From Adoption to Innovation: State-Dependent Technology Policy in Developing Countries*

Jaedo Choi
Federal Reserve Board of Governors

Younghun Shim
University of Chicago

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Abstract

Should governments in developing countries support technology adoption or promote innovation? And how does the answer change over different stages of development? To answer these questions, we digitize the universe of technology transfer contracts between domestic and foreign firms in South Korea during its growth miracle period, which has novel information on the price of technologies. When the productivity gap between domestic and foreign firms is larger, (i) firms are more likely to invest in adoption than innovation, (ii) the adoption fee is lower, (iii) productivity increases more after adoption. Motivated by these findings, we build a two-country growth model with endogenous adoption and innovation decisions. Foreign firms can sell technologies for an endogenous fee, internalizing the future loss of profit due to stronger competition with domestic firms. While innovation can make productivity higher than foreign firms, adoption cannot. Therefore, as domestic firms close the productivity gap, the expected productivity gain from adoption decreases, making an adoption subsidy less effective than an innovation subsidy. We quantitatively evaluate Korea's technology policies since 1973, which started with an adoption subsidy and shifted to an innovation subsidy as the productivity of Korean firms converged with that of foreign competitors. Our result suggests that this state-dependent policy increased consumption-equivalent welfare by 4.84%, which raises welfare more than subsidizing only innovation or adoption throughout. Furthermore, it was optimal to switch from an adoption to an innovation subsidy when Korea's GDP reached 55% of Japan's.

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1 Introduction

When Samsung Group in South Korea (Korea, hereafter) decided to enter the electronics industry in 1969, it did not have the technology necessary to produce electronic products. To tackle this problem, Samsung aggressively adopted technologies by signing technology transfer contracts with several Japanese companies. As Samsung expanded its market share using the adopted technologies, Japanese firms became reluctant to share their technologies and charged higher adoption fees. At that point, Samsung switched its strategy from adopting foreign technologies to inventing its own technologies. This transition from adoption to innovation is a sharp feature in the systematic data. As the GDP per capita of Korea converged with Japan, the aggregate adoption expenditure as a share of the sum of adoption and R&D expenditure decreased from 63% in 1970 to 13% in 2020 (Figure B.1 in Appendix B.1).[1]

Considering these firm behaviors, what are the appropriate industrial policies over different stages of development? Since technological growth involves spillovers across firms, development strategies usually include policies to subsidize investment in technologies substantially. However, how much weight policymakers should give to adoption versus innovation and how these weights should change over stages of development are relatively less explored. Korea is an important country to study since the government actively adjusted industrial policies during its growth miracle period. Specifically, the government started an adoption subsidy in 1973 and shifted to an innovation subsidy as the productivity of Korean firms converged with that of foreign firms. What would have happened if the Korean government had skipped the adoption subsidy and enacted the innovation subsidy from the beginning? Or, what if it never transitioned to an innovation subsidy and subsidized only adoption? Exploring these questions will shed light on the optimal state-dependent policy in developing countries.[2]

This paper studies the role of technology adoption and innovation in development and yields theoretical, empirical, and quantitative contributions. Empirically, we digitize a new dataset of firm-to-firm adoption contracts and their prices. We document new empirical facts about how the adoption fee and productivity gain from adoption relate to the productivity gap between domestic and foreign firms. Theoretically, we build a new model with endogenous adoption and innovation decisions in which the adoption price internalizes buyer and seller incentives. Quantitatively, we solve for the transition of the model in which Korean firms catch up with foreign firms and estimate the model along the transition using simulated method of moments. We then evaluate the actual policy in Korea over a 50-year horizon, which sheds light on the optimal state-dependent policy.

[1] Adoption expenditure is the gross payment to foreign firms for sharing industrial processes, designs, and licensing for patents and trademarks.

[2] The government in Brazil switched from an adoption to an innovation subsidy. In 2001, it taxed technology adoption from foreign firms and subsidized innovation (De Souza, 2021). Likewise, China supported technology adoption mainly through FDI in the early years. In 2016, President Xi presented innovation-driven development as the 13th five-year plan in which he specified increasing R&D and patent intensity as an important goal.

The key empirical challenge to studying technology adoption is a lack of systematic and direct measures on the adoption and its price. We overcome this challenge by digitizing data on contract-level technology imports in Korea from 1962 to 1993. These data capture all technology transfer contracts between Korean and foreign firms. We also collect adoption fees, which is novel in the literature. Furthermore, we exploit the firm-to-firm structure of the data by merging it with firm-level balance sheet and patent data for both Korean and foreign firms. This firm-to-firm structure allows us to study how the price and productivity gains from adoption change with the productivity gap between firms.

We document four stylized facts. First, firms are more likely to invest in innovation than adoption when the productivity gap with foreign firms is smaller. Second, the adoption fee is higher when the productivity gap is smaller, which suggests that foreign firms internalize the adopter's relative position to determine the adoption fee. Third, when the initial productivity gap is larger, firms that adopt technologies increase productivity more than firms that innovate. Lastly, when Korean firms adopt a foreign technology, non-adopting firms are more likely to cite patents from the foreign firm that sold the technology. This suggests that the adopted technology is diffused to other non-adopting firms, which creates spillovers across domestic firms.

Motivated by these empirical facts, we build a two-country growth model in which firms can increase productivity by adopting foreign technology or innovating. We build upon the step-by-step innovation model (Aghion et al., 2001; Akcigit and Ates, 2019) and extend it by adding another firm in a foreign country to capture the strategic interactions between domestic and foreign firms.[3] Another new element is that domestic firms can adopt technology from foreign firms. In our model, adoption is a costly investment where firms must pay a fee to the foreign firms, which is different from imitation (Perla and Tonetti, 2014). Adoption reduces the future profit of foreign firms due to the stronger competition with domestic firms. The adoption fee is determined by Nash bargaining between two firms, internalizing all future profit changes due to the adoption. The endogenous adoption price depends on the technology gap between domestic and foreign firms.

In the model, innovation is inventing a new technology, and adoption is learning an existing technology from foreign firms. Adoption differs from innovation in several ways. First, adoption cannot yield a higher productivity level than the foreign firm. Second, the adopting firm must pay an adoption fee to the foreign firm. Lastly, productivity gains from adoption and innovation differ, and the difference depends on the initial productivity gap with the foreign firm. This difference is disciplined by empirical findings, which suggest that adoption brings a larger productivity gain than innovation when domestic firms are far from foreign firms, and vice versa.[4]

Adoption and innovation generate knowledge diffusion across domestic firms. With a posi-

[3] Akcigit et al. (2021) have one domestic and one foreign firm and study the competition between domestic and foreign firms. Our model has two domestic firms and one foreign firm and studies both domestic and foreign competition.

[4] This result is in line with common assumptions in the literature, such as Acemoglu et al. (2006); Benhabib et al. (2021); König et al. (2020).

tive probability, a home follower can learn the home leader's technology and improve on it when innovating or adopting. This intertemporal spillover can make the social return of adoption and innovation larger than the private return, which motivates the government to subsidize adoption and innovation. Foreign firms also internalize knowledge diffusion and raise the adoption fee, which makes the discrepancy between the social and private returns of adoption larger. The size of the intertemporal spillover depends on the probability of knowledge diffusion and the productivity gain from adoption and innovation. Since the productivity gain depends on the current productivity gap with the foreign firm, the spillover from adoption and innovation and the optimal subsidy rate change over different stages of development.

In the quantitative section, we solve for the transition of the model from the initial state—in which Korean firms have lower productivity than foreign firms on average—to the balanced growth path. We simulate moments from the model on the transition path and estimate parameters to match moments between the model and data. Specifically, we match the average adoption fee over sales, and the regression coefficients in the motivating facts. The estimated model replicates Korea's catching-up period and matches untargeted moments such as the decreasing adoption expenditure share over time and the increasing adoption fee as a function of relative productivity.

Using the estimated model, we first decompose the growth contribution between adoption and innovation by studying counterfactuals without either adoption or innovation. We find that adoption accounted for 75% of GDP growth in 1973 but declined to 14% by 2022. The relative productivity gain from adoption decreases, and firms switch from adoption to innovation over time. Next, we evaluate Korea's technology policies since 1973, when the Korean government began subsidizing adoption through a tax credit. The government gradually decreased the adoption subsidy rate. It launched the R&D subsidy in 1982 and steadily increased the subsidy rate over time. We compare the case having the actual policies with three counterfactuals. First, we shut down both subsidies. Second, we subsidize only adoption at the initial rate (31%). Second, we subsidize only innovation at the final rate (32%). The actual policy increases consumption-equivalent welfare by 4.84% compared to the case with no subsidies. The welfare increase from this policy is higher than subsidizing only adoption (3.69%) or only innovation (3.28%). This result suggests that state-dependent policy can generate higher welfare than time-invariant policies with similar subsidy rates.

Motivated by these results, we quantitatively study the optimal subsidies. We first study the optimal timing of switching from an adoption subsidy to an innovation subsidy while allowing the government to subsidize only one of them each year at 32%, which is the maximum subsidy rate in the actual policy. We find that welfare would have been the largest when the government switched to an innovation subsidy in 1992, which is very close to the year when the Korean government substantially decreased the adoption subsidy rate and increased the innovation subsidy rate. Next, we allow the government to choose the optimal rate of adoption and innovation subsidy and the timing to switch. The optimal policy within this class of policies starts an adoption subsidy at 55% and switches to an innovation subsidy at 51% in 1985, when Korea's GDP was 55% of Japan's. This policy increases consumption-equivalent welfare by 6.42%, which is higher than the actual policy. This result suggests that the technology policy in developing countries needs to start with an adoption subsidy at a high rate. Then, the policymaker should consider switching to an innovation subsidy when the country's GDP reaches roughly half the frontier countries.

1.1 Related Literature

First, this paper is related to the endogenous growth literature. While many papers have developed growth models in which firms adopt technologies from foreign firms (e.g., Parente and Prescott, 1994; Comin and Hobijn, 2010), or models with both foreign technology adoption and innovation (Grossman and Helpman, 1991a; Barro and Sala-i Martin, 1997; Acemoglu et al., 2006; Santacreu, 2015), most papers do not have a systematic and direct measure of adoption or its fees, which makes it hard to conduct quantitative analysis. This paper is one of the first papers to use comprehensive adoption and innovation data and provide new empirical facts and policy counterfactuals. Furthermore, while most papers abstract away from the foreign firm's incentive to sell technology, we assume that adoption requires mutual agreement between two firms. This assumption leads to an endogenous adoption price incorporating both firms' incentives, which explains the empirical facts and enables quantitative evaluation of policies.[5] We capture the strategic interactions between firms by building on the step-by-step innovation literature (Aghion et al., 2001; Acemoglu and Akcigit, 2012; Akcigit et al., 2020, 2021; Akcigit and Ates, 2019; Olmstead-Rumsey, 2022; Liu et al., 2022; Sui, 2022).[6] Most step-by-step innovation models assume exogenous knowledge diffusion in which the follower can exogenously catch up with the leader. We open this black box by studying the technology adoption, which can explain a significant portion of exogenous knowledge diffusion.

Second, this paper contributes to the literature on international knowledge diffusion. Several papers develop models in which knowledge diffusion is the byproduct of trade. Coe and Helpman (1995), Coe et al. (1997), and Eaton and Kortum (2001) view knowledge as embedded in goods and diffused through international trade. Grossman and Helpman (1991b), Alvarez et al. (2017), Buera and Oberfield (2020), Hsieh et al. (2019), and Rachapalli (2021) assume technology transfer is facilitated by goods trade in which firms interact with foreign firms. In contrast to these papers, we focus on technology adoption, which is a deliberate attempt to acquire technology from foreign firms and not a byproduct of other activities. Other papers also explicitly model technology adoption (Eaton and Kortum, 1999; Santacreu, 2015; Sampson, 2019; Lind and Ramondo, 2022). While these papers use indirect adoption measures such as patents, trade, and R&D stock, we

[5]Our notion of adoption differs from imitation in Perla and Tonetti (2014) and König et al. (2020) since the firm must get approval and pay the foreign firm to adopt the technology in our model.

[6]See Ates (2021) for a thorough literature review.

use a direct measure from technology transfer data. Santacreu (2022) is an exception; she uses country-level license payment data to study the effect of trade and intellectual property policies. Instead of aggregated country-level data, our paper uses firm-to-firm adoption data, which allows us to study strategic interactions between firms.

Third, this paper contributes to the literature that studies technology policies. Bloom et al. (2002), Bronzini and Iachini (2014), Dechezleprêtre et al. (2016), Howell (2017), and Chen et al. (2021) study the effect of R&D subsidies on innovation. De Souza (2021) studies the effects of technology substitution policy on the labor market in Brazil, where the government decreased adoption subsidies but increased R&D subsidies. Jones and Williams (2000), Acemoglu et al. (2018), Atkeson and Burstein (2019), Akcigit et al. (2021), Akcigit et al. (2022), and Liu and Ma (2022) study the optimal R&D policy based on innovation-led growth models.[7] While most papers focus on innovation policy in developed countries, we study adoption and innovation policy in developing countries. Furthermore, we study the appropriate policies over different stages of development, focusing on the transitional dynamics of the model.

Lastly, this paper is related to the literature that studies the "growth miracle" period in Korea (Lucas, 1993). Lane (2022), Choi and Levchenko (2021), and Kim et al. (2021) study industrial policy in the 1970s, Connolly and Yi (2015) study trade policy reforms, and Aghion et al. (2021) study the pro-competitive reforms after the financial crisis in 1997. While most papers study the effect of temporary policies, this paper studies the policies implemented over a long horizon in which Korea developed from a low-income and non-innovative country to a high-income and innovative country. The most closely related paper is our other paper Choi and Shim (2022), in which we study the role of technology adoption in industrialization, focusing on sector-specific and temporary subsidies in the 1970s. Choi and Shim (2022) study the earlier period when Korean firms were far from the frontier. In this paper, we focus on the period in which the country transitioned from adoption to innovation, and the strategic interactions between Korean and foreign firms became more important.[8] To capture the strategic interactions between firms, we collect further information, such as adoption fees, and exploit the firm-to-firm structure of the data. We then build a dynamic general equilibrium model and study the impact of policies along the transitional dynamics.

The remainder of the paper is organized as follows. Section 2 introduces technology adoption, firm-level balance sheet, and patent data. Section 3 presents four motivating facts. Section 4 describes the two-country growth model with endogenous innovation and adoption decisions. Section 5 explains the estimation procedure and decomposes the growth contribution of adoption and innovation over time. Section 6 presents policy counterfactuals along the transitional dynamics, and Section 7 concludes.

[7] Bloom et al. (2019) summarize both empirical and theoretical papers on innovation policies.

[8] In Choi and Shim (2022), we abstract away from the reaction or incentive of the foreign firm because Korean firms were far from the frontier and not important to the foreign firms' profit. Also, Choi and Shim (2022) did not use adoption fee data. On the other hand, this paper abstracts away from sectoral differences and spatial aspects.

2 Data

We construct our main dataset by digitizing historical data and merging it with other data. The main dataset combines technology adoption, patent, and balance sheet data and covers 1970–1993. In this section, we briefly describe our data. Additional details are in Appendix A.1.

2.1 Technology Adoption Data

We construct a firm-to-firm technology adoption dataset. We collect and digitize technology transfer contracts from the National Archives of Korea and supplement them with data from Korea Industrial Technology Association (1995).[9] The data includes the universe of technology transfers between Korean firms and foreign firms for the period 1962–1993. Korean firms were required to submit the contracts to the government when they import technology from a foreign country. We collected 8,404 contracts from 2,865 unique Korean firms.[10] Figures A.1 and A.2 in Appendix A.1 show an example of contract, where we can see the contents and payment for the contract.

We collect the name of the Korean firm (buyer) and foreign firm (seller), the date and length of the contract, a description of the technology, the contents of the contract, and the adoption fee, which consists of a fixed fee and royalty rate. Table 1 shows examples of collected data. For instance, Samsung adopted technology to produce color TVs from Nippon Electronic in 1978. The agreed length of the contract was 10 years in which Samsung could get know-how transfer and licensing of patents, and it paid 800,000 dollars as a fixed fee. Japan accounts for 50% of foreign firms, the US accounts for 26.3%, and Germany, France, and the UK account for 13.1% in sum. Appendix A.1 presents summary statistics such as country distribution, contents of contracts, and average adoption fee.

2.2 Patent Data

Korean patent office data. To measure the innovation of Korean firms, we use patent data from the Korean Intellectual Property Office.[11] The data starts in 1945 and includes the universe of patents registered in Korea by domestic and foreign firms. We merge this data with firm-level data using business ID and then use fuzzy matching on firm names.

United states patent office data. One weakness of Korean patent data is that it does not have citation data until the 1990s. When we study the citation pattern of Korean firms, we use the data from the United States Patent and Trademark Office (USPTO, hereafter) as it covers the universe

[9] Compared with data that we used in Choi and Shim (2022), we add adoption fee information, foreign firm information, and include the period from 1983 to 1993.

[10] We exclude contracts within the same multi-national firm. For example, Korean IBM paid the fee to US IBM. We exclude these transactions, which account for 3% of the sample.

[11] We download the data from Korean Intellectual Property Rights Information Service, following the procedure in Lee et al. (2020).

Table 1: Examples of Technology Adoption Data

Buyer	Seller	Contract Length (year)	Date	Technology	Contents	Fee
Samsung	Nippon Electronic (Japan)	10	02/24/1978	Color TV	Know-how Transfer, Licensing	Fixed $800,000
LG	Hitachi (Japan)	9	04/01/1978	Color TV	Know-how Transfer, Licensing	Fixed $100,000 Royalty 3%
Hyundai Heavy Manufacturing	Technigaz (France)	10	09/14/1978	LNG Carrier	Know-how Transfer	Fixed FFR 1,835,000
Haengnam Electronics	EPH (US)	2	12/18/1978	Alumina	Know-how Transfer	Fixed $131,000
Hyundai Motor Company	Kyukoto Engineering (Japan)	3	06/14/1979	Concrete mixer	Know-how Transfer	Royalty 5%

of citations since 1975.[12] Also, we use USPTO data to measure the innovation of foreign firms. The detailed procedure to match foreign firms in adoption data with USPTO data is in Appendix A.3.

2.3 Firm-level Balance Sheet Data

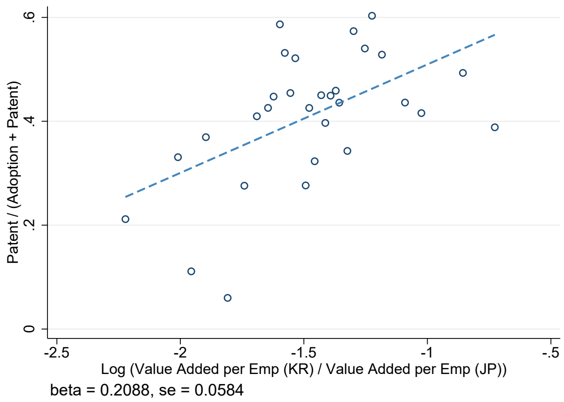
Korean firms. We use two data sources to construct firm-level balance sheet data for Korean firms. First, we digitize firm-level data from the Annual Reports of Korean Companies by the Korea Productivity Center. This is firm survey data that covers firms with more than 50 employees, which accounts for 70% of the value-added share in manufacturing. We observe firm sales, total assets, fixed assets, number of employees, profit, start year, business ID, and sector in 1970–1983. Second, we use KIS-VALUE data starting from 1980, which covers firms with assets of more than 3 billion Korean Won (2.65 million dollars in 2015).[13] By using the business ID and firm name, we merge these two data.[14] Then, we merge the balance sheet data with the technology adoption data by using firm names.

Foreign firms. We use Compustat data for the foreign firms where we can observe the listed firms. We append Compustat North America, which started in 1950, with Compustat global, which started in 1988. For variables, we use firm sales, employment, and sector. We merge this data with technology adoption data using the firm name and country. Table A.4 in Appendix A.4 shows the summarity statistics of adopting and non-adopting firms using the merged data.

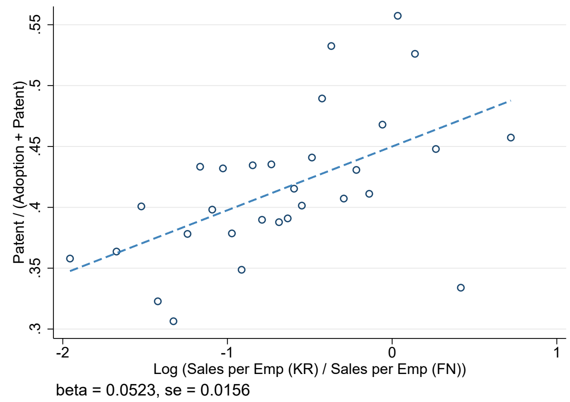
[12]We use a crosswalk between the Korean patent office firm ID and USPTO ID made by Lee et al. (2020).

[13]KIS-VALUE data is collected by a private company, which covers firms that are subject to external edit. The 1981 Act on External Audit of Joint-Stock Corporations requires that all publicly traded firms and other firms larger than the asset threshold have to report their balance sheet information.

[14]We also use the history of firm names in case the firm had changed its name mainly from www.saramin.co.kr.



A. Sector level



B. Firm level

Figure 1: Patent / (patent + adoption) over Productivity Gap

Notes: This figure is a binscatter plot where each dot has multiple sector-year or firm-year observations. We plot the number of patents as a share of the sum of the number of patents and the number of adoption contracts on the Y-axis. And we plot log productivity gap on the X-axis. Panel A is at the sector-year level, and the productivity gap is measured by value added per employment of Korea divided by value added per employment of Japan in each sector and year. We control year fixed effects. Sector-level data is from STAN OECD data. Panel B is at the firm-year level, and the productivity gap is measured by sales per employee of a Korean firm divided by sales per employee of the foreign firm which sells technology. If the firm does not have an adoption contract, we use the maximum sales per employee of foreign firms in the sector. We control for sector and year fixed effects.

3 Motivating Facts

In this section, we present four motivating facts that guide us to build a theoretical model and discipline the crucial parameters in the model.

3.1 Innovation and Adoption over Productivity Gap

The first set of facts presents how the relative proportion of innovation and adoption changes with the productivity gap with foreign firms. Figure 1 plots the innovation share over the productivity gap with foreign firms, both at the sector and firm levels. We measure innovation as the number of patents and adoption as the number of adoption contracts. The innovation share is the number of patents divided by the sum of the number of patents and adoption contracts at the sector or firm level. For sector-level analysis, we calculate the value added per employee in Korea divided by value added per employee in Japan and use this measure as the productivity gap. For firm-level analysis, we use the sales per employee of adopting firms divided by sales per employee of the technology seller. If the firm does not adopt, we use the maximum sales per employee of the foreign firm in sector and year. Table B.1 in Appendix B.2 shows the regression results.

We find a positive and statistically significant correlation between the innovation share and the gap at the sector and firm levels. Sector-level analysis spans 1980–1993 and firm level analysis spans 1970–1993. This implies that when Korean firms are close to foreign firms in terms of

Table 2: Adoption Fee and Relative Productivity

	Fixed fee	Royalty	Total fee
Relative productivity	0.141***	0.141***	0.644***
	(0.0413)	(0.0479)	(0.0493)
N	1,812	1,210	1,200
Adjusted R2	0.0947	0.0233	0.4177
Sector FE	yes	yes	yes
Year FE	yes	yes	yes

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Notes: This table shows the result of equation (1) in which we regress the adoption fee on the relative productivity. The fixed fee and total fee are logged. Royalty is the royalty rate (in percentage). The total fee is the sum of the fixed fee and royalty rate times sales times contract years. Relative productivity is the log ratio of sales per employee between the Korean firm (buyer) and the foreign firm (seller). Overlap is whether more than half of the adopter's ten most frequent patent classes are also included in the seller's list.

productivity, they are more likely to innovate instead of adopt.

3.2 Adoption Fee over Productivity Gap

One potential reason for the firm's transition from adoption to innovation is the adoption fee getting higher as the firm closes the productivity gap with foreign firms. To investigate that, we study the relationship between the productivity gap and the price of the adoption contract by running the following regression:

$$\mathcal{F}_{ijt} = \beta \log\left(\frac{z_{it}}{z_{jt}}\right) + \alpha_{s(i)} + \delta_t + \epsilon_{ijt}\,, \tag{1}$$

where $\mathcal{F}_{ijt}$ is the adoption fee that Korean firm i pays to foreign firm j in year t, and z_{it} is labor productivity measured by sales per employee of firm i. We use global Compustat data to get sales per employee of the foreign firm.[15] Our regression controls for sector fixed effects, $\alpha_{s(i)}$ and year fixed effects, δ_t. The sample period is 1970–1993.

Table 2 shows a positive and statistically significant correlation between the adoption fee and relative productivity. The adoption fee consists of a fixed fee and the royalty payment, which is the royalty rate times firm sales. In the first column, we regress the log fixed fee on the relative productivity. We find that a 1% increase in relative productivity is associated with a 0.141% increase in the fixed fee. In the second column, we regress the royalty rate (in percentage) on relative productivity. A 1% increase in relative productivity is associated with a 0.141 percentage point increase in the royalty rate. In the third column, we regress log total adoption fee, which

[15] For samples that do not have information on foreign firms, we use maximum sales per employee within sector-year.

is the sum of the fixed fee and the royalty rate times firm sales times contract years.[16] A 1% increase in relative productivity is associated with a 0.644% increase in the total adoption fee. The positive correlation suggests that when the Korean firm is closer to the foreign firm, the seller is compensated more with the adoption fee.

We use detailed information from patent data to see whether the degree of competition matters for the correlation. If two firms are in the same technology field (IPC 3 digit level) in patent data, we consider the two firms are in intense competition. Table 2 in Appendix B shows that the coefficient of the gap on the adoption fee is larger when two firms have overlap in technology fields. This suggests that the competition effect is relevant for determining adoption fees.

3.3 Productivity Growth after Adoption and Innovation

Another potential reason for the transition from adoption to innovation is that the productivity gain from adoption becomes smaller than that from innovation as firms close the technology gap with the foreign firm. To study how the productivity growth after adoption and innovation changes over the technology gap, we run the following regression:

$$\log\left(\frac{z_{i,t+5}}{z_{i,t}}\right) = \beta \cdot \log\left(\frac{z_{i,t}}{z_{j,t}}\right) + \Gamma \cdot X_{it} + \alpha_{s(i)} + \delta_t + \epsilon_{it}\,, \tag{2}$$

where $\log(\frac{z_{i,t+5}}{z_{i,t}})$ is the growth rate of labor productivity after 5 years from either innovation or adoption of firm i and $\log\left(\frac{z_{i,t}}{z_{j,t}}\right)$ is the relative productivity in the year of the adoption or innovation, which is the same measure used in the Table 2. Since the innovating firm does not have corresponding foreign firm j, we pick the foreign technology seller with the maximum sales per employee in each sector and year. $X_{i,t}$ includes control variables such as capital intensity growth, which we define as the growth rate of fixed assets per employment over 5 years. Lastly, we control for sector and year fixed effects. We exclude firms that both innovate and adopt in the same year. Again, the sample period is 1970–1993.

Figure 2 shows the result in a binscatter plot. Firms that adopt technologies increase productivity more than firms that innovate when the initial productivity gap is large. While the initial productivity gap has a negative correlation with productivity growth both for adopting and innovating firms, the absolute value of the coefficient is larger for adoption than innovation. This suggests that the productivity gap matters more for adoption than for innovation.[17] Table B.3 in Appendix B shows the result of the regression when we include an interaction term between the productivity gap and adoption. The interaction term is significantly negative, which suggests the difference in the coefficients between adoption and innovation is statistically significant.

[16]The royalty payment is usually a share of the revenue made by using the adopted technology. Since we do not have disaggregated sales data, we use the firm-level total sales as the revenue.

[17]There is a potential endogeneity problem if the firms with lower productivity are selected into adoption. In the quantitative section, we tackle this problem by using indirect inference. We simulate the same regression while considering the selection in our model and match the coefficients with the data.

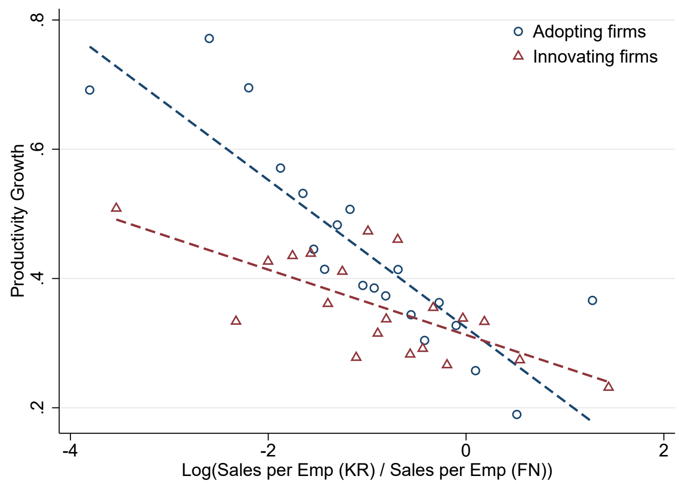


Figure 2: Productivity Growth over Initial Productivity Gap

Notes: This figure plots $\Delta \log(\text{sales / emp})_{i,t+5}$ on the Y-axis and $\log(\text{sales per emp of Korean firm / sales per emp of Korean firm})_{i,t}$ on the X-axis. It is a binscatter plot where each dot has multiple firm-year observations. Blue circles are innovating firms that have at least one patent, and red triangles are adopting firms that have at least one adoption contract. We exclude firms that have both innovation and adoption in a given year. We control the growth rate of fixed asset / employment for 5 years and include sector and year fixed effects. Since we do not have information for the foreign firm when the Korean firm is innovating, we use the maximum of $\log(\text{sales / emp})$ of foreign technology sellers in the same sector.

3.4 Knowledge Diffusion from Adoption

We now study the knowledge diffusion from the adopted technology to other firms that did not directly adopt the technology. We use patent citations to measure knowledge diffusion following the innovation literature (Jaffe et al., 1993; Cai and Li, 2019; Aghion et al., 2019). Specifically, if a Korean firm cites a foreign firm's patent, we assume that the Korean firm gets knowledge diffusion from the foreign firm. The ideal experiment would be to pick two identical foreign firms and make one sell the technology to a Korean firm while the other does not. Then, if there is a spillover from the adopted technology, Korean non-adopters would increase patent citations to the foreign technology seller compared with the other non-seller.

To mimic the ideal experiment, we use a matching-based event study. We match two foreign firms, one of which sold technology (treated) while the other did not (control). We use minimum distance matching in terms of the log patent stock while exactly matching on the country, year, and the main patent field (IPC 3 digit).[18] Table B.4 in Appendix B shows no statistically significant difference between the two groups in terms of cumulative patents or citations. The event year is when the firm sells technology to a Korean firm for the first time, and we assign the same event year as a placebo year for the control firms. Then, we compare the probability of citation from Korean non-adopters to foreign firms around the event year.[19] We exclude the citations from

[18]For the patent field, we use the most frequent three-digit IPC class in each foreign firm.
[19]These non-adopters never adopted technology from any foreign firms.

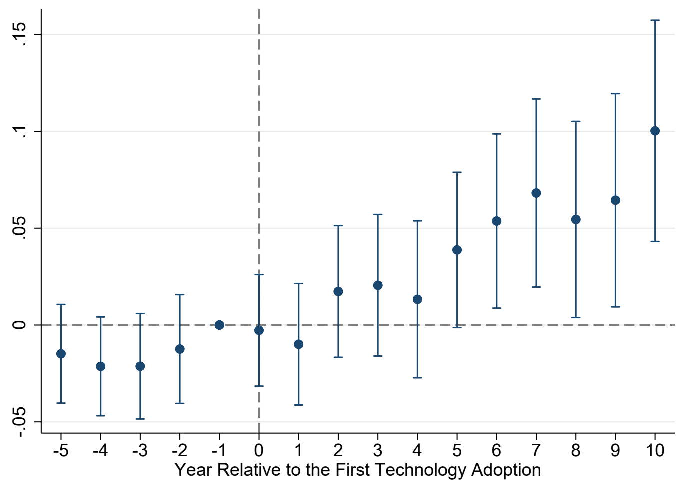


Figure 3: Event Study Result of Patent Citations

Notes: This figure plots β_k^{Seller} in equation (3), which captures the difference of the probability of receiving citations from the Korean non-adopters between the foreign firm that sold technology to a Korean firm and the foreign firm that did not sell. The vertical line is a 95% confidence interval. X-axis is the year relative to the first technology adoption by a Korean firm. The coefficient one year before the adoption (-1) is normalized to zero. The standard error is clustered at the foreign firm level.

adopters. Specifically, we estimate the below equation.

$$Y_{it} = \sum_{k=-5}^{10} \beta_{\text{k}}^{\text{Seller}} \mathbf{1}_{\{L_{it}^{\text{Seller}}=k\}} + \sum_{k=-5}^{10} \beta_k^{All} \mathbf{1}_{\{L_{it}^{\text{All}}=k\}} + \alpha_i + \gamma_t + \epsilon_{it}\,, \tag{3}$$

where Y_{it} is a citation dummy variable equal to one if a Korean firm that never adopted cites a patent of the foreign firm i in year t, and zero if not. L_{it}^{All} is the number of years from the first (placebo) adoption and L_{it}^{Seller} is the same variable but applies only to the technology seller (treated). We include foreign firm fixed effects, α_i, year fixed effects γ_t, and an error term, ϵ_{it}. While β_k^{All} captures common trends around the event year, and β_k^{Seller} captures the difference between the treated and control firms. We cluster standard errors at the technology field level (3-digit IPC) and year. The sample period of the analysis is 1975–2003, as USPTO citation data starts in 1975, and we study until post ten years from the adoption year, of which the last year is 1993.

Figure 3 plots β_k^{Seller}. There is an increase in the number of patent citations to the technology seller compared to control firms. It suggests that Korean firms build on the adopted technology of other Korean firms, which implies a positive externality of adoption. We do not find a clear pre-trend before the first technology adoption, supporting our assumption that the difference is not driven by different trends between the two groups.[20]

[20]We present additional results in Appendix B. Figure B.3 shows the raw average number of citations of technology sellers and the placebo group. Figure B.4 plots the difference of the inverse hyperbolic transformation of the number of citations to study the intensive margin as well. Table B.5 shows the entire coefficients with standard errors for

A potential identification threat is an unobserved shock to the foreign firm that increases adoption probability and the number of citations received. For example, Sony's technology turned out to be superior, Korean firms became more likely to adopt from Sony, and also citations to Sony increased after the adoption year. As a placebo test, we run the same regression with the number of citations received from all the other countries except Korea. Figure B.5 in Appendix B shows no clear difference between treated and control groups in terms of total citations, which bolsters the credibility of our event study result.

4 Model

Motivated by the previous empirical facts, we develop a dynamic general equilibrium model in which firms can increase productivity by innovating and adopting technologies. As the empirical findings suggest, productivity growth from innovation and adoption depends on the initial productivity gap between domestic and foreign firms in the model. Forward-looking firms internalize future profit loss when selling technologies to other firms and charge an endogenous adoption fee that also depends on the productivity gap between firms. Lastly, innovation and adoption generate knowledge diffusion across domestic firms, which motivates the government to subsidize them.

4.1 Setup

Time is continuous. There are two countries, home and foreign, and a continuum of a variety of goods $j \in [0, 1]$. The goods are tradable across countries with an iceberg cost of $D \geq 1$, which means firms need to ship D units of goods for one unit of the good to export to another country. In country H, there are two firms, h and $\tilde{h}$ in each sector j. We call a firm a leader if it has the highest productivity in its sector. The other firm is the follower. In country F, there is a representative firm f in each sector j. All three firms can innovate and adopt technology from firms in another country. Instead of the follower, country F has a potential entrant $\tilde{f}$ that can enter and replace the incumbent by innovating.[21]

4.2 Household

A representative household in each country consumes goods, supplies labor, pays lump-sum taxes, and owns domestic firms. Households in period t have the utility function:

$$U_{ct} = \int_t^\infty \exp(-\rho(s-t)) \ln C_{cs} ds \,, \tag{4}$$

both extensive and intensive margins. Table B.6 shows the result from a difference-in-differences specification that summarizes the results.

[21] This assumption can reduce the number of state variables since we do not need to keep track of the gap between two foreign firms.

where C_{cs} is final consumption at time s, and $\rho > 0$ is the discount factor. The budget constraint of the household is

$$r_{ct}A_{ct} + L_c w_{ct} = P_{ct}C_{ct} + T_{ct} + \dot{A}_{ct}\,, \tag{5}$$

where r_{ct} is interest rate, L_c is the labor endowment, w_{ct} is wage, P_{ct} is the price index of final consumption, T_{ct} is the lump-sum tax that finances innovation and adoption subsidies, and A_{ct} is the household's assets. Households in country c owns all the firms in country c, meaning firm profits are included in the asset A_{ct}. $\dot{A}_{ct}$ is the time derivative of A_{ct}. Final consumption C_{Ht} is given by

$$C_{Ht} = \exp\left(\int_0^1 \ln\left[\left(\psi_H^{\frac{1}{\sigma}} y_{hjt}^{\frac{\sigma-1}{\sigma}} + \psi_H^{\frac{1}{\sigma}} y_{\tilde{h}jt}^{\frac{\sigma-1}{\sigma}} + \psi_F^{\frac{1}{\sigma}} y_{fjt}^{*\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}\right] dj\right)\,, \tag{6}$$

where $y_{hjt}, y_{\tilde{h}jt}$ are goods produced by firm $h, \tilde{h}$, and consumed by the home household.[22] y^*_{fjt} is the output of the foreign firm and exported to country H. The superscript asterisk denotes the goods that are exported. ψ_H and ψ_F are demand shifters for goods produced in countries H and F.[23] The final consumption aggregates all sector j with Cobb-Douglas function, and aggregates three goods in each sector j with a constant elasticity of substitution, σ. We assume $1 < \sigma < \infty$, meaning the goods within a sector are imperfect substitutes for each other. The price index of final consumption P_{Ht} in home country is given by

$$P_{Ht} = \exp\left(\int_0^1 \ln\left[\psi_H^{\frac{1}{\sigma}} p_{hjt}^{1-\sigma} + \psi_H^{\frac{1}{\sigma}} p_{\tilde{h}jt}^{1-\sigma} + \psi_F^{\frac{1}{\sigma}} p_{fjt}^{*1-\sigma}\right]^{\frac{1}{1-\sigma}} dj\right)\,, \tag{7}$$

where $p_{hjt}, p_{\tilde{h}jt}$ are prices of goods produced by firm $h, \tilde{h}$, and sold in home market, and p^*_{fjt} is the price of goods produced by firm f, and exported to home market.

A representative household maximizes utility from equation (4) given the budget constraint from the equation (5). This generates the Euler equation

$$\frac{\dot{C}_{ct}}{C_{ct}} = \rho - \left(r_{ct} - \frac{\dot{P}_{ct}}{P_{ct}}\right)\,. \tag{8}$$

4.3 Firms

Production. The production function of the firm i is

$$\mathcal{Y}_{ijt} = z_{ijt} l_{ijt}\,, \tag{9}$$

where z_{ijt} is the productivity and l_{ijt} is labor used by firm i in sector j at time t. z_{ijt} evolves by innovation and adoption. Output can be consumed by the home household or exported to another

[22] C_{Ft} is defined symmetrically. We define equations for the foreign country in Appendix C.1.

[23] Since we have two firms in H and one firm in F, we use the demand shifters to make the two countries symmetric.

country,

$$\mathcal{Y}_{ijt} = y_{ijt} + D \cdot y^*_{ijt}. \tag{10}$$

Market structure. We assume that the three firms in each market (home and foreign) compete in prices, where they set the price given other firms' pricing decisions. As in Atkeson and Burstein (2008), we assume no interaction between home and foreign markets and do not allow dynamic collusion.[24] Firms recognize that their pricing decision changes demand for their goods.

Productivity gap. From now on, we omit the time argument when it does not cause confusion. Firms can increase productivity by λ^n through innovation or adoption. We let n denote the number of steps of improvement, and λ is a unit step size in the economy. Therefore, we can express productivity as λ^N, where N denotes the cumulative number of steps that the firms have taken. Then, the productivity gap m_{Fi} between firm i and the foreign firm in variety j, measured in steps can be written as

$$\frac{z_{ij}}{z_{fj}} = \frac{\lambda^{N_{ij}}}{\lambda^{N_{fj}}} = \lambda^{\boldsymbol{m_{Fi}}}, \quad m_{Fi} \in \mathbb{Z}, \quad i \in \{h, \tilde{h}\}. \tag{11}$$

Likewise, we can express the gap with the domestic competitor, m_{Di} as follows:

$$\frac{z_{ij}}{z_{-ij}} = \frac{\lambda^{N_{ij}}}{\lambda^{N_{-ij}}} = \lambda^{\boldsymbol{m_{Di}}}, \quad m_{Di} \in \mathbb{Z}, \quad i \in \left\{h, \tilde{h}\right\}, \tag{12}$$

where $m_{Fi} > 0$ implies that firm i has higher productivity than the foreign firm. $m_{Di} > 0$ implies that firm i has higher productivity than its domestic competitor. The state variable is a vector $\mathbf{m}_i = \{m_{Fi}, m_{Di}\} \in \mathbb{Z}^2$. Given the aggregate variables such as the wage and the consumption share, $\mathbf{m}_i$ determines the firm i's pricing, market share, and profit. The productivity gap also determines dynamic decisions such as innovation and adoption rates, which we explain in more detail later.

Innovation. Each firm chooses an innovation rate at a cost in labor is given by

$$C_{cr}(x) = \alpha_{cr} \frac{x^\gamma}{\gamma}. \tag{13}$$

We assume $\gamma > 1$, so the innovation cost function is convex. α_{cr} governs the scale of the innovation cost in country c. Since the firm needs to hire labor, the cost is proportional to the wage w_c. Innovation rate x implies that, with probability x, the firm improves its productivity by

$$z_{ij}(t + \Delta) = \lambda^n z_{ij}(t), \quad n \sim \mathbb{F}(n; m_{Fi}), \tag{14}$$

[24] In the equilibrium, there is no arbitrage opportunity since the price ratio between home and foreign goods is always less than the iceberg cost.

where n is a stochastic variable that determines the number of steps of improvement, and $\mathbb{F}(n; m_{Fi})$ is the step size distribution, which is fixed across time and country. It depends on m_F, which is the productivity gap with the foreign firm.[25] To be specific, we assume $\mathbb{E}(n \mid m_{Fi})$ weakly decreases with m_{Fi}. This is motivated by the empirical finding in Section 3.3 where the productivity growth from innovation decreases with the relative productivity.[26] The specific functional form is from Akcigit et al. (2021) and described in Appendix C.6.

Conditional on a successful innovation by firm i with step size n, the state variable of firm i changes to $(m_{Fi} + n, m_{Di} + n)$. Similarly, when the domestic competitor innovates with step size n, the state variable changes to $(m_{Fi}, m_{Di} - n)$. If the foreign firm innovates with step size n, the state variable changes to $(m_{Fi} - n, m_{Di})$.

Adoption. Firms choose an adoption rate a at a cost of labor, given by

$$C_{ca}(a) = \alpha_{ca} \frac{a^\gamma}{\gamma}. \tag{15}$$

Again, we assume that the firm hires labor to adopt, so the cost is proportional to the wage w_c. This labor cost can be interpreted as the researcher who investigates, learns, and implements the foreign technology, which is different from the adoption fee to the seller. α_{ca} governs the scale of the adoption cost in country c.

With probability a, the firm meets a foreign firm and makes an adoption contract. To simplify the model, we assume the domestic adopts technology from the foreign firm, not the home leader.[27,28] The adopter pays a one-time adoption fee to the foreign firm. The adoption fee is determined through Nash bargaining between the adopter and the foreign firm, which we discuss in detail in Section 4.4. Then, the firm improves its productivity by

$$z_{ij}(t + \Delta) = \lambda^n z_{ij}(t), \quad n \sim \mathbb{G}(n; m_{Fi}), \tag{16}$$

where $\mathbb{G}(n; m_{Fi})$ is the step size distribution, which depends on the current gap from the foreign firm m_{Fi}. $\mathbf{E}(n \mid m_{Fi})$ decreases with m_{Fi}, which is motivated by the empirical finding in Section 3.3 in which the productivity growth from adoption decreases with the relative productivity. The functional form is the same as $\mathbb{F}(n; m_{Fi})$, but the slope of the expected step size over m_{Fi} is different to match Figure 2.

[25] In the case of the firm in country F, only the gap with the domestic leader matters.

[26] This captures the advantage of backwardness in Gerschenkron (1962). When firms have lower productivity than foreign firms, they can observe what technologies are successful or not, which makes it easier to innovate.

[27] The estimated adoption expense between domestic firms is only 6.3% of the total adoption expense (Lee, 2022). In the model equilibrium, even if we allow adoption between the domestic firms, firms do not adopt from a domestic competitor under our estimated parameters. This is because two domestic firms have no wage difference and trade cost, and with enough elasticity of substitution, the total surplus from the adoption contract is negative, which makes no room for them to trade technology.

[28] Firms in country F adopt only from the home leader, not the follower.

Note that the adopter does not necessarily catch up with the foreign firm from only one adoption.[29] Let $g(n; m_{Fi})$ be the probability of improving n steps when the gap from the foreign firm is m_F. If $g(1; m_{Fi}) = 1$, our model nests the case of König et al. (2020) in which adoption (imitation) brings only one step regardless of the current gap. If we assume $g(-m_{Fi}; m_{Fi}) = 1$, our model nests the case of Perla and Tonetti (2014) and Benhabib et al. (2021) in which firms obtain the same productivity of another firm by one adoption. If $g(-m_{Fi}; m_{Fi}) = 1$, the adoption fee would always be higher when the initial productivity gap is smaller, which is not the case in the data. Hence, our more flexible specification does a better job matching the empirical patterns.

In our model, technology adoption differs from innovation in several ways. First, adoption is only possible when the firm has lower productivity than the foreign firm. In other words, $g(0; m_{Fi}) = 1$ for $m_{Fi} \geq 0$. Second, the firm cannot leapfrog the foreign firm through adoption, i.e., $g(n; m_{Fi}) = 0$ for $n > -m_{Fi}$. Third, the expected step size from adoption and innovation decreases with m_{Fi}, but the slopes are different. Our empirical finding implies that the slope is larger for adoption, which suggests the productivity gain from adoption is larger than the gain from innovation when m_{Fi} is small, and vice versa. Lastly, the adopter needs to pay the adoption fee $\mathcal{F}_{ct}(\mathbf{m}_i)$ to the foreign firm.

Knowledge diffusion. Motivated by the empirical finding in Section 3.4, we assume that the domestic follower can receive knowledge diffusion from the domestic leader. Specifically, the step size distribution for the domestic follower depends not only on the productivity gap with foreign firms but also on the gap with the domestic leader. We model this by assuming that with a probability δ, the domestic follower can build on the domestic leader's technology when innovating or adopting. Hence, The step size distribution of the follower with $m_{Di} < 0$ is

$$\begin{aligned}\tilde{f}(n; m_{Fi}, m_{Di}) &= (1-\delta) f(n; m_{Fi}) + \delta f(n + m_{Di}; m_{Fi} - m_{Di}), \\ \tilde{g}(n; m_{Fi}, m_{Di}) &= (1-\delta) g(n; m_{Fi}) + \delta g(n + m_{Di}; m_{Fi} - m_{Di}),\end{aligned} \tag{17}$$

where the first term is the case without knowledge diffusion in which the follower improves productivity from its current position, which happens with probability $(1-\delta)$. The second term is the case with knowledge diffusion in which the follower improves from the leader's position $m_{Fi} - m_{Di}$, which happens with probability δ.[30]

Knowledge diffusion generates an intertemporal spillover from both innovation and adoption. When the leader innovates or adopts, it also increases the follower's future productivity. However, this knowledge diffusion hurts the leader's future profit. Since the leader takes that into account, a higher δ reduces the leader's innovation and adoption rates.

The level of spillover is proportional to the expected productivity gain times the probability of

[29] This is a more flexible assumption compared with other papers in the technology diffusion literature (e.g., Perla and Tonetti, 2014; Benhabib et al., 2021; König et al., 2020).

[30] If $\delta = 1$, it becomes equivalent to the common assumption in the quality ladder model literature (e.g., Aghion and Howitt, 1992; Grossman and Helpman, 1991a) in which the follower can always build on the incumbent's technology.

knowledge diffusion. Since the productivity gain from adoption and innovation changes across productivity gaps, the intertemporal spillovers from adoption and innovation also change. For instance, if the productivity gain from adoption is larger than the gain from innovation, the spillover is larger from adoption than from innovation.

Exogenous spillover across countries. We allow for productivity spillovers across countries. With probability ϕ, domestic firms get the access to the technology of foreign firms for free. We include this parameter to capture unobserved international spillovers outside official adoption contracts, such as technology stealing or reverse engineering. Also, $\phi > 0$ guarantees a non-degenerate stationary distribution of the technology gap and is a common feature in step-by-step innovation models (Acemoglu and Akcigit, 2012; Liu and Ma, 2022).

Potential entrant. In country F, there is a potential entrant $\tilde{f}$ that can innovate and replace the incumbent.[31,32] The innovation cost of the entrant is the same as the innovation cost of the incumbent in equation (13). With probability $\tilde{x}$ the potential entrant improves on top of the incumbent's productivity as

$$z_{fj}(t+\Delta) = \lambda^n z_{fj}(t), \quad n \sim \mathbb{F}(n; m_{Ff}). \tag{18}$$

Government policy. We consider subsidies to adoption and innovation. The government in the home country subsidizes s_{Hat} fraction of the adoption cost, and subsidizes s_{Hrt} fraction of the innovation cost. The cost of both subsidies are financed by the lump-sum tax from the household.

4.4 Equilibrium

In this section, we define a Markov perfect equilibrium in which strategies of the firms depend only on the payoff relevant state $\mathbf{m}_i$, the productivity gap vector. Then, we characterize a balanced growth path equilibrium where aggregate productivity, output, wages, and consumption grow at the same rate. Along the balanced growth path, the distribution of the productivity gap, interest rates, and the relative price are constant over time.

Production and profits. The productivity gap $\mathbf{m}_i$ determines the production and profit of intermediate goods given the wage, total consumption in two countries, and the trade cost. Firms in each product and country compete in prices, resulting a Bertrand equilibrium. Since utility is Cobb-Douglas over sectors, the household spends the same amount of expenditure $P_c C_c$ on each

[31] For simplicity, we do not allow potential entrants to adopt the technology.

[32] When the entrant innovates in country F, the incumbent f exits. Note that in a foreign country, the potential entrant can always build on the incumbent's technology. This simplifies the computation by reducing the number of state variables.

sector j. This leads to the following equilibrium condition:

$$\sum_{i=h,\tilde{h}} p_{ij}y_{ij} + p^*_{fj}y^*_{fj} = P_H C_H. \tag{19}$$

By solving the household utility maximization problem given the variety price, the market share of firm $i \in \{h, \tilde{h}\}$ s_{ij}, and the market share of firm f in the home market, s^*_{fj} are

$$s_{ij} = \frac{\psi_H p_{ij}^{1-\sigma}}{\sum_{i=h,\tilde{h}} \psi_H p_{ij}^{1-\sigma} + \psi_F p_{fj}^{*1-\sigma}}, \quad s^*_{fj} = \frac{\psi_F p_{fj}^{*1-\sigma}}{\sum_{i=h,\tilde{h}} \psi_H p_{ij}^{1-\sigma} + \psi_F p_{fj}^{*1-\sigma}}. \tag{20}$$

And the demands, y_{ij}, y^*_{fj} are

$$y_{ij} = \frac{p_{ij}^{-\sigma}}{\sum_{i=h,\tilde{h}} p_{ij}^{1-\sigma} + p_{fj}^{*1-\sigma}} P_H C_H, \qquad y^*_{fj} = \frac{p_{fj}^{*-\sigma}}{\sum_{i=h,\tilde{h}} p_{ij}^{1-\sigma} + p_{fj}^{*1-\sigma}} P_H C_H. \tag{21}$$

Given this demand function, we can solve the firm's problem and get the optimal prices, namely,

$$p_{ij} = \frac{1 - \frac{\sigma-1}{\sigma} s_{ij}}{\frac{\sigma-1}{\sigma}(1 - s_{ij})} \frac{w_H}{z_{ij}}, \qquad p^*_{fj} = \frac{1 - \frac{\sigma-1}{\sigma} s^*_{fj}}{\frac{\sigma-1}{\sigma}(1 - s^*_{fj})} \frac{D \cdot w_F}{z_{fj}}. \tag{22}$$

The profit functions from country H are

$$\pi_{ij} = \frac{s_{ij}}{\sigma - (\sigma - 1)s_{ij}} P_H C_H, \qquad \pi^*_{fj} = \frac{s^*_{fj}}{\sigma - (\sigma - 1)s^*_{fj}} P_H C_H. \tag{23}$$

We define equilibrium in the foreign market similarly in Appendix C.1. The firm makes profits from two sources: the domestic market and the foreign market. Finally, the total profit of the firm $i \in \{h, \tilde{h}\}$ in sector j is

$$\Pi_{ij} = \pi_{ij} + \pi^*_{ij}. \tag{24}$$

If we combine equations (20) and (22), we can solve the price, market share, and profit as functions of the productivity gap, relative wage, trade costs, and household expenditure. Therefore, given the aggregate variables, the productivity gap $\mathbf{m}_i$ fully determines the static variables for all firms.

Value function. Given the aggregate variables, firm profit depends only on the productivity gap, and the innovation and adoption decision changes only the gap over time. We can represent the value function as a function of the productivity gap vector $\mathbf{m}_i = \{m_{Fi}, m_{Di}\}$ instead of using j. Without loss of generality, assume that h is the home leader and $\tilde{h}$ is the follower. For $i \in \{h, \tilde{h}\}$, m_{Fi} is the gap from firm f, and m_D is the gap from the domestic competitor. For $i = f$, m_{Fi} is the gap from the home leader h, and m_D is the gap between the home leader and follower. For example, if the productivity of h is λ^3, $\tilde{h}$ is λ^2, and f is λ^1, then the gap vector for the home leader is $\{2, 1\}$, for the home follower is $\{1, -1\}$, and for the foreign firm is $\{-2, 1\}$.

The value function of h with gap $\mathbf{m}_h = (m_{Fh}, m_{Dh})$ with $m_{Dh} > 0$ is

$$
\begin{aligned}
& r_{Ht} V_{Ht}(\mathbf{m}_h) - \dot{V}_{Ht}(\mathbf{m}_h) \qquad (25) \\
&= \max_{x_{Ht}(\mathbf{m}_h), a_{Ht}(\mathbf{m}_h)} \underbrace{\Pi_{Ht}(\mathbf{m}_h)}_{\text{profit}} - (1 - s_{Hrt}) \underbrace{\alpha_{Hr} \frac{x_{Ht}(\mathbf{m}_h)^\gamma}{\gamma} w_{Ht}}_{\text{innovation cost}} - (1 - s_{Hat}) \underbrace{\alpha_{Ha} \frac{a_{Ht}(\mathbf{m}_h)^\gamma}{\gamma} w_{Ht}}_{\text{adoption cost}} \\
&+ x_{Ht}(\mathbf{m}_h) \sum_n f(n; m_{Fh}) \underbrace{[V_{Ht}(m_{Fh} + n, m_{Dh} + n) - V_{Ht}(\mathbf{m}_h)]}_{\text{gain from innovation}} \\
&+ a_{Ht}(\mathbf{m}_h) \sum_n g(n; m_{Fh}) [\underbrace{V_{Ht}(m_{Fh} + n, m_{Dh} + n) - V_{Ht}(\mathbf{m}_h)}_{\text{gain from adoption}} - (1 - s_{Hat}) \underbrace{\mathcal{F}_{Ht}(\mathbf{m}_h)}_{\text{adoption fee}}] \\
&+ x_{Ht}(\mathbf{m}_{\tilde{h}}) \sum_n \tilde{f}(n; \mathbf{m}_{\tilde{h}}) \underbrace{[V_{Ht}(m_{Fh}, m_{Dh} - n) - V_{Ht}(\mathbf{m}_h)]}_{\text{loss from follower innovation}} \\
&+ a_{Ht}(\mathbf{m}_{\tilde{h}}) \sum_n \tilde{g}(n; \mathbf{m}_{\tilde{h}}) \underbrace{[V_{Ht}(m_{Fh}, m_{Dh} - n) - V_{Ht}(\mathbf{m}_h)]}_{\text{loss from follower adoption}} \\
&+ (x_{Ft}(\mathbf{m}_f) + \tilde{x}_{Ft}(\mathbf{m}_f)) \sum_n f(n; m_{Ff}) \underbrace{[V_{Ht}(m_{Fh} - n, m_{Dh}) - V_{Ht}(\mathbf{m}_h)]}_{\text{loss from foreign firm innovation}} \\
&+ a_{Ft}(\mathbf{m}_f) \sum_n g(n; m_{Ff}) [\underbrace{V_{Ht}(m_{Fh} - n, m_{Dh}) - V_{Ht}(\mathbf{m}_h)}_{\text{loss from foreign firm adoption}} + \underbrace{\mathcal{F}_{Ft}(\mathbf{m}_f)}_{\text{adoption fee}}] \\
&+ \phi \underbrace{(V_{Ht}(0, m_D) - V_{Ht}(\mathbf{m}_h))}_{\text{exogenous spillover}} .
\end{aligned}
$$

Firms choose the optimal innovation rate $x_{Ht}(\mathbf{m}_h)$ and the adoption rate $A_{Ht}(\mathbf{m}_h)$ to maximize the discounted sum of profits. The second line of the value function includes operating profit, which is defined in equations (23) and (24). Then, the firm spends innovation and adoption costs. s_{Hrt} and s_{Hat} are innovation and adoption subsidy rates. The next two lines show the value increase from innovation and adoption where the step size n follows the distributions $f(n; m_{Fh}), g(n; m_{Fh})$. The adoption fee $\mathcal{F}_{Ht}(\mathbf{m}_h)$ is an endogenous variable that we define in equation (29). The next two lines represent the value decrease from innovation and adoption by the domestic competitor. $x_{Ht}(\mathbf{m}_{\tilde{h}}), a_{Ht}(\mathbf{m}_{\tilde{h}})$ denote the innovation and adoption rates of the domestic competitor. Since another firm is the follower, it has different step size distribution given by $\tilde{f}(n; \mathbf{m}_{\tilde{h}}), \tilde{g}(n; \mathbf{m}_{\tilde{h}})$. The following two lines denote the value decrease from foreign firms' (incumbent and entrant) innovation and adoption. The last line has the exogenous spillover, which is governed by the parameter ϕ. The value functions of the home follower, foreign firm, and the foreign entrant are defined similarly, in equations (51), (52), and (53) in Appendix C.2.

Optimal innovation and adoption rate. From the value function equation, we can use the first order conditions to compute the optimal innovation and adoption rates. The optimal innovation rate of the home leader with gap $\mathbf{m}_h$ is given by

$$x_{Ht}(\mathbf{m}_h) = \left(\frac{\sum_n f(n; m_{Fh})[V_{Ht}(m_{Fh} + n, m_{Dh} + n) - V_{Ht}(\mathbf{m}_h)]}{(1 - s_{Hrt})\alpha_{Hr} w_{Ht}} \right)^{\frac{1}{\gamma-1}} . \tag{26}$$

Likewise, the optimal adoption rate of the home leader with gap $\mathbf{m}$ when $m_D > 0$ is

$$a_{Ht}(\mathbf{m}_h) = \left(\frac{\sum_n g(n; m_{Fh})[V_{Ht}(m_{Fh} + n, m_{Dh} + n) - V_{Ht}(\mathbf{m}_h) - (1 - s_{Hat})\mathcal{F}_{Ht}(\mathbf{m}_h)]}{(1 - s_{Hat})\alpha_{Ha} w_{Ht}} \right)^{\frac{1}{\gamma-1}} . \tag{27}$$

The optimal innovation and adoption for the home follower, foreign incumbent, and entrant are in equations (56), (57), (58) in Appendix C.4.

Adoption fee. The adoption fee is an endogenous object that is jointly determined with the value functions. It is a one-time payment that internalizes all the adopter's future gains and the seller's loss. Bargaining only happens between the adopter and the seller, and we assume they cannot make the contract contingent on future behavior. For example, we do not allow the foreign firm to prohibit the adopter from exporting to the foreign country.[33] Also, we do not allow the foreign firm to promise not to sell the technology to another domestic firm. This assumption can be micro-founded if we assume that the foreign firm cannot commit to its future behavior. Lastly, we do not allow one foreign firm to bargain with two domestic firms simultaneously.

With probability a, the adopter meets the foreign firm. If either of the firms does not agree on the contract's term, the adoption does not happen and both have no change in their values. $\mathcal{F}_{Ht}(\mathbf{m}_h)$, the adoption fee of the home leader, is determined by the Nash bargaining,

$$\begin{aligned} \mathcal{F}_{Ht}(\mathbf{m}_h) = & \underset{\mathcal{F}_{Ht}(\mathbf{m}_h)}{\operatorname{argmax}} \Big(\sum_n g(n; m_{Fh}) V_{Ht}(m_{Fh} + n, m_{Dh} + n) - \mathcal{F}_{Ht}(\mathbf{m}_h) - V_{Ht}(\mathbf{m}_h)\Big)^{\xi} \\ & \cdot \Big(\sum_n g(n; m_{Fh}) V_{Ft}(m_{Ff} - n, m_{Df} + n) + \mathcal{F}_{Ht}(\mathbf{m}_h) - V_{Ft}(\mathbf{m}_f)\Big)^{1-\xi} , \end{aligned} \tag{28}$$

where $0 \leq \xi \leq 1$ is the bargaining power of the adopter. $\sum_n g(n; m_{Fh}) V_{Ht}(m_{Fh} + n, m_{Dh} + n)$ is the expected value of the adopter after an adoption in which it improves the gap from all firms by n steps. The net value from adoption is the new value minus the price $\mathcal{F}_{Ht}(\mathbf{m}_h)$, and the home leader's outside option is the current value $V_{Ht}(\mathbf{m})$. Likewise, the expected value of the seller after the adoption is $\sum_n g(n; m_{Fh}) V_{Ft}(-m_{Ff} - n, m_{Df} + n)$, where the seller has a lower value from the decreased relative productivity, but receives adoption fee $\mathcal{F}_{Ht}(\mathbf{m}_h)$. The outside option is the current value $V_{Ft}(-m_{Ff}, m_{Df})$. When we solve the problem in equation (28), we obtain that

[33] This is very rare in the data where only 1.3% of the contracts restrict the adopter's future exports.

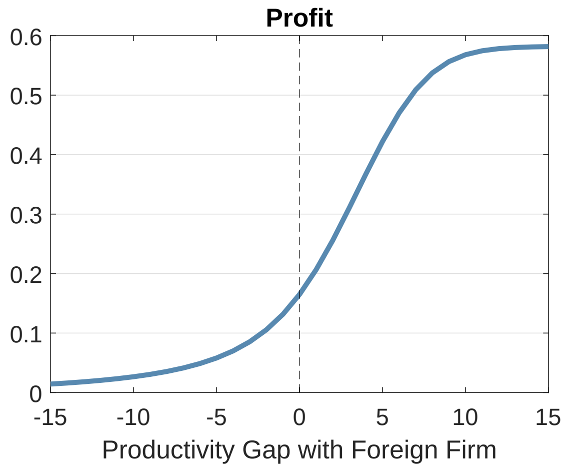


Figure 4: Profit Function over Productivity Gap with Foreign Firms

Notes: This figure plots the profit of the firm on the X-axis and productivity gap with the foreign firm on the Y-axis in the model. We fix the gap between domestic firms as zero. We impose $\sigma = 8, D = 1.2, \lambda = 1.1$.

$$\begin{aligned}\mathcal{F}_{Ht}(\mathbf{m}_h) = (1-\xi)(\sum_n g(n; m_{Fh}) V_H(m_{Fh}+n, m_{Dh}+n) - V_H(\mathbf{m}_h)) \\ - \xi(\sum_n g(n; m_{Fh}) V_F(-m_{Ff}-n, m_{Df}+n) - V_F(\mathbf{m}_f)).\end{aligned} \tag{29}$$

The adoption fee of the home follower and foreign firm are defined in a similar way in equations (54), (55) in Appendix C.3.

The adoption fee is higher if the foreign firm loses more or if the domestic firm gains more from the adoption. It depends on two forces: the extent of the advantage of backwardness and the competition effect. The advantage of backwardness makes the price higher when the productivity gap is large. The productivity gain from adoption is larger when the initial productivity gap is larger. This means the domestic firm gains more from adoption, and the foreign firm loses more, which increases the adoption fee. On the other hand, the competition effect makes the price lower when the productivity gap is large. The increased profit from productivity improvement is small when the initial gap is large. Figure 4 shows an example of the profit function over the technology gap from the foreign firm, fixing other gaps. The slope of the profit function is small when the absolute value of m_{Fi} is large. The slope of the profit function increases as the absolute value of m_{Fi} converges to zero. This is because as the relative productivity matters more when two firms have similar productivity. Therefore, the $\mathcal{F}_{Ht}(m_{Fi})$ can either increase or decrease with m_{Fi} in our model. Our empirical results in Section 3.2 suggest that the competition effect is stronger than the advantage of backwardness.

Note that if the total surplus from the contract is negative, then the adoption contract does not happen. Several circumstances increase the total surplus, making room for technology trade. First, when the wage in the home country is lower, the foreign firm's technology can make more output in the home country and generate a positive total surplus. Second, when the trade cost is high, the two markets are more segmented, and it is more profitable to produce in the home country and sell to the household in the home country. Thus, selling technology can increase the total revenue, which increases the surplus from the adoption contract.[34] Third, firms in different countries produce imperfect substitutes. Therefore, when the elasticity of substitution is smaller, producing all varieties with good technology is valuable. Lastly, when the foreign firm sells technology, the potential entrant loses its future profit, but the foreign firm does not internalize this loss.[35]

Distribution of the productivity gap. The distribution of the productivity gap is the state variable in the economy. Without loss of generality, we assume h is the home leader and use the gap from the home leader's perspective as the aggregate state variable, $\mathbf{m} \equiv (m_F, m_D)$. Note that given $\mathbf{m}$, we can always obtain $\mathbf{m}_h, \mathbf{m}_{\tilde{h}}, \mathbf{m}_f$. We define $\mathbb{T}_i(n;\mathbf{m})$ as the probability that firm i improves productivity n steps when the aggregate state variable is $\mathbf{m}$ as follows,

$$\begin{aligned}
\mathbb{T}_h(n;\mathbf{m}) &= f(n;m_{Fh})x_{Ht}(\mathbf{m}_h) + g(n;m_{Fh})a_{Ht}(\mathbf{m}_h), \\
\mathbb{T}_{\tilde{h}}(n;\mathbf{m}) &= \tilde{f}(n;\mathbf{m}_{\tilde{h}})x_{Ht}(\mathbf{m}_{\tilde{h}}) + \tilde{g}(n;\mathbf{m}_{\tilde{h}})a_{Ht}(\mathbf{m}_{\tilde{h}}), \\
\mathbb{T}_f(n;\mathbf{m}) &= f(n;m_{Ff})(x_{Ft}(\mathbf{m}_f) + \tilde{x}_{Ft}(\mathbf{m}_f)) + g(n;-m_{Ff})a_{Ft}(\mathbf{m}_f).
\end{aligned} \tag{30}$$

Let $\mu_{\mathbf{m}t}$ be the share of sectors with gap $\mathbf{m}$ at time t. For computational reason, let $\bar{m}$ be the maximum productivity gap. The law of motion for $\mu_t(\mathbf{m})$ is

$$\begin{aligned}
&\dot{\mu}_t(\mathbf{m}_h) = \\
&\sum_{n=1}^{m_F+\bar{m}} \underbrace{\mathbb{T}_h(n;m_F-n,m_D-n)\mu_t(m_F-n,m_F-n)}_{\text{leader innovation, adoption}} \\
&+ \sum_{n=1}^{m_D} \underbrace{\mathbb{T}_{\tilde{h}}(n;m_F,m_D+n)\mu_t(m_F,m_D+n)}_{\text{follower innovation, adoption without leapfrogging}} \\
&+ \sum_{n=m_D+1}^{m_F+\bar{m}} \underbrace{\mathbb{T}_{\tilde{h}}(n;m_F-(n-m_D),m_D-n)\mu_t(m_F-(n-m_D),m_D-n)}_{\text{follower innovation, adoption with leapfrogging}}
\end{aligned} \tag{31}$$

[34] It creates an interaction between trade policy and adoption. Since the adoption fee decreases and the adoption rate rises with import tariffs, the government may want to increase import tariffs to increase the adoption rate.

[35] Even if selling technology decreases the foreign country's overall welfare, the foreign firm can still sell the technology since it internalizes only the private profit. This motivates a foreign government to prevent technology from selling to another country, which we discuss in more detail in Appendix F.2.

$$+ \sum_{n=1}^{-m_F+\bar{m}} \underbrace{\mathbb{T}_f(n; m_F+n, m_D)\mu_t(m_F+n, m_D)}_{\text{foreign firms innovation, adoption}}$$

$$+ \underbrace{\mathbb{1}(m_F = 0) \cdot \phi}_{\text{exogenous spillover}} - \underbrace{\left(x_{Ht}(\mathbf{m}_h) + a_{Ht}(\mathbf{m}_h) + x_{Ht}(\mathbf{m}_{\tilde{h}}) + a_{Ht}(\mathbf{m}_{\tilde{h}}) + x_{Ft}(\mathbf{m}_f) + \tilde{x}_{Ft}(\mathbf{m}_f) + \phi\right) \mu_t(\mathbf{m})}_{\text{subtracted mass}},$$

where the first line is the added mass from the home leader's innovation and adoption. The second line is from the home follower's innovation and adoption, where the follower did not leapfrog the leader. The third line is also from home followers, but they leapfrog and become a leader in this case. The fourth line is from foreign incumbents and entrants with the same structure as domestic firms. The last line indicates the added mass from the exogenous spillover, which is added to $m_F = 0$, and the subtracted mass from innovation and adoption, exogenous spillover. Along the balanced growth path, $\dot{\mu}_t(\mathbf{m}) = 0$ for all $\mathbf{m}$.

Note that each sector has different productivity even if they have the same gap $\mathbf{m}$. Let $Z_{\mathbf{m}t}$ be the average productivity of the home leader with gap $\mathbf{m}$. Then,

$$Z_{\mathbf{m}t} = \frac{\int_{\mathbf{m}(j)=\mathbf{m}} z_{hjt} dj}{\mu_t(\mathbf{m})}. \tag{32}$$

Asset market clearing. The asset market clears in each period by the following equation:

$$A_{Ht} = \int_0^1 \sum_{i=h,\tilde{h}} V_{ijt} dj\,, \tag{33}$$

where the right-hand side is the sum of the value of all domestic firms. We do not allow international capital flows.

Labor market clearing. In each country, the labor market clears according to

$$L_{Ht} = \int_0^1 \sum_{i=h,\tilde{h}} \left(l_{ijt} + \alpha_{aH} \frac{a_{ijt}^{\gamma}}{\gamma} + \alpha_{rH} \frac{x_{ijt}^{\gamma}}{\gamma} \right) dj. \tag{34}$$

The left-hand side is the supply of labor, which is fixed over time, and the right-hand side is the demand for labor. The first term is labor demand from production, the second is from innovation, and the third term is from adoption.

Government budget balance. The government holds a balanced budget in each period, namely,

$$T_{Ht} = (1+\theta) \int_0^1 \sum_{i=h,\tilde{h}} \left(s_{Hat} \mathcal{F}_{ijt} + s_{Hat} \alpha_{Ha} \frac{a_{ijt}^{\gamma}}{\gamma} w_{Ht} + s_{Hrt} \alpha_{Hr} \frac{x_{ijt}^{\gamma}}{\gamma} w_{Ht} \right) dj\,, \tag{35}$$

where θ is the reduced form parameter for the deadweight cost of taxation. Specifically, the government needs to collect $1+\theta$ tax revenue to finance one unit of government expenditure.

Trade balance. We assume that trade is balanced between two countries in every period. In other words, the sum of imports and adoption fee expenses should be equal to the sum of exports and the adoption fee revenue as

$$\int_0^1 \left[p^*_{fjt} y^*_{fjt} + \sum_{i=h,\tilde{h}} a_{ijt} p_{ijt} \right] dj = \int_0^1 \left[\sum_{i=h,\tilde{h}} p^*_{ijt} y^*_{ijt} + a_{fjt} p_{fjt} \right] dj. \tag{36}$$

We then define a Markov perfect equilibrium of the model as:

Definition 4.1. A Markov perfect equilibrium consists of $\left\{ r_{ct}, w_{ct}, p_{ijt}, p^*_{ijt}, x_{ijt}, a_{ijt}, \mathcal{F}_{ijt}, T_{ct}, C_{ct}, A_{ct}, \mu_{\mathbf{m}t}, Z_{\mathbf{m}t} \right\}^{t\in[0,\infty), j\in[0,1], c\in\{H,F\},}_{i\in\{h,\tilde{h},f,\tilde{f}\}, m\in\{-\bar{m},\cdots,\bar{m}\}^2}$ such that:

1. The household chooses C_{ct} and A_{ct} to maximize the sum of discounted utility in equation (4) subject to the budget constraint in equation (5).

2. Firm i in sector j chooses p_{ijt} and p^*_{ijt} to maximize profit in equation (24) subject to equations (20), (22), and (23).

3. x_{ijt} and a_{ijt} solve the firm's dynamic problem in equations (26) and (27).

4. $\mathcal{F}_{ijt}$ solves Nash Bargaining between the buyer and seller in equation (29).

5. Given $\{\mu_{\mathbf{m}0}, Z_{\mathbf{m}0}\}$, $\{\mu_{\mathbf{m}t}\}_{t\in[0,\infty)}$, and $\{Z_{\mathbf{m}t}\}_{t\in[0,\infty)}$ are consistent with x_{ijt} and a_{ijt} by equation (31).

6. w_{ct} clears the labor market in equation (34), r_{ct} clears the asset market with equation (33), and T_{ct} balances the government budget by equation (35) in each country and every period.

We then define a balanced growth path equilibrium as follows:

Definition 4.2. A balanced growth path is the equilibrium defined in Definition 4.1 in which $w_{ct}, V_{ijt}, \mathcal{F}_{ijt}, T_{ct}, C_{ct}, A_{ct}$, and $Z_{\mathbf{m}t}$ grow at a rate g, and r_{ct} and $\mu_{\mathbf{m}t}$ being constant over time.

Efficiency properties of the model. The model has several forces that prevent the competitive equilibrium from being efficient. First, with a probability δ, the domestic follower can build on the domestic leader's technology. This generates the intertemporal spillover from adoption and innovation, which makes their private returns smaller than their social returns. This can create an underinvestment in innovation and adoption. Furthermore, in the case of adoption, foreign firms internalize that the spillover would decrease their future profit, which makes the adoption fee increase with the probability of knowledge diffusion δ. This amplifies the discrepancy between the private and social value of adoption, which makes the underinvestment problem of adoption more severe than for innovation. Second, innovation and adoption have a business-stealing effect. The innovation and adoption incentive includes improving productivity and stealing the market share of other firms. However, the social planner only cares about aggregate productivity and output. Firms might improve technology only marginally while spending substantial resources on adoption or innovation.[36] This can lead to overinvestment in adoption and innovation. Lastly, firms have a positive markup, which makes firms produce less than the socially optimal outputs.

5 Quantitative Exercise

In this section, we quantify our model. We first specify functional form of the model. Next, we estimate the model by matching moments with the data, and show the model can match both targeted and untargeted moments well. We then decompose growth contribution from adoption and innovation over time.

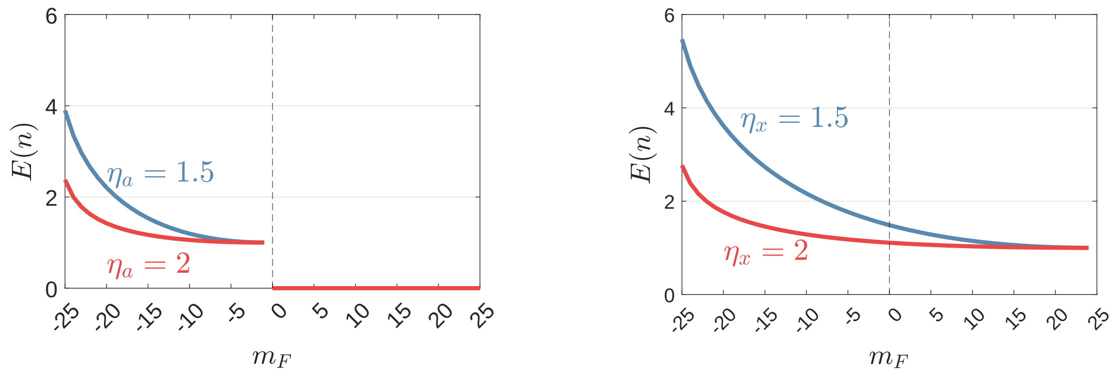
5.1 Parameterization

Step size distribution. We formally define a step size distribution from innovation $\mathbb{F}(n; m_{Fi})$ and that from adoption $\mathbb{G}(n; m_{Fi})$ are formally defined in Appendix C.6. $\mathbb{F}(n; m_{Fi})$ is defined by a single parameter η_x, and $\mathbb{G}(n; m_{Fi})$ is defined by η_a. The condition $\eta_x, \eta_a > 0$ implies that the expected step size decreases with m_{Fi}, and the slope decreases with η_x, η_a. Figure 5 shows examples of the expected step size $\mathbb{E}(n)$ over the productivity gap with foreign firm m_F. The distribution of adoption is truncated at $m_F = 0$, meaning $G(n; m_F) = 0$ if $n \geq -m_F$. Therefore, the same η generates different distributions for adoption and innovation.

5.2 Estimation

We estimate 21 parameters in three steps. Four parameters are determined directly from the data, such as populations and subsidy rates. Seven parameters are externally calibrated. We jointly estimate the remaining ten parameters by simulated method of moments (SMM). Given a guess of parameters, we solve the transition of the model with the initial condition until it converges to the balanced growth path. In the initial state, Korean firms have lower productivity than foreign firms, and this difference is governed by a parameter that is jointly estimated. Along the transition, we run the same regression in the theory and the data. We then update parameters to minimize the distance between the moments from the model and the data. We provide the computational algorithm for solving the transition in Appendix D.2.

[36]When the elasticity of substitution is larger, this business stealing effect becomes stronger.



A. Adoption

B. Innovation

Figure 5: Expected Step Size over the Initial Productivity Gap with Foreign Firms

Notes: This figure plots the expected step size from innovation and adoption on the Y-axis and the initial productivity gap with the foreign firm on the X-axis over the different values of η_a, η_x in the model. A negative gap denotes a domestic firm has lower productivity than a foreign firm. Panel A plots the case of adoption, and panel B plots the case of innovation. Since the distribution of adoption is truncated at $m_F = 0$, the same value of η makes different distribution between adoption and innovation.

5.2.1 Parameters that Directly Match the Data

We set the home country's labor supply $L_H = 1$ as a normalization and $L_F = 2$ to match Japan's relative population size. For government policy s_{Hat}, s_{Hrt}, we use the tax credit for adoption and innovation. As an adoption subsidy, the Korean government has given tax credit for the expense of adoption fees to foreign firms since 1973.[37,38] To be specific, firm gets the full tax credit from the fixed fee and royalty payment for the first five years of the adoption contract, and half the tax credit for the following three years. In 1981, the policy changed to only give tax credit for five years. In 1991, the policy limited the coverage of the adoption tax credit to "advanced technology". In the data, 42% of adoption contracts have gotten the tax credit since 1991, and we interpret this as the firms getting 42% of the tax credit from adoption costs. In 2010, the government stopped giving a tax credit for adoption costs. Using the corporate tax and formula from Bloom et al. (2002), we calculate the adoption subsidy rate over time.

Likewise, the government also subsidized innovation by giving R&D tax credits. It started in 1981 with a tax credit rate of 10%. In 1990, it increased the tax credit rate to 15%, and in 2009, it increased the rate to 25%. We again calculate the innovation subsidy rate according to the formula from Bloom et al. (2002). The tax credit rate is from Choe and Lee (2012).[39] Figure 6 shows the

[37]In the 1970s, there was also a sector-specific adoption subsidy that subsidizes the input cost of adoption-related business as we studied in Choi and Shim (2022). We abstract away from this sector-specific subsidy in this paper.

[38]We collected the adoption tax credit law over time from https://glaw.scourt.go.kr.

[39]We use the tax credit rate for medium and small-sized firms because the tax credit for big firms is more complicated. In particular, the government gives a 50% tax credit for the increment of R&D for the big firms, which is hard to calculate as an innovation subsidy rate.

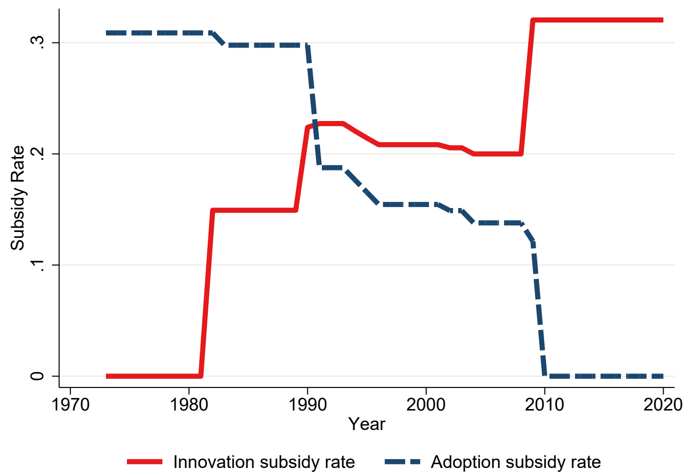


Figure 6: Innovation and Adoption Subsidy Rate in Korea

Notes: This figure plots the adoption subsidy rate in the dashed navy line and the innovation (R&D) subsidy rate in the solid red line in Korea over time. We calculate the innovation and adoption subsidy rate using using the formula from Bloom et al. (2002) using tax credit rate and corporate tax rate. Tax credit rate is from https://glaw.scourt.go.kr, R&D tax credit rate and corporate tax rate is from Choe and Lee (2012).

innovation and adoption subsidy rates over time.

We include s_{Hat}, s_{Hrt} into the model assuming perfect foresight of the agents. For country F, we impose $s_{Fat} = 0, s_{Frt} = 0$.

5.2.2 External Calibration

We use a discount rate $\rho = 0.03$, following a common value in the literature. We impose $\psi_H = 0.25$, $\psi_F = 0.5$, to make two countries symmetric, since home country has two incumbents while foreign country has one incumbent. R&D and adoption cost curvature parameter γ is set to be 2 to match the elasticity of successful innovation with respect to R&D as 0.5 (Blundell et al., 2002).[40] We impose $\sigma = 7$ following the average value in Broda and Weinstein (2006) for SITC 5 digit level. For the iceberg trade cost between Korea and Japan, we use $D = 1.5$, following the estimates of trade costs between the U.S. and Canada in Anderson and Van Wincoop (2004). We use $\theta = 1$ as a baseline value following Feldstein (1999), which implies that the government needs to collect 2 units of tax revenue to finance one unit of expenditure.[41] As robustness checks, we use different values of discount rate $0.02 \leq \rho \leq 0.05$, the elasticity of substitution $\sigma = 4, 12$, and iceberg trade cost $D = 1.25, 1.75, 2$ and present the main results in Appendix E.2.

[40]For further discussion, refer to Akcigit et al. (2021).

[41]Refer to Heckman et al. (1999), Heckman et al. (2010) for further discussion about deadweight loss of government financing.

5.2.3 Simulated Method of Moments

Since the structure of firms is different in the two countries, we adjust the cost parameter for adoption and innovation in country F by assuming $\alpha_{Fr} = \alpha_F \cdot \alpha_{Hr}$, $\alpha_{Fa} = \alpha_F \cdot \alpha_{Ha}$ and adjust α_F to make the average productivity gap along the balanced growth path equal to zero.

The remaining ten parameters $\Theta = \{\lambda, \alpha_r, \alpha_a, \alpha_F, \eta_a, \eta_r, \xi, \delta, d, \phi\}$ are estimated to target ten empirical moments. We choose Θ to minimize the distance between empirical moments M_i^D and moments from model $M_i(\Theta)$ as follows,

$$\min_{\Theta} \sum_{i=1}^{10} \left(\frac{M_i^D - M_i(\Theta)}{\frac{1}{2}(M_i^D + M_i(\Theta))} \right)^2. \tag{37}$$

We document the ten empirical moments and discuss relevant parameters that we identify from the moments.

Adoption fee / yearly sales. The adoption fee divided by the yearly sales in adoption contracts is 22.4% on average.[42] Likewise, we calculate the adoption fee over annualized sales in the model and compare both moments. The critical parameter determined by this moment is ξ, which governs the bargaining power of the adopter.

Productivity gain from adoption and innovation over the initial gap. We replicate regression (2) in the model, and compare the coefficients from Table B.3. We simulate 1,000,000 adopting firms and innovating firms by using the distribution of the productivity gap conditional on adopting/innovating. We calculate the sales per employee growth from adoption and innovation for each simulated firm. Then, we regress the growth in sales per employee from adoption and innovation with the initial sales per employee gap from the foreign firm. Finally, we compare the regression coefficients in the model and the data in Table B.3. The key parameters identified by this moment are η_x, η_a, which govern the slope of step size distributions from adoption and innovation (Figure 5).

Patent citation increase after adoption. To summarize the result in Figure 3, we run the difference-in-differences regression on patent citations from technology seller compared with control firms within 5 years from the first technology adoption in Table B.6 in Appendix B. To replicate the empirical result, we develop a simple model of patent citation. In the model, the home follower can receive knowledge diffusion from the adopted technology. We assume they must cite the foreign firm's patent when they innovate by building on the diffused knowledge. Then the increased citation from a domestic follower (non-adopters) to the foreign firm is $x \cdot \delta$, where x is the innovation rate, and δ is the probability of experiencing knowledge diffusion. We match $x \cdot \delta$ with 0.028, the

[42] If the firm pays the fee over multiple years, we sum all the payments.

coefficient in Table B.6 in Appendix B. This moment identifies δ, the probability of experiencing knowledge diffusion.

Long-run growth rate. The growth rate of Japan since 2010 is 1.6%, and we consider this the growth rate along the balanced growth path. The GDP growth rate increases with the level of λ, which is the unit productivity growth from innovation and adoption.

R&D, adoption / value added in manufacturing. The R&D expenditure divided by the value added is 2.97%, and the adoption expenditure divided by the value added is 1.48% in manufacturing, 1985–1990.[43] These inform the scale parameter of innovation cost, α_r, and the scale parameter of adoption cost α_a. From equation (26), we can calculate the innovation expenditure function, which decreases with α_r. Likewise, α_a decreases the adoption rate and adoption expenditure, which is the adoption rate times the adoption fee.

GDP ratio in 1973 and 2020. The initial ratio of GDP per capita between Korea and Japan was 0.210 in 1973.[44] It informs d, the average productivity gap between H and F in the initial period. We assume that the productivity gap from the foreign firm follows $\mathcal{N}(d, 1)$.[45] The GDP ratio became 0.981 in 2020. It informs ϕ, which is the exogenous spillover parameter. When we have higher ϕ, convergence is faster, and the GDP ratio in 2020 is smaller.

Productivity gap in the long run. Since we assume two incumbents in Korea and one incumbent in Japan, the two countries have different innovation and adoption rates even if they have the same cost parameters. Therefore, we adjust the cost function of Japan to have a symmetric productivity level along the balanced growth path. We target the long-run productivity gap as zero. The key parameter is α_F. When α_F is higher, the innovation and adoption cost in F is higher, and the long-run productivity is lower in F.

5.3 Estimation Results

Table 3 shows the estimation results. Our estimate for λ is 1.047, which implies one step improvement increases labor productivity by 4.7%. $\eta_x > \eta_a$ implies the expected productivity gain from adoption is larger when the productivity gap with foreign firms is larger. Figure 7 shows the step size distribution from the estimated parameters, which is in line with our empirical findings in Figure 2. On the other hand, $\alpha_a < \alpha_r$ means that adoption requires less labor. The bargaining power parameter for the adopting firm, ξ, is 0.464, which implies that the adopter receives less

[43] We use the value in 1985–1990 since we have sector level R&D expenses for that period. R&D expenses in manufacturing are from Ministry of Science and Technology (1990), adoption expenses are from Korea Industrial Technology Association (1995), and value-added in manufacturing is from the Input-Output table provided by the Bank of Korea.

[44] GDP per capita is using purchasing power parity rates.

[45] For simplicity, we assume the variance is one.

Table 3: Estimation Results

Parameter	Description	Value	Source
Directly From Data			
L_H	Labor in home country	1	Normalization
L_F	Labor in foreign country	2	Population in Japan
s_{Hat}, s_{Hrt}	Subsidy rate		Tax credit rate, corporate tax rate
Externally Calibrated			
ρ	Time preference	0.03	Literature
σ	Elasticity of substitution	7	Broda and Weinstein (2006)
ψ_H	Demand shifter of home good	0.25	Equal share
ψ_F	Demand shifter of foreign good	0.5	Equal share
D	Trade cost	1.5	Anderson and Van Wincoop (2004)
γ	Adoption / innovation cost curvature	2	Acemoglu et al. (2018)
θ	Deadweight cost of taxation	1	Feldstein (1999)
Jointly Calibrated through SMM			
λ	Unit step size	1.047	
η_a	Slope of step size from adoption	1.201	
η_r	Slope of step size from innovation	1.772	
α_a	Adoption cost	1.177	
α_r	Innovation cost	1.683	Jointly Estimated through SMM
ξ	Bargaining power of adopter	0.464	
δ	Knowledge diffusion	0.231	
d	Initial productivity gap	-23.672	
α_F	Relative cost in F	5.702	
ϕ	Exogenous spillover	0.025	

than half of the total surplus from the adoption. The probability of getting knowledge diffusion, δ, is 0.231.[46] The initial productivity gap, d, is -23.672, meaning the productivity of foreign firms is 2.97 times higher than Korean firms. The relative innovation and adoption cost of country F, α_F is 5.702, which implies F has a higher cost for innovation and adoption. The reason is that the entrant in F always has a higher incentive to innovate, and we target the long-run technology gap as zero. The probability of exogenous spillover, ϕ is 0.025.

Table 4 shows the target moments from the data and the model. The model tightly matches the micro and macro moments in the data. In particular, the model can replicate Korea's catching up with Japan in a short period.

5.4 Validation

To validate the model, we present the model with two untargeted moments. The left panel of Figure 8 plots adoption expenditure / (adoption expenditure + R&D expenditure) over time in the model and the data. Although we only target the average value of adoption and R&D / value

[46] Most papers in the literature assume that potential entrant can always build on the incumbent technology, which fixes the probability of knowledge diffusion as one.

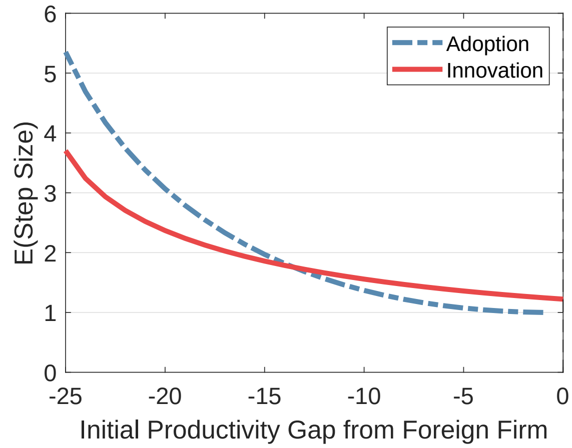


Figure 7: Step Size Distribution from Adoption and Innovation

Notes: This figure plots the expected step sizes from adoption (dashed blue line) and innovation (solid red line) over the initial productivity gap from the model. We impose $\eta_a = 1.201, \eta_r = 1.772$, which are the estimated values.

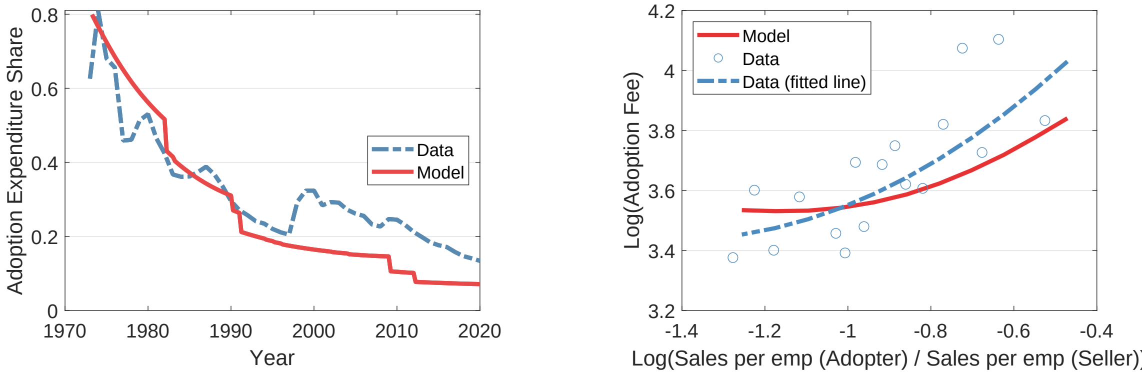
Table 4: Target Moments in Model and Data

Moment	Model	Data
Adoption fee / annual sale	0.221	0.224
β^a : productivity growth with gap (adoption)	-0.116	-0.120
β^i : productivity growth with gap (innovation)	-0.044	-0.046
β^s : Δ Patent citation after adoption	0.026	0.028
Long-run growth rate	0.017	0.016
Adoption / value added in manufacturing	0.016	0.015
R&D / value added in manufacturing	0.032	0.030
GDP ratio in 1973	0.210	0.210
GDP ratio in 2020	0.983	0.981
Long-run productivity gap	0.001	0.000

added in 1985–1990, we can match the decreasing pattern of adoption expenditure share well.[47] In the model, as firms are getting closer to the foreign firm, they are more likely to innovate instead of adopting foreign technologies.

The right panel of Figure 8 plots the log (adoption fee) over the log ratio of sales per employment between domestic and foreign firms from the model and data. In the model, firms' value change more with relative productivity when firms are closer to each other. This makes the adoption fees increase with relative productivity.

[47] While the policy partially generates the decreasing trend of adoption expenditure share, the model still produces decreasing adoption expenditure share without the policy change. Figure E.1 shows the case with no subsidies.

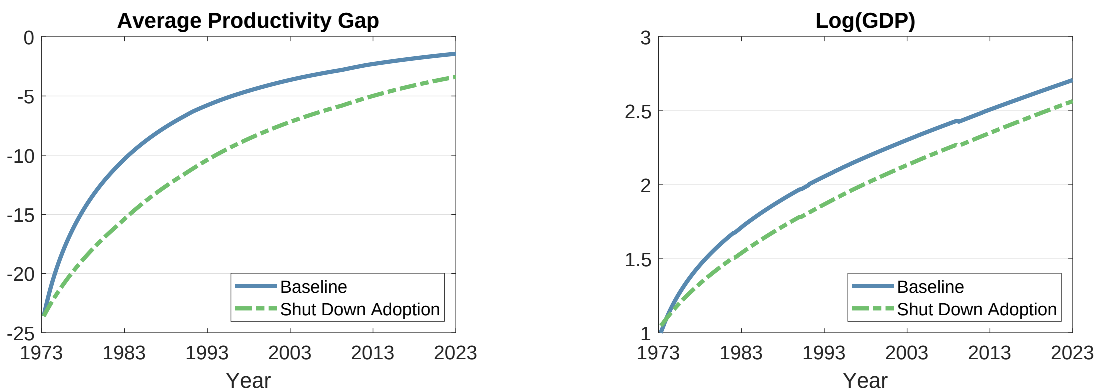


A. Adoption Expenditure Share

B. Adoption Fee over Gap

Figure 8: Untargeted Moments

Notes: This figure plots the untargeted moments from the data and the model. Panel A plots the adoption fee expenditure / (adoption fee + innovation cost) in the model (solid red line) along with the data (dashed blue line). Panel B plots the log (adoption fee) over the log ratio of sales per employment between domestic and foreign firms in the model (solid red line) along with the data (dashed blue line and circles).



A. Average Productivity Gap

B. Log(GDP)

Figure 9: Baseline and Counterfactual without Adoption

Notes: This figure plots the average productivity gap and log(GDP) in the baseline case with adoption (blue line) and the counterfactual in which we shut down the adoption channel (dashed green line). We keep the same innovation subsidy in both cases. Panel A shows the average productivity gap between Korea and Japan over time. For instance, -10 means that the labor productivity of Korean firms divided by that of Japanese firms is λ^{-10} on average. Panel B shows $\log(\text{GDP})$ in two cases over time. Both graphs have kinks when the innovation or adoption subsidy change.

5.5 Contribution of Adoption and Innovation to Growth over Time

To study the contribution of adoption to growth, we first shut down the adoption channel in the model by increasing the adoption cost to infinity. Second, we decompose GDP growth between adoption and innovation in each period.

The left panel of Figure 9 shows the average productivity gap over time in the baseline case and in the case where we shut down the adoption subsidy but keeps the innovation subsidy. It shows that convergence is much slower without adoption, especially in the early years. This is because adoption provides a better way to reduce the gap to the foreign firm in the early period. The right panel of Figure 9 compares log(GDP) over time with the baseline case and the case without adoption. Korea loses a substantial portion of GDP when we shut down adoption. In particular, the growth rate is much higher with adoption in the early period. GDP in 2023 would have been 13.3% lower, and consumption-equivalent welfare in the infinite horizon would have been 11.77% lower without adoption.

We then decompose GDP growth between adoption and innovation over time. Specifically, we calculate the counterfactual GDP growth rate while keeping either adoption or innovation. We then calculate the GDP growth from adoption and divide by the sum of growth from innovation and growth from adoption. We keep other aggregate variables such as wages.

Figure 10 shows that adoption accounts for 75% of GDP growth in 1973, whereas it accounts for 14% in 2022. In other words, the main driver of growth is technology adoption from foreign countries in the early stage of development, and it shifts to innovation as the country becomes more developed.

6 Policy Analysis

In this section, we start by discussing the policy implications of our model. Then, we evaluate the technology policies implemented in Korea since 1973, which started with an adoption subsidy and switched to an innovation subsidy as in Figure 6. Next, we study the optimal timing of the switch from adoption to innovation subsidy while fixing the subsidy rate at the maximum rate of the actual policy. Finally, we jointly study the optimal subsidy rate and timing to switch. In Appendix F, we present other policy exercises in which we study the optimal policy as linear function of time, and then study the case where the Japanese government prevents firms from exporting technology.

6.1 Policy Implications of the Model

As we discussed in Section 4, one of the reasons why the competitive equilibrium of our model is not efficient is that adoption and innovation have intertemporal spillovers through knowledge diffusion across domestic firms. The size of intertemporal spillover is proportional to the productivity gain from adoption and innovation. Since our empirical analysis suggests the productivity gain from adoption is larger than from innovation at the early stages of development, the optimal subsidy rate is larger for adoption than innovation initially. As domestic firms catch up with foreign firms, the productivity gain from adoption diminishes, and the optimal adoption subsidy

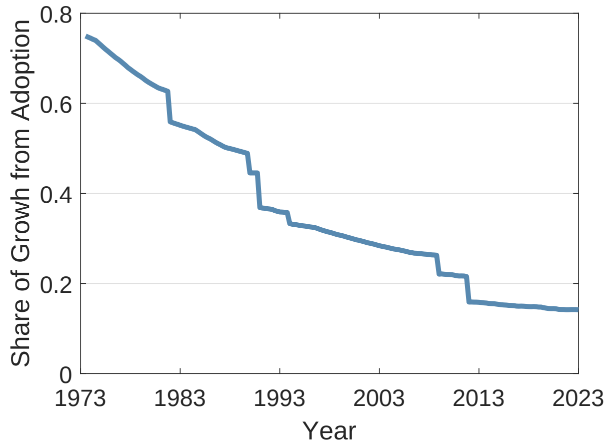


Figure 10: Share of Growth from Adoption over Time

Notes: This figure plots the growth share of adoption over time. To be specific, we calculate the counterfactual GDP growth rate while keeping either adoption or innovation. We then calculate the GDP growth from adoption and divide by the sum of growth from innovation and growth from adoption. We keep other aggregate variables such as wages. It has kinks when the adoption or innovation subsidy changes.

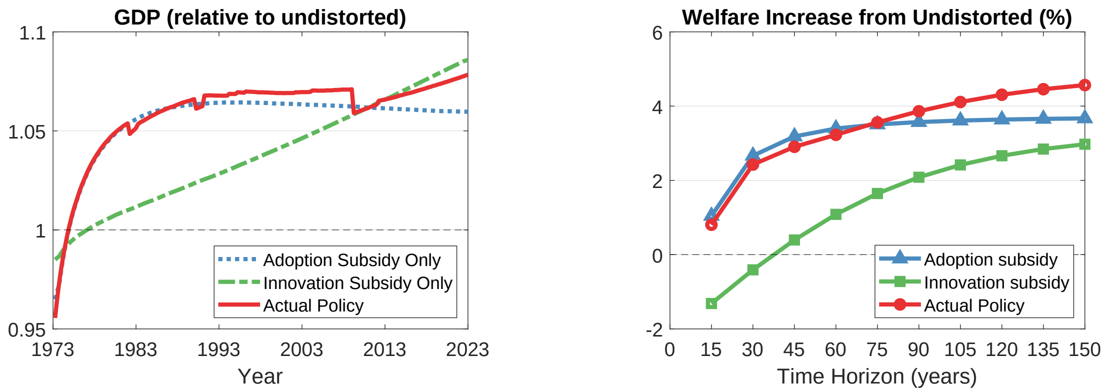
rate decreases while the optimal innovation subsidy rate increases. This logic leads to the optimal policy, which depends on the productivity gap between domestic and foreign firms. We start by evaluating the actual policy in Korea, which has changed as the productivity of Korean firms converged with foreign firms.

6.2 Evaluation of Technology Policy in Korea

We include both adoption and innovation subsidies over the year from the data as in Figure 6 in the actual policy case. We compare the actual policy with three counterfactuals. First, we shut down both subsidies, which we consider an undistorted case. Second, the government subsidizes only adoption at 31%, the initial value in the actual policy. Lastly, the government subsidizes only innovation at 32%, the final value in the actual policy.[48]

The left panel of Figure 11 shows GDP relative to the undistorted case with no subsidies over time. The adoption subsidy generates a higher growth rate in the early stage, and GDP becomes larger than undistorted case without subsidies. However, relative GDP eventually flattens and even decreases slightly, implying that subsidizing only adoption does not generate a significantly higher long-run growth rate. On the other hand, subsidizing only innovation does not yield a higher growth rate at the beginning compared with the adoption subsidy case. However, it yields a higher growth rate at later stages of development. This is because subsidizing innovation in

[48] In Figure E.2, we compare the baseline case with the cases when we shut down either adoption or innovation subsidies to decompose the contribution of actual adoption and innovation subsidies.



A. Relative GDP

B. Welfare Increase (%)

Figure 11: Results of the Counterfactual Analysis

Notes: This figure evaluates the actual policy by comparing it with counterfactuals. Panel A plots GDP in three scenarios divided by GDP in the undistorted case. The dotted blue line subsidizes only adoption at 31%, the dashed green line subsidizes only innovation at 32%, and the solid red line follows the actual policy in Figure 6. Panel B plots the welfare increase compared to the undistorted case over different time horizons. For instance, time horizon 15 means that we calculate the discounted sum of utility from year 0 to 15. The welfare increase is calculated in consumption-equivalent units using equation (38).

the early years can be distortive, allocating resources to innovation instead of adoption, even though adoption has a larger positive externality. Lastly, the actual policy yields GDP similar to the adoption subsidy case and also yields a higher growth rate at later stages of development.

The right panel of Figure 11 shows the welfare implication of the policies over the different time horizons. Specifically, we calculate the discounted sum of the utility of different time horizons. Then, we calculate the percentage increase from the undistorted case with no subsidies in terms of consumption units. The consumption-equivalent change Ψ is given such that

$$\int_{t=0}^{T} \exp(-\rho t) \log(C_{Ht}) dt = \int_{t=0}^{T} \exp(-\rho t) \log(\hat{C}_{Ht}(1+\Psi)) dt \,, \tag{38}$$

where $\hat{C}_{Ht}$ is consumption in the undistorted case. For example, $T = 15$ and $\Psi = 0.03$ means the welfare within a 15 year horizon is equivalent to the case when we uniformly increase consumption by 3% in the undistorted case. When the time horizon is short, such as 15 or 30 years, subsidizing innovation generates lower welfare than the undistorted case. This is because firms are investing much labor in innovation, which is not an efficient way to improve productivity compared with adoption at this stage. This result implies that, when developing countries follow an innovation policy, a common policy in developed countries, it may reduce welfare in the short run.

In the infinite horizon ($T = \infty$), the actual policy increases the consumption-equivalent welfare by 4.84%, which is higher than subsidizing only adoption (3.69%) or subsidizing only innovation

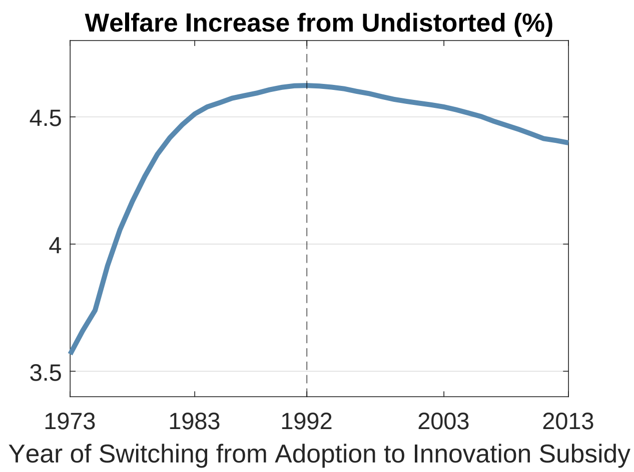


Figure 12: Welfare Increase over Different Year to Switch from Adoption to Innovation

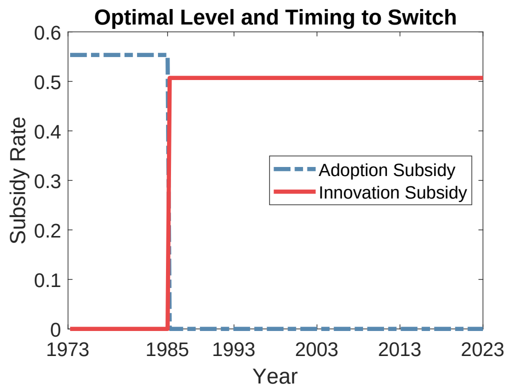
Notes: This figure plots the welfare increase compared with the case without policy when the switch from an adoption to innovation subsidy happens in different years. Welfare increase is in consumption-equivalent units. We start with an adoption subsidy of 32% and an innovation subsidy of 0% and switch to an adoption subsidy of 0% and an innovation subsidy of 32% in a certain year. In 1992, the GDP per capita in Korea was 57% of that of Japan.

(3.28%). This result suggests that the actual policy implemented in Korea was qualitatively close to the optimal policy.

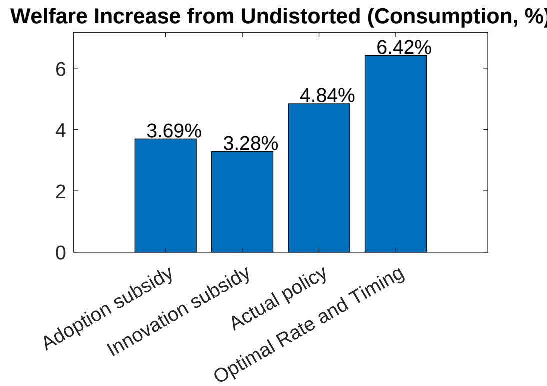
6.3 Optimal Timing to Switch

The previous result suggests that the state-dependent policy, which switched from an adoption to innovation subsidy, can generate higher welfare than other alternatives. Motivated by this, we study the optimal timing to switch from an adoption to innovation subsidy while fixing the subsidy rate. Specifically, we assume that the government starts with an adoption subsidy rate of 32% (maximum subsidy rate in the actual policy), and it can switch to an innovation subsidy of 32% in a single year. In the long run, it keeps the innovation subsidy rate at 32%. We find the optimal timing to switch to maximize infinite horizon welfare.

Figure 12 shows the welfare increase compared to the undistorted case in consumption units when the switch from an adoption to innovation subsidy happens in different years. The result suggests that it was optimal to switch from adoption to innovation subsidy in 1992, which increases consumption-equivalent welfare by 4.62%. In the early stages of development, the productivity gap with the foreign country is large, which generates more knowledge diffusion from technology adoption than innovation. Therefore, it is better to subsidize adoption instead of innovation. Later, when the gap is closed, the diffusion from innovation is greater than adoption. Thus, the government needs to switch to innovation subsidies at a certain point. The actual policy in Korea decreased the adoption subsidy in 1991 and increased the innovation subsidy in 1989



A. Optimal Subsidy Rates



B. Welfare increase (%)

Figure 13: Optimal Subsidy Rates and Welfare Increase

Notes: This figure plots the optimal subsidies and welfare results. Panel A plots the optimal adoption (dashed blue line) and innovation subsidy rate (solid red line). We allow the government to choose an adoption rate, innovation rate, and year to change from the adoption to innovation subsidy. The optimal policy is to start the adoption subsidy at 55% and switch to the innovation subsidy in 1985, at 51%. In 1985, the GDP per capita in Korea was 55% of that of Japan. Panel B plots the consumption-equivalent welfare increase from the undistorted case over different policies.

(Figure 6). Our result suggests that the actual policy was close to optimal in terms of timing to switch from an adoption to innovation subsidy. However, the actual policy yielded higher welfare than this policy because the actual policy gradually changes subsidy rates over time, and the sum of adoption and innovation subsidy rates is larger in some periods.

6.4 Optimal Rate of Subsidies and Timing to Switch

We next allow the government to choose adoption and innovation subsidy rates.[49] Specifically, the government chooses three parameters—the adoption subsidy rate, innovation subsidy rate, and the timing to switch from the adoption to the innovation subsidy—to maximize welfare in the infinite time horizon.

The left panel of Figure 13 shows the optimal subsidies over time. The optimal policy within this class of policies is to start the adoption subsidy at 55% and switch to an innovation subsidy in 1985 of 51%, which is much higher than the actual subsidy rates. The right panel of Figure 13 plots the welfare increase in different policies. The optimal subsidy increases consumption-equivalent welfare by 6.42%, substantially more than the actual policy and other counterfactuals.

To make this result applicable to other developing countries, we calculate the relative GDP per capita of Korea compared with Japan in the year of the switch. GDP per capita in Korea was 55% of Japan in 1985, which suggests that it would be better to switch from an adoption to innovation subsidy when developing countries reach roughly half the GDP per capita of the

[49] In Appendix F.1, we study the optimal linear subsidy in which we allow the government to subsidize both adoption and innovation, and the subsidy rate is a linear function of time.

frontier countries.[50]

7 Conclusion

In this paper, we study the role of adoption and innovation in development and their policy implications over different stages of development. We build a new model where firms can innovate or adopt technologies from foreign firms. The novel part of our model is that it captures the incentives of both buyers and sellers of technologies and studies strategic behaviors between them. A novel firm-to-firm technology transfer dataset from Korea disciplines this crucial part of the model.

Using the quantified model, we evaluate the actual policy in Korea, which sheds light on the optimal state-dependent policy. Korea started with an adoption subsidy and then gradually switched to an innovation subsidy. The state-dependent policy generates a 4.84% increase in welfare, which is higher than other alternatives, such as subsidizing only adoption (3.69%) or subsidizing only innovation (3.28%). When the government subsidizes only innovation, welfare is smaller than the undistorted case without either subsidies over 30 years. If the government subsidizes only adoption, it only increases short-run growth, not the long-run growth rate.

Many developing countries have been trying to improve their technology by following the technology policies that are currently implemented by developed countries. However, policies that are effective in developed countries may not work well in developing countries. There are necessary steps that developing countries should follow to develop. Since Korea started as a low-income country and became a high-income country in a short period, it provides important insights for other developing countries to design long-term policies over different stages of development. Our results suggest that governments in developing countries should start with adoption subsidies at a high rate (55%). Then, when GDP per capita reaches roughly half the frontier countries, the policymakers need to consider switching to an innovation subsidy. A gradual change in subsidy rates would perform better if it is feasible.

Our framework can be used to study broader questions. What are the experiences of other developing countries? Are there any fundamental factors that increase the effectiveness of technology adoption? How do the adoption and innovation subsidies interact with trade policies? These questions are important for giving general policy advice that can be helpful to other developing countries.

[50] This conclusion depends on the cost parameter of adoption and innovation, which depend on other variables such as human capital and the quality of institutions.

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A Appendix: Data

A.1 Technology Adoption data

Figure A.1: Example of Adoption Contract

TECHNICAL COLLABORATION AGREEMENT

BY AND BETWEEN

NIPPON ELECTROIC CO., LTD.

AND

SAMSUNG ELECTRON DEVICES CO., LTD.

Section 4 <u>Supply of Written Technical Information</u>

(a) During the term of this Agreement NEC will upon reasoable request furnish SED with one transparent copy of each drawing, specification and other technical document as well as programs and related documentation within the scope specified in Section 1 (d) hereof. The time, manner and other details of furnishing such written NEC Technical Information shall be separately determined by the parties upon mutual consultation.

Figure A.2: Example of Adoption Contract

Section 7 Compensation

(a) In consideration of the technical assistance, rights and licenses to be rendered or granted by NEC to SED hereunder, SED shall pay to NEC royalties computed at the rate of three percent (3%) of the Net Sales during the term of this Agreement.

(b) "Net Sales" means the aggregate of all Net Selling Prices with respect to each annual accounting period ending December 31 of each year.

In 1962–1993, Korean firms were strictly required to report all transactions involving foreign currencies under the Foreign Capital Inducement Act. To be specific, they reported details of technology imports to the Economic Planning Board. Therefore, the universe of technology transfer contracts between Korean and foreign firms are stored in the national archives in Korea. We collect and digitize these technology transfers. Figures A.1 and A.2 show an example of a document.

Korea Industrial Technology Association (1995) classifies contracts into five categories - sharing information, technical guidance, patent licensing, trademark licensing, etc. We consider the first two as know-how transfers and the third and fourth as licensing. Know-how transfer includes sharing blueprints, design specifications, production details, and training the Korean employees. 53% of contracts involve only know-how transfer, 41% involve both know-how and licensing, and 4% involve only licensing. Table A.1 shows the industry composition of the contracts in which 95% of contracts are in manufacturing. Table A.2 shows the share of origin countries.

The average yearly royalty rate is 3.28%, and the average contract length is 5.13 years. The average fixed fee is 1.29 million dollars, which accounts for 1.97% of yearly sales.[51] On average, total fee—which is the sum of the royalty payment and the fixed fee—accounts for 22.4% of yearly sale.

[51] 61.38% of contracts have royalty payments, 76.56% have fixed fees, and 37.97% have both.

Table A.1: Industry Composition of Technology Adoption

Sector	Frequency	Share (%)
Machinery	2,225	26.48
Electronics	2,090	24.87
Chemical manufacturing	1,359	16.17
Chemical fiber	414	4.93
Metal	412	4.90
Food	264	3.14
Non-metallic products	225	2.68
Shipbuilding	224	2.67
Pharmaceutical	204	2.43
Construction	151	1.80
Telecommunications	131	1.56
Electrics	92	1.09
Textile	66	0.79
Paper	35	0.42
Agriculture	30	0.36
Etc.	482	5.73
Total	8,404	100.00

Table A.2: Country Composition of Technology Adoption

Country	Frequency	Share (%)
Japan	4,177	50.02
United States	2,193	26.26
Germany (West)	461	5.52
France	339	4.06
United Kingdom	308	3.69
Italy	146	1.75
Switzerland	129	1.54
Netherlands	113	1.35
Canada	78	0.93
Sweden	57	0.68
Belgium	55	0.66
Norway	47	0.56
Denmark	44	0.53
Australia	37	0.44
Austria	26	0.31
Finland	23	0.28
Russia	21	0.25
Hong Kong	19	0.23
Singapore	11	0.13
Etc.	66	0.81
Total	8,350	100

Table A.3: Average Royalty Rate across Sectors

Sector	Average Royalty Rate (%)
Machinery	18.11
Electronics	17.78
Chemical manufacturing	17.91
Chemical fiber	19.48
Metal	14.22
Food	18.78
Non-metallic products	17.20
Shipbuilding	16.54
Pharmaceutical	21.88
Construction	24.35
Telecommunications	20.25
Electrics	26.17
Textile	21.56
Paper	14.50
Agriculture	10.13
Etc.	21.84

Notes: Average royalty rate is yearly royalty rate times the contract year.

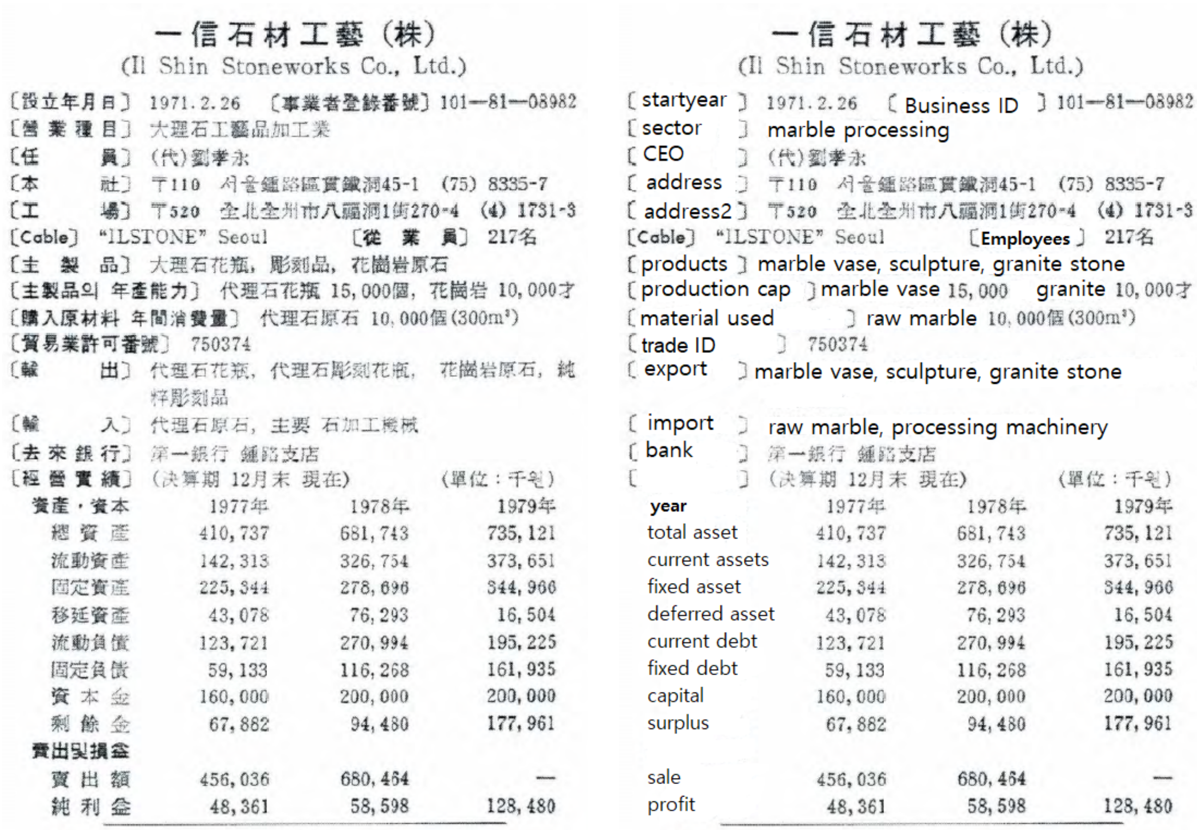
A.2 Firm-level Balance Sheet data

For the period between 1970 and 1982, we digitize Annual Reports of Korean Companies. The reports are published by the Korea Productivity Center. Figure A.3 shows the example of a firm data in the reports.

Coverage. It covers firms that have more than 50 employees. We compare the value added from the reports and the aggregate data from Bank of Korea.[52] The firms in the data covers around 70% of gross output in manufacturing. For the period from 1983, we use KIS-VALUE dataset. It covers publicly traded firms and firms with assets more than 3 billion Korean Won since 1981.

Variables. Annual Reports of Korean Companies has information including sales, total assets, fixed assets, employment, profit, export, start year. Employment data starts from 1972. Export variable is only available to small subset of firms. KIS-VALUE data includes all the variables from Annual Reports and also has R&D, cost of goods sales, wage bills. We convert all nominal values into 2015 US dollars. We validate two data by comparing overlapping period, 1981-1982. Most of the variables are the same in the two dataset.

[52]The data can be downloaded from Economic Statistics of the Bank of Korea, https://ecos.bok.or.kr/EIndex_en.jsp.



一信石材工藝 (株)

(Il Shin Stoneworks Co., Ltd.)

〔設立年月日〕 1971.2.26 〔事業者登錄番號〕 101—81—08982
〔營業種目〕 大理石工藝品加工業
〔任　　員〕 (代)劉孝永
〔本　　社〕 〒110 서울鍾路區貫鐵洞45-1 (75) 8335-7
〔工　　場〕 〒520 全北全州市八福洞1街270-4 (4) 1731-3
〔Cable〕 "ILSTONE" Seoul 〔從業員〕 217名
〔主製品〕 大理石花瓶, 彫刻品, 花崗岩原石
〔主製品의 年產能力〕 代理石花瓶 15,000個, 花崗岩 10,000才
〔購入原材料 年間消費量〕 代理石原石 10,000個(300m³)
〔貿易業許可番號〕 750374
〔輸　　出〕 代理石花瓶, 代理石彫刻花瓶, 花崗岩原石, 純粹彫刻品
〔輸　　入〕 代理石原石, 主要 石加工機械
〔去來銀行〕 第一銀行 鍾路支店
〔經營實績〕 (決算期 12月末 現在) (單位：千원)

資產・資本	1977年	1978年	1979年
總資產	410,737	681,743	735,121
流動資產	142,313	326,754	373,651
固定資產	225,344	278,696	344,966
移延資產	43,078	76,293	16,504
流動負債	123,721	270,994	195,225
固定負債	59,133	116,268	161,935
資本金	160,000	200,000	200,000
剩餘金	67,882	94,480	177,961
賣出및損益			
賣出額	456,036	680,464	—
純利益	48,361	58,598	128,480

一信石材工藝 (株)

(Il Shin Stoneworks Co., Ltd.)

〔startyear〕 1971.2.26 〔Business ID〕 101—81—08982
〔sector〕 marble processing
〔CEO〕 (代)劉孝永
〔address〕 〒110 서울鍾路區貫鐵洞45-1 (75) 8335-7
〔address2〕 〒520 全北全州市八福洞1街270-4 (4) 1731-3
〔Cable〕 "ILSTONE" Seoul 〔Employees〕 217名
〔products〕 marble vase, sculpture, granite stone
〔production cap〕 marble vase 15,000 granite 10,000才
〔material used〕 raw marble 10,000個(300m³)
〔trade ID〕 750374
〔export〕 marble vase, sculpture, granite stone
〔import〕 raw marble, processing machinery
〔bank〕 第一銀行 鍾路支店
〔 〕 (決算期 12月末 現在) (單位：千원)

year	1977年	1978年	1979年
total asset	410,737	681,743	735,121
current assets	142,313	326,754	373,651
fixed asset	225,344	278,696	344,966
deferred asset	43,078	76,293	16,504
current debt	123,721	270,994	195,225
fixed debt	59,133	116,268	161,935
capital	160,000	200,000	200,000
surplus	67,882	94,480	177,961
sale	456,036	680,464	—
profit	48,361	58,598	128,480

Figure A.3: Snapshot of Annual Reports of Korean Companies

A.3 Matching foreign firm with USPTO data

We use company name to match firms in the adoption data with the USPTO data. First, we run fuzzy matching by using Python function "fuzzymatcher". We remove words such as "co", "ltd", "inc" before running the code. We impose minimum similarity score as 0.35. For the remaining one, we manually match firms with USPTO ID from patentsview data. Patentsview data sometimes assign multiple assignee ID to one firm. We use global corporate patent dataset (Bena et al., 2017) which provides matching between global Compustat ID (gvkey) and patent ID. If two assignees have the same gvkey, we merge them and consider as one firm.

Among 8,404 adoption contracts, 7,877 contracts have foreign firm's name, and 4,657 number of observations are matched with USPTO ID of foreign firms. We have 2,073 unique USPTO ID attached to foreign firms.

Table A.4: Comparison between Adopting and Non-Adopting Firms

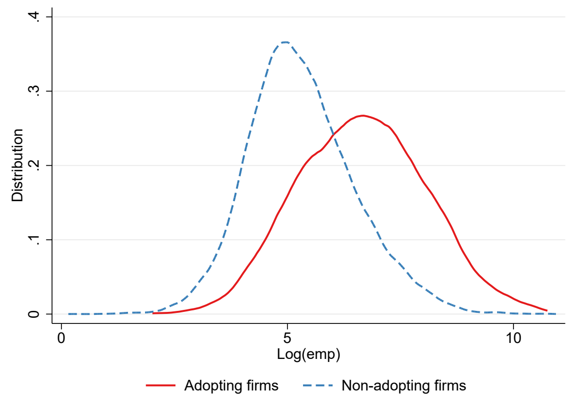
	Adopting	Non-adopting
Share	6.21%	93.79%
Emp	2,618.11	478.99
Total Asset	576.56	45.88
Sales	570.19	65.98
Sales per emp	0.21	0.16
Patenting	0.16	0.02

Notes: This table shows the average of variables between adopting and non-adopting firms. We calculate average values for 1971-1993. Adopting firm is defined as a firm that has at least one adoption contract. Total assets, sales, and sales per employee are in a million dollar converted in 2015 values.

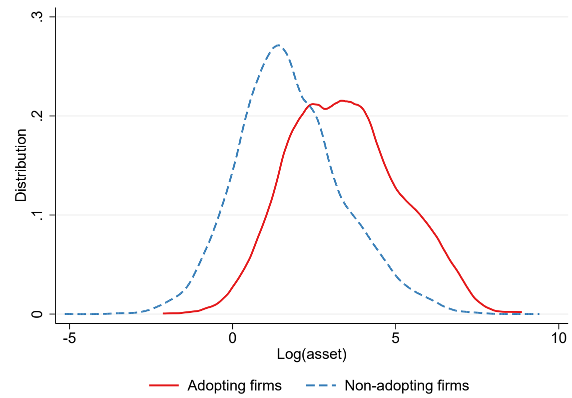
A.4 Summary Statistics

Table A.4 shows the summary statistics of adopting and non-adopting firms in 1971-1993. Adopting firms have at least one adoption contract in a given year. 6.21% of total firms adopt technology. They have a bigger size in terms of employment and total assets. Also, on average they have larger total sales and larger sales per employee. Lastly, we compare the patenting dummy variables between the two groups. Adopting firms are much more likely to apply for a patent.

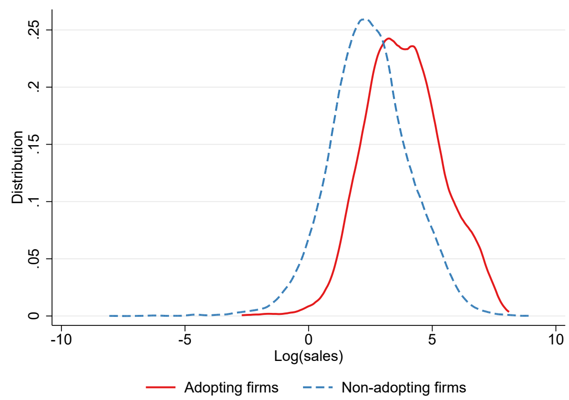
A.5 Distribution of Variables of Adopting Firms and Non-adopting Firms



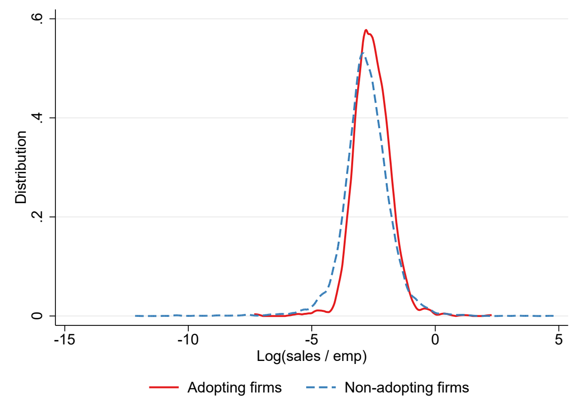
A. Employment



B. Total Asset



C. Sales



D. Sales per Employee

Figure A.4: Distribution of Adopting and Non-adopting Firms

Notes: We plot the distribution of log(employment) and log(total asset), log(sales), log(sales per employee) of adopting and non-adopting firms by using kernel density estimation. We define adopting firms if they have at least one technology adoption contract. We control sector-year fixed effects.

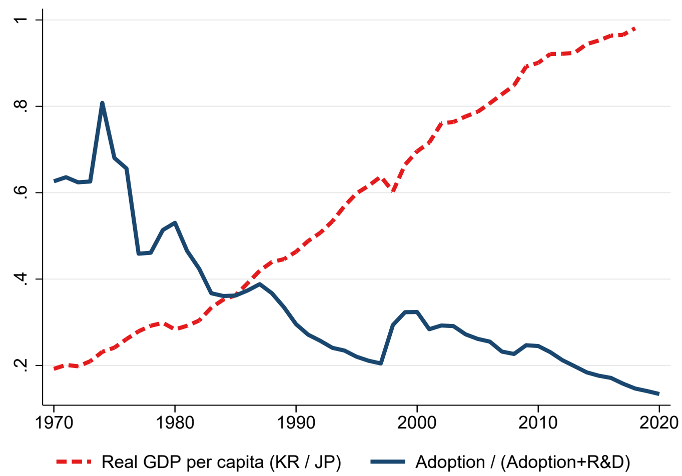


Figure B.1: GDP Gap and Adoption Expenditure Share over Time

Notes: This figure plots the ratio of real GDP per capita between Korea and Japan in the dashed red line and adoption expenditure / (adoption expenditure + R&D expenditure) in the solid navy line. Adoption expenditure is the gross payment to foreign firms for sharing industrial processes, designs, and licensing for patents and trademarks. GDP is from Maddison project (Bolt and Van Zanden, 2020; Cha et al., 2020), and R&D and adoption expense are from the Statistics Korea.

B Empirical Analysis: Robustness Checks and Additional Graphs

B.1 Adoption Expenditure Share over Time

Figure B.1 plots the time-series trend regarding GDP ratio between Korea and Japan, and the adoption expenditure share of Korea. GDP ratio is real GDP per capita of Korea divided by real GDP per capita of Japan. The adoption expenditure share is the adoption expenditure divided by sum of adoption and R&D expenditure. Adoption expenditure is the gross payment by Korean firms to foreign firms for sharing industrial processes, designs, and licensing for patents and trademarks. The adoption expenditure share has decreased over time while the GDP ratio converged to one. This suggests firms were relying more on adoption at the early periods of development, and they gradually switched to innovation over time.

The left panel of Figure B.2 plots adoption expenditure only to Japan, and the right panel of Figure B.2 plots adoption and R&D expenditure divided by GDP, separately.

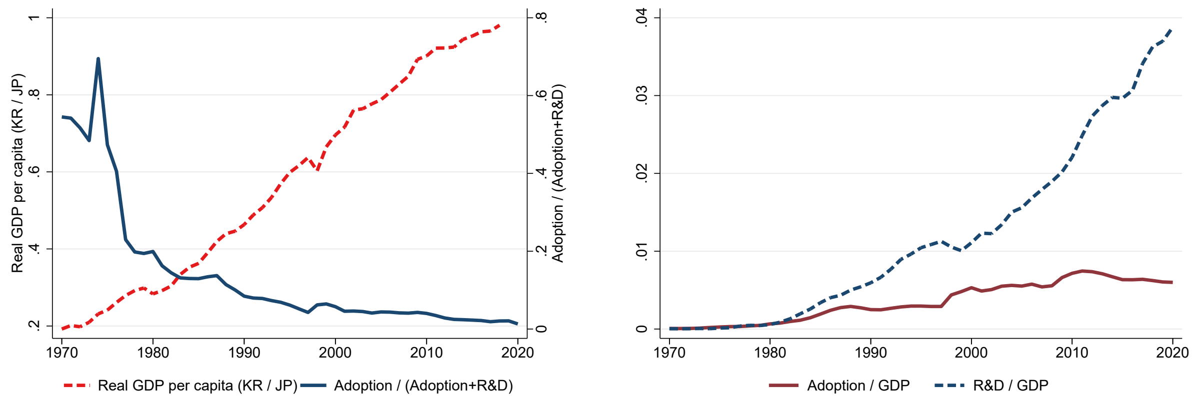


Figure B.2: Relative GDP per Capita, Adoption Expenditure, and R&D Expenditure over Time

Notes: The left panel plots the ratio of real GDP per capita between Korea and Japan in the dashed red line and adoption expenditure / (adoption expenditure + R&D expenditure) in the solid navy line. Adoption expenditure is the gross payment to only Japanse firms for sharing industrial processes, designs, and licensing for patents and trademarks. GDP is from Maddison project (Bolt and Van Zanden, 2020; Cha et al., 2020), and R&D and adoption expense are from the Statistics Korea. The right panel plots adoption expenditure (to all foreign firms) in the solid brown line, and R&D expenditure divided by GDP over time in the dashed navy line.

B.2 Innovation and Adoption over Productivity Gap

Table B.1: Regression of Patent / (Patent+Adoption) on Relative Productivity

	Innovation share	
	Sector-level	Firm-level
Relative Productivity	0.202***	0.0667***
	(0.0530)	(0.0161)
N	241	1,520
Adjusted R2	0.3625	0.2770
Sector FE	.	yes
Year FE	yes	yes

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Notes: We regress the innovation share on the relative productivity. Panel A is at the sector-year level, the innovation share is measured by the number of patents divided by the sum of the number of patents and the number of adoption contracts. The relative productivity is measured by value added per employment of Korea divided by value added per employment of Japan in each sector and year. We control year-fixed effects. Sector-level data is from STAN OECD data. Panel B is at the firm-year level, the innovation share is the share of patent over sum of patents and adoption contracts at the firm level. The relative productivity is measured by sales per employee of a Korean firm divided by sales per employee of the foreign firm which sells technology. If the firm does not have an adoption contract, we use the maximum sales per employee of foreign firms in the sector. We control for sector and year-fixed effects.

$$\text{Innovation share}_{it} = \beta \cdot \text{Relative Productivity}_{it} + \alpha_{s(i)} + \delta_t + \epsilon_{it} \tag{39}$$

Table B.1 shows the results when we run the regression in equation (39) both at the sector and firm level. 1% increase in the relative productivity is associated with 0.2% increase in the innovation share at the sector level, and 0.07% increase at the firm level.

B.3 Adoption Fee over Productivity Gap

$$\mathcal{F}_{ijt} = \beta_1 \log\left(\frac{z_{it}}{z_{jt}}\right) + \beta_2 \cdot \text{Overlap} + \beta_3 \log\left(\frac{z_{it}}{z_{jt}}\right) \cdot \text{Overlap} + \alpha_{s(i)} + \delta_t + \epsilon_{ijt}\,, \tag{40}$$

To study whether the degree of competition matters for the correlation, we use detailed information from patent data. To be specific, we list the ten most frequent patent classes of each firm. Then, we make a dummy variable which is equal to one if more than half of the patent classes in the adopter's list are also included in the seller's list. 27% of our sample have overlap in more than half of their most frequent patent classes. Table B.2 shows that the interaction term between the gap and overlap of the sector has a significant and positive coefficient. Therefore, when the two firms are in the same field, the technology gap matters more for the adoption price.

Table B.2: Adoption Fee and Relative Productivity with Overlap of Patent Fields

	Total fee	Total fee
Relative productivity	0.627***	0.561***
	(0.0545)	(0.0598)
Relative productivity x overlap		0.292***
		(0.111)
Overlap of field		0.530***
		(0.162)
N	1,022	1,022
Adjusted R2	0.4062	0.4116
Sector FE	yes	yes
Year FE	yes	yes

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Notes: This table shows the result of equation (1) in which we regress the adoption fee on the relative productivity. The fixed fee and total fee are logged. Royalty is the royalty rate (in percentage). The total fee is the sum of the fixed fee and royalty rate times sales times contract years. Relative productivity is the log ratio of sales per employee between the Korean firm (buyer) and the foreign firm (seller). Overlap is whether more than half of the adopter's ten most frequent patent classes are also included in the seller's list.

B.4 Productivity Gain from Adoption and Innovation over Technology Gap

Table B.3 shows the result from running the regression in equation (2). The first column is for adopting firms and the second column is for innovating firms. We run the regression using both adopting and innovating firms and include interaction term of the productivity gap and adoption dummy in the third column. The interaction term has negative and significant coefficient, which implies that the coefficient for adopting firms is smaller than the coefficient for innovating firms. This suggests that the productivity gap matters more for adopting firms than innovating firms.

B.5 Knowledge Diffusion from Adoption

Table B.4 shows the descriptive statistics of technology seller and the placebo group. P-value suggests that there is no statistically significant difference between two groups in terms of cumulative patent and citations.

Figure B.3 shows the raw average of patent citations between technology sellers and the placebo groups. Figure B.4 shows the event study result in which we run the equation (3) using the inverse hyperbolic of citations to study the intensive margin. This shows the number of patent citations

Table B.3: Sales per Employee Growth over the Initial Productivity Gap

	Δ log(sales/emp)		
	Adopting	Innovating	Both
Productivity gap (t)	-0.120***	-0.0457***	-0.0562***
	(0.0208)	(0.0144)	(0.0133)
Gap x adoption			**-0.0576*****
			(0.0195)
Adoption			-0.00758
			(0.0310)
N	919	439	1,362
Adjusted R2	0.4276	0.4013	0.4224

Standard errors in parentheses, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Notes: This table shows the result of regression in equation (2). The productivity gap is the log ratio of sales per employee between the adopting firm and the foreign technology seller. Since we do not have information for the foreign firm when the Korean firm is innovating, we use the maximum of $\log(\text{sales / emp})$ of foreign technology sellers in the same sector. The first column includes only adopting firms. The second column uses only innovating firms that applied for at least one patent in a year. We exclude firms that have both adoption and innovation. The third column includes all the firms. In all regression, we control the growth rate of fixed asset / employment for 5 years, and include sector and year fixed effects. Standard errors are clustered at the Korean firm level.

from non-adopters to the technology seller also increase compared to the placebo firms after the first technology adoption. Table B.5 shows the regression coefficient in equation (3) for both extensive and intensive margins.

Figure B.5 plots the event study result in which we run the equation (3) using the number of citations received from all the other countries except Korea. We cannot see significant trend around the first technology adoption, which suggests that there was no particular trend in the seller's technology.

To summarize the results, we run a simpler difference-in-differences specification in which we include a dummy variable equal to one if the year is after the first (placebo) technology adoption. The regression equation is as below.

$$Y_{it} = \beta^{\text{s}} \cdot \mathbf{1}(L_{it}^{\text{Seller}} > 0) + \beta^{\text{All}} \cdot \mathbf{1}(L_{it}^{\text{All}} > 0) + \alpha_i + \gamma_t + \epsilon_{it}. \tag{41}$$

Table B.6 shows the result in which the coefficient of post-adoption is 0.0284 within five years. It suggests that the Korean non-adopting firms increase the probability of citation by 2.84 percentage points.

Table B.4: Descriptive Statistics of Technology Seller and Placebo Group

	Technology seller	Placebo	P-value
log (cumulative patent)	4.25	4.46	0.22
	(2.24)	(2.33)	
log (cumulative citations)	1.77	1.80	0.39
	(0.49)	(0.46)	
N	374	374	

Notes: Both variables are the cumulative numbers at the year of first (placebo) technology adoption. P-value is for the null hypothesis that the difference between technology sellers and the matched group is zero.

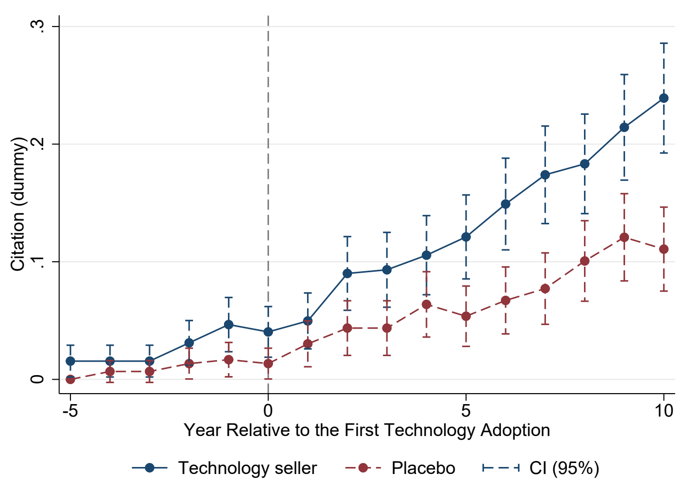


Figure B.3: Raw Average of Patent Citations Between Two Groups

Notes: The figure plots the average number of the citations from Korean never-adopters to the foreign firms that sold technology (solid navy line), and to the foriegn firms that did not (dashed red line). Vertical line is 95% confidence interval. X-axis is the year relative to the first technology adoption by a Korean firm. The coefficient one year before the adoption (-1) is normalized to zero.

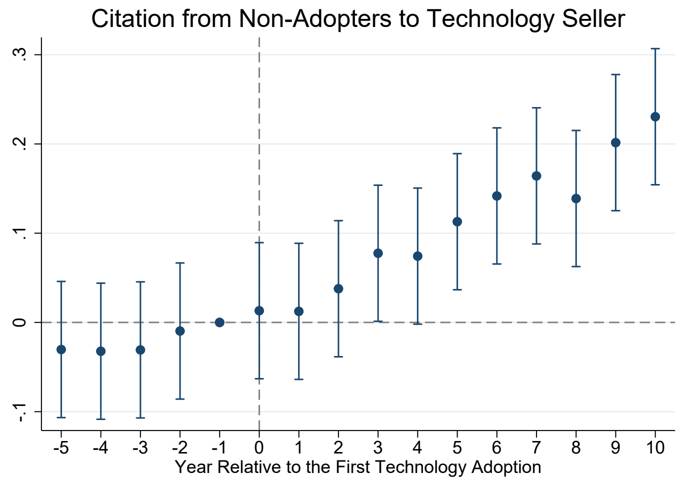


Figure B.4: Event Study Result of patent Citations: Intensive Margin

Notes: The figure plots β_k^{Seller} in equation (3), which captures the difference of the inverse hyperbolic transformation of the number of citations received from the Korean non-adopters, between the foreign firm that sold technology to a Korean firm and the foreign firm that did not sell. The vertical line is a 95% confidence interval. X-axis is the year relative to the first technology adoption by a Korean firm. The coefficient one year before the adoption (-1) is normalized to zero. The standard error is clustered at the foreign firm level.

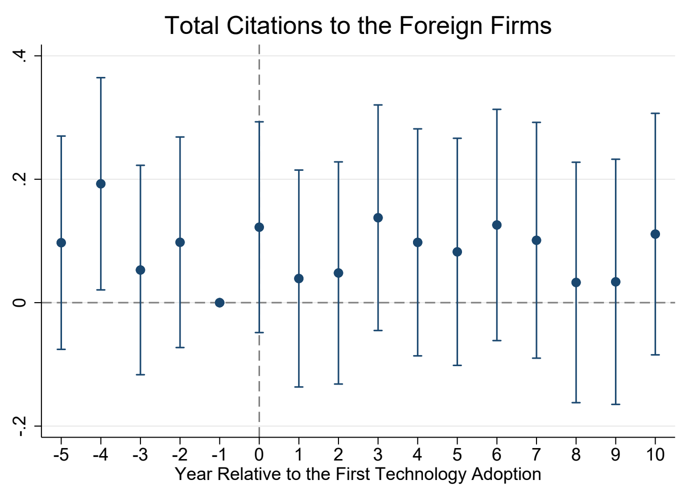


Figure B.5: Event Study Result of Patent Citations (placebo)

Notes: The figure plots β_k^{Seller} in equation (3), which captures the difference of logged number of citations that firm i received from all the other countries except Korea between the foreign firm that sold technology to a Korean firm and the foreign firm that did not sell. The vertical line is a 95% confidence interval. The coefficient one year before the adoption (-1) is normalized as zero. The standard error is clustered at the foreign firm level.

Table B.5: Event Study Result of Patent Citations

	Citation (dummy)	Citation (IHS)
5 years before event	-0.0148	-0.0304
	(0.0130)	(0.0172)
4 years before event	-0.0213	-0.0323
	(0.0130)	(0.0166)
3 years before event	-0.0213	-0.0308
	(0.0139)	(0.0172)
2 years before event	-0.0124	-0.00963
	(0.0143)	(0.0201)
1 year before event	0	0
	(.)	(.)
event year	-0.00275	0.0132
	(0.0147)	(0.0188)
1 years after event	-0.00995	0.0124
	(0.0160)	(0.0213)
2 years after event	0.0173	0.0378
	(0.0173)	(0.0238)
3 years after event	0.0205	0.0775**
	(0.0186)	(0.0287)
4 years after event	0.0133	0.0743*
	(0.0206)	(0.0339)
5 years after event	0.0388	0.114**
	(0.0204)	(0.0379)
6 years after event	0.0537*	0.143***
	(0.0229)	(0.0397)
7 years after event	0.0681**	0.166***
	(0.0247)	(0.0445)
8 years after event	0.0545*	0.140**
	(0.0258)	(0.0475)
9 years after event	0.0644*	0.204***
	(0.0280)	(0.0538)
10 years after event	0.100***	0.233***
	(0.0291)	(0.0558)
N	9,920	9,920
AR2	.4035	.5376
firm fixed	yes	yes
year fixed	yes	yes

Standard errors in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table B.6: Patent Citations to Foreign Firm after Adoption

	Citation (dummy)
Post Adoption	0.0284**
	(0.0117)
N	6,820
Adjusted R2	0.3927
Firm FE	yes
Year FE	yes

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Notes: This table displays the estimates of β^s in equation (41), which is the average difference in the probability of citations from Korean non-adopting firms to the foreign technology seller after the first technology adoption. We restrict the sample from 5 years before and post five years from the first technology adoption. Standard errors are clustered at the foreign firm level.

C Appendix: Model

C.1 Equations for Foreign Country

Final consumption C_{Ft} is given by

$$C_{Ft} = \exp\left(\int_0^1 \ln\left[\left(\psi_H^{\frac{1}{\sigma}} y_{hjt}^{*\frac{\sigma-1}{\sigma}} + \psi_H^{\frac{1}{\sigma}} y_{\tilde{h}jt}^{*\frac{\sigma-1}{\sigma}} + \psi_F^{\frac{1}{\sigma}} y_{fjt}^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}\right] dj\right). \tag{42}$$

The price index of final consumption P_{Ft} is given by

$$P_{Ht} = \exp\left(\int_0^1 \ln\left[(\psi_H^{\frac{1}{\sigma}} p_{hjt}^{1-\sigma} + \psi_H^{\frac{1}{\sigma}} p_{\tilde{h}jt}^{1-\sigma} + \psi_F^{\frac{1}{\sigma}} p_{fjt}^{*1-\sigma})^{\frac{1}{1-\sigma}} dj\right]\right). \tag{43}$$

Productivity gap for the foreign firm is given by

$$\begin{aligned} \frac{z_{fj}}{z_{hj}} &= \frac{\lambda^{N_{fj}}}{\lambda^{N_{hj}}} = \lambda^{\boldsymbol{m_{Ff}}}, \quad m_{Ff} \in \mathbb{Z} \\ \frac{z_{hj}}{z_{\tilde{h}j}} &= \frac{\lambda^{N_{hj}}}{\lambda^{N_{\tilde{h}j}}} = \lambda^{\boldsymbol{m_{Df}}}, \quad m_{Df} \in \mathbb{Z}, \end{aligned} \tag{44}$$

where we assume h is the leader without loss of generality. m_{Df} is the gap between domestic firms from firm h's perspective, which also matters for profit and dynamic decisions of the firm f.

Equilibrium. The expenditure in sector j by Household in country F is

$$\sum_{i=h,\tilde{h}} p_{ij} y_{ij} + p_{fj}^* y_{fj}^* = P_H C_H. \tag{45}$$

By solving the household utility maximization problem given the variety price, s_{ij}^*, the market share of firm $i \in \{h, \tilde{h}\}$ and s_{fj}, the market share of firm f in the foreign market are

$$s_{ij}^* = \frac{\psi_H p_{ij}^{*1-\sigma}}{\sum_{i=h,\tilde{h}} \psi_H p_{ij}^{*1-\sigma} + \psi_F p_{fj}^{1-\sigma}}, \qquad s_{fj} = \frac{\psi_F p_{fj}^{1-\sigma}}{\sum_{i=h,\tilde{h}} \psi_H p_{ij}^{*1-\sigma} + \psi_F p_{fj}^{1-\sigma}}. \tag{46}$$

And the demand y_{ij}^*, y_{fj} are:

$$y_{ij}^* = \frac{p_{ij}^{*-\sigma}}{\sum_{i=h,\tilde{h}} p_{ij}^{*1-\sigma} + p_{fj}^{1-\sigma}}, \qquad y_{fij} = \frac{p_{fj}^{-\sigma}}{\sum_{i=h,\tilde{h}}^2 p_{ij}^{*1-\sigma} + p_{fj}^{1-\sigma}}. \tag{47}$$

Given this demand function, we can solve the firm's problem and get the optimal prices, namely,

$$p_{ij}^* = \frac{1 - \frac{\sigma-1}{\sigma} s_{ij}^*}{\frac{\sigma-1}{\sigma}(1 - s_{ij}^*)} \frac{D \cdot w_H}{z_{ij}}, \qquad p_{fj} = \frac{1 - \frac{\sigma-1}{\sigma} s_{fj}}{\frac{\sigma-1}{\sigma}(1 - s_{fj})} \frac{w_F}{z_{fj}}. \tag{48}$$

The profit functions from country F are.

$$\pi_{ij}^* = \frac{s_{ij}^*(1-\frac{\sigma-1}{\sigma})}{1-\frac{\sigma-1}{\sigma}s_{ij}^*}, \qquad \pi_{fj} = \frac{s_{fj}(1-\frac{\sigma-1}{\sigma})}{1-\frac{\sigma-1}{\sigma}s_{fj}}. \tag{49}$$

Finally, the total profit of the firm f in sector j is

$$\Pi_{fj} = \pi_{fj}P_F Y_F + \pi_{fj}^* P_H Y_H. \tag{50}$$

C.2 Value Function

Value function of firm $\tilde{h}$ with a state variable $\mathbf{m}_{\tilde{h}} = \{m_{F\tilde{h}}, m_{D\tilde{h}}\}$ when $m_{D\tilde{h}} < 0$ is as below:

$$\begin{aligned}
& r_{Ht}V_{Ht}(\mathbf{m}_{\tilde{h}}) - \dot{V}_{Ht}(\mathbf{m}_{\tilde{h}}) \\
&= \max_{x_{Ht}(\mathbf{m}_{\tilde{h}}), a_{Ht}(\mathbf{m}_{\tilde{h}})} \underbrace{\Pi_{Ht}(\mathbf{m}_{\tilde{h}})}_{\text{profit}} - (1-s_{Hrt})\underbrace{\alpha_{Hr}\frac{x_{Ht}(\mathbf{m}_{\tilde{h}})^{\gamma}}{\gamma}w_{Ht}}_{\text{innovation cost}} - (1-s_{Hat})\underbrace{\alpha_{Ha}\frac{a_{Ht}(\mathbf{m}_{\tilde{h}})^{\gamma}}{\gamma}w_{Ht}}_{\text{adoption cost}} \\
&+ x_{Ht}(\mathbf{m}_{\tilde{h}})\sum_n \tilde{f}(n;\mathbf{m}_{\tilde{h}})\underbrace{[V_{Ht}(m_{F\tilde{h}}+n, m_{D\tilde{h}}+n) - V_{Ht}(\mathbf{m}_{\tilde{h}})]}_{\text{gain from innovation}} \\
&+ a_{Ht}(\mathbf{m}_{\tilde{h}})\sum_n g(n;\mathbf{m}_{\tilde{h}})[\underbrace{V_{Ht}(m_{F\tilde{h}}+n, m_{D\tilde{h}}+n) - V_{Ht}(\mathbf{m}_{\tilde{h}})}_{\text{gain from adoption}} - (1-s_{Hat})\underbrace{\mathcal{F}_{Ht}(\mathbf{m}_{\tilde{h}})}_{\text{adoption fee}}] \\
&+ x_{Ht}(\mathbf{m}_h)\sum_n \tilde{f}(n;m_{Fh})\underbrace{[V_{Ht}(m_{F\tilde{h}}, m_{D\tilde{h}}-n) - V_{Ht}(\mathbf{m}_{\tilde{h}})]}_{\text{loss from leader innovation}} \\
&+ a_{Ht}(\mathbf{m}_h)\sum_n \tilde{g}(n;m_{Fh})\underbrace{[V_{Ht}(m_{F\tilde{h}}, m_{D\tilde{h}}-n) - V_{Ht}(\mathbf{m}_{\tilde{h}})]}_{\text{loss from leader adoption}} \\
&+ (x_{Ft}(\mathbf{m}_f) + \tilde{x}_{Ft}(\mathbf{m}_f))\sum_n f(n;m_{Ff})\underbrace{[V_{Ht}(m_{F\tilde{h}}-n, m_D) - V_{Ht}(\mathbf{m}_{\tilde{h}})]}_{\text{loss from foreign firm innovation}} \\
&+ a_{Ft}(\mathbf{m}_f)\sum_n g(n;m_{Ff})\underbrace{[V_{Ht}(m_{F\tilde{h}}-n, m_D) - V_{Ht}(\mathbf{m}_{\tilde{h}})]}_{\text{loss from foreign firm adoption}} \\
&+ \phi\underbrace{(V_{Ht}(0,m_D) - V_{Ht}(\mathbf{m}_{\tilde{h}}))}_{\text{exogenous spillover}}.
\end{aligned} \tag{51}$$

Value function of foreign firm is as below:

$$
\begin{aligned}
&r_{Ft}V_{Ft}(\mathbf{m}_f) - \dot{V}_{Ft}(\mathbf{m}_f) \\
&= \max_{x_{Ft}(\mathbf{m}_f), a_{Ft}(\mathbf{m}_f)} \underbrace{\Pi_{Ft}(\mathbf{m}_f)}_{\text{profit}} - (1 - s_{Frt}) \underbrace{\alpha_{Fr} \frac{x_{Ft}(\mathbf{m}_f)^{\gamma}}{\gamma} w_{Ft}}_{\text{innovation cost}} - (1 - s_{Fat}) \underbrace{\alpha_{Fa} \frac{a_{Ft}(\mathbf{m}_f)^{\gamma}}{\gamma} w_{Ft}}_{\text{adoption cost}} \\
&+ x_{Ft}(\mathbf{m}_f) \sum_n f(n; m_{Ff}) \underbrace{[V_{Ft}(m_{Ff} + n, m_{Df}) - V_{Ft}(\mathbf{m}_f)]}_{\text{gain from innovation}} \\
&+ a_{Ft}(\mathbf{m}_f) \sum_n g(n; m_{Ff}) [\underbrace{V_{Ft}(m_{Ff} + n, m_{Df}) - V_{Ft}(\mathbf{m}_f)}_{\text{gain from adoption}} - (1 - s_{Fat}) \underbrace{\mathcal{F}_{Ft}(\mathbf{m}_f)}_{\text{adoption fee}}] \\
&+ x_{Ht}(\mathbf{m}_h) \sum_n f(n; m_{Fh}) \underbrace{[V_{Ft}(m_{Ff} - n, m_{Df} - n) - V_{Ft}(\mathbf{m}_f)]}_{\text{loss from home leader innovation}} \\
&+ a_{Ht}(\mathbf{m}_h) \sum_n g(n; m_{Fh}) [\underbrace{V_{Ft}(m_{Ff} - n, m_{Df} - n) - V_{Ht}(\mathbf{m}_f)}_{\text{loss from home leader adoption}} + \underbrace{\mathcal{F}_{Ht}(\mathbf{m}_h)}_{\text{adoption fee}}] \\
&+ x_{Ht}(\mathbf{m}_{\tilde{h}}) \sum_n \tilde{f}(n; \mathbf{m}_{\tilde{h}}) \underbrace{[V_{Ft}(\min\{m_{Ff}, m_{Ff} + m_{Df} - n\}, \max\{m_{Df} - n, n - m_{Df}\}) - V_{Ft}(\mathbf{m}_f)]}_{\text{loss from home follower innovation}} \\
&+ a_{Ht}(\mathbf{m}_{\tilde{h}}) \sum_n \tilde{g}(n; \mathbf{m}_{\tilde{h}}) \underbrace{[V_{Ft}(\min\{m_{Ff}, m_{Ff} + m_{Df} - n\}, \max\{m_{Df} - n, n - m_{Df}\}) - V_{Ft}(\mathbf{m}_f)]}_{\text{loss from home follower adoption}} + \underbrace{\mathcal{F}_{Ht}(\mathbf{m}_{\tilde{h}})}_{\text{adoption fee}}] \\
&- \underbrace{\tilde{x}_{Ft}(\mathbf{m}_{\tilde{f}}) V_{Ht}(\mathbf{m}_h)]}_{\text{replaced by entrant}} + \phi \underbrace{(V_{Ht}(0, m_D) - V_{Ht}(\mathbf{m}_h))}_{\text{exogenous spillover}}.
\end{aligned}
\tag{52}
$$

Value function of potential entrant $\tilde{f}$ in country F is defined as below:

$$
\begin{aligned}
r_{Ft}\tilde{V}_{Ft}(\mathbf{m}_f) - \dot{\tilde{V}}_{Ft}(\mathbf{m}_f) &= \max_{\tilde{x}_{Ft}(\mathbf{m}_f)} -(1 - s_{Frt}) \underbrace{\tilde{\alpha}_{Fr} \frac{(\tilde{x}_{Ft}(\mathbf{m}_f))^{\gamma}}{\gamma} w_{Ft}}_{\text{innovation cost}} \\
&+ \tilde{x}_{Ft}(\mathbf{m}_f) \sum_n g(n; m_{Ff}) V_{Ft}(m_{Ff} + n, m_{Df}).
\end{aligned}
\tag{53}
$$

C.3 Adoption Fee

The adoption fee when the home follower $\tilde{h}$ adopts from foreign firm f is

$$\begin{aligned}
&\mathcal{F}_{Ht}(\mathbf{m}_{\tilde{h}}) = \underset{\mathcal{F}_{Ht}(\mathbf{m}_{\tilde{h}})}{\operatorname{argmax}}(\sum_n \tilde{g}(n;\mathbf{m}_{\tilde{h}})V_{Ht}(m_{F\tilde{h}}+n, m_{D\tilde{h}}+n) - \mathcal{F}_{Ht}(\mathbf{m}_{\tilde{h}}) - V_{Ht}(\mathbf{m}_{\tilde{h}}))^{\xi} \\
&\cdot (\sum_{n=1}^{m_{D\tilde{h}}} \tilde{g}(n;\mathbf{m}_{\tilde{h}})V_{Ft}(-m_{F\tilde{h}}, -m_{D\tilde{h}}-n) + \sum_{n=m_D+1}^{\bar{m}-m_{F\tilde{h}}} \tilde{g}(n;\mathbf{m}_{\tilde{h}})V_{Ft}(-m_{F\tilde{h}}-(n-m_{D\tilde{h}}), n-m_{D\tilde{h}}) \\
&+ \mathcal{F}_{Ht}(\mathbf{m}_{\tilde{h}}) - V_{Ft}(\mathbf{m}_f))^{1-\xi}
\end{aligned}$$

$$\begin{aligned}
&\mathcal{F}_{Ht}(\mathbf{m}_{\tilde{h}}) = (1-\xi)(\sum_n \tilde{g}(n;\mathbf{m}_{\tilde{h}})V_{Ht}(m_{F\tilde{h}}+n, m_{D\tilde{h}}+n) - V_{Ht}(\mathbf{m}_f)) \\
&- \xi(\sum_{n=1}^{m_{D\tilde{h}}} \tilde{g}(n;\mathbf{m}_{\tilde{h}})V_{Ft}(-m_{F\tilde{h}}, -m_{D\tilde{h}}-n) + \sum_{n=m_D+1}^{\bar{m}-m_{F\tilde{h}}} \tilde{g}(n;\mathbf{m}_{\tilde{h}})V_{Ft}(-m_{F\tilde{h}}-(n-m_{D\tilde{h}}), n-m_{D\tilde{h}}) \\
&- V_{Ft}(\mathbf{m}_f)).
\end{aligned} \tag{54}$$

The adoption fee when the foreign firm f adopts technology from home leader h is

$$\begin{aligned}
&\mathcal{F}_{Ft}(\mathbf{m}_f) = \underset{\mathcal{F}_{Ft}(\mathbf{m}_f)}{\operatorname{argmax}}(\sum_n g(n;m_{Ff})V_{Ft}(m_{Ff}+n, m_{Df}) - \mathcal{F}_{Ft}(\mathbf{m}_f) - V_{Ft}(\mathbf{m}_f))^{\xi} \\
&\cdot (\sum_n g(n;m_{Ff})V_{Ht}(m_{Fh}-n, m_{Dh}) + \mathcal{F}_{Ft}(\mathbf{m}_f) - V_{Ht}(\mathbf{m}_h))^{1-\xi} \\
&\mathcal{F}_{Ft}(\mathbf{m}_f) = (1-\xi)(\sum_n g(n;m_{Ff})V_{Ft}(m_{Ff}+n, m_{Df}) - V_{Ft}(\mathbf{m}_f)) \\
&- \xi(\sum_n g(n;m_{Ff})V_{Ht}(-m_{Fh}-n, m_{Dh}) - V_{Ht}(\mathbf{m}_h)).
\end{aligned} \tag{55}$$

C.4 Optimal Policy Function

The optimal innovation rate and adoption rate of home follower $\tilde{h}$ is

$$\begin{aligned}
x_{Ht}(\mathbf{m}_{\tilde{h}}) &= \left(\frac{\sum_n \tilde{f}(n;\mathbf{m}_{\tilde{h}})[V_{Ht}(m_{F\tilde{h}}+n, m_{D\tilde{h}}+n) - V_{Ht}(\mathbf{m}_{\tilde{h}})]}{(1-s_{Hrt})\alpha_{Hr}w_{Ht}}\right)^{\frac{1}{\gamma-1}} \\
a_{Ht}(\mathbf{m}_{\tilde{h}}) &= \left(\frac{\sum_n \tilde{g}(n;\mathbf{m}_{\tilde{h}})[V_{Ht}(m_{F\tilde{h}}+n, m_{D\tilde{h}}+n) - V_{Ht}(\mathbf{m}_{\tilde{h}}) - (1-s_{Hat})\mathcal{F}_{Ht}(\mathbf{m}_{\tilde{h}})]}{(1-s_{Hat})\alpha_{Ha}w_{Ht}}\right)^{\frac{1}{\gamma-1}}.
\end{aligned} \tag{56}$$

Likewise, the optimal innovation and adoption rate of foreign incumbent is

$$\begin{aligned}
x_{Ft}(\mathbf{m}_f) &= \left(\frac{\sum_n f(n;m_{Ff})[V_{Ft}(m_{Ff}+n, m_{Df}) - V_{Ft}(\mathbf{m}_f)]}{(1-s_{Frt})\alpha_{Fr}w_{Ft}}\right)^{\frac{1}{\gamma-1}} \\
a_{Ft}(\mathbf{m}_f) &= \left(\frac{\sum_n g(n;m_{Ff})[V_{Ft}(m_{Ff}+n, m_{Df}) - V_{Ht}(\mathbf{m}_f) - (1-s_{Fat})\mathcal{F}_{Ft}(\mathbf{m}_f)]}{(1-s_{Fat})\alpha_{Fa}w_{Ft}}\right)^{\frac{1}{\gamma-1}}.
\end{aligned} \tag{57}$$

Lastly, the optimal innovation rate of foreign entrant is

$$\tilde{x}_{Ft}(\mathbf{m}_f) = \left(\frac{\sum_n f(n; m_{Ff}) V_{Ft}(m_{Ff} + n, m_{Df})}{(1 - s_{Frt}) \alpha_{Fr} w_{Ft}} \right)^{\frac{1}{\gamma - 1}} . \tag{58}$$

C.5 Other Equilibrium Conditions

Asset market clearing. The asset market clears in each period by the following equation:

$$A_{Ft} = \int_0^1 V_{fjt} + \tilde{V}_{fjt} dj \,, \tag{59}$$

where the right-hand side is the sum of the value of all foreign firms.

Labor market clearing. In each country labor market clears by the following:

$$L_{Ft} = \int_0^1 \left(l_{fjt} + \alpha_{aF} \frac{a_{fjt}^{\gamma}}{\gamma} + \sum_{i = f, \tilde{f}} \alpha_{rF} \frac{x_{ijt}^{\gamma}}{\gamma} \right) dj. \tag{60}$$

C.6 Step Size Distribution

We use the functional form of step size distribution in Akcigit et al. (2021) and Olmstead-Rumsey (2022). We assume that the step size distribution of adoption and innovation depends on the gap with the foreign firm. Specifically, the expected step size decreases with m_F.

We first define the baseline function $f(n) = f(n; -\bar{m})$ which is the probability of improving n steps for the firms that are furthest from the foreign firm, namely $m_F = -\bar{m}$, as

$$f(n) = c_0 n^{-\eta}, \qquad n \in \{1, \cdots, \bar{n}\} \,, \tag{61}$$

where c_0 is decided such that $\sum_{n=1}^{\bar{n}} f(n) = 1$. As m_F increases, the probability of improving multiple steps decreases while the probability of improving one step increases.

To be specific, we define $f(n; m_F)$, the probability of improving n step when the current gap with the foreign firm is m_F, as the following:

$$f(n; m_F) = \begin{cases} f(1 + (m_F + \bar{m})) + \sum_{s=1}^{m_F + \bar{m}} f(s) & \text{for} \quad n = 1 \\ f(n + (m_F + \bar{m})) & \text{for} \quad n \in \{2, \cdots, \bar{n}\}, \end{cases} \tag{62}$$

where $(m_F + \bar{m})$ is the distance from the furthest position $-\bar{m}$, which makes the probability of improving the same number of steps lower as the firm gets closer to foreign firms. On the other hand, the probability of improving one step has additional term $\sum_{s=1}^{m_F + \bar{m}} f(s)$, which makes the probability of improving just one step higher as the firm gets closer to foreign firms. Figure C.1 shows an example of probability mass function when $m_F = -\bar{m}$ and $m_F = -\bar{m} + 1$.

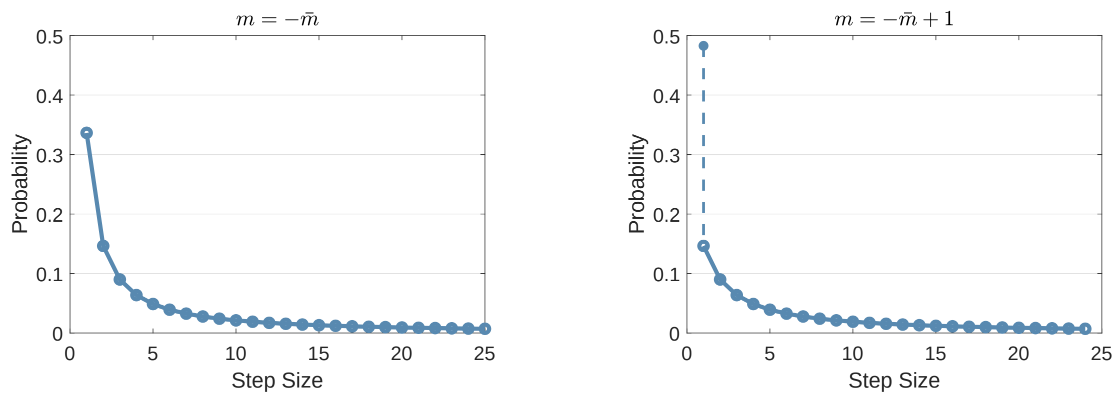


Figure C.1: Probability Mass Function of Step Size

Notes: This figure plots the probability mass function of step size. The left panel is when $m_F = -\bar{m}$, which is equal to $f(n) = c_0 n^{-\eta}$. The right panel is when $m_F = -\bar{m} + 1$. The probability of improving one step is $f(1) + f(2)$. The probability of improving $n > 1$ step is $f(n+1)$. We set $\eta = 1.2$

The expected step size decreases with m_F, and the slope decreases with η as we can see in Figure 5. Due to the additive feature of the distribution, we only need to pin down one parameter, η, which governs the degree of advantage of backwardness.[53] We use the same functional form for both $g(n; m_F)$ (adoption) and $f(n; m_F)$ (innovation), but use different slope parameter, η_a for adoption and η_r for innovation, which will be estimated using data.

D Details on Numerical Solution

This section provides details on the numerical solution of the model. $\bar{m}_F$ is the maximum technology gap from the foreign firm and is set to be 25 for a computational reason. We increase $\bar{m}_F$ until the point in which it does not affect key results. $\bar{m}_D$ is set to be 5.

D.1 Balanced Growth Path

On the balanced growth path, wage and consumption in each country grow at the same rate g, while the distribution of productivity gap $\mu_t(\mathbf{m})$, innovation rate $x_{ct}(\mathbf{m}_i)$, adoption rate $a_{ct}(\mathbf{m}_i)$, and the relative price ${P_{Ft}}$[54] stay the same. Therefore, it is useful to divide equation (25) with $P_{Ht}C_{Ht}$ and define $v_{Ht} = \frac{V_{Ht}}{P_{Ht}}$ as normalized value function, $\omega_{Ht} = \frac{w_{Ht}}{C_{Ht}}$, as normalized wage, and $\tilde{p}_{H\mathbf{m}t} = \frac{p_{H\mathbf{m}t}}{C_{Ht}}$. Also, define consumption share in each country as $\psi_{Ht} = \frac{C_{Ht}}{C_{Ht}+P_{Ft}C_{Ft}}$ and represent

[53] When $\eta \to \infty$, the model becomes a step-by-step model with only one step improvement and has no advantage of backwardness.

[54] Note that we normalize price index of home country $P_{Ht} = 1$.

profit function as below.

$$\begin{aligned}\Pi_{Ht}(\mathbf{m}_i) &= \tilde{\pi}_{Ht}(\mathbf{m}_i)\cdot C_{Ht} + \tilde{\pi}^*_{Ht}(\mathbf{m}_i)\cdot P_{Ft}C_{Ft}\\ \frac{\Pi_{Ht}(\mathbf{m}_i)}{C_{Ht}} &= \tilde{\pi}_{Ht}(\mathbf{m}_i) + \tilde{\pi}^*_{Ht}(\mathbf{m}_i)\cdot\frac{1-\psi_{Ht}}{\psi_{Ht}}\,,\end{aligned} \tag{63}$$

where $\pi_{Ht}(\mathbf{m}_i)$, and $\pi^*_{Ht}(\mathbf{m}_i)$ are the profit divided by total consumption in each market. Then, we can normalize value function of firm h as below.

$$\begin{aligned}
&(r_{Ht}-g_t)v_{Ht}(\mathbf{m})\\
&= \max_{x_{Ht}(\mathbf{m}_h),a_{Ht}(\mathbf{m}_h)} \pi_{Ht}(\mathbf{m}_h) + \pi^*_{Ht}(\mathbf{m}_h)\cdot\frac{1-\psi_{Ht}}{\psi_{Ht}}\\
&-(1-s_{Hrt})\alpha_{Hr}\frac{(x_{Ht}(\mathbf{m}_h))^\gamma}{\gamma}\omega_{Ht} - (1-s_{Hat})\alpha_{Ha}\frac{(a_{Ht}(\mathbf{m}_h))^\gamma}{\gamma}\omega_{Ht}\\
&+ x_{Ht}(\mathbf{m}_h)\sum_n f(n;m_{Fh})[V_{Ht}(m_{Fh}+n, m_{Dh}+n) - V_{Ht}(\mathbf{m}_h)]\\
&+ a_{Ht}(\mathbf{m}_h)\sum_n g(n;m_F)[(V_{Ht}(m_{Fh}+n, m_{Dh}+n) - V_{Ht}(\mathbf{m}_h) - (1-s_{Hat})\mathcal{F}_{Ht}(\mathbf{m}_h))]\\
&+ x_{Ht}(\mathbf{m}_{\tilde{h}})\sum_n \tilde{f}(n;\mathbf{m}_{\tilde{h}})[V_{Ht}(m_{Fh}, m_{Dh}-n) - V_{Ht}(\mathbf{m}_h)]\\
&+ a_{Ht}(\mathbf{m}_{\tilde{h}})\sum_n \tilde{g}(n;\mathbf{m}_{\tilde{h}})[V_{Ht}(m_{Fh}, m_{Dh}-n) - V_{Ht}(\mathbf{m}_h)]\\
&+ (x_{Ft}(\mathbf{m}_f) + \tilde{x}_{Ft}(\mathbf{m}_f))\sum_n f(n;m_{Ff})[V_{Ht}(m_{Fh}-n, m_{Dh}) - V_{Ht}(\mathbf{m}_h)]\\
&+ a_{Ft}(\mathbf{m}_f)\sum_n g(n;m_{Ff})[V_{Ht}(m_{Fh}-n, m_{Dh}) - V_{Ht}(\mathbf{m}_h) + \mathcal{F}_{Ft}(\mathbf{m}_h)\frac{1-\psi_{Ht}}{\psi_{Ht}}]\\
&+ \phi(V_{Ht}(0, m_{Dh}) - V_{Ht}(\mathbf{m}_h)).
\end{aligned} \tag{64}$$

Note that from the household Euler equation (8), we know $r_{Ht} - g_t = \rho$ in any t. We solve the balanced growth path in two layers. First, we make a guess of $\{\omega_H, \omega_F, \psi_H\}$. Then, we make a guess of value function for each $\mathbf{m}$, and iterate until it converges using the equation (64). After the normalized value functions converges, we check the labor market clearing condition from equation (34) for each country, and check the trade balance condition from equation (36). We update these three variables until labor market clears in each country and trade is balanced.

D.2 Transition Dynamics

We solve the transition of the model following the below steps.

1. We discretize the continuous time model where each period is divided as $\Delta t = 2^{-5}$.

2. Solve balanced growth path. Assume that the economy converges to the balanced growth

path until period T

3. We make the first guess of $\mathbb{X}_t^0 = \{\omega_{Ht}, \omega_{Ft}, \psi_{Ht}\}_{t=0}^{t=T}$

4. Given the guess, we solve value function, innovation, and adoption rate backward from the period T to period 0.

5. Given the innovation and adoption decisions, we solve the distribution of productivity gap $\{\mu_t(\mathbf{m})\}_{t=0}^{t=T}$ forward from period 0 to period T. $\mu_{H\mathbf{m}0}$ is given as the initial condition. We also solve implied $\tilde{\mathbb{X}}_t^1 = \{\omega_{Ht}, \omega_{Ft}, \psi_{Ht}\}_{t=0}^{t=T}$ using $\{\mu_t(\mathbf{m})\}_{t=0}^{t=T}$.

6. Get the distance $\|\mathbb{X}_t^0 - \mathbb{X}_t^1\|$ between the guess and implied value. We use Euclidean norm.

7. Update the guess as below until $\|\mathbb{X}_t^0 - \mathbb{X}_t^1\| < \epsilon$

$$\mathbb{X}_t^{i+1} = (1-\Delta)\mathbb{X}_t^i + \Delta\tilde{\mathbb{X}}_t^{i+1}, \tag{65}$$

   where $0 < \Delta < 1$ is dampening parameter

8. Once we find the equilibrium $\mathbb{X}$, we simulate 1,000,000 firms using the distribution $\mu_{H\mathbf{m}t}$, and calculate C_{Ht}.

E Quantitative Exercise

E.1 Additional Figures in Quantitative Exercise

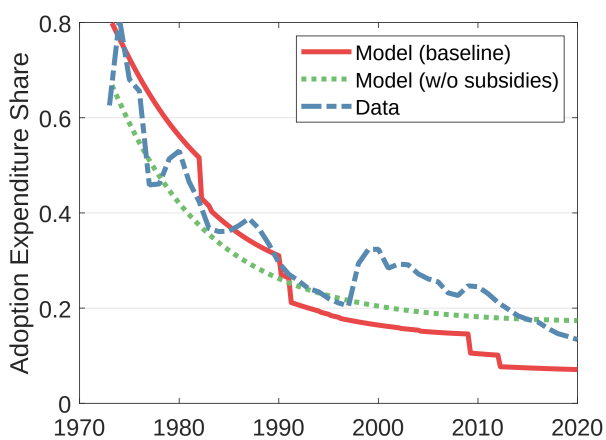
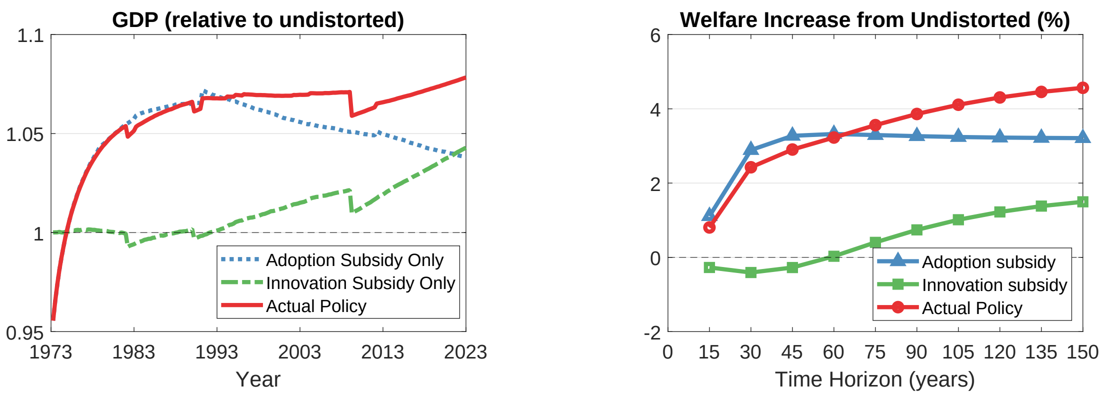


Figure E.1: Adoption Expenditure Share in the Model and the Data

Notes: This figure plots the adoption fee expenditure / (adoption fee + innovation cost) in the model and the data. The solid red line is the baseline with actual subsidies, the dotted green line is counterfactual with no subsidies, and the dashed blue line is data.

Figure E.1 shows the adoption expenditure share with subsidies and without subsidies and compare them with data. The adoption expenditure share decreases even without the subsidies. Compared with the baseline case, the adoption expenditure share is lower in the 1970s, and higher in 2020.



A. Relative GDP

B. Welfare increase (%)

Figure E.2: Results of the Counterfactual Analysis

Notes: This figure evaluates the actual policy by comparing it with counterfactuals. Panel A plots GDP in three scenarios divided by GDP in the undistorted case. The dotted blue line when we shut down the innovation subsidy, the dashed green line when we shut down the adoption subsidy, and the solid red line follows the actual policy in Figure 6. Panel B plots the welfare increase compared to the undistorted case over different time horizons. For instance, time horizon 15 means that we calculate the discounted sum of utility from year 0 to 15. The welfare increase is calculated in consumption-equivalent units using equation (38).

To decompose the contribution of adoption and innovation subsidy, we compare the baseline with counterfactuals where we shut down either adoption or innovation subsidies or both of them. Figure E.2 presents the results.

E.2 Robustness Checks

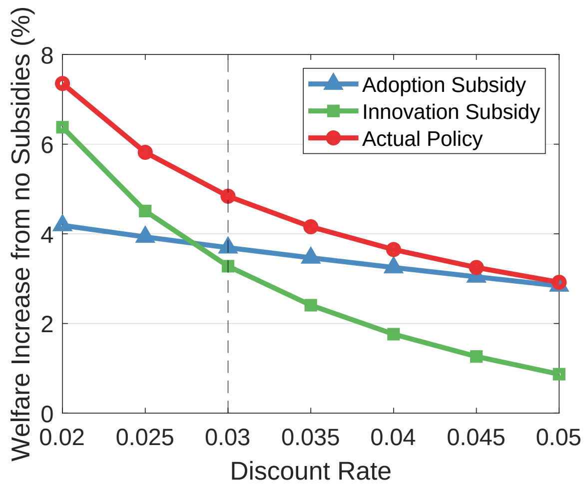


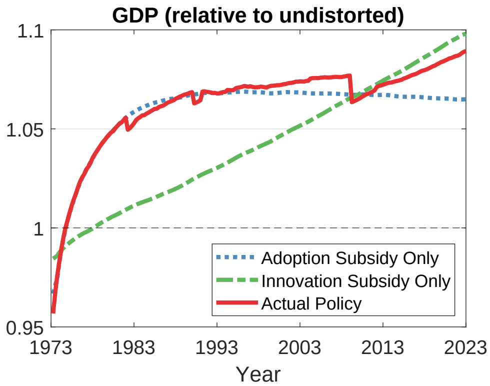
Figure E.3: Welfare Increase from Undistorted Case over Discount Rate

Notes: This figure plots the welfare increase compared to the undistorted case in infinite time horizon over different discount rate ρ. The baseline value is $\rho = 0.03$. Welfare increase is calculated in consumption-equivalent unit using the equation (38). The blue triangle is when subsidizing only adoption at 31%, the green square is when subsidizing only innovation at 32%, and the red circle is when imposing the actual policy in Figure 6.

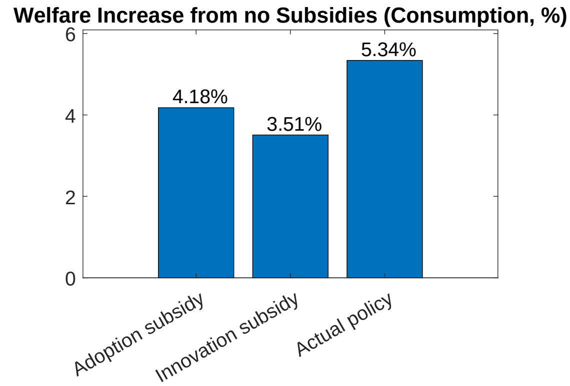
Discount rate Figure E.3 plots the consumption-equivalent welfare increase compared to the undistorted case over different values of discount rate ρ.

Iceberg trade cost As robustness checks, we present the main result with different value of D, iceberg trade cost. Figure E.4 plots the main results with $D = 0.25, 0.75, D = 1$ instead of the baseline value $D = 1$. The results are qualitatively similar to the main results.

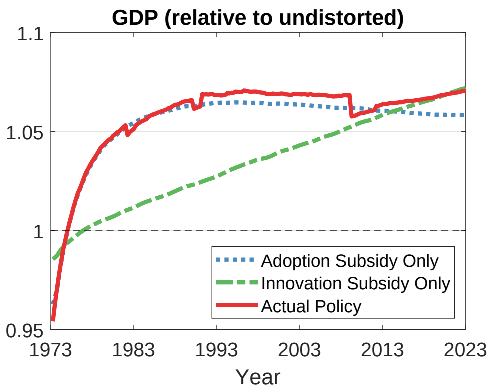
Elasticity of subtitution We also change the elasticity of substitution σ as robustness checks. Figure E.5 plots the main results with $\sigma = 4, \sigma = 12$ instead of the baseline value $\sigma = 7$. The results are qualitatively similar to the main results.



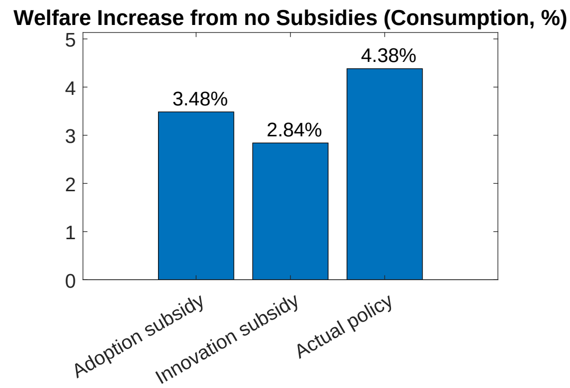
A. Relative GDP ($D = 1.25$)



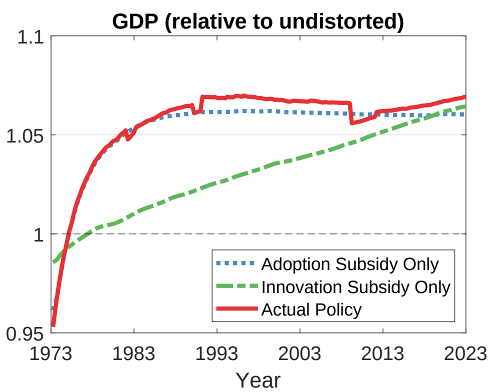
B. Welfare increase (%, $D = 1.25$)



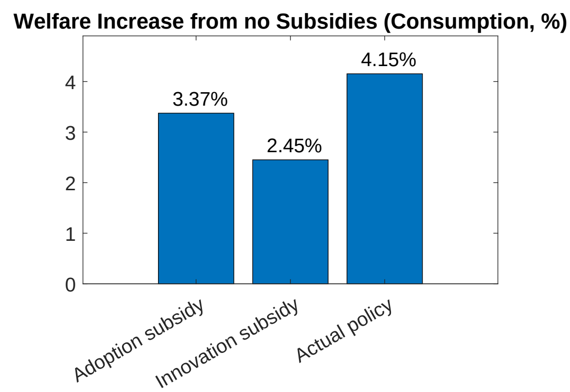
C. Relative GDP ($D = 1.75$)



D. Welfare increase (%, $D = 1.75$)



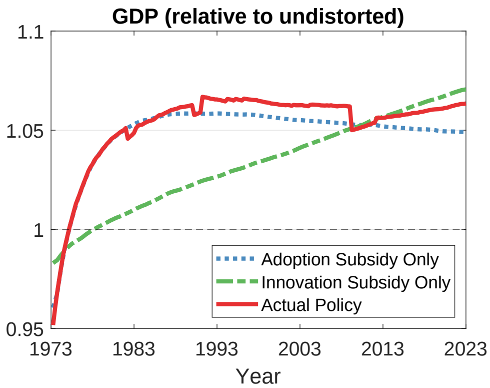
E. Relative GDP ($D = 2.0$)



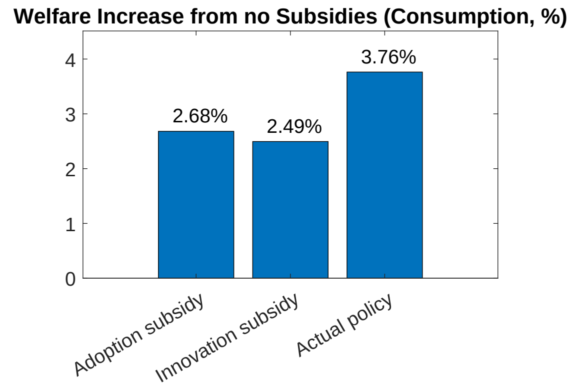
F. Welfare increase (%, $D = 2.0$)

Figure E.4: Results of the Counterfactual Analysis with Iceberg Trade Cost

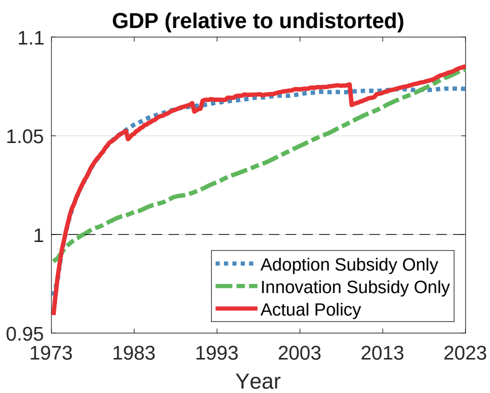
Notes: This figure evaluates the actual policy by comparing it with counterfactuals. Panel A,B plot the case with $D = 1.25$, C,D plot the case with $D = 1.75$ and E,F plot the case when $D = 2.0$. Panel A,C,E plot GDP in three scenarios divided by GDP in the undistorted case. The dotted blue line subsidizes only adoption at 31%, the dashed green line subsidizes only innovation at 32%, and the solid red line follows the actual policy in Figure 6. Panel B,D,F plot the welfare increase compared to the undistorted case over different time horizons. For instance, time horizon 15 means that we calculate the discounted sum of utility from year 0 to 15. The welfare increase is calculated in consumption-equivalent units using equation (38).



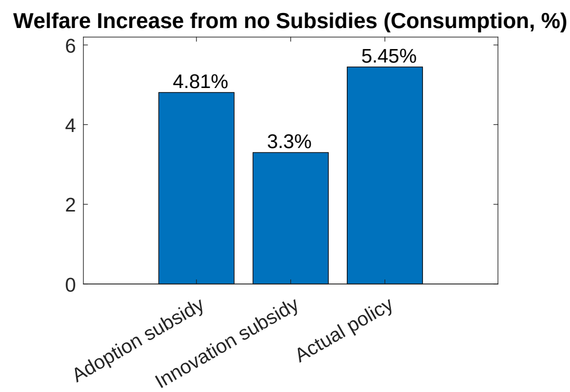
A. Relative GDP ($\sigma = 4$)



B. Welfare increase (%, $\sigma = 4$)



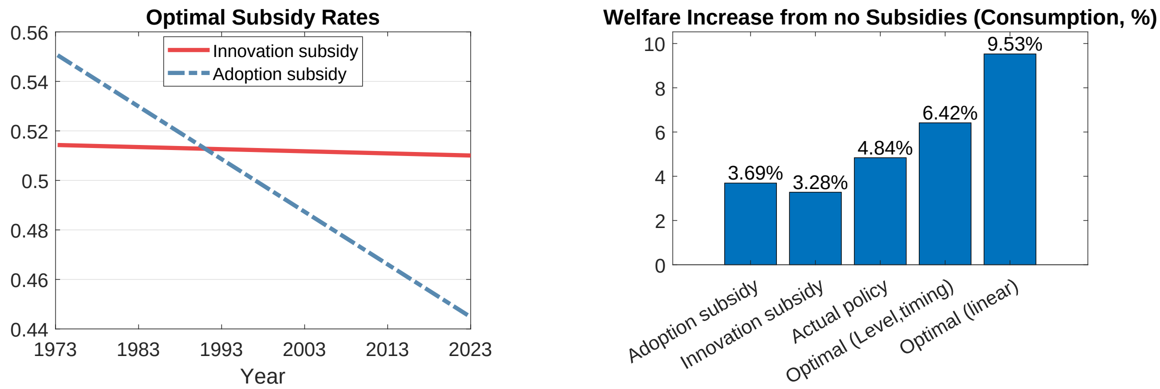
C. Relative GDP ($\sigma = 12$)



D. Welfare increase (%, $\sigma = 12$)

Figure E.5: Results of the Counterfactual Analysis with Iceberg Trade Cost

Notes: This figure evaluates the actual policy by comparing it with counterfactuals. Panel A,B plot the case with $\sigma = 4$ and C,D plot the case with $\sigma = 12$. Panel A,C plot GDP in three scenarios divided by GDP in the undistorted case. The dotted blue line subsidizes only adoption at 31%, the dashed green line subsidizes only innovation at 32%, and the solid red line follows the actual policy in Figure 6. Panel B,D plot the welfare increase compared to the undistorted case over different time horizons. For instance, time horizon 15 means that we calculate the discounted sum of utility from year 0 to 15. The welfare increase is calculated in consumption-equivalent units using equation (38).



A. Optimal Subsidy

B. Welfare increase (%)

Figure F.1: Optimal Linear Subsidy and Welfare Increase

Notes: This figure plots the optimal linear subsidy and welfare results. Panel A plots the optimal adoption and innovation subsidy rate. We allow the government can choose subsidy rate as a linear function of year. Panel B plots the welfare increase from the undistorted case with no subsidies in consumption-equivalent units.

F Additional Policy Exercise

F.1 Optimal Subsidy as a Linear Function in Time

In this section, we study the optimal subsidy in a more general setting. We set the subsidy rate as a linear function of the year and obtain the optimal subsidy rates. We first calculate the optimal adoption and innovation subsidy rates to increase welfare in the infinite horizon along the balanced growth rate. The optimal adoption subsidy rate is 0.06, and the optimal innovation subsidy rate is 0.504. Since the average productivity is zero along the balanced growth path, the productivity gain from adoption is small, and the optimal subsidy rate is also small. On the other hand, the optimal subsidy rate for innovation is much higher than adoption.

This result implies that the terminal subsidy rate for adoption is 0.06, and the terminal subsidy rate for innovation is 0.504. We then allow the government to choose the initial subsidy rate for adoption and innovation, and to set the years to take to reach the terminal rates. Let the initial subsidy rate for adoption and innovation be α_a, α_r, and the years to take to reach the terminal rates be t_a, t_r. Then, the adoption and innovation subsidy rate as a function of year t is as below:

$$
\begin{aligned}
s_{at} &= \begin{cases} \alpha_a + \left(\frac{0.06-\alpha_a}{t_a}\right) \cdot t & \text{if} \quad t \leq t_a \\ 0.06 \quad \text{if} \quad t > t_a \end{cases} \\
s_{rt} &= \begin{cases} \alpha_r + \left(\frac{0.504-\alpha_r}{t_r}\right) \cdot t & \text{if} \quad t \leq t_r \\ 0.504 \quad \text{if} \quad t > t_r \end{cases}
\end{aligned}
\tag{66}
$$

Figure F.1 shows the optimal subsidy and the welfare increase. The adoption subsidy rate

(55%) is higher than the innovation subsidy (51%) in 1973. Since the productivity gain and spillover from adoption are larger than innovation, the optimal subsidy rate is also larger for adoption. Both the adoption and innovation subsidy decrease over time. This is because the step size from adoption and innovation decreases over time, reducing the intertemporal spillover. Since the productivity gain from adoption decreases more than innovation, the adoption subsidy rate decreases more than the innovation subsidy rate.

The optimal linear subsidy increases consumption-equivalent welfare by 9.53%, which is higher than the actual policy (4.84%), and the previous case where the government chooses the rate and timing to switch (6.42%). This is because, in the previous exercise, we limit the government to subsidize only adoption or only innovation each year. Also, the smooth policy change generates a smoother consumption path, while the previous case with only one change creates a discrete jump in consumption.

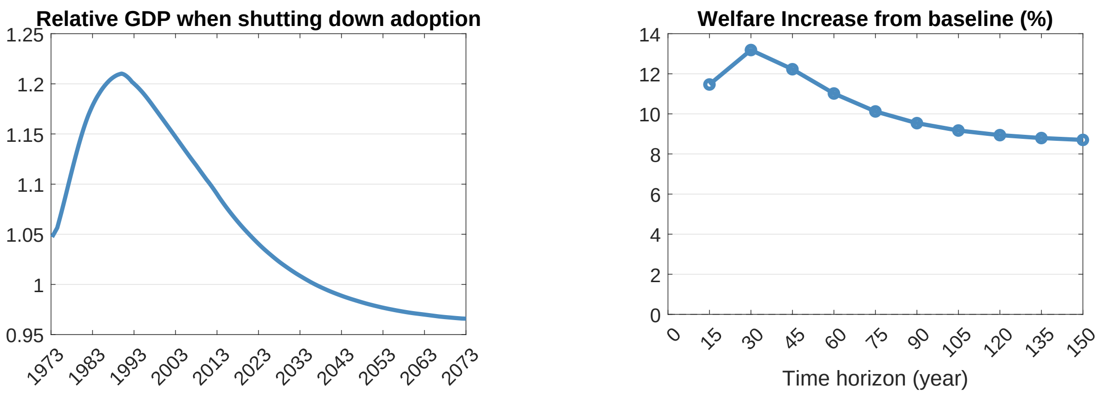
F.2 Japan's Policy to Prevent Exporting Technology

This subsection asks what happens when the Japanese government prevents firms from exporting technology. Japanese incumbents always earn benefits from selling technology; if not, they will not sell technology. However, firms might sell more technology than the socially optimal level of Japan because they do not internalize the future loss for the potential entrant. The potential entrant will get a smaller profit when the previous incumbent sells technology, and the Korean firm has relatively higher productivity. Therefore, there can be an incentive for the Japanese government to prevent exporting technology.[55]

As an example, we study the counterfactual where Japanese firms cannot export technology to Korean firms and compare the GDP of Japan with the baseline case with adoption. Case without adoption keeps the same innovation rate.

The left panel of Figure F.2 shows that in the short-run, Japan has higher GDP when shutting down the adoption channel compared with the baseline case with adoption. But in the long run, it has lower GDP because the long-run growth rate is lower without adoption. The right panel of Figure F.2 shows that Japan has higher welfare if it closes technology export. In the infinite time horizon, it has 8.54% higher welfare when it shuts down exporting technology compared with the baseline case.

[55] This is in line with the current policies of the U.S. in which they try to prevent technology leakage to China.



A. Relative GDP

B. Welfare increase (%)

Figure F.2: Results of the Counterfactual when Japan Shuts Down Adoption

Notes: This figure plots the counterfactual results when the Japanese government prevents firms from exporting technology and compares it with the baseline case with adoption. Panel A plots the GDP of Japan when the government shuts down exporting adoption and divides it by the GDP of Japan in the baseline case. Case without adoption keeps the same innovation subsidy rate in Korea. Panel B plots welfare increase compared with the case without a policy in different time horizons. Welfare is in consumption-equivalent unit.