

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

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August 11, 2026

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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. Moreover, the effects persisted after the end of the war but postwar inventions by the same inventors branched out into technology areas beyond wartime import substitution. I show that the import disruption changed the organizational environment as it led to the emergence of long-lived research assets, such as corporate laboratories and public research institutes. I also develop a formal model of the search for new knowledge as discovery to explain how embodied knowledge accumulated during temporary import suspension can lead to persistently increasingly knowledge base, while diverging into new areas.

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*“... Even if the times were ripe, nothing could be done without people willing to undertake such research. However, since 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. ...”*

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*Jōkichi Takamine.<sup>1</sup>*

## 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 could redirect and intensify innovation and technological development, not just in the short run but also in the long run, 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, and why and how does it lead to persistent, long-term consequences on innovation trajectories? Even though the extant literature provides organizational mechanisms behind innovation response to trade disruptions, it 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

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<sup>1</sup> From the address to the Chemical Society of Japan in 1913 ([https://npo-takamine.org/contribution/riken\\_takamine/](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.

54 graduating cohorts and spanning over 40 years of observations before, during, and after WWI on their careers, patents, and major field journal publications.<sup>2</sup>

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 prerequisite 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 only among those with embodied scientific knowledge: despite no difference in inventive output among chemistry graduates prior to the war, those with pre-war top chemistry field journal 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. Moreover, it 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; post-war invention in chemistry-related fields branched out into new technology areas. A natural question is how this happened.

My third empirical finding and theoretical framework address 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

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<sup>2</sup> 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](#)).

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. I also develop a theoretical framework that explains how accumulated scientific knowledge enables scientists to extend their research toward new technology areas.

Taken together, the findings in this paper elucidate an important mechanism behind sudden trade disruptions that require the development of new technologies shaping 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 long-term “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 Jōkichi Takamine in his address to the Chemical Society of Japan in 1913 in the epigraph to this paper. 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.<sup>3</sup> 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,

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<sup>3</sup> 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).

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 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 prerequisite, 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.<sup>4</sup> 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. Moreover, the mechanism I show in this paper is more nuanced than the standard directed technical change and infant industry argument, as innovation response is not limited to technology

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<sup>4</sup> 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.

areas related to import suspension but also branches out into new technology areas. I develop a formal model (in the appendix), which builds on the literature modeling search for new knowledge as discovery on a Brownian path (Callander, 2011; Carnehl and Schneider, 2025), and show how temporary incentive to substitute unknown foreign technologies and accumulated scientific knowledge enable scientists to extend their research toward broader technology areas.

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).<sup>5</sup> 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 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.<sup>6</sup> 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 my theoretical framework, I demonstrate that such pre-existing accumulated knowledge, embodied in individual scientists and engineers, can be initially dormant because of blocking foreign technologies but is “activated” by the import suspension shock, which can lead to breaking out of stagnation and to a sustained technological growth path. I show empirically that the persistence of innovation even after the end of WWI import suspension came from the durability of activated embodied human capital and a 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 poli-

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<sup>5</sup> “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).

<sup>6</sup> 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).

cies 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 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.<sup>7</sup>

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

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<sup>7</sup> See also Creanza (2025); Kim and Moser (2025); Codreanu et al. (2026) for studies using unusually granular individual-level data from important historical contexts.

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 presents the conceptual framework. 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.<sup>8</sup>

### 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.

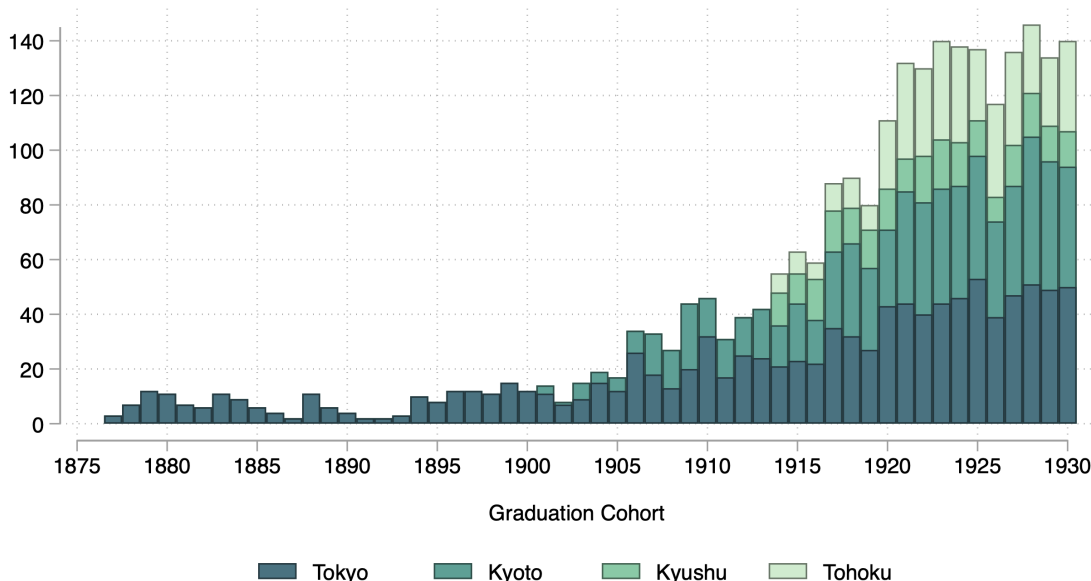
The first state-run chemistry school, *Seimikyoku*, was established right after the Meiji Restoration in Osaka, the commercial and financial center of Japan at that time and was spearheaded by a Dutch chemist, K.W. Gratama. Even though that particular school did not survive, it was attended by some prominent 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

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<sup>8</sup> 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.

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.

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 Engineering department and Chemistry division in the Science department separately.<sup>9</sup>

## 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

<sup>9</sup> 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.

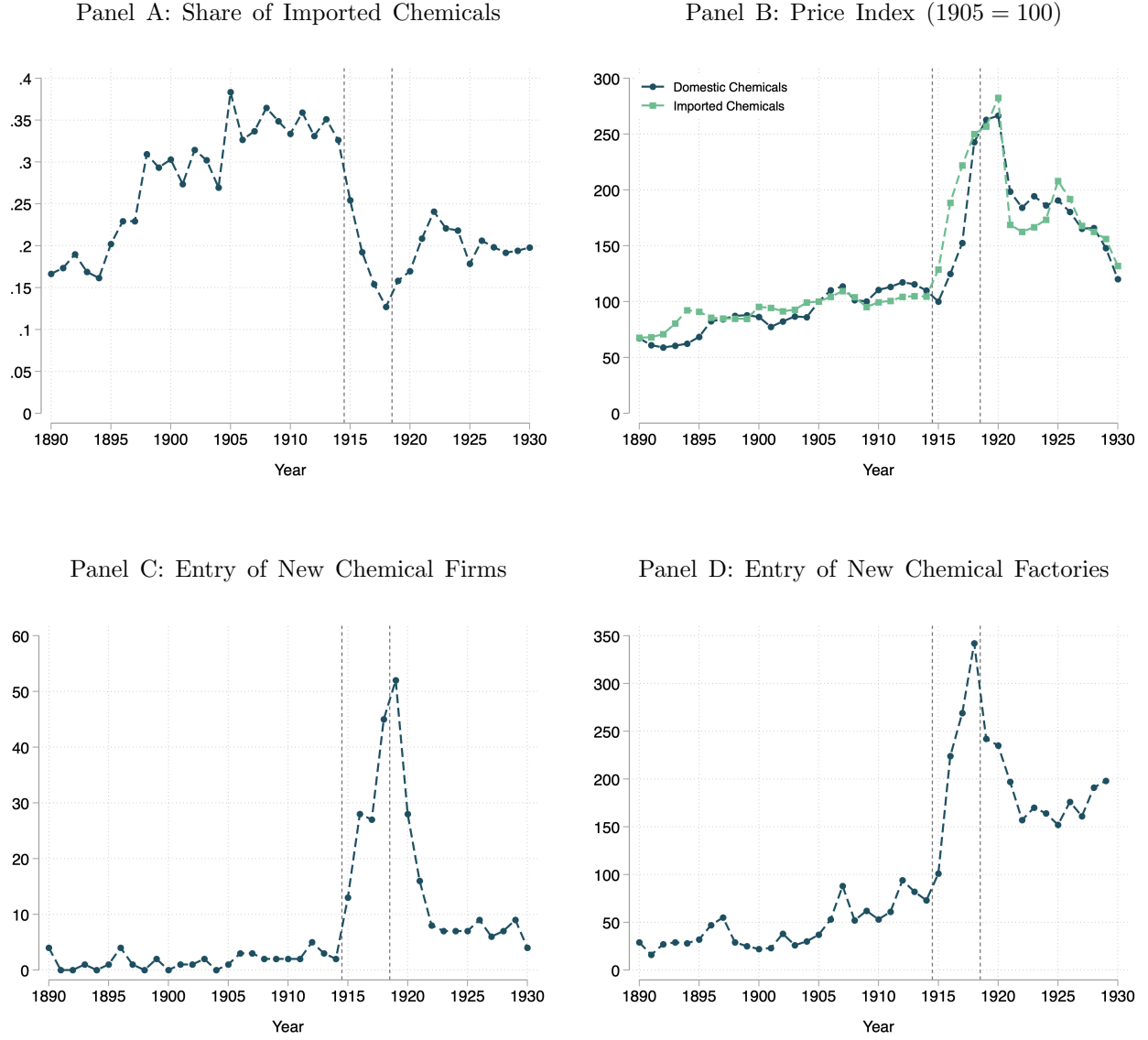
mostly driven by the demand from traditional sectors of the economy such as agriculture, the infrastructure-driven demand such as minting and road pavement, and the military-driven demand for explosives (Watanabe, 1968). Among the first products the Meiji government set its sights on were sulfuric acid, 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).

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

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

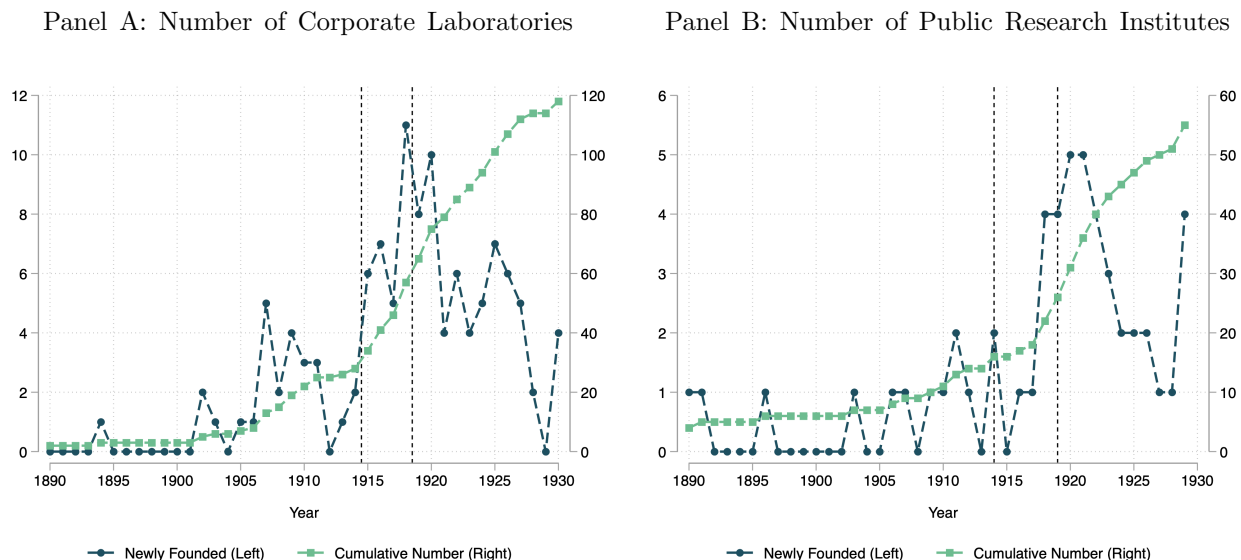


*Notes:* The figures present the time series of aggregate statistics in chemical industries from 1890-1930. Panel A shows the share of imported chemicals in chemical gross national product, Panel B shows the price indices of domestically produced and imported chemicals, Panel C shows the number of newly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

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,

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.

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 both industry and the government.<sup>10</sup> 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 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.<sup>11</sup> The

<sup>10</sup> In the already cited address to the Chemical Society of Japan in 1913, Jōkichi 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).

<sup>11</sup> 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

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 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 Sci-

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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.

ence 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.<sup>12</sup> 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, I 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. I used information on income tax schedules reported in the annual reports of Japan's Tax Bureau (*Shuzeikyoku Tokei Nemposho*, 1896-1930) to calculate incomes based on income tax information from *Who is Who*. Earnings data from *Who is Who* were matched with the graduates in chemistry-related fields from Imperial Universities using information on names, addresses, and workplaces. I was able to match 710 chemistry-related graduates (about 40 percent

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<sup>12</sup> 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.

of those with employment data) to *Who is Who* in at least one year, giving 5,211 hand-coded income tax (and income) observations in years 1902-1930.<sup>13</sup>

### 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.

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<sup>13</sup> *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.

## 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 technologies demanded by 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.<sup>14</sup>

Figure A.3 in Appendix A shows the evolution of patenting by university-educated scientists and engineers in 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 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

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<sup>14</sup> 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.

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-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.<sup>15</sup>

#### 4.1.2. Contents of Chemistry-Related Inventions during WWI

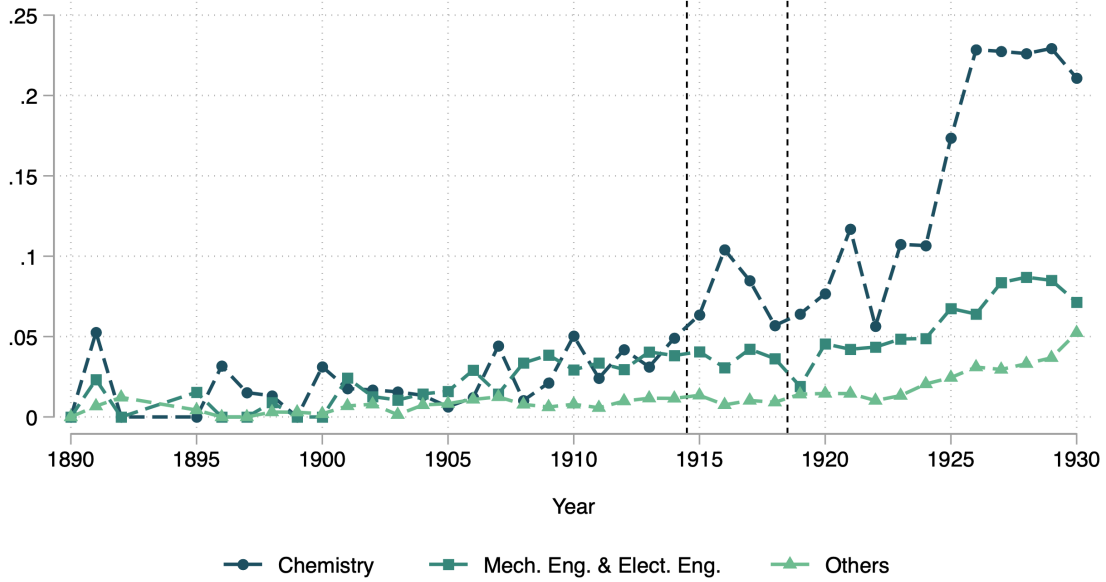
The WWI boost to patenting by university-educated chemists shown in Figure 4 is suggestive of the role played by import suspension but by itself does not establish that relationship. To verify this link, I examined the contents of patents applied for by Imperial University-educated chemists during WWI, 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 produc-

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<sup>15</sup> It is worthwhile mentioning that there were no major changes to Japan’s patent law between 1899 when the country joined the Paris Treaty and 1921. After 1921, Japan officially transitioned from the *first-to-invent* system to the *first-to-file* system. However, this legal change applied to both chemical and non-chemical patents, suggesting that there was no specific reason why the difference in patenting between chemical and non-chemical fields widened because of this change of the patent system, so the findings here and below are not necessarily attributable to changes in the legal environment.

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.

tion 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 Satō, 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, Jōkichi 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.<sup>16</sup>

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 educated 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:

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

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<sup>16</sup> 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.

where  $y_{it}$  is the number of patent applications by graduate  $i$  in year  $t$ ,  $\text{Chem}_i$  is an indicator variable for graduates from the chemistry-related divisions,  $\text{WWI}_t$  is an indicator variable for periods between 1915 and 1919,  $\text{PostWWI}_t$  is an indicator variable for periods 1920 onward, and  $d_i$  and  $d_t$  are individual and year fixed effects, respectively. The coefficient  $\beta_1$  and  $\beta_2$  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.

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 statis-

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

|                       | (1)<br>All            | (2)<br>Only High-Tech | (3)<br>No Publications | (4)<br>With Publications |
|-----------------------|-----------------------|-----------------------|------------------------|--------------------------|
| WWI $\times$ Chem     | 0.0348***<br>(0.0107) | 0.0277**<br>(0.0132)  | -0.0006<br>(0.0113)    | 0.0664***<br>(0.0231)    |
| PostWWI $\times$ Chem | 0.0700***<br>(0.0153) | 0.0571***<br>(0.0132) | 0.0109<br>(0.0166)     | 0.1354***<br>(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                   |

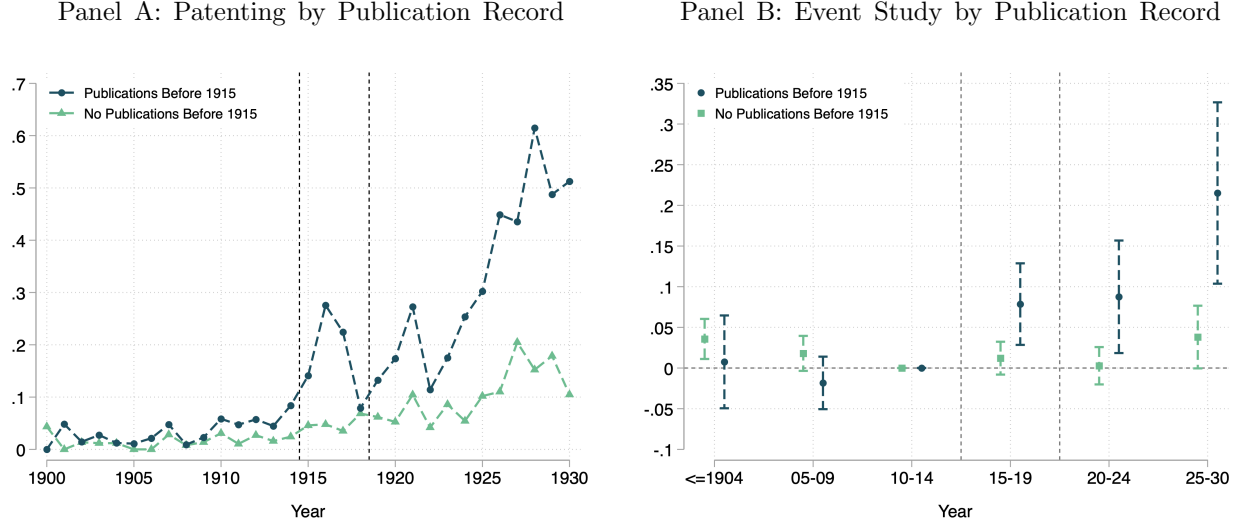
*Notes:* The table reports the estimated coefficients from the static difference-in-differences specification. Column (1) includes those from all divisions in the estimation sample. Column (2) restricts the sample to only those from chemistry-related divisions and other high-tech divisions (Mechanical 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: \*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$ .

tically 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.<sup>17</sup> Once crisis innovation happened, it was this part of highly educated human capital that could respond to

<sup>17</sup> 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



*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.

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:

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

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.<sup>18</sup> For example, Sadakichi Satō (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 (Satō, 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, Kamejirō 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.

Was it indeed embodied scientific knowledge or some 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

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<sup>18</sup> 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.

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 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.<sup>19</sup>

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](#).

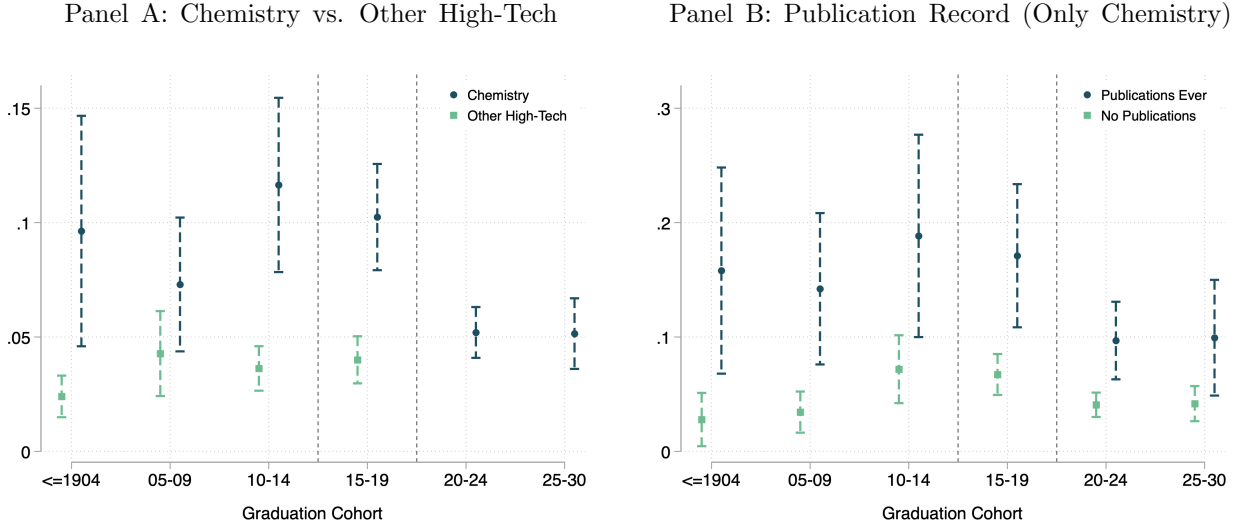
### 4.3. Do New Cohorts Contribute More to Post-war Invention?

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

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<sup>19</sup> 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.

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 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 disproportionately 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.<sup>20</sup> My findings also imply that high scientific potential can adapt

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<sup>20</sup> 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

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, its effects not only persisted but compounded for years after 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 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, and the evidence mainly points toward the latter. 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. In Section 5.4, I demonstrate why post-war invention branched into new directions by developing a theoretical model (presented in the appendix) that conceptualizes key insights from my empirical findings.

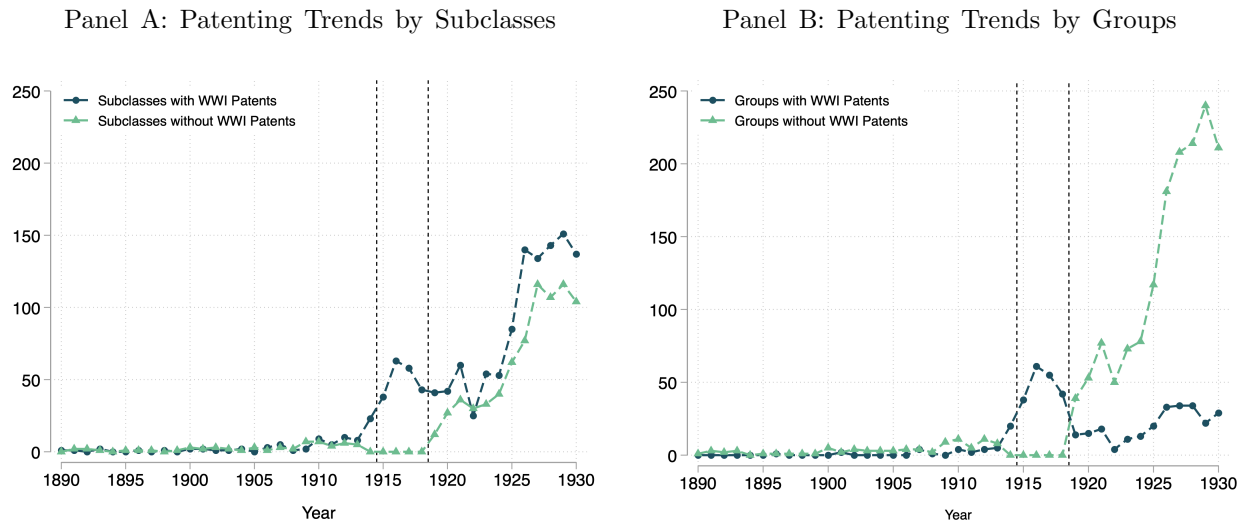
### 5.1. Was Long-term Invention Direct Continuation of Import Substitution?

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 construction, the latter group has zero patents during the war, of course. Here, 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

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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.

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. Panel A (Panel B) uses patent subclasses (groups) to define technologies where graduates had at least one patent between 1914 and 1918.

the relationship between patents filed during and after the war by the graduates in the sample.<sup>21</sup> 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, 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. Figure D.1 and Figure D.2 in Appendix D show that differences between WWI and post-WWI patents can be seen even at the broader, three-digit IPC class level.

In Table A.4, I 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

<sup>21</sup> 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.

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. Qualitative evidence similar to that in Section 4.2.2 further supports these estimation results. Table D.2 in Appendix D documents eight examples of post-WWI patents by the same inventors whose patents during WWI were also presented in Table D.1. Only one or two of those new patents can be positioned as directly continuing the research done during WWI. Most others, while applying similar or related methods (not surprisingly so because it is the same inventors, after all), move into new technology classes. While wartime patents tended to cluster on the products where German supply was most severely hit, post-war patents by the same inventors branched out into new technology areas, beyond import substitution. To sum up, the evidence does not support the notion that post-war increase in patents was simply a direct continuation of WWI-related invention.

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.

Taken together, the evidence in Section 4 and in this section presents two non-trivial puzzles. First, why did the scientists who contributed to invention during WWI continue invention at all even if there was no longer acute necessity to build technologies related to import suspension? Second, why did their invention diverge to new technology areas that were not necessarily related to the import suspension? I address the first question in Section 5.2, followed by further examination in Section 5.3, and the second question in Section 5.4.

## 5.2. Emergent and Long-lived Research Systems

The examination in the previous section indicates that even though temporary import suspension during WWI 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 orga-

nizations 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 the Imperial University system emerged as the cornerstone of basic research in Japan at that time (Hiraiwa et al., 2025a). Finally, the education sector includes all other education institutions other than Imperial Universities, such as technical colleges, high schools, military schools, and so on.

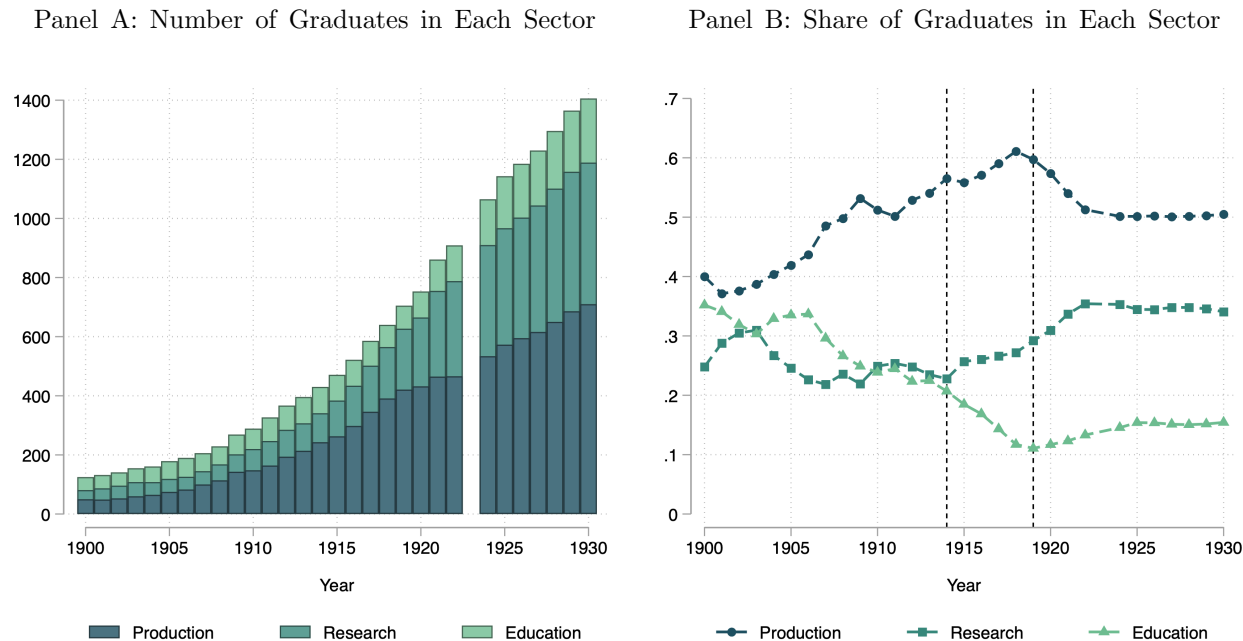
Panels A and B in Figure 8 show the aggregate trends in the numbers and shares of university-educated scientists and engineers in each sector, respectively.<sup>22</sup> Although not shown in the figure, in the 1890s, when the number of graduates was still small, the majority worked in the education 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 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.

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. As organizational innovation toward establishing a research system emerged, the research sector increased its demand for university-educated graduates while 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

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<sup>22</sup> 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



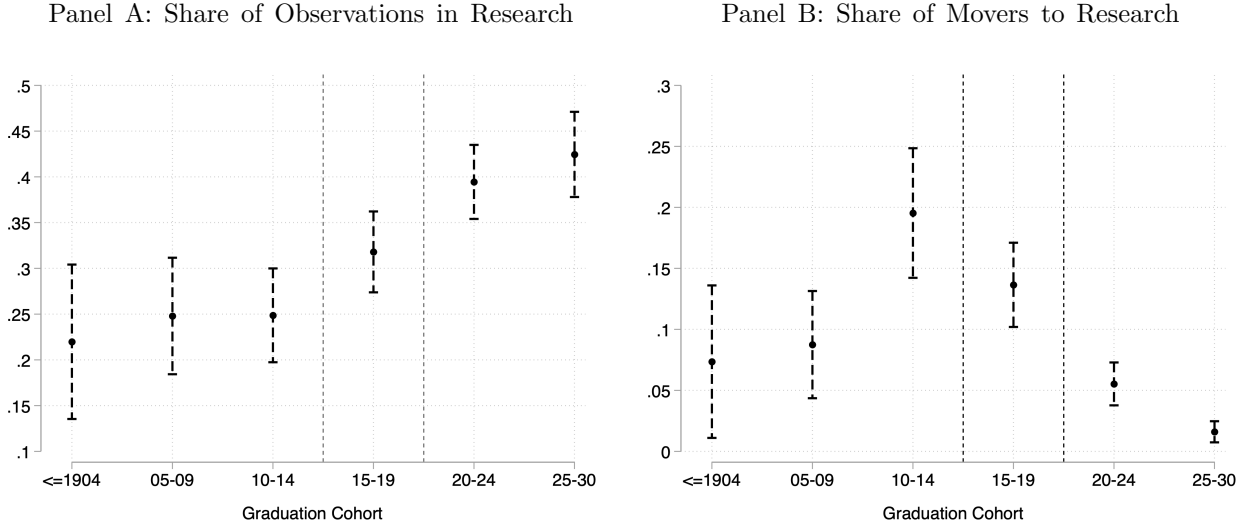
*Notes:* The figure shows the number and share of Imperial University graduates from chemistry-related divisions in each sector by year. Each bar and line represent the number and share of graduates in the production, research, and education sector, respectively.

of reallocation into the research sector did not end with the end 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.<sup>23</sup> Note,

<sup>23</sup> 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

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).

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). Importantly, as mentioned, we do not observe any trend reversal after WWI at all in chemistry-related research.

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 and especially after the war ended, with the share of those employed in research reaching more than 40 percent among the cohorts graduating in 1920-1930.

Second, post-war increase in the share of graduates in the research sector was also driven by

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with financing from gas companies that previously employed those engineers. Details are available upon request.

the reallocation of incumbent scientists and engineers. 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 time (the 1910-1914 cohorts). 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. Interestingly, if we look at the trends in earnings in each sector, [Figure A.8](#) in [Appendix A](#) shows that those followed similar trajectories up to 1920, but after that, the pay gap between the production sector and other sectors became quite pronounced. As explained in [Appendix B](#), due to the nature of our earnings data, we observe mid- and later career earnings more than early post-graduation earnings, so that the trends in [Figure A.8](#) largely reflect the differences in earnings across sectors for mature, incumbent scientists and engineers. One interpretation is that the research sector became more attractive to incumbents by providing more non-pecuniary payoffs, such as better research environment, catering to the top talent “taste for science” ([Stern, 2004](#)).<sup>24</sup> If that is so, it is also possible that the production sector, especially private industry may have been forced to increase the salaries of their top-talented scientists to prevent them from leaving. 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 Jōkichi Takamine. Increased supply of research labs and institutes after the onset of the war changed the situation. Either way, the evidence indicates that the emerging research environment was attractive enough not just for new graduates but also for incumbent talent to change the direction of their careers, and this was another important source of human capital for research.

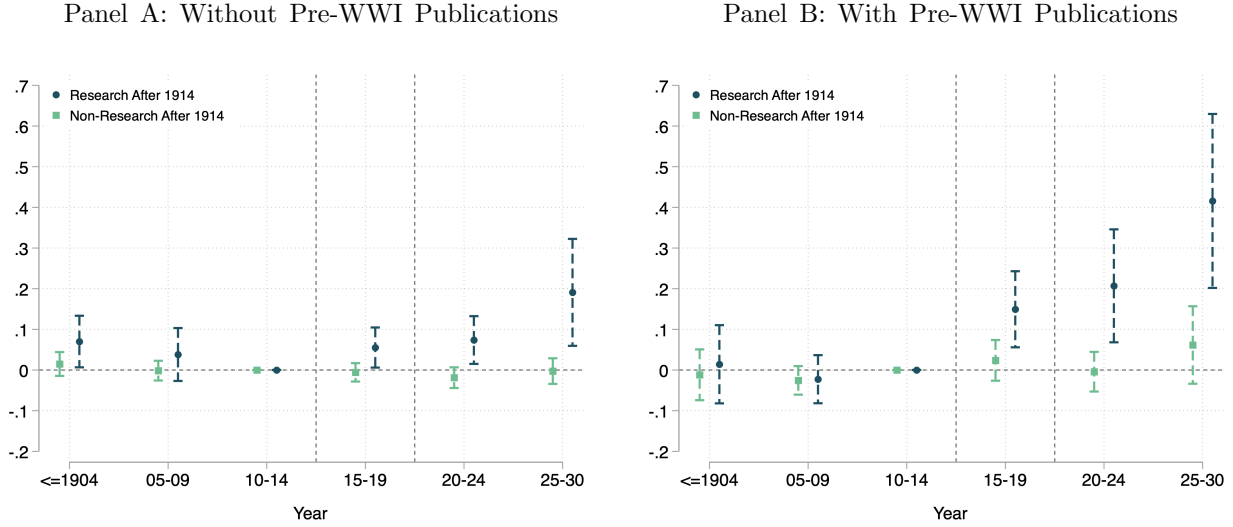
### 5.2.2. “Researchers” in Corporate Laboratories and Research Institutes

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 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 sec-

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<sup>24</sup> 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.

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. “Research After 1914” group refers to chemistry graduates with at least one year of experience working in the research sector after 1914, while “Non-Research After 1914” refers to those with no such experience. 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.

tor for at least one year after 1915 and those who never worked in research after 1914. 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 1914. 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 the graduate worked in the research sector in a given year and zero otherwise. The sample is limited to graduates from

Table 2: Patenting by Graduates in Research Sector

|                | (1)<br>Baseline       | (2)<br>Within-Individual | (3)<br>Staggered DiD  |
|----------------|-----------------------|--------------------------|-----------------------|
| Research       | 0.0905***<br>(0.0175) | 0.101***<br>(0.0303)     | 0.0907***<br>(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: \*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$ .

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 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 still seems to be an important moderator for post-1914 patenting outcomes.

### 5.3. The Source of Long-term Boost: “Activation Effect” Revisited

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 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,<sup>25</sup> 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.<sup>26</sup> 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 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

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<sup>25</sup> 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.

<sup>26</sup> 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 $\times$ $\mathbb{1}\{\text{PreWWI Publications}\}$                       | 0.113**<br>(0.0540) | -0.0363<br>(0.0560)  | -0.0363<br>(0.0561) |
| PostWWI $\times$ Research                                                         | 0.129**<br>(0.0646) |                      | 0.133**<br>(0.0635) |
| PostWWI $\times$ Research $\times$ $\mathbb{1}\{\text{PreWWI Publications}\}$     | 0.0332<br>(0.121)   |                      | -0.0229<br>(0.128)  |
| PostWWI $\times$ PostResearch                                                     |                     | 0.0143<br>(0.0368)   | -0.0131<br>(0.0347) |
| PostWWI $\times$ PostResearch $\times$ $\mathbb{1}\{\text{PreWWI Publications}\}$ |                     | 0.223***<br>(0.0819) | 0.203**<br>(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: \*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$ .

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). In this fully saturated specification, there is 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 Theoretical Framework

So far, I have shown the following three main facts. First, 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 long-term robust innovation. Second, this was supported by the emergence of corporate laboratories and public research institutions and sorting of talent into such organized research environment. Third, while the emergence of the organized research sector played an important role, the most salient feature 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. Moreover, while all scientists and engineers employed in research organizations at a given time generated inventions 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.

While the second and third points show how post-war invention continued, they do not tell us why such inventions went beyond the technology areas related to WWI import suspension. Of course, organized research environment was a prerequisite for the extension of research into various technology areas, but why scientists could do that is another issue and requires further examination. Moreover, if post-war invention was no longer driven by the necessity to develop import-substitution technologies, then why do we not see invention in post-war technology areas even before the war? The question therefore is, what do these empirical findings tell us about the conditions under which a temporary shock such as import suspension can lead to long-term consequences in terms of a sustained technological growth path? To answer this question, I develop a model inspired by the literature modeling search for new knowledge as discovery on a Brow-

nian path (Callander, 2011; Carnehl and Schneider, 2025).<sup>27</sup> The formal model can be found in Appendix E, while here I present a non-mathematical overview of the model.

Following the literature, research is conceptualized as a costly search process where the researcher picks a question to investigate and also chooses the intensity with which to conduct the investigation. The core innovation in this literature is to model the learning of correlated outcomes by representing the uncertain outcome mapping as the realized path of a stochastic process. Researchers “observe outcomes at selected alternatives and draw inferences about other alternatives” (Bardhi and Callander, 2026). More precisely, the universe of questions are represented by the real line and each question  $x$  on this real line has a unique answer,  $y(x)$ , determined by the “truth” represented by the graph of the realization of a random variable that follows a standard Brownian motion defined over the entire real line. The truth is fixed but answers are unknown until successfully discovered. As in Carnehl and Schneider (2025), the cost of research effort depends on how well existing knowledge reduces research uncertainty and the incentive for research is related to how novel the question is, balanced against the research cost. I assume that rewards to successful research are tied to the novelty of new technologies generated by finding answers to previously unknown questions. In the baseline version of the model, this reward takes the form of a step function — if a newly answered question is close enough to a question the answer to which is already known, the incremental value of the new technology is zero, while if the distance from the newly answered question to any question the answer to which is known is above a certain threshold, then the new technology generates a given positive reward.<sup>28</sup>

Two more assumptions adapt my model to the empirical context of this paper. First, I assume that existing knowledge is “embodied” in the sense that only a particular type of agents, whom I call “scientists” have access to the whole body of accumulated knowledge, that is, at any point in time, they know the answers to all questions anyone has ever discovered an answer to. Since this knowledge reduces their research uncertainty, it improves the precision of their conjectures about the answer to any given new question compared to non-scientists who can only rely on the knowledge about the questions they themselves previous discovered. Second, I introduce the set of foreign technologies which are not part of the domestic body of knowledge but whose presence nevertheless affects rewards to domestic research. More specifically, if a foreign technology is at a point  $z$  on the real line, any domestic research that finds the answer to a question close enough to such  $z$  does not result in producing a technology that can generate a positive reward. Proposition 1 in Appendix E shows that because of this, the presence of foreign technologies can stifle domestic research in areas that are in the vicinity of the space occupied by foreign technologies.

I then introduce a temporary war-time shock during which the supply of imported products based on foreign technologies is suspended, resulting in a product-market scarcity premium for products that substitute for imports. Proposition 2 in Appendix E shows that, during this import

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<sup>27</sup> See Bardhi and Callander (2026) for a recent survey of this literature.

<sup>28</sup> The reward function can be generalized to an S-shaped continuous function. See Appendix E.

suspension, these extra rewards activate domestic research which had been previously blocked by the proximity to foreign technologies. That is, since during import suspension, novelty is measured against only domestic discoveries, research can now be conducted at wartime problems — questions adjacent to the suspended foreign technologies that previously did not generate enough rewards. Since only scientists with embodied human capital have access to the whole domestic stock of knowledge, including previous answers to questions that border the foreign technology areas, such new research in the import-substituting areas is predominantly conducted by scientists as opposed to non-scientists.

Furthermore, the wartime shock, though temporary, affects future research even after imported products and foreign technologies come back. Intuitively, while before the war, questions that were novel relative to the entire technology set were too uncertain to be worth researching, new knowledge obtained through finding solutions to war-time problems expands the set of questions the answers to which are now known (to scientists). The same Proposition 2 in [Appendix E](#) formalizes the sense in which this has permanent effects on the knowledge structure: once the domestic knowledge frontier reaches the boundary of the foreign technology set, frontier questions are now far enough away from every foreign technology, so the novelty constraint imposed by foreign technologies no longer binds even as they come back. As a result, scientists with embodied knowledge can generate more precise conjectures at every question, which translate into a larger success probability both during and after the war. In other words, the wartime shock acts as a springboard: during the war, research is pulled into the wartime problems; once the war ends and foreign supply resumes, the novelty constraint once again implies that import-substituting questions are no longer rewarded, but post-war research can now move beyond those, into adjacent spaces where the uncertainty had been too high before the war. The wartime import-substitution phase is thus transitional by construction: it supplies the stepping stones across the foreign technology set, after which research permanently migrates to genuinely new territory.

Note that the mechanism in this framework is different from the standard directed technical change ([Acemoglu, 2002](#)) and infant industry argument ([Juhász, 2018](#)). Compared to the standard theory of directed technical change, in this framework technologies can develop not only in the directions driven by the emerging demand, but also in new directions beyond temporarily demanded technologies. The reason is that previous discoveries reduce the variance of conjectures about answers to questions that are sufficiently close to questions the answers to which had already been found, and this leads to a continuous expansion of knowledge (see Figure E.2 in [Appendix E](#) for a visual illustration). Also, while in the conventional infant industry argument, the dynamic externality (learning-by-doing) implies continued growth along the same technological path, my framework shows that temporary demand for some technologies could lead to research spillovers into other, broadly related technology areas. Another distinctive feature of my framework is that innovation response would occur only among researchers with accumulated embodied scientific knowledge obtained before the onset of import suspension.

While the current model focuses on the heterogeneity of short-term and long-term research response between scientists with embodied human capital and non-scientists, it can be extended to incorporate the emergence of organized research environment, which, as shown in Section 5.3 is empirically relevant. In such an extension, research institutes serve as vehicles that give non-scientists employed there access to the accumulated body of knowledge similar to what scientists have, but only while they actually work in the research sector.

## 6. Conclusion and Discussion

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, despite the supply of such talent, 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.

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 necessity to build a technological basis for developing the domestic chemical industry. The immediate effect was a burst of chemistry-related invention, many aimed at substituting for imported products that became unavailable or extremely expensive during wartime. I show that WWI import suspension shock harnessed 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. 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 returned and domestic chemical industry was plunged into crisis. That is, the temporary import suspension served as a catalyst for a persistent, long-term impact on chemistry-related invention in Japan and 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 which mushroomed during and immediately after WWI. The newly created organized research hired a large number of chemistry graduates, including both incumbent workers who relocated to research during and after the shock, and new graduates who only graduated after WWI, and 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 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.

At a high level of abstraction, my findings and conceptual framework can be interpreted in terms of a dynamic learning externality reminiscent of infant industry protection or industrial policy argument (Juhász, 2018; Alfaro et al., 2025), or targeted government research programs (Gross and Sampat, 2023, 2025). There are important differences, however. One such difference is that the dynamic externality in my framework and in empirical evidence presented in this paper affects only researchers with embodied scientific knowledge obtained before the onset of import suspension and is not shared by those without such embodied knowledge. The second important difference is that while the conventional dynamic externality implies continued growth along the same technological path, empirical evidence presented in Section 5.1 and Appendix D shows that after the end of the war, technology growth did not continue along the same path as during wartime import suspension but branched into new areas. This means that import suspension did not simply lead to the removal of the barriers to some specific sub-industries or technology areas, but opened new horizons for top-level human capital that had been dormant until then, as also reflected in my conceptual framework and the formal model.

My investigation of the “microfoundations” of the effects of WWI import suspension shock on innovation revealed that even among the knowledge elite, only those with 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 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 future, and policies, markets, and firms need to pro-actively invest in

building and sustaining top-notch human capital without waiting for a crisis to happen.

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 eventual 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)<br>Graduates | (2)<br>Non-Graduates | (3)<br>Difference  |
|--------------------------------------------------------------|------------------|----------------------|--------------------|
| Number of Patents                                            | 3.84<br>(6.62)   | 1.74<br>(3.17)       | 2.11***<br>(13.58) |
| $\mathbb{1}\{\text{More Than Two Patents}\}$                 | 0.56<br>(0.50)   | 0.26<br>(0.44)       | 0.30***<br>(25.68) |
| $\mathbb{1}\{\text{Listed in Imperial Inventor Directory}\}$ | 0.16<br>(0.37)   | 0.06<br>(0.24)       | 0.10***<br>(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)<br>Publications | (2)<br>No Publications | (3)<br>Difference |
|----------------------------------------------|---------------------|------------------------|-------------------|
| Number of Patents                            | 3.73<br>(7.52)      | 1.12<br>(2.71)         | 2.61***<br>(4.67) |
| $\mathbb{1}\{\text{More Than Two Patents}\}$ | 0.39<br>(0.49)      | 0.18<br>(0.38)         | 0.21***<br>(5.35) |
| Doctoral Degree                              | 0.34<br>(0.48)      | 0.07<br>(0.25)         | 0.28***<br>(7.57) |
| Science Degree                               | 0.31<br>(0.46)      | 0.30<br>(0.46)         | 0.01<br>(0.22)    |
| University Graduation Ranking                | 0.63<br>(0.33)      | 0.43<br>(0.33)         | 0.20***<br>(6.00) |
| High School Graduation Ranking               | 0.59<br>(0.31)      | 0.46<br>(0.30)         | 0.13***<br>(4.12) |
| Study Abroad                                 | 0.36<br>(0.48)      | 0.12<br>(0.32)         | 0.25***<br>(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 $\times$ Chem | -0.000242<br>(0.0125) | 0.00741<br>(0.0188)   | 0.0706**<br>(0.0305) | 0.0989**<br>(0.0422) |
| Post WWI $\times$ Chem   | 0.00282<br>(0.0148)   | 0.0656***<br>(0.0251) | 0.114*<br>(0.0661)   | 0.214***<br>(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 $\times$ Chem | -0.00292<br>(0.00976) | 0.0219<br>(0.0625)  | 0.0318<br>(0.0196) | 0.111**<br>(0.0495)  |
| Post WWI $\times$ Chem   | 0.00133<br>(0.0117)   | 0.122**<br>(0.0600) | 0.0267<br>(0.0248) | 0.301***<br>(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)                   | (2)                    | (3)                   | (4)                    |
|                | WWI Areas             | Non-WWI Areas          | WWI Areas             | Non-WWI Areas          |
| During WWI     | 0.0901***<br>(0.0211) | -0.00977*<br>(0.00508) | 0.0970***<br>(0.0215) | -0.0167**<br>(0.00803) |
| Post WWI       | 0.0918***<br>(0.0219) | 0.0881***<br>(0.0193)  | 0.0196*<br>(0.0106)   | 0.160***<br>(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)                  | (2)                  | (3)                  | (4)                  |
|                | WWI Areas            | Non-WWI Areas        | WWI Areas            | Non-WWI Areas        |
| During WWI     | 0.384***<br>(0.0474) | 0.00696<br>(0.0115)  | 0.382***<br>(0.0474) | 0.00902<br>(0.0188)  |
| Post WWI       | 0.119***<br>(0.0428) | 0.156***<br>(0.0386) | 0.0140<br>(0.0236)   | 0.261***<br>(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                |

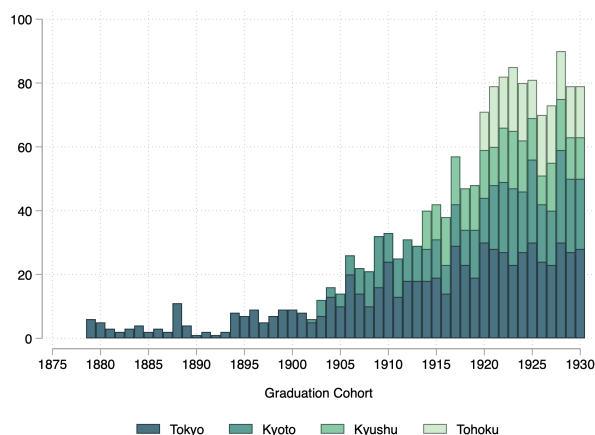
*Notes:* The table reports the estimated coefficients from the following regression specification using the sample of graduates from chemistry-related divisions:

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

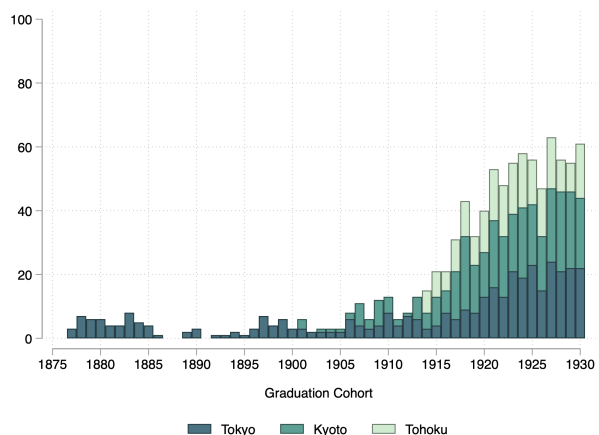
where  $y_{it}$  is the number of patent applications by graduate  $i$  in year  $t$  in technology areas where some chemistry graduates did (did not) have at least one patent during WWI,  $\text{WWI}_t$  is an indicator variable for periods during,  $\text{PostWWI}_t$  is an indicator variable for periods 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

Panel A: Engineering Department

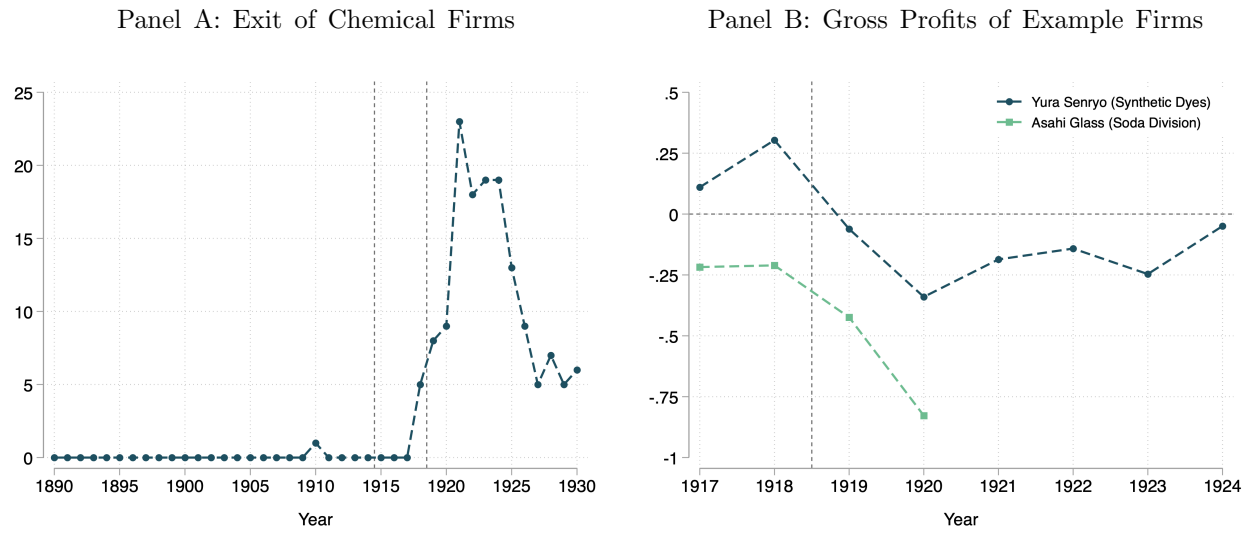


Panel B: Science Department



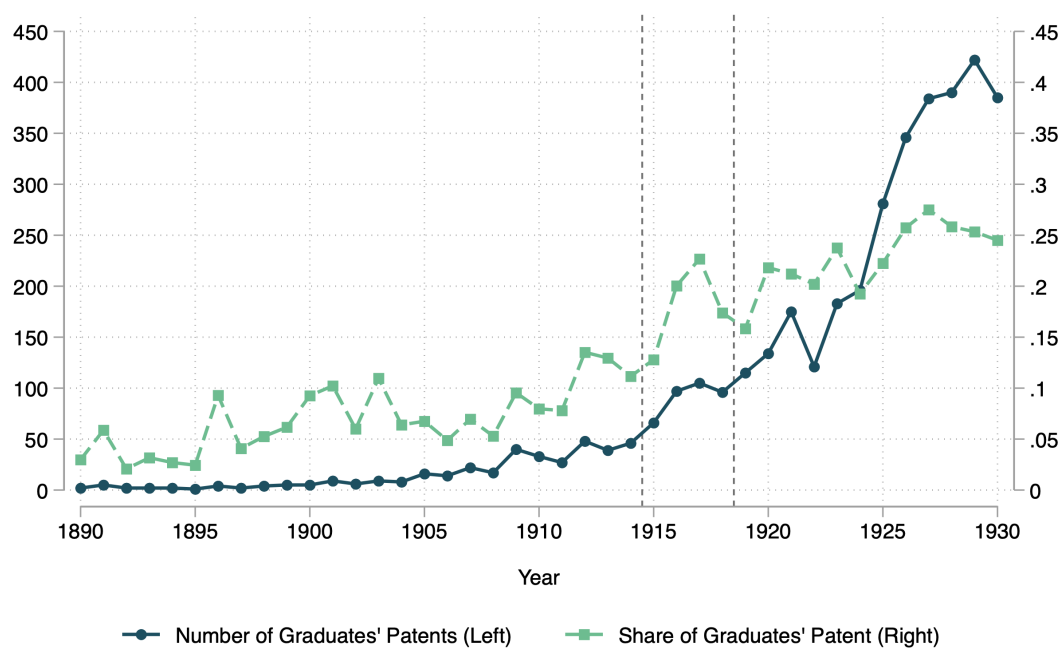
*Notes:* The figure shows the number of Imperial University graduates from chemistry-related divisions in Engineering and Science departments, respectively, by graduation cohorts. Each bar represents the number of graduates from four Imperial Universities. Note that Kyushu Imperial University did not 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



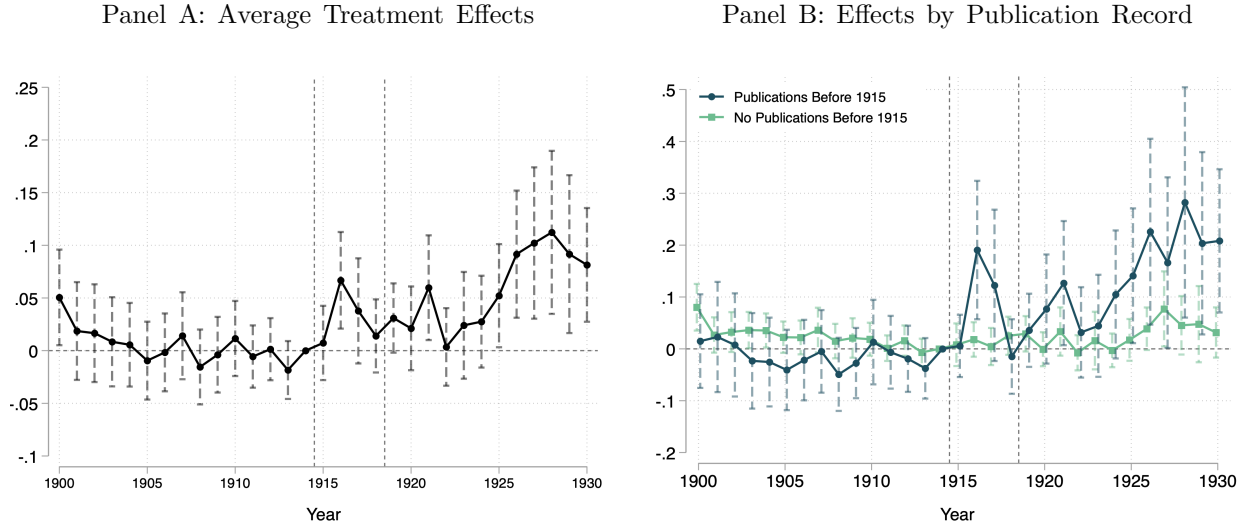
*Notes:* In Panel B, the profits are plotted in millions of yen. *Yura Senryo* was founded in 1914 and incorporated in 1917. It was the first producer of synthetic dyes in Japan and survives until the present day as Y.S.K. ([https://www.yskco.jp/en\\_company.html](https://www.yskco.jp/en_company.html)). *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

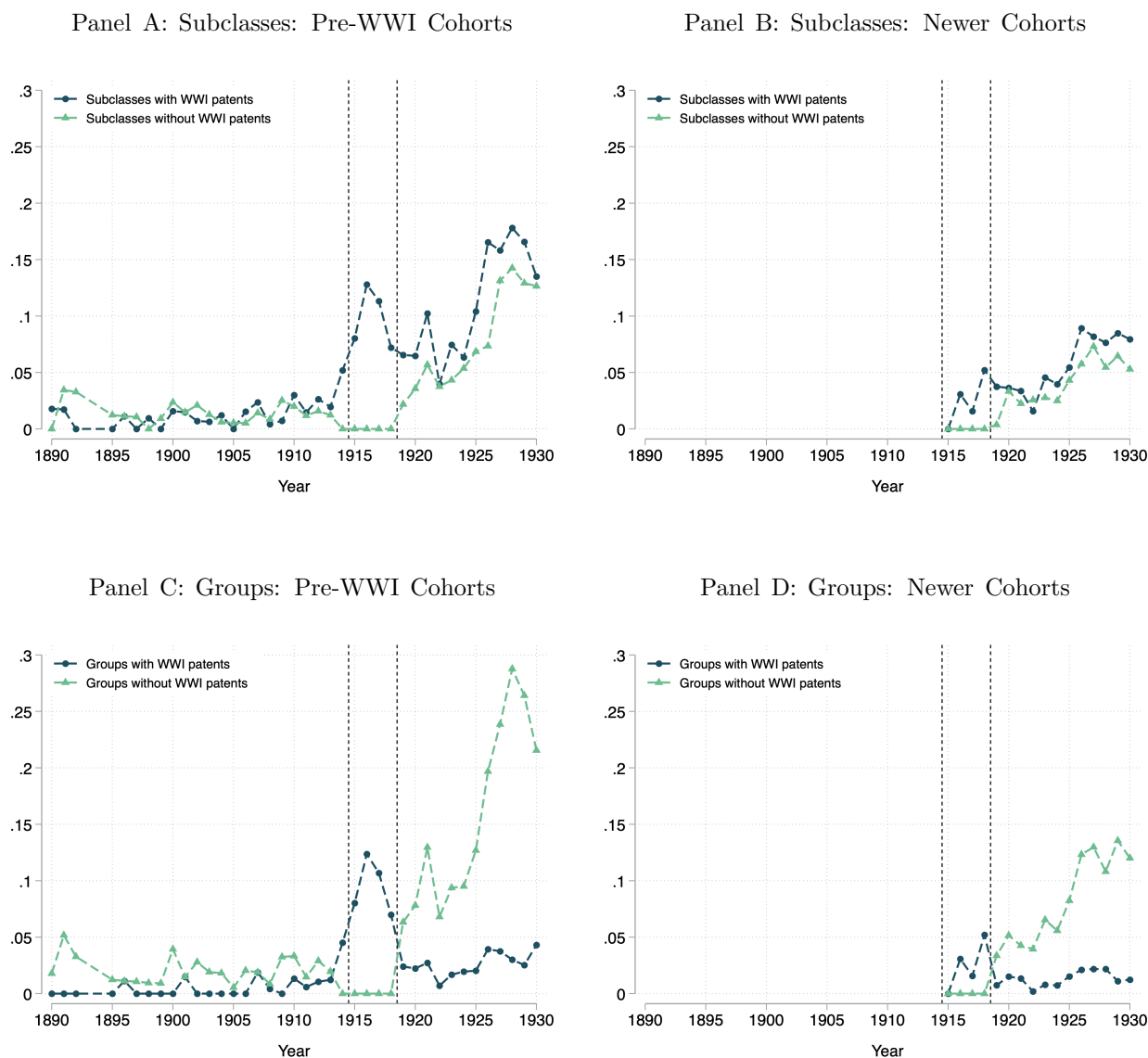


*Notes:* The figure shows the estimated annual event study coefficients from the following dynamic difference-in-differences specification with the reference year 1914:

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

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.

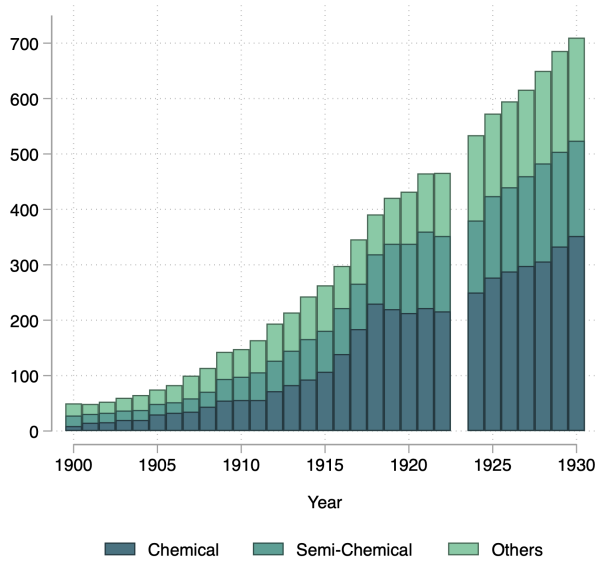
Figure A.5: Chemical Patents by WWI Patent Classification: Pre-WWI vs. Newer Cohorts



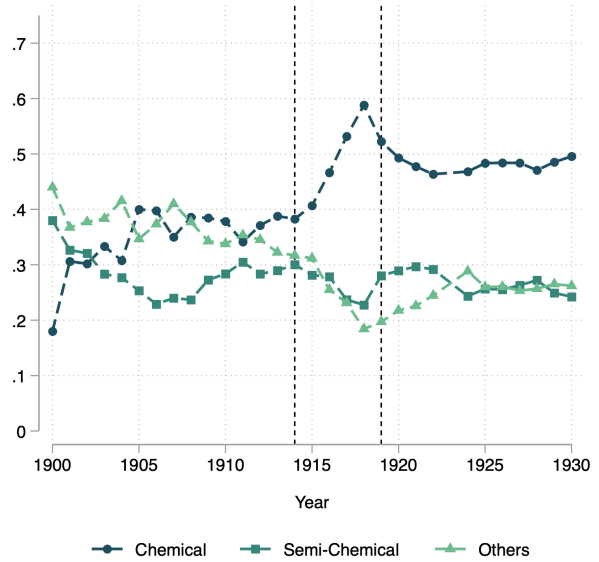
*Notes:* The figure shows the trends of chemical-related patents by Imperial University graduates from 1890 to 1930, split by technology categories where graduates had at least one patent between 1914 and 1918 and those where they did not, separately by cohorts that graduated before WWI and later cohorts.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

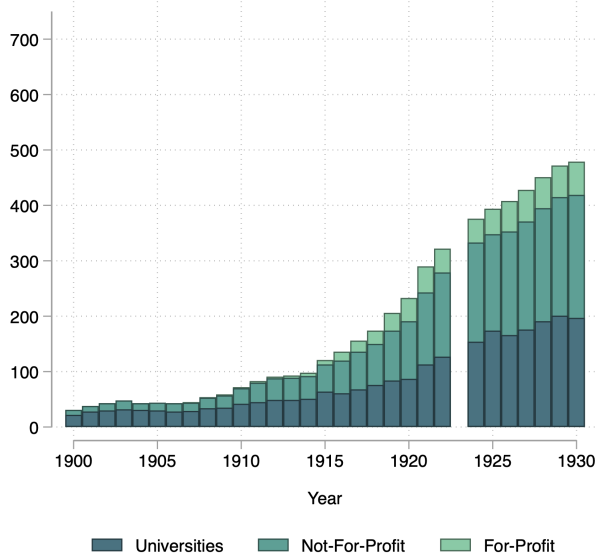
Panel A: Graduates in Production Sector



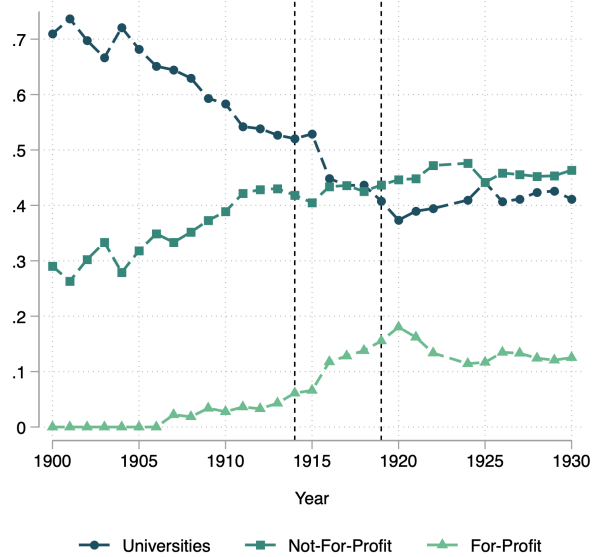
Panel B: Share in Production Sector



Panel C: Graduates in Research Sector



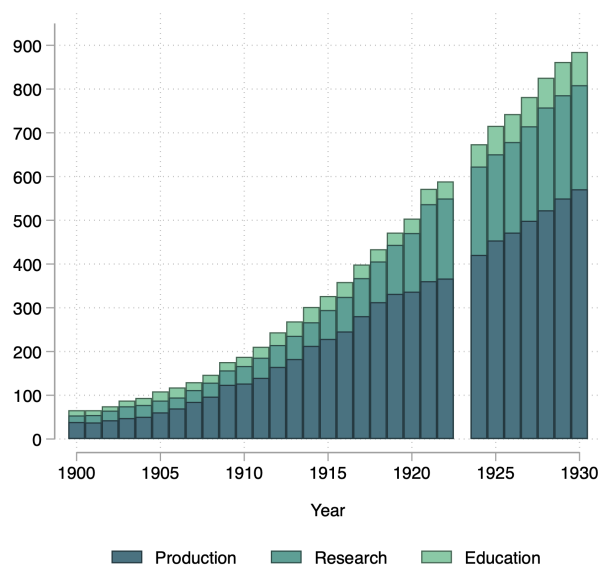
Panel D: Share in Research Sector



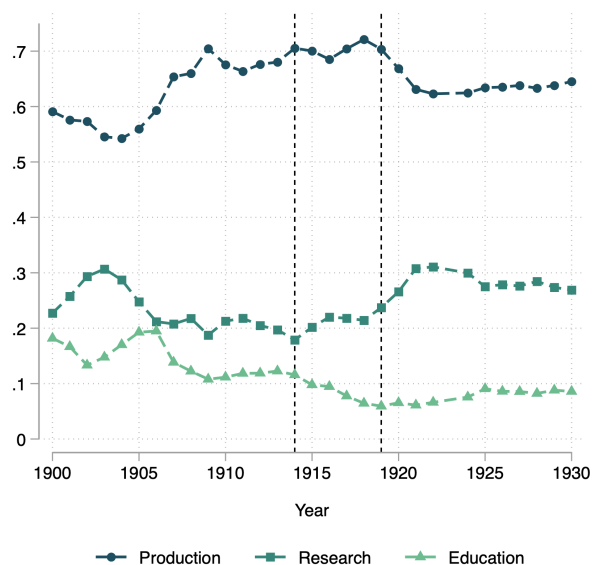
*Notes:* The figure shows the number and share of Imperial University graduates from chemistry-related divisions in each sub-categories of sectors by year. Panels A and B (C and D) decompose the number and share in production (research) sectors into sub-categories, respectively.

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

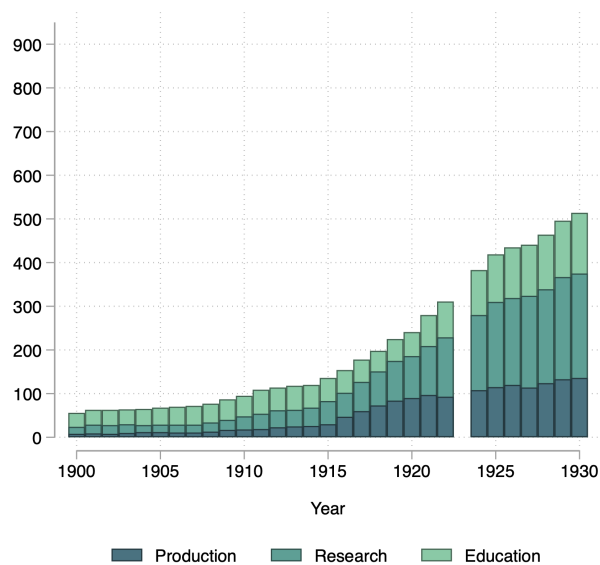
Panel A: Graduates from Engineering Department



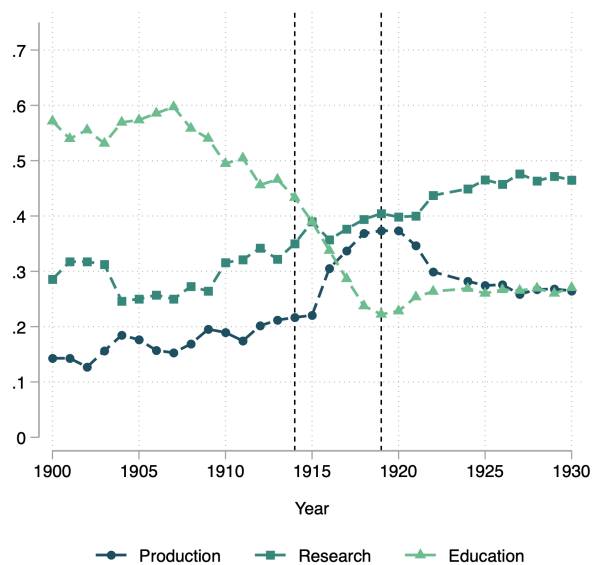
Panel B: Share of Engineering Department



Panel C: Graduates from Science Department

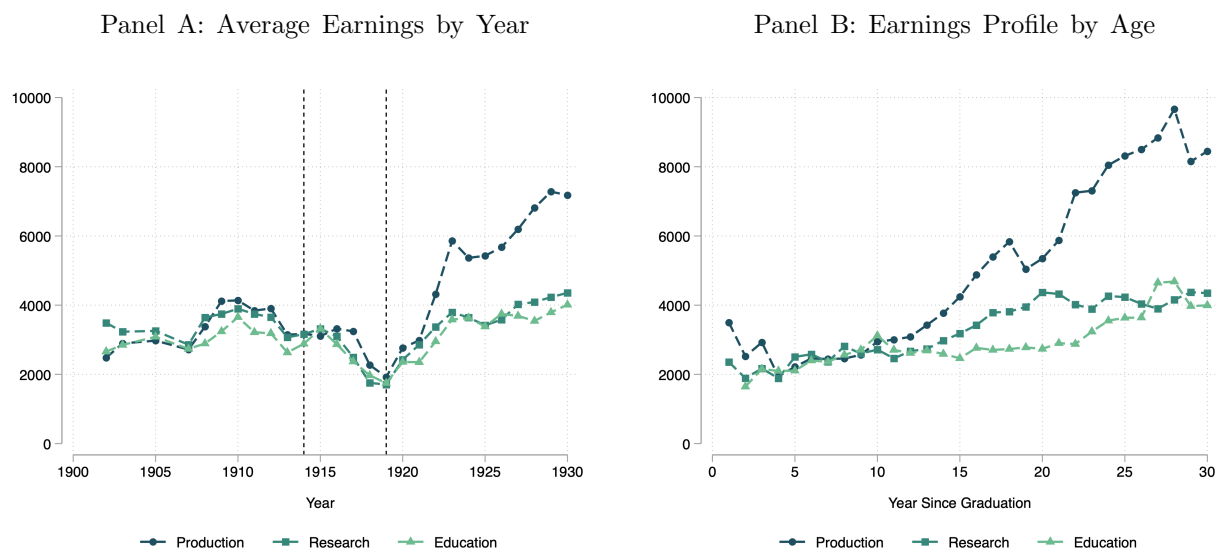


Panel D: Share of Science Department



*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*

Graduate Name /  
Birth Prefecture  
(Jokichi Takamine,  
Tokyo)

Graduation Year /  
Month

Division  
(Applied Chemistry)

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.

When creating the full longitudinal database from the alumni surveys the track was kept of name changes that were common in Japan at that time, mostly due to frequent cases of adult adoption. Fortunately, those name changes were noted in appendices to *Gakushikai Kaiin Shimeiroku* which are 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. I also triangulated across various other sources, including but not limited to Japanese Personnel Inquiry Records (*Jinji Koushinroku*), 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 discovered that updates in the surveys were lagging the actual changes in employment or addresses. At this stage, I was 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 per graduate.<sup>29</sup>

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<sup>29</sup> 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.

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

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

### 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 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.<sup>30</sup> 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.

For the purpose of this paper, I hand-matched the author names in all articles published in those two journals from their first volumes and until 1930 to the data on the census of all chemistry-related graduates from Imperial Universities and inventors among them. The total number of publications by chemists in my sample across the two journals is 2,917, with 1,908

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<sup>30</sup> 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.

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. I 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) and *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.

## B.7. Earnings Data

Earnings data are not available systematically for the universe of Imperial University graduates from any source I am aware of. It turned out, however, that *Who is Who in Japan* (*Nihon Shinshiroku*) contains information on income taxes paid by the individuals included in its listings, starting from the volume published in 1902. *Who is Who in Japan* was first published in 1889 by a private company called *Kojunsha* with the aim of creating a list of prominent people across various professions, based on information about income taxation and some additional criteria (*Nihon Shinshiroku*, Vol. 2, p. 4). For more than a decade, it included only names, workplaces and addresses, but from the 1902 edition, it started publishing also income (and business) tax data.

Using names, addresses and workplaces in Alumni surveys, chemistry graduates who comprise my sample were hand-matched with those who appeared in *Who is Who in Japan* between 1902-1930, and the data on income taxes they paid were hand-coded. To convert income tax data into actual earnings I used tax schedules in annual reports by Japan’s Tax Bureau (Shuzeitokoku Tokei Nemposho) (details are available upon request). To obtain real earnings, nominal earnings were deflated by the consumer price index.

As mentioned in the main text, I could match about 40 percent of all chemistry-related graduates in my sample to *Who is Who in Japan* in at least one year between 1902-1930. The data are missing for two main reasons. First, the data collected by *Who is Who in Japan* did not cover the whole country and coverage areas changed over time. While the coverage included taxpayers residing in six major cities and areas surrounding them: Tokyo, Yokohama, Osaka, Kyoto, Kobe, and Nagoya, throughout my sample, other areas were included in some but not in other years.

Second, *Who is Who in Japan* only included “gentlemen” above a certain income tax threshold. When income tax data were first published in 1902, the threshold below which individuals were not included was set at the tax amount of five yen, corresponding to 500 yen of personal income. This threshold was then increased multiple times in subsequent editions. Since earnings increase with age, one consequence is that the graduates were less likely to clear the threshold for being included in *Who is Who in Japan* at younger ages. As a result, earnings data especially for cohorts that graduated in the 1920s are sparse. Hence, as mentioned in main text, comparisons between earnings of chemistry-related graduates in various sectors of employment rely mostly on data points pertaining to older cohorts at mid- later-career observations.

## 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 Jōkichi 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 Jōkichi 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 Jōkichi 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-

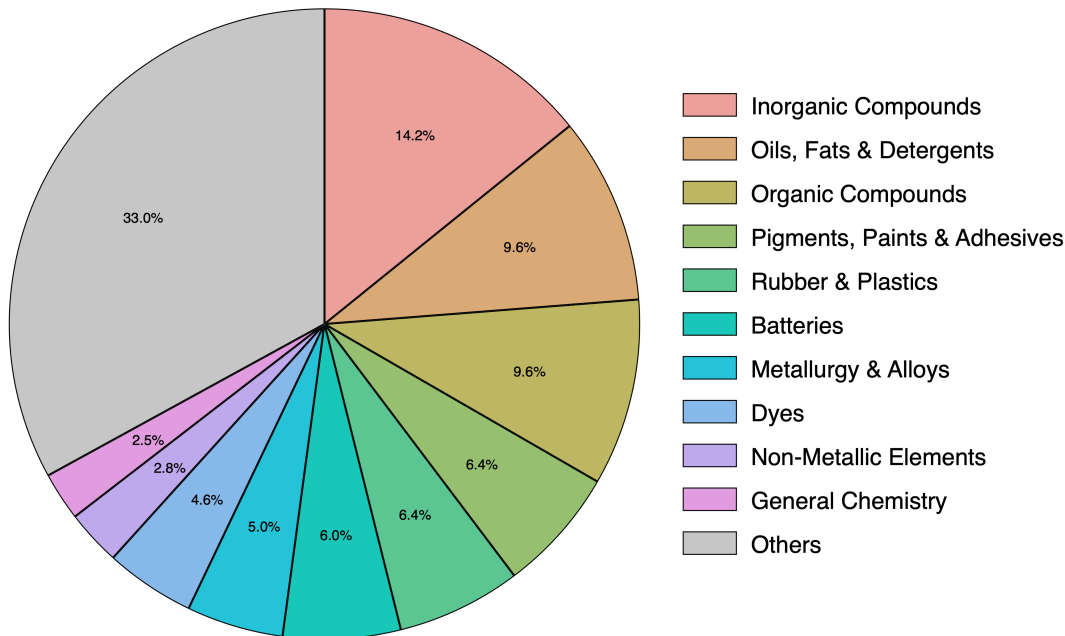
eral hundred chemistry division graduates relocated to the private industry. Chemistry graduates from the 1914-1918 cohorts were also more likely than earlier graduates to start their careers in the private industry. As a result, the share of employment in the private sector among chemistry division 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 and After WWI

Figure D.1 shows the shares of technology classes of 227 patents filed during WWI, with top 10 technology classes displayed as separate groups. We can see relatively large shares of patents in areas most strongly affected by import suspension — “Oils, Fats & Detergents,” “Pigments, Paints & Adhesives,” “Rubber & Plastics,” and “Dyes.” 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 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).

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 during WWI. Top 10 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 $\beta$ -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”)**

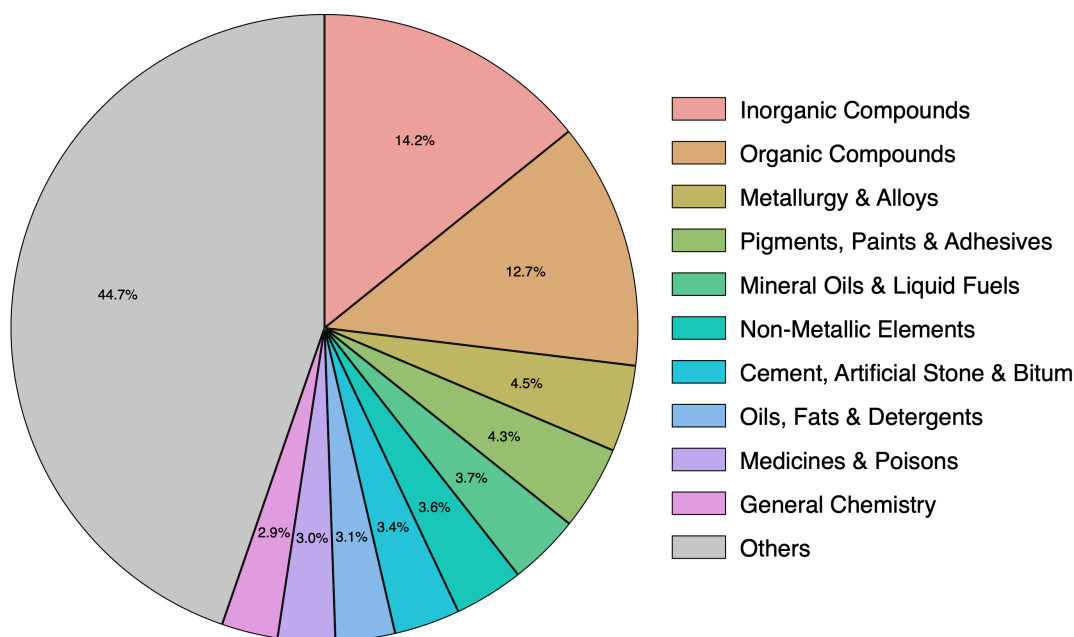
|                        |                                                                                        |
|------------------------|----------------------------------------------------------------------------------------|
| Inventor/assignee      | Satō Sadakichi, Imperial Univ. graduate and 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                     |

*Note:* 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>.

In [Figure D.2](#), I show the shares of technology classes for patents filed between 1920 and 1930, with top 10 technology classes once again displayed as separate groups. “Inorganic Compounds” is still the largest class, but there are important changes after that. Note especially the reduction in shares of patents in classes where war-time invention was driven by import substitution: “Oils, Fats & Detergents” was the second-largest patent class during WWI with 9.6 percent share but now is in the eighth place with just 3.4 percent share; “Rubber & Plastics” and “Dyes” dropped out of the top 10 altogether. Instead, we see an increased share of “Organic Compounds” which are now the second-largest class and the rise of new technology classes that did not make the top 10 during WWI, such as “Mineral Oils & Liquid Fuels,” “Cement, Artificial Stone & Bitumen,” and “Medicines & Poisons.” The patent classes are also becoming more diverse.

[Table D.2](#) presents eight patents filed after the end of WWI by the same inventors whose patents were presented in [Table D.1](#) as examples of import-substituting inventions. Only one patent, Marusawa’s patent No.45447 which explicitly cites his own previous WWI patents, is definitively a direct continuation of the research done during WWI. Also, patent No.63781 with Jinkichi Inoue as a co-inventor is related to his work on dyes during WWI, applied to anti-corrosion dyeing of fishing nets. Other patents, even though they often use similar methods, branch out into fertilizers, building materials, ink, pen nibs and so on; that is, the targets are new products for the consumer and agricultural markets rather than substituted imports.

Figure D.2: The Share of Technology Classes of Patents Filed in 1920-1930



*Notes:* The figure shows the share of technology classes of patents filed between 1920-1930. Top 10 technology classes are displayed in the graph as separate groups.

Table D.2: Select Post-WWI Patents (Filed 1920–1930) by Inventors in Table D.1

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|                                             |                                                                                                                                                                                                                  |
|---------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>No. 28815 — Iridium substitute alloy</b> |                                                                                                                                                                                                                  |
| Inventor/assignee                           | Ogawa Masataka/Kamiya Ken'ichirô                                                                                                                                                                                 |
| Filed/granted; class                        | 1920-03-31/1921-06-04; Cl. 85                                                                                                                                                                                    |
| What is made                                | Gold–tungsten–nickel–iridium alloy for fountain-pen nib tips, made by fusing Ni–W and Ni–Ir alloys separately and adding them to molten gold; acid-resistant, hard, wear-resistant, and weldable to the gold nib |
| Novel vs. reproduction                      | Novel formulation — cuts iridium to ~10 % of the alloy while retaining the properties of natural osmiridium; osmium impurity is tolerated rather than removed                                                    |

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|                                                                      |                                                                                                                                                                                                        |
|----------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>No. 45447 — Rapid cooking method for papermaking raw material</b> |                                                                                                                                                                                                        |
| Inventor/assignee                                                    | Marusawa Tsuneya/Tsutsumi Seiroku                                                                                                                                                                      |
| Filed/granted; class                                                 | 1922-11-25/1923-05-25; Cl. 167                                                                                                                                                                         |
| What is made                                                         | Sulphite pulp: lignocellulose is first raised to 140–170 °C by high-pressure steam, then magnesium bisulphite plus sulphurous acid liquor is added and cooking continued at that temperature           |
| Novel vs. reproduction                                               | Process improvement — magnesia-base liquor is stable and soluble where the conventional calcium-base liquor precipitates, cutting cooking time to roughly one-half to one-third (8–9 h versus 12–18 h) |

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|                                                   |                                                                                                                                                                                                                               |
|---------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>No. 61697 — Indoor hydrogen-gas eliminator</b> |                                                                                                                                                                                                                               |
| Inventor/assignee                                 | Yoshikawa Kamejirô/Yuasa Storage Battery Manufacturing Co.                                                                                                                                                                    |
| Filed/granted; class                              | 1923-06-25/1924-11-11; Cl. 146                                                                                                                                                                                                |
| What is made                                      | Platinum black or palladium fixed on asbestos, held in a dish-shaped mesh plate with an embedded electric heating wire; catalytically recombines hydrogen with atmospheric oxygen to water in poorly ventilated battery rooms |
| Novel vs. reproduction                            | Apparatus — adds electric pre-heating to a known catalyst, without which recombination will not start cold; mountable on a lamp so bulb radiant heat assists                                                                  |

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|                                                                                                   |                                                                                                                                                                                                                                                                                                                                     |
|---------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>No. 63628 — Manufacture of acetone-soluble cellulose acetate in the original fibrous state</b> |                                                                                                                                                                                                                                                                                                                                     |
| Inventor/assignee                                                                                 | Satô Sadakichi and Taniguchi Kazuyoshi                                                                                                                                                                                                                                                                                              |
| Filed/granted; class                                                                              | 1922-11-07/1925-04-22; Cl. 182                                                                                                                                                                                                                                                                                                      |
| What is made                                                                                      | Acetone-soluble cellulose acetate: fibre is uniformly part-hydrolysed in dilute mineral acid, acetylated with acetic anhydride and a swelling promoter while retaining fibre form, then further hydrolysed until acetone-soluble. Sold for artificial silk, film, cine film, lacquers, insulating paint and non-flammable celluloid |
| Novel vs. reproduction                                                                            | Novel process route — the whole sequence is heterogeneous, so the material never enters solution and the costly chloroform-soluble intermediate and its solvent recovery are avoided; the product filters, washes and dries as a fibre                                                                                              |

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continued on next page

Table D.2 (continued)

**No. 67729 — Ceiling and wall material**

|                        |                                                                                                                                                                                                                        |
|------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Inventor/assignee      | Yamamoto Nobuo and Satô Sadakichi                                                                                                                                                                                      |
| Filed/granted; class   | 1924-05-30/1926-03-12; Cl. 157                                                                                                                                                                                         |
| What is made           | Board for ceilings and walls: magnesia mixed with sawdust and kneaded with dilute sulphuric acid (20–30 °Bé), the exothermic heat accelerating set; formed into sheet, faced with paper or cloth and pressed or rolled |
| Novel vs. reproduction | Improvement on a known cement — sulphate rather than the chloride of standard magnesium oxychloride cement (cf. No. 41180), avoiding its hygroscopicity and corrosion                                                  |

**No. 63781 — Manufacture of water- and acid-resistant black ink**

|                        |                                                                                                                                                                                                                                                                                                                                    |
|------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Inventor/assignee      | Inoue Jinkichi                                                                                                                                                                                                                                                                                                                     |
| Filed/granted; class   | 1924-05-10/1925-05-07; Cl. 160                                                                                                                                                                                                                                                                                                     |
| What is made           | Black writing ink: $\beta$ -naphthol heated with copper(II) oxide or manganese dioxide in a sealed vessel gives dinaphthylene dioxide ( $C_{20}H_{12}O_2$ ); this is nitrated or nitro-sulphonated and taken up in ammonia as a purple-black colloid. Acidification precipitates a solid “ink element” that redissolves in ammonia |
| Novel vs. reproduction | Novel product — neutral rather than acidic, so it does not corrode nibs; water- and acid-resistant and unerasable once dry; shippable as a dry solid instead of as bulk liquid                                                                                                                                                     |

**No. 90846 — Antiseptic dyeing method for fishing nets**

|                        |                                                                                                                                                                                      |
|------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Inventor/assignee      | Inoue Jinkichi, Saitô Takeshi, and Fukuoka Kunio                                                                                                                                     |
| Filed/granted; class   | 1930-07-30/1931-03-31; Cl. 179                                                                                                                                                       |
| What is made           | Rot-proofed netting: net yarn is treated with the gas liquor or tar from the dry distillation of coal/lignite/peat, then with copper/iron salt solution, then with a tannin material |
| Novel vs. reproduction | Novel application — the gas liquor acts at once as dye, bactericide and mordant, so one cheap by-product replaces a multi-reagent sequence                                           |

**No. 73776 — Manufacture of fertiliser with potassium phosphate as principal component**

|                        |                                                                                                                                                                                                                                                              |
|------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Inventor/assignee      | Tanahashi Toragorô                                                                                                                                                                                                                                           |
| Filed/granted; class   | 1926-01-25/1927-10-06; Cl. 184                                                                                                                                                                                                                               |
| What is made           | Acid potassium phosphate fertiliser: sulphuric acid is added to potassium chloride and heated, and the hydrogen chloride evolved is made to act <i>in situ</i> on phosphate rock added in small portions, giving superphosphate and $KH_2PO_4$ in one vessel |
| Novel vs. reproduction | Novel process integration — consumes the awkward hydrogen chloride by-product of potassium sulphate manufacture inside the process instead of disposing of it, yielding a combined potash–phosphate fertiliser and shortening the plant                      |

*Note:* 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>.

## E. Explaining Invention Trajectories: A Formal Model

In this appendix, I provide a formal model of knowledge creation underpinning the theoretical framework in Section 5.4 of the main text. The formal apparatus draws on the literature modeling search for new knowledge as discovery on a Brownian path (Callander, 2011; Carnehl and Schneider, 2025) and has two key ingredients. First, the cost of research depends on how well existing knowledge reduces research uncertainty. Second, incentive for research is driven by how novel the questions researchers address are. I introduce two new elements into this model. First, scientific knowledge is “embodied” in the sense that only a particular type of agents, whom I call “scientists” have access to the whole body of accumulated knowledge. Second, I introduce the set of foreign technologies which are not part of the domestic body of knowledge but whose presence restricts domestic research activities by affecting rewards. If a temporary import suspension generates such rewards, this can activate domestic research which will then continue and go beyond the wartime research areas, driven by agents with embodied scientific knowledge. I first provide the simplest version of the model and discuss its assumptions and potential extensions later. The proofs are provided in Appendix F.

### E.1. A Model of Knowledge Creation

Time is discrete and infinite,  $t \in \{0, 1, \dots\}$ . There are two representative agents: a “scientist” and a “non-scientist.” The scientist lives in a scientific community (such as Japan Chemical Association) and is observable empirically through publications in top scientific journals produced by such communities. I assume that in each period  $t$ , the scientist can know all question–answer pairs discovered by anyone up to period  $t - 1$ . The “non-scientist” does not belong in a scientific community and is assumed to only know question–answer pairs he discovered by himself. Thus, the knowledge accumulated by the scientific community is “embodied” in scientists but not in non-scientists.

#### E.1.1. Knowledge and Conjectures

I represent the universe of questions by the real line: a question is an element  $x \in \mathbb{R}$ . Each question  $x$  has a unique answer,  $y(x) \in \mathbb{R}$  determined by the “truth”, which is represented by the graph of the realization of a random variable  $Y(x)$  that follows a standard Brownian motion defined over the entire real line. The truth is fixed throughout the entire period but answers are unknown until successfully discovered.

I define knowledge as the finite collection of known question–answer pairs. I assume that, in each period  $t$ , the scientist can know all question–answer pairs discovered by anyone up to period  $t - 1$ , while the non-scientist can know only question–answer pairs discovered by himself. Denote by  $\mathcal{F}_{jt} = \{(x_i, y(x_i))\}_{i \in \mathcal{I}_{jt}}$  the knowledge set of agent  $j \in \{S, N\}$ , where  $S$  and  $N$  represent the scientist and non-scientist, respectively, and  $\mathcal{I}_{jt}$  represents the index set of knowledge of agent

$j$  in period  $t$ . For notational convenience, I assume that  $x_i$  is ordered. Let  $N_{jt} = |\mathcal{I}_{jt}|$  denote the number of question-answer pairs agent  $j$  has access to in period  $t$ . Knowledge determines a partition of the real line consisting of  $N_{jt} + 1$  elements:

$$\mathcal{P}_{N_{jt}} = \{(-\infty, x_1), [x_1, x_2), \dots, [x_{N_{jt}-1}, x_{N_{jt}}), [x_{N_{jt}}, \infty)\}.$$

I call  $(-\infty, x_1)$  area 0,  $[x_1, x_2)$  area 1, and so on until area  $N_{jt}$ , which is  $[x_{N_{jt}}, \infty)$ . The length of area  $i$  is  $X_i = x_{i+1} - x_i$ , and  $X_0 = X_{N_{jt}} = \infty$ .

A conjecture by agent  $j$  is the cumulative distribution function  $G_x(Y|\mathcal{F}_{jt})$  of the answer  $y(x)$  to question  $x$  given knowledge  $\mathcal{F}_{jt}$ . Because  $Y(x)$  is determined by a Brownian motion, the conjecture follows a normal distribution with mean  $\mu_x(Y|\mathcal{F}_{jt})$  and variance  $\sigma_x^2(Y|\mathcal{F}_{jt})$ . The conditional variance  $\sigma_x^2(Y|\mathcal{F}_{jt})$  follows from the properties of the Brownian motion:

$$\sigma_x^2(Y|\mathcal{F}_{jt}) = \begin{cases} x_1 - x, & \text{if } x < x_1, \\ \frac{(x_{i+1} - x)(x - x_i)}{X_i}, & \text{if } x \in [x_i, x_{i+1}), x_i, x_{i+1} \in \mathcal{F}_{jt}, \\ x - x_k, & \text{if } x > x_k, \end{cases} \quad (1)$$

Note that  $\mathcal{F}_{Nt} \subset \mathcal{F}_{St}$ , so the perceived variance of  $Y$  at a given  $x$  is smaller for the scientists for any knowledge structure:  $\sigma_x^2(Y|\mathcal{F}_{St}) \leq \sigma_x^2(Y|\mathcal{F}_{Nt})$ . The perceived variance is determined by the length of the research area,  $X_i$ , the discovery occurs in, and how distant question  $x$  is from existing knowledge. Let  $\mathcal{Q}_{jt} = \{x_i\}_{i \in \mathcal{I}_{jt}}$  denote the set of questions to which agent  $j$  knows the answers. The distance of question  $x$  from knowledge  $\mathcal{F}_{jt}$  is defined as:

$$d_t(x) = \min_{\xi \in \mathcal{Q}_{jt}} |x - \xi|. \quad (2)$$

Note that the variance of a question with distance  $d$  in an area of length  $X$  can be written as  $\sigma_x^2(Y|\mathcal{F}_{jt}) = \sigma^2(d, X) = d(X - d)/X$ . Thus, for each agent,  $(d, X)$  is the sufficient statistics for uncertainty. I denote  $\sigma_x^2(Y|\mathcal{F}_{jt}) = \sigma^2(d, X) = \sigma_x^2$  for ease of exposition.

### E.1.2. Technologies and Novelty

Technologies are also represented by the real line. When each question-answer pair is discovered, agents transform such a question point into a new technology that can generate one-time revenue in that period. However, there is already the foreign technology set based on the subset of questions, which is represented by  $\mathcal{Z} \subset \mathbb{R}$ .<sup>31</sup> I assume that the value of  $y(x)$  for  $x \in \mathcal{Z}$  is unknown unless (domestic) agents discover the answers to those questions by themselves. I define the entire technology space  $\mathcal{Q}_t \cup \mathcal{Z}$  as the union of the domestic and foreign technology set, where

<sup>31</sup> For simplicity, I assume that the foreign technology set is exogenously given in the first period. We can extend the model so that the foreign technologies evolve over time without changing the main conclusions.

$\mathcal{Q}_t = \{x_i\}_{i \in \mathcal{I}_t}$  represents all domestic discoveries. For each technology associated with question  $x$ , novelty is defined as follows:

$$\delta_t(x) = \min_{\xi \in \mathcal{Q}_t \cup \mathcal{Z}} |x - \xi|. \quad (3)$$

That is, technology  $x$  has high novelty if it is far from any points in existent knowledge set.

I assume that one-time revenue of technology  $x$  is a function of its novelty (3),  $R(\delta_t(x))$ . For simplicity, I assume that the revenue can be written in the following step-function form, where it is equal to zero for technology points close enough to the known technology space  $\mathcal{Q}_t \cup \mathcal{Z}$  and equals some positive constant for any technology point with novelty above:

$$R(\delta) = \lambda \cdot \mathbb{1}\{\delta \geq \delta_0\}. \quad (4)$$

for  $\lambda > 0$  and  $\delta_0 > 0$ . That is, agents face a novelty constraint, as the market does not reward incremental discoveries: within  $\delta_0$  of an existing technology, new technology can be substitutable at negligible cost and is worthless, but beyond  $\delta_0$ , substitution is costly and the technology generates positive revenue  $\lambda$ . I will discuss how more general forms of the reward function can be incorporated later in Appendix E.2.

### E.1.3. Research

For each question  $x \notin \mathcal{Q}_{jt}$ , agents can conduct research to discover the value of  $y(x)$ . Each agent decides how much effort to exert to find the answer. I assume that increasing the probability of discovery requires costly effort and adopt the reduced-form cost function similar to [Carnehl and Schneider \(2025\)](#). Specifically, let  $c : [0, 1) \rightarrow [0, \infty)$  be continuously differentiable, strictly convex, with  $c(0) = 0$ ,  $c'(0) = \underline{c} > 0$ , and  $c'(\rho) \rightarrow \infty$  as  $\rho \rightarrow 1$ . In period  $t$ , each agent selects a question  $x$  and a success probability  $\rho \in [0, 1)$ , and the period cost is written as:

$$C_{jt}(x, \rho) = \sigma_x^2(Y|\mathcal{F}_{jt}) \cdot c(\rho), \quad (5)$$

The key assumption, similar to [Carnehl and Schneider \(2025\)](#), is that the cost of increasing discovery probability scales in uncertainty: discovering  $y(x)$  with a given probability  $\rho$  is more costly if the conjecture about  $y(x)$  is less precise. Upon success, the pair  $(x, y(x))$  enters the knowledge and technology sets. Upon failure, the knowledge and technology sets are unchanged. I assume that each agent maximize the expected net payoff in each period. The agent's expected payoff given the choice of a question  $x$  and success probability  $\rho$  can be written as:

$$\max_{x, \rho} \left\{ \rho R(\delta_t(x)) - C_{jt}(x, \rho) \right\}.$$

Note that, given  $x$ , the choice of  $\rho$  depends only on the ratio of the revenue to the variance of the question  $m = R(\delta(x))/\sigma_x^2$ . Therefore, the optimization can be written as

$$\max_x \left\{ \sigma_x^2 \cdot \max_{\rho} \{ \rho m - c(\rho) \} \right\} = \max_x \left\{ \sigma_x^2 \cdot \varphi(R(\delta(x))/\sigma_x^2) \right\}, \quad (6)$$

where  $\varphi(m) = \max_{\rho} \{ \rho m - c(\rho) \}$ . We can show that  $\varphi$  is convex, non-decreasing,  $\varphi(m) = 0$  for  $m \leq \underline{c}$ , and  $\varphi(m) > 0$  for  $m > \underline{c}$ . The envelope theorem implies that the optimal probability is  $\rho^* = \varphi'(m)$ , which satisfies  $\rho^* = (c')^{-1}(m) > 0$  for  $m > \underline{c}$  and  $\rho^* = 0$  for  $m \leq \underline{c}$ .

**Lemma 1** *If the optimal  $\rho^*$  is positive, the optimal novelty is  $\delta(x^*) = \delta_0$ .*

*Proof.* See Appendix F. ■

Intuitively, the optimal choice of the question always minimizes the distance from the existing technology set given the novelty constraint. Note that the optimal distance from the agent's own knowledge can be larger than  $\delta_0$ :  $d_t(x^*) \geq \delta_0$ , and the inequality can be strict when foreign technologies in  $\mathcal{Z}$  — or, for the non-scientist, domestic discoveries he has not absorbed — occupy the least uncertain questions satisfying the novelty constraint.

Now, we can show that the availability of foreign technologies can discourage domestic research, both in its level and growth. For a closed set  $\mathcal{Z} \subset \mathbb{R}$ , denote by  $\rho_{jt}^*(\mathcal{Z})$  the optimal success probability of agent  $j$  in period  $t$  when the foreign technology set is  $\mathcal{Z}$ .

**Proposition 1** (i) *For any agent  $j \in \{S, N\}$  and any closed sets  $\mathcal{Z} \subseteq \mathcal{Z}'$ ,  $\rho_{jt}^*(\mathcal{Z}') \leq \rho_{jt}^*(\mathcal{Z})$ .*

(ii) *Suppose  $\rho_{jt}^*(\emptyset) > 0$  and every question  $x^*$  that is optimal in the benchmark problem without foreign technologies satisfies  $\min_{z \in \mathcal{Z}} |x^* - z| < \delta_0$ . Then,  $\rho_{jt}^*(\mathcal{Z}) < \rho_{jt}^*(\emptyset)$  for any nonempty  $\mathcal{Z}$ .*

(iii) *Suppose  $\delta_0 < \bar{\sigma}^2 \equiv \lambda/\underline{c}$ , so that  $\rho_{St}^*(\emptyset) > 0$ : absent foreign technologies, the agent conducts research with positive success probability in each period. If foreign technologies are sufficiently dense in the vicinity of domestic knowledge, that is, if*

$$\{x \in \mathbb{R} : \sigma_x^2(Y|\mathcal{F}_{St}) < \bar{\sigma}^2\} \subseteq \bigcup_{\xi \in \mathcal{Q}_t \cup \mathcal{Z}} (\xi - \delta_0, \xi + \delta_0), \quad (7)$$

*then,  $\rho_{jt}^*(\mathcal{Z}) = 0$  for both agents, no discovery occurs in period  $t$ , and condition (7) holds in every subsequent period. Consequently,  $\rho_{j\tau}^*(\mathcal{Z}) = 0$  and  $N_{j\tau} = N_{jt}$  for all  $\tau \geq t$  and  $j \in \{S, N\}$ . Moreover, condition (7) cannot be satisfied if  $\mathcal{Z} = \emptyset$ .*

*Proof.* See Appendix F. ■

Claim (i) says that more foreign technologies without knowledge lead to less domestic research intensity because no reward can be expected from a costly discovery. Similarly, Claim (ii) implies

that domestic research intensity would be strictly decreasing in the size of the foreign technology set. Claim (iii) describes the condition where the domestic research permanently stops even though the scientist would keep conducting research absent foreign technologies. Condition (7) basically means that profitable research opportunities are fully destroyed by the foreign technology set (by the novelty constraint), so there is no incentive for both the scientist and non-scientist to conduct research in any subsequent period. The following lemma describes a specific case that provides a sufficient condition for condition (7) to hold and thus for research stagnation.

**Lemma 2** *Suppose that the economy starts with a finite set of knowledge,  $\mathcal{F}_{j0} = \{(x_i, y(x_i))\}_{i=1}^n$  for  $j \in \{S, N\}$  with  $x_1 < \dots < x_n$  and  $\mathcal{Q}_0 = \{x_1, \dots, x_n\}$ , and that foreign technologies surround the initial knowledge frontier, in the sense that there exist  $a \leq x_1$  and  $b \geq x_n$  such that*

$$[a - \bar{\sigma}^2, a] \cup [b, b + \bar{\sigma}^2] \subseteq \bigcup_{z \in \mathcal{Z}} (z - \delta_0, z + \delta_0). \quad (8)$$

*Then, almost surely, there exists a finite period  $T$  such that condition (7) holds for all  $t \geq T$ .*

*Proof.* See Appendix F. ■

That is, if domestic knowledge is surrounded by the bands of foreign technologies, then domestic discovery will stop within a certain finite period and there will not be any sustained growth of domestic knowledge and technologies. Also, the next lemma formalizes that similar logic operates inside domestic knowledge set: areas that contain foreign technologies with sufficient density are never researched, and they create holes in the domestic knowledge set.

**Lemma 3** *Let  $x_i < x_{i+1}$  be adjacent questions in  $\mathcal{Q}_t$  with  $X_i = x_{i+1} - x_i$ , and define  $w_i = \min\{2\bar{\sigma}^2, X_i/2\}$ . Suppose that foreign technologies cover the two bands adjacent to the domestic knowledge points, in the sense that*

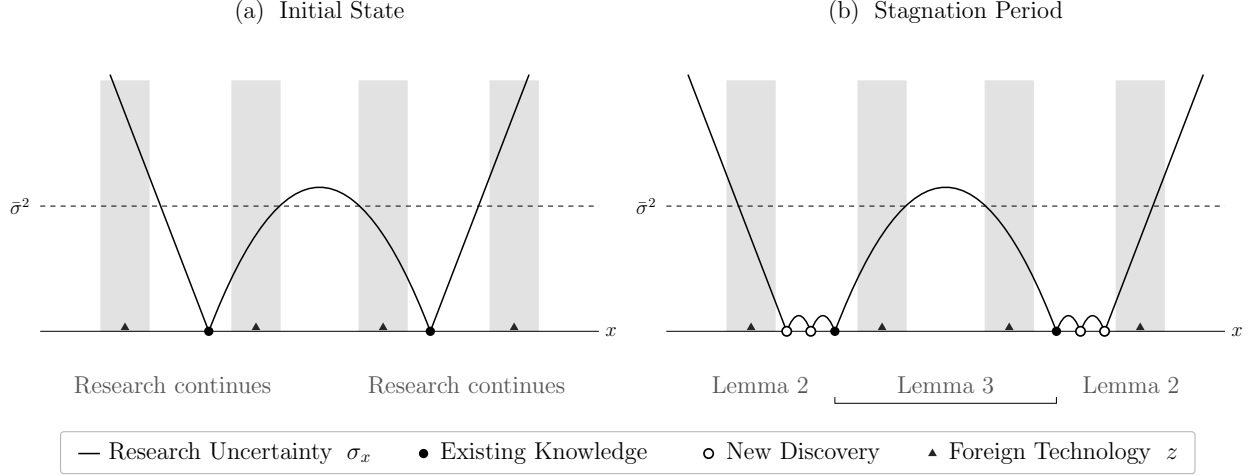
$$[x_i + \delta_0, x_i + w_i] \cup [x_{i+1} - w_i, x_{i+1} - \delta_0] \subseteq \bigcup_{z \in \mathcal{Z}} (z - \delta_0, z + \delta_0). \quad (9)$$

*Then, along every path and in every period  $\tau \geq t$ , no agent researches any question in  $(x_i, x_{i+1})$  with positive success probability, and hence no discovery ever occurs in the gap:  $\mathcal{Q}_\tau \cap (x_i, x_{i+1}) = \emptyset$  for all  $\tau \geq t$  and  $j \in \{S, N\}$ .*

*Proof.* See Appendix F. ■

Lemma 3 shows that the destruction of research opportunities by foreign technologies is not confined to the frontier: foreign technologies located *between* domestic discoveries carve permanent holes in the interior of domestic knowledge. The mechanism combines the two blocking forces of Proposition 1. Within distance  $\delta_0$  of the domestic points  $x_i, x_{i+1}$  or of foreign technologies,

Figure E.1: Illustration of Lemma 2 and 3



*Notes:* The figure illustrates Lemma 2 and 3. The solid line represents the conditional variances of the conjectures, black circles represent the knowledge points already discovered, white circles represent new discoveries, and black triangles represent unknown foreign technologies. The shaded areas show  $\delta_0$ -neighborhood around foreign technologies.

the novelty constraint binds and the reward is zero; beyond the covered bands, in the middle of the gap, the distance to domestic knowledge exceeds  $w_i$ , so the variance of the conjecture exceeds  $\bar{\sigma}^2$  and research is unprofitable at any positive effort. Since any foreign technology whose  $\delta_0$ -neighborhood intersects the bands in (9) must itself lie strictly inside  $(x_i, x_{i+1})$ , condition (9) indeed describes foreign technologies sandwiching the hollow area from within the gap.

Figure E.1 illustrates the stagnation patterns demonstrated in Lemma 2 and 3. Agents conduct research only if the conditional variances of the conjectures about the answers are less than the threshold  $\bar{\sigma}^2$ , so knowledge can be expanded from a situation in Panel (a) to a situation in Panel (b). However, once it reaches Panel (b), since unknown foreign technologies block all regions where the conditional variances are less than the threshold, research will be never conducted further, both inside and at the edges of the domestic knowledge set.

#### E.1.4. Temporary wartime shock

Assume now that the supply of foreign technologies is suspended during a time window  $t \in \{t_0, \dots, t_1\}$  because of the temporary war-time shock. Denote by  $\mathcal{W}$  wartime problems

$$\mathcal{W} = \bigcup_{z \in \mathcal{Z}} (z - \delta_0, z + \delta_0). \quad (10)$$

I assume that solving any  $x \in \mathcal{W}$  yields an additive product-market scarcity premium  $p > 0$  since it can be a substitute for the corresponding imported product. The agents can earn the premium

whenever the domestic novelty at that time is greater than  $\delta_0$ . Formally, the wartime premium and domestic novelty during the wartime are defined as:

$$P(x) = p \cdot \mathbb{1}\{x \in \mathcal{W}, \delta_t^-(x) \geq \delta_0\}, \quad \text{where} \quad \delta_t^-(x) = \min_{\xi \in \mathcal{Q}_t} |x - \xi|. \quad (11)$$

After period  $t_1$ , foreign technologies come back and the additional premium vanishes. Let  $R_t^w(x) = R(\delta_t(x)) + P(x)$  be the payoff from discovering the answer to question  $x$  in a wartime period  $t \in \{t_0, \dots, t_1\}$ . The optimization problem (6) is the same during the war except that  $R(\delta_t(x))$  is replaced by  $R_t^w(x)$ . Note that the two terms in  $R_t^w(x)$  are mutually exclusive:  $x \in \mathcal{W}$  implies  $\delta_t(x) < \delta_0$ , so that  $R_t^w(x) \in \{0, \lambda, p\}$ . The next proposition shows that the temporary wartime shock encourages research, and it *permanently* undoes the stagnation of Lemma 2.

**Proposition 2** *Suppose  $\delta_0 < \min\{\lambda, p\}/\underline{c}$ . Define  $\underline{m} > \underline{c}$  and  $\underline{\rho} \in (0, 1)$  as follows:*

$$\underline{m} = \frac{\min\{\lambda, p\}}{\delta_0}, \quad \underline{\rho} = \frac{\delta_0 \varphi(\underline{m})}{\max\{\lambda, p\}}.$$

(i) *In every wartime period  $t \in \{t_0, \dots, t_1\}$ ,  $\rho_{S_t}^*(\mathcal{Z}) \geq \underline{\rho} > 0$ . In particular, if condition (7) holds at the outbreak of the war — so that, absent the shock,  $\rho_{S_\tau}^*(\mathcal{Z}) = 0$  and  $N_{S_\tau} = N_{S_{t_0}}$  for all  $\tau \geq t_0$  by Proposition 1 — the shock strictly raises the discovery probability. Moreover, in any wartime period in which condition (7) holds, every optimal question lies in the wartime problem:  $x^* \in \mathcal{W}$ .*

(ii) *Suppose that  $\mathcal{Z}$  is bounded and nonempty, and let  $\underline{z} = \inf \mathcal{Z}$  and  $\bar{z} = \sup \mathcal{Z}$ . Suppose that, by the end of the war, wartime discoveries push the domestic knowledge frontier to the boundary of the foreign technology set, in the sense that there exists a period  $\tau^* \leq t_1 + 1$  such that*

$$\max \mathcal{Q}_{\tau^*} \geq \bar{z} \quad \text{or} \quad \min \mathcal{Q}_{\tau^*} \leq \underline{z}. \quad (12)$$

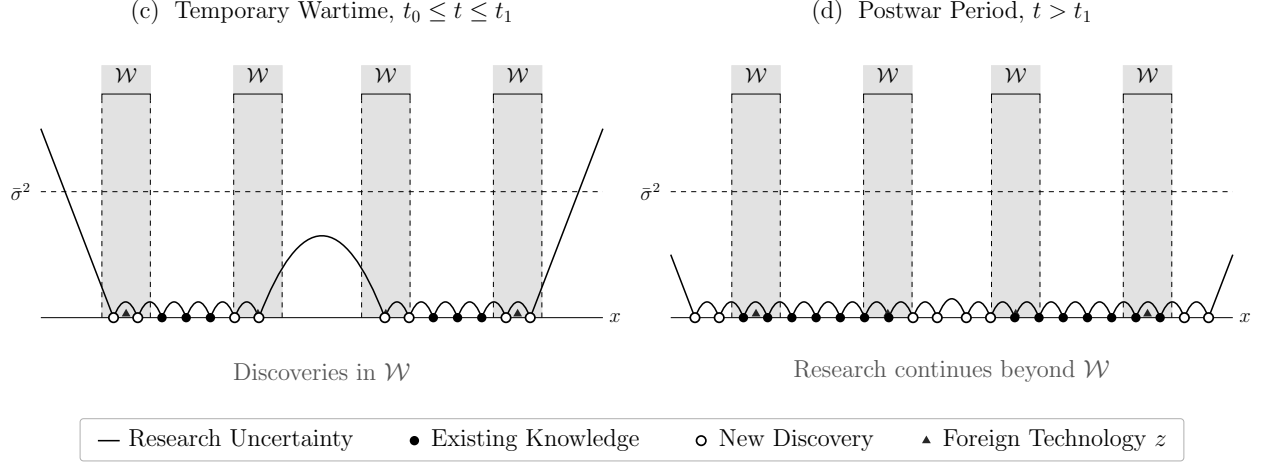
*Then condition (7) fails in every period  $t \geq \tau^*$ ; consequently,  $\rho_{S_t}^*(\mathcal{Z}) \geq (c')^{-1}(\lambda/\delta_0) > 0$  in every post-war period  $t > t_1$ , and  $N_{S_t} \rightarrow \infty$  almost surely.*

(iii) *The scientist has larger success probability than the non-scientist:  $\rho_{N_t}^*(\mathcal{Z}) \leq \rho_{S_t}^*(\mathcal{Z})$  in every wartime period  $t_0 \leq t \leq t_1$  in which condition (7) holds, and in every post-war period  $t > t_1$ .*

*Proof.* See Appendix F. ■

Proposition 2 formalizes the sense in which a temporary wartime shock has permanent effects on the knowledge structure. Under condition (7), every question that is novel relative to the entire technology set  $\mathcal{Q}_t \cup \mathcal{Z}$  is too uncertain to be worth researching, and the economy is trapped. The war changes the reward structure: because imported products are unavailable, novelty for questions in  $\mathcal{W}$  is measured against only domestic discoveries. Research therefore restarts, and it restarts precisely at the wartime problems  $\mathcal{W}$ , that is, at questions adjacent to the suspended

Figure E.2: Illustration of Proposition 2 and Corollary 1



*Notes:* The figure illustrates Proposition 2 and Corollary 1. The solid line represents the conditional variances of the conjectures, black circles represent the knowledge points already discovered, white circles represent new discoveries, and black triangles represent unknown foreign technologies. The shaded areas show  $\delta_0$ -neighborhood around the foreign technologies.

foreign technologies. Part (ii) makes the escape condition: once the domestic knowledge frontier reaches the boundary of the foreign technology set, the frontier question is at least  $\delta_0$  away from every foreign technology, so the novelty constraint imposed by  $\mathcal{Z}$  can never bind again. Part (iii) is a direct consequence of embodied knowledge: since  $\mathcal{F}_{Nt} \subseteq \mathcal{F}_{St}$ , the scientist's conjecture is weakly more precise at every question, and both in wartime period and in post-war period, more precise conjectures translate directly into a larger success probability.

**Corollary 1** *Suppose  $\delta_0 < \min\{\lambda, p\}/c$ , and suppose that  $\mathcal{Z}$  is closed, bounded, and nonempty, and the frontier condition (12) holds for some  $\tau^* \leq t_1 + 1$ .*

(i) *Every question  $x$  discovered in a post-war period  $t > t_1$  satisfies  $\min_{z \in \mathcal{Z}} |x - z| \geq \delta_0$ ; in particular, no post-war discovery lies in the wartime problem set:  $x \notin \mathcal{W}$ .*

(ii) *Almost surely, all but finitely many discoveries lie strictly beyond the outer boundary of the foreign technology set, in the sense that  $x \geq \bar{z} + \delta_0$  or  $x \leq \underline{z} - \delta_0$ , and the domestic knowledge frontier diverges:  $\max \mathcal{Q}_t \rightarrow \infty$  or  $\min \mathcal{Q}_t \rightarrow -\infty$ .*

*Proof.* See Appendix F. ■

Corollary 1 says that the wartime shock acts as a springboard. During the war, research is pulled into the wartime problems: under condition (7), every optimal question, until at least one answer is discovered, lies in  $\mathcal{W}$ , adjacent to a suspended foreign technology. Once the war ends and foreign supply resumes, the novelty constraint imposed by  $\mathcal{Z}$  pushes every new discovery out of

$\mathcal{W}$ : import-substituting questions are no longer rewarded, so post-war research never revisits the wartime problems. The wartime import-substitution phase is thus transitional by construction: it supplies the stepping stones across the foreign technology set, after which research permanently migrates to genuinely new territory. [Figure E.2](#) illustrates this process.

## E.2. Discussion of Model Assumptions and Extensions

**Research Costs.** A key assumption that drives most of the results is that the cost of research scales in uncertainty. The cost function (5), under which achieving a given success probability is more expensive when the conjecture is less precise, resembles the formulation in [Carnehl and Schneider \(2025\)](#), but this admits several interpretations. For example, suppose that discovering answers requires sequentially testing candidate answers at a constant cost per test. A closely related argument is the logic of parallel research paths ([Nelson, 1961](#)), suggesting that the more dispersed the prior over where the answer lies, the more independent approaches must be pursued simultaneously to reach a given probability of success, so the research budget scales with uncertainty. Alternatively, financing frictions can create such scaling, as more uncertain R&D faces a higher cost of external capital ([Hall and Lerner, 2010](#)), and motivating exploration requires expensive incentive structures that tolerate early failure over long horizons ([Manso, 2011](#)).

**Foreign Technologies.** The baseline model assumes that the answers  $y(z)$  for  $z \in \mathcal{Z}$  remain unknown to domestic agents unless discovered by themselves. Practically, however, we do not need to interpret  $\mathcal{Z}$  as the set of *all* foreign technologies, but as the subset of foreign technologies that arrive without knowledge transfer. In the model, a foreign technology transferred with its underlying knowledge can be simply one whose question-answer pair  $(x, y(x))$  is known to domestic agents, and it can be included in the initial knowledge set  $\mathcal{F}_{S0}$ , where it reduces the variance of conjectures in its vicinity. The set  $\mathcal{Z}$  is thus defined residually, and the maintained assumption is not that foreign technologies never transmit knowledge, but only that some subset of them does not. This interpretation also clarifies why mere availability of foreign technologies does not reduce the cost of domestic research in the model. That is, possessing an artifact without the body of knowledge that produced it leaves the conjecture unchanged, which is consistent with the well-documented difficulty of obtaining knowledge about complex products from reading patents without tacit knowledge ([Hounshell and Smith, 1988](#)). The stagnation results in Proposition 1 and Lemmas 2 and 3 hinge on the existence of such technologies. Empirically, the residual set  $\mathcal{Z}$  is nonempty and plausibly large especially for complex products such as in chemistry: imported products embody artifacts rather than blueprints, much of the knowledge underlying technologies is tacit and is not transferred with the products.

**General Reward Functions.** Here, I briefly discuss how the results extend when the step reward function (4) is replaced by a general non-decreasing reward function  $R : [0, \infty) \rightarrow [0, \infty)$

with  $R(0) = 0$ . The results are qualitatively robust as long as  $R$  retains three features of the step function, formalized as the following conditions.

- (R1) There exists  $\underline{\delta} > 0$  such that  $R(\delta) \leq (\underline{c}/2)\delta$  for all  $\delta \in [0, \underline{\delta}]$ .
- (R2) There exists  $\delta' > 0$  such that  $R(\delta') > \underline{c}\delta'$ .
- (R3) The reward function  $R(\delta)$  is bounded by  $\bar{\lambda} \equiv \sup_{\delta \geq 0} R(\delta) < \infty$ . Redefine  $\bar{\sigma}^2 \equiv \bar{\lambda}/\underline{c}$ .

First, marginal novelty must not be essentially rewarded: there exists  $\underline{\delta} > 0$  such that  $R(\delta) \leq (\underline{c}/2)\delta$  for all  $\delta \leq \underline{\delta}$ . This condition creates a zone of radius  $\underline{\delta}$  around every point of  $\mathcal{Q}_t \cup \mathcal{Z}$  in which research is not profitable, so that  $\underline{\delta}$  plays the role of the novelty constraint  $\delta_0$ . Second, research must be profitable at some intermediate novelty,  $R(\delta') > \underline{c}\delta'$  for some  $\delta' > 0$ , so that the benchmark economy without foreign technologies keeps growing. Together, the first two conditions require the reward-novelty ratio  $R(\delta)/\delta$  to cross the marginal cost  $\underline{c}$  from below. Third,  $R$  must be bounded, so that highly uncertain questions remain unprofitable. Taken together,  $R$  must be S-shaped, with the step function (4) being the limiting case, so globally concave reward functions with  $R(0) = 0$ , whose average reward is non-increasing, are ruled out. Such functional feature is realistic given that technologies sufficiently close to existing ones are not likely to be rewarded, while there is some upper bound on the reward for novel technologies. Under these three conditions, Lemmas 2 and 3, Proposition 1 (ii) and (iii), Proposition 2 (i) and (ii), and Corollary 1 continue to hold, qualitatively unchanged, with  $\delta_0$  replaced by  $\underline{\delta}$ ,  $\bar{\sigma}^2$  redefined as  $\sup R/\underline{c}$ , and the wartime premium satisfying  $p > \underline{c}\underline{\delta}$ . In Lemma 1, the optimal novelty is now determined by a first-order trade-off between a higher reward and a higher variance rather than by the binding constraint  $\delta_t(x^*) = \delta_0$ , although it remains bounded. The monotone comparative statics for the success probability in Proposition 1 (i) and Proposition 2 (iii) exploit the fact that the reward is constant on the set of eligible questions, so that maximizing the payoff is equivalent to minimizing the variance. With a general increasing  $R$ , the payoff and the benefit-cost ratio are no longer co-monotone across questions, and these two statements survive in terms of the value of research and of research participation, whereas the success probability itself can respond non-monotonically. In this case, the scientist has higher success probability than the non-scientist if the scientist's optimal question is weakly less novel than the non-scientist's,  $\delta_t(x_S^*) \leq \delta_t(x_N^*)$ , then  $\rho_{Nt}^*(\mathcal{Z}) \leq \rho_{St}^*(\mathcal{Z})$ . This condition is automatically satisfied under the step function (4), by Lemma 1, and more generally whenever both optimal questions lie in a region where the reward is constant, including the wartime research under the stagnation condition.

**General Knowledge Spaces.** My baseline model assumes that the universe of questions can be represented on the real line. That is, I implicitly assume an order on questions. However, as discussed in [Carnehl and Schneider \(2025\)](#), the results also extend beyond the real line to the more general question spaces. Knowledge may partition the question space into a finite collection of bounded intervals and at least one unbounded interval, as long as (i) the space contains no cir-

cular paths, (ii) the set of questions is piecewise convex-valued, and (iii) at least one unbounded area exists. For instance, a finite forest network in which nodes represent knowledge, edges represent areas, and the truth is generated by Brownian bridges over each edge and a Wiener process along each unbounded frontier. On such a space, I measure both the distance  $d_t(x)$  in (2) and the novelty  $\delta_t(x)$  in (3) by the intrinsic path distance and place the foreign technology set  $\mathcal{Z}$  as a closed subset of the network. Because paths are unique, the pair  $(d, X)$  remains a sufficient statistic for uncertainty within each area, and Lemma 1, Proposition 1, Lemma 3, Proposition 2 (i) and (iii), and Corollary 1 (i) hold with the open intervals  $(\xi - \delta_0, \xi + \delta_0)$  replaced by path-distance bands. The remaining results require only a natural reformulation. In Lemma 2, foreign technologies must cover a band of length  $\bar{\sigma}^2$  along every unbounded direction leaving the initial knowledge. In Proposition 2 (ii), the frontier condition (12) becomes the requirement that, along some unbounded direction, wartime discoveries push the domestic frontier weakly past every foreign technology on that direction, after which condition (7) fails permanently. Corollary 1 (ii) can be just restated as the unbounded domestic knowledge set. Since  $\mathcal{F}_{Nt} \subseteq \mathcal{F}_{St}$  still implies  $\sigma_x^2(Y|\mathcal{F}_{St}) \leq \sigma_x^2(Y|\mathcal{F}_{Nt})$ , the scientist's advantage in Proposition 2 (iii) is preserved.

**Organized Research Environment.** I have so far assumed that the scientists' embodied knowledge comes from their mastery of the whole body of science accumulated by the scientific community to which they belong. This makes their discovery capability largely independent of their workplaces, consistent with the data. The model can be extended in a straightforward manner to make the research sector (private and public research institutes) a vehicle in which those who work there gain shared access to accumulated scientific knowledge through their job duties or through their colleagues who are scientists, making them also productive inventors while and only while they are employed in the research sector. Since non-scientists, by definition, do not carry embodied scientific knowledge, once they move away from the research sector, they also lose access to such knowledge.

## F. Proofs

**Lemma 1** *If the optimal  $\rho^*$  is positive, the optimal novelty is  $\delta(x^*) = \delta_0$ .*

*Proof.* Let  $F_t = \{x \in \mathbb{R} : \delta_t(x) \geq \delta_0, \sigma_x^2 \leq \bar{\sigma}^2\}$  denote the set of questions for which the reward is attainable and the conjecture is sufficiently precise, where  $\bar{\sigma}^2 = \lambda/\underline{c}$ . Let  $(x^*, \rho^*)$  be an optimal research plan with  $\rho^* > 0$ . Since  $c'$  is strictly increasing with  $c'(0) = \underline{c}$ , the optimal success probability  $\rho^*(m) = \varphi'(m) = (c')^{-1}(m)$  is strictly positive if and only if  $m = R(\delta_t(x))/\sigma_x^2 > \underline{c}$ . Under equation (4),  $m = \lambda/\sigma_x^2$  if  $\delta_t(x) \geq \delta_0$  and  $m = 0$  otherwise, so  $\rho^* > 0$  implies  $x^* \in F_t$ .

I first show that the payoff is strictly decreasing in the variance on  $F_t$ . By the envelope theorem,  $\varphi(m) = \rho^*(m)m - c(\rho^*(m))$  and  $\varphi'(m) = \rho^*(m)$ , so that

$$\varphi(m) - m\varphi'(m) = -c(\rho^*(m)) < 0,$$

for all  $m > \underline{c}$ , where the strict inequality holds because  $\rho^*(m) = (c')^{-1}(m) > 0$  for  $m > \underline{c}$ , since  $c'$  is strictly increasing with  $c'(0) = \underline{c}$ , and strict convexity of  $c$  together with  $c(0) = 0$  implies  $c(\rho) > c(0) + c'(0)\rho = \underline{c}\rho > 0$  for all  $\rho \in (0, 1)$ . Now, for any  $x \in F_t$ , we have  $R(\delta_t(x)) = \lambda$  and  $m = \lambda/\sigma_x^2 > \underline{c}$ , so the value of researching question  $x$  equals  $g(\sigma_x^2)$ , where  $g(\sigma_x^2) = \sigma_x^2\varphi(\lambda/\sigma_x^2) > 0$  for  $\sigma_x^2 \in (0, \bar{\sigma}^2)$ . Differentiating with  $\sigma_x^2$  and substituting  $m = \lambda/\sigma_x^2 > \underline{c}$ ,

$$g'(\sigma_x^2) = \varphi(\lambda/\sigma_x^2) - (\lambda/\sigma_x^2) \cdot \varphi'(\lambda/\sigma_x^2) = \varphi(m) - m\varphi'(m) < 0.$$

Hence, among questions in  $F_t$ , the payoff is strictly decreasing in the variance  $\sigma_x^2$ .

Note that novelty is dominated by the distance to knowledge. Every discovered question-answer pair is transformed into a technology, so  $\mathcal{Q}_{jt} \subseteq \mathcal{Q}_t \subseteq \mathcal{Q}_t \cup \mathcal{Z}$ . Since the minimum over a larger set is weakly smaller, equations (2) and (3) imply  $\delta_t(x) \leq d_t(x)$  for every  $x$ . In particular, every  $x \in F_t$  satisfies  $d_t(x) \geq \delta_t(x) \geq \delta_0 > 0$ .

We can also show that the variance is strictly increasing in the distance within each area. In an interior area of length  $X < \infty$ , the feasible distance satisfies  $d_t(x) \in (0, X/2]$ , and  $\sigma^2(d, X) = d(X-d)/X$  is strictly increasing in  $d$  on  $[0, X/2]$ . In the unbounded areas 0 and  $N_{jt}$ , the variance is  $\sigma^2 = d$ , which is strictly increasing in  $d$ .

Using these properties, we can show that the optimal novelty equals  $\delta_0$  if  $\rho^*(m)$  is positive by contradiction. Suppose that  $\delta_t(x^*) > \delta_0$ . As the distance to the set  $\mathcal{Q}_t \cup \mathcal{Z}$ , the function  $\delta_t$  is 1-Lipschitz, so every  $x$  with  $|x - x^*| < \varepsilon = \delta_t(x^*) - \delta_0$  satisfies

$$\delta_t(x) \geq \delta_t(x^*) - |x - x^*| > \delta_t(x^*) - \varepsilon = \delta_0,$$

and hence satisfies the novelty requirement of  $F_t$ . Note that  $d_t(x^*) \geq \delta_0 > 0$ . Now, take any  $\eta \in (0, \min\{\varepsilon, d_t(x^*)\})$  and let  $x'$  be the question obtained by moving  $x^*$  by  $\eta$  toward the knowledge point attaining  $d_t(x^*)$  — that is, toward the nearer endpoint if  $x^*$  lies in an interior area, and

toward the frontier point  $x_1$  or  $x_{N_{jt}}$  if  $x^*$  lies in an unbounded area. Then  $x'$  remains in the same area as  $x^*$  and has strictly smaller distance  $d_t(x') = d_t(x^*) - \eta$ . Hence  $\sigma_{x'}^2 < \sigma_{x^*}^2 < \bar{\sigma}^2$ , which together with  $\delta_t(x') > \delta_0$  gives  $x' \in F_t$ . Since  $\sigma_{x'}^2 < \sigma_{x^*}^2$ , and the payoff is strictly decreasing in the variance on  $F_t$ , the value of researching  $x'$  strictly exceeds the value  $g(\sigma_{x^*}^2)$  of the optimal plan, which is a contradiction. Hence,  $\delta_t(x^*) = \delta_0$ . ■

**Proposition 1** (i) For any agent  $j \in \{S, N\}$  and any closed sets  $\mathcal{Z} \subseteq \mathcal{Z}'$ ,  $\rho_{jt}^*(\mathcal{Z}') \leq \rho_{jt}^*(\mathcal{Z})$ .

(ii) Suppose  $\rho_{jt}^*(\emptyset) > 0$  and every question  $x^*$  that is optimal in the benchmark problem without foreign technologies satisfies  $\min_{z \in \mathcal{Z}} |x^* - z| < \delta_0$ . Then,  $\rho_{jt}^*(\mathcal{Z}) < \rho_{jt}^*(\emptyset)$  for any nonempty  $\mathcal{Z}$ .

(iii) Suppose  $\delta_0 < \bar{\sigma}^2 \equiv \lambda/\underline{c}$ , so that  $\rho_{jt}^*(\emptyset) > 0$ : absent foreign technologies, the scientist conducts research with positive success probability in each period. If foreign technologies are sufficiently dense in the vicinity of domestic knowledge, that is, if

$$\{x \in \mathbb{R} : \sigma_x^2(Y|\mathcal{F}_{St}) < \bar{\sigma}^2\} \subseteq \bigcup_{\xi \in \mathcal{Q}_t \cup \mathcal{Z}} (\xi - \delta_0, \xi + \delta_0),$$

then,  $\rho_{jt}^*(\mathcal{Z}) = 0$  for both agents, no discovery occurs in period  $t$ , and condition (7) holds in every subsequent period. Consequently,  $\rho_{j\tau}^*(\mathcal{Z}) = 0$  and  $N_{j\tau} = N_{jt}$  for all  $\tau \geq t$  and  $j \in \{S, N\}$ . Moreover, condition (7) cannot be satisfied if  $\mathcal{Z} = \emptyset$ .

*Proof.* Fix a period  $t$  and an agent  $j$  with  $\mathcal{F}_{jt} \neq \emptyset$ , and write  $\sigma_x^2 = \sigma_x^2(Y|\mathcal{F}_{jt})$  and  $\delta_t(x; \mathcal{Z}) = \min_{\xi \in \mathcal{Q}_t \cup \mathcal{Z}} |x - \xi|$ . Since the answers  $y(z)$  for  $z \in \mathcal{Z}$  are unknown, the knowledge set  $\mathcal{F}_{jt}$ , and hence the map  $x \mapsto \sigma_x^2$ , do not depend on  $\mathcal{Z}$ ; the foreign technology set enters the research problem only through the novelty  $\delta_t(\cdot; \mathcal{Z})$ .

I first characterize the optimal success probability. For a closed set  $\mathcal{Z}$ , define the eligible set and its affordable subset,

$$E_t(\mathcal{Z}) = \{x \in \mathbb{R} : \delta_t(x; \mathcal{Z}) \geq \delta_0\}, \quad K_t(\mathcal{Z}) = E_t(\mathcal{Z}) \cap \{x \in \mathbb{R} : \sigma_x^2 \leq \bar{\sigma}^2\}.$$

By equations (4) and (6), researching  $x \notin E_t(\mathcal{Z})$  yields the payoff  $\sigma_x^2 \varphi(0) = 0$ , while researching  $x \in E_t(\mathcal{Z})$  yields  $v(\sigma_x^2)$ , where  $v(\sigma_x^2) = \sigma_x^2 \varphi(\lambda/\sigma_x^2)$  for  $\sigma_x^2 > 0$ . Since  $\varphi(m) = 0$  for  $m \leq \underline{c}$  and  $\varphi(m) > 0$  for  $m > \underline{c}$ , we have  $v(\sigma_x^2) = 0$  for  $\sigma_x^2 \geq \bar{\sigma}^2$  and  $v(\sigma_x^2) > 0$  for  $\sigma_x^2 \in (0, \bar{\sigma}^2)$ . Moreover, as shown in the proof of Lemma 1,  $v$  is strictly decreasing on  $(0, \bar{\sigma}^2)$ . Next, note that the constraint set  $K_t(\mathcal{Z})$  is compact:  $x \mapsto \delta_t(x; \mathcal{Z})$  is a distance function to a nonempty closed set and hence continuous, so  $E_t(\mathcal{Z})$  is closed;  $x \mapsto \sigma_x^2$  is continuous on  $\mathbb{R}$ , being continuous within each area by equation (1) and converging to 0 at every knowledge point from both sides; and  $\{x : \sigma_x^2 \leq \bar{\sigma}^2\}$  is closed and contained in  $[x_1 - \bar{\sigma}^2, x_{N_{jt}} + \bar{\sigma}^2]$ , because  $\sigma_x^2 = x_1 - x$  on area 0 and  $\sigma_x^2 = x - x_{N_{jt}}$  on area  $N_{jt}$ . If  $K_t(\mathcal{Z}) \neq \emptyset$ , let  $s^*(\mathcal{Z}) = \min_{x \in K_t(\mathcal{Z})} \sigma_x^2$ , which is attained by compactness and

continuity; otherwise, set  $s^*(\mathcal{Z}) = +\infty$ . Whenever finite,  $s^*(\mathcal{Z}) > 0$ : since  $\mathcal{Q}_{jt} \subseteq \mathcal{Q}_t \cup \mathcal{Z}$ , every  $x \in E_t(\mathcal{Z})$  satisfies  $d_t(x) \geq \delta_t(x; \mathcal{Z}) \geq \delta_0$ , so that  $\sigma_x^2 = d_t(x) \geq \delta_0$  in the unbounded areas, and  $\sigma_x^2 = d_t(x)(X - d_t(x))/X \geq d_t(x)/2 \geq \delta_0/2$  in an interior area of length  $X$ , where the first inequality uses  $d_t(x) \leq X/2$ . Because the payoff is zero outside  $K_t(\mathcal{Z})$  and equals  $v(\sigma_x^2)$ , strictly decreasing in  $\sigma_x^2$ , on  $K_t(\mathcal{Z})$ , the optimal success probability satisfies

$$\rho_{jt}^*(\mathcal{Z}) = \begin{cases} (c')^{-1}(\lambda/s^*(\mathcal{Z})) > 0, & \text{if } s^*(\mathcal{Z}) < \bar{\sigma}^2, \\ 0, & \text{otherwise,} \end{cases}$$

and, in the first case, the set of optimal questions is  $A(\mathcal{Z}) = \{x \in K_t(\mathcal{Z}) : \sigma_x^2 = s^*(\mathcal{Z})\} \neq \emptyset$ . Finally, observe that  $s \mapsto (c')^{-1}(\lambda/s)$  is strictly decreasing on  $(0, \bar{\sigma}^2)$ , since  $c'$  is strictly increasing and  $s \mapsto \lambda/s$  is strictly decreasing.

(i): Let  $\mathcal{Z} \subseteq \mathcal{Z}'$ . Since the minimum over a larger set is weakly smaller,  $\delta_t(x; \mathcal{Z}') \leq \delta_t(x; \mathcal{Z})$  for every  $x$ , and hence  $E_t(\mathcal{Z}') \subseteq E_t(\mathcal{Z})$ . Because the affordability constraint  $\sigma_x^2 \leq \bar{\sigma}^2$  does not depend on the foreign technology set,  $K_t(\mathcal{Z}') \subseteq K_t(\mathcal{Z})$ , and the minimum of  $\sigma_x^2$  over a smaller set is weakly larger:  $s^*(\mathcal{Z}') \geq s^*(\mathcal{Z})$ . The characterization of  $\rho_{jt}^*(\mathcal{Z})$  and the monotonicity of  $(c')^{-1}(\lambda/\cdot)$  then yield  $\rho_{jt}^*(\mathcal{Z}') \leq \rho_{jt}^*(\mathcal{Z})$ .

(ii): Since  $\rho_{jt}^*(\emptyset) > 0$ , the characterization of  $\rho_{jt}^*(\mathcal{Z})$  implies  $s^*(\emptyset) < \bar{\sigma}^2$  and  $A(\emptyset) \neq \emptyset$ . By assumption, every  $x \in A(\emptyset)$  satisfies  $\min_{z \in \mathcal{Z}} |x - z| < \delta_0$ , and hence  $\delta_t(x; \mathcal{Z}) < \delta_0$ , so that  $A(\emptyset) \cap K_t(\mathcal{Z}) = \emptyset$ . If  $K_t(\mathcal{Z}) = \emptyset$  or  $s^*(\mathcal{Z}) \geq \bar{\sigma}^2$ , then  $\rho_{jt}^*(\mathcal{Z}) = 0 < \rho_{jt}^*(\emptyset)$ . Otherwise,  $s^*(\mathcal{Z})$  is attained at some  $x' \in K_t(\mathcal{Z}) \subseteq K_t(\emptyset)$  with  $x' \notin A(\emptyset)$ . Since  $A(\emptyset)$  collects all minimizers of  $\sigma_x^2$  on  $K_t(\emptyset)$ , it follows that  $s^*(\mathcal{Z}) = \sigma_{x'}^2 > s^*(\emptyset)$ . The strict monotonicity of  $(c')^{-1}(\lambda/\cdot)$  on  $(0, \bar{\sigma}^2)$  then gives  $\rho_{jt}^*(\mathcal{Z}) < \rho_{jt}^*(\emptyset)$ .

(iii): Suppose  $\delta_0 < \bar{\sigma}^2$ . I first verify that research is profitable for the scientist absent foreign technologies. Recall that the scientist has access to all domestic discoveries, so  $\mathcal{Q}_{St} = \mathcal{Q}_t$ . Consider the frontier question  $x = x_{N_{St}} + \delta_0$ , which lies in the unbounded area  $N_{St}$ . Its nearest point in  $\mathcal{Q}_t$  is  $x_{N_{St}}$ , so  $\delta_t(x; \emptyset) = d_t(x) = \delta_0$  and  $\sigma_x^2(Y|\mathcal{F}_{St}) = \delta_0 < \bar{\sigma}^2$ . Hence  $x \in K_t(\emptyset)$ , so  $s^*(\emptyset) \leq \delta_0 < \bar{\sigma}^2$ , and the characterization of  $\rho_{jt}^*(\mathcal{Z})$  implies  $\rho_{St}^*(\emptyset) \geq (c')^{-1}(\lambda/\delta_0) > 0$ .

Now, suppose that condition (7) holds in period  $t$ . Take any  $x$  with  $\delta_t(x; \mathcal{Z}) \geq \delta_0$ , and then  $|x - \xi| \geq \delta_0$  for every  $\xi \in \mathcal{Q}_t \cup \mathcal{Z}$ , so  $x$  does not belong to the union of open intervals on the right-hand side of (7), and therefore  $\sigma_x^2(Y|\mathcal{F}_{St}) \geq \bar{\sigma}^2$  by the covering condition. Every question that clears the novelty threshold thus satisfies  $m = \lambda/\sigma_x^2(Y|\mathcal{F}_{St}) \leq \underline{c}$  and  $\varphi(m) = 0$ , so  $\rho_{St}^*(\mathcal{Z}) = 0$ : the scientist does not conduct research. For the non-scientist,  $\sigma_x^2(Y|\mathcal{F}_{Nt}) \geq \sigma_x^2(Y|\mathcal{F}_{St}) \geq \bar{\sigma}^2$  for every such  $x$  since  $\mathcal{F}_{Nt} \subseteq \mathcal{F}_{St}$ , and the same argument yields  $\rho_{Nt}^*(\mathcal{Z}) = 0$ . Hence, neither agent exerts effort and no discovery occurs in period  $t$ :  $\mathcal{F}_{j,t+1} = \mathcal{F}_{jt}$  for  $j \in \{S, N\}$  and  $\mathcal{Q}_{t+1} = \mathcal{Q}_t$ . Since  $\mathcal{Z}$  is fixed, both sides of condition (7) are unchanged, so the condition holds verbatim in period  $t + 1$ . By induction,  $\rho_{j\tau}^*(\mathcal{Z}) = 0$  and  $N_{j\tau} = N_{jt}$  for all  $\tau \geq t$  and  $j \in \{S, N\}$ .

Finally, suppose  $\mathcal{Z} = \emptyset$ . The frontier question  $x = x_{N_{St}} + \delta_0$  satisfies  $\sigma_x^2(Y|\mathcal{F}_{St}) = \delta_0 < \bar{\sigma}^2$ , so it belongs to the left-hand side of (7), while  $|x - \xi| \geq \delta_0$  for every  $\xi \in \mathcal{Q}_t$ , so it does not belong to the union of open intervals  $\bigcup_{\xi \in \mathcal{Q}_t} (\xi - \delta_0, \xi + \delta_0)$  on the right-hand side. Hence, condition (7) fails if  $\mathcal{Z} = \emptyset$ , which proves the last claim. ■

**Lemma 2** *Suppose that the economy starts with a finite set of knowledge,  $\mathcal{F}_{j0} = \{(x_i, y(x_i))\}_{i=1}^n$  for  $j \in \{S, N\}$  with  $x_1 < \dots < x_n$  and  $\mathcal{Q}_0 = \{x_1, \dots, x_n\}$ , and that foreign technologies surround the initial knowledge frontier, in the sense that there exist  $a \leq x_1$  and  $b \geq x_n$  such that*

$$[a - \bar{\sigma}^2, a] \cup [b, b + \bar{\sigma}^2] \subseteq \bigcup_{z \in \mathcal{Z}} (z - \delta_0, z + \delta_0).$$

*Then, almost surely, there exists a finite period  $T$  such that condition (7) holds for all  $t \geq T$ .*

*Proof.* Throughout, recall from the proof of Proposition 1 that, in any period  $t$ , condition (7) is equivalent to  $\rho_{St}^*(\mathcal{Z}) = 0$ : condition (7) states that every question with  $\sigma_x^2(Y|\mathcal{F}_{St}) < \bar{\sigma}^2$  satisfies  $\delta_t(x; \mathcal{Z}) < \delta_0$ , which holds if and only if no question is both eligible and affordable for the scientist, that is,  $s^*(\mathcal{Z}) \geq \bar{\sigma}^2$  and hence  $\rho_{St}^*(\mathcal{Z}) = 0$ .

I first verify that  $\mathcal{Q}_t \subseteq [a, b]$  for every  $t$ . The claim holds at  $t = 0$  since  $a \leq x_1 < \dots < x_n \leq b$ . Suppose it holds in period  $t$ ; then every point of every knowledge set lies in  $[a, b]$  as well, since  $\mathcal{F}_{jt}$  consists of discovered pairs and the initial pairs. Consider a discovery at  $x^*$  by agent  $j$  in period  $t$ . The novelty restriction implies  $|x^* - z| \geq \delta_0$  for every  $z \in \mathcal{Z}$ , so  $x^*$  does not belong to  $\bigcup_{z \in \mathcal{Z}} (z - \delta_0, z + \delta_0)$ , and hence, by the surrounding condition (8),  $x^* \notin [a - \bar{\sigma}^2, a] \cup [b, b + \bar{\sigma}^2]$ . Now, suppose  $x^* > b$ . Then  $x^* > b + \bar{\sigma}^2$ , and since all of agent  $j$ 's knowledge lies in  $[a, b]$ , the question  $x^*$  lies in agent  $j$ 's unbounded area  $N_{jt}$ , so  $\sigma_x^2(Y|\mathcal{F}_{jt}) = x^* - x_{N_{jt}} \geq x^* - b > \bar{\sigma}^2$ , contradicting the optimality. The case  $x^* < a$  is symmetric:  $x^* < a - \bar{\sigma}^2$  would imply  $\sigma_x^2(Y|\mathcal{F}_{jt}) = x_1 - x^* \geq a - x^* > \bar{\sigma}^2$ , where  $x_1$  denotes agent  $j$ 's smallest knowledge point. Hence  $x^* \in [a, b]$  and  $\mathcal{Q}_{t+1} \subseteq [a, b]$ . Note that no condition is imposed on the interior of  $[x_1, x_n]$ : research may actively fill the gaps between the initial questions, and only the two flanks of the initial frontier need to be surrounded.

Every discovery lies at distance at least  $\delta_0$  from all previously discovered questions and from the initial questions  $x_1, \dots, x_n$ . Consequently, discoveries made in different periods are at least  $\delta_0$  apart. The initial questions themselves are not discoveries and do not enter the count. Partition  $[a, b]$  into  $K = \lceil (b - a)/\delta_0 \rceil + 1$  intervals of length at most  $\delta_0$ . Every discovery lies in  $[a, b]$ , so the total number of discoveries is at most  $K$  along every path of the process.

For each period  $k$ , let  $A_k$  denote the event that  $\rho_{Sk}^*(\mathcal{Z}) > 0$  and no discovery occurs in any period  $t \geq k$ . On  $A_k$ , the state  $(\mathcal{F}_{St}, \mathcal{F}_{Nt}, \mathcal{Q}_t)$  remains equal to its period- $k$  value forever, so the scientist's optimal success probability remains equal to the constant  $\bar{\rho} = \rho_{Sk}^*(\mathcal{Z}) > 0$  and, in every period  $t \geq k$ , the scientist researches an eligible question and succeeds with probability  $\bar{\rho}$ , independently across periods. Hence, conditional on the history up to period  $k$ , the probability

that no discovery occurs in the following  $\tau$  periods is at most  $(1 - \bar{\rho})^\tau \rightarrow 0$  as  $\tau \rightarrow \infty$ , which implies  $\Pr(A_k) = 0$  for every  $k$ . Now consider the event  $E$  that condition (7) fails in every period, that is,  $\rho_{S_t}^*(\mathcal{Z}) > 0$  for all  $t$ . Since the number of discoveries along any path is at most  $K$ , on  $E$ , there exists a period  $k$  after which no discovery ever occurs, and therefore  $E \subseteq \bigcup_{k \geq 0} A_k$ . Hence,  $\Pr(E) \leq \sum_{k \geq 0} \Pr(A_k) = 0$ . Almost surely, therefore, there exists a finite period  $T$  in which condition (7) holds. ■

**Lemma 3** *Let  $x_i < x_{i+1}$  be adjacent questions in  $\mathcal{Q}_t$  with  $X_i = x_{i+1} - x_i$ , and define  $w_i = \min\{2\bar{\sigma}^2, X_i/2\}$ . Suppose that foreign technologies cover the two bands adjacent to the domestic knowledge points, in the sense that*

$$[x_i + \delta_0, x_i + w_i] \cup [x_{i+1} - w_i, x_{i+1} - \delta_0] \subseteq \bigcup_{z \in \mathcal{Z}} (z - \delta_0, z + \delta_0).$$

*Then, along every path and in every period  $\tau \geq t$ , no agent researches any question in  $(x_i, x_{i+1})$  with positive success probability, and hence no discovery ever occurs in the gap:  $\mathcal{Q}_\tau \cap (x_i, x_{i+1}) = \emptyset$  for all  $\tau \geq t$  and  $j \in \{S, N\}$ .*

*Proof.* For ease of exposition, write  $\mathcal{O} = (x_i, x_{i+1})$ ,  $X = X_i$ , and  $w = w_i$ . I prove by induction that, for every  $\tau \geq t$ ,  $\mathcal{Q}_\tau \cap \mathcal{O} = \emptyset$  and no discovery occurs in  $\mathcal{O}$  in period  $\tau$ . Note that  $\mathcal{Q}_t \cap \mathcal{O} = \emptyset$  holds because  $x_i$  and  $x_{i+1}$  are adjacent in  $\mathcal{Q}_t$ .

Suppose  $\mathcal{Q}_\tau \cap \mathcal{O} = \emptyset$  for some  $\tau \geq t$ . Since knowledge is never lost, we have  $x_i, x_{i+1} \in \mathcal{Q}_\tau \subseteq \mathcal{Q}_\tau$ , so  $x_i$  and  $x_{i+1}$  are adjacent in  $\mathcal{Q}_\tau$ . Because the scientist has access to all domestic discoveries,  $\mathcal{Q}_{S\tau} = \mathcal{Q}_\tau$ , the interval  $[x_i, x_{i+1})$  is an area of the scientist's knowledge partition, and

$$\sigma_x^2(Y|\mathcal{F}_{S\tau}) = \frac{d(X-d)}{X}, \quad d = \min\{x - x_i, x_{i+1} - x\} \in (0, X/2],$$

for all  $x \in \mathcal{O}$ , while  $\sigma_x^2(Y|\mathcal{F}_{N\tau}) \geq \sigma_x^2(Y|\mathcal{F}_{S\tau})$  since  $\mathcal{F}_{N\tau} \subseteq \mathcal{F}_{S\tau}$ . Now take any  $x \in \mathcal{O}$  and consider the following three cases according to  $d$ .

*Case 1:*  $d < \delta_0$ . The nearer of two points,  $x_i$  or  $x_{i+1}$ , belongs to  $\mathcal{Q}_\tau \subseteq \mathcal{Q}_\tau \cup \mathcal{Z}$ , so  $\delta_\tau(x) \leq d < \delta_0$  and, the reward function implies  $R(\delta_\tau(x)) = 0$ .

*Case 2:*  $\delta_0 \leq d \leq w$ . Then  $x \in [x_i + \delta_0, x_i + w] \cup [x_{i+1} - w, x_{i+1} - \delta_0]$ , so by condition (9) there exists  $z \in \mathcal{Z}$  with  $|x - z| < \delta_0$ . Hence,  $\delta_\tau(x) < \delta_0$  and  $R(\delta_\tau(x)) = 0$ .

*Case 3:*  $d > w$ . Because  $d \leq X/2$ , this case happens only if  $w = 2\bar{\sigma}^2 < X/2$ , so that  $d > 2\bar{\sigma}^2$ . Since the variance takes the maximum value at  $d = X/2$ ,

$$\sigma_x^2(Y|\mathcal{F}_{S\tau}) = \frac{d(X-d)}{X} \geq \frac{d}{2} > \bar{\sigma}^2,$$

and also  $\sigma_x^2(Y|\mathcal{F}_{N\tau}) > \bar{\sigma}^2$ . Hence, for either agent  $j$ , even if the novelty constraint is satisfied,

$$m = R(\delta_\tau(x))/\sigma_x^2(Y|\mathcal{F}_{j\tau}) \leq \lambda/\sigma_x^2(Y|\mathcal{F}_{j\tau}) < \lambda/\bar{\sigma}^2 = \underline{c}.$$

In Cases 1 and 2,  $R(\delta_\tau(x)) = 0$  and hence  $m = 0 < \underline{c}$  for both agents. In Case 3,  $m < \underline{c}$  for both agents. As shown in the proof of Lemma 1, the optimal success probability at question  $x$  is  $\rho^*(m) = (c')^{-1}(m)$ , which is strictly positive if and only if  $m > \underline{c}$ . Hence, in period  $\tau$ , no agent researches any question in  $\mathcal{O}$  with positive success probability, and no discovery occurs in  $\mathcal{O}$ . Since every discovery in period  $\tau$  therefore lies outside  $\mathcal{O}$ , we obtain  $\mathcal{Q}_{\tau+1} \cap \mathcal{O} = \emptyset$ , which completes the induction. ■

**Proposition 2** *Suppose  $\delta_0 < \min\{\lambda, p\}/\underline{c}$ . Define  $\underline{m} > \underline{c}$  and  $\underline{\rho} \in (0, 1)$  as follows:*

$$\underline{m} = \frac{\min\{\lambda, p\}}{\delta_0}, \quad \underline{\rho} = \frac{\delta_0 \varphi(\underline{m})}{\max\{\lambda, p\}}.$$

(i) *In every wartime period  $t \in \{t_0, \dots, t_1\}$ ,  $\rho_{St}^*(\mathcal{Z}) \geq \underline{\rho} > 0$ . In particular, if condition (7) holds at the outbreak of the war — so that, absent the shock,  $\rho_{S\tau}^*(\mathcal{Z}) = 0$  and  $N_{S\tau} = N_{St_0}$  for all  $\tau \geq t_0$  by Proposition 1 — the shock strictly raises the discovery probability. Moreover, in any wartime period in which condition (7) holds, every optimal question lies in the wartime problem:  $x^* \in \mathcal{W}$ .*

(ii) *Suppose that  $\mathcal{Z}$  is bounded and nonempty, and let  $\underline{z} = \inf \mathcal{Z}$  and  $\bar{z} = \sup \mathcal{Z}$ . Suppose that, by the end of the war, wartime discoveries push the domestic knowledge frontier to the boundary of the foreign technology set, in the sense that there exists a period  $\tau^* \leq t_1 + 1$  such that*

$$\max \mathcal{Q}_{\tau^*} \geq \bar{z} \quad \text{or} \quad \min \mathcal{Q}_{\tau^*} \leq \underline{z}.$$

*Then condition (7) fails in every period  $t \geq \tau^*$ ; consequently,  $\rho_{St}^*(\mathcal{Z}) \geq (c')^{-1}(\lambda/\delta_0) > 0$  in every post-war period  $t > t_1$ , and  $N_{St} \rightarrow \infty$  almost surely.*

(iii) *The scientist has larger success probability than the non-scientist:  $\rho_{Nt}^*(\mathcal{Z}) \leq \rho_{St}^*(\mathcal{Z})$  in every wartime period  $t_0 \leq t \leq t_1$  in which condition (7) holds, and in every post-war period  $t > t_1$ .*

*Proof.* First, note that  $\underline{\rho} \in (0, 1)$ : since  $\underline{m} > \underline{c}$ ,  $\varphi(\underline{m}) > 0$ , and since  $c(\rho) > 0$  for  $\rho > 0$ ,  $\varphi(\underline{m}) = \rho^*(\underline{m})\underline{m} - c(\rho^*(\underline{m})) < \underline{m}$ , so that  $\underline{\rho} < \delta_0 \underline{m} / \max\{\lambda, p\} = \min\{\lambda, p\} / \max\{\lambda, p\} \leq 1$ .

(i): Let  $\bar{q}_t = \max \mathcal{Q}_t = x_{N_{St}}$ . Consider the frontier question  $x_f = \bar{q}_t + \delta_0$ . It lies in the scientist's unbounded area  $N_{St}$ , so  $\sigma_{x_f}^2(Y|\mathcal{F}_{St}) = \delta_0$ , and its nearest domestic point is  $\bar{q}_t$ , so  $\delta_t^-(x_f) = \delta_0$ . If  $x_f \in \mathcal{W}$ , then  $\min_{z \in \mathcal{Z}} |x_f - z| < \delta_0$ , hence  $\delta_t(x_f) < \delta_0$  and  $R_t(\delta_t(x_f)) = 0$ , while  $P(x_f) = p$  since  $\delta_t^-(x_f) = \delta_0 \geq \delta_0$ , so  $R_t^w(x_f) = p$ . If  $x_f \notin \mathcal{W}$ , then  $\min_{z \in \mathcal{Z}} |x_f - z| \geq \delta_0$ , which together with  $\min_{\xi \in \mathcal{Q}_t} |x_f - \xi| = \delta_0$  gives  $\delta_t(x_f) = \delta_0$ , so  $R_t^w(x_f) = \lambda$ . In either case,  $R_t^w(x_f) \geq \min\{\lambda, p\}$ , and the value of researching  $x_f$  is

$$\sigma_{x_f}^2 \varphi(R_t^w(x_f)/\sigma_{x_f}^2) = \delta_0 \varphi(R_t^w(x_f)/\delta_0) \geq \delta_0 \varphi(\underline{m}) > 0,$$

where the first inequality uses the monotonicity of  $\varphi$  and the second uses  $\underline{m} > \underline{c}$ . Hence the wartime value of the research problem satisfies  $V_t^* \geq \delta_0 \varphi(\underline{m}) > 0$ , and the optimal plan  $(x^*, \rho^*)$  has  $\rho^* > 0$ . Since costs are nonnegative,

$$V_t^* = \rho^* R_t^w(x^*) - \sigma_{x^*}^2 c(\rho^*) \leq \rho^* R_t^w(x^*) \leq \rho^* \max\{\lambda, p\},$$

which yields  $\rho_{St}^*(\mathcal{Z}) = \rho^* \geq \delta_0 \varphi(\underline{m}) / \max\{\lambda, p\} = \underline{\rho}$ . The comparison with the counterfactual path follows from Proposition 1 (iii): if condition (7) holds at  $t_0$ , then absent the wartime shock  $\rho_{S\tau}^*(\mathcal{Z}) = 0$  for all  $\tau \geq t_0$ , while under the shock,  $\rho_{St}^*(\mathcal{Z}) \geq \underline{\rho} > 0$  in every wartime period.

Finally, suppose condition (7) holds in wartime period  $t$ . I show that researching any question outside  $\mathcal{W}$  yields exactly zero expected payoff, so that no optimal question can lie outside  $\mathcal{W}$ . Take any  $x \notin \mathcal{W}$ . The premium term  $P(x)$  is zero, so  $R_t^w(x) = \lambda \cdot \mathbb{1}\{\delta_t(x; \mathcal{Z}) \geq \delta_0\}$ . If  $\delta_t(x; \mathcal{Z}) < \delta_0$ , then  $R_t^w(x) = 0$  and the payoff at  $x$  is zero. If  $\delta_t(x; \mathcal{Z}) \geq \delta_0$ , then, as in the proof of Proposition 1 (iii), condition (7) implies  $\sigma_x^2(Y|\mathcal{F}_{St}) \geq \bar{\sigma}^2 = \lambda/\underline{c}$ , so  $R_t^w(x) = \lambda \leq \underline{c} \cdot \sigma_x^2(Y|\mathcal{F}_{St})$  and the payoff at  $x$  is again zero. Hence, the payoff from researching any  $x \notin \mathcal{W}$  is zero, whereas the optimal plan attains  $V_t^* \geq \delta_0 \varphi(\underline{m}) > 0$  as shown above, so every optimal question satisfies  $x^* \in \mathcal{W}$ . Moreover, since  $x^* \in \mathcal{W}$  implies  $\delta_t(x^*; \mathcal{Z}) < \delta_0$ , an optimal question with  $\delta_t^-(x^*) < \delta_0$  would have  $R_t^w(x^*) = 0$  and zero payoff as well. Hence,  $\delta_t^-(x^*) \geq \delta_0$  and  $R_t^w(x^*) = p$ .

(ii): Suppose  $\max \mathcal{Q}_{\tau^*} \geq \bar{z}$ . The proof for the case  $\min \mathcal{Q}_{\tau^*} \leq \underline{z}$  is symmetric. Since knowledge is never lost,  $\mathcal{Q}_t$  is nondecreasing in  $t$ , so  $\bar{q}_t = \max \mathcal{Q}_t \geq \bar{z}$  for every  $t \geq \tau^*$ . Take any  $t \geq \tau^*$  and consider the frontier question  $x_f = \bar{q}_t + \delta_0$ , which satisfies  $\sigma_{x_f}^2(Y|\mathcal{F}_{St}) = \delta_0 < \bar{\sigma}^2$ , where the inequality uses  $\delta_0 < \min\{\lambda, p\}/\underline{c} \leq \lambda/\underline{c}$ . For every  $\xi \in \mathcal{Q}_t$ ,  $\xi \leq \bar{q}_t$  implies  $|x_f - \xi| \geq \delta_0$ , and for every  $z \in \mathcal{Z}$ ,  $z \leq \bar{z} \leq \bar{q}_t$  implies  $|x_f - z| = x_f - z \geq x_f - \bar{z} \geq \delta_0$ . Hence  $x_f$  belongs to the left-hand side of condition (7) but not to the union of open intervals on its right-hand side, and condition (7) fails in period  $t$ . Now, consider any post-war period  $t > t_1$ . In the notation of the proof of Proposition 1,  $\delta_t(x_f; \mathcal{Z}) \geq \delta_0$  and  $\sigma_{x_f}^2(Y|\mathcal{F}_{St}) = \delta_0 < \bar{\sigma}^2$  imply  $x_f \in K_t(\mathcal{Z})$  and hence  $s^*(\mathcal{Z}) \leq \delta_0$ , and the proof of Proposition 1 implies  $\rho_{St}^*(\mathcal{Z}) = (c')^{-1}(\lambda/s^*(\mathcal{Z})) \geq (c')^{-1}(\lambda/\delta_0) > 0$ .

It remains to show that  $N_{St} \rightarrow \infty$  almost surely. In every wartime period  $t \in \{\tau^*, \dots, t_1\}$ ,  $\rho_{St}^*(\mathcal{Z}) \geq \underline{\rho}$ , and in every post-war period,  $\rho_{St}^*(\mathcal{Z}) \geq (c')^{-1}(\lambda/\delta_0)$  as just shown. Hence, in every period  $t \geq \tau^*$ , conditional on the history up to  $t$ , the scientist researches some question and succeeds with probability at least  $\rho' = \min\{\underline{\rho}, (c')^{-1}(\lambda/\delta_0)\} > 0$ . Moreover, every success is a discovery of a question not previously in  $\mathcal{Q}_t$ : a question researched with positive effort has positive value, which requires  $\delta_t(x; \mathcal{Z}) \geq \delta_0$  or, during the war,  $\delta_t^-(x) \geq \delta_0$ , and in both cases  $\delta_t^-(x) = \min_{\xi \in \mathcal{Q}_t} |x - \xi| \geq \delta_0 > 0$ , since  $\delta_t(x; \mathcal{Z}) \leq \delta_t^-(x)$ . Each success therefore adds a new pair to  $\mathcal{F}_{St}$ . For each  $k \geq 0$ , let  $A_k$  denote the event that no discovery occurs in any period  $t \geq \max\{k, \tau^*\}$ . Conditional on the history up to period  $\max\{k, \tau^*\}$ , the probability that no discovery occurs in the following  $\tau$  periods is at most  $(1 - \rho')^\tau \rightarrow 0$  as  $\tau \rightarrow \infty$ , which implies  $\Pr(A_k) = 0$  for every  $k$ , as in the proof of Lemma 2. Since the event that only finitely many dis-

coveries occur is contained in  $\bigcup_{k \geq 0} A_k$ , almost surely infinitely many discoveries occur, and each of them raises  $N_{St}$  by one. Hence  $N_{St} \rightarrow \infty$  almost surely.

(iii): Note that  $\mathcal{F}_{Nt} \subseteq \mathcal{F}_{St}$  implies  $\sigma_x^2(Y|\mathcal{F}_{St}) \leq \sigma_x^2(Y|\mathcal{F}_{Nt})$  for every  $x$ . In any period in which the revenue is given by (4), in particular, any post-war period, the characterization in the proof of Proposition 1, applied to agent  $j$ , gives  $\rho_{jt}^*(\mathcal{Z}) = (c')^{-1}(\lambda/s_j)$  if  $s_j < \bar{\sigma}^2$  and  $\rho_{jt}^*(\mathcal{Z}) = 0$  otherwise, where  $s_j = \min_{x \in E_t(\mathcal{Z})} \sigma_x^2(Y|\mathcal{F}_{jt})$  and  $E_t(\mathcal{Z})$  is the eligible set, common to the two agents. In any wartime period in which condition (7) holds, every question  $x$  with  $\delta_t(x; \mathcal{Z}) \geq \delta_0$  satisfies  $\sigma_x^2(Y|\mathcal{F}_{Nt}) \geq \sigma_x^2(Y|\mathcal{F}_{St}) \geq \bar{\sigma}^2$ , as in the proof of Proposition 1 (iii), so the payoff of either agent is positive only on the common set  $\mathcal{W}_t = \{x \in \mathcal{W} : \delta_t^-(x) \geq \delta_0\}$ , where the revenue is  $p$  and the payoff of agent  $j$  equals  $\sigma_x^2(Y|\mathcal{F}_{jt})\varphi(p/\sigma_x^2(Y|\mathcal{F}_{jt}))$ . Hence,  $\rho_{jt}^*(\mathcal{Z}) = (c')^{-1}(p/s_j)$  if  $s_j = \min_{x \in \mathcal{W}_t} \sigma_x^2(Y|\mathcal{F}_{jt}) < p/\underline{c}$  and  $\rho_{jt}^*(\mathcal{Z}) = 0$  otherwise. In both cases, therefore, each agent minimizes his own variance over a set of questions and at a revenue level that are common to the two agents. Taking minimum of  $\sigma_x^2(Y|\mathcal{F}_{St}) \leq \sigma_x^2(Y|\mathcal{F}_{St})$  over the common set gives  $s_S \leq s_N$ , and the monotonicity of  $(c')^{-1}(R/\cdot)$ , where  $R$  is common revenue, yields  $\rho_{Nt}^*(\mathcal{Z}) \leq \rho_{St}^*(\mathcal{Z})$ . ■

**Corollary 1** *Suppose  $\delta_0 < \min\{\lambda, p\}/\underline{c}$ , and suppose that  $\mathcal{Z}$  is closed, bounded, and nonempty, and the frontier condition (12) holds for some  $\tau^* \leq t_1 + 1$ .*

(i) *Every question  $x$  discovered in a post-war period  $t > t_1$  satisfies  $\min_{z \in \mathcal{Z}} |x - z| \geq \delta_0$ ; in particular, no post-war discovery lies in the wartime problem set:  $x \notin \mathcal{W}$ .*

(ii) *Almost surely, all but finitely many discoveries lie strictly beyond the outer boundary of the foreign technology set, in the sense that  $x \geq \bar{z} + \delta_0$  or  $x \leq \underline{z} - \delta_0$ , and the domestic knowledge frontier diverges:  $\max \mathcal{Q}_t \rightarrow \infty$  or  $\min \mathcal{Q}_t \rightarrow -\infty$ .*

*Proof.* (i): Suppose question  $x$  is researched with positive effort in period  $t > t_1$ . Since there is no premium after period  $t_1$ , the revenue is given by equation (4), so a positive expected payoff requires  $R(\delta_t(x)) = \lambda$  and hence  $\delta_t(x; \mathcal{Z}) \geq \delta_0$ , that is,  $|x - \xi| \geq \delta_0$  for every  $\xi \in \mathcal{Q}_t \cup \mathcal{Z}$ . In particular,  $\min_{z \in \mathcal{Z}} |x - z| \geq \delta_0$ , so  $x$  does not belong to  $\mathcal{W} = \bigcup_{z \in \mathcal{Z}} (z - \delta_0, z + \delta_0)$ .

(ii): Note that any question researched with positive effort lies at distance at least  $\delta_0$  from every point of  $\mathcal{Q}_t$ . Hence, along every path of the process, discovered questions are pairwise at least  $\delta_0$  apart, and any interval of length  $L$  contains at most  $\lfloor L/\delta_0 \rfloor + 1$  of them. By Proposition 2 (ii),  $N_{St} \rightarrow \infty$  almost surely, so infinitely many discoveries occur. Since infinitely many points that are pairwise at least  $\delta_0$  apart cannot be contained in any bounded interval, the set of discovered questions is almost surely unbounded. As  $\max \mathcal{Q}_t$  is nondecreasing and  $\min \mathcal{Q}_t$  is nonincreasing in  $t$ , it follows that, almost surely,  $\max \mathcal{Q}_t \rightarrow \infty$  or  $\min \mathcal{Q}_t \rightarrow -\infty$ . ■