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

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Abstract

Should governments in developing countries prioritize supporting technology adoption or promoting innovation? We use a newly digitized dataset on technology imports and patents in South Korea to answer this question. Empirically, we find that when the productivity gap between domestic and foreign firms is smaller, (i) the adoption fee is higher, (ii) the productivity gain from adoption is smaller compared with innovation, and (iii) firms are more likely to innovate than adopt technologies. Motivated by these findings, we build a two-country growth model with endogenous adoption and innovation decisions. Foreign firms sell technology for an endogenous fee, internalizing the future loss of profit due to stronger competition with domestic firms. The endogenous fee makes firms invest less in adoption, motivating governments to subsidize adoption at the early stage of development. As domestic firms catch up with foreign firms, productivity gain from adoption diminishes, making adoption subsidy less effective. After estimating the model on the transition with microdata, we evaluate Korea's technology policy since 1973, which started with an adoption subsidy and shifted its weight to an innovation subsidy. Our result suggests that the stage-dependent policy increased consumption-equivalent welfare by 4.84%, which is higher than subsidizing only innovation or adoption.

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1 Introduction

The Samsung Group, which was founded in South Korea in 1938 as a small company that produced noodles, entered the electronics industry in 1969. However, it did not have the technology necessary to produce electronic products. To tackle this problem, Samsung aggressively adopted technologies by making technology transfer contracts with Japanese companies.[1] Using the adopted technology, it started to produce electronic products and expand market share. As Samsung developed into a strong competitor, Japanese firms became more reluctant to share their technology and charged higher adoption fees. At that point, Samsung switched its strategy from adopting foreign technology to innovating its own technology. This transition from adoption to innovation can also be found in systematic data. Figure 1 shows that South Korea (Korea, hereafter) gradually decreased its expenditure share of adoption and increased R&D as it caught up with Japan.

This observation leads to the following questions. What are the contributions of technology adoption and innovation to growth over different stages of development? If these change over development stages, government policy also needs to change over stages. Even if R&D subsidy works well in developed countries, it might not work for developing countries in which most growth comes from technology adoption. For instance, Korea launched

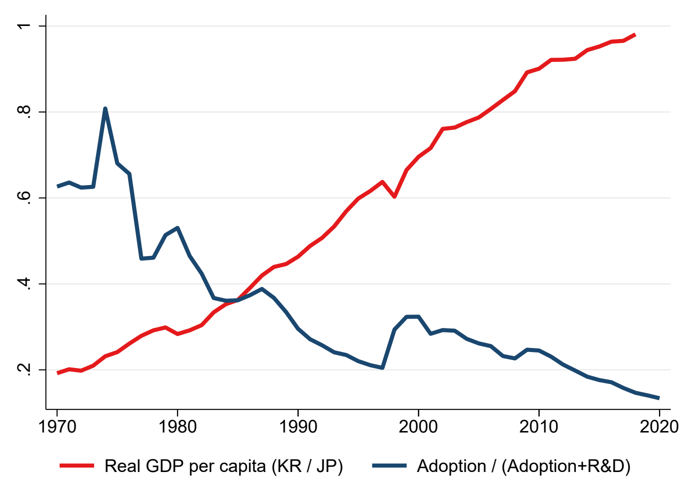


Figure 1: Relative GDP per capita and Expenditure Share of Adoption over time

Notes: This figure plots the ratio of real GDP per capita between Korea and Japan and the adoption expenditure share. 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. Figure C.1 shows the same graph with adoption only from Japan.

[1]Samsung adopted technology mostly from Japanese companies such as Sanyo, Sony, and NEC.

its technology policy by subsidizing adoption in 1973 and gradually switched to subsidizing innovation.[2] What would have happened if the Korean government had skipped the adoption subsidy and enacted the innovation subsidy, as in developed countries? Exploring this question will shed light on the optimal policy in developing countries.

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

In the theoretical part, we build a two-country growth model in which firms can increase productivity by adopting foreign technology or innovating. To capture the strategic interactions between firms, we build on step-by-step innovation model (Akcigit and Ates, 2019) and extend it to add another firm in the foreign country.[3] A novel aspect is that we study the incentives of both domestic firms that adopt technology and foreign firms that sell technology. Foreign firms lose future profit when they sell technology to other firms, which they internalize through charging an endogenous adoption fee. 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 gap between domestic and foreign firms, which is matched with the adoption price data.

In the model, adoption differs from innovation in several ways. First, adoption cannot cause productivity to be higher than the foreign firm from which firms are adopting technology.[4] 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 governed by two key parameters, which are estimated from the data. Our estimation result suggests that adoption brings

[2]To be specific, it started to subsidize adoption at 30% in 1973, decreased to 15% in 1993, and 0% in 2010. It started to subsidize R&D at 15% in 1982, increased to 23% in 1991, and to 32% in 2009. Figure 8 shows the full picture. Adoption subsidy exempted corporate tax for the expenditure to import technology from foreign firms. Innovation subsidy exempted corporate tax for the R&D expenditure.

[3]While Akcigit and Ates (2019) have two domestic firms in each sector and study the competition between domestic firms, 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 domestic competition and foreign competition.

[4]Therefore, domestic firms do not adopt technology when they have higher productivity than foreign firms.

a larger productivity gain when domestic firms are far from foreign firms, and innovation brings larger gains when they are closer to foreign firms.[5]

Furthermore, adoption and innovation generate knowledge diffusion within domestic firms. With a positive probability, a home follower can learn the home leader's technology and improve on it when innovating.[6] This intertemporal spillover can make the social return larger than the private return, which motivates the government to subsidize adoption and innovation. Foreign firms internalize the knowledge diffusion and increase the adoption fee, which makes the discrepancy between the social and private return of adoption larger. The size of the intertemporal spillover depends on the probability of knowledge diffusion, which will be estimated through patent citation data, and the size of the productivity gain. Since the productivity gain from adoption or innovation depends on the current productivity gap with the foreign firm, the spillover from adoption and innovation and the optimal subsidy rate would also depend on the gap.

In the empirical part, we overcome the challenge of finding systematic data on firm-level technology adoption by digitizing data on contract-level technology imports in Korea from 1962 to 1993. These data capture all technology adoption contracts between Korean and foreign firms, with detailed information such as adoption fees.[7] Furthermore, we exploit the firm-to-firm structure of the data by merging it with firm-level balance sheets and patent data for both Korean and foreign firms.[8] The firm-to-firm structure allows us to observe strategic interactions between firms, which is a crucial feature of the model.

We document four new empirical findings that discipline the main blocks of the model. We measure the productivity gap between domestic firms and foreign firms. First, firms are more likely to innovate than adopt when the productivity gap is smaller. Second, the adoption fee is higher when the productivity gap is smaller. This shows that foreign firms endogenize the adopter's relative position to determine the adoption fee. Third, when the productivity gap is larger, the productivity gain from adoption is relatively larger than that from innovation. This result identifies the stage-dependent productivity gain and intertemporal spillover from adoption and innovation in the model. Lastly, when Korean firms adopt a foreign technology, non-adopting firms are more likely to cite patents of the foreign firm that sold the technology.

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

[6]Without knowledge diffusion, it must start from its own productivity level. If we assume the probability is one, our model nests the common assumption in the literature whereby the potential follower can always build on the incumbent's technology.

[7]Most of the adoption contracts involve know-how transfer in which Korean firms receive blueprints, detailed information of technologies. In many cases, Korean engineers could visit foreign firms and learn the know-how by interacting with foreign engineers.

[8]Firm-level balance sheet data contains basic information such as sales, employment, total assets, fixed assets, and industry at firm-year level.

This implies that the adopted technology is diffused to other non-adopting firms and identifies the probability of the knowledge diffusion in the model.

In the quantitative section, we solve the transition of the model from the initial state—in which Korean firms have lower productivity than foreign firms—to the balanced growth path in which two countries have symmetric productivity.[9] We simulate moments from the model along the transition and estimate parameters to match moments between the model and data. The estimated model replicates the catching-up period of Korea and match untargeted moments such as decreasing adoption expenditure share over time, and increasing adoption fee over the relative productivity.

Using the estimated model, we first decompose growth between adoption and innovation. We find that adoption accounted for 76% of TFP growth in 1973, then decreased to 15% in 2022. This is because our estimates suggest that the productivity gain from adoption decreases faster than the gain from innovation as the country catches up, 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 by giving a tax credit. Then, it gradually decreased the adoption subsidy rate. It launched the R&D subsidy in 1982 and steadily increased the subsidy rate over time. We compare this policy with three counterfactuals. First, we fix the adoption subsidy rate at the initial rate (31%). Second, we fix the innovation subsidy rate at the final rate (32%). Third, we shut down both subsidies. The actual policy generates welfare 4.84% higher than the case without subsidies in a consumption unit. The welfare increase from this policy is higher than subsidizing only adoption (3.69%) or only innovation (3.28%). This result suggests that stage-dependent policy can generate higher welfare than the time-invariant policies.

Motivated by these results, we study the optimal subsidies. First, we study the optimal timing of switching from an adoption subsidy to an innovation subsidy while keeping the subsidy rate at 32%.[10] 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 decreased the adoption subsidy rate and increased the innovation subsidy rate. Furthermore, we allow the government to choose the optimal rate of adoption and innovation subsidy and the timing of the switch. The optimal policy is to start an adoption subsidy at 52% and switch to an innovation subsidy at 53% in 1985, when Korea's GDP was 60% of Japan's. This subsidy increases welfare by 6.46% in consumption equivalent units, which is

[9]The initial state is not in the steady state but along the transition of the model.

[10]To be specific, the government started adoption subsidy at 32%, and can choose one year to shut down adoption subsidy and start innovation subsidy at 32%. We take the maximum subsidy rate of both adoption and innovation.

higher than the actual policy.

1.1 Related Literature

First, this paper is related to the endogenous growth literature. While many papers develop adoption-led growth models (e.g., Parente and Prescott, 1994; Comin and Hobijn, 2010; Perla and Tonetti, 2014), or models with both adoption and innovation (Grossman and Helpman, 1991a; Barro and Sala-i Martin, 1997; Santacreu, 2015; Benhabib et al., 2021; König et al., 2020), most papers do not have systematic and direct measure on adoption, which makes it hard to conduct quantitative analysis. This paper is one of the first papers in the literature to use comprehensive adoption and innovation data and provide new empirical facts and policy counterfactuals. Acemoglu et al. (2006) also study the optimal innovation and adoption policy depending on the distance to the frontier. While they abstract away from the foreign firm's incentive to sell technology, we model adoption that requires mutual agreement between two firms and endogenize adoption price while incorporating both firms' incentive.[11] We capture the strategic interactions between firms by building on step-by-step innovation literature (Aghion et al., 2001; Acemoglu and Akcigit, 2012; Akcigit et al., 2021, 2020; Akcigit and Ates, 2019; Olmstead-Rumsey, 2022; Liu et al., 2022; Sui, 2022).[12] 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 the 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 is 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 use a direct measure from technology imports data. Santacreu (2022) is an exception; she uses country-level license

[11] Our notion of adoption differs from imitation in Acemoglu et al. (2006), Perla and Tonetti (2014), and König et al. (2020) since the firm must get approval from the foreign firm to adopt the technology in our model.

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

payment data to study the effect of trade and intellectual property policies. Our work differs by using firm-to-firm-level adoption data instead of country-level data.

Third, this paper contributes to the literature that studies technology policies. For empirical papers, 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 subsidy on innovation and its spillover. De Souza (2021) study the effects of technology substitution policy on the labor market in Brazil, where the government decreased adoption subsidies but increased R&D subsidies. For quantitative papers, 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.[13] While most papers focus on innovation policy in developed countries, we study adoption and innovation policy in developing countries over different stages of development. Furthermore, we study the optimal stage-dependent policy over a long time horizon.

Lastly, this paper is related to the literature that studies the rapid growth of Korea. 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. 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. While Choi and Shim (2022) study the earlier period when Korean firms were far from the frontier, this paper focuses on the period in which the country transitioned from adoption to innovation and the strategic interactions between Korean and foreign firms became important.[14] Furthermore, this paper contributes to the literature by studying the growth of Korea and its policy over a long horizon in which it developed from a low-income and non-innovative country to a high-income and innovative country.

The remainder of the paper is organized as follows. Section 2 describes a two-country growth model with innovation and adoption. Section 3 introduces technology imports, firm-level balance sheet, and patent data. Section 4 shows reduced-form evidence from the data and discusses how we use it to identify model parameters. Section 5 explains the estimation procedure and validates the model. Section 6 presents policy counterfactuals, and section 7 concludes.

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

[14] 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. On the other hand, this paper abstracts away from sectoral differences and spatial aspects.

2 Model

2.1 Environment

General setup Time is continuous. There are two countries $c \in \{H, F\}$. We have a continuum of a variety of goods $j \in [0, 1]$ which are consumed by the household. Also, the goods are tradable across countries with an iceberg cost of $D \geq 1$. Firms need to ship D units of goods to export one unit to another country. In country H, there are two firms, $H1, H2$ in each product line j. We call a firm a leader if it has higher productivity than another firm and call the other firm a follower. Both can innovate and adopt to increase productivity. In country F, we assume that there is a representative firm F in each product line j. It can also innovate and adopt technology from firm in H. Instead of the follower, there is a potential entrant which can enter and replace the incumbent by innovating in country F.[15]

Household A representative household consumes various goods, supplies labor, pays lump-sum tax, and owns domestic firms in each country. Household in period t has the following utility function:

$$U_{ct} = \int_t^{\infty} \exp(-\rho(s-t)) \ln C_{cs} ds \tag{1}$$

where C_{cs} is the final consumption at s, and $\rho > 0$ is the discount factor. Household maximizes utility subject to the following budget constraint:

$$r_{ct} A_{ct} + L_c w_{ct} = P_{ct} C_{ct} + T_{ct} + \dot{A}_{ct} \tag{2}$$

where r_{ct} is interest rate, L_c is 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 asset. The asset market is cleared in each period by the following equation:[16]

$$A_{ct} = \int_0^1 \sum_{i=1,2} V_{cijt} dj \tag{3}$$

The right-hand side is the sum of the value of all domestic firms.[17]

Final consumption C_{ct} is the aggregated variety of goods as below:

[15] In this way, we can reduce the number of state variables since we do not need to keep track of the gap between two foreign firms.

[16] We do not allow international capital flows.

[17] In the case of country F, V_{F1jt} is the value of the incumbent, and V_{F2jt} is that of the potential entrant.

$$C_{Ht} = \exp(\int_0^1 \ln((\psi_H^{\frac{1}{\sigma}} y_{H1jt}^{\frac{\sigma-1}{\sigma}} + \psi_H^{\frac{1}{\sigma}} y_{H2jt}^{\frac{\sigma-1}{\sigma}} + \psi_F^{\frac{1}{\sigma}} y_{Fjt}^{*\frac{\sigma-1}{\sigma}})^{\frac{\sigma}{\sigma-1}})dj) \tag{4}$$

y_{H1jt}, y_{H2jt} are the output in product line j, consumed by the home household and produced by $H1$ and $H2$. y^*_{Fjt} is the output produced by 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 country H and F.[18] C_{Ft} is defined in a symmetric way.

Goods are aggregated by constant elasticity of substitution (CES) aggregator within a product line. We assume $1 < \sigma < \infty$, meaning the goods within a product line are imperfect substitutes to each other with the elasticity of substitution σ. Then, they are aggregated by Cobb-Douglas across product lines. Accordingly, the price index of final consumption P_{ct} is below:

$$P_{Ht} = \exp(\int_0^1 \ln((\psi_H^{\frac{1}{\sigma}} p_{H1t}^{1-\sigma} + \psi_H^{\frac{1}{\sigma}} p_{H2t}^{1-\sigma} + \psi_F^{\frac{1}{\sigma}} p_{Ft}^{*1-\sigma})dj) \tag{5}$$

p_{it} is a price of firm i in the domestic market, and p^*_{it} is a price in a foreign market.

Market structure We assume that three firms in each market (home and foreign) participate in the Bertrand competition, 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[19] and do not allow dynamic collusion. Firms recognize that their pricing decision changes the demand for their goods.

Production The production function of a variety is linear in labor:

$$\mathcal{Y}_{ijt} = q_{ijt} l_{ijt} \tag{6}$$

q_{ijt} is the productivity and l_{ijt} is labor used by firm i in product line j at time t. q_{ijt} evolves by innovation and adoption. The output can be consumed by home household or exported to another country as follows:

$$\mathcal{Y}_{ijt} = y_{ijt} + D \cdot y^*_{ijt} \tag{7}$$

[18]Since we have two firms in H and one firm in F, we put the demand shifters to make two country symmetric.

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

Productivity gap From now on, we omit the time argument when it does not cause confusion. Firms can increase productivity by λ^h through innovation or adoption. h is the number of steps that the firm improves and λ is a unit step size in the economy. Therefore, we can express the productivity as λ^n in which n denotes the cumulative number of steps that the firms improved. Then, the productivity gap m_F with the foreign firm in variety j can be written as

$$\frac{q_{ij}}{q_{Fj}} = \frac{\lambda^{n_{ij}}}{\lambda^{n_{Fj}}} = \lambda^{\boldsymbol{m_F}}, \quad m_F \in \mathbb{Z}, \quad i \in \{H1, H2\} \tag{8}$$

Likewise, we can get the gap with domestic competitor, m_D as following:

$$\frac{q_{ij}}{q_{-ij}} = \frac{\lambda^{n_{ij}}}{\lambda^{n_{-ij}}} = \lambda^{\boldsymbol{m_D}}, \quad m_D \in \mathbb{Z}, \quad i \in \{H1, H2\} \tag{9}$$

$m_F > 0$ implies the firm has higher productivity than the foreign firm. $m_D < 0$ implies the firm has lower productivity than the domestic competitor. The relevant state of the firm is a vector $\mathbf{m} = \{m_F, m_D\} \in \mathbb{Z}^2$. $\mathbf{m}$ fully characterizes the relative productivities in a given product line. Given the aggregate variables such as wage, consumption share, $\mathbf{m}$ determines the firms' pricing, market share, and profit. The productivity gap also determines dynamic decisions such as innovation and adoption rates, which will be explained in more detail later.

Innovation Firms choose innovation rate x by hiring innovation labor as below:

$$C_{cr}(x) = \alpha_{cr} \frac{x^\gamma}{\gamma} \tag{10}$$

We assume $\gamma > 1$, so the innovation cost function is convex. α_{cr} governs the scale of the required innovation labor. Since it hires labor, the cost is proportional to the wage w_c. With probability x, it improves productivity as

$$q_{ij}(t + \Delta) = \lambda^n q_{ij}(t), \quad n \sim \mathbb{F}_{m_F}(n) \tag{11}$$

n is a stochastic variable which is the number of steps that the firm improves, and $\mathbb{F}_{m_F}(n)$ 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.[20] We assume the expected step size is weakly decreasing with m_F to capture the advantage of backwardness. The specific functional form will be introduced later.

[20] We interpret this gap as the distance to the frontier as in Acemoglu et al. (2006). In the case of the firm in country F, only the gap from $H1$ matters.

Conditional on successful innovation of home leader with step size n, the gap from the foreign firm and domestic competitor changes to $(m_F + n, m_D + n)$. When the domestic competitor innovates with step size n, it changes to $(m_F, m_D - n)$. When the foreign firm innovates with step size n, it changes to $(m_F - n, m_D)$

Adoption Firms choose adoption rate a by hiring labor as follows:[21]

$$C_{ca}(a) = \alpha_{ca} \frac{a^\gamma}{\gamma} \tag{12}$$

Again, we assume that the firm hires labor to adopt, so the cost is proportional to the wage w_c. With probability a, the firm meets a foreign firm and makes an adoption contract. To simplify the model, we assume it adopts technology from the foreign firm, not the home leader.[22,23] The adopter pays a one-time adoption fee to the foreign firm, which improves productivity. The adoption fee is determined through Nash bargaining between the adopter and the foreign firm, which will be explained in detail in Section 2.2. Conditional on probability a, the firm improves its productivity as

$$q_{ij}(t + \Delta) = \lambda^n q_{ij}(t), \quad n \sim \mathbb{G}_{m_F}(n) \tag{13}$$

$\mathbb{G}_{m_F}(n)$ is the step size distribution, which depends on the current gap from the foreign firm m_F. The adopter does not necessarily catch up with the foreign firm from only one adoption, which is a more flexible assumption compared with other papers in technology diffusion literature (e.g., Perla and Tonetti, 2014; Benhabib et al., 2021; König et al., 2020). Let $g_{m_F}(n)$ is the probability of improving n steps when the gap from foreign firm is m_F. If we assume $g_{m_F}(m_F) = 1$, it nests the case of Perla and Tonetti (2014) and Benhabib et al. (2021). If $g_{m_F}(1) = 1$, it nests the case of König et al. (2020) in which adoption (imitation) brings only one step regardless of the current gap. Our assumption is consistent with the empirical facts that the adopter does not fully catch up with the foreign firm in terms of productivity after one technology adoption.[24] Moreover, if the adoption brings full

[21]This labor cost can be interpreted as the researcher who investigates the foreign technology, learn, and implement, which is different from the adoption fee to the seller.

[22]This assumption is motivated by the estimated size of 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 level of elasticity of substitution, the total surplus from the adoption contract is negative, which makes no room for them to trade technology.

[23]Firms in the country F adopts only from the home leader, not the follower.

[24]The firm might not be able to implement foreign technology with full capacity. We can capture this aspect by assuming their realized productivity can be lower than that of the leader.

catching-up, the adoption fee would always be higher when the initial relative productivity of the adopter is lower, which is not the case in the data.

In the 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, $g_{m_F}(0) = 1$ for $m_F \geq 0$. Second, the firm cannot leapfrog the foreign leader through adoption, i.e., $g_{m_F}(n) = 0$ for $n > -m_F$. Third, the expected step size from adoption and innovation decreases with m_F, but the slopes are different. It implies that the degree of advantage of backwardness is different for adoption and innovation. Lastly, the adopter needs to pay the adoption fee $\mathcal{F}_{i,\mathbf{m}}$ to the foreign firm.

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 from the foreign leader. To make the computation feasible, we impose the maximum technology gap as $\bar{m}$. Since the number of potential m_F is $2\bar{m} + 1$, we need $2\bar{m} + 1$ different distributions in principle.

To make the model tractable, we construct the distribution in additive way as follows. Let $\bar{n}$ be the maximum number of potential step sizes from adoption and innovation. For innovation, $\bar{n} = 2\bar{m}$ as the firm can start from $-\bar{m}$ and improve to $\bar{m}$. For adoption, $\bar{n} = \bar{m}$ as the firm can start from $-\bar{m}$ and improve to 0.[25]

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

$$f(m) = c_0 n^{-\eta}, \qquad n \in \{1, \cdots, \bar{n}\} \tag{14}$$

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 $f_{m_F}(n)$, the probability of improving n step when the current gap with the foreign firm is m_F, as the following:

$$f_{m_F}(n) = \begin{cases} f(1 + (m_F + \bar{m})) + \sum_{s=1}^{m_F+\bar{m}} f(s) & \text{for} \quad n = 1 \\ f(n + (m_F + \bar{m})) & \text{for} \quad n \in \{2, \cdots, \bar{n}\} \end{cases} \tag{15}$$

$(m_F + \bar{m})$ is the distance from the furthest position $-\bar{m}$, which makes the probability of improving the same number of steps be lower as the firm gets closer to foreign firms. On the other hand, probability of improving one step has additional term $\sum_{s=1}^{m_F+\bar{m}} f(s)$, which makes

[25]Firms cannot leapfrog by adoption.

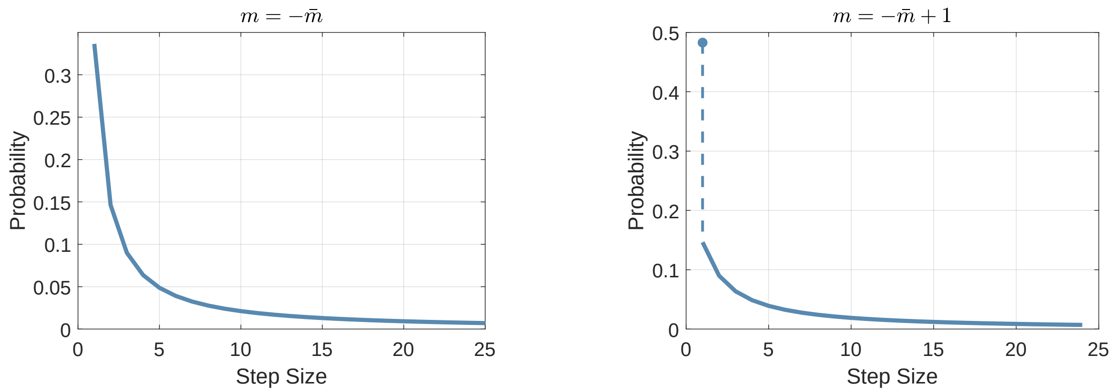


Figure 2: Probability Mass Function of Step Size when $m_F = -\bar{m}, -\bar{m}+1$

Notes: The left panel is probability mass function of step size when $m_F = -\bar{m}$, $f(m) = c_0 n^{-\eta}$. 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 $f(n+1)$. $\eta = 1.2$

the probability of improving just one step be higher as the firm gets closer to foreign firms. Figure 2 shows an example of probability mass function when $m_F = -\bar{m}$ and $m_F = -\bar{m}+1$.

The expected step size decreases with m_F, and the slope decreases with η as we can see in figure 3. 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.[26] We use the same functional form for both $g_{m_F}(n)$ (adoption) and $f_{m_F}(n)$ (innovation), but use different slope parameter, η_a for adoption and η_r for innovation, which will be estimated using data.

Potential entrant In country F, there is a potential entrant which can innovate and replace the incumbent.[27] The innovation cost of the entrant is the same as that of the incumbent in equation (10). With probability x, they improve on top of the incumbent's productivity, and the incumbent exit the market as below:[28]

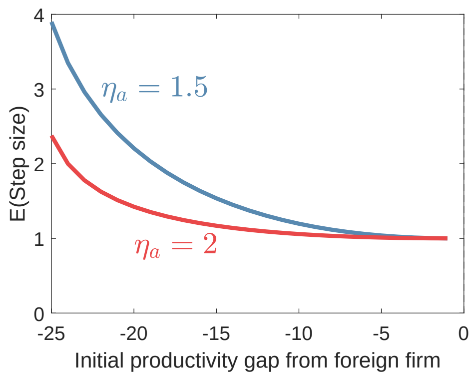
$$q_{Fj}(t+\Delta) = \lambda^n q_{Fj}(t), \quad n \sim \mathbb{F}_{m_F}(n) \tag{16}$$

Knowledge diffusion The follower has the same structure of innovation and adoption, except that its step size distribution depends not only on the productivity gap with foreign firms, but also on the gap with the domestic leader. We model this by assuming the domestic

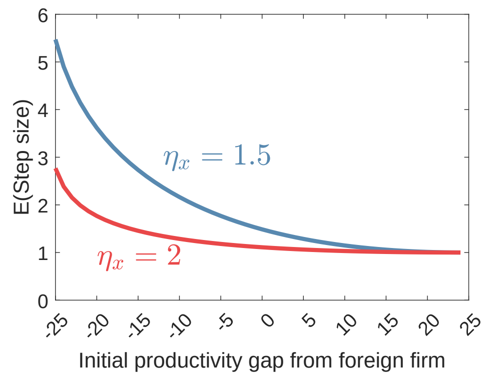
[26]When $\eta \to \infty$, the model becomes a step-by-step model with only one step improvement.

[27]For simplicity, we do not allow it to adopt the technology.

[28]Note that in a foreign country, the potential entrant can always build on the incumbent's technology. It simplifies the computation by reducing the number of state variables.



A. Adoption



B. Innovation

Figure 3: A.

Notes: X-axis is the productivity gap from the foreign firm, Y-axis is the expected step size from innovation / adoption over different values of η in the model.

follower can build on the home leader's technology when innovating or adopting with a fixed probability δ. The step size distribution of the follower with $m_D < 0$ is

$$\begin{aligned} \tilde{f}_{m_F,m_D}(n) &= (1-\delta)f_{m_F}(n) + \delta f_{m_F-m_D}(n+m_D) \\ \tilde{g}_{m_F,m_D}(n) &= (1-\delta)g_{m_F}(n) + \delta g_{m_F-m_D}(n+m_D) \end{aligned} \tag{17}$$

The first term is when there is no diffusion in which it improves productivity from its current position m_F, and the second is step size distribution with knowledge diffusion in which it improves from the leader's position $m_F - m_D$. 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 generates an intertemporal spillover from both innovation and adoption. When the leader innovates or adopts, it also increases the future productivity of the follower. However, this knowledge diffusion would hurt the leader's profit in the future. Since the leader takes that into account, it reduces the innovation and adoption rate when the knowledge diffusion rate is higher in the economy.

The level of positive externality is governed by $\mathbb{E}(n) \cdot \delta$, which is the expected step size times the probability of knowledge diffusion. If the step size is larger, it improves productivity more and creates a larger spillover to the follower. Since the productivity gain from adoption and innovation change over the productivity gap, the intertemporal spillover from adoption and innovation also change. For instance, if the productivity gain from adoption is larger than innovation, the spillover is larger from adoption than innovation.

Lastly, we allow that there is an exogenous productivity spillover across countries. With probability ϕ, domestic firms have the same productivity with foreign firms.[29]

Government policy We consider two subsidies - adoption and R&D subsidy. The government subsidizes s_{cat} fraction of the adoption cost, and subsidizes s_{crt} fraction of innovation cost. The expenses for two subsidies are financed by the lump-sum tax from the household. The government holds a balanced budget in each period as follows:

$$T_{ct} = (1+\theta)\int_0^1 \sum_{i=1}^{2}(s_{cat}\mathcal{F}_{cijt} + s_{cat}\alpha_{ca}\frac{a_{cijt}^{\gamma}}{\gamma}w_c + s_{crt}\alpha_{cr}\frac{x_{cijt}^{\gamma}}{\gamma}w_c)dj \tag{18}$$

θ is the reduced form parameter of the deadweight cost of taxation. Specifically, the government needs to collect $1+\theta$ tax revenue to finance one unit of government expenditure. We use $\theta = 1$ as a baseline value following Feldstein (1999).[30]

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

$$L_{ct} = \int_0^1 \sum_{i=1}^{2}(l_{cijt} + \alpha_{ac}\frac{a_{cijt}^{\gamma}}{\gamma} + \alpha_{rc}\frac{x_{cijt}^{\gamma}}{\gamma})dj \tag{19}$$

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

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

$$\int_0^1 (p_{Fjt}^{*}y_{Fjt}^{*} + \sum_{i=1}^{2} a_{Hijt}p_{Hijt})dj = \int_0^1 (\sum_{i=1}^{2} p_{Hijt}^{*}y_{Hijt}^{*} + a_{Fjt}p_{Fjt})dj \tag{20}$$

2.2 Equilibrium

In this section, we define a Markov perfect equilibrium in which strategies of the firms depend only on the payoff relevant state $\mathbf{m}$, the productivity gap vector. Then, we characterize

[29]This parameter captures other international spillovers outside of the official adoption contracts, which is technology stealing or reverse engineering.

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

the balanced growth path equilibrium where the aggregate productivity, output, wage, and consumption grow at the same rate. Also, the distribution of productivity gap, interest rates, and the relative price is constant over time.

Household A representative household maximizes utility from the equation (1) given the budget constraint from the equation (2). It generates the following Euler equation:

$$\frac{\dot{C}_{ct}}{C_{ct}} = \rho - (r_{ct} - \frac{\dot{P}_{ct}}{P_{ct}}) \tag{21}$$

Production and profits The productivity gap $\mathbf{m}$ determines the production and profit of intermediate goods given the wage, total consumption in two countries, and trade cost. Firms in each product country participate in the Bertrand competition. Since the final consumption is Cobb-Douglas of the variety goods, the household spends the same amount of expenditure $P_c C_c$ on each product line j, which leads to the following equation:

$$\sum_{i=1}^{2} p_{Hij} y_{Hij} + p^*_{Fj} y^*_{Fj} = P_H C_H \tag{22}$$

p_{Hij},y_{Hij} is the price and quantity of the goods produced by the firm Hij, consumed in country H, and p^*_{Fj},y^*_{Fj} is the price and output of the goods produced by F and exported to H.

By solving the household utility maximization problem given the variety price, the market share of each firm s_{Hij}, s^*_{Fj} in the home market is as

$$s_{Hij} = \frac{\psi_H p_{Hij}^{1-\sigma}}{\sum_{i=1}^{2} \psi_H p_{Hij}^{1-\sigma} + \psi_F p_{Fj}^{*1-\sigma}}, \qquad s^*_{Fj} = \frac{\psi_F p_{Fj}^{*1-\sigma}}{\sum_{i=1}^{2} \psi_H p_{Hij}^{1-\sigma} + \psi_F p_{Fj}^{*1-\sigma}} \tag{23}$$

And the demand y_{cij}, y^*_{cij} is as follows:

$$y_{Hij} = \frac{p_{Hij}^{-\sigma}}{\sum_{i=1}^{2} p_{Hij}^{1-\sigma} + p_{Fj}^{*1-\sigma}}, \qquad y^*_{Fij} = \frac{p_{Fj}^{*-\sigma}}{\sum_{i=1}^{2} p_{Hij}^{1-\sigma} + p_{Fj}^{*1-\sigma}} \tag{24}$$

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

$$p_{Hij} = \frac{1 - \frac{\sigma-1}{\sigma} s_{Hij}}{\frac{\sigma-1}{\sigma}(1 - s_{Hij})} \frac{w_c}{q_{Hij}}, \qquad p^*_{Fj} = \frac{1 - \frac{\sigma-1}{\sigma} s^*_{Fj}}{\frac{\sigma-1}{\sigma}(1 - s^*_{Fj})} \frac{D \cdot w_F}{q_{Fj}} \tag{25}$$

The profit functions from country c are.

$$\pi_{Hij} = \frac{s_{Hij}(1 - \frac{\sigma-1}{\sigma})}{1 - \frac{\sigma-1}{\sigma}s_{Hij}}, \qquad \pi^*_{Fj} = \frac{s^*_{Fj}(1 - \frac{\sigma-1}{\sigma})}{1 - \frac{\sigma-1}{\sigma}s^*_{Fj}} \tag{26}$$

The equilibrium in the foreign market is defined similarly. The firm makes a profit from two sources: the domestic market and the foreign market. Finally, the total profit of the firm in country c, position i, and product line j is.

$$\Pi_{cij} = \pi_{cij}P_cY_c + \pi^*_{cij}P_{-c}Y_{-c} \tag{27}$$

If we combine the equation (23) and (25), we can solve the price, market share, and profit as functions of the productivity gap, relative wage, trade costs, and household expenditure P_HC_H, P_FC_F. Therefore, given the aggregate variables, the productivity gap $\mathbf{m}$ fully determines the static variables of the firms.

Value function Note that given the aggregate variables, firm profit depends only on the productivity gap, and the innovation and adoption decision only changes the gap. We can represent the value function as a function of the productivity gap vector $\mathbf{m} := \{m_F, m_D\}$. For domestic firms, m_F is the gap from the foreign leader, and m_D is the gap from the domestic competitor. For foreign firms, m_F is the gap from the home leader, and m_D is the gap between the home leader and follower. For example, if the productivity of the home leader is λ^3, that of the home follower is λ^2, and that of the foreign firm 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 $\{-2, 1\}$. We will use $\mathbf{m}$ instead of j as a state variable. The value function of a home firm with gap $\mathbf{m} = (m_F, m_D)$ when $m_D > 0$ is as follows:

$$
\begin{aligned}
& r_{Ht}V_{Ht}(\mathbf{m}) - \dot{V}_{Ht}(\mathbf{m}) \\
& = \max_{x_{H\mathbf{m}t}, a_{H\mathbf{m}t}} \underbrace{\Pi_{Ht}(\mathbf{m})}_{\text{profit}} - (1 - s_{Hrt}) \underbrace{\alpha_{Hr} \frac{(x_{H\mathbf{m}t})^{\gamma}}{\gamma} w_{Ht}}_{\text{innovation cost}} - (1 - s_{Hat}) \underbrace{\alpha_{Ha} \frac{(a_{H\mathbf{m}t})^{\gamma}}{\gamma} w_{Ht}}_{\text{adoption cost}} \\
& + x_{H\mathbf{m}t} \sum_{n} f_{m_F}(n) \underbrace{[V_{Ht}(m_F + n, m_D + n) - V_{Ht}(\mathbf{m})]}_{\text{gain from innovation}} \\
& + a_{H\mathbf{m}t} \sum_{n} g_{m_F}(n) [(\underbrace{V_{Ht}(m_F + n, m_D + n) - V_{Ht}(\mathbf{m})}_{\text{gain from adoption}}) - (1 - s_{Hat}) \underbrace{\mathcal{F}_{H\mathbf{m}t}}_{\text{adoption fee}}\ )] \\
& + \tilde{x}_{H\mathbf{m}t} \sum_{n} \tilde{f}_{m_F - m_D, -m_D}(n) \underbrace{[V_{Ht}(m_F, m_D - n) - V_{Ht}(\mathbf{m})]}_{\text{loss from follower innovation}} \\
& + \tilde{a}_{H\mathbf{m}t} \sum_{n} \tilde{g}_{m_F - m_D, -m_D}(n) \underbrace{[V_{Ht}(m_F, m_D - n) - V_{Ht}(\mathbf{m})]}_{\text{loss from follower adoption}} \\
& + (x_{F\mathbf{m}t} + \tilde{x}_{F\mathbf{m}t}) \sum_{n} f_{-m_F}(n) \underbrace{[V_{Ht}(m_F - n, m_D) - V_{Ht}(\mathbf{m})]}_{\text{loss from foreign firm innovation}} \\
& + a_{F\mathbf{m}t} \sum_{n} g_{-m_F}(n) \underbrace{[V_{Ht}(m_F - n, m_D) - V_{Ht}(\mathbf{m})}_{\text{loss from foreign firm adoption}} + \underbrace{\mathcal{F}_{F\mathbf{m}t}}_{\text{adoption fee}}\ ] \\
& + \underbrace{\phi(V_{Ht}(\mathbf{0}) - V_{Ht}(\mathbf{m}))]}_{\text{exogenous spillover}}
\end{aligned}
\tag{28}
$$

The first line of the value function includes the operating profit, which is defined in equation (26) and (27). Then, the firm spends innovation and adoption costs. s_{Hrt} and s_{Hat}, are innovation and adoption subsidy rate, respectively. Next two lines show the gain from innovation and adoption where the step size n follows the distribution $f_{m_F}(n), g_{m_F}(n)$. The adoption fee $\mathcal{F}_{H\mathbf{m}t}$ is jointly determined and explained later in equation (30). The next two lines represent the value change from the innovation and adoption of the domestic competitor. $\tilde{x}_{H\mathbf{m}t}, \tilde{a}_{H\mathbf{m}t}$ denote the innovation and adoption rate of the domestic competitor when the current gap is $\mathbf{m}$. Since another firm is a follower, it has different step size distribution as $\tilde{f}_{m_F - m_D, -m_D}(n), \tilde{g}_{m_F - m_D, -m_D}(n)$. The following two lines denote the foreign firms' (incumbent and entrant) innovation and adoption. The last line has the exogenous spillover, which is governed by the parameter ϕ. Value function of home follower, foreign firm, foreign entrant are defined similarly, in equation (42), (43), and (44) in Appendix A.1.

Adoption fee The adoption fee is a one-time payment that internalizes all the adopter's future profit gain and the seller's loss. The 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's exporting to the foreign country.[31] 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 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, and their outside option is zero, which is not having the contract. $\mathcal{F}_{H\mathbf{m}t}$, the adoption fee of a home firm when $m_D > 0$ is determined by the following equation:

$$\begin{aligned}\mathcal{F}_{H\mathbf{m}t} = \underset{\mathcal{F}_{H\mathbf{m}t}}{\text{argmax}}(\sum_n g_{m_F}(n) V_{Ht}(m_F+n, m_D+n) - \mathcal{F}_{H\mathbf{m}t} - V_{Ht}(\mathbf{m}))^{\xi} \\ \cdot (\sum_n g_{m_F}(n) V_{Ft}(-m_F-n, m_D+n) + \mathcal{F}_{H\mathbf{m}t} - V_{Ft}(-m_F, m_D))^{1-\xi}\end{aligned} \tag{29}$$

$0 \leq \xi \leq 1$ is the bargaining power of the adopter. $\sum_n g_{m_F}(n) V_{Ht}(m_F+n, m_D+n)$ is the expected value of the adopter after the adoption in which it improves gap from all firms as n steps. Note that the adoption fee is jointly determined with $V_{Ht}(\mathbf{m})$, the value of firm. Net value from adoption is the new value minus the price $\mathcal{F}_{H\mathbf{m}t}$ and its outside option is the current value $V_{Ht}(\mathbf{m})$. Likewise, the expected value of the seller after the adoption is $\sum_n g_{\mathbf{m}}(n) V_{Ft}(-m_F-n, m_D+n)$ where it has lower value from the decreased relative productivity, but receives adoption fee $\mathcal{F}_{H\mathbf{m}t}$. The outside option is the current value $V_{Ft}(-m_F, m_D)$. When we solve the equation (29), we get the following price equation:

$$\begin{aligned}\mathcal{F}_{H1\mathbf{m}} = (1-\xi)(\sum_n g_{m_F}(n) V_H(m_F+n, m_D+n) - V_H(\mathbf{m})) \\ - \xi(\sum_n g_{m_F}(n) V_F(-m_F-n, m_D+n) - V_F(-m_F, m_D))\end{aligned} \tag{30}$$

Adoption fee of home follower and foreign firm are defined in a similar way in equation (45), (46) in Appendix A.2. The adoption fee is higher if the leader loses more or the follower gains more from the adoption. It depends on two forces: the degree of advantage of backwardness and the competition effect. From the advantage of backwardness, the productivity gain from adoption is larger when the initial productivity gap is larger. This means the follower gains more, and the leader loses more when the follower adopts technology. It makes the price higher when the productivity gap is larger.

On the other hand, the profit gain from productivity improvement increases when the initial gap is smaller. Figure 4 shows the example of the profit function over the technology gap from the foreign leader while fixing other gaps. We can see that the profit increase is

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

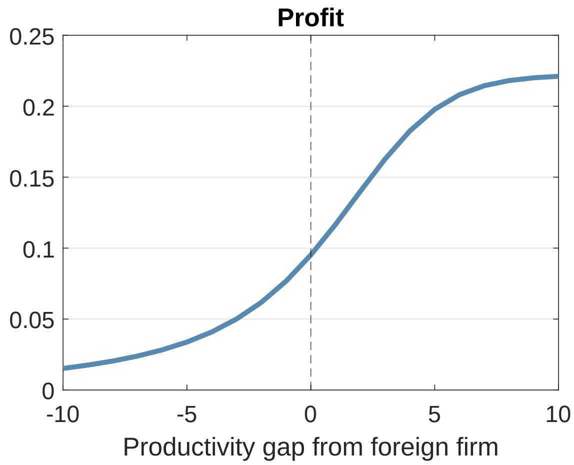


Figure 4: Profit function over technology gap

Notes: X-axis is the productivity gap from the foreign firm and Y-axis is the profit of the firm when we fix the gap between domestic firms as zero. $\sigma = 8, D = 1.2, \lambda = 1.1$

small when the follower is far from the leader, i.e., m_F is small. The slope of the profit function increases as the firm gets closer to the leader. Therefore, the willingness to pay for technology adoption is larger when the gap is smaller, which makes the price increase with m_F.

Room for trade of technology Note that an adoption contract is not always possible. If the total surplus from the contract is negative, then no adoption fee makes the adoption contract possible. Several cases increase the total surplus, making room for technology trade. First, when the wage in the follower's 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 segregated, 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 entire surplus from the adoption contract.[32] Third, firms in different countries produce imperfect substitutes. Therefore, if they share the technology, the total utility can increase and total surplus can be positive. Lastly, when the foreign firm sells technology, the potential entrant also loses its future profit, but the foreign firm does not internalize it. Even if selling technology decreases the foreign country's overall welfare, the foreign firm can still sell the technology

[32]It creates an interaction between trade policy and adoption. Since the adoption fee decreases and the adoption rate rises with the import tariff, the government may want to increase the import tariff when it wants to increase the adoption rate.

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.1.

Optimal innovation and adoption rate The optimal innovation rate of home leader with gap $\mathbf{m}$ when $m_D > 0$ is as

$$x_{H\mathbf{m}t} = \{\frac{1}{(1-s_{Hrt})\alpha_{Hr}w_{Ht}} \sum_n f_{m_F}(n)[V_{Ht}(m_F+n, m_D+n) - V_{Ht}(\mathbf{m})]\}^{\frac{1}{\gamma-1}} \tag{31}$$

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

$$a_{H1\mathbf{m}t} = \{\frac{1}{(1-s_{Hat})\alpha_{Ha}w_{Ht}} \sum_n g_{m_F}(n)[V_{Ht}(m_F+n, m_D+n) - V_{Ht}(\mathbf{m}) - (1-s_{Hat})\mathcal{F}_{H\mathbf{m}t}]\}^{\frac{1}{\gamma-1}} \tag{32}$$

The optimal innovation and adoption rate of home follower, foreign incumbent, and entrant is in (47), (48), (49) in Appendix A.3.

Distribution of technology gap The distribution of the technology gap is the state variable in the economy. We use the gap from the home leader's perspective as the aggregate state variable and denote $\mathbf{m} = (m_F, m_D)$ where m_F is the home leader's gap from the foreign firm, and m_D is from the home follower. We define $\mathbb{T}_i(\mathbf{m}, n)$ as the probability of firm i improves productivity n steps when the aggregate state variable is $\mathbf{m}$ as follows:

$$\begin{aligned}
\mathbb{T}_{H1}(\mathbf{m}, n) &= f_{m_F}(n)x_{H1t}(m_F, m_D) + g_{m_F}(n)a_{H1t}(m_F, m_D) \\
\mathbb{T}_{H2}(\mathbf{m}, n) &= \tilde{f}_{m_F-m_D}(n)x_{H2t}(m_F-m_D, -m_D) + g_{m_F-m_D}(n)a_{H1t}(m_F-m_D, -m_D) \\
\mathbb{T}_{F}(\mathbf{m}, n) &= f_{-m_F}(n)x_{Ft}(-m_F, m_D) + g_{-m_F}(n)a_{H1t}(-m_F, m_D)
\end{aligned} \tag{33}$$

Let $\mu_{\mathbf{m}t}$ the share of product lines with gap $\mathbf{m}$ in time t. The law of motion of $\mu_{\mathbf{m}t}$ is

$$
\begin{aligned}
&\dot{\mu}_{Ht}(m_F, m_D) = \\
&\sum_{n=1}^{m_F+\bar{m}} \mathbb{T}_{H1}(m_F - n, m_D - n, n)\mu_{Ht}(m_F - n, m_F - n) \\
&+ \sum_{n=1}^{m_D} \mathbb{T}_{H2}(m_F, m_D + n, n)\mu_{Ht}(m_F, m_D + n) \\
&+ \sum_{n=m_D+1}^{m_F+\bar{m}} \mathbb{T}_{H2}(m_F - (n - m_D), m_D - n, n)\mu_{Ht}(m_F - (n - m_D), m_D - n) \\
&+ \sum_{n=1}^{-m_F+\bar{m}} \mathbb{T}_F(m_F + n, m_D)\mu_{Ht}(m_F + n, m_D) \\
&+ \mathbb{1}(\mathbf{m} = \mathbf{0}) \cdot \phi - (\sum_{c=\{H,F\}} \sum_{i=1}^{2} (x_{Hi\mathbf{m}t} + a_{Hi\mathbf{m}t}) + \phi)\mu_{Ht}(\mathbf{m})
\end{aligned} \tag{34}
$$

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

Note that each product line has different productivity even if they have the same gap $\mathbf{m}$. Let Q_{cmt} be the average productivity of the leader with gap $\mathbf{m}$ as

$$
Q_{\mathbf{m}t} = \sum_{\mathbf{m}} q_{H1jt}\mu_{\mathbf{m}t} \tag{35}
$$

Definition 2.1. A Markov perfect equilibrium is an allocation
$\{r_{ct}, w_{ct}, p_{cijt}, p^*_{cijt}, y_{cijt}, y^*_{cijt}, l_{cijt}, x_{cijt}, a_{cijt}, \mu_{\mathbf{m}t}, Q_{\mathbf{m}t}, C_{ct}, A_{ct}, T_{ct}\}^{t\in[0,\infty), j\in[0,1], c\in\{H,F\}}_{i\in\{1,2\}, m\in\{-\bar{m},\cdots,\bar{m}\}}$

1. Given r_{ct}, household choose C_{ct}, A_{ct} to maximize sum of discounted utility
2. Given $\{p_{cijt}, p^*_{cijt}\}$, household choose y_{cijt}, y^*_{cijt} to minimize expenditure
3. Given $\{w_{ct}, \mathbf{m}_{jt}\}$, firms in product line j choose $p_{cijt}, p^*_{cijt}, l_{cijt}, l^*_{cijt}$ to maximize profit
4. Given $\{r_{ct},\ w_{ct}, \mathbf{m}_{jt}, \mathcal{F}_{cijt}\}$, x_{cijt}, a_{cijt} solve firm's dynamic problem
5. Given $\{r_{ct}, w_{ct}, \mathbf{m}_{jt}, x_{cijt}, a_{cijt}\}$, $\mathcal{F}_{cijt}$ solves Nash Bargaining between buyer and seller.

6. Given $\mu_{\mathbf{m}0}, Q_{\mathbf{m}0}$, $\{\mu_{\mathbf{m}t}\}_{t\in[0,\infty)}, \{Q_{\mathbf{m}t}\}_{t\in[0,\infty)}$ is consistent with x_{cijt}, a_{cijt}

7. w_{ct} clears labor market in each country

8. r_{ct} satisfies household Euler equation.

9. T_{ct} balances government budget in every period.

Definition 2.2. Balanced growth path is the equilibrium defined in Definition 2.1 with $w_{ct}, y_{ijt}, y^*_{ijt}, C_{ct}, T_{ct}, Q_{\mathbf{m}t}$ grow at a rate g, and $p_{cijt}, p^*_{cijt}, l_{cijt}, l^*_{cijt}, x_{cijt}, a_{cijt}, \mu_{\mathbf{m}t}$ are constant over time.

Inefficiency in the model The model has several forces that make the competitive equilibrium not efficient. First, innovation and adoption have positive externality through knowledge diffusion and exogenous productivity spillover, which can potentially lead to underinvestment. While firms try to avoid generating spillover to other firms as it decreases their profit, social planner cares about the productivity of both firms. Furthermore, in the case of adoption, the foreign firm internalizes the externality of adoption when it determines the adoption fee. Since the value function incorporates future profit, which is affected by both the leader and follower, the adoption fee increases with the knowledge diffusion, it amplifies the discrepancy between the private and social value of adoption, which makes the underinvestment problem of the adoption more severe than the innovation. Second, innovation and adoption have a business stealing effect, which can potentially lead to overinvestment. The innovation and adoption incentive includes improving productivity and stealing the market share of other firms. However, social planner only cares about aggregate productivity and output. If the step size from innovation or adoption is small, firms might improve technology only marginally while spending substantial resources on innovation or adoption.[33] Lastly, firms have positive markup, which makes firms produce less than socially optimal.

3 Data

3.1 Technology Adoption Data

We construct a firm-to-firm level technology import dataset. To be specific, we collect and digitize the contracts from the National Archives of Korea and supplement them with Korea Industrial Technology Association (1995).[34] These have the universe of technology import

[33] When the elasticity of substitution is smaller, this business stealing effect becomes smaller.

[34] We extend the data used in Choi and Shim (2022) which is until 1982 to 1993 and add adoption fee information.

Table 1: Example of Technology Adoption Data

Buyer	Seller	Length (year)	Date	Technology	Contents	Fee
Samsung	Nippon Electronic (Japan)	10	78.2.24	Color TV	Know-how Transfer, Licensing	Fixed $800,000
LG	Hitachi (Japan)	9	78.4.1	Color TV	Know-how Transfer, Licensing	Fixed $100,000 Royalty 3%
Haengnam Electronics	EPH (US)	2	78.12.18	Alumina	Know-how Transfer	Fixed $131,000

in 1962-1993 since the domestic firms were required to submit the related documents to the government when they import technology from a foreign country.[35] As a result, we collected 8,512 contracts from 2,902 unique firms.[36,37]

We collect the name of the Korean firm (buyer) and foreign firm (seller), date and length of the contract, description of the technology, contents of the contract, and the adoption fee, which consists of a fixed fee and royalty rate. Table 1 shows the example of collected data. In terms of the country's origin, Japan accounts for 50%, the US accounts for 26.3%, and Germany, France, and the UK account for 13.1% in sum.[38] 95% of contracts involve know-how transfer among which 40% also involve licensing of patents or trademarks. 95% of contracts is by manufacturing.[39] The average royalty rate is 3.28%, the average fixed fee is 1.29 million dollars which account for 1.97% of yearly sale on average, and the length of the contract is 5.13 year.[40]

3.2 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. It is firm survey data that covers more than 50 employees.[41] We can observe firm sales, total assets, fixed assets, number of employees, profit, start

[35]Korean firms are strictly required to report all transactions involving foreign currencies under the Foreign Capital Inducement Act. To be specific, it reported details of technology import to Economic Planning Board.

[36]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 whole sample.

[37]Figure B.1 and B.2 show the snapshot of contracts where we can see the contents and payment of the contract.

[38]Table B.2 shows the distribution of countries in adoption contracts.

[39]Appendix B.1 shows summary statistics of the data.

[40]61.38% of contracts have royalty payments, 76.56% have fixed fees, and 37.97% have both.

[41]It accounts for 70% of the value-added share in manufacturing.

year, business ID, and sector between 1970 and 1983. Second, we use KIS value data starting from 1980, which covers firms with assets of more than 3 billion Korean Won (2.65lmn 2015 USD).[42] By using business ID and firm name, we merge these two data.[43] Then, we merge this balance sheet data with the technology adoption data by using firm names. On average, 6.26% of firms adopt technology each year.

Foreign firms We use Compustat data for the foreign firms where we can capture 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. Then we merge it with technology adoption data using the firm name and country.

3.3 Patent Data

Korean patent office data To measure the innovation of Korean firms, we use patent data from Korean Intellectual Property Office. We download the data from Korean Intellectual Property Rights Information Service, following the procedure in Lee et al. (2020). The data starts in 1945 and captures a universe patent 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 Also, we use the United States Patent Office data (USPTO, hereafter) to measure the innovation of foreign firms. It started in 1975 and covered all the patents registered in the US. We use crosswalk by Bena et al. (2017) to merge USPTO with global and North America Compustat. We also merge USPTO data with the technology adoption data by using the name of the foreign firm. The detailed procedure of matching foreign firm names with USPTO data can be found in Appendix B.3.

One caveat 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 USPTO instead of Korean Patent data since USPTO has citations for all periods. We use a crosswalk between the Korean patent office firm ID and USPTO ID made by Lee et al. (2020).

Table 2: Average of variables of Adopting and Non-adopting Firms

Average	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: We calculate the average value of variables for the firms in 1971-1993 between adopting and non-adopting firms. Adopting firm is defined as the firm that has at least one adoption contract. Total asset, sales and sales per employee are in million dollar.

3.4 Summary Statistics

Table 2 shows the summary statistics between adopting and non-adopting firms in 1971-1993. We define adopting firms when they have at least one adoption contract in a given year. 6.21% of total firms adopt the technology. They have bigger size in terms of employment and total assets. Also, they, on average, have larger total sales and larger sales per employee. Lastly, we compare the patenting dummy variables between two groups. Adopting firms are more likely to apply for a patent.

In general, foreign technologies were adopted by larger and more productive firms in Korea. It is consistent with our assumption that we have two incumbents in each product line. Figure B.4 plots the distribution of variables between two groups after controlling for sector-year fixed effects.

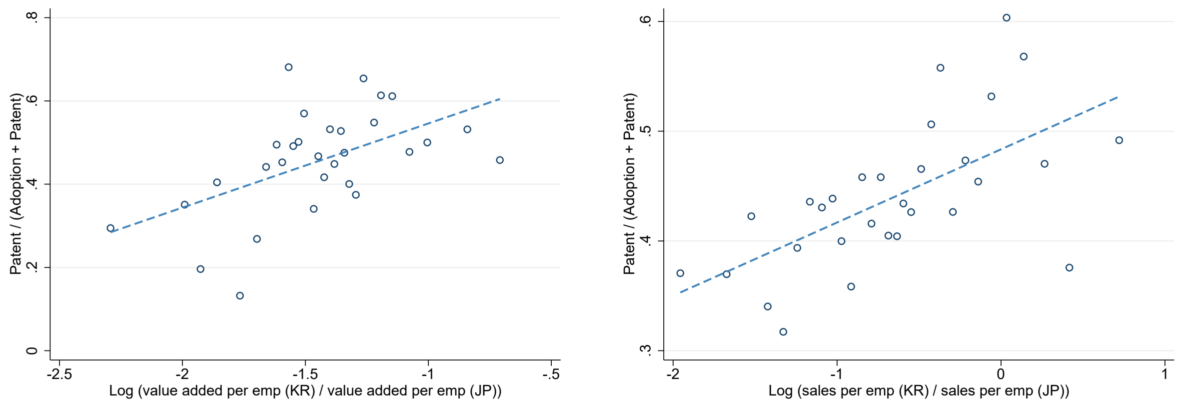
4 Empirical Analysis

4.1 Innovation and Adoption over Productivity Gap

Figure 5 plots the innovation share over the productivity gap, both at the sector and firm levels. We measure innovation as the number of patents and adoption as the number of adoption contracts. 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. At the sector level, we use the log ratio of value added per employee in Korea and Japan. At the firm level, we use

[42] The 1981 Act on External Audit of Joint-Stock Corporations require that all the publicly traded firm and other firms larger than the asset threshold have to report their balance sheet information.

[43] 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 5: Patent / (patent + adoption) over Productivity Gap

Notes: We plot the number of patents divided by the sum of the number of patents and the number of adoption contracts over the productivity gap. Panel A is at the sector-year level, and the productivity gap is the log value added per employment of Korea divided by that 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 log sales per employee of a Korean firm divided by that of the foreign firm that 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 sector and year-fixed effects.

the log ratio of sales per employee of adopting firms and 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 C.1 shows the regression result.

We find a positive and statistically significant correlation between the innovation share and the gap at the sector and firm levels. It implies when Korean firms are close to foreign firms in terms of productivity, they are more likely to innovate instead of adopting foreign technology. This result shows that the firms rely more on innovation at the cross-section, which complements the time-series evidence in the figure 1 in which Korea has been increasing innovation expenditure share as it catches up with foreign countries.

4.2 Productivity Gap and Adoption Fee

One potential reason for the transition from adoption to innovation is the adoption fee getting higher as firms close the gap with foreign firms. We study the relationship between the productivity gap and the price of the adoption contract by running the following regression:

$$\text{Adoption Fee}_{ijt} = \beta \log(\frac{\text{Sales/emp}_{it}}{\text{Sales/emp}_{jt}}) + \alpha_{s(i)} + \delta_t + \epsilon_{ijt} \tag{36}$$

Table 3: Regression of adoption price with technology gap

	Fixed Fee	Royalty	Total Fee	Total Fee
Relative Productivity	0.117**	0.124***	0.627***	0.561***
	(0.0503)	(0.0465)	(0.0545)	(0.0598)
Relative Productivity x Overlap				0.292***
				(0.111)
Overlap of field				0.530***
				(0.162)
N	1,436	1,029	1,022	1,022
Adjusted R2	0.1106	0.0634	0.4062	0.4116
Sector FE	yes	yes	yes	yes
Year FE	yes	yes	yes	yes

Standard errors in parentheses

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

Notes: 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.

Adoption Fee_{ijt} is the adoption fee that Korean firm i pays to foreign firm j. $\log(\frac{\text{Sales/emp}_{it}}{\text{Sales/emp}_{jt}})$ is the relative productivity between Korean firm i and foreign firm j. We use global Compustat data to get sales per employee of the foreign firm.[44] $\alpha_{s(i)}$ is sector fixed effects, and δ_t is year fixed effects.

Table 3 shows a positive and statistically significant correlation between the adoption fee and the 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 fixed fee with the relative productivity. We find that a 1% increase in relative productivity is associated with a 0.16% increase in the fixed fee. In the second column, we regress the royalty rate (in percentage) with the relative productivity. 1% increase in relative productivity is associated with a 0.17 percent point increase in the royalty rate. In the third column, we regress the total adoption fee, which is the sum of fixed fee and royalty rate times firm sales times contract years.[45] 1% increase in

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

[45]Royalty payment is usually a share of revenue using the adopted technology. Since we do not have disaggregated sales data, we use the firm-level total sales as the revenue. Also, the contract often specifies that it is a net sale after tax and other expenses, but we abstract away from it. We run the regression with the royalty rate and fixed fee separately as a robustness check.

the relative productivity is associated with a 0.85% increase in the total adoption fee.

The positive correlation suggests when the Korean firm is closer to the foreign firm, the seller is compensated more by the adoption fee. Through the lens of our model, the seller loses more profit when the productivity gap from the buyer is smaller. This is because the profit is more sensitive to the productivity gap when the gap is close to zero. And the adoption fee reacts more to the technology gap when the competition between two firms is stronger.

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 since they compete in the same product market. To be specific, we list the ten most frequent patent classes. Then, we make a dummy variable whether 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.

The positive correlation between the adoption fee and the buyer's relative productivity is stronger when the two firms are in the same technology field. The last column in table 3 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 in the adoption price. This suggests that the competition effect is important in deciding on adoption fees.

4.3 Productivity Gain over the Initial Productivity Gap

Another potential reason for the transition from adoption to innovation is that the productivity gain from adoption becomes smaller as firms close the gap from the foreign firm. Our model suggests that the expected productivity gain depends on the distance to the foreign firm. To estimate the slope of step size distribution, we run a regression as below:

$$\log\left(\frac{\text{Sales/emp}_{i,t+5}}{\text{Sales/emp}_{i,t}}\right) = \beta \cdot \text{relative productivity}_{it} + \Gamma \cdot X_{it} + \alpha_{s(i)} + \delta_t + \epsilon_{it} \tag{37}$$

$\log(\frac{\text{Sales/emp}_{i,t+5}}{\text{Sales/emp}_{i,t}})$ is the growth rate of labor productivity after innovation or adoption. relative productivity$_{it}$ is log(Sales per emp of Korean firm/Sales per emp of Foreign firm) in the year of the adoption or innovation, which is same as in the figure 5. In the case of innovation, we use the maximum sales per employee of the foreign firm in sector and year. $X_{i,t}$ includes control variables such as capital intensity growth which is defined as the growth rate of fixed assets per employment in 5 years. Lastly, we control sector and year-fixed effects.

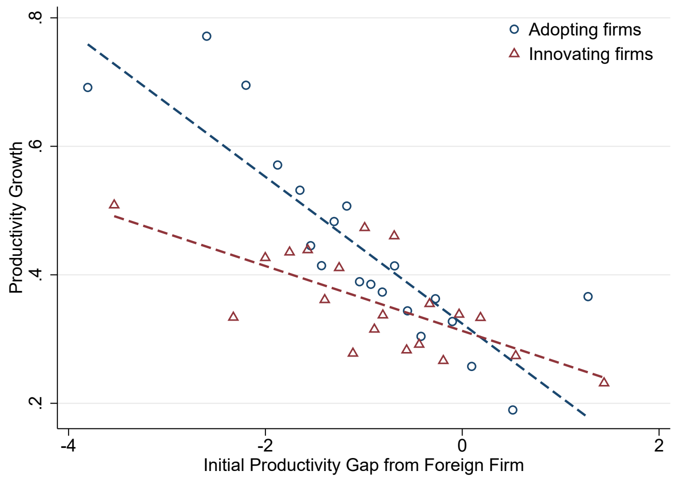


Figure 6: Productivity Growth over Initial Productivity Gap from Adoption and Innovation

Notes: This figure is a binscatter plot where each dot has multiple firm-year observations. Y-axis is $\Delta \log(\text{sales / emp})_{i,t+5}$ and X-axis is log(sales per emp of Korean firm/sales per emp of Korean firm)$_{i,t}$. Blue circle is innovating firms that have at least one patent, and red triangle is adopting firms that have at least one adoption contract. We exclude firms that have both innovation and adoption in a given year. We control 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(sales / emp) of foreign technology sellers in the same sector.

Note that we exclude firms that both innovate and adopt in the same year.

Figure 6 shows the result in a binscatter plot. Initial productivity gap has negative correlation with productivity growth both for adopting and innovating firms. It implies that there is advantage of backwardness for adoption and innovation, and consistent with negative correlation between the expected step size and the relative productivity in the model. Moreover, the absolute value of the slope is larger for adoption than innovation, which implies the productivity gap matters more for adoption than innovation.

Table C.2 shows the result of the regression. The first column runs the regression with productivity gain after adoption, the second column with the one after innovation, and the third column pulls both innovation and adoption with an interaction term. The difference of the coefficients is statistically significant as the interaction term in the third column is significant. In the model, η_a, η_x that govern the slope of step size distribution will be estimated to match the coefficient from this regression.

4.4 Knowledge Diffusion from Adoption

We study whether there is knowledge diffusion from the adopted technology to other firms that did not directly adopt the technology. We use patent citation 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 citation to the foreign technology seller compared with the other one.

To mimic the ideal experiment, we use a matching-based event study.[46] We matched two foreign firms, one of which sold technology (treated) while the other did not (control). We use minimum distance matching in terms of logged patent stock while exactly matching on the country, year, and the main patent field (IPC 3 digit).[47] Table C.3 shows that there is no statistically significant difference between two groups in terms of cumulative patent and 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 never-adopters to foreign firms around the event year. We exclude the citations from adopters to measure spillovers. Specifically, we estimate the below equation.

$$Y_{it} = \sum_{k=-5}^{10} \beta_{\mathrm{k}}^{\mathrm{Seller}} \mathbf{1}_{\left\{L_{it}^{\mathrm{Seller}}=k\right\}} + \sum_{k=-5}^{10} \beta_{k}^{All} \mathbf{1}_{\left\{L_{it}^{\mathrm{All}}=k\right\}} + \alpha_i + \gamma_t + \epsilon_{it} \tag{38}$$

Y_{it} is a citation dummy variable which is equal to one if any Korean never-adopters cite 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). α_i is the foreign firm fixed effects, γ_t is year fixed effects, and ϵ_{it} is the error term. Therefore, β_k^{All} captures common trend around the event year, and $\beta_k^{\mathrm{Seller}}$ captures the difference between treated and control firms. We cluster standard error at the technology field level (3-digit IPC) and year.

Figure 7 plots β_k^{Real} in which there is an increase in the number of patent citations to the technology seller compared with control firms. It suggests that Korean firms build on the adopted technology when they innovate, which implies a positive externality of the adoption. We do not find a clear pre-trend before the first technology adoption, supporting that the difference is not driven by the different trends between the two groups. This result would identify the model's knowledge diffusion parameter δ. Details of model counterpart is in Section 5.1.3.

[46]Specification is similar to Jaravel et al. (2018), Humlum (2019), and Prato (2022).

[47]For patent field, we use the most frequent three digit IPC class in each foreign firm.

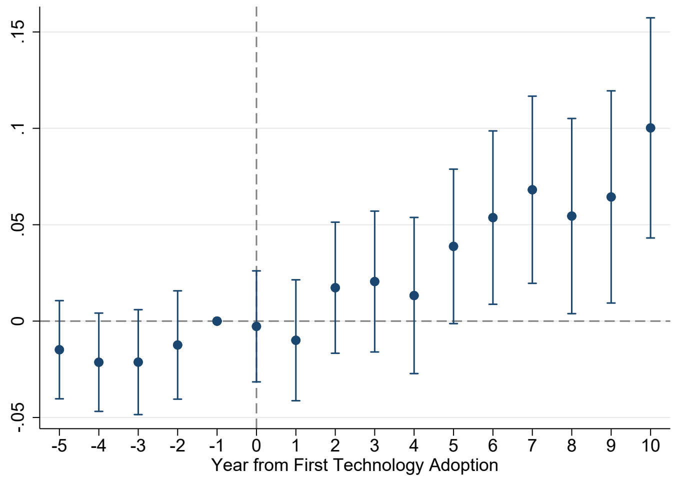


Figure 7: Event Study Result of Patent Citations

Notes: The figure plots β_k^{Seller} in equation (38), which captures the difference between the foreign firm that sold technology to a Korean firm and the foreign firm that did not sell in terms of the probability of citation received from the Korean never-adopters. The vertical line is a 95% confidence interval. The coefficient one year before the adoption is normalized as zero. The standard error is clustered at the foreign firm level.

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 C.2 shows no clear difference between treated and control groups in terms of total citations, which bolsters the credibility of the event study result. To study the intensive margin as well, figure C.4 plots the difference of the inverse hyperbolic transformation of the number of citations. Table C.4 shows the entire coefficient with standard errors for both extensive and intensive margins.

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

$$Y_{it} = \beta^{\text{Seller}} \cdot \mathbf{1}(L_{it}^{\text{seller}} > 0) + \beta^{\text{All}} \cdot \mathbf{1}(L_{it}^{\text{All}} > 0) + \alpha_i + \gamma_t + \epsilon_{it} \tag{39}$$

Table 4 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 4: 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^{seller} in equation (39), which is the 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.

5 Quantitative Exercise

5.1 Estimation

We estimate 20 parameters in three steps. First, four parameters are directly from the data, such as population and subsidy rates. Then, six parameters are externally calibrated. The remaining ten parameters are jointly estimated by the simulated method of moments (SMM). To be specific, 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 simulate the same regression in our empirical analysis and calculate the coefficients. Then, we update parameters to minimize the distance between the moments from the model and the data. The computational algorithm to solve the transition is in Appendix D.2.

5.1.1 Directly from Data

We set labor supply $L_H = 1$ as normalization and $L_F = 2$ to match Japan's relative population size. For government policy s_{Hat}, s_{Hrt}, we use tax credit for adoption and innovation. As an adoption subsidy, the Korean government has exempted corporate tax from the expense of adoption fees to foreign firms since 1973.[48,49] To be specific, firm gets full tax credit from the fixed fee and royalty payment for the first five years of the adoption contract, and half tax credit for the following three years. In 1981, the policy changed to give tax credit only for five years. In 1991, the policy limited the coverage of adoption tax credit to "advanced technology". In the data, 42% of adoption contracts have gotten tax credit since 1991, and we interpret this as the firms get 42% of the tax credit from adoption costs. Lastly, 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 by the formula from Bloom et al. (2002). The tax credit rate is from Choe and Lee (2012).[50]

We include s_{Hat}, s_{Hrt} into the model while assuming the perfect foresight of the agents. For country F, $s_{Fat} = 0, s_{Frt} = 0$.[51]

5.1.2 External Calibration

We use discount rate $\rho = 0.03$, following common value in the literature. R&D and adoption cost curvature parameter γ is set to be 2 to follow the estimate in the innovation literature (Refer to Acemoglu et al., 2018, for the discussion.). We impose $\sigma = 7$ following Burstein et al. (2021). For iceberg trade cost, we use $D = 1.5$ following Anderson and Van Wincoop (2004).

5.1.3 Internal Calibration using 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 in the balanced growth path be 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.

[48] In the 1970s, there was also sector-specific adoption subsidy which subsidizes 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.

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

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

[51] Since we calibrate α_{Fa}, α_{Fr} different from home country to make two countries symmetric in the long run, abstracting away from policy in country F does not change the result a lot.

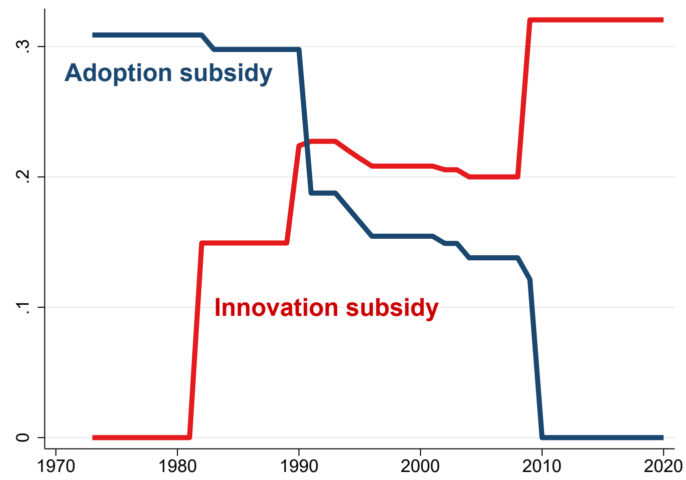


Figure 8: Innovation and Adoption Subsidy Rate in Korea

Notes: We plot adoption and innovation (R&D) subsidy rate. We calculate innovation and adoption subsidy rate 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).

$$\min_{\Theta} \sum_{i=1}^{10} \left(\frac{M_i^D - M_i(\Theta)}{\frac{1}{2}(M_i^D + M_i(\Theta))} \right)^2 \tag{40}$$

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

Adoption fee / yearly sale The adoption fee over the yearly sale from the adoption contract is 22.4% on average.[52] Likewise, we calculate the adoption fee over annualized sales in the model and compare two moments. The critical parameter is ξ which governs the bargaining power of the adopter.

Productivity gain over the gap from adoption and innovation We replicate the regression 37 in the model, and compare the coefficients from table C.2. We simulate 100,000 adopting / innovating firms by using the distribution of productivity gap conditional on adopting/innovating. We calculate the sales per employee growth from adoption and innovation for each simulated firm. Then, we regress it with the initial sales per employee gap from the foreign firm. Then, we compare the regression coefficient in the model and the data in table C.2. The key parameters are η_x, η_a which govern the slope of step size distribution from adoption and innovation (Figure 3).

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

Patent citation increase from non-adopters after adoption To replicate the result in figure 7, we develop a simple model of patent citation. In the model, the home follower can receive knowledge diffusion from 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 getting knowledge diffusion. Therefore, we match $x \cdot \delta = 0.0284$, which informs δ.

Long-run growth rate The growth rate of Japan since 2010 is 1.6%, and we consider it as the growth rate in the balanced growth path. 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 over the value added in manufacturing is 2.97%, and that of adoption is 1.48% in 1985-1990.[53] These inform the scale parameter of innovation cost, α_r, and the scale parameter of adoption cost α_a. From equation (31), we can calculate the innovation expenditure function, which decreases with α_r. Likewise, α_a decreases adoption rate and adoption expenditure which is adoption rate times adoption fee.

GDP gap in 1973 and 2020 The initial log ratio of GDP per capita[54] between Korea and Japan was 1.562 in 1973. 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 $N(d, 1)$. The GDP gap became 0.019 in 2020. It informs ϕ, which is the exogenous spillover parameter. When we have higher ϕ, convergence is faster, and the GDP gap in 2020 is smaller.

Productivity gap in 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 in 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.

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

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

Table 5: Estimation Result

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	Burstein et al. (2021)
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)
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	

Table 6: Moments

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
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 gap in 1973	1.560	1.562
GDP gap in 2020	0.017	0.019
Long-run productivity gap	0.001	0.000

5.2 Estimation Result

Table 5 shows the result of estimation. λ is estimated to be 1.047, which means one step improvement increases 4.7% of labor productivity. $\eta_x > \eta_a$ implies the slope of the step size distribution of adoption is larger than that of the innovation. This is because, from the regression (37), sales per employee is more sensitive to the initial productivity gap for

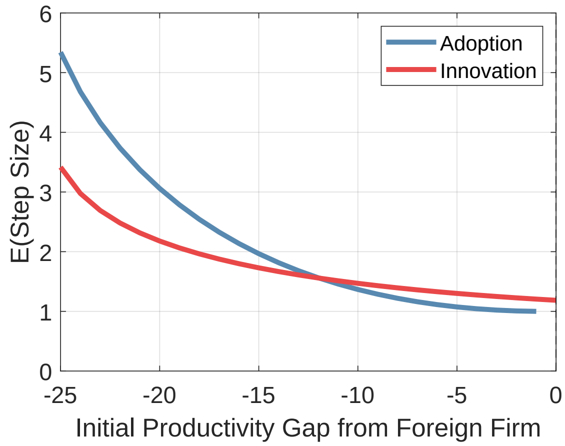


Figure 9: Step Size Distribution from Adoption and Innovation

Notes: We plot the expected step size from adoption and innovation in the model with $\eta_a = 1.203, \eta_r = 1.832$.

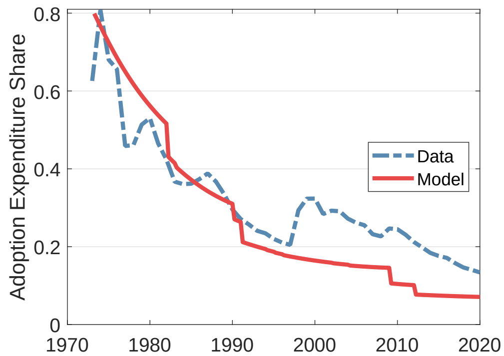
adoption than innovation. Figure 9 shows the step size distribution from the estimated parameters, which is in line with empirical findings in figure 6. On the other hand, $\alpha_a < \alpha_r$ means adoption requires smaller number of labor. ξ, the bargaining power parameter of the adopting firm is 0.464, which implies that the adopter takes less than half of the total surplus from the adoption. δ, the probability of getting knowledge diffusion is 0.231, which is much lower than one.[55] d, the initial productivity gap is -23.672, meaning the productivity of foreign firms is 2.97 times higher than that of Korean firms. α_F is 5.702, which implies F has a higher cost for innovation and adoption. It is because the entrant in F always has a higher incentive to innovate, and we target long-run technology gap as zero. ϕ is 0.025, so the firms are getting exogenous spillover with 2.5% every period.

Table 6 shows the target moment from the data and the model. The model could tightly match the micro and macro moments in the data. In particular, the model can replicate Korea started with a large GDP gap and caught up with Japan within a short period.

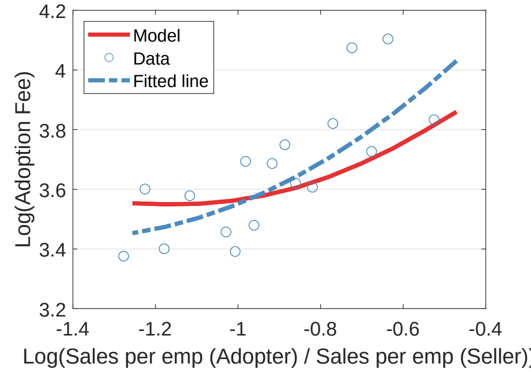
5.3 Validation of Model

To validate the model, we present two untargeted moments in the model and compare them with the data. The left panel of figure 10 plots the adoption expenditure / (adoption expenditure + R&D expenditure) over time in the model and the data. Although we only

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



A. Adoption Expenditure Share



B. Adoption Fee over Gap

Figure 10: Untargeted Moments

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

target the average value of adoption and R&D / value added in 1985-1990, we can match the decreasing pattern of adoption expenditure share well.[56] This is because, in the model, as the firms are getting closer to the foreign firm, they are more likely to innovate instead of adopting foreign technologies.

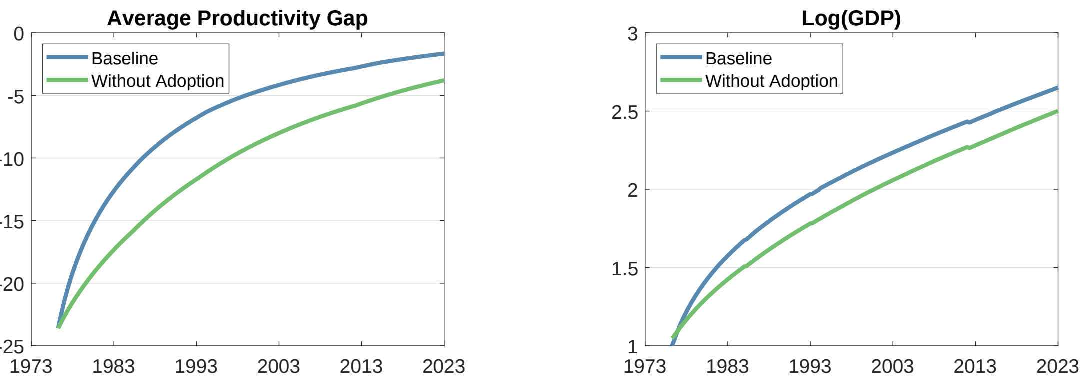
The right panel of figure 10 plots log (adoption fee) over log ratio of sales per employment between domestic and foreign firms from the model and data. In the model, the adoption fee is larger when domestic firms are closer to the foreign firms in terms of productivity. As the value function changes more with the relative productivity when firms are closer to each other, which makes the gain and loss from adoption larger, and increases the adoption fee.

5.4 Contribution of Adoption and Innovation

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

The left panel of figure 11 shows the average productivity gap over time in the baseline case and the case where we shut down the adoption but keeps innovation subsidies. It shows that convergence is much slower without adoption, especially in the early years. This is

[56]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 without both subsidies.



A. Average Productivity Gap B. Log(GDP)

Figure 11: Counterfactual without Adoption

Notes: The baseline case is with adoption and subsidies. Without adoption is when we shut down the adoption channel but keep the innovation subsidy.

because adoption provides a better way to reduce the gap from the foreign firm in the early period. The right panel of figure 11 compares log(GDP) over time with the baseline case and the case without adoption. We can see Korea loses a substantial portion of GDP when we shut down GDP. In particular, the growth rate is much higher with adoption in the early period. GDP in 2023 would have been 13.5% lower, and welfare in the infinite horizon would have been 11.88% lower in consumption equivalent unit without adoption.

Next, we decompose the TFP growth between adoption and innovation over time. We define TFP as below.

$$\text{TFP}_{Ht} = \exp\Big(\int_0^1 \ln\big((\psi_H^{\frac{1}{\sigma}} q_{H1jt}^{\frac{\sigma-1}{\sigma}} + \psi_H^{\frac{1}{\sigma}} q_{H2jt}^{\frac{\sigma-1}{\sigma}})^{\frac{\sigma}{\sigma-1}}\big) dj\Big) \tag{41}$$

Specifically, we simulate TFP in the next period with innovation only and adoption only and get the growth rate separately. Then, we decompose TFP growth between adoption and innovation.

Figure 12 shows the contribution of adoption on growth is 76% in 1973, and it decreases to 15% 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. Again, the policy change has contributed to this decreasing trend, but the model still has decreasing pattern even without both subsidies.

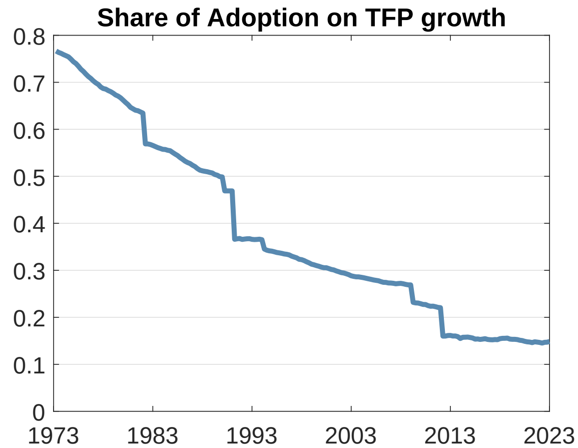


Figure 12: Share of TFP Growth from Adoption

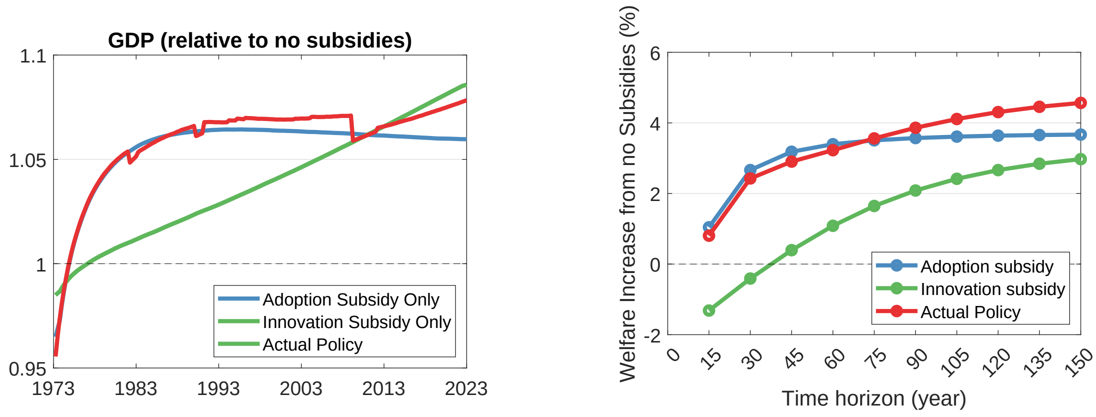
Notes: Growth share of adoption is TFP growth from adoption / (TFP growth from adoption + TFP from innovation).

6 Policy Analysis

In this section, we first discuss the policy implication of the model. Then, we evaluate the technology policies implemented in Korea since 1973, which started with an adoption subsidy and switched to an innovation subsidy. Next, we study the optimal timing of the switch from adoption to innovation subsidy. Then, we study the optimal subsidy rate over the year. In Appendix F.1, we study Japan's policy where the Japanese government prevents firms from exporting technology.

6.1 Policy Implications of the Model

As we discussed in Section 2, the competitive equilibrium of our model is not efficient because adoption and innovation have intertemporal spillovers. The size of intertemporal spillover is proportional to the productivity gain from adoption and innovation. Therefore, the social value of adoption and innovation depends on the relative step size. Since our empirical analysis suggests the productivity gain from adoption is larger than that from innovation at the early stage of development, the optimal subsidy rate would be 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 rate decreases while the optimal innovation subsidy rate increases.



A. Relative GDP

B. Welfare increase (%)

Figure 13: Results of the Counterfactual Analysis

Notes: This figure plots the counterfactual results. Panel A plots GDP in three scenarios divided by GDP in the benchmark case without subsidies. The blue line is when subsidizing only adoption with 31%, the green line is when subsidizing only innovation with 32%, and the red line follows the actual policy in figure 8. Panel B plots welfare increase compared to the case without subsidies in different time horizons. Welfare is in consumption equivalent unit.

6.2 Evaluation of Technology Policy in Korea

As a baseline case, we include both adoption and innovation subsidies over the year from the data as in figure 8. We compare the baseline with three counterfactuals. First, there is no subsidy at all. Second, the government subsidizes only adoption with 31%, the initial value in the baseline. Lastly, the government subsidizes only innovation with 32%, the final value in the baseline.[57]

The left panel of figure 13 shows the relative GDP compared with the case without both subsidies over time. When we subsidize adoption only, it brings a higher growth rate at the early stage. It gets higher GDP compared to the case without policy. However, the relative GDP does not grow exponentially, implying that subsidizing only adoption does not generate a significantly higher long-run growth rate. On the other hand, when we subsidize only innovation, it does not have a higher growth rate at the beginning compared with the adoption subsidy case. However, it has a higher growth rate at the late stage of development. This is because subsidizing innovation in the early years can be distortive, allocating resources to innovation instead of adoption, although adoption has a larger positive externality. Lastly, the baseline case has a GDP similar to the adoption subsidy case and has a higher growth rate at the late stage of development.

[57]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 the actual adoption and innovation subsidies.

The right panel of figure 13 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 benchmark without both subsidies in terms of consumption units. For example, a 3% increase means the welfare is equivalent to the case when we uniformly increase consumption by 3%. When the time horizon is small such as 15 or 30 years, subsidizing innovation generates lower welfare than the benchmark case without both subsidies. 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. The result implies that when developing countries follow an innovation policy which is common in developed countries, it may reduce short-run welfare, which makes it hard to sustain.

In the infinite horizon, subsidizing only adoption is equivalent to a 3.69% increase in consumption, subsidizing only innovation is 3.28%, and the baseline case with policy change is 4.84%. This result implies that the stage-dependent policy performs better than the time-invariant policies.

6.3 Optimal Timing to Switch

The previous result suggests that the stage-dependent policy, which switched from adoption to innovation subsidy generates higher welfare than other alternatives. Motivated by this, we study the optimal timing to switch from adoption to innovation subsidy. 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 the welfare in the infinite horizon.

Figure 14 shows the welfare increase compared with the case without both subsidies in consumption units over different timing to switch. The result suggests that it was optimal to switch from adoption to innovation subsidy in 1992 when the GDP per capita in Korea was 57% of that of Japan. In the early stages of development, the productivity gap from the foreign country is large, which generates larger 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 larger than that from adoption. Thus, the government needs to switch to adoption subsidies at a certain point. The actual policy in Korea decreased the adoption subsidy in 1991 and increased the innovation subsidy in 1989. Our result suggests that the actual policy was close to the optimal in terms of timing to switch from adoption to innovation subsidy.

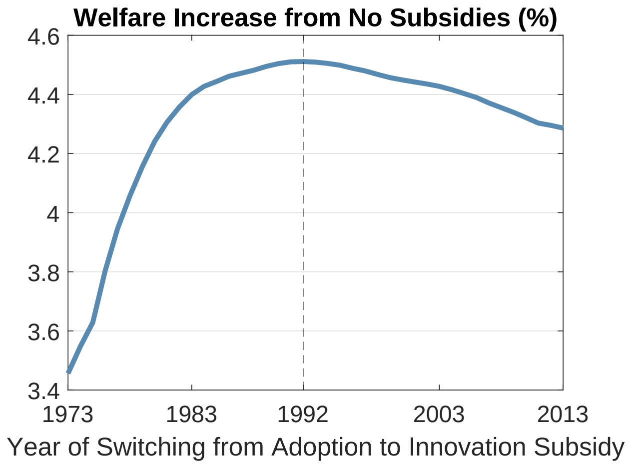


Figure 14: Welfare Increase over Different Year to Switch from Adoption to Innovation

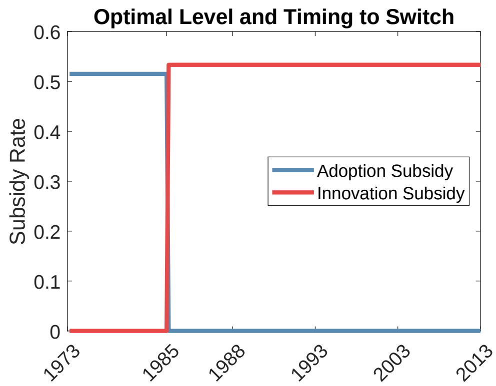
Notes: We plot welfare increase compared with the case without policy over different timings of switching. Welfare increase is in consumption equivalent unit. We start with adoption subsidy 32% and innovation subsidy 0% and switch to adoption subsidy 0% and innovation subsidy 32% in a certain year. In 1992, the GDP per capita in Korea was 57% of that of Japan.

6.4 Optimal Rate of Subsidy and Timing to Switch

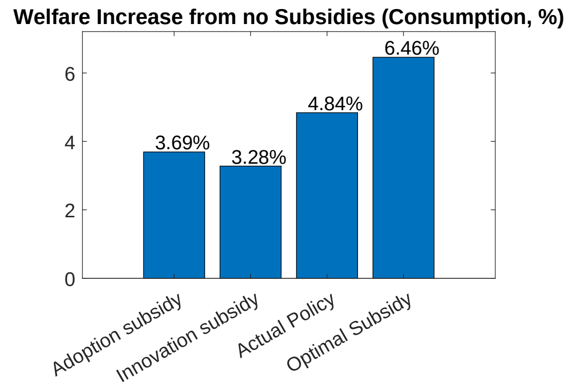
In this section, we study the optimal policy in a more general setting. We allow the government to choose the adoption subsidy rate, innovation subsidy rate, and the timing to switch from adoption to innovation subsidy.[58]

Figure 15 shows the optimal subsidies over time. The optimal policy is to start adoption subsidy at 52% and switch to innovation subsidy in 1985, at 53%. In 1985, the GDP per capita in Korea was 54% of that of Japan. The timing of switch is earlier than the previous exercise because the adoption subsidy rate is higher, Korea catches up with Japan more quickly.

[58]We assume that the government can change the policy only once due to commitment issues or political costs.



A. Optimal Subsidy



B. Welfare increase (%)

Figure 15: Optimal Policy and Welfare Increase

Notes: This figure plots the optimal subsidy and welfare results. Panel A plots the optimal adoption and innovation subsidy rate. We allow the government can choose an adoption rate, innovation rate, and year to change from adoption to innovation subsidy. The optimal policy is to start adoption subsidy at 52% and switch to innovation subsidy in 1985, at 53%. In 1985, the GDP per capita in Korea was 60% of that of Japan. Panel B plots the welfare increase from the benchmark case without both subsidies in consumption equivalent units.

7 Conclusion

Many developing countries have been trying to improve their technology by following the technology policies of developed countries. However, the way firms grow in developing countries differs from developed countries, which requires different policies.

In this paper, we study how firms in developing countries grow over different stages of development. We focus on two different ways to improve technology: adoption from foreign countries and innovation. Our contribution is to provide a novel micro dataset, find new empirical findings, and build a novel theoretical framework to study growth from innovation and adoption. In particular, we capture strategic interactions between adopters and technology sellers. Based on this framework, we quantify the contribution of adoption and innovation and study the policy implications.

We show that the contribution of technology adoption to TFP growth was 76% in Korea in 1973, but it decreased to 15% in 2022. Korea started with an adoption subsidy and then gradually switched to an innovation subsidy. The stage-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%). Especially when the government subsidizes only innovation, the welfare is smaller than the case without both subsidies until 30 years. Furthermore, we study the optimal timing of the switch from adoption to innovation subsidy.

Our result suggests that the country needs to switch from adoption to innovation subsidy when it reaches 57% of the frontier country's GDP.

We believe that our framework can be used to study broader questions. Cross-country comparison would be a very interesting future research. How was adoption subsidy in Korea different from other developing countries? Are there any fundamental factors that increase the effectiveness of technology adoption? These questions are important for making general policy advice that can be helpful to many developing countries.

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A Appendix: Model

A.1 Value Function

Value function of a home firm with a state variable $\mathbf{m} = \{m_F, m_D\}$ when $m_D < 0$ is as below:

$$
\begin{aligned}
& r_{Ht}V_{Ht}(\mathbf{m}) - \dot{V}_{Ht}(\mathbf{m}) \\
& = \max_{x_{H\mathbf{m}t}, a_{H\mathbf{m}t}} \underbrace{\Pi_{Ht}(\mathbf{m})}_{\text{profit}} - (1 - s_{Hrt}) \underbrace{\alpha_{Hr}\frac{(x_{H\mathbf{m}t})^{\gamma}}{\gamma} w_{Ht}}_{\text{innovation cost}} - (1 - s_{Hat}) \underbrace{\alpha_{Ha}\frac{(a_{H\mathbf{m}t})^{\gamma}}{\gamma} w_{Ht}}_{\text{adoption cost}} \\
& + x_{H\mathbf{m}t} \sum_n \tilde{f}_{\mathbf{m}}(n) \underbrace{[V_{Ht}(m_F + n, m_D + n) - V_{Ht}(\mathbf{m})]}_{\text{gain from innovation}} \\
& + a_{H\mathbf{m}t} \sum_n \tilde{g}_{\mathbf{m}}(n) [(\underbrace{V_{Ht}(m_F + n, m_D + n) - V_{Ht}(\mathbf{m})}_{\text{gain from adoption}} - \underbrace{(1 - s_{Hat})\mathcal{F}_{H\mathbf{m}t}}_{\text{adoption fee}})] \\
& + \tilde{x}_{H\mathbf{m}t} \sum_n f_{m_F - m_D}(n) \underbrace{[V_{Ht}(m_F, m_D - n) - V_{Ht}(\mathbf{m})]}_{\text{loss from follower innovation}} \\
& + \tilde{a}_{H\mathbf{m}t} \sum_n g_{m_F - m_D}(n) \underbrace{[V_{Ht}(m_F, m_D - n) - V_{Ht}(\mathbf{m})]}_{\text{loss from follower adoption}} \\
& + (x_{F\mathbf{m}t} + \tilde{x}_{F\mathbf{m}t}) \sum_n f_{-m_F + m_D}(n) \underbrace{[V_{Ht}(m_F - n, m_D) - V_{Ht}(\mathbf{m})]}_{\text{loss from foreign firm innovation}} \\
& + a_{F\mathbf{m}t} \sum_n g_{-m_F + m_D}(n) \underbrace{[V_{Ht}(m_F - n, m_D) - V_{Ht}(\mathbf{m})]}_{\text{loss from foreign leader adoption}} \\
& + \underbrace{\phi(V_{Ht}(\mathbf{0}) - V_{Ht}(\mathbf{m}))]}_{\text{exogenous spillover}}
\end{aligned}
\tag{42}
$$

$\tilde{x}_{H\mathbf{m}t}, \tilde{a}_{H\mathbf{m}t}$ are the innovation and adoption rate of domestic competitor when the current gap is $\mathbf{m}$.

Value function of foreign firm is as below:

$$
\begin{aligned}
& r_{Ht}V_{Ht}(\mathbf{m}) - \dot{V}_{Ht}(\mathbf{m}) \\
& = \max_{x_{F\mathbf{m}t}, a_{F\mathbf{m}t}} \underbrace{\Pi_{Ft}(\mathbf{m})}_{\text{profit}} - (1 - s_{Frt}) \underbrace{\alpha_{Fr} \frac{(x_{F\mathbf{m}t})^{\gamma}}{\gamma} w_{Ft}}_{\text{innovation cost}} - \underbrace{(1 - s_{Fat}) \alpha_{Fa} \frac{(a_{F\mathbf{m}t})^{\gamma}}{\gamma} w_{Ft}}_{\text{adoption cost}} \\
& + x_{F\mathbf{m}t} \sum_n f_{m_F}(n) \underbrace{[V_{Ft}(m_F + n, m_D) - V_{Ft}(\mathbf{m})]}_{\text{gain from innovation}} \\
& + a_{F\mathbf{m}t} \sum_n g_{m_F}(n) [(\underbrace{V_{Ft}(m_F + n, m_D) - V_{Ft}(\mathbf{m})}_{\text{gain from adoption}} - \underbrace{(1 - s_{Fat}) \mathcal{F}_{F\mathbf{m}t}}_{\text{adoption fee}})] \\
& + x_{H1\mathbf{m}t} \sum_n f_{-m_F}(n) \underbrace{[V_{Ft}(m_F - n, m_D) - V_{Ft}(\mathbf{m})]}_{\text{loss from home leader innovation}} \\
& + a_{H1\mathbf{m}t} \sum_n g_{-m_F}(n) [\underbrace{V_{Ft}(m_F - n, m_D) - V_{Ft}(\mathbf{m})}_{\text{loss from home leader adoption}} + \mathcal{F}_{H1\mathbf{m}t}] \\
& + x_{H2\mathbf{m}t} \sum_n \tilde{f}_{-m_F - m_D, -m_D}(n) \underbrace{[V_{Ft}(\min\{m_F, m_F + m_D - n\}, \max\{m_D - n, n - m_D\}) - V_{Ft}(\mathbf{m})]}_{\text{loss from home follower innovation}} \\
& + a_{H2\mathbf{m}t} \sum_n \tilde{g}_{-m_F - m_D, -m_D}(n) [\underbrace{V_{Ft}(\min\{m_F, m_F + m_D - n\}, \max\{m_D - n, n - m_D\}) - V_{Ft}(\mathbf{m})}_{\text{loss from home follower adoption}} + \mathcal{F}_{F2\mathbf{m}t}] \\
& - \underbrace{\tilde{x}_{F\mathbf{m}t} V_{Ft}(m_F, m_D)}_{\text{replaced by Entrant}} + \underbrace{\phi(V_{Ht}(\mathbf{0}) - V_{Ht}(\mathbf{m}))}_{\text{exogenous spillover}}
\end{aligned}
\tag{43}
$$

Value function of potential entrant in country F is defined as below:

$$
\begin{aligned}
r_{Ft}\tilde{V}_{Ft}(\mathbf{m}) - \dot{\tilde{V}}_{Ft}(\mathbf{m}) = & \max_{\tilde{x}_{F\mathbf{m}t}} - (1 - s_{Frt}) \underbrace{\tilde{\alpha}_{Fr} \frac{(\tilde{x}_{F\mathbf{m}t})^{\gamma}}{\gamma} w_{Ft}}_{\text{innovation cost}} \\
& + \tilde{x}_{F\mathbf{m}t} \sum_n g_{m_F}(n) V_{Ft}(m_F + n, m_D)
\end{aligned}
\tag{44}
$$

A.2 Adoption Fee

Adoption fee when the home follower adopts from foreign firm is as below when the gap from foreign firm is $\mathbf{m} = \{m_F, m_D\}$, with $m_D < 0$.

$$
\begin{aligned}
\mathcal{F}_{H\mathbf{m}t} &= \underset{\mathcal{F}_{H\mathbf{m}t}}{\text{argmax}}(\sum_n \tilde{g}_{\mathbf{m}}(n)V_{Ht}(m_F+n, m_D+n) - \mathcal{F}_{H\mathbf{m}t} - V_{Ht}(\mathbf{m}))^{\xi} \\
&\cdot (\sum_{n=1}^{m_D} \tilde{g}_{m_F}(n)V_{Ft}(-m_F, -m_D-n) + \sum_{n=m_D+1}^{\bar{m}-m_F} \tilde{g}_{m_F}(n)V_{Ft}(-m_F-(n-m_D), n-m_D) \\
&+ \mathcal{F}_{H\mathbf{m}t} - V_{Ft}(-m_F+m_D, -m_D))^{1-\xi} \\
\mathcal{F}_{H\mathbf{m}t} &= (1-\xi)(\sum_n g_{m_F}(n)V_{Ht}(m_F+n, m_D+n) - V_{Ht}(\mathbf{m})) \\
&- \xi(\sum_n g_{m_F}(n)V_{Ft}(-m_F+m_D-n, -m_D-n) - V_{Ft}(-m_F+m_D, -m_D))
\end{aligned} \tag{45}
$$

Adoption fee when the foreign adopts technology from home leader is as below when the gap from domestic firm is m_F, and the gap of home leader from home follower is m_D.

$$
\begin{aligned}
\mathcal{F}_{F\mathbf{m}t} &= \underset{\mathcal{F}_{F\mathbf{m}t}}{\text{argmax}}(\sum_n g_{m_F}(n)V_{Ft}(m_F+n, m_D) - \mathcal{F}_{F\mathbf{m}t} - V_{Ht}(\mathbf{m}))^{\xi} \\
&\cdot (\sum_n g_{m_F}(n)V_{Ht}(-m_F-n, m_D) + \mathcal{F}_{F\mathbf{m}t} - V_{Ht}(-m_F, m_D))^{1-\xi} \\
\mathcal{F}_{F\mathbf{m}t} &= (1-\xi)(\sum_n g_{m_F}(n)V_{Ht}(m_F+n, m_D) - V_{Ht}(\mathbf{m})) \\
&- \xi(\sum_n g_{m_F}(n)V_{Ft}(-m_F-n, m_D) - V_{Ft}(-m_F, m_D))
\end{aligned} \tag{46}
$$

A.3 Optimal Policy Function

The optimal innovation rate and adoption rate of home follower when the gap is $\mathbf{m}$ and $m_D < 0$ is as below:

$$
\begin{aligned}
x_{H\mathbf{m}t} &= \{\frac{1}{(1-s_{Hrt})\alpha_{Hr}w_{Ht}} \sum_n \tilde{f}_{m_F}(n)[V_{Ht}(m_F+n, m_D+n) - V_{Ht}(\mathbf{m})]\}^{\frac{1}{\gamma-1}} \\
a_{H\mathbf{m}t} &= \{\frac{1}{(1-s_{Hat})\alpha_{Ha}w_{Ht}} \sum_n \tilde{g}_{m_F}(n)[V_{Ht}(m_F+n, m_D+n) - V_{Ht}(\mathbf{m}) - (1-s_{Hat})\mathcal{F}_{H\mathbf{m}t}]\}^{\frac{1}{\gamma-1}}
\end{aligned} \tag{47}
$$

Likewise, the optimal innovation and adoption rate of foreign incumbent with gap $\mathbf{m}$ is as follows.

$$x_{F1\mathbf{m}t} = \{\frac{1}{(1-s_{Frt})\alpha_{Fr}w_{Ft}} \sum_n f_{m_F}(n)[V_{Ft}(m_F+n, m_D) - V_{Ft}(\mathbf{m})]\}^{\frac{1}{\gamma-1}}$$
$$a_{F1\mathbf{m}t} = \{\frac{1}{(1-s_{Fat})\alpha_{Fa}w_{Ft}} \sum_n g_{m_F}(n)[V_{Ft}(m_F+n, m_D) - V_{Ht}(\mathbf{m}) - (1-s_{Fat})\mathcal{F}_{F\mathbf{m}t}]\}^{\frac{1}{\gamma-1}} \tag{48}$$

Lastly, the optimal innovation rate of foreign entrant is as below.

$$x_{F2\mathbf{m}t} = \{\frac{1}{(1-s_{Frt})\alpha_{Fr}w_{Ft}} \sum_n f_{m_F}(n)V_{Ft}(m_F+n, m_D)\}^{\frac{1}{\gamma-1}} \tag{49}$$

B Appendix: Data

B.1 Technology Adoption data

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. 95% of contracts are in manufacturing in which the distribution is in Table B.1.

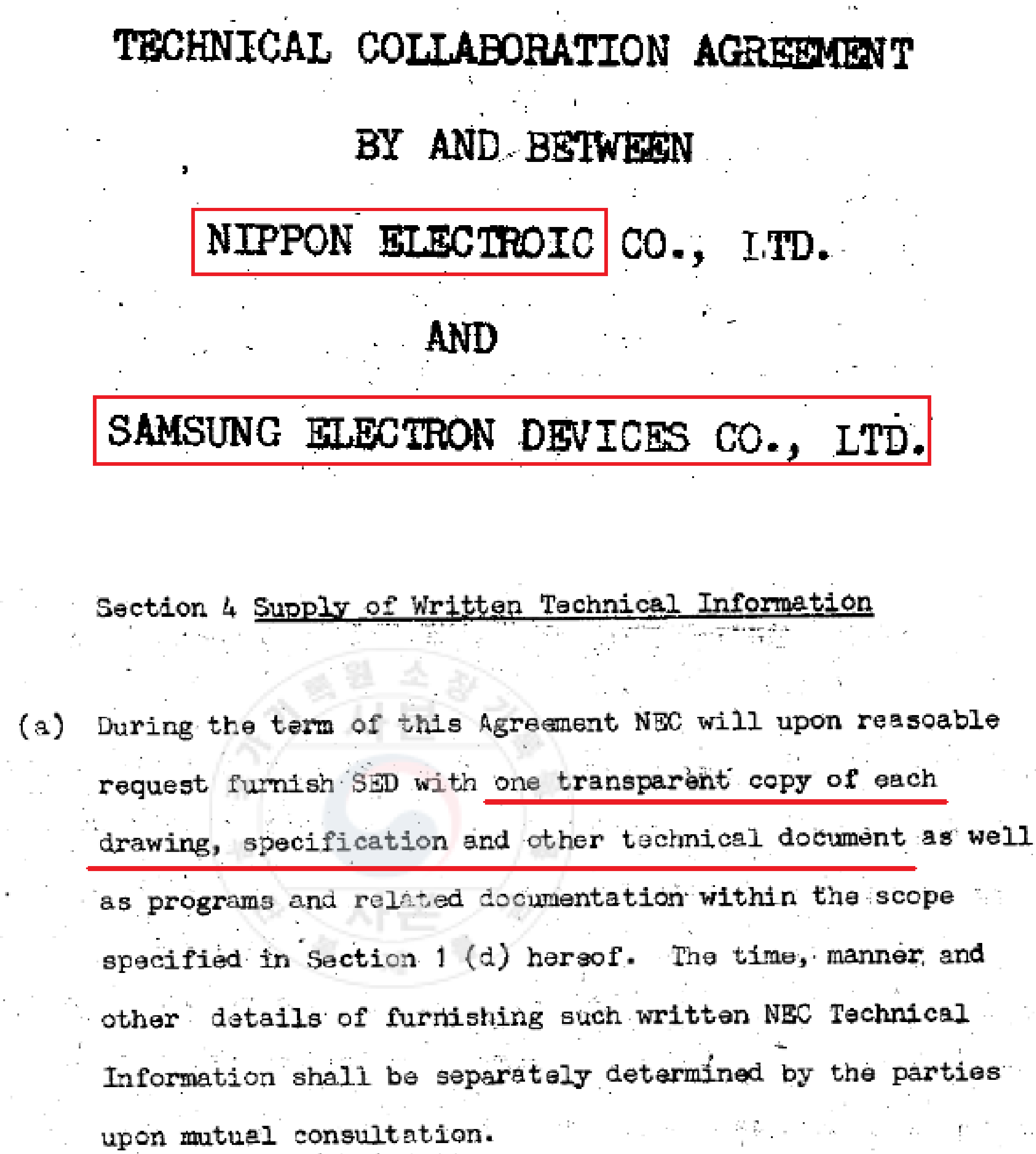
B.2 Firm-level Balance Sheet data

For the period between 1970 and 1982, we digitize Annual Reports of Korean Companies. The reports are published by the Korea Productivity Center. Figure B.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.[59] 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.

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

Figure B.1: Example of Adoption Contract



TECHNICAL COLLABORATION AGREEMENT

BY AND BETWEEN

NIPPON ELECTROIC CO., LTD.

AND

SAMSUNG ELECTRON DEVICES CO., LTD.

Section 4 Supply of Written Technical Information

(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.

Table B.1: Industry Composition of Technology Adoption

Sector	Frequency	Percent
machinery	2,261	26.55
electronics	2,111	24.79
chemical manufacturing	1,369	16.08
chemical fiber	423	4.97
metal	422	4.96
food	265	3.11
non-metallic products	230	2.70
shipbuilding	226	2.65
pharmaceutical	211	2.48
contruction	155	1.82
telecommunications	132	1.55
electrics	92	1.08
textile	66	0.78
paper	35	0.41
agriculture	31	0.36
etc.	487	5.72
Total	8,516	100.00

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. The variables are mostly same in the two dataset.

B.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 9,051 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

Figure B.2: Example of Adoption Contract

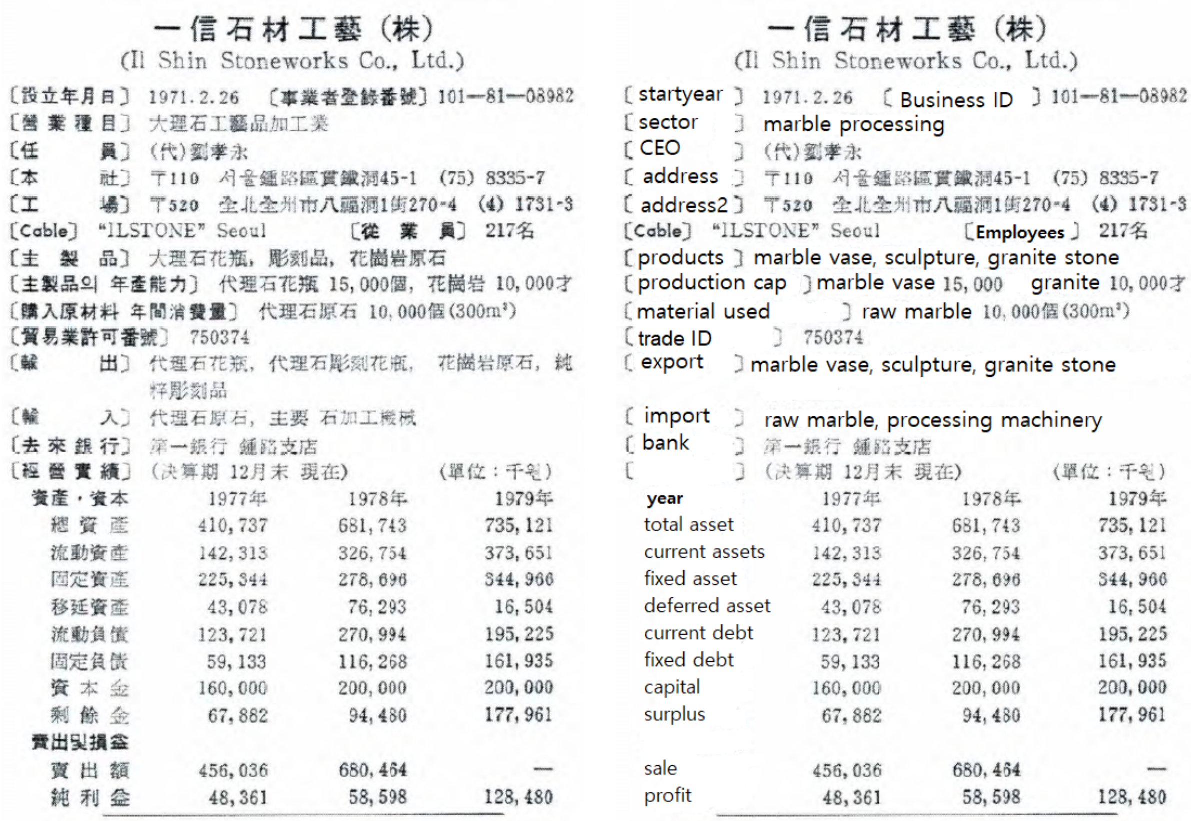
Section 7 Compensation

(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.

Table B.2: Country Composition of Technology Adoption

Country	Frequency	Percent
JPN	4,225	50.00
USA	2,224	26.32
DEU	470	5.56
FRA	339	4.01
GBR	310	3.67
ITA	148	1.75
CHE	133	1.57
NLD	114	1.35
CAN	78	0.92
SWE	58	0.69
BEL	55	0.65
NOR	47	0.56
DEN	44	0.52
AUS	38	0.45
AUT	26	0.31
FIN	23	0.27
RUS	21	0.25
HKG	19	0.22
SGP	11	0.13
etc.	67	0.79
Total	8,450	100



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)

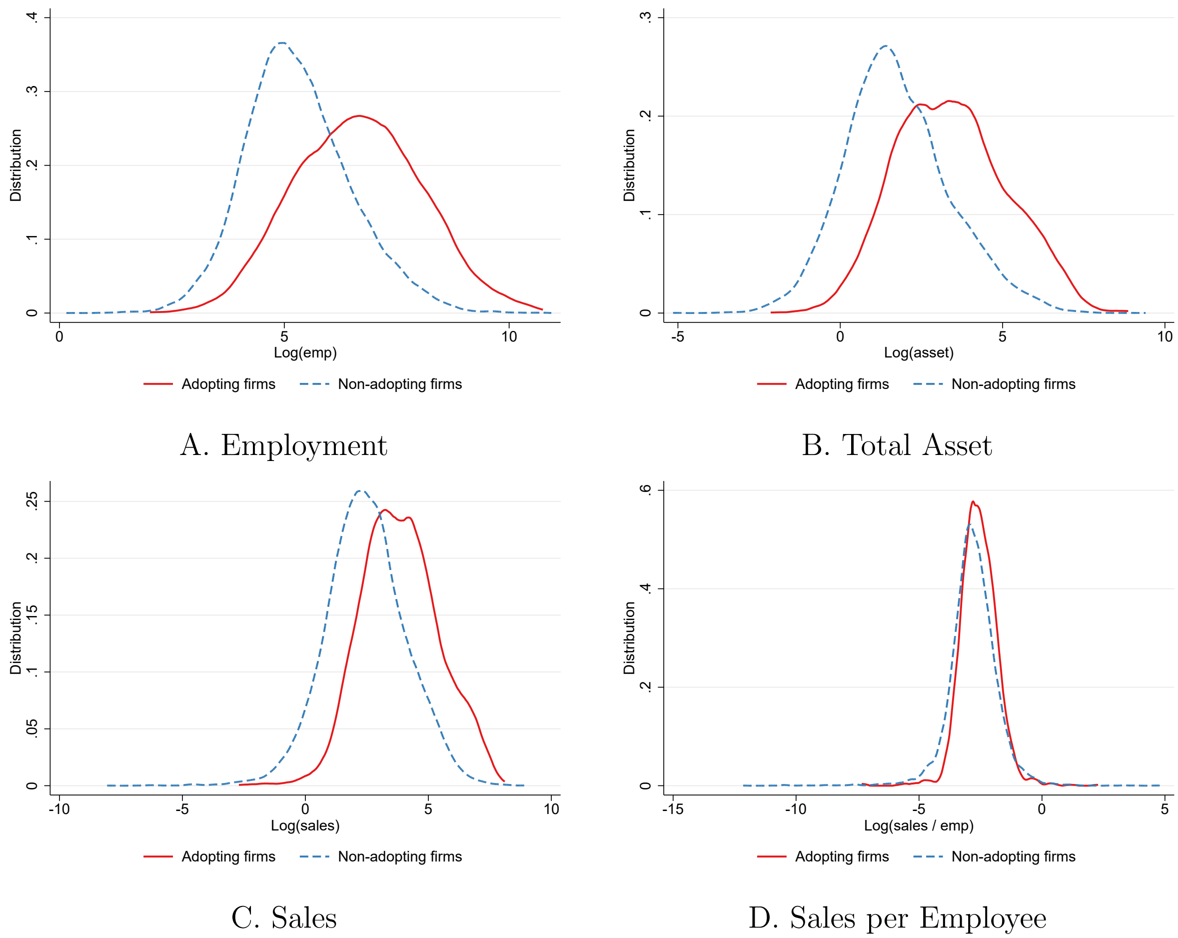
year	1977年	1978年	1979年
total asset	410,737	681,743	735,121
current assets	142,313	326,754	373,651
fixed asset	225,344	278,696	344,966
deferred asset	43,078	76,293	16,504
current debt	123,721	270,994	195,225
fixed debt	59,133	116,268	161,935
capital	160,000	200,000	200,000
surplus	67,882	94,480	177,961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

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

Notes: Both graph is in the balanced growth path of the model. We fix the gap between two domestic firms as zero.

USPTO ID attached to foreign firms.

B.4 Distribution of Variables of Adopting Firms and Non-adopting Firms



A. Employment

B. Total Asset

C. Sales

D. Sales per Employee

Figure B.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) by using kernel density estimation. We control sector-year fixed effects.

C Empirical Analysis: Robustness Checks and Additional Graphs

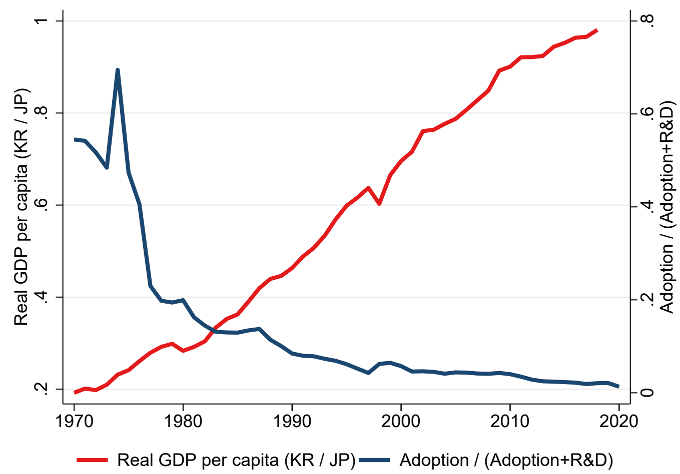


Figure C.1: Relative GDP per capita and Expenditure Share of Adoption over time

Notes: This figure plots the ratio of the real GDP per capita between Korea and Japan and the adoption expenditure share. Adoption expenditure is (gross) payment to Japanese 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), R&D and adoption expense are from World Bank DataBank.

Table C.1: Regression of Patent / (Patent+Adoption) with Productivity Gap

	Innovation share	
	Sector-level	Firm-level
Gap	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: In the first column, we regress the number of patents divided by the sum of the number of patents and the number of adoption contracts over the productivity gap at the sector-year. Productivity gap is the log value added per employment of Korea divided by that of Japan in each sector and year. Sector-level data is from STAN OECD data. We include year fixed effects. Second column is the same regression at the firm-level. The productivity gap is log sales per employee of a Korean firm divided by that of the foreign firm that 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 sector and year fixed effects.

Table C.2: 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 (37). 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(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.

Table C.3: 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.

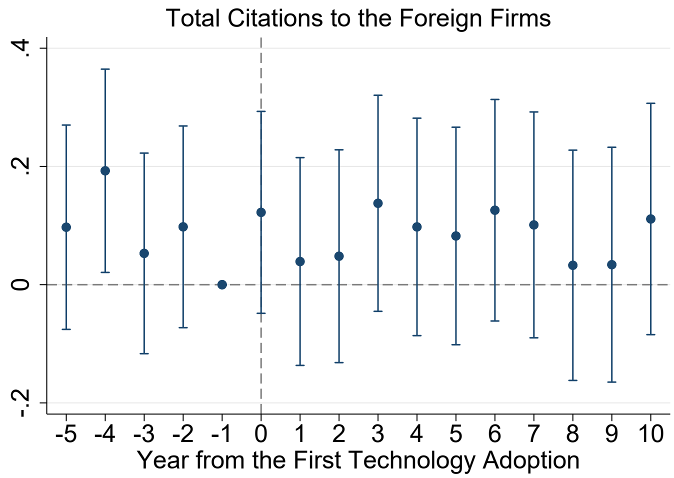


Figure C.2: Event Study Result of Patent Citations (placebo)

Notes: The figure plots β_k^{Seller} in equation (38), which captures the difference between the foreign firm that sold technology to a Korean firm and the foreign firm that did not sell in terms of logged number of citations that firm i received from all the other countries except Korea. The vertical line is a 95% confidence interval. The coefficient one year before the adoption is normalized as zero. The standard error is clustered at the foreign firm level.

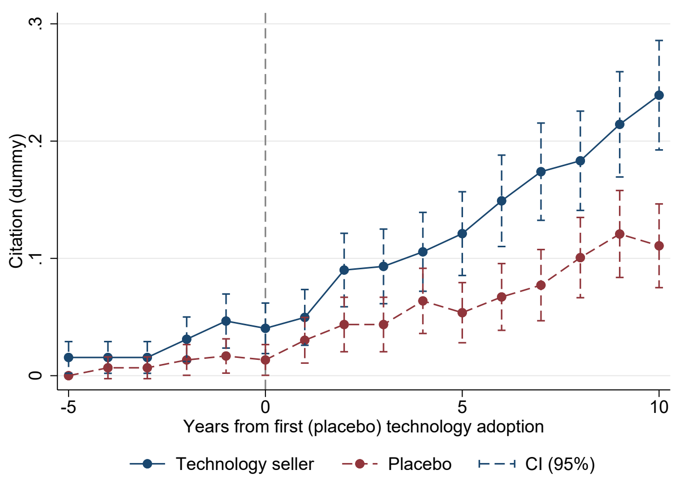


Figure C.3: Raw average of patent citations between two groups

Notes: The figure plots the average number of the citations from Korean never-adopters to the foreign firms in two groups (seller and placebo). Vertical line is 95% confidence interval.

Table C.4: Event study result of citations from the first technology adoption

	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

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

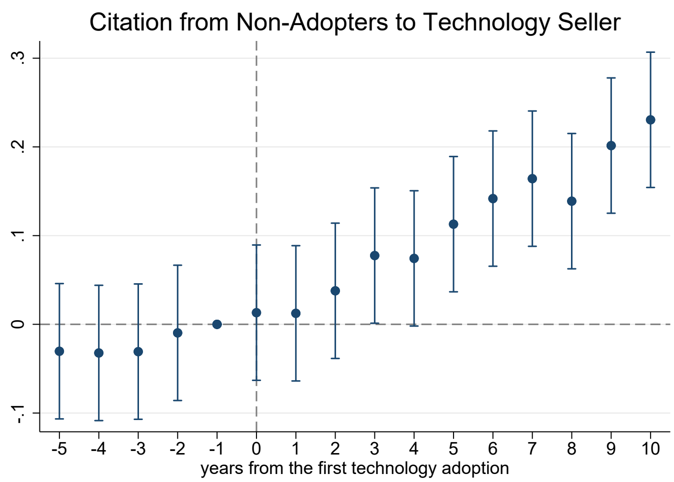


Figure C.4: Event study result of patent citations: intensive margin

Notes: The figure displays the difference between the foreign firm that sold technology to Korean firm and the foreign firm that did not in terms of the inverse hyperbolic transformation of the number of citations received from the Korean never-adopters.

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 of each country, consumption grows at the same rate g_t, while the distribution of productivity gap $\mu_{\mathbf{m}t}$, innovation rate $x_{\mathbf{cm}t}$, adoption rate $a_{\mathbf{cm}t}$, and the relative price P_{Ft}[60] stay the same. Therefore, it is useful to divide equation (28) 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 profit function as below.

$$\begin{aligned} \Pi_{Ht}(\mathbf{m}) &= \pi_{Ht}(\mathbf{m}) \cdot C_{Ht} + \pi^*_{Ht}(\mathbf{m}) \cdot P_{Ft}C_{Ft} \\ \frac{\Pi_{Ht}(\mathbf{m})}{C_{Ht}} &= \pi_{Ht}(\mathbf{m}) + \pi^*_{Ht}(\mathbf{m}) \cdot \frac{1-\psi_{Ht}}{\psi_{Ht}} \end{aligned} \tag{50}$$

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

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

$$
\begin{aligned}
&(r_{Ht}-g_t)v_{Ht}(\mathbf{m})\\
&=\max_{x_{H1\mathbf{m}t},a_{H1\mathbf{m}t}} \pi_{Ht}(\mathbf{m})+\pi^*_{Ht}(\mathbf{m})\cdot\frac{1-\psi_{Ht}}{\psi_{Ht}}-(1-s_{Hrt})\alpha_{Hr}\frac{(x_{H1\mathbf{m}t})^\gamma}{\gamma}w_{Ht}-(1-s_{Hat})\alpha_{Ha}\frac{(a_{H1\mathbf{m}t})^\gamma}{\gamma}w_{Ht}\\
&+x_{H1\mathbf{m}t}\sum_n f_{m_F}(n)[V_{Ht}(m_F+n,m_D+n)-V_{Ht}(\mathbf{m})]\\
&+a_{H1\mathbf{m}t}\sum_n g_{m_F}(n)[(V_{Ht}(m_F+n,m_D+n)-V_{Ht}(\mathbf{m})-(1-s_{Hat})\mathcal{F}_{H1\mathbf{m}t})]\\
&+x_{H2\mathbf{m}t}\sum_n \tilde{f}_{m_F-m_D}(n)[V_{Ht}(m_F,m_D-n)-V_{Ht}(\mathbf{m})]\\
&+a_{H2\mathbf{m}t}\sum_n \tilde{g}_{m_F-m_D}(n)[V_{Ht}(m_F,m_D-n)-V_{Ht}(\mathbf{m})]\\
&+(x_{F\mathbf{m}t}+\tilde{x}_{F\mathbf{m}t})\sum_n f_{-m_F}(n)[V_{Ht}(m_F-n,m_D)-V_{Ht}(\mathbf{m})]\\
&+a_{F\mathbf{m}t}\sum_n g_{-m_F}(n)[V_{Ht}(m_F-n,m_D)-V_{Ht}(\mathbf{m})+\mathcal{F}_{F\mathbf{m}t}\frac{1-\psi_{Ht}}{\psi_{Ht}}]\\
&+\phi(V_{Ht}(\mathbf{0})-V_{Ht}(\mathbf{m}))]
\end{aligned} \tag{51}
$$

Note that from the household Euler equation (21), 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 (51). After the normalized value functions converges, we check the labor market clearing condition from equation (19) for each country, and check the trade balance condition from equation (20). 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 $\mathbb{X}^0_t=\{\omega_{Ht},\omega_{Ft},\psi_{Ht}\}_{t=0}^{t=T}$
4. Given the guess, we solve value function, innovation, and adoption rate backward from the period T to period 0.

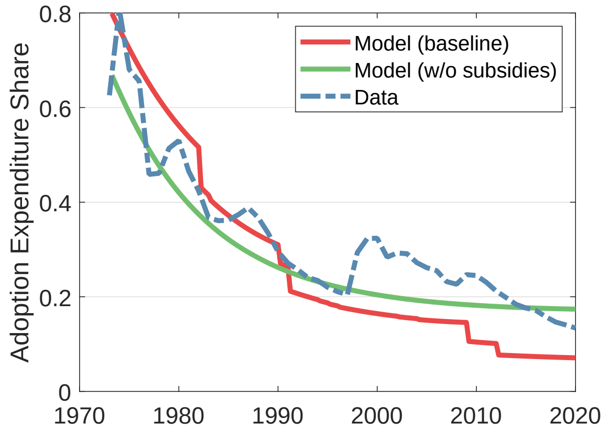


Figure E.1: Adoption Expenditure Share in the Model and the Data

Notes: We plot the adoption fee expenditure / (adoption fee + innovation cost) in the model (solid line) along with the data (dashed line). The Red line is the baseline with actual subsidies, and the green line is counterfactual without both subsidies.

5. Given the innovation and adoption decisions, we solve the distribution of productivity gap $\{\mu_{H\mathbf{m}t}\}_{t=0}^{t=T}$ 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 $\{\mu_{H\mathbf{m}t}\}_{t=0}^{t=T}$.

6. Get the distance $\|\mathbb{X}_t^0 - \mathbb{X}_t^1\|$ between the guess and implied value.[61]

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

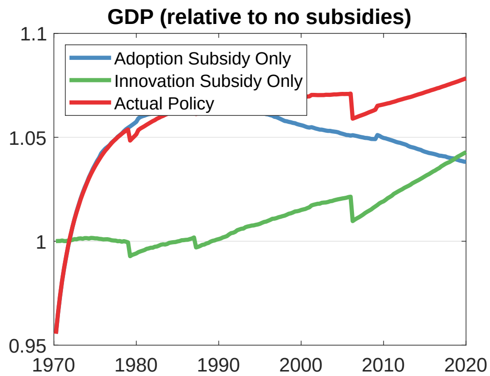
$$\mathbb{X}_t^{i+1} = (1-\Delta)\mathbb{X}_t^i + \Delta\tilde{\mathbb{X}}_t^{i+1} \tag{52}$$

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

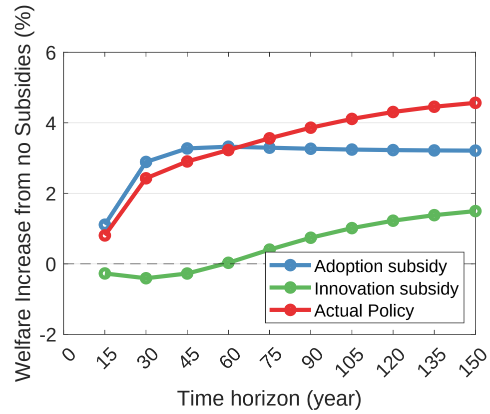
E Additional Figures in Quantitative Exercise

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.

[61]We use Euclidean norm.



A. Relative GDP



B. Welfare increase (%)

Figure E.2: Results of the Counterfactual Analysis

Notes: This figure plots the counterfactual results. Panel A plots GDP in three scenarios divided by GDP in the benchmark case without subsidies. Blue line is when we shut down innovation subsidy, green line is when we shut down adoption subsidy, and the red line is following the real policy in figure 8. Panel B plots welfare increase compared to the case without subsidies in different time horizons. Welfare is in consumption equivalent unit.

F Additional Policy Exercise

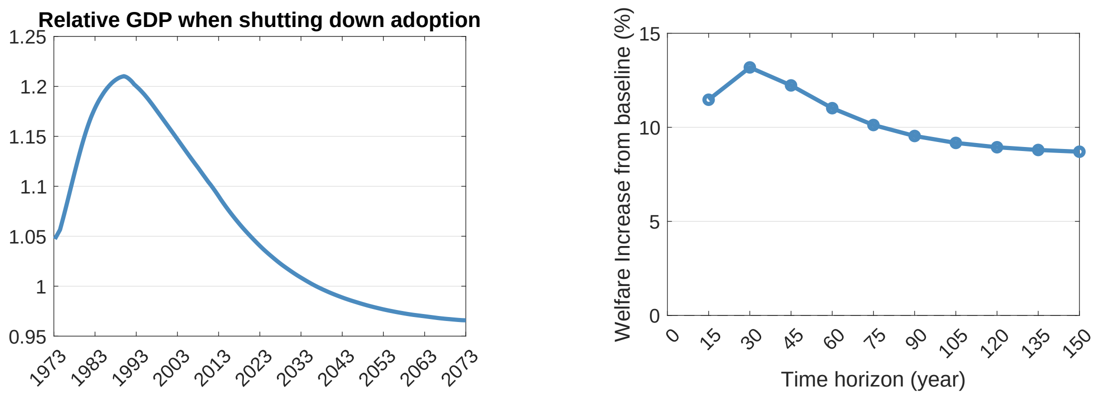
F.1 Japan's Policy to Prevent Exporting Technology

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.[62]

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.1 shows that in the short-run, Japan has higher GDP when shutting down the adoption channel compared with the benchmark 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.1 shows that Japan has higher welfare if it closes

[62]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.1: 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 benchmark 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.

technology export. In the inifite time horizon, it has 8.54% higher welfare when it shuts down exporting technology compared with the benchmark case.

F.2 Optimal Linear Subsidy

In this section, we allow the government to choose adoption and innovation subsidy as a linear function of year. The functional form is the following.

$$\begin{aligned} s_{at} &= \min(A_a - \beta_a \cdot t, 0) \\ s_{rt} &= \max(\beta_r \cdot t, A_r) \end{aligned} \tag{53}$$

We choose four parameters to maximize the welfare in the infinite horizon. The optimal policy parameters are $A_a = 0.6730, \beta_a = 0.006, A_r = 0.527, \beta_r = 0$. This generates welfare 9.72% higher than the case without both subsidies, which is higher than actual policy (4.84%), and the case where the government could choose the rate and timing to switch (6.05%). This is because the smooth policy change generates smoother consumption change while the case in which the government change only once generates discrete jump in the consumption.

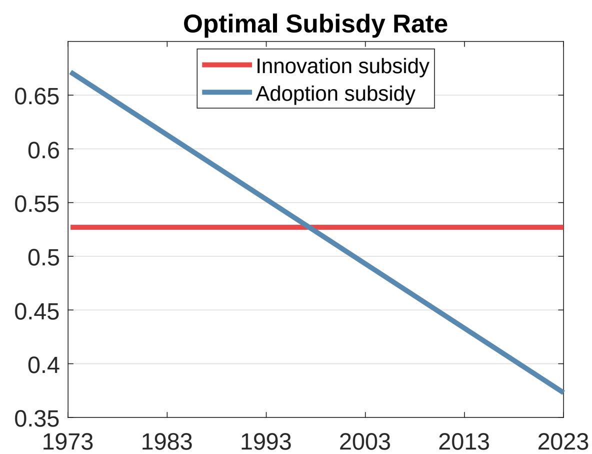


Figure F.2: Optimal Adoption and Innovation Subsidy (Linear Function)

Notes: We plot the optimal adoption and innovation subsidy rate. We allow the government can choose subsidy rate as a linear function of year. The optimal adoption subsidy rate is $s_{at} = \min(0.673 - 0.006 \cdot t, 0)$ and the optimal innovation subsidy rate is $s_{rt} = 0.527$.