Tapping into Scientific Talent: The Rise of Corporate and Public R&D in Japan's Chemical Industry

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Abstract

Sudden import disruptions redirect and intensify technological development, but innovation response to acute necessity in the midst of such disruptions depends on the supply of individuals capable of generating new technologies. I combine the examination of the impact of sudden suspension of imports from Europe during World War I in Japan that led to an abrupt emergence of the demand for technological development in chemistry-related fields with individual-level data on allocation and invention outcomes of highly educated scientists and engineers. Using granular data on the census of graduates in chemistry-related fields from Japan's Imperial Universities, I show that the suspension of imports triggered by the onset of World War I led to a large increase in the inventive output of incumbent scientists and engineers but only among those with pre-war accumulation of embodied scientific knowledge. Though World War I import suspension was transient, it permanently changed the allocation of talent, research trajectories and individual research productivity despite the return of imports after the end of the war. Both the emergence of corporate laboratories and public research institutes and the embodied human capital of individual scientists and engineers are shown to be critical components of the long-lived research assets that led to the long-term increase in invention and eventual takeoff of Japan's chemical industry.

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"... [S]ince the Meiji Restoration, the education system has expanded, and the number of people receiving higher education has increased significantly. Nearly 2,000 chemists have graduated from universities. ... Thus, there are already people with the potential to invent. However, they are just busy with their jobs and lack the time to invent and innovate. Even if they come up with some kind of ideas, there are no funds to test them, and no required equipment in factories. These chemists, despite their genius, are denied the opportunity to demonstrate it. This is not only a misfortune for these chemists, but a great loss for the nation. ..."

Jōkichi Takamine.[1]

1. Introduction

We live in the era of rapid scientific and technological progress, on the one hand, and global policy uncertainty, particularly with regard to trade restrictions (Fajgelbaum et al., 2020; Alfaro et al., 2025), on the other hand. Such policy uncertainty and trade restrictions have been increasingly disrupting the normal course of economic affairs and/or upending the established organization and routines of the innovation process. A growing body of literature has examined how such trade disruptions redirect and intensify innovation and technological development in various historical and contemporaneous contexts (Hanlon, 2015; Juhász, 2018; Alfaro et al., 2025). However, how exactly are new technologies developed in response to acute necessity in the midst of such disruptions? The extant literature still does not fully incorporate the supply side, which requires an examination at the level of individual scientists and engineers (Codreanu et al., 2026). Such examination is important because new technologies do not come about in a "putty clay" fashion (Schmookler, 1966) but require paying attention to "the manner in which the state of knowledge at any time shapes and structures the possibilities for inventive activity" (Rosenberg, 1974).

In this paper, I study the short-term and longer-term innovation response by highly educated scientists and engineers to an abrupt suspension of imports of chemical products from Europe during World War I (WWI) in Japan. Upper-tail human capital is generally known to be central to innovation and long-term industrial growth (Mokyr, 2005; Squicciarini and Voigtländer, 2015; Maloney and Caicedo, 2022), but this paper examines how different types of such knowledge elites contributed to technological development in response to the sudden import disruption at the granular individual level. Specifically, I utilize the data on the census of all graduates in chemistry-related fields from all four top-tier Imperial Universities existing at the time, covering 54 graduating cohorts and spanning over 40 years of observations before, during, and after WWI on their careers, patents, and major field journal publications.[2]

[1] From the address to the Chemical Society of Japan in 1913 (https://npo-takamine.org/contribution/riken_takamine/). Takamine was the world-famous Japanese chemist who discovered adrenaline, the top graduate in the first cohort of Imperial College of Engineering Applied Chemistry division. He left for the U.S. in 1890.

[2] In prior studies, patents have been used as a good measure of innovation in chemistry because chemical innovations are exceptionally suitable to patent protection (Cohen et al., 2000; Moser, 2012; Moser et al., 2014).

Japan established a modern higher technical education system, which included both basic and applied chemistry education that churned out highly educated scientists and engineers, already in the late 19th century. This was an important pre-requisite for the subsequent outburst of innovation, but prior to the onset of WWI, the country relied on imports of chemical products from Europe, lacking robust domestic industry and private and public R&D system in chemistry-related fields. As WWI disrupted trade with Europe, Japan faced a sudden acute necessity to develop the technological base for its own chemical industry. The immediate effect of the import disruption was a range of technological advances which were not just limited to direct import substitution, but also the development of domestic alternatives to imported products. Moreover, its long-term impact was to reshape the whole trajectory of the chemical innovation system.

I document three main findings. First, incumbent scientists and engineers in chemistry fields who until then produced very few industrial patents responded with a burst of new patented inventions during the WWI import suspension period. Furthermore, I observe strong heterogeneity in this response — the surge in new patents was concentrated among those university-educated chemists who had been doing science and publishing scientific papers in top chemistry field journals *before* import suspension happened, with no such surge among similarly educated chemists without publication records. This implies that the accumulation of scientific knowledge, embodied in scientific human capital, was a key to responding to the sudden import disruption.

Second, the war-time temporary import suspension had persistent, long-term effects on individual patent productivity: despite no difference in inventive output among chemistry graduates prior to the war, those with pre-war scientific publications continued to produce more patents relative to other graduates after the end of the war, even though imports from Europe returned, plunging the fledgling domestic industry into a deep crisis. That is, similar to Gross and Sampat (2023, 2025), the response to the transient shock permanently changed how productive top talent could be in terms of their research output. However, it also turns out that it was mostly technologies that were *not* necessarily a direct continuation of WWI-era import substitution that experienced the largest increase in invention in the long run.

My third finding reveals the mechanisms behind such long-term effects. Import suspension triggered large-scale new entry into the chemical industry, and both new and incumbent firms set up corporate R&D labs, with public and not-for-profit research institutes following with a few years' lag. The research sector continued to grow, and in response, more highly educated chemists started to work in better-organized research environment, which further enhanced their inventive output. Accomplished scientists and engineers, who drew on the totality of their accumulated embodied scientific knowledge, could continue using or building upon such long-lived research assets and harness their inventive potential even after the war ended. I find that those with pre-war scientific publications experienced a long-term boost to invention only if they engaged in research at some point. At the same time, I also find that those and only those with embodied scientific knowledge could *carry over* their research experiences into other organizations and produce more

inventive outputs even after they moved from research labs or institutes to other organizations, which was the main driver of the long-term boost to post-war invention.

Taken together, the findings in this paper provide us with an important mechanism behind how sudden trade disruptions requiring the development of new technologies shape invention and innovation. Using the data on the universe of all university-educated chemists, I show that human capital with embodied scientific knowledge (observed through top journal publications) is an essential element of such a mechanism (Hounshell and Smith, 1988, Chapter 3). Sudden emergence of an acute necessity to develop new technologies led to the "activation" of such human capital that was previously hampered in harnessing their full innovative potential due to either lack of funding, or being busy with other aspects of their jobs and lacking time to invent and innovate, or both, as emphasized by Jôkichi Takamine in his address to the Chemical Society of Japan in 1913 in the epigraph to this paper.[3] This also has important implications for organizations. For scientists and engineers to develop technologies to meet the newly emerging acute necessity, they need to be provided with complementary assets that support research activities (Teece, 1986; Babina et al., 2023b) and, more fundamentally, a well-organized research environment. Most of the literature focuses either on the general supply of human capital, such as education policies, or on the creation of research institutions, private or public, but not on the two brought together.[4] My study shows that heterogeneous human capital responds differently to the same organizational needs and opportunities, and thus more attention needs to be paid to the matching process and to securing talent with broad embodied scientific knowledge, which is essential for an organization's capability to respond to various shocks.

While my study is grounded in a particular historical context of the emergence of R&D in Japan's chemical industry in the early 20th century, I believe the lessons are quite general. Of course, Japan's import suspension shock during WWI has some unique, idiosyncratic features but this is true of all unanticipated shocks, including but not limited to all the shocks studied in the extant literature cited above. Thus, the uniqueness aspect is beside the point. Furthermore, while the context of this paper is about import disruption, the lessons can be extended to innovation in the time of crises, from wars (Gross and Sampat, 2023, 2025; Bergeaud et al., 2025) to the COVID-19 pandemic (Shah and Tripsas, 2020; Davis et al., 2026). The critical question that needs to be addressed is the question of who and how can respond with new invention and innovation once the next, not yet predictable shock hits. Also, given that the WWI import suspension shock was transient (again, as most if not all shocks are), why did it nevertheless have

[3] Jôkichi Takamine himself was one of the first graduates from Japan's higher chemistry education but left for the United States in 1890, and all his major inventions, including the discovery and isolation of adrenaline, were accomplished in his lab in New York.

[4] For the supply of human capital and education policies, see, e.g., Becker et al. (2011); Toivanen and Väänänen (2016); Akcigit et al. (2017); Bell et al. (2019); Biasi et al. (2020); Akcigit et al. (2025). For the impacts of the creation of research institutions, see, e.g., Furman and Stern (2011); Valero and Van Reenen (2019); Andrews (2023); Helper et al. (2026), and for the impact of national research programs, see, e.g., Klepper (2016); Azoulay et al. (2019); Gross and Sampat (2021, 2023, 2025).

a long-term effect; in other words, why was the capability "activated" during the war so long-lived? The availability of long-term, rich individual-level panel data makes it possible to address the above questions at the level of detail not easily available in other studies.

The case examined in this paper also presents considerable interest in its own right because only a handful of countries (Japan most prominent among them until recently) were able to establish internationally competitive science-based industries. As I show in this paper, while creating a strong higher technical education system that churned out scientists and engineers with advanced knowledge was an important pre-requisite, the path toward establishing a robust chemical industry involved overcoming several critical barriers. Thus, Japanese experience contains valuable lessons for today's developing nations that are looking to develop industries requiring not just availability but also the right allocation of and research environment for educated scientists and engineers.[5] It may also contain lessons for modern advanced nations, including the United States, as they face new global challenges and need to maintain and enhance the right kind of environment to continue to harness the talent of their scientists and engineers.

Related Literature. The important role of shifts in demand in shaping the direction of innovation features prominently in the literature on directed technical change (Acemoglu, 2002). Recent studies have found empirical support for such effects in various settings, from Napoleonic blockade (Juhász, 2018) to import suspension due to American Civil War (Hanlon, 2015) to conscription in WWI (Bergeaud et al., 2025) to China's restrictions on rare earth elements exports (Alfaro et al., 2025). A related emerging stream of literature in both strategy and economics has focused on the role of innovation at the times of crises (Shah and Tripsas, 2020; Gross and Sampat, 2021; Babina et al., 2023a; Davis et al., 2026). But whether such shocks or crises produce inventions critically depends on the supply of specific individuals capable of generating inventions and whether they are matched to the organizations that provide them with the right kind of research environment. My study examines this latter aspect at the level of individual careers of scientists and engineers. As such, it speaks to the literature on microfoundations of organizational innovative capability.

The literature on microfoundations of strategic organization starts from the premise that organizational and industry-level capabilities ultimately reduce to knowledge and skills embodied in individuals (Felin and Foss, 2005; Felin et al., 2012, 2015).[6] This view also connects to the notion that scientific human capital represents tacit knowledge embodied in individual scientists and engineers (Hounshell and Smith, 1988; Bozeman et al., 2001). This literature, however, has remained largely theoretical — the claim that a capability relies on a particular embodied stock

[5] The experiences of the emerging new global powers (such as China and India) clearly show the importance of the issues I analyze in this paper. These countries had suffered from brain drain even though they had robust education systems, but more recently, proactive efforts to retain talent by providing right incentives and dedicated research labs led to unleashing their growth potential.

[6] "Organizations are made up of individuals, and there is no organization without individuals. There is nothing quite as elementary; yet this elementary truth seems to have been lost in the increasing focus on structure, routines, capabilities, culture, institutions and various other collective conceptualizations in much of recent strategic organization research" (Felin and Foss, 2005).

of individual knowledge is hard to test empirically because such knowledge is rarely observable *before* the capability emerges (Winter, 2013). My study examines this issue empirically from several important angles — not only do I have the data on all future inventors *before* they started making invention in response to a large exogenous demand shock, but I also have the data on the *census* of all highly-educated scientists and engineers in the chemistry field so that I can observe not just the inventors who succeeded but also those who did not produce inventions even though they faced the same demand-driven necessity shock.[7] The finding that the post-shock invention response was concentrated among university-educated chemists who had already accumulated scientific knowledge (observable in the data on scientific publications years earlier) provides the kind of individual-level evidence that the extant microfoundations literature largely had to assume.

The key role played by the pre-existing stock of embodied scientific human capital in building new technologies for a nascent industry also speaks to the literature on industry incubation (Moeen and Agarwal, 2017; Moeen et al., 2020). This literature demonstrates that industry emergence hinges on prior accumulation of heterogeneous technical knowledge and complementary assets, often well before any market exists. In a recent working paper, Caplin (2026) models such prior knowledge accumulation as "staged discovery" where early-stage inquiry generates "planning capital" which reduces the costs of later innovations that can go beyond the initial ones. In my study, such planning capital is the outcome of staged discovery initially not by organizations, but by individual scientists and engineers and is embodied in their accumulated human capital observed through scientific publications. Importantly, despite the transient nature of the shock, its effects on invention were persistent and grew over time. I show that this persistence of innovation even after the end of WWI import suspension came from the durability of activated embodied human capital and the match with the complementary private and public organizations which built R&D capabilities.

My study is related to the large stream of literature centering around the discussion of policies to promote innovation (Bloom et al., 2019). The social return to innovation is likely to be less than its private return, creating the need for public interventions and policies to encourage research and development (Azoulay et al., 2019; Myers and Lanahan, 2022; Gross and Sampat, 2023, 2025; Babina et al., 2023b). However, without the sufficient supply of human capital, such efforts end in vain (Goolsbee, 1998; Van Reenen, 2022). Building on the studies that document the key role played by higher technical education in generating the supply of people with inventive potential (Akcigit et al., 2017; Bell et al., 2019), my research demonstrates that education policies alone may not be enough without also building the right kind of research environment around highly educated human capital to secure its proper allocation. In other words, the supply of scientific human capital does not automatically clear through independent labor market mechanism, as there are always lower-bound outside options for educated scientists and engineers to

[7] Observing the effects of sudden increase in *demand* makes my study different from extant studies which utilize exogenous shifts in the *supply* of knowledge or research inputs to identify the effects of technology-push factors (Borjas and Doran, 2012; Moser et al., 2014).

work outside of the research sector if the demand for scientific labor is not enough in the market. Concerted effort on the parts of both government and private business is needed to secure the environment where this scientific talent can work as effective skilled labor.

My study also contributes to the literature on the role of human capital in modern development (Mokyr, 1992; Goldin, 2001; Galor and Moav, 2006; Becker et al., 2011). This literature emphasizes the importance of the upper tail of human capital distribution (Mokyr, 2005; Squicciarini and Voigtländer, 2015), especially engineering human capital (Maloney and Caicedo, 2022) and argues that it is critical to provide this human capital the right incentives to invent and to allow their free mobility (Mokyr, 2005). My microfoundational analysis sharpens this insight: what matters is absorbed, embodied scientific knowledge, not the degree itself (a point developed in a more general context in Hiraiwa et al. (2025b)). Because embodied knowledge is usually unobservable, I operationalize it through pre-shock journal publication, which serves as a rare revealed measure of which individuals had converted their education into genuine scientific capability.[8]

Finally, my paper speaks to the strategic human capital literature (Coff and Kryscynski, 2011; Campbell et al., 2012, 2021). This literature demonstrates that talent allocation and the match between human capital and organization employing it is an important mechanism through which talent can realize itself. The wartime shock I examine in this paper simultaneously "activated" the incumbent human capital and created complementary research organizations, inducing the reallocation of talent into the research sector. This allows me to examine each of those factors separately and in their interaction.

The rest of the paper is organized as follows. In the next section, I present a brief historical overview of Japan's higher education in chemistry-related fields and the emergence of the chemical industry, including a description of events surrounding WWI and its end. Section 3 describes the data. In Section 4, I first present some basic evidence on how WWI import suspension affected invention output among top-educated scientists and engineers in chemistry-related fields, both in the short run and in the long run, and show who developed such invention. Section 5 examines the mechanism behind the long-term boost to invention after the war and the role played by the creation of the well-organized research environment around WWI. Section 6 concludes.

2. Historical Background

I first briefly describe the historical context of this study, specifically focusing on details about Japan's chemical industries and chemistry education. More details on the historical background are in Appendix C.[9]

[8] See also Creanza (2025); Kim and Moser (2025); Codreanu et al. (2026) for studies using unusually granular individual-level data from important historical contexts.

[9] See also Hiraiwa et al. (2025a) for the general research context of Japan's industrialization and Hiraiwa et al. (2025b) for the details about Japan's higher technical education in general at that time.

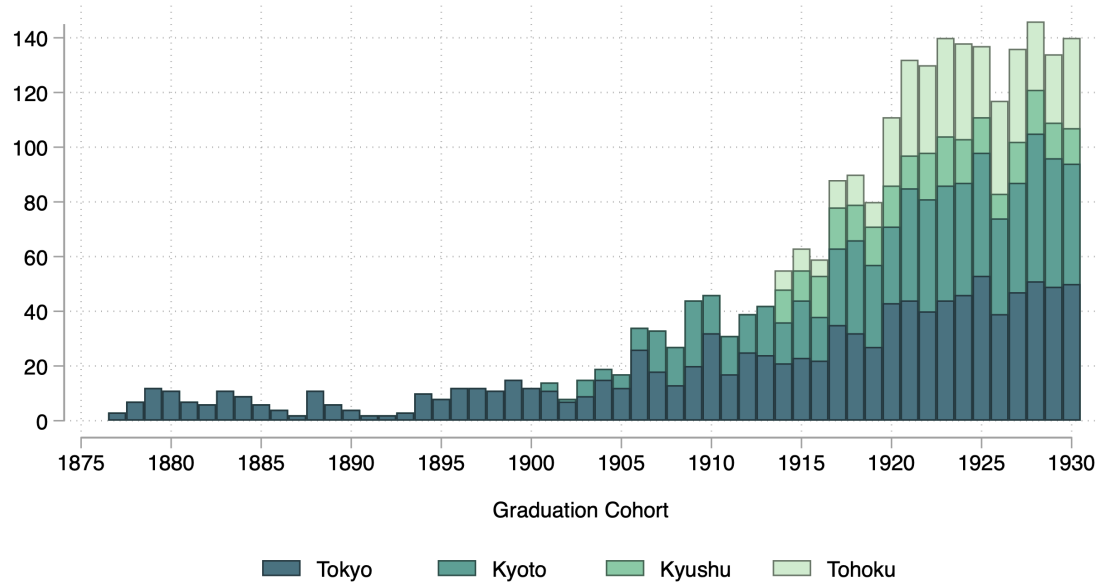
2.1. Higher Chemistry Education at Imperial Universities

As is well known, Japan had been in self-imposed isolation from the rest of the world for more than two centuries until it was forced to open up in the mid-1850s. The Meiji Restoration of 1868 ushered in the era of economic and political modernization but at that point, the country had neither modern industries nor any system of science and engineering education to speak of. The supply of educated scientists and engineers is a key to any science-based industry, and chemical industry in the late 19th and early 20th century was one of the first such industries. The emergence of higher chemistry education was thus one of the most important prerequisites for this industry to be created in Japan.

The first state-run chemistry school, *Seimikyoku*, was established right after the Meiji Restoration in Osaka, the commercial and financial center of Japan at that time and was spearheaded by a Dutch chemist, K.W. Gratama. Even though that particular school did not survive, it was attended by some prominent future educated first-generation chemists. In 1874, Chemistry division was established under the leadership of a British chemist, R.W. Atkinson, in the state-run *Tokyo Kaisei Gakko* which later became Chemistry division in Tokyo Imperial University College of Science. Imperial College of Engineering, which later became Tokyo Imperial University College of Engineering was founded three years later, in 1877, and had Applied Chemistry division from the outset. Thus, chemistry and applied chemistry education were already put in place in Japan very early in its process of modernization. The initial goal was for the graduates from this education system to assist in early government-led efforts to establish the chemical industry (more on this in the next subsection).

Over time, the number of university-educated scientists and engineers in the economy increased as new cohorts kept graduating from chemistry-related divisions in Imperial Universities. Figure 1 shows the number of graduates from chemistry-related divisions (Chemistry and Applied Chemistry) in Imperial Universities by graduation cohorts. Early chemistry-related graduation cohorts were small and the total number of graduates in chemistry-related fields from the only Imperial University in Tokyo was barely above 100 individuals in the mid-1890s. The second, Kyoto Imperial University was established in 1897 with the first cohort graduating in 1901, and two more Imperial Universities, Kyushu and Tohoku, were established in the 1910s to provide higher technical education. In the early 1910s, on average more than 30 individuals in chemistry and applied chemistry fields graduated from Imperial Universities each year, and right before the onset of WWI, the total cumulative number of Imperial University graduates in the chemistry-related fields stood at 620. The annual number of graduates then once again rose sharply after the onset of WWI, partly reflecting newly added universities, and partly reflecting urgent demand for chemical knowledge elites in response to the temporary import suspension detailed below. Figure A.1 in Appendix A shows the number of graduates from Applied Chemistry division in the

Figure 1: The Number of University Graduates by Graduation Cohorts



Notes: The figure shows the number of Imperial University graduates from chemistry-related divisions by graduation cohorts. Each bar represents the number of graduates from four Imperial Universities.

Engineering department and Chemistry division in the Science department separately.[10]

2.2. Japan's Chemical Industry Before World War I

As a latecomer to industrialization, Japan embarked on developing domestic chemical industry in the environment where advanced nations had already established modern factory systems in this industry. The first tangible moves to set up a modern chemical industry in Japan came from the Meiji government's industrial policy in the late 1870s. The industrial policy efforts were mostly driven by the demand from traditional sectors of the economy such as agriculture, the infrastructure-driven demand such as minting and road pavement, and the military-driven demand for explosives (Watanabe, 1968). Among the first products the Meiji government set its sights on were sulfuric acid, alkaline products (caustic soda and soda ash), bleaching powder as well as superphosphate fertilizers, which were initially produced by state-run factories. However, besides sulfuric acid and superphosphate fertilizers, the government's attempt to launch domestic production did not bear fruit. Similarly to other government-led industry promotion efforts (see, e.g., Braguinsky (2015) for the cotton spinning industry case), in part this was due to the government's inability to effectively choose appropriate production technologies (see Appendix C for more details).

[10] Kyushu Imperial University did not have a Science department until 1939. Also, Tohoku Imperial University added Applied Chemistry division to Science department in 1917, and then this division was moved to newly established Engineering department in 1919.

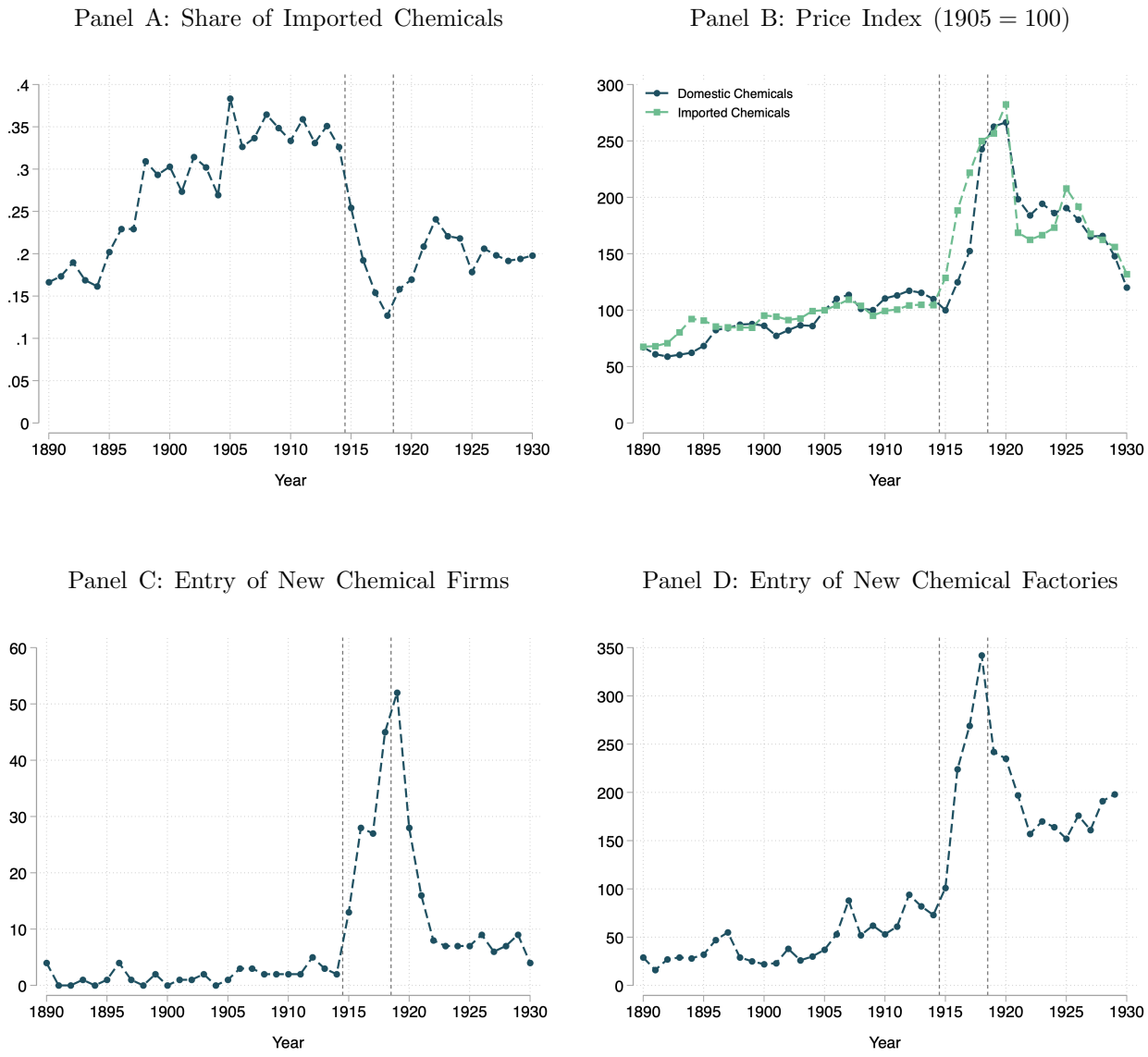
The Meiji government abandoned its industry-promotion policies in the second half of the 1880s. State-run factories, including those in the chemical industry, were privatized. As the number of university-educated human capital increased, Japan's ability to absorb and implement advanced chemical technologies gradually improved. Nevertheless, industrial production of a broad range of chemical products (with a notable exception of fertilizers) remained largely hampered. I observe in my data how some top-notch Imperial University graduates worked on new technologies on their own and started experimenting with new products already at that stage, such as potassium sulfate production started by Toragorô Tanahashi in 1898, carbide production pioneered by Tsuneichi Fujiyama in 1900, first experimental caustic soda electrolysis by Bunjirô Masujima in 1902, and so on (see Appendix C for more details). Not all those experiments were successful, however, and even in successful cases, domestically developed technologies were shunned by the market. As the demand for chemical products increased, Japan continued to import most of such products from advanced European countries. Fierce competition from foreign imported chemicals and the lack of demand for domestic chemicals did not provide enough revenue to domestic innovators, and this did not allow them to accumulate experience of efficient production.

2.3. World War I and Japan's Chemical Industry

The onset of the First World War (WWI) in late July 1914 abruptly changed the situation. Japan did not actively participate in the hostilities and the most important impact the war had on the country was through the disruption of trade flows. Imports from Europe, especially from Germany but also from Great Britain, became virtually impossible. Panel A in Figure 2 shows the sharp drop in chemical-related imports relative to Japan's (chemical) GNP during WWI, with gradual recovery after the war ended. The impact on prices was even more dramatic: as shown in Panel B in Figure 2, price indices for both domestically produced and imported chemical goods were stable during 10 years preceding the onset of WWI, but increased to about 2.7-2.8 times the pre-war level by 1921 before sharply declining in subsequent years. As can be seen from the same Figure, the increase in import prices also significantly outpaced the increase in prices for domestically produced chemical products in 1915-1918. Thus, temporary import suspension during WWI created both an acute need to develop domestic production and an opportunity for Japan's chemical industry to finally capture the market.

In response, the number of new firms entering the industry as well as the number of new establishments sharply increased (Panels C and D in Figure 2). This generated the annual growth rate of 35 percent in gross national product in the chemical industry during WWI years. Importantly, the critical need to develop domestic production also dramatically changed the environment for and attitude toward chemistry-related research which until then had been an afterthought for

Figure 2: The Impact of WWI on Chemical Imports, Prices, and Firm Entries

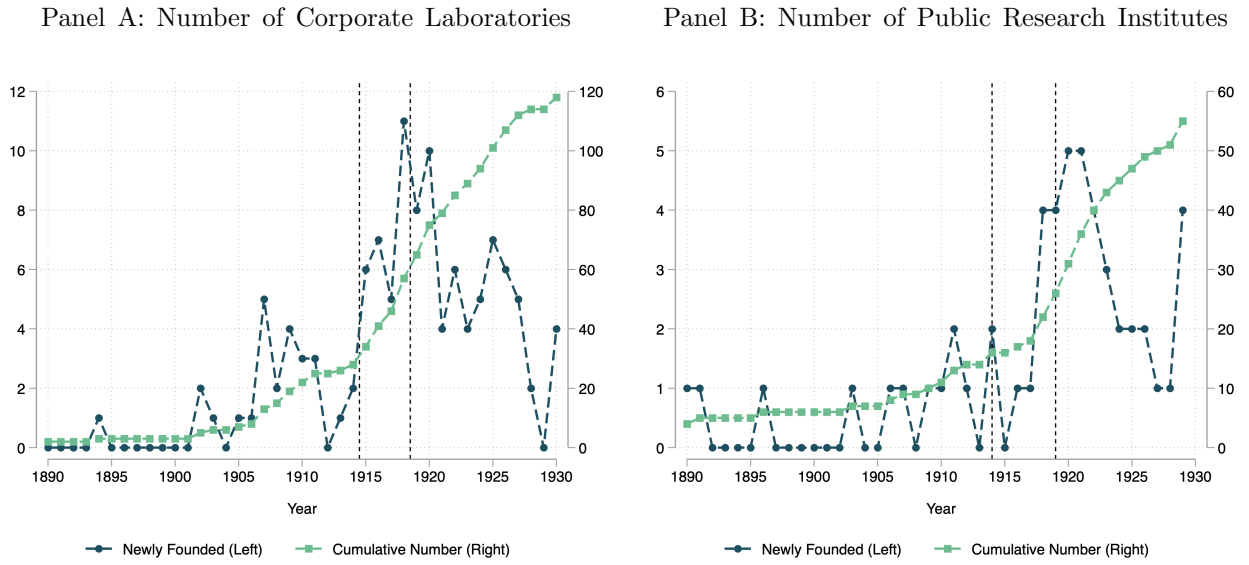


Notes: The figures present the time series of aggregate statistics in chemical industries from 1890-1930. Panel A shows the share of imported chemicals in chemical gross national product, Panel B shows the price indices of domestically produced and imported chemicals, Panel C shows the number of newly founded chemical firms, and Panel D shows the number of newly founded chemical factories.

both industry and the government.[11] Panel A in Figure 3 shows that the private corporate sector responded almost immediately: the number of corporate research labs in chemical-industry firms increased dramatically during war years. This was followed, with some time lag, by the

[11] In the already cited address to the Chemical Society of Japan in 1913, Jôkichi Takamine gave a stark warning: "Japan's industrial technologies present extremely little originality ... it is not feasible to stick with copying others forever" (Kamatani, 2006).

Figure 3: Number of Chemistry-Related Corporate Laboratories and Research Institutes by Year



Notes: The figure shows the number of newly established and cumulative number of corporate laboratories in the chemical industry (Panel A) and public (including not-for-profit and academic) research institutes which conducted chemistry-related research activities (Panel B) in each year from 1890-1930.

big increase in the number of public research institutes (Panel B in Figure 3) which included government-run, private-not-for-profit, as well as academic institutes, set up in affiliation with Imperial Universities.

The end of World War I in 1918 resulted in another crisis as the return of chemical imports led to plunging prices (Figure 2) and deep recession in the industry. As can be seen from Panel A in Figure A.2 in Appendix A, close to 100 firms (two-thirds of the cumulative new entry during WWI years, although not necessarily the same firms) exited in 1920-1924. Even major firms that made large pioneering investments in developing domestic technological capabilities (such as the two firms shown in Panel B in Figure A.2 in Appendix A) faced years of losing money, leading them to pause production, lease out production facilities to foreign capital, and so on.[12] The response, however, was not a return to the previous status quo that existed before WWI. Instead, crisis innovation gathered further momentum, now leaning heavily on the not-for-profit, public, and academic parts of the research sector.

A concerted push from academics and business leaders, directly stemming from the aforementioned Takamine's address to the Chemical Society of Japan, led to the inauguration in 1917 of

[12] The first example firm in Figure A.2, *Yura Senryo* was the first producer of synthetic dyes in Japan; the second firm, *Asahi Glass*, founded in 1907 as a glass-making firm, became the first company in Japan to produce caustic soda using the Solvay method; its soda-making division could not generate profits even during WWI, however, and suffered even larger losses after the war ended. Both firms eventually grew and survived to the present day.

the private not-for-profit Institute of Physical and Chemical Research (*Riken*) which became the largest hotbed of basic and applied research in chemistry-related fields, with dozens of industry-related patents. Specialized research institutes in chemistry were also set up at Kyoto and Tohoku Imperial Universities, giving university faculty opportunities to engage in research full time, without teaching or administrative duties (see Hiraiwa et al. (2025a)). Prompted by the realization of the importance of modern chemical industry not just for industrial development but also for military purposes, the government also moved to expand public research institutes in chemistry-related areas, such as Osaka Industrial Research Institute established in 1918, Army Scientific Research Laboratory in 1919, and Naval Technical Research Institute in 1923.

As can be seen from Panel B in Figure 3, the proliferation of public (including private-not-for-profit and academic) research institutes conducting chemistry-related research came just about the time when private industry suffered from the post-war recession and kept the domestic innovation engine revving. Most importantly, the emergence of public research institutes allowed top scientific talent to engage in basic research crucial for establishing the basis for further growth of the chemical industry.

In subsequent sections, I examine how these historical developments affected the innovation productivity of Imperial Universities'-educated scientists and engineers using granular individual-level data. I first describe the data in the next section.

3. Data

I leverage multiple sources to build a unique longitudinal database on the census of scientists and engineers in chemistry-related fields who graduated from Japan's Imperial Universities. In this section, I briefly describe the data used in this paper. Appendix B has more details.

3.1. Imperial University Graduates

First, we draw upon the annual Imperial Universities' Calendars (such as *Tokyo Teikoku Daigaku Ichiran*, 1886-1939), available in open access from the National Diet Library Digital Collections (NDL, `https://dl.ndl.go.jp/en/`). These Calendars contain information about graduation year, division, and birth prefectures of all graduates from each university. For the purpose of this paper, we digitized information on all graduates in chemistry-related divisions from Colleges of Science and Colleges of Engineering (renamed Science Departments and Engineering Departments, respectively, in 1919) from all four Imperial Universities that had those colleges (departments) from the first cohorts that graduated from the predecessors of the first Imperial University in 1877 and until 1930. The total number of individuals in this census of all University-degreed chemistry scientists and engineers from 1877-1930 is 2,462. Importantly, the data on Tokyo Imperial University graduates from the University Calendars includes additional rich information about students' academic achievement. Specifically, according to Tokyo Imperial University rules in place from its

inception and through 1918, its students in each year and graduates at the time of graduation were listed in the order of how they ranked based on academic achievement relative to peers (see Appendix B for details). Furthermore, for about 75 percent of all graduates we have information about high schools they graduated from immediately before entering the university.[13] Most of those high-school graduates (1,289 out of 1,332) were listed in their high-school calendars (also in the public domain) in the order based on their academic achievement relative to peers at the time of graduating from high schools. We use both Tokyo Imperial University graduation rankings (available until 1918) and high school graduation rankings available for almost the universe of all high-school graduates, regardless of which Imperial University they attended, as appropriate in our analyses below.

3.2. Employers and Earnings

The university graduates data above were hand-matched with the annually released lists of the Alumni Association of Imperial Universities (*Gakushikai Kaiin Shimeiroku*, 1890-1939) which start from 1890 and contain address and workplace information updated each year. We were able to match more than 90 percent of graduates in the Universities' Calendars to the alumni lists; this enabled annual updates for their employers and addresses, which resulted in an employer-employee matched dataset for the universe of Imperial University graduates in chemistry-related fields which we also verified and complemented through other sources (see Appendix B for details). We also examine employer characteristics, such as industry and ownership using various organization-level data sources. See Appendix B for more details on the disambiguation process.

To obtain individual earnings data, we relied on Japan's *Who is Who* (*Nihon Shinshiroku*), the first issue of which dates back to 1889 and which reported income taxes paid by those listed in it from 1902 onward. We used information on income tax schedules reported in the annual reports of Japan's Tax Bureau (*Shuzeikyoku Tokei Nemposho*, 1896-1933) to calculate incomes based on income tax information from *Who is Who*. Earnings data from *Who is Who* was matched with the graduates in chemistry-related fields from Imperial Universities using information on names, addresses, and workplaces. We were able to match 710 chemistry-related graduates (about 40 percent of those with employment data) to *Who is Who* in at least one year, giving us 5,211 hand-coded income tax (and income) observations in years 1902-1930.[14]

[13] Old-system high schools (*kyusei koto gakko*) were designated gateways to Imperial Universities. The students passed competitive entrance exams to enter those high schools and those who graduated from them were admitted to Imperial Universities without further entrance exams, resulting in almost all graduates from those high schools moving on to the Imperial Universities.

[14] *Nihon Shinshiroku* only reported income tax data for individuals above a certain threshold and in select geographical areas, varying from year to year. The main economic and business centers of Tokyo, Osaka, Kyoto, and Yokohama were included in all issues, however. See Appendix B.

3.3. Patents and Publications

The above individual-level data were then matched with the patent data from the Japan Patent Office starting from 1885 (the year the patent system was introduced in Japan for the first time) and until 1940 (around 126,000 patents). The data include patent numbers and titles, technology classes, inventors' and assignees' names and addresses, and application and grant dates. To obtain the data on patents with global reach, we also hand-matched the names and addresses of Japanese inventors to Google patents data with application dates prior to 1940. The details about these data and the matching process are described in Appendix B.

We also collected the data on scientific publications from two most important chemistry-related academic journals in Japan during the sample period: *Journal of the Tokyo Chemical Society* (*Tokyo Kagaku Kaishi*, 1880-1920) together with its continuation, *Journal of the Chemical Society of Japan* (*Nihon Kagaku Kaishi*, 1921-1932), and *The Journal of Chemical Industry* (*Kogyo Kagaku Zasshi* 1898-1932). The first journal tended to publish articles related to pure science, mostly by those in academia, while the second one was more about industry-related (although still basic, according to Japanese historians) research and the articles published in it include those written also by scientists and engineers working in industry and government. The data include publication numbers and titles, author's names, and publication dates. We also match the publication data with the above individual-level data as detailed in Appendix B.

3.4. Research Institutes

As mentioned, academia and research sector played a key role in building the foundation for internationally competitive chemical industry in Japan. This role appears to have become especially important during and especially post-WWI as many research institutes, both state-run and private, were established and were actively conducting chemical industry-related research during my sample period. I have investigated and created an exhaustive list of all corporate laboratories and research institutes, both private and public from several administrative survey data. These data include names and addresses as well as founding dates and main research items as of the survey periods. The total number is 391 private research labs and institutes, including private-not-for-profit institutes, and 223 public research institutes, including those affiliated with Imperial Universities. We matched these data with the above employer information. For details of the data sources and matching process, see Appendix B.

4. Import Disruption and Invention by Scientific Talent

The abrupt, large-scale WWI import disruption documented in Section 2 created the immediate and acute necessity to build the basis for a domestic chemical industry. However, unless we unconditionally subscribe to Schmookler (1966)'s story of "putty clay" supply of invention, it is the agency of human capital that largely determines whether developing and implementing the tech-

nologies demanded by the import disruption is going to be successful or not. I start this section by empirically examining individual-level inventive outputs of university educated scientists and engineers in the chemistry field around WWI. These empirical results will be presented in three groups. First, I present aggregate evidence on invention around the temporary import suspension and show that many such inventions were indeed about new technologies aimed at substituting for or finding alternatives to imports. Second, I look at individual incumbent workers at the time of WWI and how their invention output changed in response to the demand shock. Third, I provide cohort-level analyses to examine also the contribution to invention by new graduates after WWI. I conclude this section with the discussion of the implications of these empirical findings.

4.1. Do Knowledge Elites Meet Necessity during Import Disruption?

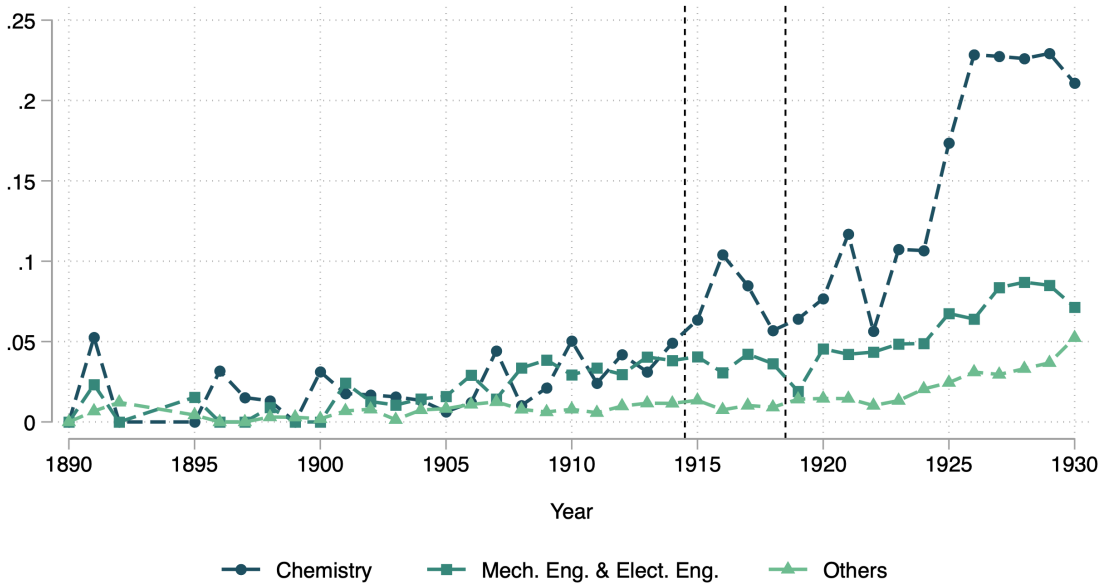
4.1.1. Aggregate Trends in Invention by Chemistry Graduates

The sudden large shift in demand for the development of substitutes for imported chemicals triggered by the onset of WWI created an acute need for domestic technologies. While inventors in early industrial revolution tended to be mostly "tinkerers" who did not necessarily rely on formal technical education (Mokyr, 1992), highly educated engineers and scientists started to play a pivotal role in generating invention since the early 20th century, and Japan was not an exception (Akcigit et al., 2017; Yamaguchi et al., 2022; Hiraiwa et al., 2025b). Table A.1 in Appendix A compares patent outcomes by university-educated inventors with those by other inventors in the universe of all Japanese inventors between 1890 and 1940. Although university-educated inventors were a relatively small fraction of the total, they tended to produce more inventions than other inventors and more impactful inventions.[15]

Figure A.3 in Appendix A shows the evolution of patenting by university-educated scientists and engineers in the chemical fields over time. Before WWI, the number of patents was less than 50 per year, but this number started to increase sharply after the onset of WWI and reached more than 400 around 1930. Some of the sharp increase in chemical invention was supported by the increased supply of university graduates in the chemistry-related fields during and after WWI, as shown in Figure 1. Importantly, however, we can observe a significant increase in patent productivity *per graduate* as the new demand for domestic products and technologies to support them emerged. I first present here aggregate visual evidence. Figure 4 depicts the number of patents per graduate by each year between 1890 and 1930, where each of the three lines represents the numbers for those who graduated from chemistry-related divisions, high-tech divisions most relevant for the Second Industrial Revolution (Mechanical and Electrical Engineering), and all other divisions, respectively. The sample is limited in this Figure to graduates up to the 1920 graduating cohort because we only have the data on graduates from non-chemistry divisions up to the 1920 cohort. Before the onset of WWI, even patents per graduate per year from high-

[15] This tendency is more pronounced among chemical-related patents compared with the results in Yamaguchi et al. (2022) which cover the universe of patents in all areas.

Figure 4: Number of Patents per Graduate by Years



Notes: The figure shows the average number of patents per graduate up to the 1920 cohort in each year from 1890-1930. Each line represents the time series of per graduate patents from chemistry-related divisions, other high-tech divisions (Mechanical Engineering and Electrical Engineering), and all other divisions, respectively.

tech divisions were less than 0.05 on average, with no significant difference between chemistry and other high-tech fields. The number of patents per graduate per year for chemistry-related divisions sharply increased after 1914, however, and reached around 0.23 after 1925. It is worth emphasizing that we observe the divergence in the trend of patents per graduate for chemistry-related fields even compared with patenting by those from other high-tech divisions already during WWI and continuing after the war ended. Hence, although in a naive way, this graph most unequivocally demonstrates the impact of the necessity shock: sudden onset of the demand for chemical invention to support the domestic industry clearly elevated patent output by university graduates; moreover, this effect was not limited to the short-term but persisted in the long run.

4.1.2. Contents of Chemistry-Related Inventions during WWI

The WWI boost to patenting by university-educated chemists shown in Figure 4 is suggestive of the role played by import suspension but by itself does not establish that relationship. To verify this link, I examined the contents of patents applied for by Imperial University-educated chemists during WWI, between 1914 and 1918. The total count of such patents is 227, filed by 104 inventors in our sample. I extract them and trace their role in chemistry-related technological development. It appears that patents by educated chemists during this period can be classified into two major types.

Import substitution. The first type is the development of technological processes to directly replace imports that became scarce or altogether unavailable at the onset of WWI. This pattern is also documented in Juhász (2018), which shows that temporary import suspension encouraged technology adoption when countries fell behind technologically. Two examples of such patents on technologies targeting two of the products most affected by the onset of WWI (synthetic dyes and caustic soda) are the patents by Jinkichi Inoue, "the leading light" in Japan's dye industry from its inception (Shibata, 1961), and by Kamejirô Yoshikawa and Michiwake Kadota, professor at Kyoto Imperial University and his former student (for these and other patents, see Table D.1 in Appendix D for details). Inoue's patent was for a process used in the production of azo dyes Japan could no longer import, while Yoshikawa and Kadota's patent was for an electrolytic process to produce caustic soda. The latter patent was immediately commercialized by a private company founded in 1915, Osaka Soda Inc. which still survives until the present day as a diversified chemical company (https://www.osaka-soda.co.jp/en/company/history.html). Another patent in this category listed in Table D.1 was filed in 1915 by Toragorô Tanahashi, 1893 graduate from Tokyo Imperial University College of Engineering, who founded what is currently Nippon Chemical Industrial corporation in 1893 (https://www.nippon-chem.co.jp/en/company/outline/). The invention established a method of manufacturing chlorate salts used, in particular, in the production of matches, as a result of which Japan's match industry (already a major industry in Japan at the time but still dependent on imported input components) could continue production without interruption (Commission for Editing the Handbook of Chemical Patents, 1970). Also, a patent by Masataka Ogawa, 1889 graduate of Tokyo Imperial University College of Science and a professor at Tohoku Imperial University at the time, was for inventing a process to manufacture bromine which had been German monopoly until WWI. See Appendix D for details.

Import alternative. The second type are patents for technologies that targeted developing domestic alternatives to products imports of which became suspended, including alternative input technologies. This pattern resonates with the findings in Alfaro et al. (2025), who examine a recent case where China restricted exports of rare earths. For example, the process for hardening fish oil into solid fat by Mitsumaru Tsujimoto, 1901 Tokyo Imperial University College of Engineering graduate (see Table D.1), applied the process of catalytic hydrogenation of oils developed in Germany (which Tsujimoto had studied throughout his career — see Tsujimoto (1911)) to fish oil which Japan had an abundant supply of. This led to the first output in Japan of hydrogenated oil used in the production of soap and glycerin (imports of both these products dropped sharply during WWI) by private firms Suzuki Shoten and Dalian Yushi Kogyo already in 1916 (Nihon Kagaku Kai, 1978). The second patent in this category listed in Table D.1, by Tsuneya Marusawa, 1907 graduate from Tokyo Imperial University College of Engineering and professor at Kyushu Imperial University at the time, is on a new chemical process of wood cooking to produce pulp for the paper industry. The import substitution motivation guiding Marusawa's research can be

mostly clearly seen in the article he published in 1910 (four years before the onset of WWI and six years before he filed for this patent) — (Marusawa and Mori, 1910). In this article, Marusawa and his coauthor sound alarm about the high cost of using imported caustic soda for soda pulping and propose sulfite process instead, applied to domestically abundant rice-straw raw material. While the 1916 patent does not explicitly mention replacing the soda process (the patented technology is about a specific reagent already within the sulfite process), it clearly builds on this line of research and it is easy to see that WWI suspension of caustic soda import affected the timing of the new technology development.

Naturally, not all the technologies tried by educated chemists during WWI were successful. Another patent by Jinkichi Inoue (who also patented import-substituting azo dye-producing component mentioned in the previous paragraph) claimed the development of a new method to produce, at industrial scale, a dye intermediary which the Germans could previously only produce in "trace" amounts. I could not verify, however, that this process was ever implemented in Japan's dye industry. Also, Sadakichi Satô, 1912 graduate from Tokyo Imperial University College of Engineering, filed 20 patents during WWI (one of which is summarized in Table D.1), all of them on "Satolite" technologies (named after his last name), aimed at developing alternatives to chemical products such as celluloid, bakelite, and synthetic rubbers using protein obtained from soy beans. Satō, who was hired as a professor at Tohoku Imperial University in 1914, secured funding for his research from Sankyo Corporation, whose co-founder, Jôkichi Takamine, was also a co-inventor on two of his WWI patents (Kamatani, 2006). With the help from Sankyo Corporation, he established his own company which he named "Satolite" in 1916. The technology proved to be flawed, however, and the firm was forced to stop production in 1919 while Satō resigned from his professorial position. He did stay as a lecturer at Tohoku Imperial University, however. More importantly, the Temporary Institute of Physical and Chemical Research, which was established at this university initially to support his research, survived the demise of "Satolite" and grew into a premier research institute called "Institute of Material Research" with a much broader research agenda in the 1920s (Kamatani, 2006). We will discuss such consequences in Section 5.[16]

Overall, we can clearly see a boost in patent applications by educated scientists and engineers in chemistry-related areas during WWI, many of those driven by the acute need to develop new domestic technologies against the background of import suspension. The question remains, however, who exactly was responsible for the long-term increase in patent productivity in those fields. Theoretically, such increase could come either from incumbent scientists and engineers or from new cohorts of university graduates. As noted in Section 2, a considerable number of highly ed-

[16] It should also be mentioned that some patents filed during WWI do not appear to be driven by import suspension. One prominent example are several patents filed by Kikunae Ikeda, an 1889 graduate of Tokyo Imperial University College of Science, on glutamic acid-related products. While Ikeda actually made his discovery in 1908, the patents and the commercialization which marked the beginning of currently world-famous "umami" had to wait until the WWI-driven new entry boom into the industry, so even in this case we can see the impact of WWI, although not related to import suspension.

ucated chemists had already worked in the economy by the onset of WWI. Such pre-war accumulation of educated talent in chemistry fields could be one of the crucial factors behind the successful takeoff of chemical invention after the onset of WWI. That said, not all those highly educated scientists and engineers may have had inventive potential — one may conjecture that only those who were close to frontier scientific knowledge could respond to the urgent demand for new technologies. Indeed, this is what the examples discussed immediately above seem to suggest. Alternatively, new generations of university graduates who absorbed more up-to-date knowledge relevant to the development of new technologies could account for increased invention output, especially for the long-term trend, in which case the locus of invention would shift toward younger cohorts. Using individual-level data, I next dig into this more systematically and then discuss the implications of my empirical findings.

4.2. Pre-war Accumulation of Incumbent Talent and "Activation Effect"

I first examine how the WWI import suspension shock affected patenting by incumbent workers who had already graduated from Imperial Universities before 1915. As noted above, the primary questions are whether pre-war accumulation of higher chemistry knowledge was relevant for meeting acute demand for domestic technologies in response to the import suspension and whether it also led to the long-term boost in invention even after the end of the war. To evaluate the impact of temporary import suspension during and after the war time on future patenting activity by those graduates, I adopt a difference-in-differences design on the individual panel of graduates from all divisions up to the 1914 graduation cohort. The dependent variable is the number of patent applications per year. Then, I estimate the following specification:

$$y_{it} = \beta_1 \times \text{WWI}_t \times \text{Chem}_i + \beta_2 \times \text{PostWWI}_t \times \text{Chem}_i + d_i + d_t + \varepsilon_{it},$$

where y_{it} is the number of patent applications by graduate i in year t, Chem_i is an indicator variable for graduates from the chemistry-related divisions, WWI_t is an indicator variable for periods between 1915 and 1919, PostWWI_t is an indicator variable for periods 1920 onward, and d_i and d_t are individual and year fixed effects, respectively. The coefficient β_1 and β_2 measure how much incumbent workers who graduated from chemistry-related divisions increased their patenting during the war-time temporary import suspension periods and after the end of the war, respectively, under the identifying assumption that graduates from different divisions would have followed parallel patenting trends. This may not be satisfied in all divisions, but we could expect that high-tech divisions related to the Second Industrial Revolution technologies, such as Mechanical Engineering and Electrical Engineering, would provide reasonable control groups and counterfactual patenting trends for the chemistry-related divisions. In fact before the war, the number of patents per graduate from chemistry-related divisions followed the trajectory similar to trajectories in other divisions, including those from high-tech divisions.

Table 1: Individual Patent Productivity: Difference-in-Differences Estimates

	(1) All	(2) Only High-Tech	(3) No Publications	(4) With Publications
WWI × Chem	0.0348***	0.0277**	-0.0006	0.0664***
	(0.0107)	(0.0132)	(0.0113)	(0.0231)
PostWWI × Chem	0.0700***	0.0571***	0.0109	0.1354***
	(0.0153)	(0.0132)	(0.0166)	(0.0376)
Mean of DV	0.0271	0.0484	0.0397	0.0484
Year FEs	Yes	Yes	Yes	Yes
Individual FEs	Yes	Yes	Yes	Yes
Adj R-Squared	0.150	0.154	0.139	0.163
Observations	124,904	50,437	45,394	40,750

Notes: The table reports the estimated coefficients from the static difference-in-differences specification. Column (1) includes those from all divisions in the estimation sample. Column (2) restricts the sample to only those from chemistry-related divisions and other high-tech divisions (Mechanical Engineering and Electrical Engineering). Column (3) (Column (4)) define the treated groups as graduates from chemistry-related divisions who did not (did) have publications in top field journals prior to 1915 and use all graduates from other high-tech divisions as control groups. Standard errors are clustered by individuals and reported in parentheses. Stars indicate significance levels: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

The coefficient estimates from the above specification are displayed in Table 1. Column (1) presents the results with the sample of those from all divisions as the control group. It shows that graduates from chemistry-related divisions became more than twice as productive in terms of patenting as the average patenting rate during the war-time import suspension periods. Moreover, they showed the long-term increase in patenting after the end of WWI, and the size of this long-term effect was double that of the short-term effect. Column (2) restricts the sample to only those from high-tech divisions (Chemistry, Mechanical Engineering, and Electrical Engineering). This is designed to address the possible concern that increases in patents by chemistry graduates were driven by general trends of the Second Industrial Revolution or progress in science. As can be seen from the coefficient estimate in Column (2), even though graduates from high-tech divisions tended to have way more patents than graduates from other divisions on average, chemistry graduates were still more than 50 percent more productive than those from other high-tech divisions during the war time, and the long-term effect after the end of the war was still double that of the short-term effect. Overall, this evidence suggests that the war-time import suspension "activated" the pre-war accumulation of incumbent chemistry knowledge elites.

4.2.1. The Role of Embodied Scientific Human Capital

While the above evidence shows that chemistry graduates finally could harness their inventive potential after the onset of WWI and show the long-term invention boost, further examination reveals sharp heterogeneity within the sample of chemistry graduates. In Columns (3) and (4) in Table 1, I keep using non-chemistry high-tech divisions as control groups, while splitting chemistry graduates into two subgroups. The first group, in Column (3) are chemistry graduates who did not publish any scientific papers in the top two chemistry-related field journals prior to 1915. The coefficient estimate on the interaction of the WWI dummy and these chemistry-related graduates shows an almost null effect, and the long-term impact is also both economically and statistically not significant. Thus, those graduates who had not produced "science" before WWI did not (could not) produce industry-relevant patents after the onset of WWI either.

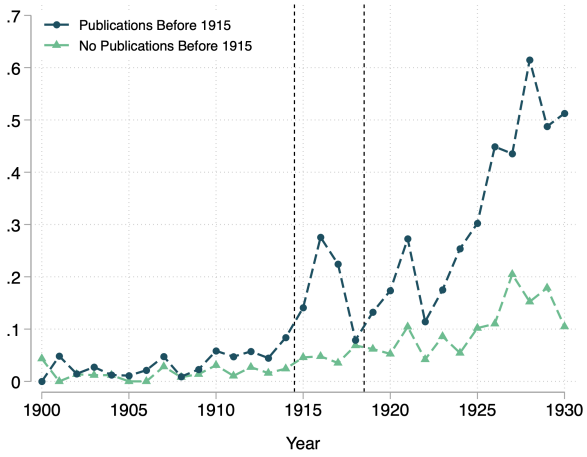
In contrast, the coefficient on the same interaction term estimated on the subsample of chemistry graduates who had published at least once (and many of them multiple times) in top scientific field journals *before* the onset of the import suspension is more than twice the magnitude of the coefficient in Column (2) and indicates 2.4 times higher patent productivity of those graduates compared to the average patenting rate in the sample during war time. Also, the long-term effect was almost four times higher than the average patenting rate. Hence, we observe the "activation effect" only for those graduates in chemistry-related fields who had been engaged in scientific research leading to journal publications long before (some of them from more than 10-15 years before) the necessity shock. In other words, this and only this part of highly educated human capital appears to have accumulated *embodied scientific* human capital that just could not translate into patents (commercialized innovation) without the right environment.[17] Once crisis innovation happened, it was this part of highly educated human capital that could respond to it immediately. I will examine this further in the context of the organizational innovation that created corporate and public R&D system in Japan's chemical sector in Section 5 below.

In Figure 5, I present the dynamic patenting response by chemistry graduates. In Panel A, I plot the aggregate time series of patenting by chemistry graduates who had and had not published at least once in top chemistry field journals before the onset of WWI. In Panel B, I present the dynamic event study versions of the empirical specifications in Columns (3) and (4) in Table 1 for each group using non-chemistry high-tech divisions as control groups. Formally, I estimate the following dynamic difference-in-differences specification:

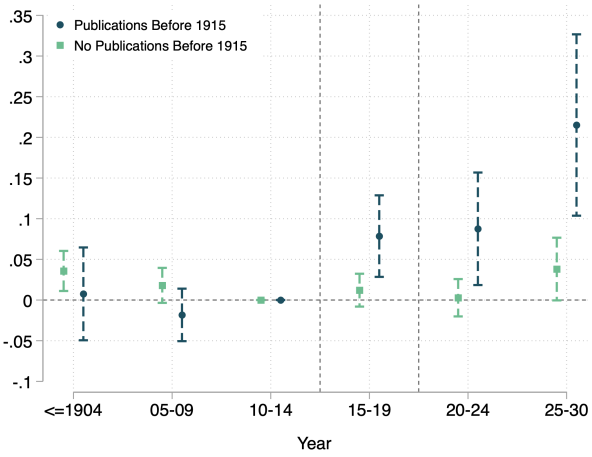
[17] In his 1911 Presidential address to the Chemical Society of Japan, Toyokichi Takamatsu, himself a prominent chemist, lamented that while "members [of the Chemical Society] create business plans based on successfully developing new production technologies using domestic inputs or make improvements to existing technologies, the resulting journal publications ... do not get attention from industrialists, giving no chance to explain them, and as a result, cannot be implemented in industry, which is a deeply regrettable situation" ((Takamatsu, 1911, p. 420-421), translated from the Japanese by the author).

Figure 5: Individual Patent Productivity: Dynamic Patenting Response

Panel A: Patenting by Publication Record



Panel B: Event Study by Publication Record



Notes: The figure shows the estimated event study coefficients from the dynamic difference-in-differences specification. The control groups consist of graduates from other non-chemistry high-tech divisions (Mechanical Engineering and Electrical Engineering). Panel A plots the average effects for graduates from chemistry-related divisions. Panel B defines the treated groups as graduates from chemistry-related divisions who did and did not have publications in top field journals prior to 1915, respectively. Standard errors for the confidence intervals are clustered by individuals.

$$y_{it} = \sum_{k} \left(\beta_k \times \mathbb{1}\{t = k\} \times \text{Chem}_i\right) + d_i + d_t + \varepsilon_{it},$$

where $\mathbb{1}\{t = k\}$ is an indicator variable for each five-year bin. We do not see the pre-trends before WWI. Consistent with the static specifications, only those with pre-war journal publication records showed a significant increase in patenting during WWI and a persistent shift of patent productivity even after the end of WWI. Figure A.4 in Appendix A also estimates the annual event study coefficients and shows very similar results.

4.2.2. Qualitative Validation and Other Heterogeneous Effects

How exactly did pre-WWI scientific publications translate into inventive activity during WWI? To answer this question, I read the articles published before WWI by future WWI inventors. In some cases, WWI patents clearly grew out of the pre-war research reflected in publications. For example, as mentioned, the patent for Marusawa-type cooking method for paper-pulp stock was a clear outgrowth of his research into sulfite pulping as an alternative to import-dependent caustic soda pulping (see Marusawa and Mori (1910) already cited when discussing this patent above). Similarly, before he applied for his first two patents on the catalytic process of hardening fish oil during WWI (see Table D.1), Mitsumaru Tsujimoto published 26 papers in 1902-1913 in

one of the top two chemistry-field journals, *Kogyo Kagaku Zasshi*, 12 of which were on the subject of fatty acids in fish oil. Such direct relationship between scientific publications and future WWI patents, however, was far from universal and, indeed, appears to apply to only a minority of cases. To a large degree, scientific contents of published papers appear to be much broader or even unrelated to the content of subsequent patents.[18] For example, Sadakichi Satô (he of 20 patents during WWI, one of which is presented in Table D.1) published a paper in *Kogyo Kagaku Zasshi* in 1912 on the technology of producing dyes from the skin of wax myrtle (Japanese bayberry) fruit. As Satō himself later recalled (Satô, 1919), even though it was before the war, he was driven by the desire to find an alternative to aniline dyes Japan imported from Germany, spending up to 20 million yen annually on those imports alone (*ibid.*, p. 54). Unfortunately, the production turned out to be economically unfeasible so that, as he somewhat self-deprecatingly noted, the only tangible outcome of that research was a scientific article (*ibid.*). Also, Kamejirô Yoshikawa, who developed a critically important import-substituting technology to produce caustic soda (see Table D.1) had two publications in 1898 and 1900 but neither of those directly anticipated the patent. All in all, my reading suggests that, in the majority of cases, when responding to new acute need for domestic technologies during WWI, accomplished scientists and engineers drew on the totality of their accumulated scientific human capital, not necessarily just on the specific pre-war research agendas.

The above findings demonstrate that it was those with accumulated embodied scientific human capital who could help during the sudden import disruption. However, the question remains whether it was actually embodied scientific knowledge or other individual characteristics correlated with the publication record that mattered for invention during and after WWI. Table A.2 in Appendix A shows that those with pre-war top journal publications tended to have higher academic rankings and were also more likely to have earned doctoral degrees. While these statuses seemed to be prerequisites for scientific publications and highly correlated with the publication record, I can exploit some heterogeneous variations in these statuses to look at the importance of embodied scientific human capital itself.

Specifically, I first estimate static difference-in-differences specifications, using non-chemistry high-tech divisions as control groups, by splitting chemistry graduates into four subgroups based on whether they had published in top scientific field journals before the onset of WWI and whether their high-school graduation rankings were below or above the median. Panel A in Table A.3 in Appendix A reports the coefficient estimates for each group. If we look at chemistry graduates with above-the-median high-school graduation rankings, only those with publications before WWI showed increases in patenting during the war, and they showed more increases in patenting even after the end of the war. At the same time, those with below-the-median high-school rankings also showed significant increases in patenting during and after the war if (and only if) they had

[18] Patent applications in Japan at that time did not customarily cite either prior art or related scientific publications, so we do not have direct information about this relationship and have to infer it from reading and comparing the texts.

published before the war. Panel B in Table A.3 in Appendix A replaces high-school graduation rankings status with doctoral degree, and the results are similar except for Column (3), showing that those with publications but without doctoral degree were not more likely than the control group to increase patenting. Overall, these results suggest that accumulated embodied scientific knowledge was still a key factor even if taking account of other measures of academic ability.[19]

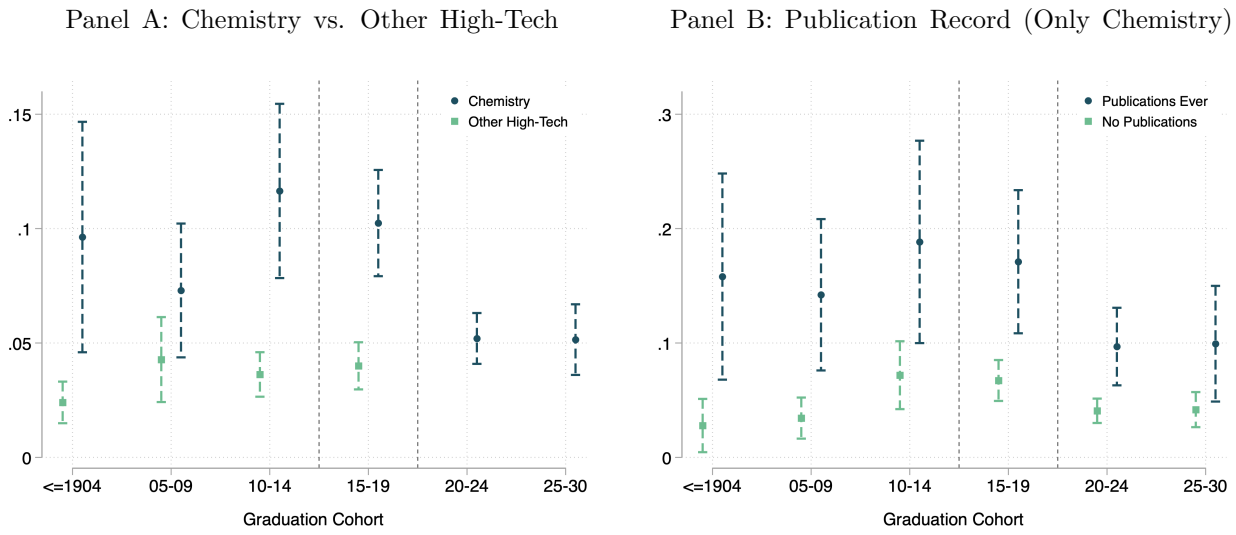
Taken together, the results so far suggest that the WWI demand for chemical knowledge shaped the trajectories of invention by incumbent workers. Those graduates had already absorbed higher technical knowledge in chemistry fields, including those related to imported chemicals, by the time of WWI, and such knowledge actually helped during the sudden import disruption period. Importantly, however, graduates with demonstrated embodied scientific knowledge, as manifested in top field journal publications, mainly drove invention during the import disruption periods, while graduates without such publications experienced no such boost in invention. Furthermore, we observed the long-term effects beyond the war time: the import disruption "activated" the dormant human capital of incumbent workers with embodied scientific knowledge in the long run. I will examine more details of the nature of such long-term effects in Section 5.

4.3. Do New Cohorts Contribute More to Post-war Invention?

Another potential explanation behind the long-term increase in patent productivity by chemistry graduates is that new generations could absorb more knowledge relevant to the development of new technologies in response to WWI, and then the locus of invention would shift toward younger cohorts. To investigate this, I examine patent productivity differences across graduation cohorts. Panel A in Figure 6 compares the post-WWI patent productivity (average number of patents per year after 1915) of those from chemistry-related and other high-tech divisions, respectively, by university graduation cohorts (by five-year bins). For non-chemistry divisions, I do not have data on those who graduated after 1920, so the comparison between divisions can be made up to that point. Post-WWI patent productivity was consistently higher for chemistry graduates, but this was more pronounced for earlier cohorts, rather than later cohorts. This should be interpreted carefully, however, because the difference could also reflect age or experience effects, so that later cohorts would mechanically exhibit lower patenting rates given the fixed time window of my sample periods. Nevertheless, it is clear that the post-WWI rise of patent productivity of chemistry graduates was not specifically biased toward new graduates after the onset of WWI and that incumbent workers, as already noted above, also became more productive, especially those who graduated right before the onset of WWI, relative to those from other high-tech divisions. We also see the cohorts that graduated during the war (between 1915-1919) also had higher patent productivity, so long-term effects on patenting manifested themselves for all pre- and during-WWI

[19] I also conducted the same analysis using university graduation rankings as a proxy for academic ability and found very similar results. However, university graduation rankings are only available for a subsample of graduates from Tokyo Imperial University up to 1918. More details on these results are available upon request.

Figure 6: Post-WWI Individual Patent Productivity by Graduation Cohorts



Notes: The figure shows post-WWI individual patent productivity (average number of patents per year after 1915) by each five-year graduation cohort bin from 1900-1930. In Panel A, the dark green plots represent the post-war patent productivity by graduates from chemistry-related divisions, and the light green plots represent the post-war patent productivity by those from other high-tech divisions (Mechanical Engineering and Electrical Engineering). In Panel B, the dark green plots represent the post-war patent productivity by chemistry graduates with publications before 1915, and the light green plots represent the post-war patent productivity by chemistry graduates without publications before 1915. Standard errors for the confidence intervals are clustered by individuals.

cohorts.

Panel B in Figure 6 looks at the post-WWI patent productivity differences within chemistry-related divisions, dividing the sample into graduates who had published in top chemistry-related journals and those who had no publications. Consistent with the results in Section 4.2.1, those with top journal publications produced more patents, but this was also more pronounced for those who graduated before and during WWI. The importance of embodied scientific knowledge, however, was also pronounced even among later cohorts, which contributed to the long-term increase in invention. I will revisit this in more detail in Section 5.

Overall, the evidence suggests that while university graduates from all cohorts, earlier and later, reasonably contributed to the rise of invention after the onset of WWI, it does not appear to be the case that younger generations disproportionally contributed to this trend.

4.4. Summary and Discussion

In this section, I have documented the following three main facts. First, chemical invention by university educated scientists and engineers, not just the total amount, but also invention per individual, significantly increased in response to the temporary import suspension during WWI;

moreover, this effect was persistent. Second, such chemical invention was generated not just by new generations of educated talent, but also (or even primarily) by the graduates who had already been working in the economy with technical knowledge acquired before the onset of WWI. Third, such necessity-driven increases in chemical invention were mostly produced by graduates with demonstrated embodied scientific knowledge as manifested in their pre-war publication record.

At first glance, the first fact above is consistent with the theory of directed technical change (Acemoglu, 2002; Hanlon, 2015; Davis et al., 2026), which implies that demand-pull forces are crucial for the direction and amount of invention, and the import-substitution infant industry argument (Juhász, 2018). However, my context and individual-level analyses provide deeper insights into the underlying phenomena. While Japan had already established higher chemical education even before WWI, those who obtained such education did not generate many inventions. However, those same individuals started to harness their research potential when chemical imports from Europe were disrupted. We know from extant studies that highly educated scientists and engineers play a key role in invention and technological progress (Akcigit et al., 2017; Maloney and Caicedo, 2022), but my analyses show that most of their inventive potential would remain dormant until activated by the directed demand for technologies. The second fact in the above summary corroborates this, consistent also with Jôkichi Takamine's insight expressed in his address to the Chemical Society of Japan in 1913 in the epigraph to this paper. The key difference with the extant literature (e.g., Moser et al. (2014) who find that German Jewish emigres' arrival increased patenting by new but not incumbent researchers) is that they examined the technology-push case while my case is that of demand-pull where dormant incumbent human capital needed effective demand to harness their potential. The third fact is of first-order importance. It shows that even among highly educated scientists and engineers, only those who had accumulated an embodied stock of scientific knowledge (observed in publications in scientific journals) were capable of generating a significant immediate response to increased demand from import suspension. In other words, it is not enough just to obtain higher education (Akcigit et al., 2025), but it is really important to utilize this education, even before any invention, in a way that develops the individual's scientific capacity.[20] My findings also imply that high scientific potential can adapt to changing demand so that harnessing the dormant inventive potential of top scientists could be the best strategy when an effective response is required to acute demand for new technologies.

5. Invention in Longer Run and Emergence of the Research Sector

Despite the fact that the WWI chemical import disruption was inherently temporary, the results in the previous section indicate that its effects not only persisted but compounded for years af-

[20] The first Japanese Nobel Laureate in chemistry, Kenichi Fukui (not in our sample as he graduated from Kyoto Imperial University only in 1941) recalled the first advice he received from his mentor, Gen-itsu Kita (who is in our sample): 'You must study basic science if you want to do excellent applied chemistry' (Buckingham and Nakatsuji (2001), p.227). Hiraiwa et al. (2025b) show in a more general context that the degree of absorption of academic knowledge, rather than just a higher technical degree, is important for future invention outcomes.

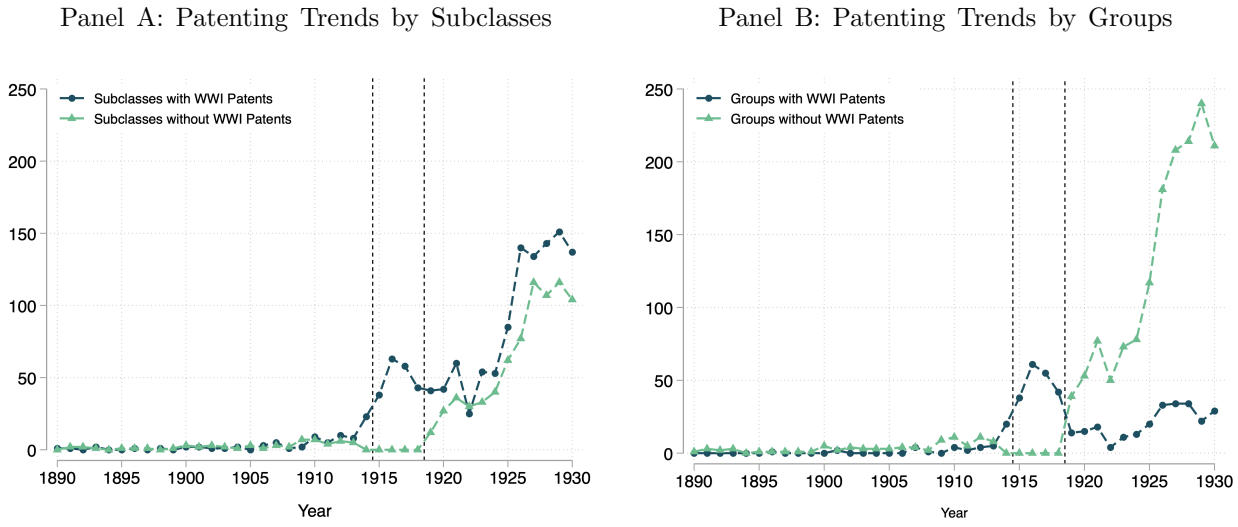
ter the end of the war (and the corresponding import disruption). A natural question is why: how exactly did the necessity demand during WWI lead to substantial long-lasting increases in individual-level inventive productivity? To understand the mechanisms of such persistence, in Section 5.1 I start by examining whether the direction of necessity-driven invention stayed the same or changed after the end of WWI. I then introduce the key new factor that affected the direction of post-WWI innovation and gave it a major boost — the emergence of an organized R&D system. As shown in Section 2.3, the WWI import suspension induced an important structural change: the emergence of corporate laboratories and public research organizations. New technologies are developed by individual scientists and engineers, but ultimately, even those with proven academic record need to be provided with sufficient complementary assets to support research activities. Also, enough top-notch human capital needs to select (and be selected) to work in research. In Section 5.2, I examine how the emergence of corporate laboratories and public research organizations changed aggregate allocation of knowledge elites. In Section 5.3 I bring together the analysis of individual-level accumulated embodied scientific knowledge and the reallocation of talent to organized research, and examine their roles independently and in interaction. I conclude this section with a discussion of these empirical findings.

5.1. Was Long-term Invention Direct Continuation of Import Substitution?

I first examine how closely invention by chemistry graduates after the end of WWI was related to technological areas that experienced the boost in patenting during the WWI import suspension period. Figure 7 shows the trends in patenting by chemistry graduates over time, split by technology categories where chemistry graduates had at least one patent between 1914 and 1918 and those where they did not. By definition, the latter group has zero patents during the war in the figures. I use two levels of historical Japanese patent classification in my data corresponding to a four-digit "subclass" and four-digit-plus "group" in the modern International Patent Classification (IPC, `https://www.wipo.int/en/web/classification-ipc`), respectively, to measure the relationship between patents filed during and after the war by the graduates in the sample.[21] Using the four-digit subclass patent classification (Panel A in Figure 7), technology subclasses which had at least one patent by chemistry graduates during WWI show persistent increases in patenting after the end of the war. Importantly, however, subclasses that had no patents during the war also took off shortly after 1919 at almost the same rate as the WWI patents. Furthermore, looking at a more detailed, group classification (Panel B in Figure 7), it can be seen that while there is some persistence in the trajectory of technology groups that spiked during WWI, it was other groups, with no patents during the war that skyrocketed after the war ended. Together,

[21] The Japanese Patent Office had its own patent classification at the time, and each patent in my data is assigned three levels of classification, "*rui*," "*dai-bunrui-meisho*," and "*sho-bunrui-meisho*." The "*rui*" category maps into a three-digit class in the IPC classification, "*dai-bunrui-meisho*" maps into a four-digit subclass, and "*sho-bunrui-meisho*," into four-digit-plus group in the IPC classification (Hatsumei Kyokai, 1963). I therefore refer to "*dai-bunrui-meisho*" as patent subclass and to "*sho-bunrui-meisho*" as patent group.

Figure 7: Evolution of Chemical Patents by University Graduates by WWI Patent Classification



Notes: The figure shows the trends of chemical-related patents by Imperial University graduates from 1890 to 1930, split by technology categories where graduates had at least one patent between 1914 and 1918 and those where they did not. Panels A-B (Panels C-D) use patent subclasses (groups) to define technologies where graduates had at least one patent between 1914 and 1918.

these two findings imply that while chemical technologies grew broadly in the same direction after the war, it was not necessarily the same narrowly-defined technology areas as those patented during the war that evolved and grew after the war.

I also examined whether there were tangible differences between incumbent workers and new cohorts in terms of the trends in technology subclasses and groups in which they patented. In Figure A.5 in Appendix A, I split the patenting trends per graduate into those who graduated before and after WWI and, apart from the afore-mentioned higher patent productivity of earlier graduates, found little, if any difference in the trends in patent subclasses and groups between these two categories of graduates. In other words the patenting trajectories seen in Figure 7 are observed for both incumbents and new graduates.

In Table A.4 I also present the results from estimating trends in patenting in different technology areas during and after WWI among those who contributed to the WWI invention — those who had published in top chemistry field journals before the war (Panel A) and those who had patents during the war (Panel B). The regression results indicate that while in both cases, graduates showed a persistent increase in inventive outputs in post-WWI periods, as we already saw in Section 4, they tended to have more patents even in technology areas where no chemistry graduates filed patents during war time. Overall, the evidence goes against the interpretation that post-war increase in patents was simply a direct continuation of WWI-related invention.

5.2. Emergent and Long-lived Research Systems

The examination in the previous section indicates that even though the WWI temporary import suspension triggered the takeoff of chemical innovation, the evidence does not necessarily support the notion that long-term impacts can be attributed to narrowly-defined technological developments directly related to import substitution. Instead, and similar to Gross and Sampat (2025), the mechanisms behind the long-term impacts appear to be related to long-lived research assets, which were a target or byproduct of R&D on the specific WWI import substitution efforts: the emergence of corporate laboratories and public research institutions. Figure 3 above shows that both types of research organizations significantly increased during WWI and right after the end of WWI, and researchers could continue using or building upon such research-oriented organizations even after the war ended. In this section I address the role played by the emergence of such an organized research sector in transforming the short-term WWI import suspension shock into a long-term increase in invention by top educated chemists.

5.2.1. Sorting into Research

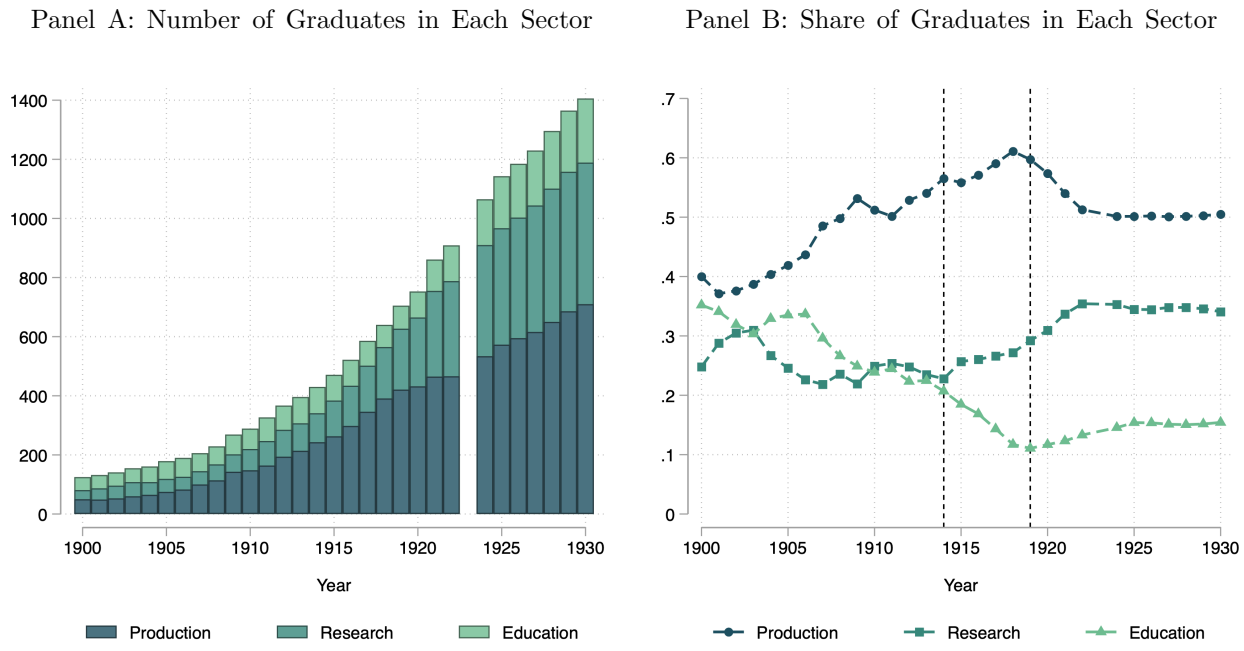
An important derivative question that needs to be addressed to support the storyline about the role of the emergence of research organizations is whether enough top-notch human capital selects (and is selected) to work in the newly emergent research system. I first look at the aggregate trend of the allocation of university-educated graduates at the broadly defined sector level. For convenience, I define three sectoral categories: production, research, and education. The production sector is defined as private industrial firms or government-owned production facilities related to chemical production, such as minting, explosives, etc. I also include military and other government non-research institutions in this category. The research sector is defined as corporate laboratories or research-focused institutes, both private and public. I include Imperial Universities in the research sector, even though they had an aspect of education institutions, since much research at that time had been conducted in universities too.[22] Finally, the education sector includes any other education institutions other than universities, such as technical colleges, high schools, junior high schools, military/navy schools, and so on.

Panels A and B in Figure 8 show the aggregate trends in the numbers and shares of university-educated scientists and engineers in each sector, respectively.[23] Although not shown in the figure, in the 1890s, when the number of graduates was still small, the majority worked in the education sector. The number and share of graduates who worked in the production sector became larger than in education already around the early 1900s and started increasing further right after 1905, as the number of private chemical companies increased and the number of graduates in

[22] The empirical results are robust to excluding universities from the definition of the research sector.

[23] I also examined sectoral allocation of graduates from the Engineering and Science departments separately in Figure A.7 in Appendix A. The majority of graduates from the Engineering department worked in the production sector, while graduates from the Science department tended to work in the research and education sectors.

Figure 8: The Allocation of University Graduates Across Sectors by Year



Notes: The figure shows the number and share of Imperial University graduates from chemistry-related divisions in each sector by year. Each bar and line represent the number and share of graduates in the production, research, and education sector, respectively.

the chemistry fields also expanded, while the share of graduates in the education sector consistently decreased over time. The share of graduates in the research sector, on the other hand, was relatively stable at around 25 percent before the onset of WWI.[24]

The temporary import suspension during war time changed the pattern of sectoral allocation of talent both in the short run and in the long run. First, both the number and share of graduates in the research sector started to increase right after the onset of WWI. Not surprisingly, this coincided with the emergence of many corporate laboratories and public research organizations during and after WWI, as documented in Section 2.3. Before 1914, there were few organizations that enabled university graduates to engage in research activities in a well-organized environment (one notable exception was Tokyo Industrial Research Institute founded by the government in 1900). As organizational innovation toward establishing a research system emerged, the research sector increased its hiring of university-educated graduates. At the same time, more graduates, incumbents and new graduates alike, started finding a well-organized research environment attractive. It is important that the trend of reallocation into the research sector did not end with the end

[24] The increase in the share in the research sector around early 1900s was related to new employment at newly established Kyoto Imperial University. Also, the total number of graduates in early periods was small, so the shares in those periods tend to fluctuate more with small changes in the absolute numbers.

of WWI but continued after it, and the share of graduates in the research sector reached more than one-third in the 1920s.

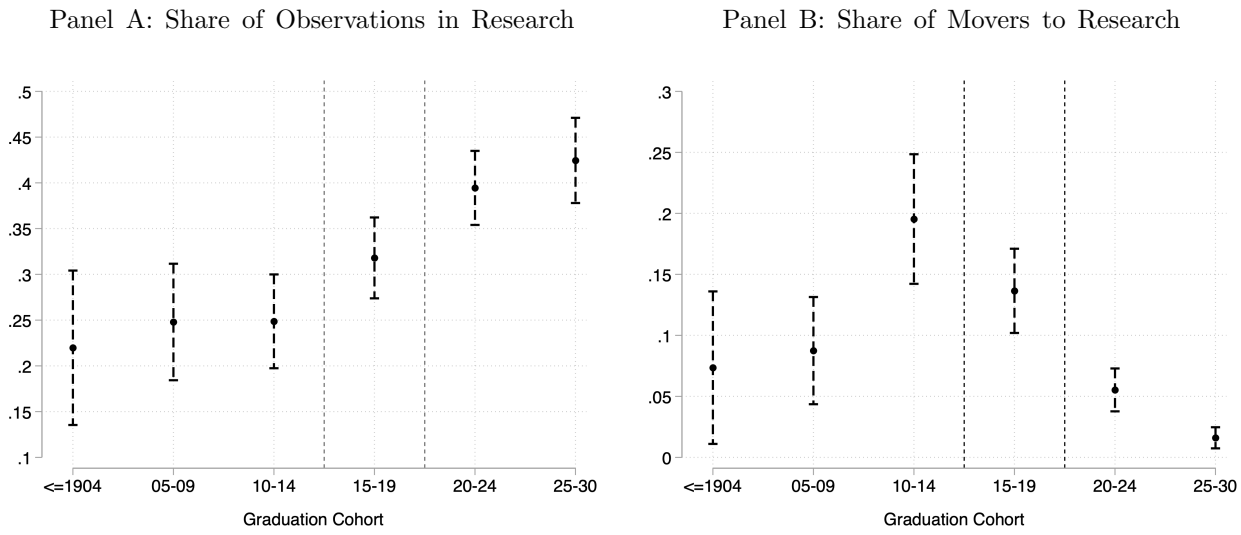
The number and share of graduates in the production sector also kept increasing after the onset of WWI, partly driven by temporary import suspension. In this case, the aggregate production sector data shown in Figure 8 do not fully capture the magnitude of the demand-driven reallocation of talent into the chemical industry as most of the reallocation actually occurred within the production sector itself. Figure A.6 in Appendix A shows the breakdown of the share of graduates in the production sector into three categories: chemical, semi-chemical, and others. The chemical sector includes organizations producing chemicals, such as soda products, synthetic dyes, medicines, synthetic rubber, rayon, etc. Semi-chemical covers organizations using chemicals as inputs (e.g., cement, paper and pulp, glass, metal and iron) or producing byproduct chemicals (e.g., coke oven gas). We can see from Figure A.6 that the share of graduates in the chemical sector started to increase sharply after the onset of WWI, reinforcing the notion that temporary import suspension created urgent demand for knowledge elites in specialized chemistry fields.[25] Note, however, that the share of graduates in the production sector (Figure 8) and their share in the chemical sector within the production sector (Figure A.6) both declined after the end of WWI as imports of chemical products from Europe resumed and the private industry experienced a shakeout-like recession. Nevertheless, the share of production workers employed in the chemical sector remained much higher in absolute terms compared to the semi-chemical and other sectors and also much higher than it had been before WWI (Figure A.6). Also importantly, in the chemistry-related research, we do not observe any trend reversal after WWI at all.

Examining the reallocation into the research sector in more detail, we can see it was driven by two forces. First, the demand for knowledge elites was met at the cohort level. Panel A in Figure 9 depicts the average share of graduates in the research sector by graduation cohorts (by five-year bins). The figure shows a stark change in the pattern of employment of university graduates: consistent with the time-series evidence in Figure 8, cohorts that graduated during and after WWI were more likely to work in the research sector, suggesting that the research sector successfully attracted recent graduates after the onset of the war. Around 25 percent of graduates were employed in the research sector before the onset of the war, but this share kept gradually increasing and reached more than 40 percent after the end of the war.

Second, the post-war increase in the share of graduates in the research sector was also driven by the reallocation of incumbent scientists and engineers to the research sector. Panel B in Figure 9 shows the share of graduates in each five-year cohort bin who moved from a non-research to the research sector at some point after the onset of WWI (hereafter, "movers"). The graph shows a big increase in the share of such movers among the cohorts that graduated right before war

[25] For example, multiple incumbent engineers in our data who had worked in gas companies which produced chemicals as byproducts of gas production (generated in coke ovens at that time) moved to specialized chemical companies producing synthetic dyes and other similar products, including but not limited to new startups set up with financing from gas companies that previously employed those engineers. Details are available upon request.

Figure 9: The Allocation of University Graduates into Research Sector by Graduation Cohort



Notes: The figure shows the average shares of Imperial University graduates from chemistry-related divisions working in the research sector by each five-year graduation cohort bin from 1900-1930 (Panel A), and the average shares of those who moved into the research sector from a non-research sector at some point after the onset of WWI, also by each five-year graduation cohort bin from 1900-1930 (Panel B).

time (1910-1914). Those more recent pre-WWI graduates were presumably easier to recruit by the newly emerging research labs and institutes compared to older graduates who may have had higher mobility costs. That said, around 7-10 percent of graduates from earlier cohorts still moved to the research sector during and after WWI, comparable to or even slightly higher than the share of movers among the graduates of the youngest (post-WWI) cohorts. All in all, this indicates that the emerging research environment was attractive enough also for incumbent talent to change the direction of their careers, and this was another important source of human capital for research.

An auxiliary but important question is how research labs and institutes attracted top-talented graduates to research jobs in response to the urgent demand during war time and then in the long run. Figure A.8 in Appendix A shows that earnings in each sector followed a similar trajectory up to 1920, but after that, the pay gap between the production sector and other sectors became quite pronounced. This suggests that research sector might have kept attracting talent by providing more non-pecuniary payoffs, such as better research environment, catering to the top graduates' "taste for science" (Stern, 2004).[26] Alternatively, research jobs may have been attractive to graduates all along, but there was simply not enough supply of those before the war — an interpretation that would also resonate with the opening epigraph by Jôkichi Takamine. Increased supply of research labs and institutes after the onset of the war changed the situation.

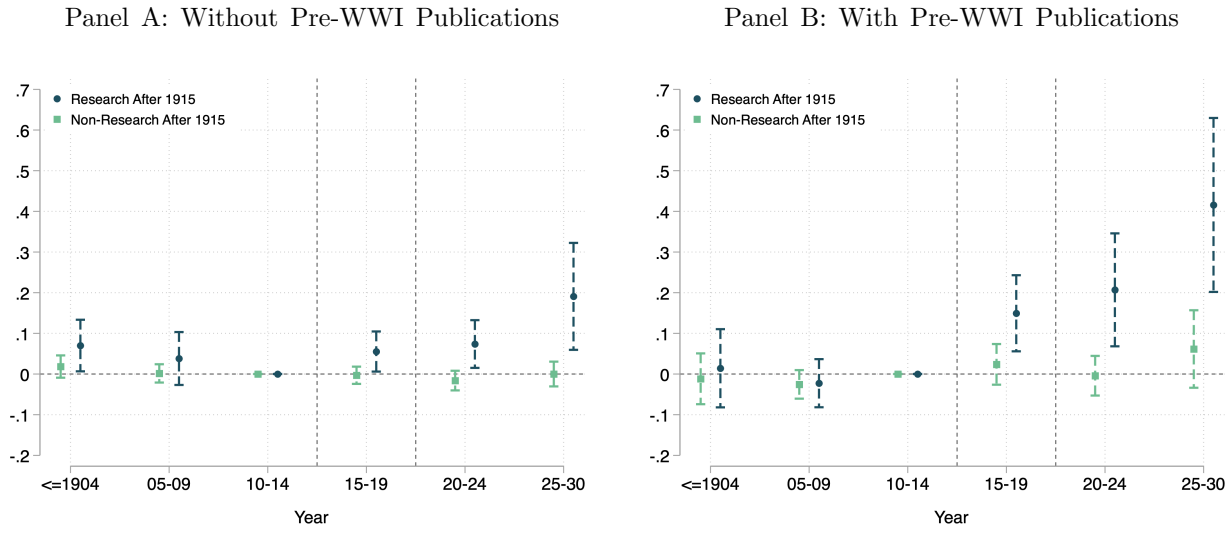
[26] See also Hiraiwa et al. (2025a) for how Imperial Universities successfully attracted top graduates to academia through institution building processes while facing an increasing pay gap between industry and academia.

5.2.2. "Researchers" in Corporate Laboratories and Research Institutes

Given the rise of corporate laboratories and public research organizations and associated reallocation of university educated scientists and engineers in response to the WWI import suspension, how did such reallocation contribute to the long-term increase in invention shown in Section 4? To examine this, I first re-estimate the research productivity gains separately for those who had experience working in the research sector after the onset of WWI and those who did not. Panels A and B in Figure 10 show the event study plots, as in Panel B in Figure 5, limiting the treated groups to chemistry graduates without and with publications in top chemistry field journals before 1915, respectively, while using graduates from other high-tech divisions as control groups. In this Figure, I further divide the treated graduates into those who had worked in the research sector for at least one year after 1915 and those who never worked in research after 1915. The graphs clearly show that increased patent productivity comes from those who worked in the research sector, while there is no difference in patent productivity with the control group among chemistry graduates who never worked in research after 1915. Moreover, the long-term boost to invention was more pronounced among those with pre-war accumulation of embodied scientific knowledge (publication record in top chemistry journals), but even among them, most of the effect comes from those who worked in the research sector. While not surprising perhaps, this helps to rule out a possible alternative story whereby increased invention productivity by chemists was driven by some general trend in innovation, not the establishment of the organized R&D environment. Note that at this stage I am not separating chemists who worked in research into those who had worked there even before the onset of WWI and those who moved into research after that — this examination is important in its own right and I conduct it in the next subsection.

I also conducted an analysis of the direct effects of working in the research sector, whether before or after the war, on patent productivity. Table 2 shows the results from estimating panel regressions where the dependent variable is the number of patent applications in a given year, while the explanatory variable of interest is the dummy equal to one if they worked in the research sector in a given year and zero otherwise. The sample is limited to graduates from chemistry-related divisions. In the baseline specification Column (1), I only include year fixed effects to control for the overall time trend and other time-variant macroeconomic conditions. The coefficient on being employed in the research sector dummy in Column (1) indicates that graduates who worked in the research sector were twice as productive as those in other sectors. This specification compares people with different inventive potentials, so it can just reflect the selection, not the assignment effect. Hence, in Column (2), I estimated the same regression, using only within-individual variation by including individual fixed effects. It turns out that even the same individuals became more productive inventors after they moved into the research sector, and the size of the effect is similar to that in Column (1). Identification in the specification in Column (2) is based on those who moved between the research and non-research sectors, implying that the patent productivity-improving effect of moving into research for a given individual was comparable to the difference in

Figure 10: Individual Patent Productivity: Job Experiences in Research Sector



Notes: The Figure plots the estimated event study coefficients from the dynamic difference-in-differences specification. The control groups consist of graduates from other high-tech divisions (Mechanical Engineering and Electrical Engineering). In Panel A the treated groups are chemistry graduates without pre-WWI publications with and without research job experience while in Panel B the treated groups are chemistry graduates who had pre-WWI publications with and without research job experience.

productivity between individuals in and outside of the research sector. In Column (3), I checked the robustness of the results in Column (2) applying de Chaisemartin and d'Haultfoeuille (2020) (i.e., not using already-treated units' variation), as mobility into the research sector is generally staggered. The findings are basically the same. These findings by themselves may not be that surprising, as the research sector by definition lets workers do research jobs, but the point is that the reallocation into the research sector was likely to be a major factor explaining the surge in chemical inventions in post-WWI periods. However, as shown in Figure 10, the pre-war publication record also seems like an important moderator for post-1914 patenting outcomes.

5.3. The Source of Long-term Boost: "Activation Effect" Revisited

In the previous section, we saw that accumulated scientific embodied knowledge was critically important to harness the human capital potential for invention after the arrival of acute demand due to import suspension. Organizational innovations were also implemented in the corporate and public (including academia and not-for-profit) sectors at the same time, resulting in a much more robust research sector. This raises the question of which of these factors (scientific human capital or/and research organizations) was the primary source of the long-term boost to invention. Here, I examine how each of those contributed to the sharp increase in invention by incumbent scientists and engineers after the onset of the war separately and jointly. Specifically, I first estimate

Table 2: Patenting by Graduates in Research Sector

	(1) Baseline	(2) Within-Individual	(3) Staggered DiD
Research	0.0905***	0.101***	0.0907***
	(0.0175)	(0.0303)	(0.0303)
Mean of DV	0.0989	0.0994	0.0994
Year FEs	Yes	Yes	Yes
Individual FEs	No	Yes	Yes
Adj R-Squared	0.0168	0.160	-
Observations	19,941	19,826	19,826

Notes: The table shows the estimated coefficients from the panel regression of individual patents on an indicator of working in the research sector. These are estimated within the sample of graduates from chemistry-related divisions. Column (3) uses the estimator developed by de Chaisemartin and d'Haultfoeuille (2020) to deal with the staggered timing of mobility into the research sector. Standard errors are clustered by individuals and reported in parentheses. Stars indicate significance levels: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

a panel regression with two-way fixed effects on the sample of graduates from chemistry-related fields up to the 1914 graduation cohort, where the dependent variable, as in Table 2 above, is the number of patent applications in a given year, while the explanatory variables are the fully saturated interaction terms of the dummy equal to one for all years after WWI and zero otherwise,[27] the dummy equal to one if the graduate worked in the research sector in a given year (and zero otherwise), and the dummy equal to one for graduates with at least one publication prior to 1915. For the ease of exposition, I only report the coefficients interacted with the post-war dummy.[28] The estimation results are shown in Column (1) of Table 3. Both interacting work in the research sector and the individual-level dummy capturing if the graduate published in a top chemistry journal prior to the onset of the war with the post-war dummy economically and statistically significantly positively affect patenting rates, while the three-way interaction term does not show a significant effect.

At this stage, it may seem like accumulated embodied scientific knowledge had an independent impact on patenting by graduates whether or not they worked in the research sector. However, looking at the long-term effects of working in the research sector, we see more nuanced impacts of embodied scientific knowledge. In Column (2) of Table 3, I replace the dummy equal to one if the graduate worked in the research sector in a given year with the dummy equal to one for all years after the graduate experienced working in the research sector for the first time. That is, instead

[27] Since the focus here is on long-term effects of the WWI import suspension shock, this dummy is set equal to zero for all years before and during WWI. Setting it to one for war years produces very similar results.

[28] Consistent with the previous findings, working in the research sector before the post-war era has no impact on patenting output compared with working in some other sector.

Table 3: Patenting by Graduates: Research and Embodied Scientific Knowledge

	(1)	(2)	(3)
PostWWI × 𝟙{PreWWI Publications}	0.113**	-0.0363	-0.0363
	(0.0540)	(0.0560)	(0.0561)
PostWWI × Research	0.129**		0.133**
	(0.0646)		(0.0635)
PostWWI × Research × 𝟙{PreWWI Publications}	0.0332		-0.0229
	(0.121)		(0.128)
PostWWI × PostResearch		0.0143	-0.0131
		(0.0368)	(0.0347)
PostWWI × PostResearch × 𝟙{PreWWI Publications}		0.223***	0.203**
		(0.0819)	(0.0895)
Mean of DV	0.101	0.101	0.101
Year FEs	Yes	Yes	Yes
Individual FEs	Yes	Yes	Yes
Adj R-Squared	0.177	0.172	0.178
Observations	11,012	11,012	11,012

Notes: The table shows the estimated coefficients from the panel regression of individual patents on an indicator of working in the research sector, interacted with the post-WWI dummy, and the interaction of an indicator of publishing in top field journals before 1915 and the post-WWI dummy. These are estimated within the sample of graduates from chemistry-related divisions. Standard errors are clustered by individuals and reported in parentheses. Stars indicate significance levels: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

of looking at the contemporaneous effect of working in the research sector, I examine the impact of having had job experience in the research sector regardless of whether the individual was employed in research in a particular year. The coefficient on the interaction term between pre-war publication record and post-war dummy becomes economically and statistically unimportant in this specification, while the coefficient on the triple interaction term between post-war years, having previous experience working in the research sector and a pre-war publication record in top chemistry journals is positive, large and statistically highly significant. This indicates that embodied scientific knowledge (pre-war publication record) led to more invention post WWI only if combined with at least some experience working in a research organization. Notably, there was no increase in post-war patents even by those with job experience in research if they did not have pre-war publication record either.

The above findings and the findings in Column (1) that showed the impact of pre-war publications independent of work in research can be reconciled by including both research-related variables at the same time (that is, both the dummy equal to one if the graduate worked in the research sector in a given year and the dummy equal to one for all years after the graduate worked

in the research sector for the first time) in Column (3). This fully saturated specification shows, first, that there was no difference in the impact of working in the research sector on invention in a given year between those with and without pre-war scientific publications (insignificant coefficient on the interaction term between post-war dummy, research job in a given year dummy, and pre-war publication dummy). That is, contemporaneous research job boosted invention output regardless of pre-war publication status. As can be seen in the last two rows of Column (3) in Table 3, however, the coefficient on the interaction term between post-war years, previous experience working in a research organization, and pre-war publication record remains large and statistically significant while the coefficient on the interaction term between post-war years and research job experience is economically and statistically indistinguishable from zero. Note that contemporaneous work in the research sector and all its interaction terms are controlled for, so this means that among the individuals who gained experience in research and subsequently moved to another sector (industry), only those with pre-war publication record maintained and even increased their invention productivity, while those with no such publication record "lost" all advantage over an average graduate in terms of patent output once they left a research organization.

Hence, the findings presented in Table 3 are consistent with the finding in Figure 10 that showed post-war research experience having been more important for those with embodied scientific knowledge. The additional insight obtained from the estimations in Table 3 is that only those with embodied scientific knowledge were able to *carry over* their research experiences into other sectors, while those without pre-war accumulation of embodied scientific knowledge only had more inventions during the time they actually worked in the research sector.

5.4. Summary and Discussion

I have shown in this section that after WWI import suspension ended, invention in chemistry-related fields in Japan continued unabated and, moreover, branched out into new technology subclasses and groups, resulting in robust innovation that paved the way for a competitive chemical industry which eventually overcame the post-WWI shock. The key factor appears to be the reallocation of top talent into the newly emergent organized research sector (private labs established by corporations, but even more so top-notch public research institutes, such as The Institute of Physical and Chemical Research ("*Riken*") and multiple government labs and institutes affiliated with Imperial Universities). The most salient feature, demonstrated in Section 5.3, is that job experience in research boosted long-term post-war inventive output particularly strongly when combined with accumulated embodied scientific knowledge by scientists and engineers with proven academic record (publications in top journals) already before WWI, that is, *before* the research environment emerged and their inventive potential could be harnessed. While all scientists and engineers employed in research organizations at a given time could generate inventions at similar rates after the end of the war, only those with high-level embodied scientific knowledge could take the inventive capability with them as they moved from research to industry (production)

and enhanced this capability even further after the move.

How exactly does embodied accumulated knowledge produce superior inventive performance, especially if combined with experience in a research organization (private or public)? Conceptually, one answer is suggested by the notion of "planning capital" (Caplin, 2026).[29] Planning capital is built through the process of staged discovery — costly inquiry actions that produce answers to questions and change the cost of future inquiries. Even though Caplin (2026)'s framing is at the organizational level, his argument and formal model can be applied to individual inquiry with trivial adjustments. Indeed, my reading of pre-WWI scientific publications by those who then jumped in to contribute to generating new technologies during WWI import suspension gave multiple examples of such "staged discovery" inquiries conducted by scientists and engineers in my sample, inquiries that reduced the cognitive costs for them of pivoting toward WWI import-substituting inventions, whether those were directly related to the previous stages or not.[30] This "staged discovery" by individual scientists and engineers then received further impetus as WWI shock led to the creation of private and public R&D institutions that provided them with the environment that was even more facilitating to invention-generating research.

In other words, the chemists who had published in top journals before the onset of WWI, already invested into the cognitive stock that potentially could reduce the cost of future inventions. When production firms and other organizations hired those chemists, their cognitive stock could be converted into firm-level (organization-level) "planning capital," giving those firms (organizations) a sustainable competitive advantage.

6. Conclusion

Using long-term historical panel data on the census of all Imperial University-educated scientists and engineers in chemistry, I examined the evolution of their contribution to the development of Japan's chemical industry through science and industry-related invention. Japan created a world-class higher technical education system already toward the end of the 19th century, which, in particular, produced high-level educated specialists in theoretical and applied chemistry. However, their contribution to developing the domestic chemical industry remained limited as Japan relied on imports of chemical products from Europe for most of its needs. As a result, most educated chemists worked in government or education with few of them contributing to either industry-related research or domestic production.

[29] Caplin (2026) defines planning capital as "the accumulated diagnostic understanding a firm has built through costly inquiry and operation: understanding of technologies, processes, customers, tools, partners, failures, constraints, and opportunities, together with the capacity to keep learning. It becomes valuable because it helps the firm choose what to investigate, make the question answerable, interpret what happened, and carry what it learned into later investment stages."

[30] One example already discussed in Section 4 above is the attempt by Sadakichi Satô to produce aniline-replacing dyes from wax myrtle fruit. Even though this attempt did not succeed, according to his own testimony (Satô, 1919), he gained a lot of useful experience in research from that.

The situation changed dramatically with the onset of World War I (WWI) which brought about abrupt suspension of imports from Europe, especially Germany, and created an urgent, acute need to build a technological basis for developing the domestic chemical industry. The immediate effect was an outburst of chemistry-related invention (patents), many aimed at substituting for imported products that became unavailable or extremely expensive or developing domestic alternatives. Thus, WWI import suspension shock "activated" the invention potential of top-notch chemists that had been dormant until then. However, this response was not uniform — I find that the boost in invention during WWI was concentrated among those educated chemists who had invested in scientific inquiry (which I can observe in their publication records in top chemistry field journals) even prior to the onset of WWI and the emergence of the need for developing domestic technologies. That is, only those among highly educated chemists who engaged in "pure" scientific research were capable of pivoting to industry-related invention when the import suspension hit and the industry needed their creative input.

Most importantly, while the WWI import suspension shock was of a transient nature, the situation did not snap back to where it had been before the war even as imports from Europe came back and domestic chemical industry was plunged into crisis. That is, the temporary import suspension generated a persistent, long-term impact on chemistry-related invention in Japan. Digging deeper into the mechanisms that generated such long-term impact, I find that temporary import suspension during WWI permanently changed the trajectory of both research and industry itself. While WWI invention by chemists with accumulated embodied human capital targeted specific import-substitution areas, the same chemists branched out into multiple other chemistry-related areas, most of which were not the target of research during war time. Further examination showed that while it originated from WWI imports suspension, the long-term increase in invention after the end of WWI and its new trajectories were fostered by the emergence of private corporate laboratories and public research institutes in chemistry-related areas which mushroomed during and immediately after WWI. This created an organized research sector, and as this sector hired an increasing number of top-notch chemistry graduates (including both older cohorts that had graduated prior to WWI and relocated to research during and after the shock, and new graduates who only graduated after WWI), those graduates found even more opportunities to engage in industry-related research, producing patents in a wide array of chemistry-related patenting classes. Importantly, I find that while all researchers, whether they had pre-war record of scientific publications or not, contributed to chemistry-related patents if they worked in the research sector, only those who had scientific publications in pre-war years could "carry over" their inventive capacity even as they moved from the research sector to industry. Thus, the advantage of accumulated embodied scientific capital continued to manifest itself in the long run, but it was mediated by experience working in the newly emerged organized research sector.

The fact that temporary import suspension led to permanent increase in invention and the development of new directions can potentially be interpreted in terms of targeted government re-

search programs (Gross and Sampat, 2023, 2025) or industrial policy (Juhász, 2018; Alfaro et al., 2025). In fact, my study reveals a more nuanced picture. For one thing, WWI import suspension was not a planned industrial policy, but an exogenous shock which already makes this different from deliberate protectionist policies often associated with rent-seeking behavior and lack of incentives for innovation on the part of protected firms and industries. It is true that the Japanese government, as most other governments at the time, did implement protectionist and industrial policy measures during and after WWI, starting with the dyestuff industry already during the war. Such measures with respect to other parts of the chemical industry were introduced much later, however, if at all, and the role they played in industry growth is not clear. For example, the production of soda which grew remarkably since WWI due to the adoption of the Solvay method for producing soda ash and the electrolysis process for making caustic soda, benefited from only limited support in the form of exempting it from government salt procurement monopoly during my sample period (Watanabe, 1968; Tsushosangyosho, 1968). Other areas, such as ammonium sulfate production grew rapidly without any government protectionist measures at all (Tsushosangyosho, 1968) and major growing sub-industries, such as photographic film and manmade fiber only became the targets of industrial policy in the 1930s.

My investigation of the "microfoundations" of the short-term and long-term effects of WWI import suspension shock revealed that even among the knowledge elite, only those who had accumulated embodied scientific knowledge can respond with industry-relevant invention when the need arises, while those without such prior investment in their human capital are not likely to foster such a response. This suggests that if a government research program or industrial policy are to be successful, they need to engage human capital with intrinsic motivation to work on scientific problems. Without such human capital, new invention may not be forthcoming.

My findings have important implications for policy and strategy. First, the speed and strength of response to the crisis I observe in my data is, in a sense, an indictment of public policy and business strategy's earlier failure to provide the right kind of environment to begin with. Similar situations are likely to happen also in mature economies, and in such cases policies, market responses, and firm strategies need to react pro-actively to emerging opportunities by providing top human capital with all it needs without waiting for a crisis to arrive.

Second, it is worth elaborating on the fact that *incumbent* researchers showed large increase in their inventive output in response to the shock. Some had even already worked in research-oriented organizations before the shock, while others moved to such organizations in response to the shock. Either way, both responded with increased productivity to the creation of a well-organized research environment. This suggests that while tapping into new generations of talent through education and hiring policies is important, it is also important for both policy makers and firms to provide resources and the right kind of environment that would "activate" the untapped potential among scientists and engineers who are already out there.

Third, the transient import suspension shock led to a long-term increase in invention and even-

tual takeoff of the industry. The mechanisms behind this long-term impact appear to be related to long-lived research assets. My analysis reveals that such long-lived research assets were not limited to organizations but also consisted of durable embodied knowledge of individual scientists and engineers. The role of individual human capital as a "carrier" of durable research assets has remained understudied compared to the role of organizations. The unique nature of my historical context, where such human capital emerged and engaged in scientific research *before* an exogenous shock provided the need and opportunity to engage in invention, allows me to clearly show the independent importance of embodied scientific human capital as one of the cornerstones of invention and industry incubation. In turn, this suggests that simply providing funding and resources in the form of national programs or corporate R&D labs may not be enough, but should be accompanied by strategic implementation of the system of incentives that would ensure that the best among the overall pool of educated scientists and engineers feel motivated to engage in basic science which could then be applied to develop new technologies in times of acute necessity.

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Appendix

A. Additional Tables and Figures

Table A.1: Chemical-Related Patents by University-Educated Inventors and Other Inventors

	(1) Graduates	(2) Non-Graduates	(3) Difference
Number of Patents	3.84	1.74	2.11***
	(6.62)	(3.17)	(13.58)
𝟙{More Than Two Patents}	0.56	0.26	0.30***
	(0.50)	(0.44)	(25.68)
𝟙{Listed in Imperial Inventor Directory}	0.16	0.06	0.10***
	(0.37)	(0.24)	(11.43)
Observations	1,851	26,404	28,255

Notes: Standard deviations (t-statistics) are reported in parentheses in Columns (1)-(2) (Column (3)). Stars indicate significance levels: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table A.2: Pre-WWI Graduates with Publications and without Publications

	(1) Publications	(2) No Publications	(3) Difference
Number of Patents	3.73	1.12	2.61***
	(7.52)	(2.71)	(4.67)
𝟙{More Than Two Patents}	0.39	0.18	0.21***
	(0.49)	(0.38)	(5.35)
Doctoral Degree	0.34	0.07	0.28***
	(0.48)	(0.25)	(7.57)
Science Degree	0.31	0.30	0.01
	(0.46)	(0.46)	(0.22)
University Graduation Ranking	0.63	0.43	0.20***
	(0.33)	(0.33)	(6.00)
High School Graduation Ranking	0.59	0.46	0.13***
	(0.31)	(0.30)	(4.12)
Study Abroad	0.36	0.12	0.25***
	(0.48)	(0.32)	(6.36)
Observations	192	428	620

Notes: Standard deviations (t-statistics) are reported in parentheses in Column (1)-(2) (Column (3)). Stars indicate significance levels: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table A.3: Difference-in-Differences Estimates: Other Heterogeneous Effects

Panel A. Publication vs. Academic Ranking

	No Publications		With Publications	
	(1)	(2)	(3)	(4)
	Rank < Median	Rank > Median	Rank < Median	Rank > Median
During WWI × Chem	-0.000242	0.00741	0.0706**	0.0989**
	(0.0125)	(0.0188)	(0.0305)	(0.0422)
Post WWI × Chem	0.00282	0.0656***	0.114*	0.214***
	(0.0148)	(0.0251)	(0.0661)	(0.0613)
Mean of DV	0.0378	0.0398	0.0405	0.0456
Year FEs	Yes	Yes	Yes	Yes
Individual FEs	Yes	Yes	Yes	Yes
Adj R-Squared	0.144	0.144	0.145	0.169
Observations	40,264	38,535	37,410	38,020

Panel B. Publication vs. Doctoral Degree

	No Publications		With Publications	
	(1)	(2)	(3)	(4)
	Non-Doctor	Doctor	Non-Doctor	Doctor
During WWI × Chem	-0.00292	0.0219	0.0318	0.111**
	(0.00976)	(0.0625)	(0.0196)	(0.0495)
Post WWI × Chem	0.00133	0.122**	0.0267	0.301***
	(0.0117)	(0.0600)	(0.0248)	(0.0829)
Mean of DV	0.0379	0.0397	0.0397	0.0469
Year FEs	Yes	Yes	Yes	Yes
Individual FEs	Yes	Yes	Yes	Yes
Adj R-Squared	0.138	0.148	0.141	0.174
Observations	44,644	36,457	38,755	37,702

Notes: The table reports the estimated coefficients from the static difference-in-differences specification. For all specifications, I use all graduates from other high-tech divisions (Mechanical Engineering and Electrical Engineering) as control groups. In both panels, Columns (1)-(2) (Columns (3)-(4)) first limit the treated groups to graduates from chemistry-related divisions who did not (did) have publications in top field journals prior to 1915. In Panel A, I further split the treated sample into those whose high-school graduation rankings were below or above the median among the same division-cohorts in each case. Panel B splits the treated sample into those with and without doctoral degrees in each case. Standard errors are clustered by individuals and reported in parentheses. Stars indicate significance levels: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table A.4: Technology Categories of Patents by Incumbent Scientific Talent and WWI Inventors

Panel A. Patenting by Graduates with Publications Before 1915

	Categories		Sub-categories	
	(1) WWI Areas	(2) Non-WWI Areas	(3) WWI Areas	(4) Non-WWI Areas
During WWI	0.0901***	-0.00977*	0.0970***	-0.0167**
	(0.0211)	(0.00508)	(0.0215)	(0.00803)
Post WWI	0.0918***	0.0881***	0.0196*	0.160***
	(0.0219)	(0.0193)	(0.0106)	(0.0306)
Mean of DV	0.0834	0.0442	0.0445	0.0830
Individual FEs	Yes	Yes	Yes	Yes
Adj R-Squared	0.156	0.0978	0.0965	0.132
Observations	5,614	5,614	5,614	5,614

Panel B. Patenting by Graduates with Patents during WWI

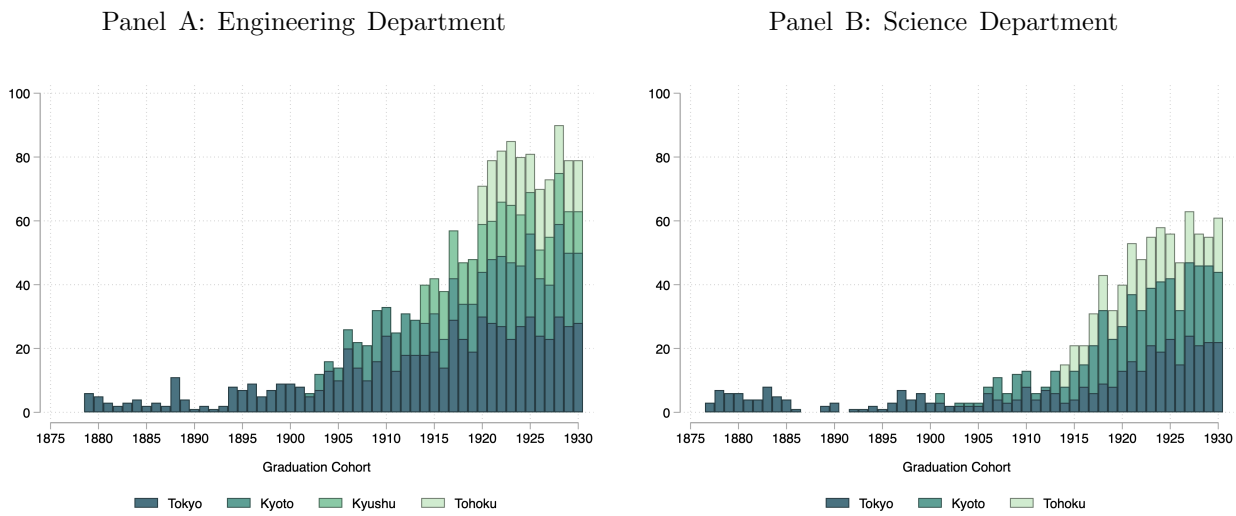
	Categories		Sub-categories	
	(1) WWI Areas	(2) Non-WWI Areas	(3) WWI Areas	(4) Non-WWI Areas
During WWI	0.384***	0.00696	0.382***	0.00902
	(0.0474)	(0.0115)	(0.0474)	(0.0188)
Post WWI	0.119***	0.156***	0.0140	0.261***
	(0.0428)	(0.0386)	(0.0236)	(0.0586)
Mean of DV	0.198	0.0766	0.133	0.141
Individual FEs	Yes	Yes	Yes	Yes
Adj R-Squared	0.142	0.129	0.115	0.162
Observations	2,271	2,271	2,271	2,271

Notes: The table reports the estimated coefficients from the following regression specification using the sample of graduates from chemistry-related divisions:

$$y_{it} = \beta_1 \times \text{WWI}_t + \beta_2 \times \text{PostWWI}_t + d_i + \varepsilon_{it},$$

where y_{it} is the number of patent applications by graduate i in year t in technology areas where some chemistry graduates did (did not) have at least one patent during WWI, WWI_t is an indicator variable for periods during, PostWWI_t is an indicator variable for periods after WWI, and d_i represents individual fixed effects. In both panels, Columns (1)-(2) (Columns (3)-(4)), I use patent subclasses (groups) to define the technology areas with at least one patent during WWI. Panel A shows patenting by graduates with at least one top chemistry journal publication before 1915. Panel B shows patenting by graduates with at least one patent during WWI. Standard errors are clustered by individuals and reported in parentheses. Stars indicate significance levels: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

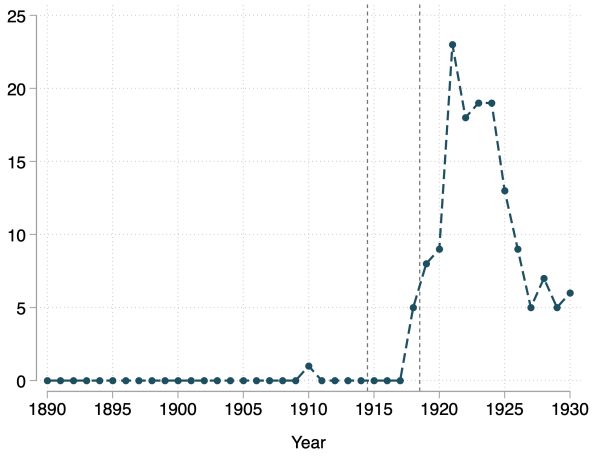
Figure A.1: The Number of University Graduates by Graduation Cohorts



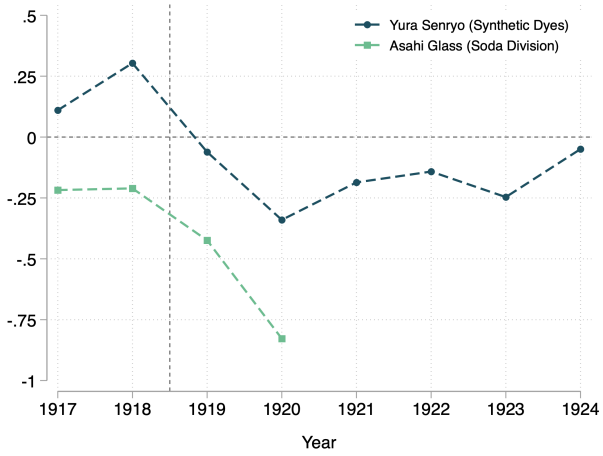
Notes: The figure shows the number of Imperial University graduates from chemistry-related divisions in Engineering and Science departments, respectively, by graduation cohorts. Each bar represents the number of graduates from four Imperial Universities. Note that Kyushu Imperial University did not have its Science department until 1939. Also, Tohoku Imperial University added its Applied Chemistry division to Science department in 1917, and then this division was moved to newly established Engineering department in 1919. Those graduates from Applied Chemistry division at Tohoku Imperial University are classified as Engineering.

Figure A.2: Exit and Profits of Chemical Firms Around WWI

Panel A: Exit of Chemical Firms

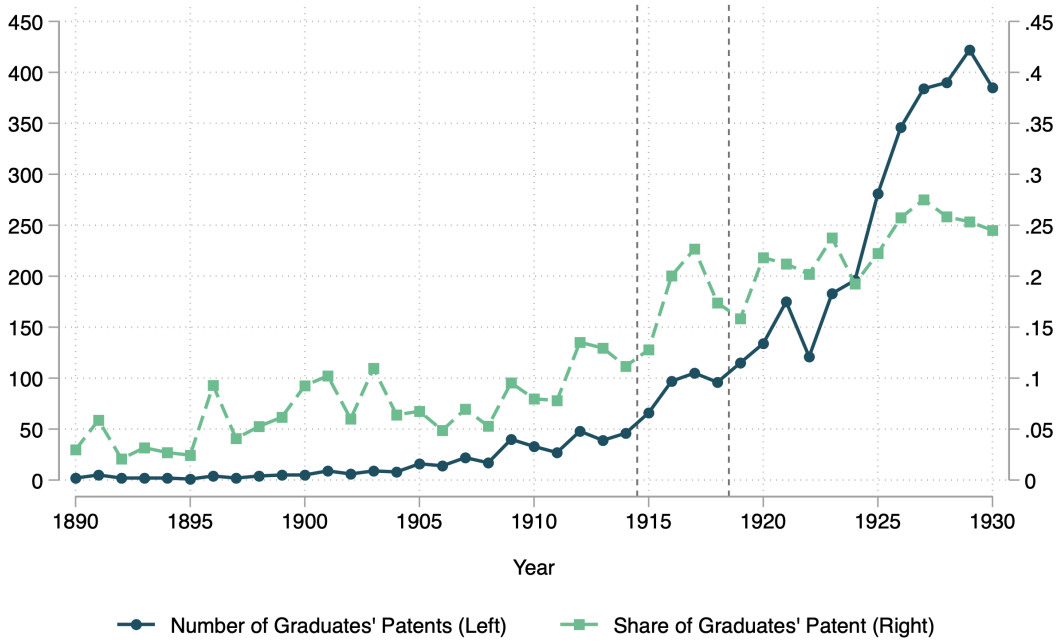


Panel B: Gross Profits of Example Firms



Notes: In Panel B, the profits are plotted in millions of yen. *Yura Senryo* was founded in 1914 and incorporated in 1917. It was the first producer of synthetic dyes in Japan and survives until the present day as Y.S.K. (https://www.yskco.jp/en_company.html). *Asahi Glass*, founded in 1907 as a glass-making firm and also surviving until today as A.G.C. (https://www.agc.com/en/), was the first company in Japan to produce caustic soda using the Solvay method. Its profit data end in 1920 because the company stopped publishing separate financials for its soda division after that year.

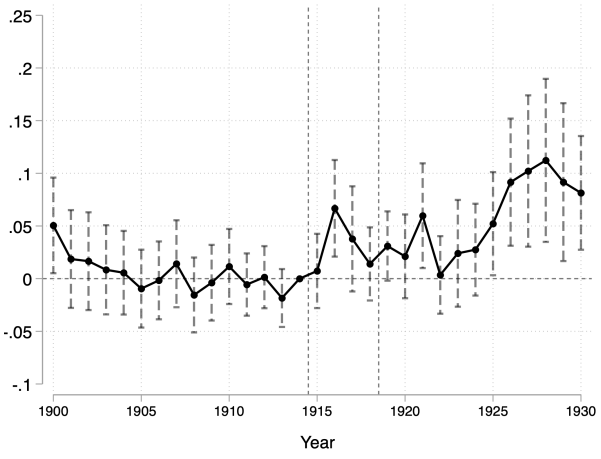
Figure A.3: The Number of Chemical Patents by University Graduates by Year



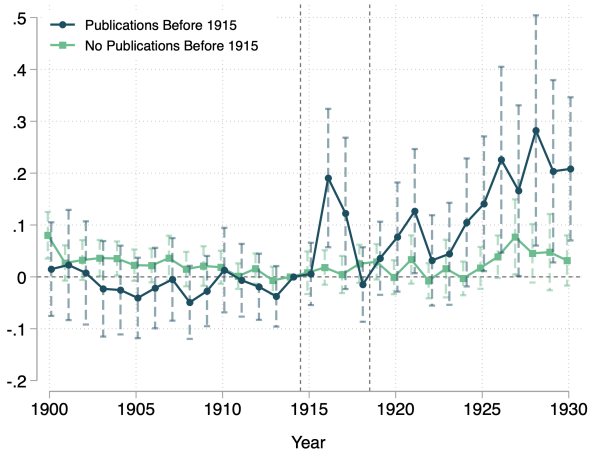
Notes: The figure shows the trend of chemical-related patents by Imperial University graduates from 1890 to 1930. The solid line with circles (dark green) represents the number of chemical-related patents by university graduates, and the dashed line with squares (light green) represents the share of chemical-related patents by university graduates among all chemical-related patents.

Figure A.4: Individual Patent Productivity: Annual Event Study Plots

Panel A: Average Treatment Effects



Panel B: Effects by Publication Record



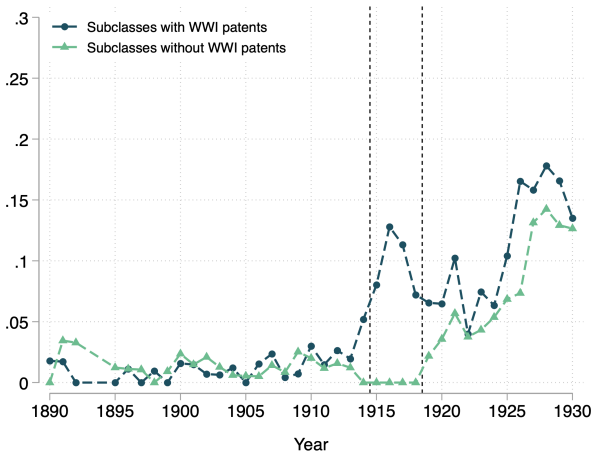
Notes: The figure shows the estimated annual event study coefficients from the following dynamic difference-in-differences specification with the reference year 1914:

$$y_{it} = \sum_{k=1900}^{1930} \left(\beta_k \times \mathbb{1}\{t = k\} \times \text{Chem}_i\right) + d_i + d_t + \varepsilon_{it},$$

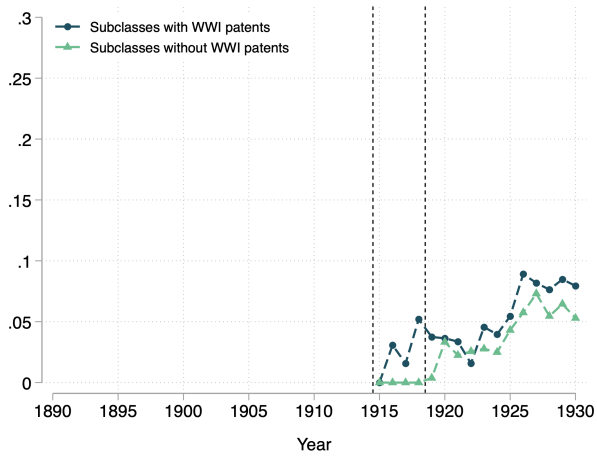
where the control groups consist of graduates from other non-chemistry high-tech divisions (Mechanical Engineering and Electrical Engineering). Panel A plots the average effects for graduates from chemistry-related divisions. Panel B defines the treated groups as graduates from chemistry-related divisions who did and did not have publications in top field journals prior to 1915, respectively. Standard errors for the confidence intervals are clustered by individuals.

Figure A.5: Chemical Patents by WWI Patent Classification: Pre-WWI vs. Newer Cohorts

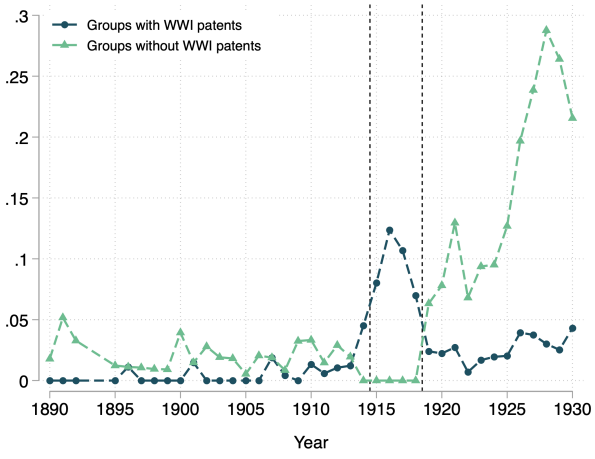
Panel A: Subclasses: Pre-WWI Cohorts



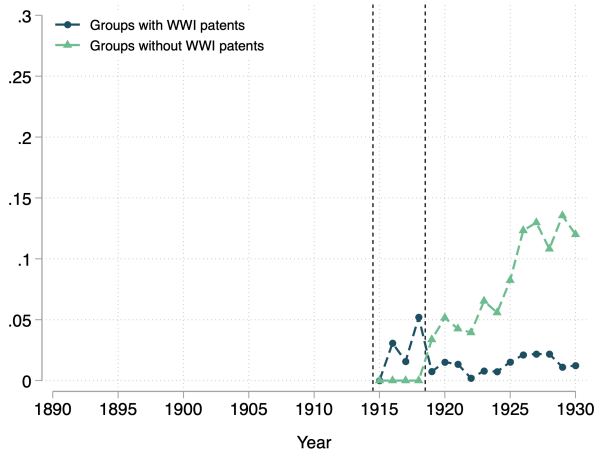
Panel B: Subclasses: Newer Cohorts



Panel C: Groups: Pre-WWI Cohorts



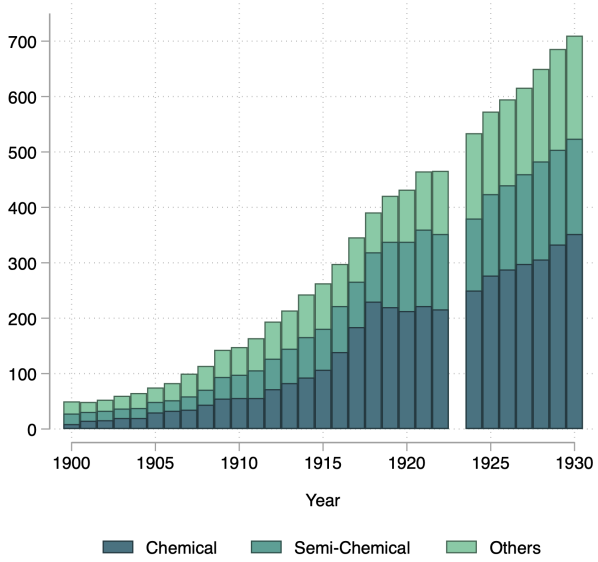
Panel D: Groups: Newer Cohorts



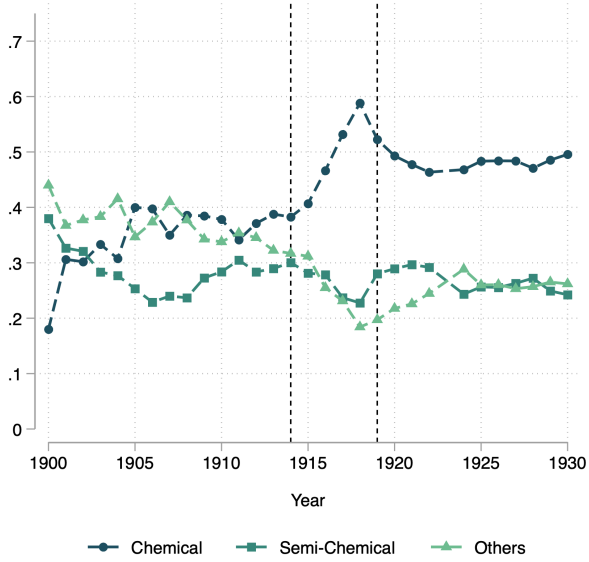
Notes: The figure shows the trends of chemical-related patents by Imperial University graduates from 1890 to 1930, split by technology categories where graduates had at least one patent between 1914 and 1918 and those where they did not, separately by cohorts that graduated before WWI and later cohorts. Panel A (Panel B) uses patent subclasses (groups) to define technologies where graduates had at least one patent between 1914 and 1918.

Figure A.6: The Allocation of University Graduates Within Each Sector by Year

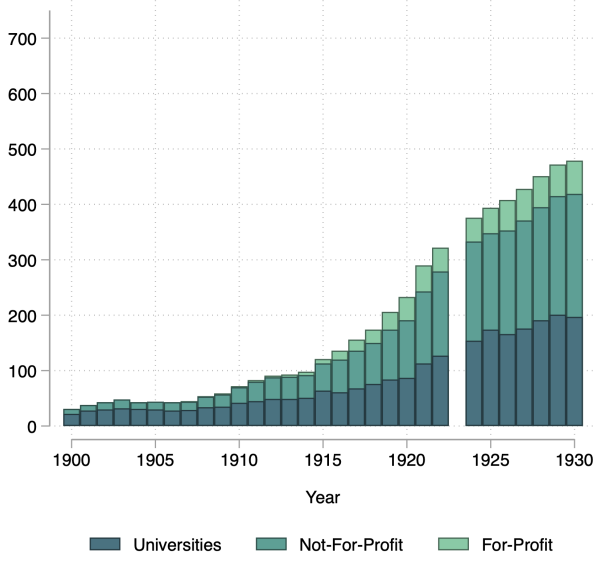
Panel A: Graduates in Production Sector



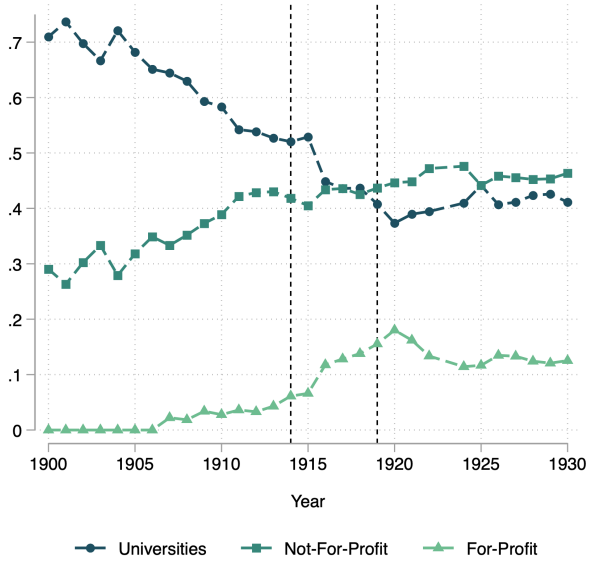
Panel B: Share in Production Sector



Panel C: Graduates in Research Sector



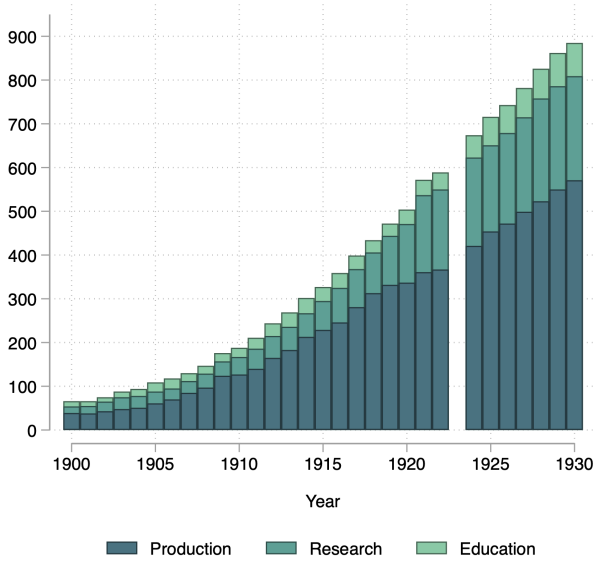
Panel D: Share in Research Sector



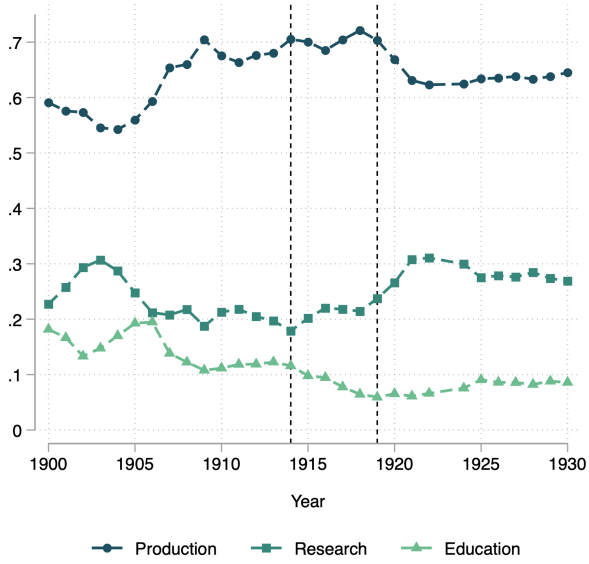
Notes: The figure shows the number and share of Imperial University graduates from chemistry-related divisions in each sub-categories of sectors by year. Panels A and B (C and D) decompose the number and share in production (research) sectors into sub-categories, respectively.

Figure A.7: The Allocation of Graduates Across Sectors by Year: Engineering and Science

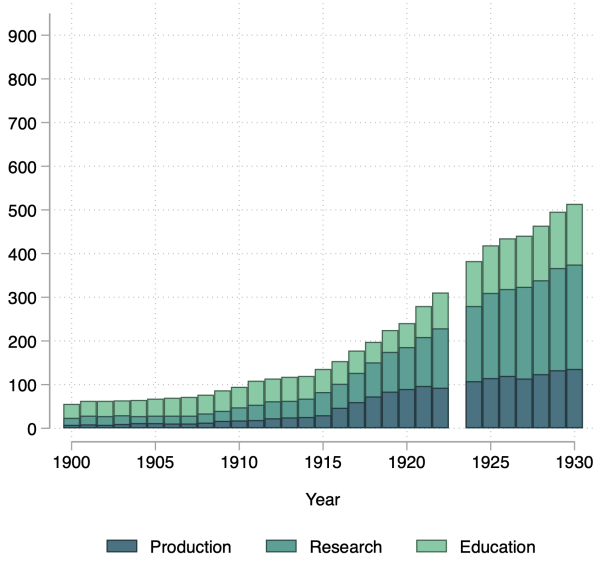
Panel A: Graduates from Engineering Department



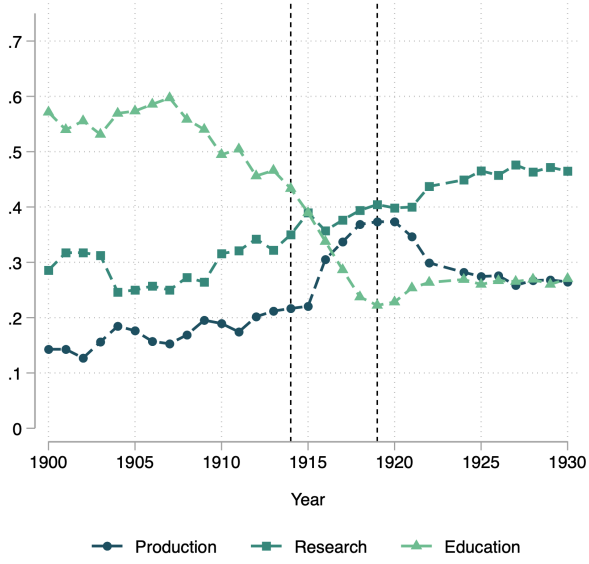
Panel B: Share of Engineering Department



Panel C: Graduates from Science Department

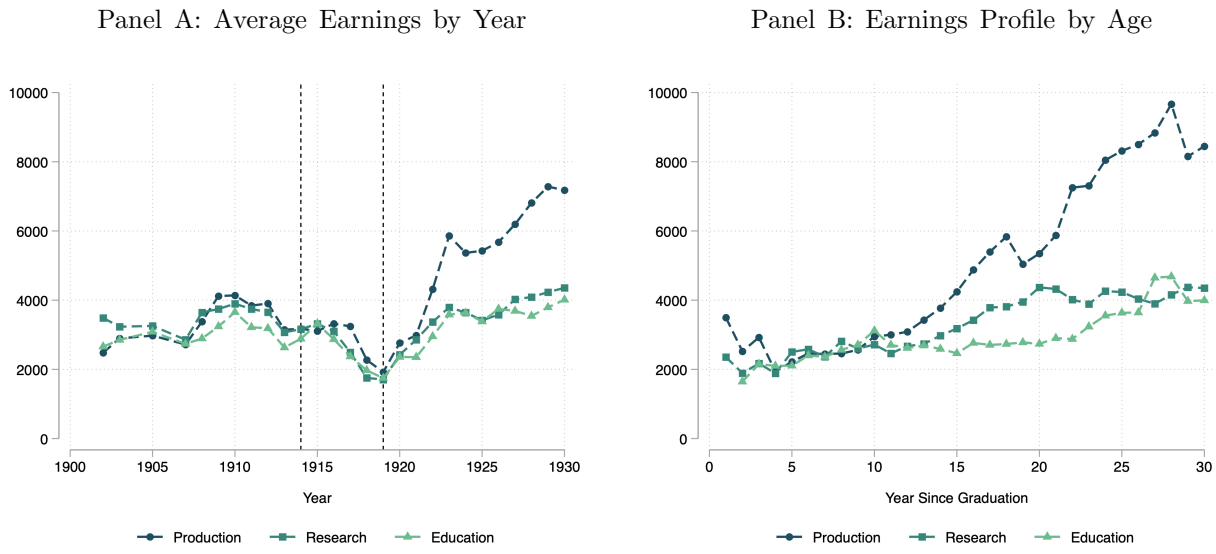


Panel D: Share of Science Department



Notes: The figure shows the number and share of Imperial University graduates from Engineering and Science departments in each sector by year, respectively. Each bar and line represent the number and share of graduates in the production, research, and education sector, respectively.

Figure A.8: Real Earnings of University Graduates Across Sectors



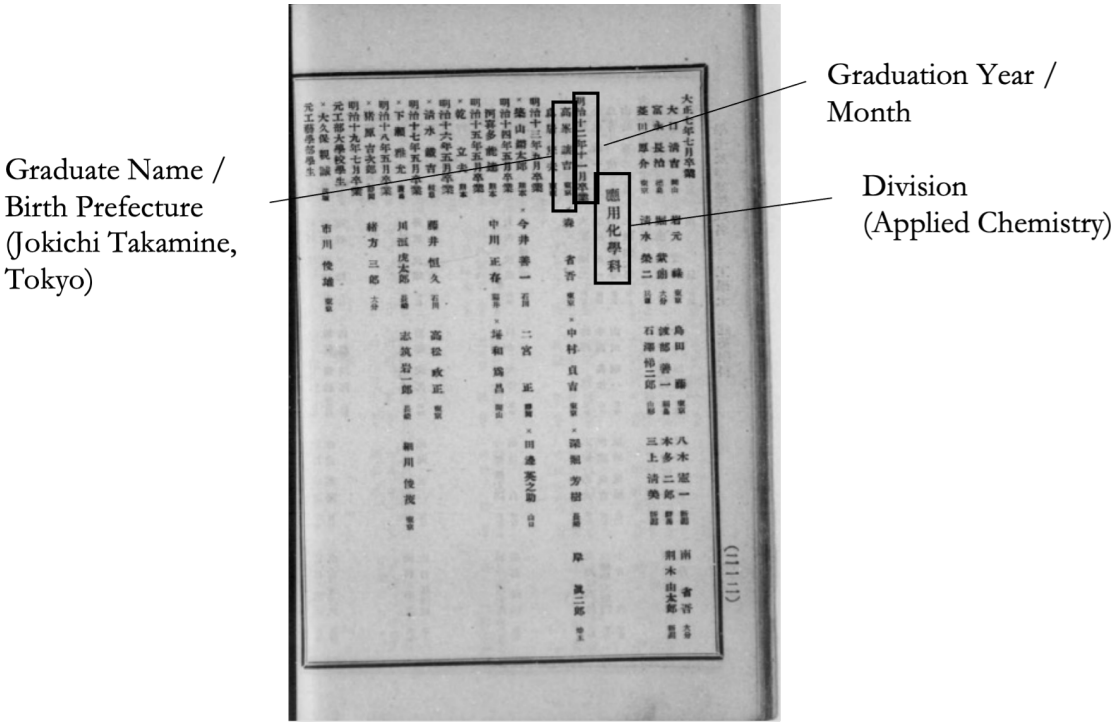
Notes: The figures describe real earnings of Imperial University graduates from chemistry-related divisions in each sector. Panel A shows the aggregate time series of average real earnings of chemistry graduates in each sector from 1902-1930, and Panel B shows age profiles of real earnings averaged across chemistry graduates in each sector. I winsorize both the top and the bottom of the distribution of real earnings at 1 percent.

B. Data Construction Details

B.1. Annual Calendars of Imperial Universities (*Ichiran*)

As mentioned in the main text, our first data source is annual Calendars of Imperial Universities (such as *Tokyo Teikoku Daigaku Ichiran*) available in open access from the National Diet Library Digital Collections (https://dl.ndl.go.jp/en/). These calendars contain names, birth prefectures, and divisions of all students during their years at the university as well as graduation years and months after graduation. Importantly, up until 1918, Tokyo Imperial University Calendars listed the students in the order (*Sekiji*, in Japanese) of the average of their test scores in each year, while the graduates were listed in the order of average test scores over all three years of university education, with the score of their graduation diploma added as the fourth component. Thus, the ordering of names is reflective of academic performance relative to peers (in the same division and cohort). As an example, Figure B.1 shows that Jôkichi Takamine (the discoverer of adrenaline) graduated from the applied chemistry division at the top of the class of six people in the 1879 graduation cohort.

Figure B.1: A Sample Page of Graduates Lists in *Tokyo Imperial University Ichiran*



Source: Annual Calendar of Tokyo Imperial University (*Ichiran*) Taisho 7 (1918).

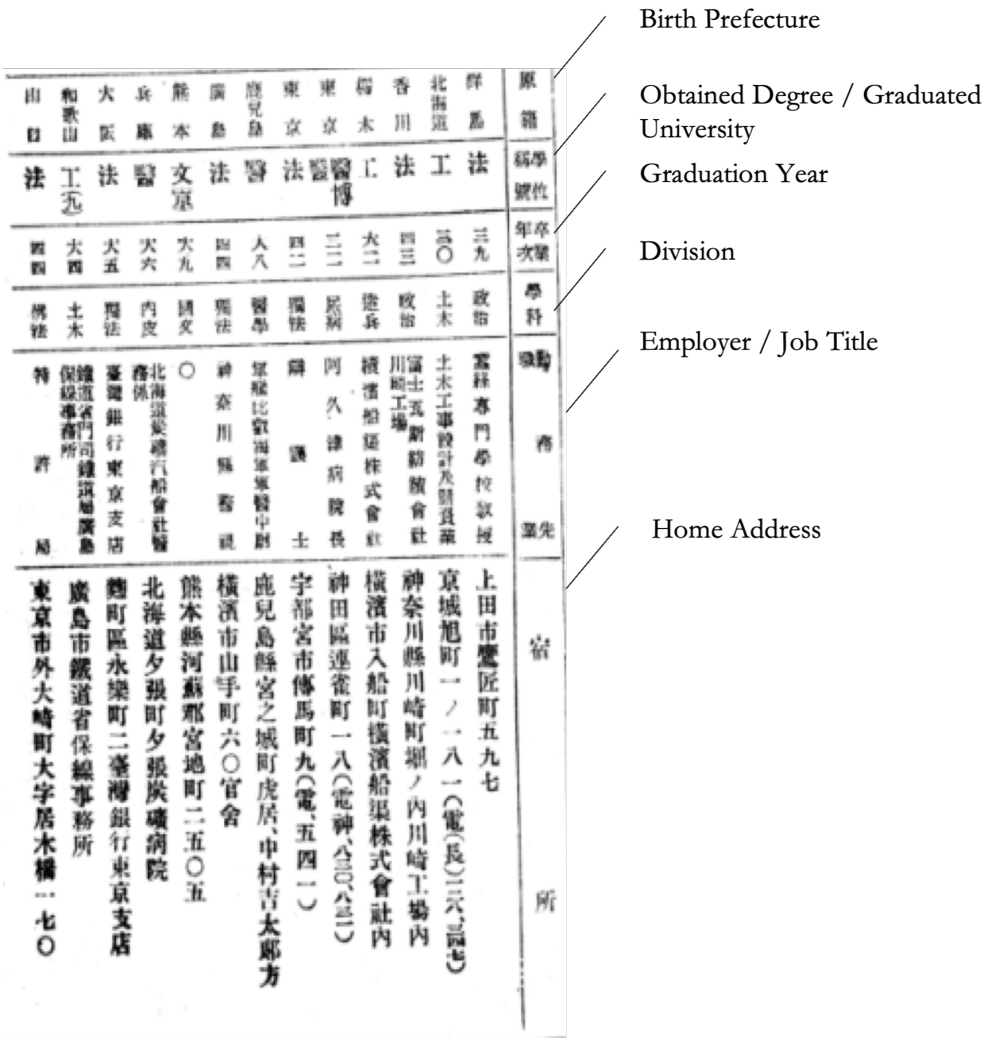
From these calendars, we digitized the data on all bachelor's degree recipients in chemistry-related fields (in both science and engineering schools) from four Imperial Universities that had chemistry-related divisions during our sample period (Tokyo Imperial University, Kyoto Imperial University, Kyushu Imperial University, and Tohoku Imperial University) from their first graduating cohorts (in the late 1870s for the predecessors of Tokyo Imperial University) and until the 1930 graduation cohorts. Thus, our data covers the census of all Imperial Universities-educated chemists and science and engineering from the inception of higher chemical education in Japan and until 1930. The total number of graduates in our sample is 2,462, of which 620 graduated before the onset of World War I (in summer 1914 or earlier), and 301 more graduated between 1915 and 1918, that is, during World War I.

B.2. Annual Alumni Surveys of Imperial Universities' Graduates (*Gakushikai Kaiin Shimeiroku*)

We hand-matched the data on all the graduates described in the previous section with *Gakushikai Kaiin Shimeiroku*, the Alumni Surveys of Imperial Universities' Graduates. Images of those surveys for every year from 1890 to 1939 (with two missing years, 1893 and 1894) were provided to us by *Gakushikai* (the Alumni Association), and they contain information about addresses and workplaces for each graduate belonging to the association, updated annually. We digitized information for all the graduates in our sample who were found in these surveys (about 90% of the universe of all graduates) to construct longitudinal data on their employers and addresses. Figure B.2 shows how the information for each graduate appears in these surveys.

While some parts of the alumni surveys were used in past studies by Japanese historians, we are the first to use all the data available on science and engineering graduates from those surveys. One of the most challenging aspects in creating the full longitudinal database from the alumni surveys was to keep track of name changes that were common in Japan at that time, mostly due to frequent cases of adult adoption. These name changes were noted in appendices to *Gakushikai Kaiin Shimeiroku* which we consulted and reflected in our data. The writing of characters in the names also varies from year to year, which presented another challenge when matching the data. This issue was addressed by visual comparisons, after the first-round matching using script coding. We also triangulated across various other sources, including but not limited to Japanese Personnel Inquiry Records (*Jinji Koushinroku*), Japan Doctors Index (*Dainihon Hakushiroku*), Japan Industrial Handbook (*Nihon Kogyo Yokan*), as well as various biographical databases and online sources, such as historical narratives, company history books, and websites, to supplement the Alumni Surveys data and sometimes corrected those data when we discovered that updates in the surveys were lagging the actual changes in employment or addresses. At this stage, we were able to definitively match 1,889 graduates out of the total of 2,462 (77%) to their employers in at least one year, with the average number of 13.5 years of non-missing observations on employers

Figure B.2: A Sample Page from the Alumni Surveys of Imperial Universities' Graduates



Source: Annual Alumni Surveys of Imperial Universities' Graduates (*Gakushikai Kaiin Shimeiroku*) Taisho 9 (1920). The graduate names are not displayed.

per graduate.[31]

B.3. Patent Publication Records

The Japanese patent system was inaugurated by the Patent Monopoly Act (*Senbai Tokkyo Jōrei*), promulgated on April 18, 1885. During our sample, it underwent two major reforms. The first

[31] Since our sample ends in 1930, the number of observations per graduate is naturally small for those who graduated close to 1930. For those who graduated before the onset of WWI, we have almost 25 years on average per person of observations with non-missing employers.

such reform came in 1899, the year Japan became a member of the Paris Convention for the Protection of Industrial Property, and it allowed foreigners to file patents in Japan for the first time. The second major reform was enacted in 1921; its provisions included a "first-to-file" system, employee ownership of patent rights (although the inventor could assign the right to obtain a patent to the firm, in which case the firm paid the inventor appropriate compensation), and an opposition system. Importantly, no changes to the patent system were enacted during the WWI period which forms the core of our analyses.

Every original patent specification (beginning with the first patent issued in 1885) is preserved at the Japan Patent Office; image data are available through the Patent Information Platform (J-PlatPat), operated by the Industrial Property Information and Training Institute (INPIT; https://www.j-platpat.inpit.go.jp/). We digitized bibliographic information—patent numbers, titles, technology classes, and inventors' and assignees' names and addresses—for all patents granted between 1885 and 1940 (approximately 126,000 records).

The matching with the graduates' records was initially conducted through a text-analysis script, followed by the disambiguation process and manual checks to remove wrong matches. To avoid false matches of same-name but different individuals, we manually checked the consistency of employer and address information between the graduates' records and the patent records for all individual matches. Different combinations and old forms of characters in which names were written were considered and name changes of university graduates were tracked by extensively investigating various sources, including Calendars of Imperial Universities, Japanese Personnel Inquiry Records (*Jinji Koushinroku*), and online searches. The fraction of cases dropped through this manual check was about 10 percent of the total number of initial matches.[32] Overall, 838 graduates in our sample (34% of all graduates) had at least one patent through 1940.

B.4. Scientific Publication Records

The beginning of academic basic and applied chemical science in Japan dates back to the establishment of Tokyo University and the Imperial College of Engineering in 1877, which later merged to form the Imperial University in 1886 which included College of Science and College of Engineering. The Chemical Society was founded in 1878 (renamed Tokyo Chemical Society, *Tokyo Kagaku Kai* in the following year) and it started publishing the first scientific journal dedicated to chemical science, called *Tokyo Kagaku Kaishi* in 1880 (renamed *Nihon Kagaku Kaishi* in 1921) (Nihon Kagaku Kai, 1978, p.98). In 1898 Industrial Chemistry Association was founded and in its turn started publishing the scientific journal called *Kogyo Kagaku Zasshi*. Even though this second journal was tailored toward industry, it is still classified by Japanese historians as publishing articles that present basic scientific research (Nihon Kagaku Kai, 1978, p.110). These two journals remained the top two chemistry field journals in Japan during our sample.

[32] In determining if the patent record belonged to a given graduate or not we chose to err on the side of caution and rejected a match if we could not definitively ascertain that we had a positive match.

For the purpose of this paper, we hand-matched the author names in all articles published in those two journals from their first volumes and until 1930 to our data on the census of all chemistry-related graduates from Imperial Universities and inventors among them. The total number of publications by chemists in our sample across the two journals is 2,917, with 1,908 written by (future) inventors. The number of unique authors is 767, with 361 among them represented by graduates who had at least one patent during our sample period. We also collected the data on the article titles (and full texts in some cases) and conducted similarity analysis with patent titles and abstracts by the same individuals as indicated in the main text.

B.5. Private and Public Research Institutes

The information on private and government (public) research institutes was collected and published in several surveys conducted by Japanese government agencies and Japan Society for the Promotion of Science, starting from the late 1920s. The first such survey containing information about location, founding dates, main research items, budget, and research personnel of 146 public and private research institutes was conducted by the Industry Department of *Shokosho* (Ministry of Trade and Industry) and published in 1929 (Shokosho Komukyoku, 1929). It was followed in the next year by two comprehensive surveys, Shigenkyoku (1930a,b), commissioned by the Resource Department (*Shigenkyoku*) under the auspices of the Treasury (*Okurasho*). These surveys cover 782 government (public) and 331 private research institutions (not limited to chemistry) and they also contain the descriptions of research focus of each research organization, although not about budget or personnel. Finally, Nihon Gakujutsu Shinkokai (1935), a survey published in 1935 by semi-government fJapan Society for the Promotion of Science also contains information on names, locations, dates of founding, research agendas, main personnel and operating budgets of 143 government and non-government research institutes and labs. Since the surveys were conducted by different agencies, they contain some non-overlapping institutions, so I have combined the data from all these three surveys to construct the data used in this paper (391 private and 223 public research institutes).

B.6. Macro and Firm (Establishment) Data

I used Ohkawa et al. (1974) to extract macroeconomic data on Japan's GNP and price indices. The data on GNP in the chemical industry is available from Watanabe (1968) while Okurasho (1925) contains detailed data on Japan's imports by countries and import items.

Firm-level data used in this paper come from the restricted-use Business Archives Online (BAO), provided by the Japan Digital Archives Center (2026). These data contain scanned shareholders' reports for over 14,000 companies. The reports provide brief histories of major events—incorporation, mergers and acquisitions, takeovers, bankruptcies, and dissolution. I used information about primary industry classification and founding dates of the firms in this source to construct the data on firm entry and exit. It is important to note that Japan Digital Archives

Center (2026) does not cover the universe of all firms, although it is a large and representative sample of major firms in all industries. For this reason, I also supplemented these data by comprehensive establishment-level data described in the next paragraph.

Establishment-level data were obtained from Noshomusho (1919, 1921); Shokosho (1931). These are comprehensive surveys of all Japanese manufacturing facilities, conducted at irregular intervals. Each survey contains the date an establishment started operating, the name of the owner and the main product(s) produced, classified into industries. For the purpose of this paper I used three surveys, published in 1919, 1921, and 1931. The establishment founding dates in the 1919 survey were used to construct establishment data for those that started operating before that survey, with the data from the other two surveys added to construct entry dates of establishments that had not yet operated at the time of the 1919 survey.

C. Further Details on Historical Background

C.1. Higher Chemical Education Before and Right After Meiji Restoration

While higher technical education system in Japan was only launched in the late 1870s (see Section 2), chemistry was one area where the Japanese had made some inroads even prior to the Meiji Restoration of 1868 as part of *Rangaku* (Western studies, based on contacts with the Dutch). Yoan Udagawa published the first scholarly book in chemistry, largely a compilation of texts translated from Dutch (some of which were themselves translations from other languages) in 1835 (Shiba, 1964). In 1856 the Tokugawa government (the feudal government prior to Meiji) set up a government-run school that conducted chemistry-related studies and taught a few pupils (*ibid.*) This establishment had little impact, however. Serious chemical education in Japan started in 1869 (the year after the Meiji Restoration) when a state-run chemistry school (Seimikyoku) was established in Osaka, spearheaded by a Dutch chemist, K.W. Gratama. Among the students at this school were such great Japanese chemists as Jôkichi Takamine, a world-renowned chemist who discovered adrenaline and founded several companies in the chemical industry, including Sankyo, Kikunae Ikeda whose research in glutamic acid eventually led to the world-famous Ajinomoto company, and so on. According to (Shiba, 1964, p.34), "even though Seimikyoku itself faded away without producing tangible results, it gave an impetus for the emergence of several top talented individuals who created the basis for Japanese chemistry."

Even though Seimikyoku did not survive, more schools were established already during early Meiji years, preceding the inauguration of the Imperial University. Chemistry division was established, under the leadership of a British chemist, R.W. Atkinson, in Tokyo Kaisei Gakko in 1874 and later became the chemistry division in the College of Science in the Imperial University. Joji Sakurai who was a student of Atkinson and studied in England came back to Japan in 1881 to become the first Japanese chemistry professor.

The Imperial College of Engineering, which later became the College of Engineering at the Imperial University, was founded in 1877 and had the applied chemistry division from the outset. The afore-mentioned Jôkichi Takamine attended this division and graduated from it at the top of his cohort in 1879. Thus, chemistry and applied chemistry education were already put in place in Japan relatively early, and the graduates were recruited by the government to assist in its early efforts to establish the chemical industry in Japan, starting from the 1880s.

C.2. Government Efforts to Build Chemical Industry and Its Limitations

As a latecomer to the industrialization process, Japan embarked on its domestic chemical industry development in the environment where advanced nations had already established modern factory system in this industry. England, in particular, had grown its output and exports of key chemical products such as caustic soda, soda ash, bleaching powder, etc. five to seven times from the mid 1850s-mid 1870s (Watanabe, 1968, p.27-28). The first tangible moves to set up a modern chemi-

cal industry in Japan came from the Meiji government's industrial policy in the late 1870s. One characteristic feature of those policies was its ad hoc approach which put resources into particular products without considering the supply chain issues and the need to systematically overcome technological, marketing, and other barriers to the industry as a whole. As noted by Watanabe (1968), the industrial policy efforts were mostly driven by the demand from traditional sectors of the economy, such as agriculture, and from the military-driven demand for explosives.

The first product the Meiji government set its sights on was sulfuric acid, an important basic chemical commodity used to produce various final chemical products, but especially superphosphate fertilizers. A state-run factory producing sulfuric acid was built with imported machinery and under the guidance of British engineers and started operating already in 1873. By the time it was privatized in 1886, it was producing about 2,000 tons per year and exporting about a quarter of that output to Shanghai. Private domestic production took off shortly after and by 1907, the country was already producing more than 100,000 tons of sulfuric acid per year (Watanabe, 1968, Appendix, p.27), most of which was used in superphosphate fertilizers production by several private companies, including one founded in 1887 with the afore-mentioned Jôkichi Takamine as its chief engineer.

A similar attempt to launch domestic production of other key basic chemical commodities, such as alkaline products (caustic soda and soda ash) as well as bleaching powder ended in failure. While England produced more than 200,000 tons of soda ash already in 1878, the factory set up by the Meiji government could not take off, and the first production data in Japan available in 1905 shows total domestic output of soda ash of just 100 tons (the imports, mostly from England, were almost 10,000 tons in the same year) (Watanabe, 1968, Appendix, p.35).

Inability to start industrially producing a broader range of chemical products, except for sulfuric acid and superphosphate fertilizers in the late 19th century stemmed from various factors, not the least of those being lack of the necessary technological skills and expertise. For instance, when the government tried to launch soda ash production as part of its industrial policy, it utilized the LeBlanc method while a much more economical Solvay method was already being widely adopted in advanced countries at the same time. It wasn't until private companies, led by university-educated engineers started introducing this new technology after the turn of the 20th century that Japan finally could start its own caustic soda and soda ash production.

C.3. Pioneering Efforts by Early University Graduates

While industrial production of chemical commodities remained largely hobbled in Japan, the country kept accumulating university-educated human capital as new cohorts kept graduating from chemistry-related divisions in Imperial Universities. Early chemistry-related graduation cohorts were small and the total number of bachelor's degree recipients in chemistry and applied chemistry from the Imperial University was barely above 100 individuals in the mid-1890s. This number doubled by the early 1900s, and doubled again by 1910. With not many opportunities

of employment in industry or specialized research institutions available to the graduates, a large fraction of them found employment in Imperial Universities themselves, teaching (including secondary schools) or government ministries and administrative establishments.

Anecdotal evidence shows that graduates from those earlier cohorts (many of whom also added experience of studying abroad) possessed the education, talent, and desire to contribute to developing domestic technologies. Some top-notch Imperial University graduates who worked on new technologies on their own and started producing new products include Toragorô Tanahashi who launched his own startup producing iodine right after graduating in 1893 and conducted pioneering experiments in Japan with potassium chemicals (potassium nitrate, potassium sulfate etc.) already in the 1890s. Tanahashi then went on to found several major chemical companies that survived until the present day. Another example is provided by pioneering efforts at carbide production by Tsuneichi Fujiyama in 1900, first experimental caustic soda electrolysis by Bunjirô Masujima who moved into the private sector from a secondary school teaching position in 1902, and so on. Only a handful of those experiments were scaled into industry production at the time, however — while Fujiyama's carbide production led to the establishment of one of the predecessors of *Nicchitsu* (a major chemical-industry conglomerate surviving until the present day under the name of *Chisso*), Masujima's experiment with electrolysis in soda production ended in failure of the company he tried to spearhead and he returned to the teaching profession. The point, however, is that these other efforts furnish a proof that Japanese chemical science and engineering was maturing but needed proper research and organizational conditions to flourish.

Some moves on the government side to assist the industry by creating research organizations also predate WWI. The creation in 1900 of the government-run industrial testing laboratory (which later became Tokyo Industrial Research Institute), in particular, is credited with generating complementary resources in the form of chemical experimentation facilities, a necessary component of developing chemical industry technologies (Watanabe, 1968). The municipal authorities in Osaka and Kyoto also funded and supported research institutes of their own, but those efforts, just as efforts by the private sector noted above were not enough to generate research environment and the factory base to implement new technological ideas on an industrial scale, as noted by Jôkichi Takamine in his address to the Chemical Society of Japan in 1913 cited in the main text.

C.4. World War I and Japan's Chemical Industry

As described in the main text, the situation changed almost overnight with the onset of World War I which created both an acute need to develop domestic production and to generate domestic technologies to support it.

The first impetus came from the private sector, which could finally utilize rich high-level human capital already available in the form of chemistry graduates from Imperial Universities. Several hundred new private chemical industry firms were founded during World War I years, and sev-

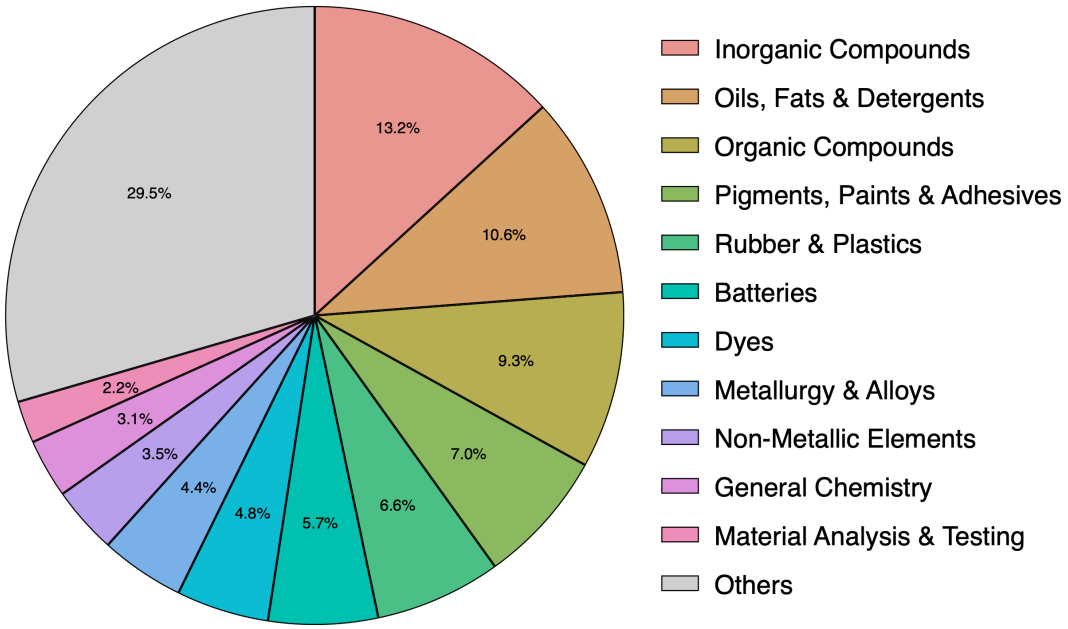
eral hundred chemistry division graduates relocated to the private industry. Chemistry graduates from the 1914-1918 cohorts were also more likely than earlier graduates to start their careers in the private industry. As a result, the share of employment in the private sector among chemistry division graduates tripled between 1911 and 1918 and. Including also closely related industries, such as the newly emerging glass industry, this share exceeded one-third of all chemistry graduates by the end of World War I.

The war-time boom did not last. Once the war was over, imports resumed, although gradually, and the industry suffered a shakeout (Figure 2 in the main text). The continued effort to build a solid research base described in the main text and the ability of the newly emerged research sector (which now included prominent public research institutions) to hire and retain top talent from among university-educated scientists and engineers eventually led to the industry revival and Japan establishing a foothold in the global markets. Recall that Japan completely failed in its attempt to generate soda ash production before the 1910s. After the imports were shut down during World War I, the domestic output, driven by the adoption of frontier technological process picked up steam and by 1920, domestic output had grown to over 7,000 tons per year (compared to less than 1,000 tons at the onset of World War I) but the country still imported more than 62,000 tons from abroad to meet the growing demand. Although outside of the time frame of the current paper, it is worthwhile to note that following concerted public and private R&D efforts, domestic output of soda ash finally exceeded imports in the early 1930s and exports started in 1934. Other chemical products which Japan had not been able to develop before World War I, from alkaline chemicals to synthetic fibers, to celluloid, to photographic film followed a similar growth pattern.

D. Examples of Some Patents Filed during WWI

Figure D.1 shows the share of technology classes of 227 patents filed during WWI. In Table D.1, I present eight patents by Imperial University-educated chemists filed during WWI as examples of two types of import substitution discussed in the main text. The first four patents are examples of technologies developed to produce direct substitutes of imported products whose imports were suspended or severely disrupted during WWI: azo dyes (patent No. 32352), caustic soda (patent No. 28049), potassium chlorate (patent No. 28944), and bromine and bromine compounds (patent No. 29095). The latter four patents are examples of technologies developed by the chemists in our sample to substitute for inputs that became unavailable or extremely expensive during the war or import alternatives. These include using fish oil to produce hydrogenated oil (patent No. 27233), wood cooking method to produce input substituting for imported pulp (patent No. 31676), dye intermediates (patent No. 30718), and cellulose-like product obtained from soy protein (patent No. 32293). Patent details (inventor, dates, class, claim) were obtained from the patent files that can be downloaded at https://www.j-platpat.inpit.go.jp/s0100.

Figure D.1: The Share of Technology Classes of Patents Filed during WWI



Notes: The figure shows the share of technology classes of 227 patents filed between 1914 and 1918. Top 11 technology classes are displayed in the graph as separate groups.

Table D.1: Select Examples of Japanese Chemistry-Related Patents during WWI

Tier 1 — Import-substitution exemplars

No. 32352 — Method for a solid diazo compound that converts to an acid azo dye	
Inventor/assignee	Inoue Jinkichi
Filed/granted; class	1916-04-17/1918-03-11; Cl. 70
What is made	Isolates the diazo compound (from naphthylamine-sulfonic acid) as a stable solid that converts to an acid azo dye on boiling
Displaced import	Acid azo dyes (German pre-war monopoly); a handling-grade intermediate
Novel vs. reproduction	Domestic isolation process for specific diazo salts that Japan could no longer import
No. 28049 — Graphite-electrode arrangement for a mercury-process electrolytic cell	
Inventor/assignee	Yoshikawa Kamejirô/Kadota Michiwake
Filed/granted; class	1915-02-18/1915-07-10; Cl. 100 (electrochem.)
What is made	Graphite-anode arrangement for a mercury-cell chlor-alkali electrolyzer (caustic soda + chlorine); safety valve; easy electrode servicing
Displaced import	Caustic soda/chlorine — heavily imported; WWI cut soda imports and spiked prices, driving domestic soda plants
Novel vs. reproduction	Apparatus/configuration — electrode layout within an existing cell type
No. 28944 — Electrolytic manufacture of chlorate salts	
Inventor/assignee	Tanahashi Toragorô, Imperial Univ. graduate and entrepreneur
Filed/granted; class	1915-07-26/1916-01-28; Cl. 100 (electrochem.)
What is made	Electrolytic production of potassium chlorate, with in-cell sulfate removal (barium chloride / lime / potassium dichromate) enabling continuous operation
Displaced import	German imports of chlorate of potash; used to produce matches, munitions, oxidizers, dyeing
Novel vs. reproduction	Novel electrolytic process – higher chlorate yield/production rate (claimed in patent)
No. 29095 — Method of manufacturing bromine	
Inventor/assignee	Ogawa Masataka
Filed/granted; class	1916-01-16/1916-02-26; Cl. 88
What is made	Bromine from bittern (the magnesium-rich residue of sea-salt making) via nitric acid; bittern recovered for reuse
Displaced import	Bromine and bromine compounds imported from Germany; used in dyes, pharmaceuticals, photographic chemicals
Novel vs. reproduction	Novel simpler/cheaper process — economy through recycling of the nitrogen oxides

continued on next page

Table D.1 (continued)

Tier 2 — Input-substitution / import alternative

No. 27233 — Manufacture of hardened oil (hydrogenated oil)

Inventor/assignee	Tsujimoto Mitsumaru (inventor); Industrial Experiment Laboratory, govt. lab (holder)
Filed/granted; class	1914-10-19/1915-02-08; Cl. 62
What is made	Catalytic hydrogenation of oils: hardening fish/marine oil with a tungsten–nickel catalyst into solid fat (feedstock for soap, glycerin, stearin)
Displaced import	Oil-hardening was European-controlled process technology; applied the catalytic process to fish oil abundant in Japan
Novel vs. reproduction	Applying German-pioneered technology (catalytic hydrogenation) to unsaturated fish-oil fatty acids

No. 31676 — Marusawa-type cooking method for paper-pulp stock

Inventor/assignee	Marusawa Tsuneya
Filed/granted; class	1916-09-06/1917-10-27; Cl. 68
What is made	Sulfite pulping: cooking wood/bamboo with bisulfite liquor; shorter time, lower temperature, chemical recovery, higher yield
Displaced import	Pulp/paper-making technology (European origin); substitutes for imported pulp
Novel vs. reproduction	Process improvement on an existing sulfite method

No. 30718 — Method for a compound serving as a dye raw material

Inventor/assignee	Inoue Jinkichi
Filed/granted; class	1915-05-29/1917-02-02; Cl. 70
What is made	Dye intermediate ("J compound," m.p. 142–144 °C) by oxidizing β-naphthol with a metal oxide; structure undetermined
Displaced import	Dye intermediates (German chemistry); feeds domestic azo/vat dyes
Novel vs. reproduction	(Claimed in patent) German chemists obtained this compound only in trace amounts by a wet oxidation method; dry, sealed-vessel, metal-oxide method makes it at scale

No. 32293 — Non-flammable material resembling celluloid ("Satolite")

Inventor/assignee	Satô Sadakichi, Imperial Univ. graduate and entrepreneur
Filed/granted; class	1915-08-25/1918-03-01; Cl. 91
What is made	Soy-protein thermoset: alkali-extracted soy protein cured with formalin; non-flammable
Displaced import	Targeted Bakelite/ebonite replacement
Novel vs. reproduction	Novel domestic material — a casein/Galalith-family protein plastic