for a very large number of patents computationally demanding, but converges in reasonable time for more than 350,000 full texts of patent grant documents in the time span of interest for chemical patents. To speed up the execution, multiprocessing is used, i.e. multiple processor cores run the code. This however might introduce slight numerical deviations between every training execution, even after setting seeds. The correlations of quality scores between executions are on the order of 0.86.

Quality of a patent Q_i is defined as the ratio between the forward similarity FS_i and backward similarity BS_i towards other patents in the same technology class. Forward similarity is seen as a measure of how influential a particular patent was, how much its language is taken up by subsequent patents. Backward similarity in contrast is seen as a measure of derivativeness, how much a patent took up language from previous patents.

$$\begin{aligned} FS_i &= \frac{1}{N(F_i)} \sum_{F_i} \rho_{ij} \\ F_i &= \{j : t(j) = t(i) + \tau \wedge tc(i) = tc(j)\},\ \tau \in \{1..5\} \end{aligned} \tag{5}$$

$$\begin{aligned} BS_i &= \frac{1}{N(B_i)} \sum_{B_i} \rho_{ij} \\ B_i &= \{j : t(j) = t(i) - \tau \wedge tc(i) = tc(j)\},\ \tau \in \{1..5\} \end{aligned} \tag{6}$$

$$Q_i = \frac{FS_i}{BS_i} \tag{7}$$

$tc(i)$ is the technology class of patent i, $t(i)$ is the application year of patent i. $N(F_i)$ and $N(B_i)$ indicate the cardinality of F_i and B_i, i.e. number of patents j within five years in the same technology class.

For practical purposes, the so-obtained quality scores are adjusted and normalized. They are winsorized at the 1st and 99th percentile and are standardized to have mean three and standard deviation one. This ensures that there are no negative values in any quality measure (which would occur with standardization to mean one) and that results are easy to interpret. Finally, the number of patents in 1945 is very small. For that reason, 1945 is not considered for quality scores. 1946 and 1947 are disregarded as in all other regressions as the German patent office was closed in these years. This gap is skipped for purposes of calculating the previous or next five years in equations 5 and 6. So, for a patent in 1950, the previous five years are 1949, 1948, 1944 and 1943.

These measures are inspired by Kelly et al. (2021) but differ in that instead of the total forward/backward similarity, the average forward/backward similarity are used. As long as the number of patents in the previous and subsequent years are the same, there is little difference. However, the number of patent applications at the German patent office changes considerably across years, as Figure 4b shows. Therefore, not normalizing by the amount of patent applications in consideration would incorporate future and past changes in patent numbers into current quality measures, which is not desirable for event study estimates. Since this measure is calculated within technology classes (also different to Kelly et al.), the past and future development of the size of technology classes would directly enter the quality calculation - but this is itself the base outcome measure on top of which the quality scores are applied. On the other hand, to some extent these concerns apply also to forward citation counts, which are necessarily correlated with the number of future patent applications in the close technology space. Text-based quality measure calculated based on total future similarities are conceptually closer to forward citation counts than those based on average future similarities.

Kelly et al. (2021) account for dynamically changing terminology by adjusting their measure of similarity. Their TF-IDF measures that are separately calculated for each time period, intended to reflect the updated corpus of words. While this adjustment offers an important methodological advantage, it also vastly increases computational complexity. Next to calculating a separate text model for each year, this approach is not easily integrated into the otherwise advantageous Doc2Vec methodology. A middle ground approach is to calculate the text model based on patents well before the policy change and to extrapolate it to the remaining time period. In a robustness check, only patents between 1920 and 1940 train the Doc2Vec model. This model is then extrapolated to 1941-1965 patents. With this, new words in patent texts after the policy change around 1952 do not influence the underlying similarity scores. As it turns out, regressions based on this alternative approach yield qualitatively very similar results, although the correlation between the quality scores yielded by the different approaches is only around 0.48 (0.66 for pre-war patents). Figure B-3 compares estimates based on the two types of quality scores. Quality scores take only patent grant documents into account, as the availability of application documents after the Second World War would artificially inflate quality scores.

Validating quality scores with lists of notable patents The external validity of the quality scores can only be tested with additional data. A separate publication series compiles notable patents in inorganic chemistry from 1877 until roughly 1935 (Bräuer and D'Ans, 1921, 1925, 1930, 1934, 1940). Industry experts first list and then reprint the 4265 patents most relevant to industrial users. As a first test, 97.9 % of the listed patents are covered technology classes in 'Chemistry', as defined above. On the flip side, inorganic chemistry is only a subset of chemistry, but still 50.4 % of 'Chemistry' technology classes contain patents in organic chemistry. For a test of the correlation between quality scores and highlighted patents, only technology class-year pairs with at least ten patents in inorganic chemistry between 1924 and 1935 are considered. After this restriction, 2738 inorganic chemistry patents remain.[26] Table A-2 lists regression results and finds positive and statistically significant semi-elasticities between highlighted patents and their estimated quality. The correct control group would be other patents in inorganic chemistry, but this remains for future research.

Table A-2: Validating quality scores

log(Quality)	(1) Doc2Vec for all	(2) Doc2Vec for $t \leq 40$
Featured patent	0.014^{*}	0.014^{***}
	(0.008)	(0.005)
Tech-Year FE	Yes	Yes
Adj. R-Square	0.083	0.133
Observations	19004	19004

Notes: In columns 1 and 2, quality is based on all patents. In columns 3 and 4, quality is based on patents in 1940 and before. Featured patent is a dummy variable for being featured in a publication series listing significant advances in inorganic chemistry. The sample consists of all patents between 1924 and 1935 with at least ten patents featured in the inorganic chemistry list.

[26] 2738 highlighted patents remain after restricting to the 1924-1935 time period. The further restriction is useful as a strong positive correlation should only be expected for technology classes where inorganic chemistry actually plays an important role. Also, some of the selections are due to the digitization of the lists being still in progress.

A.5 Reassigning IG Farben Patents

During the period in question, journeys to work are typically short. Pooley and Turnbull (1999) collect historical journey-to-work records for 1813 British individuals, totaling more than 12,000 individual journeys. In Table 4 therein, they list for the 1920-1939 time period an average workplace distance of 11.1 km (London), 5.6 km (other cities with >100,000 population) and 4.4 km (Towns < 100,000 population). The overall average is 6.8 km. (Pooley and Turnbull, 1999, p. 287) In the (not tabulated) variance around these estimates, inventors are likely on the upper end. Because of this, the upper boundary for reassignment of 30km is chosen. In this light, the travel distances reported in Table A-3 are reasonable. They are slightly smaller due to the coarse measurement of inventor locations (which are available at the city or, for larger cities, city-quarter level).

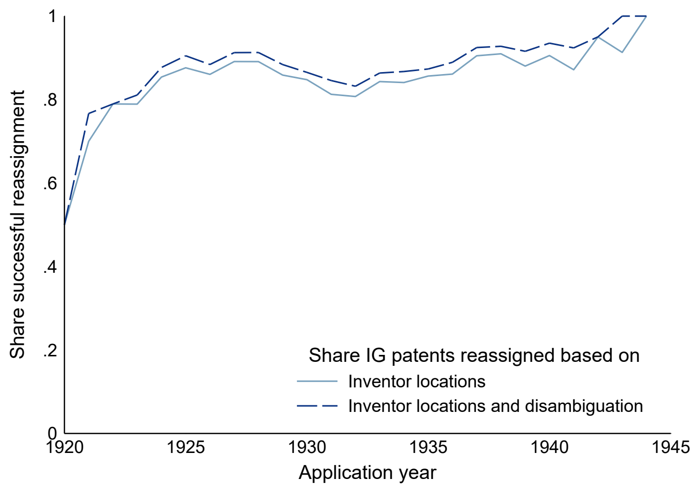
Table A-3: Distance between geocoded inventor and IG plant locations

	Mean distance	Std. Dev.	Min	Max	Total Patents
Agfa	4.08	6.05	0.07	27.32	284.00
BASF	2.58	5.57	0.02	27.81	3333.00
Bayer	1.93	3.12	0.06	24.83	2128.00
Cassella	1.46	0.89	0.01	7.78	314.00
Hoechst	3.02	4.69	0.05	26.29	2465.00
Huels	12.07	10.39	0.03	29.81	35.00
East Germany	11.19	8.50	0.02	25.21	1359.00
Overall	3.77	6.21	0.01	29.81	9918.00

Notes: The minimum distance is often zero as inventor and plant locations are coarse and only available at the city-quarter (for large cities) or town level. East Germany subsumes several locations such as Leuna, Schkopau or Premnitz. See also map A-7.

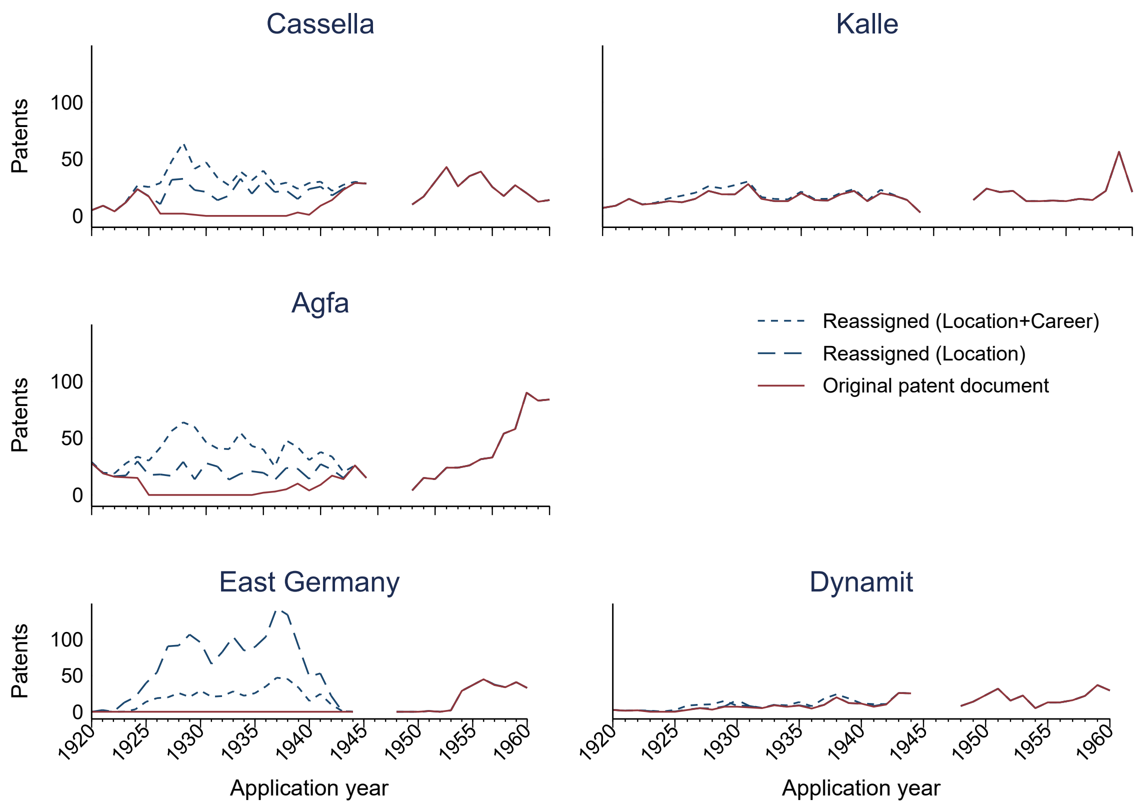
The only subsidiaries where the geographical assignment is challenged are Bayer/Agfa and Cassella/Hoechst. For Bayer/Agfa, Agfa's Leverkusen plant is at the same physical location as Bayer's Leverkusen plant. Therefore, Agfa's Leverkusen operation is subsumed under Bayer's label. Cassella is located in Frankfurt-Mainkur, a suburb of Frankfurt (Main). Hence Hoechst, located in several other parts of Frankfurt (Main), cannot fully be distinguished from Cassella. As far as possible, the deduplication of inventor profiles is used to rectify both problems. Inventors whose patents are subsequently assigned to Agfa or Cassella are also previously assigned to these companies. Map A-7 visualizes the issue.

Figure A-5: Success rate of IG Farben patent reassignment



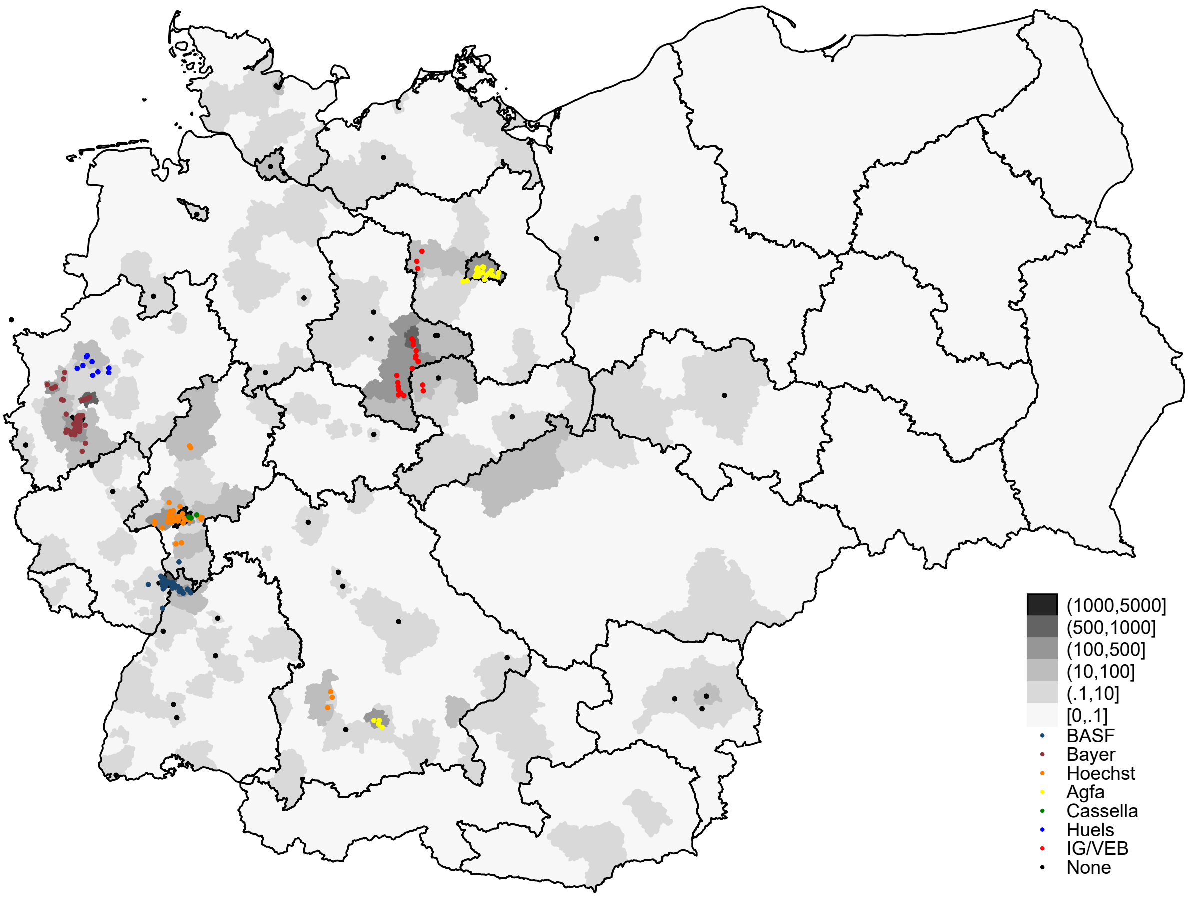
Notes: Share of IG Farben patents that could be reassigned to a successor company. Remaining patents typically have no inventor information. In some cases, inventor locations is not at any successor plant or the inventor could not observed before or after IG's existence.

Figure A-6: Patents of successor companies, assigned by inventor locations (smaller successors)



Notes: The core IG Farben company applied all patents from the Frankfurt headquarter. However, unlike most companies at the time, almost all patents list the inventors. Due to the geographic spread of IG Farben's research facilities, inventor locations allow the reassignment to eventual successors. Only in some cases, the inventor careers from deduplicated patent applications are more informative. Here, inventors are reassigned to their post-war place of employment. The graph shows the yearly number of granted patent applications for the three large successor companies and the newly independent Huels. Numbers are as listed on the original patent documents (red solid line), as reassigned to eventual successors using location information (blue dash line) and as reassigned to eventual successors using location information and inventor name disambiguation (solid blue line). For BASF, Bayer, Hoechst and Huels see Figure 3.

Figure A-7: Map: Inventor reassignment locations

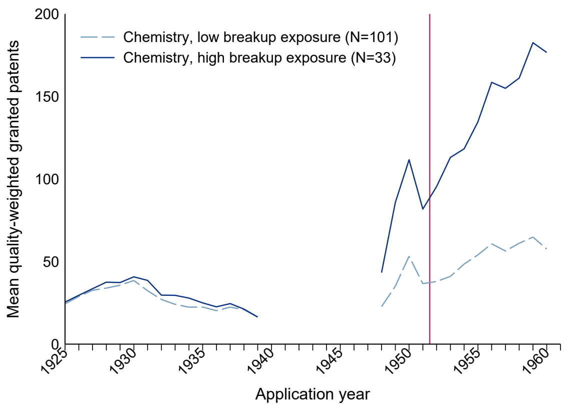


Notes: Shows the location of inventors (with number of patents above a threshold) and the successor company that they are assigned to in the location-based reassignment. The background maps shows modern European regional boundaries of Germany, Austria, Poland and Czech Republic, colored with the number of IG Farben patents assigned to NUTS3 regions. Maximum intensity regions are typically not visible below the reassignment location markers. Map source: European Commission.

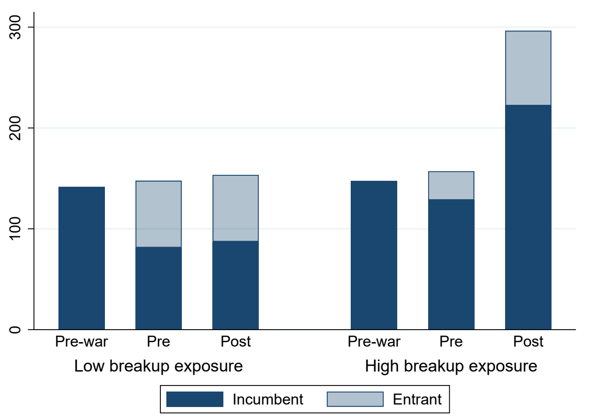
B Supplementary Results: Innovation in Technology Classes

Figure B-1: Foreign patenting and incumbent vs. entrant

(a) Foreign patents



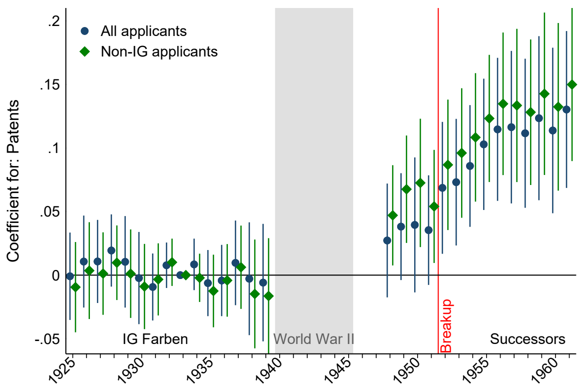
(b) Incumbent vs. entrant



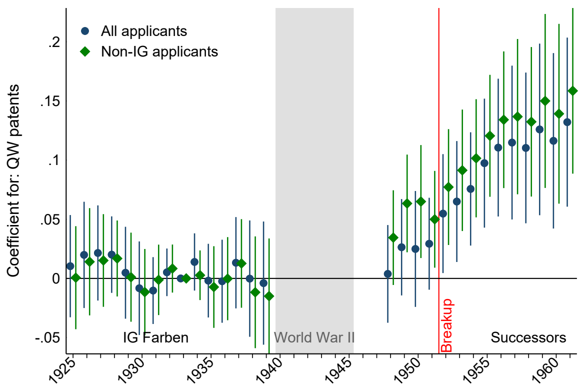
Notes: Average quality-weighted patents in technology classes with high and low exposure to the IG Farben breakup, as defined by the 75th percentile of ΔHHI (185). Exposure is measured using pre-war (1925-1939) data, but the breakup is finalized and effective around 1952 (which divides the years in 1948 and later into 'Pre' and 'Post'). Average quality is three. Domestic/Foreign is determined based on applicant and inventor locations where possible, and Incumbent/Entrant is based on whether the applicant had any pre-1945 patent applications. The German patent office closed from 1945 to 1947. Wartime patent applications are largely prosecuted post-war and hence omitted.

Figure B-2: Event studies: Poisson estimates

(a) Patent count



(b) Quality-weighted patents



Notes: Technology-year panel Poisson regression with 95% confidence intervals. Regressions comparing technology classes by their exposure to the IG Farben breakup, as defined as $D_i = log(\Delta\text{HHI})$ with $D_i = 0$ for $\Delta\text{HHI} \leq 1$. Exposure is measured using pre-war (1925-1939) data, but the breakup is finalized and effective around 1952. Shows quality-weighted counts of granted patents, with average patent quality winsorized and rescaled to have average three and standard deviation one to exclude negative values. The German patent office closed from 1945 to 1947. Wartime patent applications are largely prosecuted post-war and hence omitted.

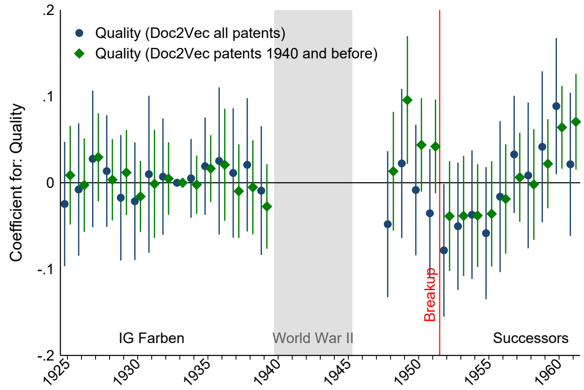
Table B-1: Effects in technology class-level regression (Robustness)

	(1)	(2)	(3)	(4)	(5)	(6)
	Exposure: ΔHHI 1925-1939					
log(Patents)	Default	Excl Plastics	Control Dismantle	Control East	Control Destr	Control All
β_{48-51}	0.003	−0.010	0.002	−0.008	0.005	−0.006
	(0.020)	(0.018)	(0.021)	(0.023)	(0.021)	(0.022)
β_{52-61}	0.092***	0.077***	0.095***	0.096***	0.094***	0.092***
	(0.023)	(0.020)	(0.023)	(0.024)	(0.023)	(0.023)
δ_{48-51}: Dismantle (%)			−0.950			−0.468
			(0.777)			(0.932)
δ_{52-61}: Dismantle (%)			1.932***			2.186**
			(0.694)			(0.891)
δ_{48-51}: East/Berlin (%)				−0.987		−0.968
				(0.600)		(0.774)
δ_{52-61}: East/Berlin (%)				0.285		−0.425
				(0.555)		(0.779)
δ_{48-51}: Destruction (%)					−0.518	−1.220
					(1.145)	(1.198)
δ_{52-61}: Destruction (%)					−0.342	−0.664
					(1.210)	(1.317)
$\beta_{52-61} - \beta_{48-51}$	0.089***	0.086***	0.092***	0.104***	0.089***	0.098***
	(0.021)	(0.022)	(0.020)	(0.024)	(0.021)	(0.022)
Tech FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Classes	135	132	135	135	134	134
Dep. var. mean	4.044	4.010	4.044	4.044	4.048	4.048
Adj. R-Square	0.789	0.793	0.792	0.789	0.788	0.792
Observations	3730	3648	3730	3730	3724	3724

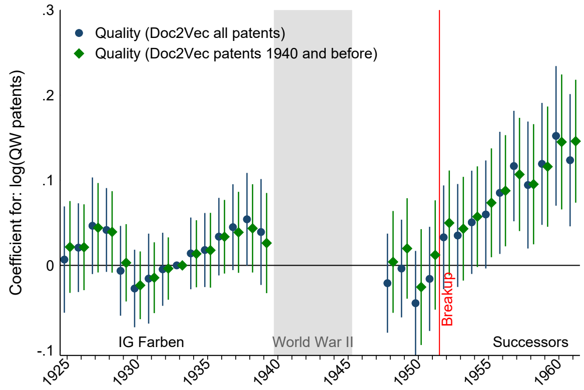
Notes: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ Standard errors clustered on the technology class level in parentheses. Dependent variable: quality-weighted non-IG Farben patents. Exposure is $D_i = \log(\Delta\text{HHI}^{+})$, where $D_i = 0$ for $\Delta\text{HHI} \leq 1$. ΔHHI is the difference between technology-level concentration, considering IG Farben as one block or as broken up according to the 1952 successors. Column 2 excludes technology section 39 (classes 39A, 39B and 39C), referring to chemical synthesis plastics and handling of plastics. See also Figure B-5. Column 3 controls for the share of non-IG firms targeted for dismantling. The inclusion of IG Farben in this measure would control directly for the IG Farben share, mechanically highly correlated to the breakup indicator. The more appropriate test for effects of dismantlement is a firm-level regression as described in Section F. Column 4 controls for the share of patents located in East Germany or Berlin. Column 5 controls for war destruction, proxied by the share of destroyed flats in the city of patent inventor or applicant. The number of observations differs as for small technology classes, text similarities and quality scores cannot be calculated. The difference in differences coefficients in turn compare patent counts in 1948-1951 and 1952-1961 with the pre-war period. The main effect is the difference between these two coefficients, tabulated in row {52-61}-{48-51}.

Figure B-3: Event studies: Alternative calculation of quality scores

(a) Average quality



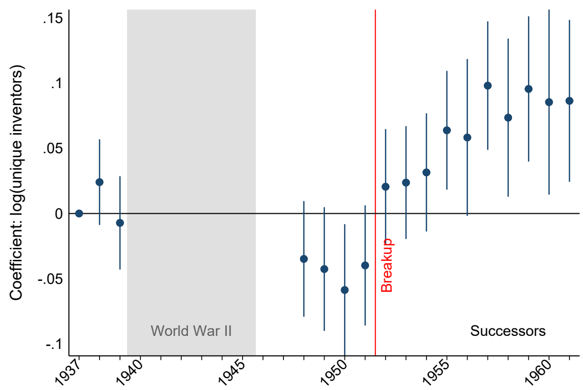
(b) Quality-weighted patents



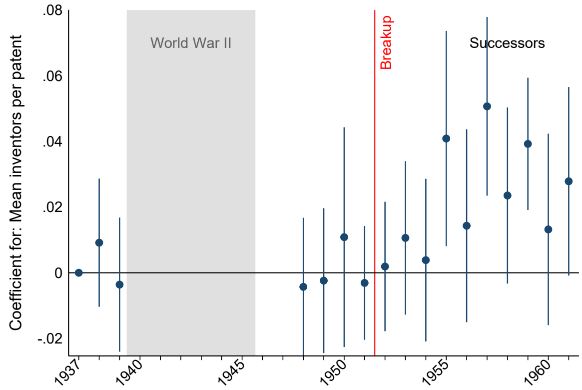
Notes: Technology-year panel regression with 95% confidence intervals. Regressions comparing technology classes by their exposure to the IG Farben breakup, as defined as $D_i = log(\Delta\text{HHI})$ with $D_i = 0$ for $\Delta\text{HHI} \leq 1$. Exposure is measured using pre-war (1925-1939) data, but the breakup is finalized and effective around 1952. Round estimate markers rely on quality-scores where the Doc2Vec model was trained on the full corpus of chemical patents. Diamond estimate markers rely on a Doc2Vec model trained only with patents until 1940 and extrapolated for later years. Patent quality is winsorized and rescaled within technology classes to have average three and standard deviation one to exclude negative values. B-3a shows average yearly quality within technology classes as dependent variable. B-3b shows quality-weighted counts of granted patents. The German patent office closed from 1945 to 1947. Wartime patent applications are largely prosecuted post-war and hence omitted.

Figure B-4: Regressions based on disambiguated inventors

(a) Number of unique inventors



(b) Mean inventors per patent



Notes: Technology-year panel regression with 95% confidence intervals. Regressions comparing technology classes by their exposure to the IG Farben breakup, as defined as $D_i = log(\Delta\text{HHI})$ with $D_i = 0$ for $\Delta\text{HHI} \leq 1$. Exposure is measured using pre-war (1925-1939) data, but the breakup is finalized and effective around 1952. The German patent office closed from 1945 to 1947. Wartime patent applications are largely prosecuted post-war and hence omitted. Before 1937, inventor information on German patents is only available for large companies such as IG Farben. See Appendix A.

Table B-2: Effects in technology class-level regression (alternative exposure specifications)

	DV: log quality-weighted patent counts of non-IG Farben applicants							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
D_i	log(ΔHHI^{+})		log(ΔHHI)		log(ΔHHI adj)		ihs(ΔHHI)	
β_{48-51}	0.003	−0.006	0.018	0.006	−0.001	−0.006	0.002	−0.006
	(0.020)	(0.022)	(0.018)	(0.023)	(0.013)	(0.014)	(0.019)	(0.021)
β_{52-61}	0.092***	0.092***	0.083***	0.101***	0.051***	0.050***	0.084***	0.083***
	(0.023)	(0.023)	(0.024)	(0.022)	(0.014)	(0.014)	(0.021)	(0.021)
β_{52-61}	0.089***	0.098***	0.065***	0.095***	0.052***	0.055***	0.081***	0.089***
$-\beta_{48-51}$	(0.021)	(0.022)	(0.023)	(0.024)	(0.014)	(0.015)	(0.020)	(0.021)
Tech FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Controls		Yes		Yes		Yes		Yes
Classes	135	134	104	104	135	134	135	134
DV mean	4.044	4.048	4.253	4.253	4.044	4.048	4.044	4.048
Adj. R^2	0.789	0.792	0.793	0.800	0.787	0.791	0.788	0.792
N	3730	3724	2944	2944	3730	3724	3730	3724

Notes: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ Standard errors clustered on the technology class level in parentheses. ΔHHI is the difference between technology-level concentration, considering IG Farben as one block or as broken up according to the 1952 successors. ΔHHI is strongly right-skewed, but its logarithm is not. log(ΔHHI^{+}) denotes the default specification, where $D_i = 0$ for $\Delta\text{HHI} \leq 1$. log(ΔHHI) is the unadjusted log-specification, where technologies with ΔHHI = 0 drop out. log(ΔHHI adj) replaces D_i with the observed minimum where ΔHHI = 0. ihs(ΔHHI) uses the inverse hyperbolic sine transformation. The difference in differences coefficients in turn compare patent counts in 1948-1951 and 1952-1961 with the pre-war period. The main effect is the difference between these two coefficients, $\beta_{52-61} - \beta_{48-51}$. The number of observations differs in columns 2 and 3 for technologies where ΔHHI = 0.

Table B-3: Effects in technology class-level regression (Extended)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
	Exposure: ΔHHI 1925-1939								1930-1939	1925-1935	1948-1952
log(Patents)	All (Quality)	All (Quality)	Non-IG (Quality)	Non-IG (Quality)	All (Count)	Non-IG (Count)	Domestic (Quality)	Foreign (Quality)	Non-IG (Quality)	Non-IG (Quality)	Non-IG (Quality)
β_{48-51}	-0.039^{*}	-0.043^{*}	0.003	-0.006	-0.033	-0.002	-0.109^{***}	0.072^{***}	-0.005	-0.004	0.005
	(0.022)	(0.024)	(0.020)	(0.022)	(0.024)	(0.022)	(0.025)	(0.026)	(0.022)	(0.021)	(0.022)
β_{52-61}	0.069^{***}	0.071^{***}	0.092^{***}	0.092^{***}	0.073^{***}	0.091^{***}	0.030	0.148^{***}	0.090^{***}	0.087^{***}	0.087^{***}
	(0.025)	(0.023)	(0.023)	(0.023)	(0.022)	(0.022)	(0.023)	(0.025)	(0.023)	(0.022)	(0.024)
$\beta_{52-61} - \beta_{48-51}$	0.107^{***}	0.114^{***}	0.089^{***}	0.098^{***}	0.106^{***}	0.094^{***}	0.140^{***}	0.076^{***}	0.095^{***}	0.091^{***}	0.083^{***}
	(0.020)	(0.023)	(0.021)	(0.022)	(0.022)	(0.021)	(0.026)	(0.018)	(0.022)	(0.022)	(0.026)
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Controls		Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Classes	135	134	135	134	134	134	134	134	133	134	133
Dep. var. mean	4.169	4.173	4.044	4.048	3.068	2.945	3.746	3.011	4.055	4.048	4.055
Pseudo R-Square	0.792	0.796	0.789	0.792	0.830	0.829	0.764	0.744	0.791	0.791	0.791
Observations	3757	3751	3730	3724	3766	3739	3690	3360	3715	3724	3715

Notes: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ Standard errors clustered on the technology class level in parentheses. Exposure is $D_i = \log(\Delta\text{HHI}^{+})$, where $D_i = 0$ for ΔHHI ≤ 1. ΔHHI is the difference between technology-level concentration, considering IG Farben as one block or as broken up according to the 1952 successors. The difference in differences coefficients in turn compare patent counts in 1948-1951 and 1952-1961 with the pre-war period. The main effect is the difference between these two coefficients, tabulated in row {52-61}-{48-51}. The dependent variables are quality-weighted patent counts, except columns (3) and (4) with simple patent counts. Quality weights are normalized to mean three, standard deviation one. The columns restrict patents by applicants, either all (columns 1, 3) or applicants unconnected to IG Farben (columns 2, 4, 7-9). Columns 5-6 restrict patents by location, where inventor location is preferred if available. Domestic patents refer to patents with a German location, foreign patents to patents with a foreign location. Controls include the share of non-IG firms targeted for dismantling, the share of patents located in East Germany or Berlin and war destruction, proxied by the share of destroyed flats in the city of patent inventor or applicant. For details see Section F and Table B-1. The number of observations differs if for some technologies, the ΔHHI or quality scores could not be computed.

Table B-4: Effects in technology class-level regression (Exposure within IG Farben)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Exposure	Standardized ΔHHI within IG Farben				Standardized ΔHHI by occupation zones			
log(Patents)	All (Quality)	All (Quality)	Non-IG (Quality)	Non-IG (Quality)	All (Quality)	All (Quality)	Non-IG (Quality)	Non-IG (Quality)
β_{48-51}	−0.082	−0.083	−0.045	−0.052	−0.035	−0.034	0.003	−0.008
	(0.059)	(0.059)	(0.057)	(0.056)	(0.068)	(0.071)	(0.065)	(0.066)
β_{52-61}	0.135**	0.127**	0.152**	0.140**	0.179***	0.175***	0.215***	0.203***
	(0.061)	(0.062)	(0.061)	(0.062)	(0.065)	(0.060)	(0.065)	(0.061)
$\beta_{52-61} - \beta_{48-51}$	0.217***	0.210***	0.196***	0.193***	0.214***	0.209***	0.212***	0.211***
	(0.060)	(0.061)	(0.059)	(0.059)	(0.071)	(0.070)	(0.069)	(0.068)
Tech FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Controls		Yes		Yes		Yes		Yes
Classes	113	113	113	113	114	114	114	114
Dep. var. mean	4.350	4.350	4.204	4.204	4.324	4.324	4.181	4.181
Adj. R-Square	0.784	0.789	0.784	0.789	0.789	0.793	0.789	0.793
Observations	3235	3235	3212	3212	3247	3247	3221	3221

Notes: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ Standard errors clustered on the technology class level in parentheses. $\Delta\text{HHI}_{\text{Within}}$ is the difference between technology-level concentration among IG Farben-related patents, considering IG Farben as one block or as broken up according to the 1952 successors. $\Delta\text{HHI}_{\text{Occ}}$ breaks up the IG Farben block by occupation zones, ignoring subsidiary structures. In both cases, patents from the Soviet occupation zone are ignored, see Section 5 for details. Both ΔHHI are standardized to mean zero and standard deviation one. The difference in differences coefficients in turn compare patent counts in 1948-1951 and 1952-1961 with the pre-war period. The main effect is the difference between these two coefficients, tabulated in row {52-61}-{48-51}. Columns 1-2 and 5-6 count all patents, columns 3-4 and 7-8 only non-IG patents. Controls include the share of non-IG firms targeted for dismantling, the share of patents located in East Germany or Berlin and war destruction, proxied by the share of destroyed flats in the city of patent inventor or applicant. For details see Section F and Table B-1. For dynamic estimates, see Figure 5.

Table B-5: Effects in technology class-level regression (Poisson)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
	Exposure: ΔHHI 1925-1939								1930-1939	1925-1935	1948-1952
Poisson(Patents)	All (Quality)	All (Quality)	Non-IG (Quality)	Non-IG (Quality)	All (Count)	Non-IG (Count)	Domestic (Quality)	Foreign (Quality)	Non-IG (Quality)	Non-IG (Quality)	Non-IG (Quality)
β_{48-51}	0.018	0.004	0.054^{***}	0.035	0.016	0.043^{*}	-0.075^{***}	0.153^{***}	0.034	0.034	0.038
	(0.017)	(0.020)	(0.018)	(0.022)	(0.022)	(0.023)	(0.022)	(0.028)	(0.022)	(0.022)	(0.023)
β_{52-61}	0.097^{***}	0.135^{***}	0.124^{***}	0.159^{***}	0.134^{***}	0.156^{***}	0.080^{***}	0.212^{***}	0.159^{***}	0.154^{***}	0.167^{***}
	(0.024)	(0.022)	(0.025)	(0.023)	(0.023)	(0.024)	(0.021)	(0.030)	(0.024)	(0.023)	(0.025)
$\beta_{52-61} - \beta_{48-51}$	0.079^{***}	0.130^{***}	0.070^{***}	0.124^{***}	0.118^{***}	0.113^{***}	0.155^{***}	0.060^{***}	0.125^{***}	0.120^{***}	0.130^{***}
	(0.021)	(0.019)	(0.022)	(0.019)	(0.017)	(0.017)	(0.020)	(0.021)	(0.019)	(0.019)	(0.019)
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Controls		Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Classes	135	134	135	134	134	134	134	134	133	134	133
Dep. var. mean	163.319	163.826	143.781	144.226	52.917	46.529	106.234	47.452	144.826	144.226	144.708
Pseudo R-Square	0.915	0.919	0.915	0.920	0.902	0.901	0.908	0.874	0.919	0.919	0.920
Observations	3792	3780	3792	3780	3886	3886	3780	3780	3764	3780	3767

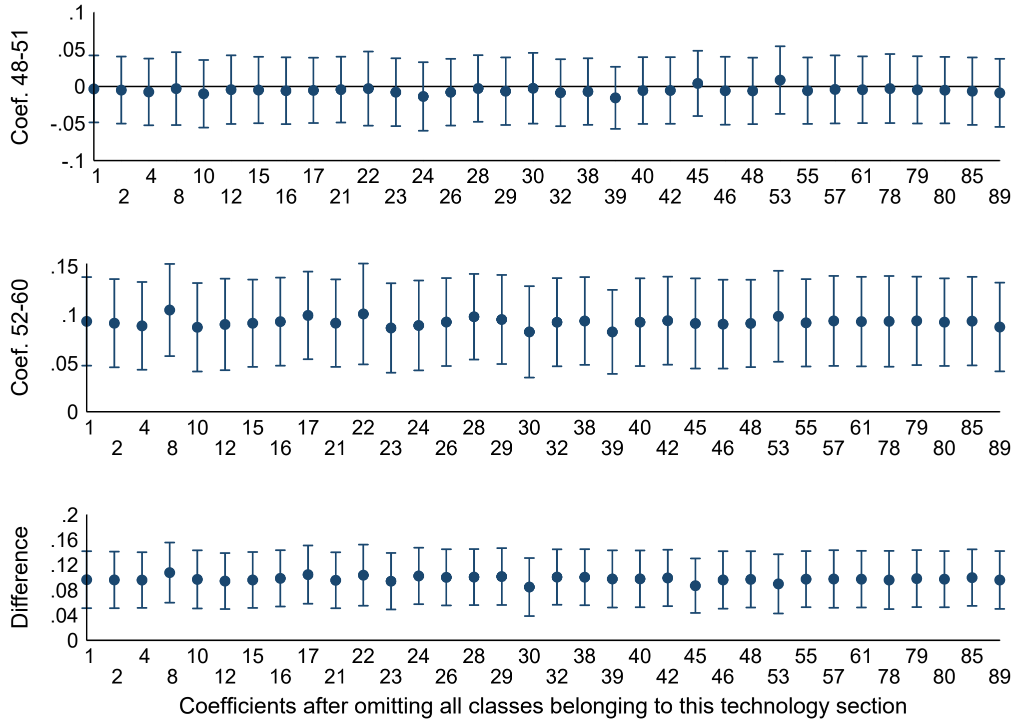
Notes: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ Standard errors clustered on the technology class level in parentheses. Exposure is $D_i = \log(\Delta\text{HHI}^{+})$, where $D_i = 0$ for $\Delta\text{HHI} \leq 1$. ΔHHI is the difference between technology-level concentration, considering IG Farben as one block or as broken up according to the 1952 successors. The difference in differences coefficients in turn compare patent counts in 1948-1951 and 1952-1961 with the pre-war period. The main effect is the difference between these two coefficients, tabulated in row {52-61}-{48-51}. The dependent variables are quality-weighted patent counts, except columns (3) and (4) with simple patent counts. Quality weights are normalized to mean three, standard deviation one. The columns restrict patents by applicants, either all (columns 1, 3) or applicants unconnected to IG Farben (columns 2, 4, 7-9). Columns 5-6 restrict patents by location, where inventor location is preferred if available. Domestic patents refer to patents with a German location, foreign patents to patents with a foreign location. Controls include the share of non-IG firms targeted for dismantling, the share of patents located in East Germany or Berlin and war destruction, proxied by the share of destroyed flats in the city of patent inventor or applicant. For details see Section F and Table B-1. The number of observations differs if for some technologies, the ΔHHI or quality scores could not be computed.

Table B-6: Effects in technology class-level regression (Robustness)

	(1)	(2)	(3)
	Exposure: ΔHHI 1925-1939		
log(Patents)	Uncontrolled	Controlled	Oster
48-51× High ΔHHI	−0.08	−0.14	−0.17
52-61× High ΔHHI	0.41	0.39	0.39
{52-61}-{48-51}	0.49	0.53	0.55

Notes: Shows coefficients from regression with and without controls as well as resulting Oster (2019) bounds. Dependent variable: quality-weighted non-IG Farben patents. Exposure is $D_i = \log(\Delta\text{HHI}^{+})$, where $D_i = 0$ for $\Delta\text{HHI} \leq 1$. ΔHHI is the difference between technology-level concentration, considering IG Farben as one block or as broken up according to the 1952 successors. Controls are the share of non-IG firms targeted for dismantling, the share of patents located in East Germany or Berlin as well as war destruction, proxied by the share of destroyed flats in the city of patent inventor or applicant. Control variables are interacted with a full set of year indicators. The difference in differences coefficients in turn compare patent counts in 1948-1951 and 1952-1961 with the pre-war period. The main effect is the difference between these two coefficients, tabulated in row {52-61}-{48-51}. Bounds are calculated as: $\beta^* = \tilde{\beta} - [\dot{\beta} - \tilde{\beta}] \frac{R_{max} - \tilde{R}}{\tilde{R} - \dot{R}}$, where $\dot{\beta}$ and $\dot{R}$ refer the uncontrolled coefficient and R-Squared and $\tilde{\beta}$ and $\tilde{R}$ to the controlled coefficient and R-Squared. R_{max} is set to $1.3 \times \tilde{R}$. The underlying assumption is that reaction of coefficients to observable controls informs about the potential importance of omitted variable bias.

Figure B-5: Effects in technology-class level regressions after omitting technology sections



Notes: Shows the results of technology-year panel regression with 95% confidence intervals and one technology section (group of technology classes) left out. Shows that the results are not driven by any individual technology. The dependent variable is the quality-weighted non-IG patent count. The coefficients in turn compare patent counts in 1948-1951 and 1952-1961 with the pre-war period. The main effect is the difference between these two coefficients, shown in the third row. Exposure is measured using pre-war (1925-1939) data, but the breakup is finalized and effective around 1952.

C Innovation Analysis in Firm Panel

Robustness analysis can be conducted at varying levels. Some variables directly apply to the product level (cartels, production restrictions), and tests for their relevance can be best implemented in product-level regressions that are beyond the scope of this paper and are discussed in Poege (2022). Some variables can be collected and aggregated to a technology class level (war destruction, dismantlement, Soviet sector). Such analysis is bound to remain indirect as the shocks affect firms, not technologies. In a firm-level analysis, measurement and control are more direct. In this section, I construct a firm panel to offer an additional robustness check for the innovation analysis, leading to comparable results.

Building a firm panel To construct the firm panel, I combine various firm data sources. These are supplier lists from historical product catalogs, handbooks of listed corporations (Hoppenstedt-Aktienführer, via https://digi.bib.uni-mannheim.de/aktienfuehrer/), firms slated for dismantlement (Harmssen, 1951), and manually collected complementary entries. I first match the firm entries with each other, and then match the resulting clusters to patent applicants. Appendix A discusses details. The subsequent regressions consider patents in classes relevant to the chemical industry. I focus on incumbent firms for whom exposure measures to the IG Farben breakup and other shocks can be calculated with pre-war variables. I keep only firms with patent applications in at least four pre-war (1925-1939) years. Overall, more than 350 firms remain. The pre-1945 patent count of the eventual IG Farben successors follows the hypothetical reassignment according to the breakup rules.

I calculate the technological exposure of firms to the IG Farben breakup. For this, I weigh the technology class-specific exposure (ΔHHI) by the pre-war patent portfolio of the firms. Table C-1 tabulates the main firm characteristics, separated between highly exposed firms in the top 25% by exposure (Threshold 327) and comparison firms. Both groups have similar pre-war levels of patenting and are similarly exposed to the Soviet sector and to the war destruction of German cities. Exposed firms are moderately more likely to be foreign (as measured by patent locations) but substantially less likely to be a target of dismantlement.

Product catalogs Product catalogs are intended for industrial purchasers and list, for a large number of chemical products, the firms supplying them. These are chemical substances and refined chemical products, such as industrial cleaners or paints. Figure C-1 shows an example of product listings. Typically, a chemical is given by its German name and translations into several other languages. Subsequently follows a list of chemical companies from which the chemical can be procured. A separate part of the book lists company contact information such as address

Table C-1: Descriptive statistics for IG/non-IG exposed technology classes

	Comparing firms: High vs low breakup exposure				
N=85 (T) 254 (C)	Exposed	Comparison	Difference	(SE)	p-value
Weighted ΔHHI	801.67	66.09	−735.59	(27.64)	0.000***
Quality-weighted patents	203.11	305.00	101.89	(174.79)	0.560
- (log)	4.50	4.32	−0.19	(0.16)	0.242
Foreign (%)	0.20	0.11	−0.09	(0.04)	0.035**
Pre-war US patent ratio (%)	0.25	0.15	−0.10	(0.04)	0.005***
Patents in Soviet sector (%)	0.36	0.37	0.02	(0.06)	0.757
War destruction (%)	0.28	0.30	0.02	(0.03)	0.481
Any plants dismantled (%)	0.12	0.29	0.17	(0.05)	0.001***
IG competitor (1940 catalogue)	0.72	0.19	−0.53	(0.05)	0.000***
IG competitor (1952 catalogue)	0.66	0.24	−0.41	(0.06)	0.000***
IG competitor (Any catalogue)	0.81	0.32	−0.49	(0.06)	0.000***

Notes: Shows difference between firms with high and low breakup exposure. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. All data refers to patents applied for in 1925-1939. The shock exposure ΔHHI for technology classes is calculated first assuming all IG Farben members to be one entity, then separately according to their post-1952 split-up. A firm's value of shock exposure is weighted according to pre-war patent counts in the respective technology classes. Patents counts are totals. Patents are weighted according to forward text similarity divided by backward text similarity, on patent-level normalized to mean three and standard deviation one. Firm locations follow the predominant patent location, where domestic and foreign patents are identified using inventor locations if available, applicant locations otherwise. Domestic are such located in present-day Germany or Poland, Soviet sector patents all located in present-day East Germany, Berlin or Poland. The inclusion of Poland is a coarse reference to Germany's pre-war territory. The pre-war US patent ratio divides the 1925-1939 US patent count of the firm by the 1925-1939 German patent count. For non-German firms this variable typically takes values much larger than one and are winsorized there. War destructions refers to the share of flats destroyed between 1939 and 1945, weighted by the patent locations of a firm. Dismantlement is an indicator for whether the firm occurs in any dismantlement list.

and telephone number. I digitize the lists of firms and products for the volumes covering late 1939, mid-1952, and 1961.

The introductory remarks in each of the volumes describe the process of their creation and their content. Specifically, the remarks describe the chemical industry as producing a myriad of final products from a small set of inputs, which necessitates listing only products usual in trade (Wegner, 1940; Barth, 1952). The catalogs rely on the information supplied by producers, and appearance in the volume is free of charge (*Wenzel* 1930). The books finance themselves by featuring advertisements in the books and by the sales price. The books also typically do not list foreign suppliers. Until 1932, a parallel publication series tried to keep track of this different set of firms, but this effort proved too cumbersome. The books also comment on specific events impacting their publication. The 1940 edition, for example, remarks that war-related changes could not be represented in the book to not delay its publication further, whereas firms from recently occupied areas are covered (Wegner, 1940). As the editorial was written in December 1939, this references the recent invasion of Poland. Therefore, the volume entitled 1940 is referenced by the date of its publication, 1939. The 1952 edition (Barth, 1952, editorial dated April 1952) describes itself as the first address and product listing of the West-German chemical industry since the end of the war. Turnover of firms between editions is typically high. The

1930 edition drops 1500 firms and adds 600 new ones (*Wenzel* 1930). Based on these remarks, the listed products represent the current supplier status of Germany's chemical industry for a cross-section of common, relevant products.

Figure C-1: Product listing examples in 1939 and 1952

(a) ASS, 1939

Acetylsalicylsäure [Acidum acetylosalicylicum], *e.* Acetylsalicylic acis, *f.* Acide acétylsalicylique, *sp.* Acido acetilsalicílico, *i.* Acido acetilsalicilico.

»Bayer« I. G. Farbenindustrie Aktiengesellschaft, Leverkusen-I. G. Werk [DAB. 6].
Chemische Fabrik Aubing, Aubing b. München.
Chemische Fabrik von Heyden A.-G., Radebeul-Dresden.
Gehe & Co. A.-G., Dresden-N 6.
I. G. Farbenindustrie Aktiengesellschaft, Frankfurt a. M.
E. Merck, Darmstadt.
J. D. Riedel—E. de Haën A.-G., Berlin.
Schering A.-G., Berlin N 65.

(b) Phthalic anhydride, 1939

Phthalsäureanhydrid [Acidum phthalicum anhydricum], *e.* anhydrous, *f.* anhydre, *sp.* anhidro, *i.* anidro.

I. G. Garbenindustrie Aktiengesellschaft, Frankfurt a. M.
J. D. Riedel—E. de Haën A.-G., Berlin.

(c) ASS, 1952

62. **Acetylsalicylsäure**
Acetylsalicylic acid
Acide acétyl-salicylique
Acido acetilsalicilico

Chemische Fabrik Aubing Dr. Kurt Bloch, München-Aubing
Chemische Fabrik von Heyden AG, München 23
Farbenfabriken Bayer Aktiengesellschaft, Leverkusen
Farbwerke Hoechst AG, vorm. Meister Lucius & Brüning, Frankfurt/M.-Höchst
E. Merck, Chemische Fabrik, Darmstadt

(d) Phthalic anhydride, 1952

5538. **Phthalsäureanhydrid**
Phthalic anhydride
Anhydride phtalique
Anhidrido ftálico

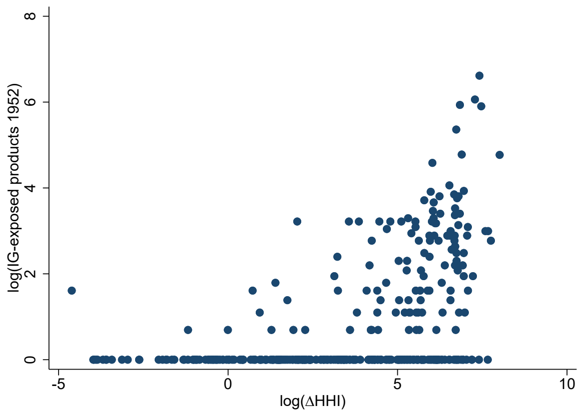
Badische Anilin- & Soda-Fabrik, Ludwigshafen/Rh.
Dr. Kurt Herberts & Co. vorm. Otto Louis Herberts, Wuppertal
Farbenfabriken Bayer Aktiengesellschaft, Leverkusen
E. Merck, Chemische Fabrik, Darmstadt
Ruhröl GmbH, Bottrop

Notes: Entry from 1939 and 1952, where ex-post IG Farben successors competed with each other. Acetylsalicylic acid, better known as Aspirin, is a pharmaceutical product. Phthalic anhydride is an input product to the dyestuffs, plastics and pharmaceutical industry. Acetylsalicylic acid was in 1939 offered by IG Farben (with two listings, one as "Bayer") and several others. In 1952, with Bayer and Hoechst, two IG Farben successors as well as many of the previously active non-IG suppliers offer the product. For phthalic anhydride, BASF and Bayer compete in 1952, after the product was already offered by IG Farben in 1939.

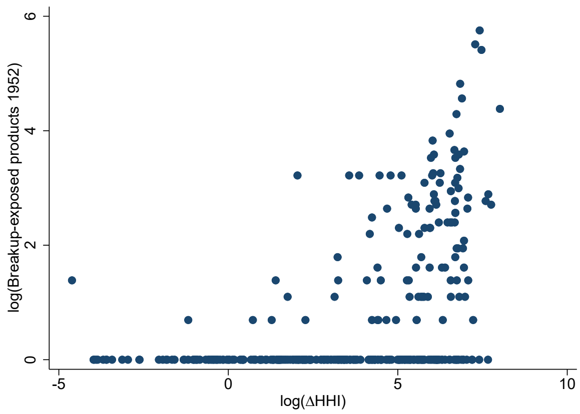
Firm-level results Table C-2 shows the regression results. The empirical strategy follows the main innovation analysis, with the level of observation shifted to firms. I include firm and year fixed effects and cluster standard errors in the regressions at the firm level (Bertrand, Duflo, and Mullainathan, 2004). Compared to comparison firms, firms in technologies with high exposure to the IG Farben breakup strongly increased their patenting output after the breakup. Columns 1-4 individually include the main control variables, and columns 5-7 include them all at the same time. Dismantlement, exposure to the Soviet sector, and war destructions predict decreases in patenting in the post-war periods, but the main effect estimates remain unchanged. The effects also remain qualitatively unchanged when excluding IG Farben firms (columns 1-5), when excluding foreign firms (column 6), or considering all firms, including the IG Farben successors (columns 7-8). The results are smaller in magnitude than the technology-class level regressions of Section 6, hinting towards entry by new innovators playing a role.

Figure C-2: Scatter plots of firm-level exposure

(a) Number of IG products



(b) Number of breakup-exposed products



Notes: Scatter plot comparing the technology-based and product-based exposure measures from the 1952 product catalog. Products are called breakup-exposed if two or more IG Farben successors offered the product in 1952. log(Product exposure) is set to zero for firms without products or firms without listed products in the product catalog. Correlation coefficients are 0.48 (Panel A) and 0.47 (Panel B).

Table C-2: Firm-level regressions with control variables

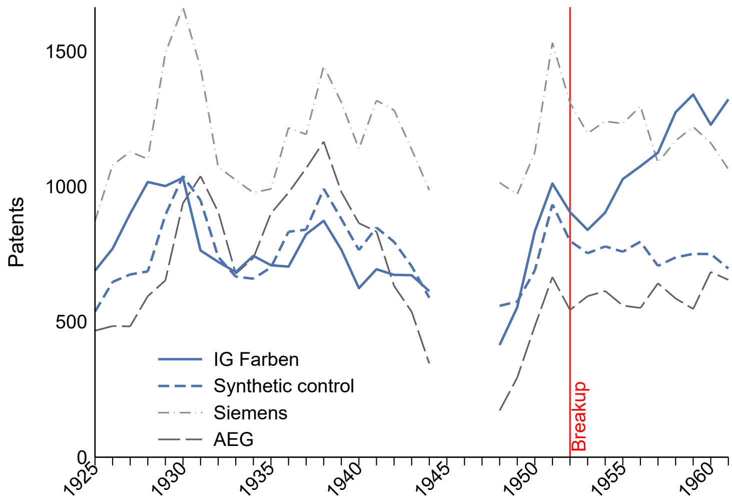
	Exposure: log ΔHHI 1925-1939							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
ihs(Patents)	No IG	No IG	No IG	No IG	No IG	Domestic	All	All
β_{48-51}	0.018	0.008	0.020	0.017	0.018	−0.009	0.014	0.004
	(0.024)	(0.025)	(0.022)	(0.024)	(0.023)	(0.019)	(0.022)	(0.021)
β_{52-61}	0.065**	0.051*	0.067**	0.063**	0.061**	0.039*	0.067***	0.048**
	(0.028)	(0.029)	(0.026)	(0.028)	(0.027)	(0.022)	(0.025)	(0.024)
δ_{48-51}: Dismantle		−0.241*			0.025	0.063	−0.013	0.035
		(0.142)			(0.123)	(0.115)	(0.117)	(0.115)
δ_{52-61}: Dismantle		−0.358**			−0.045	0.113	−0.040	0.052
		(0.146)			(0.141)	(0.125)	(0.130)	(0.123)
δ_{48-51}: East			−1.242***		−1.309***	−1.060***	−1.278***	−1.124***
			(0.123)		(0.125)	(0.119)	(0.122)	(0.126)
δ_{52-61}: East			−1.387***		−1.489***	−0.979***	−1.467***	−1.170***
			(0.141)		(0.149)	(0.133)	(0.144)	(0.141)
δ_{48-51}: Destruction				−0.168	−0.714**	−0.217	−0.685**	−0.304
				(0.372)	(0.333)	(0.290)	(0.330)	(0.314)
δ_{52-61}: Destruction				−0.641	−1.255***	0.001	−1.231***	−0.498*
				(0.417)	(0.377)	(0.289)	(0.372)	(0.302)
δ_{48-51}: Pre-war US								0.991***
								(0.261)
δ_{52-61}: Pre-war US								1.908***
								(0.254)
$\beta_{52-61} - \beta_{48-51}$	0.047**	0.042**	0.047**	0.046**	0.043**	0.048**	0.053***	0.044**
	(0.019)	(0.020)	(0.019)	(0.019)	(0.020)	(0.020)	(0.019)	(0.019)
Firm, Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N Firms	339	339	339	339	339	309	355	355
Adj. R-Square	0.562	0.563	0.587	0.563	0.591	0.647	0.621	0.636
Observations	11526	11526	11526	11526	11526	10506	12070	12070

Notes: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ Standard errors clustered on the firm level in parentheses. The dependent variables are inverse hyperbolic sine transformed quality-weighted patents in technology classes related to the chemical industry. In columns 1-5, the sample consists of firms not related to IG Farben. In column 6, all firms are included and column 7 excludes foreign firms. High ΔHHI refers to the top 25% of firms in terms of pre-war-weighted exposure to ΔHHI in technology. Dismantle is a dummy of whether the firm was featured on a dismantlement list. East Pat is the share of pre-war patents in East Germany or Berlin. Destruction is the average war destruction in the German cities, weighted by pre-war patent locations. Pre-war US is the ratio of 1925-1939 US patent count of the firm, divided by the 1925-1939 German patent count. Poisson regressions or regressions without quality-weighting deliver qualitatively similar results.

D Synthetic control for IG Farben

While finding appropriate control firms for IG Farben and its successors is difficult, the best attempt at a descriptive analysis is the comparison with firms in electronics (Feldenkirchen, 1987). The electronics sector was dominated by a duopoly of Siemens and AEG, with some smaller companies like Bosch contributing a smaller share. While Bosch and Siemens were at some point targeted for decartelization measures equivalent to IG Farben, these remained largely without effect. Other candidate sectors drop out as they were also affected by Allied breakups (Heavy industry/Steel) or disproportionately benefited from the war (Automotive engineering). Figure D-1 shows that patenting by IG Farben successors increased relative to AEG, Siemens, or a synthetic control group (Abadie, Diamond, and Hainmueller, 2010) of electronics firms, but this result should be interpreted cautiously.

Figure D-1: IG Farben patenting in comparison to firms in the electronics industry



Notes: Patenting of IG Farben and its successors compared to firms in the electronics industry. Only patents located in West Germany and Berlin are counted. AEG includes Telefunken and Licentia. Siemens includes Siemens & Halske and Siemens Schuckertwerke. Other firms entering the synthetic control are Bosch, C Lorenz/Standard Elektronik Lorenz, Tenovis and Voigt & Haeffner. The synthetic control procedure (Abadie, Diamond, and Hainmueller, 2010) only fits on the 1925-1944 patent counts, resulting in 65% combined weight for AEG and Siemens. A synthetic control using normalized weights yields similar results, with more balanced shares.

E Specialization of Research

Theoretical research on competition, especially mergers, has discussed the role of duplication and breadth of research. Duplication of research between merging companies may be wasteful, and its removal may be a merger efficiency (Denicolò and Polo, 2018). Duplication of research might also be beneficial, especially if the outcomes offer consumers benefits in variety and price - advantages that may be lost after a merger (Letina, 2016; Gilbert, 2019). In this section, I discuss approaches for extending the previous analyses to approach this topic in the context of the IG Farben merger. In the historical context, it is plausible that research in the same technology led to differentiated new products. For example, research in synthetic polymers led to multiple types of plastics with various practical applications.

Empirical research into duplication of research remains scarce because it is difficult to measure outside of individual fields such as pharmaceuticals (Cunningham, Ederer, and Ma, 2021). However, the application of measures of technology and text similarity allows some approximation. In this section, I will approach the topic of overlap by measures of technological similarity derived from technology classes and the text content of words. This falls short of defining duplication, as it is difficult to measure when some patents cover the same technological content. However, some progress is attainable when considering the converse, specialization.

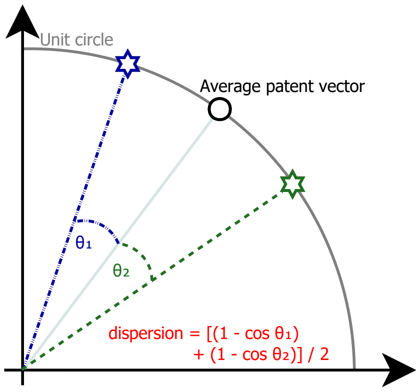
I construct a technology-level measure of the dispersion of technological content, which allows me to return to the empirical strategy of Section 4. Section 7 already presented a descriptive analysis of the technology portfolios of the IG Farben successors, which indicated that they remained active in the same technologies but specialized within them as the pairwise similarity of patent portfolios diverged. While indicative, this finding does not inform about the development of the industry at large. For this, I return to a numerical representation of the technological content of patents. Each patent is again represented by a vector v. Now, I consider the average vector $\bar{v}$ within a set of patents T. Dispersion is given by the average distance - one minus cosine similarity - of all patent vectors v to the average.

$$s = 1/N(T) \sum_{k \in T} (1 - v_k \cdot \bar{v})$$

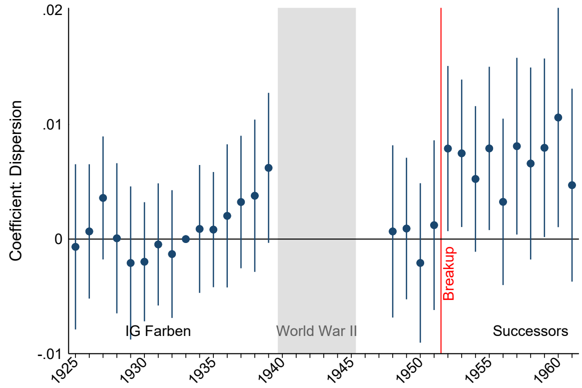
For the empirical test, I calculate the dispersion of yearly patent applications in a technology. I choose T as the set of patents in technology class i and year t. Figure E-1 shows first a graphical illustration and then results. After the breakup, the dispersion increases, indicating a greater average spread of texts within the affected technology classes than before the breakup. At the same time, the number of patents in the affected technologies increases, which suggests that the new patents tend to be farther from the typical patent in the respective technologies.

Figure E-1: Dispersion of technology over time

(a) Visualization: Dispersion



(b) Class-level dispersion of text context



Notes: E-1a: Visualization of dispersion in two-dimensional space and two patents. E-1b: Event study regression with dependent variable dispersion of text content within the technology class, defined as the average cosine distance of patent text vectors from the average patent text vector.

Suppose the reversal of a merger had strongly led to duplication of research. In that case, the average research similarity between successors and the aggregate similarity within technology classes should have stayed the same (same distribution of technology content) or even increased (duplicative marginal patents). The empirically observed decrease points to the diversification of approaches, in line with Letina (2016). The historical evidence indeed points in the same direction. All successors invested in technologies such as plastics, synthetic fibers, or switching from coal to oil as feedstock. However, seeking the same goal in all these technologies led to different approaches and outcomes. Indeed, the explosion of the type of plastics products available to consumers is one of the legacies of chemical research of the 1950s and 1960s (Teltschik, 1992).

Necessarily, this discussion assumes that the assignment of patents to technology classes and the technological disclosure of patents consistently reflects the research investments done at the applicant company. If the breakup changed the drafting style or induced strategic behavior of the successor companies or the non-IG Farben competitors, the measures might overstate changes. However, both research and the patenting process within IG Farben were organized at the plant-level (ter Meer, 1953, p. 30). In the 1930s, all major and several minor plants had a patent office; see Table F-2. Given this, and since any such discussion is absent in the historical literature, the patenting process itself was likely not disturbed by the breakup very much.

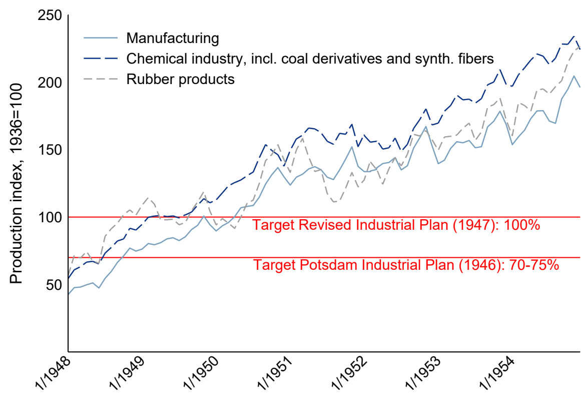
F Robustness to Historical Factors

This section discusses critical historical factors and parallel events surrounding the IG Farben breakup. As the breakup happens during one of the most turbulent episodes of German history, the core question is whether the end of the Second World War set off a complete renewal ("Hour Zero") or was rather characterized by continuity. This question was the subject of intense debate in post-war German society. Both for society and the economy historians emphasize continuity and reject notions of a radical divergence (e.g. Morsey, 2010).

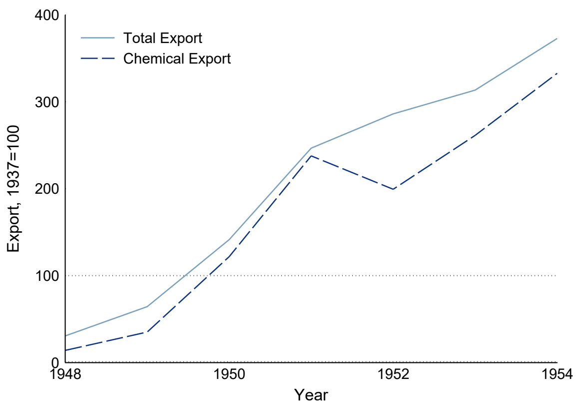
When analyzing the effects of the war, the three main themes are the direct impact of the war, such as bombing, Allied occupation policies, and the separation of the Soviet occupation zone, as well as the German postwar policy and recovery. Insofar as these effects impact both IG Farben-related areas of chemistry and unrelated areas, they are a part of the parallel trends assumption justifying the difference in differences analysis. While in general untestable, in some cases, it is possible to appraise their effect by constructing appropriate control variables. Most control variables can be introduced directly in the regressions on the technology class level. Oster (2019) bounds allow an explicit assessment of biases by unobservable confounders. Robustness checks in a firm-level panel offer a different view and yield similar results. Appendix C discusses the construction of this panel and reports corresponding results.

Figure F-1: Germany's economic recovery

(a) Production recovery



(b) Trade recovery



Notes: F-1a: Monthly German production index with reference level 1936. F-1b: Yearly German chemical and total exports with reference level 1937. Source: Statistical yearbooks for West Germany.

War damages The war damages to German cities were extensive, but according to the historical literature, the effect on the German industry was smaller than often thought. For example, the US Strategic Bombing Survey conducted after the war concluded that of Germany's war industry, at most 20% had been destroyed (Jeffreys, 2010, p. 295). Overall, the German economy recovered quickly and could return to pre-war export levels by 1950 (Figure F-1b). Due to their central role for war-related industries such as synthetic fuels and explosives, IG Farben facilities were likely the primary targets of Allied air campaigns. For example, the Leverkusen plant was hit by 14 aerial attacks since 1944.[27] Nevertheless, the machines were left rather intact, with only 15% of the factory beyond repair (Jeffreys, 2010, p. 295). To the extent that IG Farben facilities were specifically targeted and destroyed, the damages could result in negative effects on innovation by IG Farben successors, i.e., in smaller estimates.[28] Systematic data on the war-time destruction of companies is not available. However, the devastation of a city's housing stock is an indirect proxy. Robustness checks based on Kästner (1949) and Hohn (1991) match patents to the closest city within 10 km and assign the destruction ratio of that city. Including this proxy variable does not materially impact estimation results.[29]

Besides damage to the physical infrastructure, the war may have led to the loss of life through battles and aerial attacks. In the wake of a re-appraisal of its history, the German Chemical Society studied public death announcements as well as internal information about the fate of its members (Maier, 2015). They found the death rate of chemists to be vastly below the general male population (2.7% vs. 16.8%), for example, because many Society members of military age were exempt from service. Although deaths were concentrated among junior members, the Society concluded in 1947 that even losses among the younger generation had not been 'overly large' (Maier, 2015, p. 570).

Figure F-2 reports descriptive statistics derived from death notices in journals of the German Chemical Society. Deaths are underreported for 1945 and 1946, as the publication of the journals first ceased and then resumed in 1947. Even so, the data suggest that most deaths were concentrated among (doctoral) student members of the Society. The median age of the war-related deceased was 27, and only 25% were older than 34. Even within IG Farben, the median age for war-related death is 35. Between 1939 and 1945, 25% of reported deaths were war-related. The decrease in deaths after 1945 is likely due to a decrease in the overall workforce, possibly selected by age.

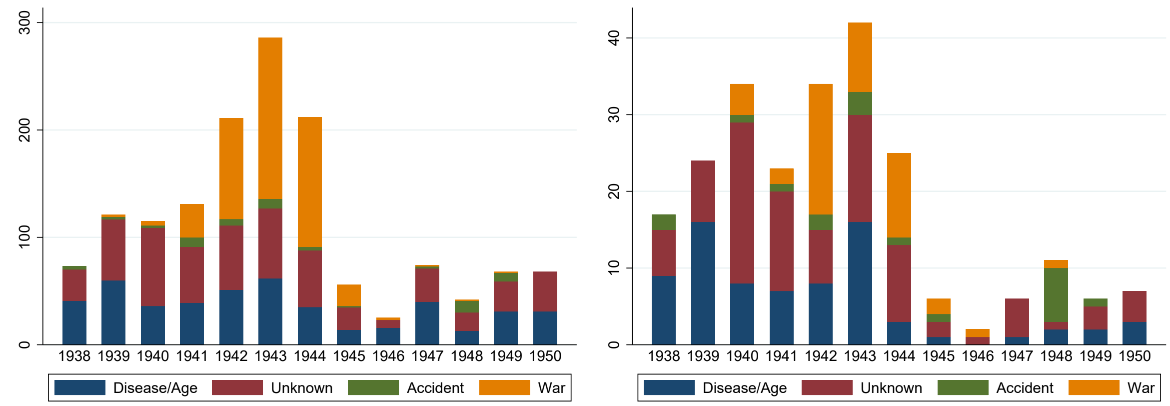
[27]The Leverkusen example represents a middle ground for the IG story. Of the West German plants, the BASF facilities were hardest hit by the war, while the Hoechst facilities were spared. On the other hand, the Hoechst facilities suffered from underinvestment. The strongest attacks against IG plants targeted the East German synthetic fuel plants at Leuna, which were completely destroyed.

[28]Yet, Waldinger (2016) exploits bombing damage to universities and does not find long-run effects on research output. Likewise, Baruffaldi and Gaessler (2021) find that the loss of research infrastructure has little effect on research output over ten years. Renewal of obsolete infrastructure might even have a positive effect.

[29]Table 2 shows that the destruction ratio does not vary between technology classes differentially exposed to the IG Farben shock. In technology-level (Tables B-1), firm-level (Table C-2) and product-level regressions (Poege, 2022), the inclusion of war destruction as a control variable does not alter results.

Figure F-2: Deaths of German Chemical Society members

(a) All reported deaths (b) Reported IG Farben deaths



Notes: Shows the number of death notices in journals of the German Chemical Society (Angewandte Chemie, Chemische Fabrik, Chemie-Ingenieur-Technik) by reported cause and year of death. The left panel shows all listed deaths, the right panel only IG Farben chemists. War-related deaths after 1945 are prisoners of war.

Allied economic policies, German recovery and technological opportunity In the initial period after the war, with the economy in disarray and the population's basic needs unmet, the Allies assumed direct control over the economy. With this initially came a set of production restrictions. These were primarily targeted toward dismantling all war-related capacity, discussed in detail below, and the restriction of strategic goods production. Table F-1 in the appendix gives a detailed account of the relevant products and industries and the development of the regulations over time. According to the 1946 Potsdam Industrial Plan, the German economy was to be limited to 70-75% of the pre-war 1936 level. The ceilings were never reached before the 1947 Revised Industrial Plan increased figures to 100% of the 1936 level. By mid-1950, also this restriction was lifted. After the middle of 1950, restrictions were still placed on war-related chemicals and some parts of the plastics value chain. These were only relaxed in 1951.

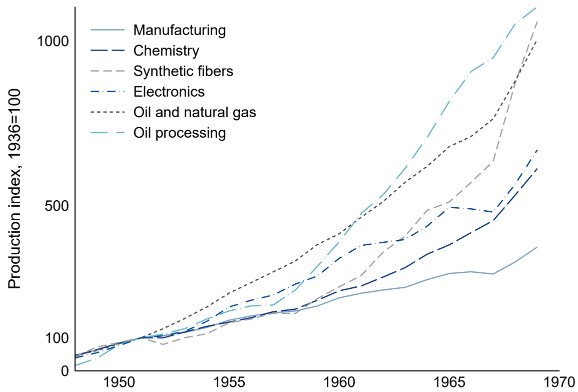
For the empirical strategy, relaxations in the 1950s are of the largest concern. If these relaxations would differentially affect production areas with IG Farben activity, they would constitute a parallel event of concern. In particular of concern is the plastics industry, where relaxation only occurred by 1951. Robustness checks thus repeat the analysis while disregarding products (Poege, 2022) or technology areas relevant for the plastics industry (Table B-1). The consistency of results is also reassuring, given the dominance of IG Farben in these fields. The removal of restrictions on the civilian industry by the Petersberg Industrial Plan, effective in late 1950, is unlikely to have significant confounding effects. First, the restrictions did not regulate individual products within a broad class of chemicals. Fixed effect controls for the broad chemical class are available. Second, removing restrictions did not lead to an immediate, marked increase in production. Figure F-1a shows the output of the German manufacturing and chemical industry relative to the pre-war level. The chemical industry did not show a substantial output increase in mid-1950, indicating that the policy was either not binding or that not much additional capacity was available. This is consistent with the historical literature (Morsey, 2010, p. 5).

The swift German economic recovery and the economic boom starting in the early 1950s could confound the IG Farben shock. However, the number of granted patents in technology classes not exposed to the breakup does stay constant, both within and outside of chemistry, see Figure 4b. It is hard to think of a technology-level comparison that alleviates these concerns. If the economic shocks driving the recovery were global (e.g., the Korean war), they would similarly affect counts of, e.g., US patents. Even if they were specific to technologies in Germany, affected German companies' patenting activities would likely spill over to other patent systems. A better argument is that in product-level regressions - as in (Poege, 2022) - effects can be traced to such products where multiple IG Farben successors were active. It is unlikely that macroeconomic shocks driving recovery and boom exactly correlate with the microstructure of the IG Farben successors' product portfolios.

More broadly, the historical narrative has it that IG Farben specifically invested in technology areas at the technological frontier. In particular, the transition to oil-based chemistry and the development of modern plastics throughout the 1950s come to mind. If IG Farben had picked future winners and past investments started to pay off after the Second World War, the analysis could be picking up the omitted variable of technological opportunity. This alternative hypothesis is inherently difficult to assess as technological opportunity is difficult to measure independently from technological success. However, the argument contrasts with other historical narratives and empirical results. For one, much of the technology developed for the target of German autarky was not immediately applicable in the post-war world. Specifically, oil-based chemistry was a distinctly post-war development for the German chemical industry (Stokes, 1994). Further, the increase in patenting in technology classes affected by the breakup is not driven by any particular technology area. Results remain consistent even after, in turn, omitting every group of technology section, see Figure B-5. The aggregate output growth of chemistry is on par with the overall economy and accelerated only in the 1960s. The same is true for synthetic fibers (see Figure F-3). Output in chemistry even stays below other sectors such as electronics, and the category of oil and oil processing dwarfs both.

Dismantlement of factories After the war, the Allies sought to limit Germany's war potential and recuperate some of their own economic losses. The extent and impact of these policies can be captured using data given by Harmssen (1951, pp. 98–126). Harmssen prints the official dismantlement targets for the Western Zones as of 1947 and reported dismantlements

Figure F-3: Industrial production (long-run)



Notes: Index of net industrial production. Synthetic fibers is a subset of chemistry. Time series reported in 1956, 1965 and 1971 are reset to base year 1951 and chained to create the long-run index. Source: Statistical Yearbooks for West Germany.

for the Soviet zone. There are almost 2000 factory entries pertaining to some 1700 firms. However, only 100 firms in the chemical industry occur in the dismantlement lists, consistent with the over 80% of entries classified as aerospace, defense, machinery, or mining. The list of actually dismantled plants is much smaller as the Western allies adjusted the lists. The list of dismantlement targets for the Western zones starts with 1500 entries and is halved by 1949 (Wallich, 1955, p. 369). For a technology class analysis, the share of patents by firms slated for dismantlement can be calculated. Among non-IG Farben firms, around 8% of pre-war patents were applied by targeted firms, balanced between classes by IG shock exposure. Controlling for this variable leaves results unchanged.[30]

Next to the effect of dismantlements in the broader chemical industry, the effect on IG Farben is important. IG Farben was a primary target, and all factories were contained in the lists. This mechanically leads to a strong correlation between breakup exposure and dismantlement share on a technology class level. Studying the issue in more detail, it is unlikely that damages to the IG Farben successors through dismantlement drive the effect. Some plants on the dismantlement lists were to be fully disassembled or destroyed. However, most of the time, only parts of listed plants were intended for dismantling. For example, IG Farben in Leverkusen was set to lose production facilities for seven types of chemicals, a small subset of its portfolio.[31] In West Germany, whole plants were slated for dismantlement only in the French zone. Abelshauser (2003, pp. 349–350) discusses their history. After much controversy, dismantlements only affected synthetic fuels and plastics. Crucial other plants were saved. If dismantlements had

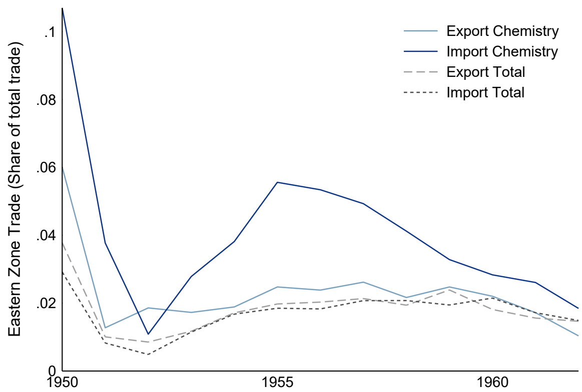
[30]See Table 2 and Table B-1, respectively. The firm-level regressions in Table C-2 show that the patent output of firms exposed to dismantlement permanently suffers, but the estimates for IG Farben exposure remain unchanged.

[31]Listed were, for example, a drug against Malaria, some plastics, and substances relevant as rocket fuel. Bayer still offered all substances listed in the 1952 product listing. See Table F-3 for the 1947 dismantlement entries related to IG Farben.

been realized as originally intended, they would have implied considerable damages for the recovery of BASF. Ultimately, they never affected the supply of in-house production or other industries. While lacking counterfactuals, it is notable that the IG Farben successors could recover quickly to pre-war levels of economic activity, as discussed in Section 7.

The Soviet sector and German separation Quickly after Germany's liberation and the division into occupation zones, the Soviet sector started to develop on a diverging path. Here, the authorities introduced the harshest reparation policies. Large parts of the surviving industry were dismantled and brought to the Soviet Union. As in the Western zones, the Soviets took direct control of the IG Farben plants even before nationalization efforts were begun in earnest. Stokes (1995) discusses the history of IG Farben in East Germany after 1945. Latest with the currency reforms in East and West, West and East German industry began to disintegrate. The supplier lists of 1952 list no East German chemical firms. Figure F-4 shows the importance of interzonal (East-West) trade by comparing it with overall trade. Visibly, interzonal trade was initially important, but the amount declined in the 1950s and never recovered. Before the Second World War, a sizable share of chemical companies was located in East Germany or Berlin. Of those, some were able to relocate their operations and are still active in West Germany in 1952. For inventive activity, it is possible to control for the pre-war share of inventive activity taking place in the Soviet sector. Dismantlement targets for the Soviet sector are available from Harmssen (1951).

Figure F-4: East-West trade flows



Notes: Interzonal trade as a share of total trade, in the chemical industry and total. Earlier numbers are not available from statistical yearbooks. Source: Statistical Yearbooks for West Germany.

Robustness checks can account for differential exposure to the Soviet sector. For innovation, analysis on the technology class and firm levels is feasible. Table 2 shows that patents in technologies with and without exposure to the IG were located in East Germany with the same rate. However, the share of patents located in Berlin is higher for IG-exposed technologies, consistent with some IG plants located there. Explicitly controlling for the share, Table B-1 finds estimates unchanged. Firm-level regressions in Appendix C explicitly introduce control variables and show the robustness of the innovation analysis.

Allied competition policy and Germany's GATT accession Before the war, the German laws regulating cartels were anti-competitive, as considered from today's perspective. Maintaining high prices to strengthen the industry was a policy objective. Cartels were allowed, and their general form was regulated by law, to the extent that Germany's cartel court was largely arbitrating grievances between cartel members. Early during the Allied occupation, in 1947, such cartels were dissolved. However, Germany itself did not introduce competition regulation until 1958 (Murach-Brand, 2004). Whether the 1947 dissolution of cartels affected the innovation activities of chemical companies is unclear, but for example Kang (2020) suggests a negative effect. In principle, areas with IG Farben activity (see for example Stokes, 2016, p. 174) and such without were affected, and cartels were frequent throughout the economy. Nevertheless, since IG Farben was the dominant force in its areas of activity, the effect in non-IG areas would likely be stronger. Therefore, if patenting activity in non-IG areas drops more strongly immediately following the war, this could be a reason. In product catalogs, I can collect information on the product-level presence of cartels in the pre-war period, which allows for robustness checks.

In 1951, Germany entered the General Agreement on Tariffs and Trade (GATT), a predecessor of today's World Trade Organization. At that time, Germany's tariff system underwent major changes in terms of how tariffs were listed, the structure of the tariffs, and the tariff level. Overall, tariffs increased compared to the pre-accession level (Wallich, 1955). To quantify the tariff change for given chemicals and to discuss the potential effects of the changes, product-level information on prices is necessary.

For the historical factors of cartel dissolution and the GATT accession, the technology- or firm-level is not the appropriate analysis level. In Poege (2022), I present product-level information on prices and the number of suppliers. This data stems from the historical product catalogs introduced in Section C, as well as industry journals. However, the comprehensive analysis of prices and market structure requires a thoroughly different set of theory and a different analysis level, so a detailed discussion is omitted here. In summary, including a control variable for cartelization leaves estimates for price effects of the IG Farben breakup unchanged. Further, including a control variable for the tariff change does not alter the conclusions about the product-level effect of the IG Farben breakup (Poege, 2022).

Other factors Next to the previously discussed factors, others elude measurement attempts. Direct expropriation and exploitation of German intellectual property and tacit knowledge occurred during and after the war. German IP in foreign countries was confiscated, and the Allied survey groups took stock of German firms' technology level. Scientists - especially in war-related fields such as rocketry and chemical weapons - were recruited (Jacobsen, 2014). The effect of these policies is not easily quantifiable. Historians who tried to judge their economic impact determined it to be large and significant (Gimbel, 1990). On the other hand, confiscated technical specifications often required additional tacit knowledge (Stokes, 1991, p. 15) or were about to be obsolete due to new technological developments (Murmann and Landau, 2000, p. 61). To the extent that civilian research was concerned, contact between US and German scientists might have helped to facilitate post-war collaboration. The results of Baten, Bianchi, and Moser (2017) suggest that such policies positively affect subsequent innovation, resulting in a possible upwards bias. Whether such a bias materializes depends on whether the policies more strongly targeted fields with IG Farben activity. However, Allied technical survey efforts covered a broad set of targets.[32] In a rough approach, including a proxy for the exposure to the confiscation of foreign IP does not change the conclusions about the IG Farben breakup.[33] Labor-related channels are beyond the scope of this paper. These include the loss of life during the war (but see the discussion under 'war destruction' above), the relocation of East-German inventors, and the change in monopsony power in the labor market. On the management level, the loss of experienced personnel due to war crime trials is another possible factor. However, the number of convicted managers is small, and their sentences were short (Jeffreys, 2010). Oster (2019) bounds allow an explicit assessment of biases by unobservable confounders. Table B-6 shows corresponding results.

[32]Gimbel (1990, pp. 64–67) details the cases of chemical companies Merck, Degussa, and Linde next to IG Farben and its subsidiary Wacker. The survey teams worked on 20,000 targets, later narrowed to 400.

[33]Table C-2 includes the ratio of pre-war US patents by pre-war German patents of individual firms. Firms with larger exposure increase their post-war patenting, but the coefficients of breakup exposure do not change much. While this result is compatible with Baten, Bianchi, and Moser (2017), a full analysis would require more nuance.

Table F-1: Post-war production and capacity restrictions until 1951

Materials	Potsdam Industrial Plan	Revised Industrial Plan	Washington/Petersberg Industrial Plan	Agreement on Industrial Monitoring
Announcement	Mar 46	Aug 47	Apr 49 / Nov 49	Apr 51
Effect	N/A		Sept 50	Apr 51
Target level	70-75% of 1936 Dismantle 1500 plants	100% of 1936 859 plants, later 700	Unrestricted Dismantlement stop	Unrestricted
Chemical industry				
Basic chemicals	40% of 1936	98% of 1936	Unrestricted	
Others chemicals	70% of 1936	97% of 1936		
Pharmaceuticals	80% of 1936	84% of 1936		
Colors	36k t	96% of 1936		
	Export restricted	Export allowed		
Synthetic ammonia	Prohibition of production		Post-dismantlement capacity	None
Chlorine	Basic chemicals / Only upon approval		Post-dismantlement capacity	None
Synthetic fuels	Prohibition of production			Monitoring
Plastics value chain				
Styrene	70% of 1936	100% of 1936	20k t	None
Butadiene	Not mentioned		Prohibition of production	
Synthetic rubber, gum	Prohibition of production (ex. small Q)			Monitoring
Synthetic fibers	185k t	Not mentioned	None	
Consumer products	Q Restrictions	Unrestricted	None	
Metals				

Table F-1: Post-war production and capacity restrictions until 1951

Materials	Potsdam Industrial Plan	Revised Industrial Plan	Washington/Petersberg Industrial Plan	Agreement on Industrial Monitoring
Copper, zinc, lead, tin, nickel	ca. 50% of 1936	up to 100% of 1936	None	
Aluminium	Prohibition of production		Capacity restriction	None
Magnesium	Prohibition of production			
Beryllium	Prohibition of production			None
Vanadium	Prohibition of production		None	
War-related products	Prohibition of production			
War material, including explosives, warfare gases, biological weapons				
Firearm propellants, e.g. Nitroguanidine, Nitroglycerin, Diethylene glycol, Nitrocellulose				
Rocket fuels: Hydrogen peroxide (>37%), Hydrazine hydrate, Methyl nitrate				
White phosphorus and other burn agents				

Notes: Summarizes post-war production restrictions until 1951. Not all restrictions laid out came into effect. For example, the Potsdam Industrial Plan had little practical consequence. This was due to a breakdown of coordination among the Allies and changed priorities in the wake of the coming Cold War. Also, the German industry did not reach ceilings before they were adjusted (Morsey (2010, p. 5) and Wallich (1955, p. 369)). Exemplary, with respect to plastics and synthetic ammonia, the Potsdam plan outlawed production, but halted this restriction until sufficient imports were viable. After this, all capital equipment should be removed. Specialized metals are listed as IG Farben subsidiaries were involved in their production. Aluminium, Magnesium, Beryllium and Vanadium are either light metals or ingredients for specialty steel.Butadiene and Styrene - in 3:1 ratio - are ingredients for the synthetic rubber “Buna”, among other chemical substances. Styrene was only explicitly regulated in the Washington Industrial Plan, before it was regulated as ‘generic chemicals’. With the Washington Agreement, capacity restrictions on civilian production such as cement, paper, textiles and shoes, cars, trains etc. were lifted. Other goods more tightly restricted were steel, heavy machine tools, aircraft, ships and electronic and optical components. Under the agreement on industrial monitoring (1951), industries such as synthetic rubber and synthetic fuels required approval for capacity expansion, but were otherwise free to operate. Source: Harmssen (1951). Factory numbers from Wallich (1955, p. 369).

Table F-2: Plants within IG Farben

Plant	Work group	Successor	R&D	Patent	Description
British zone					
Dormagen	Lower rh.	Bayer	Y	N	
Elberfeld	Lower rh.	Bayer	Y	N	
Leverkusen	Lower rh.	Bayer	Y	Y	Core of successor Bayer
		Agfa			Photo materials
Uerdingen	Lower rh.	Bayer	Y	Y	
Zweckel	Upper rh.	Bayer	N	N	
Hüls	Upper rh.	Hüls	N	N	Plastics. From 1938, joint venture with Hibernia AG (under IG leadership)
US zone					
Höchst	Middle rh.	Hoechst	Y	Y	Core of successor Hoechst
Griesheim	Middle rh.	Hoechst	Y	N	
G.-Autogen	Middle rh.	Hoechst	Y	Y	Industrial gases, located at Griesheim
Bobingen	Berlin	Hoechst	Y	N	Artificial Silk
Offenbach	Middle rh.	Hoechst	Y	Y	
Mainkur	Middle rh.	Cassella	Y	Y	As subsidiary
Wiesbaden	Middle rh.	Kalle	Y	Y	As subsidiary
Munich	Berlin	Agfa	Y	Y	Camera manufacturing
Gendorf		Hoechst			Chemical warfare gases, subsidiary, independent 1952-1955, then Hoechst
French zone					
Ludwigshafen	Upper rh.	BASF	Y	Y	Core of successor BASF
Oppau	Upper rh.	BASF	Y	Y	
Rheinfelden	Middle Ger.	Dynamit	N	N	Artificial silk
Rottweil	Berlin	Rottweil	N	N	Explosives and artificial silk, later as Rottweiler Kunstseidefabrik AG
Soviet zone					
Aken	Middle Ger.	IG East	N	N	Light metals (from 1934)
Wolfen-Film	Berlin	IG East	Y	Y	Photo materials and artificial silk
Wolfen-Farben	Middle Ger.	IG East	Y	Y	Colors
Schkopau	Upper rh.	IG East	N	N	From 1937, before Leuna
Leuna	Upper rh.	IG East			Ammoniakwerk Merseburg
Premnitz	Berlin	IG East	Y	N	Artificial silk. Very small patent-related expenditure
Bitterfeld	Middle Ger.	IG East	Y	Y	
Döberitz	Middle Ger.	IG East	N	N	Artificial silk. Near Premnitz

Notes: IG Farben plants and their organization according to works groups (Betriebsgemeinschaften - among them Lower, Middle and Upper rhine, Middle Germany and Berlin) and according to successor companies. Further lists the existence of R&D and patent offices as given by internal IG Farben accounting documents from 1935-1939. These are unavailable for some subsidiaries, e.g. Leuna or Anorgana. See also Plumpe (1990, p. 142). Smaller plants at Bochum, Karlsruhe, Gapel, Teutschenthal, Staßfurt, ... omitted. Foreign plants omitted. Subsidiaries - except selected - omitted. Groups as after 1926. Autogen and IG subsidiaries involved primarily in the production of industrial gases became part of Knapsack-Griesheim AG under the leadership of Hoechst.

Table F-3: Dismantling of IG Farben

Successor	Plant	Type	Products / Description
British-American zone			
Bayer	Dormagen	Part	Perlon (en: Nylon)
Bayer	Elberfeld	Part	Cellulose derivatives, artifical resins
Bayer	Holten	Part	1,2-Dichloroethane
Bayer	Leverkusen	Part	Sodium sulfide, "Atebrin" (Mepacrine), polyamides, artificial resins, hydrazine hydrate (Propellant), activated carbon, toluene nitrate (Explosives)
Bayer	Uerdingen	Part	Chloride, causic soda, alkydal artifical resins
Bayer	Zweckel	Part	Diethyl ether, 1,2-Dichloroethane, polyethylene, bleaching powder
Other	Duisburg	N/A	Liquid oxygen
Anorgana	Gendorf	Part	Bleach und sodium hydroxide, acetaldehyde, glycol
Wacker	Burghausen	Part	No details
Kalle	Wiesbaden	Part	Methyl, ethyl, Cellulose derivatives
Hoechst	Frankfurt/M	Part	"Uresin" (Pastics), acetate, carboresin, black sulfur, solvents, chloride solutions, dinitrobenzene
Hoechst	Griesheim	N/A	Industrial gases
Other	Kassel	N/A	Industrial gases
Dynamit	Fürde/Grevenbrück	Part	Explosives, fuses
Dynamit	Schlebusch	Part	Glycerine, toluene nitrate
Dynamit	Troisdorf	Part	Nitrogen, vulcanized fiber, phenol formaldehyde resin, celluloid
Dynamit	Claustal-Zellerfeld	Part	High explosives, grenades
Dynamit	Empelde-Hannover	Full	Ammunition
Dynamit	Near Hamburg	Full	(At Düneburg/Krümel) Explosives
Dynamit	Nürnberg	Full	Bullet casings
Dynamit	Kauferin/Landsberg	Full	Ammunition
Dynamit	Stadeln	Full	Bullet casings
Dynamit	Hamm	Full	Gunpowder
French zone			
Other	Rottweil	Part	Hunting ammunition
BASF	Ludwigshafen	Full	38 plants (unspecified)
BASF	Oppau	Full	11 plants (unspecified)
Other	Rheinfelden	Full	Unspecified
Soviet zone			
IG East	Aken	Full	
IG East	Wolfen	Full	Agfa plants
IG East	Schkopau	Full	Buna plant
IG East	Leuna	Full	Leuna plant

Table F-3: Dismantling of IG Farben

Successor	Plant	Type	Products / Description
IG East	Piesteritz	Full	Nitrogen plant
IG East	Bitterfeld	Full	
IG East	Coswig	Full	(Former WASAG)

qualifications contained in the lists of the dismantlement targets, if available. Soviet zone lists actual dismantlements. In the Western zones, actual dismantlement rarely reached the originally intended level, see discussion in Section F.
Notes: Dismantlement targets as reported in Harmssen (1951), lists as of 1947. Type of dismantlement and product/description lists