Uneven Firm Growth in a Globalized World[*]

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June 10, 2023

Abstract

I study how globalization contributes to uneven firm growth and its implications for industrial concentration and productivity growth in OECD countries. I document new facts showing that industry leaders grow faster in sales and patenting than followers, particularly in industries with increasing export intensities; sales divergence is mainly driven by exports rather than domestic sales. To rationalize these facts, I develop a two-country endogenous growth model with strategic domestic and international competition and an 'innovation disadvantage of backwardness' that captures how firms innovate less when left behind. Globalization, modelled as decreasing trade iceberg costs and increasing international knowledge spillovers, triggers a stronger innovation response among leaders than followers via the market size effect, inducing an increase in domestic concentration that depresses firm innovation via *weaker domestic competition*: followers and leaders reduce innovation due to the innovation disadvantage of backwardness and decreasing returns to innovation, respectively. The globalization-induced *harsher foreign competition* also reduces innovation via lower profits. In the calibrated model, globalization explains 80% of the rise in industrial concentration and 50% of the productivity growth slowdown in the data, mainly due to weaker domestic competition. The increasing international knowledge spillover force of globalization dominates.

Keywords: productivity, economic growth, concentration, firm heterogeneity, international trade, knowledge spillover.

JEL classification: E20, F10, F60, O30, O40.

[*]I am greatly indebted to Yan Bai, George Alessandria, and Gaston Chaumont for their continuous advice and encouragement. I am extremely grateful to Harun Alp, David Argente, David Autor, Martin Beraja, Mark Bils, Francisco Buera, Santiago Caicedo, Jaerim Choi, Andres Drenik, Hamid Firooz, Rafael Guntin, Lu Han, Oleg Itskhoki, Pete Klenow, Narayana Kocherlakota, Mariana Kudlyak, Fernando Leibovici, Dan Lyu, Song Ma, Christina Patterson, Ronni Pavan, Marta Prato (discussant), Marla Ripoll, Elisa Rubbo, Ana Maria Santacreu, Joseph Steinberg, Walter Steingress, Younghun Shim, Michael Sposi, Mathieu Taschereau-Dumouchel, Iván Werning, Kai-Jie Wu, Wei Xiang, Daniel Yi Xu, and Shaoshuang Yang (discussant) for their inspiring comments and suggestions. I also thank seminar participants at the University of Rochester, the Economics Graduate Student Conference (WUSTL), Midwest International Trade Conference (Purdue, Notre Dame), Midwest Macro Conference (USU, SMU), RES Junior Symposium, YES Annual Conference (Yale), SEFI Workshop, ES Australasia meeting, ES Africa meeting, CES NA Annual Conference, International Conference on European Studies and INFER Annual Conference for their helpful discussions. All errors are my own.

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1 Introduction

A new and growing literature documents uneven firm growth in OECD countries in recent decades. Industry leaders - firms with large market shares - grew productivity and sales faster than their domestic follower competition, leading to rising industrial concentration (e.g., Andrews et al. (2016), Bajgar et al. (2019)).[1] Recently, a heated debate has examined the possible causes of uneven firm growth, igniting numerous concerns around the nature of industrial concentration and the future of aggregate productivity growth.[2] Globalization has been proposed as a potential cause of uneven firm growth (see, e.g., Autor et al. (2020b)), but there is limited empirical or quantitative investigation of this hypothesis in the literature. Undoubtedly, the declines in trade barriers and advances in transportation and communication technologies have fostered globalization, increasing trade and the diffusion of knowledge across countries (e.g., Rivera-Batiz and Romer (1991), Stiglitz (2004)). Such changes significantly reshaped the market environment and firms' growth incentives.

Does globalization play a role in generating uneven firm growth? If so, in what ways? How does it affect industrial concentration and aggregate productivity growth? This paper answers these questions empirically and quantitatively using a novel two-country endogenous growth model disciplined by cross-country firm-level patent and balance sheet data. The analysis reveals that globalization has significantly driven uneven firm growth, increased industrial concentration and short-run aggregate productivity growth, but lowered long-run productivity growth in OECD countries. The key mechanism is that a larger foreign market size due to globalization triggers a stronger innovation response among leaders than followers. Leaders' increased innovation effort first induces higher industrial concentration and short-run productivity growth, followed by reduced innovation via weaker domestic competition. That is, followers innovate less when they are further behind the leaders while leaders innovate less due to less competition from followers. Despite the negative long-run growth effect, globalization generates welfare gains. The welfare gains are front-loaded due to the long-run growth loss.

I start by expanding the facts on uneven firm growth. Using ORBIS data, I classify firms into leaders and followers for each industry-country pair in OECD countries between 1999 and 2015. I show that leaders grow faster than followers in innovation-related measures (e.g., patents), especially in industries with larger increases in export intensities; this sales divergence is mainly driven by exports rather than domestic sales. These findings suggest the potentially important role of globalization in generating uneven firm growth within a country.

To evaluate the role of globalization in generating uneven firm growth, I build a two-country endogenous growth model based on dynamic competition literature (e.g., Aghion et al. (2001), Akcigit et al. (2018), Liu et al. (2022)), in which leaders and followers compete strategically by

[1]Industrial concentration captures the extent to which a small fraction of businesses account for a large share of production output within a country.

[2]e.g., Aghion et al. (2019b), Akcigit and Ates (2019), Liu et al. (2022), Olmstead-Rumsey (2022), Peters and Walsh (2022).

investing in innovation for higher productivity and profits. My model includes two new features: oligopolistic domestic *and* international competition among leaders and followers from both countries; firms could either have an innovation *disadvantage* or *advantage* of backwardness, capturing that firms innovate *less* or *more* if they are more left behind the domestic or global technology frontier.

The first new feature, the inclusion of oligopolistic domestic and international competition, enables firms to make strategic decisions. Unlike previous papers that have concentrated on either domestic or international competition, my model encompasses both aspects. This approach not only enables an examination of the impact of globalization on uneven firm growth within a country, but also captures the strategic interactions between domestic and foreign firms. Consequently, firms strategically make decisions based on their relative technological distance, thereby facilitating the functioning of the second new feature.

The second new feature, an innovation *disadvantage* or *advantage* of backwardness, is generated via two modelling choices: innovation step size and innovation cost. The innovation disadvantage of backwardness is primarily due to slow catch-up. More-behind firms catch up with the technology frontier slowly (mostly step-by-step innovation) and hence benefit less from innovation if more left behind, as marginal innovation does not make them competitive in the markets. Additionally, lagging firms face more costs that decrease their innovation, further contributing to innovation disadvantage of backwardness.[3] As detailed later, this innovation cost mechanism is necessary to rationalize my empirical observations and is new to the literature. In contrast, innovation *advantage* of backwardness assumes more-behind firms innovate more and have greater returns to innovation through larger improvements in technology (e.g., quickly catching up with the technology frontier) or lower innovation costs.

Both innovation *disadvantage* and *advantage* of backwardness are considered because existing models have different assumptions on firm innovation behavior. While some papers (e.g., Aghion et al. (2005), Akcigit and Ates (2019), Liu et al. (2022)) consider more left behind firms innovate less, featuring an innovation *disadvantage* of backwardness, quite a few papers assume an innovation *advantage* of backwardness.[4] As discussed below, I utilize the different model predictions of innovation disadvantage or advantage of backwardness to provide suggestive evidence that the former is supported by the patent data. Despite the innovation disadvantage of backwardness, the model still captures that backward firms have the potential to grow faster than leading domestic or foreign firms due to the knowledge spillovers from those leading ones, which is often referred to as the "benefits to backwardness" summarized by Klenow and Rodriguez-Clare (2004).[5] In particular, more knowledge spillovers lead to a catch-up growth of left behind firms

[3] The innovation costs are inferred from a state-dependent innovation cost function, disciplined by firm-level patent and balance sheet data. They can be later micro-founded by financial frictions or other frictions/costs that are more severe for smaller firms.

[4] Recent papers that argue for an innovation *advantage* of backwardness include Akcigit et al. (2018), Peters (2020), Peters and Zilibotti (2021), Olmstead-Rumsey (2022), etc. Klenow and Rodriguez-Clare (2004) provide an excellent summary of earlier papers, including Grossman and Helpman (1993), and Aghion and Howitt (1992).

[5] Previous work that assumes firm innovation has an advantage of backwardness often aims to generate cross-country

or countries during the transition, though they share a common growth rate in the long run.

Globalization is modelled by two forces. The first force is decreasing trade iceberg costs, which generates the standard *market size effect* and *import competition effect*: firms have higher export profits by exporting more to the foreign market but lose domestic profits to foreign firms. The second force of globalization is increasing international knowledge spillovers, which gives rise to a unique *international business stealing effect*: productive firms are less likely to maintain their initial global technological advantage and face future profit loss due to a smaller global market share. Those spillovers also lead to market size and import competition effects: by improving the relative productivity of foreign competitors, foreign sales and demand are increased, leading to both harsher import competition and larger foreign market size.

Due to the presence of oligopolistic domestic competition and innovation disadvantage of backwardness, which are two novel additions to existing *open economy* growth or innovation models, domestic leaders and followers have asymmetric innovation responses to globalization.[6][7] The market size effect of globalization predicts domestic leaders increase export profits by more and hence have larger returns to innovation. The additional innovation of domestic leaders relative to followers increases leaders' relative technological advantages and hence market shares, leading to short-run productivity growth increase and rising industrial concentration among domestic firms. The increase in industrial concentration in turn depresses firm innovation and long-run productivity growth via weaker domestic competition: followers innovate less due to the innovation disadvantage of backwardness, and leaders innovate less due to reduced competition from followers. Therefore, the two model elements, oligopolistic domestic competition and innovation disadvantage of backwardness, yield a market size effect of globalization that decreases innovation. This negative market size effect updates the long-established view that the larger foreign market size only positively affects innovation (cf. Akcigit and Melitz (2021)). Conversely, import competition and international business stealing effect of globalization predict larger declines in innovation of domestic leaders than followers as the payoff to innovation falls, which reduces leaders' relative technological advantage and market shares. In addition, the decreased innovation reduces firms' global technological advantage, further depressing their innovation due to the innovation disadvantage of backwardness.

The model produces testable implications for the innovation disadvantage of backwardness: followers in industries with higher domestic concentration have lower innovation probability, as do leaders and followers in industries with lower global technological advantage and hence lower global market shares. These implications, which contrast with those of the innovation advantage

technological convergence, e.g., Akcigit et al. (2018). While I separately model knowledge spillovers and firm innovation and use the change of international knowledge spillovers to generate cross-country technological convergence. At the same time, I can capture firm innovation has the disadvantage of backwardness.

[6]A related open economy growth model is developed by Akcigit et al. (2018), who study oligopolistic *international* competition between two countries and assume firm has an innovation *advantage* of backwardness.

[7]In modern model environments with firm heterogeneity, the link between globalization and innovation is still shaped by these effects (Grossman and Helpman (2015)), but my model redefines firms' innovation responses to globalization due to the new model features.

of backwardness, are supported by the data: firms have fewer patents and citations as domestic concentration increases (or global market share decreases). Therefore, I provide original evidence for not only a domestic but an international *disadvantage* of backwardness. It is worth mentioning that I find the "extensive margin" of the disadvantage of backwardness by considering firms with and without patents: firms are less likely to have patents as their market share decreases. This margin is crucial in inferring a disadvantage of backwardness but is overlooked by the existing papers (e.g., Aghion et al. (2005), Acemoglu et al. (2018)), which generally restrict their focus to firms with patents and hence underestimate the disadvantage of backwardness.[8] On the other hand, I document domestic leaders have fewer patents and citations as domestic concentration increases, further supporting the model mechanism of weaker domestic competition.

Although building such a rich model generates substantial technical complexity (cf. Akcigit et al. (2018)), I provide a tractable computational algorithm by utilizing the model properties. The two countries are parameterized as an advanced OECD country (denoted by OECD) and the rest of the world (denoted by ROW). The international knowledge spillover parameter, one of the keys for quantifying globalization, is disciplined by OECD TFP relative to ROW with a newly constructed TFP dataset comparable across countries, controlling for confounding factors. The model is then validated by several out-of-sample tests, e.g., the industry distribution of firms.

The quantitative analysis suggests that the market size effect dominates. Globalization leads to a short-run aggregate productivity growth increase, while after 7 years growth decreases towards a lower long-run level. Overall, globalization accounts for around 50% of the aggregate productivity growth slowdown and 80% of the increasing industrial concentration in the data. On the other hand, the harsher foreign competition induced by import competition and international business stealing effect reduce OECD's global technological advantage over ROW, and hence OECD firms are less likely to remain global leaders. The decomposition of the two globalizing forces indicates that the increasing international knowledge spillover force dominates the declining trade iceberg cost force because the former generates a much larger market size effect and a unique international business stealing effect.

To highlight the role of the new model features for aggregate predictions, I first shut down oligopolistic domestic competition and only keep oligopolistic international competition. Interestingly, the rise in industrial concentration and the productivity growth slowdown due to globalization are explained mainly by weaker domestic competition as opposed to harsher foreign competition. The minor role of the latter is mainly driven by the "escape competition" motive of OECD firms with a high technological advantage relative to the ROW. I then shut down the *disadvantage* of backwardness in the domestic market and find it is crucial to generate increasing industrial concentration and slower productivity growth. When followers have an *advantage* of backwardness, the market size effect still dominates but increases follower innovation relative to leaders and hence reduces industrial concentration and facilitates productivity growth. The advantage of backwardness results in followers expecting a large increase in export profits once

[8] My data allows me to observe not only firms with patents, but also firms without patents by matching with the balance sheet data in ORBIS.

they close the technology gap to leaders, and hence they counterfactually innovate more. Next, I shut down the disadvantage of backwardness in the international market and find it plays a role in explaining globalization-induced slower productivity growth. However, its role is quantitatively smaller than the disadvantage of backwardness in the domestic market.

The insights from the model have implications for innovation and trade policies. To raise productivity growth, innovation policies that promote domestic competition are more effective than reducing foreign competition. Moreover, innovation or trade policies that aim to reduce foreign competition may hurt growth by further weakening domestic competition.

I conclude with additional discussions of the model predictions for the ROW, comparisons with other secular trends nested in the model, the robustness of model assumptions and extensions, further evidence on the model mechanism, and additional counterfactuals.

Contribution to the literature. I contribute several theoretical innovations and new empirics illustrating how globalization is causing rising industrial concentration and slower productivity growth in OECD countries. Existing papers study different drivers of these two outcomes within one-country (usually closed economy) frameworks (e.g., Aghion et al. (2019b), Olmstead-Rumsey (2022), Peters and Walsh (2022), and Liu et al. (2022)).[9] I instead develop a two-country open economy framework. I provide a theoretical explanation for the recent empirical evidence (see, e.g., Olmstead-Rumsey (2022), Gutiérrez and Philippon (2020)) where followers have declining innovativeness and leaders have not become more productive, and domestic leaders are more likely to remain so but less likely to be global leaders. I also find globalization dominates in explanatory power compared to other drivers discussed in the literature and nested in my model, i.e., declining interest rates, domestic knowledge spillovers, and research productivity. Other drivers have counterfactual predictions for relative productivity changes across countries and play a minor role in generating a larger foreign market size. My empirics also reveal the dominant contribution of the foreign over the domestic market in generating uneven firm growth.[10]

Second, I contribute to the literature on trade, innovation, international knowledge spillovers, and heterogeneous firms. A body of theoretical work examines different mechanisms yielding market size or competition effects of trade on innovation (or technology adoption) without considering international knowledge spillovers (e.g., Atkeson and Burstein (2010), Aghion et al. (2018), Lim et al. (2018), Impullitti and Licandro (2018), Perla et al. (2021), Cavenaile et al. (2022)). A set of papers instead show increasing international knowledge spillovers in recent decades (e.g., Berkes et al. (2022), Keller (2002), Coe and Helpman (1995), Coe et al. (2009)) and their positive effect on domestic productivity growth (e.g., Eaton and Kortum (1999),Cameron et al. (2005),

[9]Relatedly, a growing body of work studies increasing industrial concentration or slow productivity growth in isolation. A set of papers, e.g., Akcigit and Ates (2019, 2021), Gutiérrez and Philippon (2017), Gutiérrez et al. (2019), Amiti and Heise (2021), Cavenaile et al. (2022), Hopenhayn et al. (2022), Ekerdt and Wu (2022), Firooz et al. (2022) focus on the rise in concentration and propose different mechanisms. Several other papers study forces possibly driving the productivity growth slowdown, e.g., Bloom et al. (2020), Rachel (2022), and Acemoglu et al. (2020).

[10]Gutiérrez and Philippon (2020) focus on multinational production and document that leaders have had larger increases in their foreign than domestic market shares in the last decade with U.S. Compustat data. While I restrict the focus to exports.

Buera and Oberfield (2020), Cai et al. (2021), Hsieh et al. (2019, 2022)). While several recent papers point out their potentially damaging effect on productivity growth or welfare via international business stealing effects (Akcigit et al. (2018), Akcigit et al. (2020), Holmes et al. (2015)). I not only reveal the dominant role of international knowledge spillovers, but also demonstrate that the market size effect dominates other effects of globalization. My model redefines firms' innovation responses to globalization and uniquely shows a negative market size effect (cf. Akcigit and Melitz (2021)) by introducing strategic domestic competition and innovation *disadvantage* of backwardness into an open economy environment.[11] The model predictions are consistent with my data and evidence provided by other papers.[12]

Third, I contribute to the Schumpeterian growth literature empirically and theoretically. I provide empirical facts for an innovation *disadvantage* of backwardness in both domestic and international markets. Using the language of step-by-step innovation models pioneered by Aghion et al. (2001, 2005), my findings suggest that we mainly observe the decreasing (increasing) part of the "inverted-U" in the domestic (international) market.[13] My facts for the innovation *disadvantage* of backwardness reveals the "extensive" margin: firms are less likely to have patents when they are further behind. Previous papers generally focus on firms that have patents and hence fail to uncover this extensive margin effect, underestimating firms' innovation disadvantage of backwardness. On the theoretical side, I infer from the model that part of the disadvantage of backwardness is from greater innovation costs faced by further-behind followers which has non-negligible effects on aggregate productivity growth, but this has been generally ignored by the existing literature. I also show modelling innovation *disadvantage* or *advantage* of backwardness has opposing effects on aggregates, highlighting the importance of micro-founding firm innovation behaviors when evaluating aggregate implications of globalization.

Fourth, I provide new insights into the burgeoning literature on misallocation, innovation, and firm dynamics. The seminal work of Restuccia and Rogerson (2008) and Hsieh and Klenow (2009) reveals the importance of reallocating resources to more productive firms to increase aggregate productivity given fixed firm productivity. I instead argue that resources allocated to more productive firms due to globalization may generate long-run growth losses. This highlights the necessity of studying misallocation from a dynamic view, and contributes to the recent discussions on growth effects of misallocation (e.g., Acemoglu et al. (2018), König et al. (2022), Sui

[11] For example, my model predicts import competition decreases the innovation incentives of large firms relatively more, while Perla et al. (2021) argue import competition increases the innovation incentives of small firms, and Aghion et al. (2018) claim harsher competition disincentivizes innovation by small firms more. Cavenaile et al. (2022) argue decreasing trade iceberg costs increase the innovation incentives of global leaders and aggregate growth for two symmetric countries by considering strategic international competition without explicitly modelling strategic domestic competition or domestic and international knowledge spillovers.

[12] Aghion et al. (2018) document that in French manufacturing only the most productive firms increase innovation in response to more foreign demand, while less productive firms innovate less. Peters et al. (2018) and Maican et al. (2020) document that firms' export profits are a substantial source of the expected return to R&D, and innovations have a larger impact on exports than domestic sales using German and Swedish manufacturing data.

[13] That is, the Schumpeterian motive of innovation dominates (is dominated by) the desire to escape competition in the domestic (international) market.

(2022)), which emphasize that market frictions or policy distortions reduce aggregate productivity growth by affecting firm innovation or the composition of firms.

Finally, I expand on the literature focusing on trade, heterogeneous firms, and the role of large firms. Several papers use models of oligopolistic competition to study the role of large firms in international trade and their markups, prices, and market shares (e.g., Atkeson and Burstein (2008), Amiti et al. (2014, 2019), Edmond et al. (2015), Gaubert and Itskhoki (2021), Graziano (2021)). However, they consider a static environment or add exogenous productivity dynamics, and so cannot speak to the formation of large firms or their endogenous productivity growth. Accordingly, I build a two-country endogenous growth model to fill the gap.[14]

Layout. The rest of the paper is organized as follows. Section 2 provides the motivating facts. Section 3 presents the model. Section 4 provides the empirical facts for an innovation disadvantage of backwardness. Section 5 outlines the parameterization and conducts quantitative analysis. Section 6 concludes. The Appendix contains details on the data, additional empirical evidence, additional model details, proofs, the computational algorithm, and additional quantitative results.

2 Motivating Facts

In this section, I present the data, classify firms into leaders and followers, and illustrate the motivating facts.

2.1 Data

I use firm-level data for twelve European OECD countries from the ORBIS database.[15] ORBIS is the best publicly available database for comparing firm panels across countries (Kalemli-Ozcan et al. (2022)). One merit of the European data is that company reporting is regulated and standardized even for small private firms (Gopinath et al. (2017)).

My analysis focuses on firms in non-government non-financial industries from 1999 to 2015.[16] I classify industries according to their two-digit NACE Rev.2 industry classification. I use the unconsolidated accounts of firms to identify their operating industry and isolate the contribution of foreign subsidiaries to focus on domestic activities.[17] Variables of interest are real sales, which

[14] My model is also related to but different from Melitz (2003), which has inspired much work on trade and heterogeneous firm dynamics. Consistent with Melitz (2003), my model predicts that large firms will expand and small non-exporters contract following decreasing trade iceberg costs. Unlike Melitz (2003), I focus on heterogeneous firm innovation response to globalization and evaluate the effect on aggregate productivity growth.

[15] The twelve countries are France, Germany, the UK, Greece, Spain, Italy, Portugal, Finland, Sweden, the Netherlands, Denmark, and Belgium. I pick these countries due to their relatively good data coverage. Eight provide material costs, enabling me to compute total factor productivity using value-added.

[16] Kalemli-Ozcan et al. (2022) documents that the data coverage before 1999 is poor as the regulations for filing changed in 1999 requiring all firms to file with the registries if they are located in a EU country.

[17] Using the consolidated accounts has two main problems. First, a multi-industry firm is classified according to its main activity, so its activities in other industries are obscured. Second, the foreign subsidiaries of the firm are

include both domestic and export sales, export intensity (exports-sales ratio), number of patents, patent citations, revenue-based total factor productivity (TFPR), intangible capital, and intangible capital intensity. Due to limitations of the firm-level export and import data in ORBIS,[18] I use industry-level data from the 2021 edition of the OECD Input-Output Tables to construct measures of export and import intensity. Specifically, I define export (import) intensity at the two-digit industry level for each country as the ratio of exports (imports) to gross output. A larger ratio means a higher export (import) intensity. I also define import intensity by import penetration (imports/(gross output + imports - exports)) as a robustness check. The procedural details of data cleaning and variable construction are relegated to Appendix D.

2.2 Identifying Leaders and Followers

In keeping with the existing literature (e.g., Kroen et al. (2021), Hsieh and Rossi-Hansberg (2019)), I define leaders as the top 5 percent of firms by sales within each two-digit industry and year in each country.[19] Other firms are defined as followers. I use this measure instead of the fraction of sales accumulated by the four or twenty largest firms (CR4 or CR20) due to several reasons summarized by Kwon et al. (2022). First, the number of firms differs considerably across industries and the number of firms in an economy changes substantially over the past decades. So using CR4 or CR20 cannot properly capture the variation across industries and over time. Second, analyzing top percentiles is also the standard approach in research on household income and wealth inequality.

2.3 Motivating Facts

I document three facts on uneven firm growth and its correlation with trade openness, and provide robustness checks and discussion on additional facts.

Fact 1. Divergence in sales, patenting, patent citations, revenue productivity, intangible capital, and intangible intensity between leaders and followers. I define the *leader premium* as the log difference between leaders and followers.[20][21] I compute leader premiums within each two-digit industry and year in each country, and illustrate the uneven firm growth by means of regression with appropriate fixed effect structures. The empirical specification is as

bundled together with its domestic operations. See Online Appendix of De Loecker et al. (2020) for a more detailed discussion. On the other hand, though multinational production is important for large firms, the data coverage of multinational production in Orbis is good after 2008, which is not enough to study the secular trends since 1990s.

[18]Unfortunately, in my sample only France and Greece provide good information on exports.

[19]Kroen et al. (2021) define leaders as within the top 5 percent by market capitalization in their industry. Hsieh and Rossi-Hansberg (2019) measure the market share of the top 1 percent or top 10 percent of firms to study national employment and sales concentration.

[20]The leader premium in sales means the difference in the natural log of sales between leader and follower firms. The leader premium in export intensity is the difference in absolute value between the leader and follower. For level measures I take the log difference while for ratio measures I take the absolute difference.

[21]For all leader premiums, I first take the average within each group to represent the leader and follower.

follows. For industry j in country c and year t,

$$y_{j,c,t} = \beta_0 + \beta_{1,t}\mathbb{1}_t + \alpha_{j,c} + \epsilon_{j,c,t} \tag{2.1}$$

where $y_{i,j,t}$ denotes the leader premium for variables of interest, $\mathbb{1}_t$ denotes the year dummy, and $\alpha_{j,c}$ denotes the industry-country fixed effect. The regression is weighted by time-invariant industry output in each country. Equation (2.1) hence analyses the evolution of a given leader premium over time. The key coefficients are $\beta_{1,t}$, which are normalized to zero in 1999. An increasing $\beta_{1,t}$ over time means an increasing leader premium, i.e., divergence between leaders and followers. Figure 2.1 indicates the leader premium in sales from 1999 to 2015 has increased by more than 50%. This fact resonates with the existing literature (e.g., Bajgar et al. (2019)) that documents the increase in industrial concentration in advanced OECD countries in recent decades.[22] Unlike existing literature that focuses on sales concentration, I further document the divergence between leaders and followers in patenting, patent citations, revenue-based productivity (TFPR), intangible capital, and intangible intensity. Therefore, I not only provide a comprehensive picture of uneven firm growth, but also shed light on potential mechanisms that contribute to uneven firm growth. In particular, sales divergence could be related to innovation or productivity divergence through productivity-enhancing related investment (intangible investment) divergence.[23] Figure A.1 uses the raw data to show the divergence is driven by growing leaders versus stagnating followers.

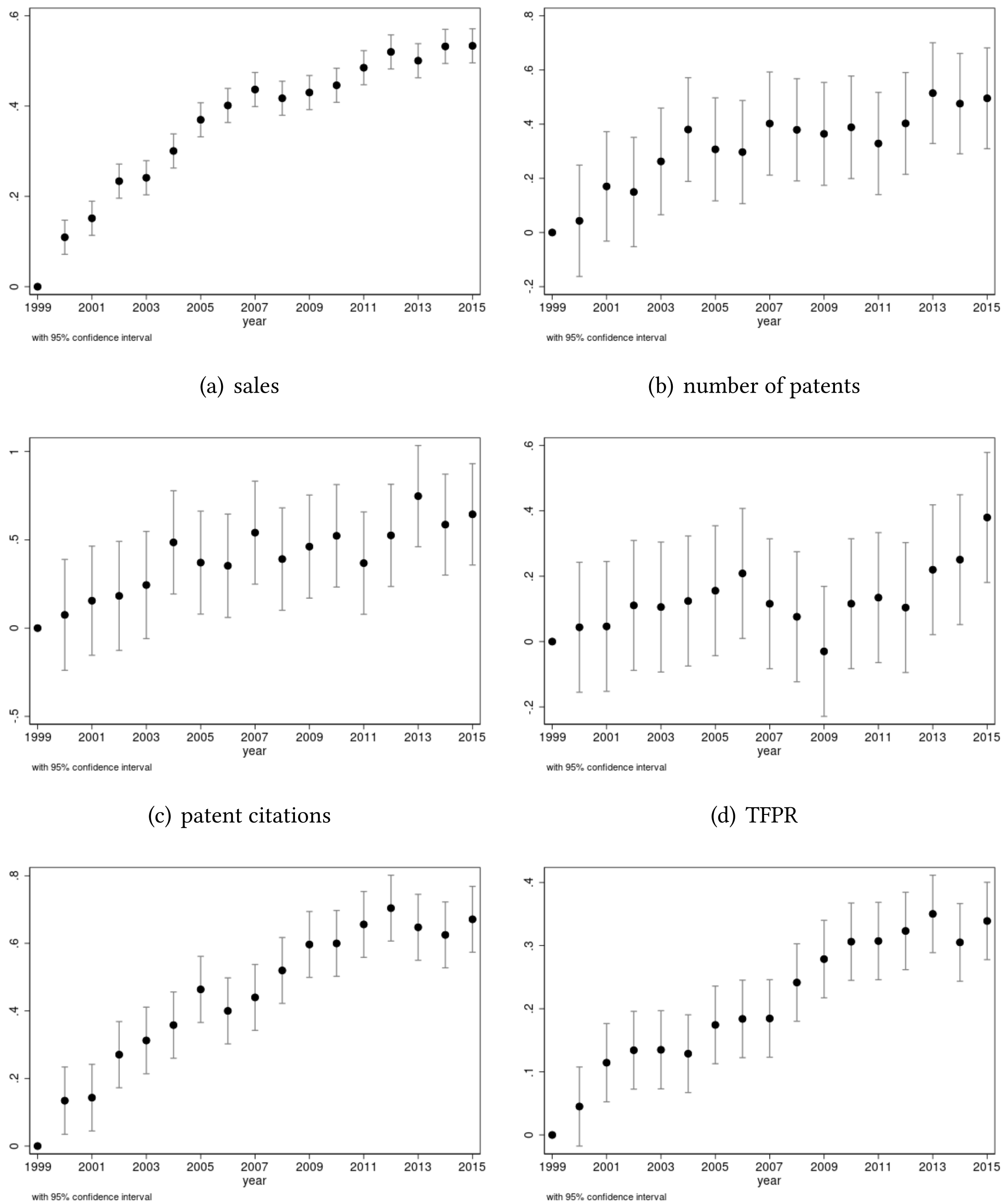
Fact 2. Sales divergence is mainly driven by the foreign than the domestic market. Firm sales includes both domestic and foreign sales (exports). To disentangle how sales in different markets contribute to the divergence between leaders and followers, I compute leader premiums in domestic sales and exports separately using the same classification of leaders and followers and conduct a similar empirical specification as in (2.1).[24] Strikingly, as shown in Figure 2.2, the divergence in exports is larger than in domestic sales (exports have twice the increase in $\beta_{1,t}$ over time as domestic sales). Leaders have increasingly higher export intensity than followers, indicating that leaders are increasingly exposed to the foreign market relative to followers. The leader premium in exports and export intensity is computed for all firms. Firms that do not export will have zero exports and zero export intensity. I also restrict the sample to firms that have positive exports in all years (named as *always exporters*) while keeping the same identification of leaders and followers. Figure A.3 shows the results are similar to Figure 2.2, indicating the robustness of this divergence pattern.

[22] Bajgar et al. (2019) defines concentration by the share of the 10% largest companies in industry sales. Two datasets are utilized for the analysis: the first one is representative OECD MultiProd data used to calculate concentration at the firm level, while the second one is ORBIS data used to calculate concentration at the business-group level. Kalemli-Ozcan et al. (2022) defines concentration by the share of top 8 firms instead and argues different findings compared to Bajgar et al. (2019).

[23] Patents are a widely adopted measure of innovativeness (see, e.g., Griliches (1998), Hall et al. (2001)), and there is a tight connection between intangible capital growth, innovation investment, and technology adoption (see, e.g., Midrigan and Xu (2014), Atkeson and Burstein (2019)).

[24] As discussed earlier, here I restrict the sample to France and Greece because only these two countries have good data coverage on exports.

Figure 2.1: Uneven Firm Growth in Advanced OECD Countries



(a) sales

(b) number of patents

(c) patent citations

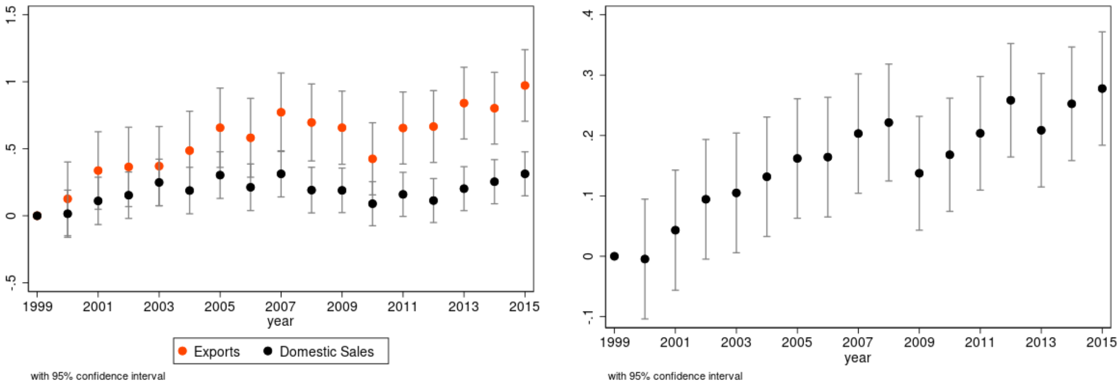
(d) TFPR

(e) intangibles

(f) intangible intensity

Notes: This figure plots the coefficient $\beta_{1,t}$ in equation (2.1) over time using ORBIS data in twelve countries with 95% confidence intervals. The coefficient in 1999 is normalized to 0.

Figure 2.2: Uneven Firm Growth in Domestic and Foreign Markets



(a) domestic sales and exports (b) export intensity

Notes: The figure plots the coefficient $\beta_{1,t}$ in equation (2.1) over time for firms in France and Greece with 95% confidence intervals. The coefficient in 1999 is normalized to 0.

Fact 3. The increase in export intensity is associated with the divergence between leaders and followers. It is well-known that advanced OECD countries have experienced a large increase in trade openness in terms of both export intensity and import intensity in recent decades. I provide new evidence that links increasing export intensity to leader-follower divergences. As mentioned in section 2.1, I define export intensity at a two-digit industry level for each country as the ratio of exports to gross output. I run the following set of regressions. In industry j and country c for year t,

$$\Delta y_{jct} = \beta_0 + \beta_1 \Delta \text{EXO}_{jct} + \gamma_{ct} + \epsilon_{jct}, \tag{2.2}$$

where Δ denotes the long (five year, which is widely used in the literature) difference operator, which captures the change from year $t-5$ to t. I maximize the use of the data by using overlapping five-year differences (e.g., 2000–2005 and 1999-2004) and cluster standard errors at the two-digit industry level. y_{jct} is the leader premium as detailed before, EXO_{jct} denotes export intensity, γ_{ct} denotes the country-year fixed effect to absorb country-specific unobservable macroeconomic shocks that vary over time. ϵ_{ijct} is an error term capturing all omitted factors. The regression is weighted by time-invariant industry output in each country. The coefficient of interest is β_1. A higher β_1 indicates a larger increase in export intensity is correlated with a larger divergence between leaders and followers. Regression results are summarized in Table 2.1, showing that industries with larger increase in export intensities have significantly more divergence in sales, patenting, patent citations, TFPR, intangibles, intangible intensity and export intensity, and more divergence in exports relative to domestic sales. Interestingly, Table A.1 and A.2 indicate increasing import intensity is insignificantly related to a decrease in leader premiums. I do not assign these regression coefficients a causal interpretation, as causality may run either way or from unobserved factors. Instead, I interpret the coefficients as correlations highlighting the central tendencies in the data.

Table 2.1: Export Intensity Increase and Uneven Firm Growth

	(1) Δsale	(2) Δpatents^N	(3) Δcitations	(4) ΔTFPR	(5) Δint.	(6) Δints^{int}	(7) Δsale^{do}	(8) Δsale^{ex}	(9) Δints^{exp}
ΔEXO	0.761***	0.475***	0.131**	0.138*	1.127**	0.008*	1.752***	3.071***	0.519**
	(0.272)	(0.062)	(0.159)	(0.078)	(0.447)	(0.004)	(0.617)	(1.143)	(0.231)
Adjusted R^2	.19	.19	.01	.04	.089	.076	.19	.12	.19
Country-Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Obs.	15,866	1,225	1,225	9,927	15,866	15,866	3,331	3,331	3,331

Notes: This table presents results from estimating equation (2.2). Standard errors are clustered at the 2-digit industry level. The regression is weighted by time-invariant industry output in each country. Columns (1) to (6) use data from all twelve countries. "patents^N" denotes the number of patents applied for by the firm, "citations" denotes patent citations received by the firm, "int." denotes intangible capital, and "ints^{int}" denotes intangible intensity. Columns (7) to (9) use data from France and Greece. "sale^{do}" denotes domestic sales, "sale^{ex}" denotes exports, and "ints^{exp}" denotes export intensity. * $p < 0.10$, ** $p < 0.05$,*** $p < 0.01$.

Additional facts. In Appendix A.4, I provide evidence that leaders and followers have heterogeneous innovation responses to an increase in export intensity. Leaders initially have higher patent quantities and citations which then later decline. In comparison, followers have lower patent quantities and citations. I also find that leaders are more likely to remain leaders after 5 years, consistent with recent literature (see, e.g., Olmstead-Rumsey (2022), Andrews et al. (2016)) that documents declining leadership turnover.

Robustness. I establish the robustness of the empirical facts using alternative definitions of leaders and an alternative classification of industries. Specifically, I consider defining leaders as the top 1, 10, or 25 percent of firms by sales in each two-digit industry and by the top 5 percent in each four-digit industry. I find qualitatively consistent facts.

To summarize, these facts highlight interesting correlations between trade openness and uneven firm growth. In the following sections I propose a model to rationalize these facts and quantify the macroeconomic implications of globalization.

3 The Model

In this section I introduce the two-country endogenous growth model, characterize the stationary balanced growth equilibrium, and discuss the model properties. The economy is in continuous time and consists of two countries, Home and Foreign, indexed by $c \in \{H, F\}$. In keeping with standard assumptions in the trade literature, I assume a single factor of production, labor, that is inelastically supplied and immobile between countries. I focus on the steady state in which aggregate productivity, output, and consumption in each country grow at constant rates, the price level declines at a constant rate, and the interest rate and wage are constant along the balanced growth path.

The model has three key elements: (i) oligopolistic competition in the domestic and international market à la Atkeson and Burstein (2008); (ii) endogenous innovation investment of firms for improving their productivity; (iii) domestic and international knowledge spillovers.[25]

3.1 Household

In each country there is a representative household with a logarithmic utility function

$$U_{ct} = \int_t^{\infty} \exp(-\rho(s-t)) \log(C_{cs}) ds, \tag{3.1}$$

where $\rho > 0$ is the discount factor and C_{ct} represents consumption at time t in country c. The representative household in country c owns all domestic firms, supplies a fixed measure of labor inelastically for intermediate good production and trade costs, and consumes a final good Y_{ct}, which is also used for innovation investment as discussed below. The representative household in country c at time t maximizes its utility (3.1) subject to the flow budget constraint

$$P_{ct}C_{ct} + \dot{A}_{ct} = w_{ct}L_c + r_{ct}A_{ct}, \tag{3.2}$$

where P_{ct} denotes the price of the consumption good, L_c is the fixed amount of labor, w_{ct} is the wage, $A_{ct} = \int_0^1 \sum_{i=1}^2 V_{ijct} dj$ is the sum of firm values, and r_{ct} is the rate of return on the portfolio of firms in country c at time t.[26] Throughout, I take the Home wage as the numeraire. The utility maximization problem of the representative household generates an Euler equation:

$$r_{ct} = \frac{\dot{C}_{ct}}{C_{ct}} + \frac{\dot{P}_{ct}}{P_{ct}} + \rho, \tag{3.3}$$

where $\frac{\dot{C}_{ct}}{C_{ct}}$ is the growth rate of aggregate consumption and $\frac{\dot{P}_{ct}}{P_{ct}}$ is the growth rate of the price level. As detailed below, aggregate consumption increases while the price level declines at the same constant rate along the balanced growth path relative to the numeraire (w_H), so $r_{ct} = \rho$ in balanced growth path equilibrium.

3.2 Final Good Technology

Perfectly competitive firms in each country produce a non-tradable final good Y_{ct} for consumption and innovation investment using inputs Y_{jct} from a continuum of industries $j \in [0, 1]$ according to the following technology:

$$Y_{ct} = \exp[\int_0^1 \ln(Y_{jct}) dj], \tag{3.4}$$

where Y_{jct} is output in industry j and country c. In each industry there are two domestic firms and two foreign firms producing imperfectly substitutable varieties of intermediate goods. Figure 3.1 plots the structure of the model economy. Industry output Y_{jct} is combined using the following

[25]The innovation is modelled by own-product productivity improvement of incumbent firms instead of variety expansion or entrants' creative destruction, consistent with the evidence provided by Garcia-Macia et al. (2019).

[26]Trading in assets across countries is not allowed so there is no international borrowing and lending.

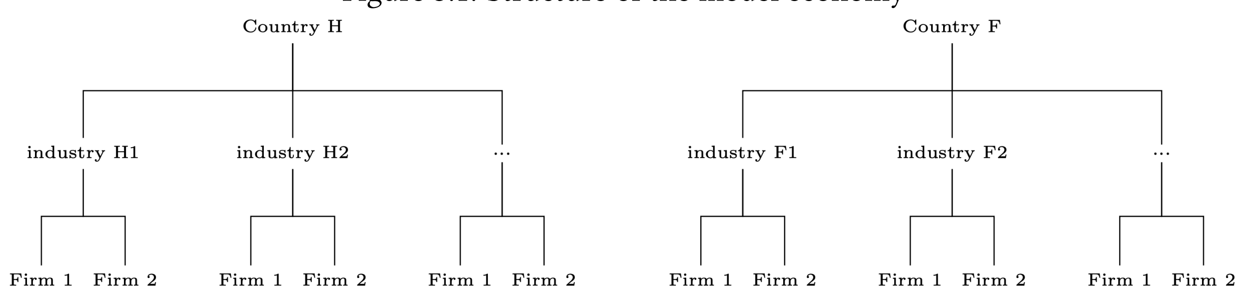
technology:

$$Y_{jHt} = [\sum_{i=1}^{2} \omega_{ijHt}(z_{ijHt}y_{ijHt})^{\frac{\epsilon-1}{\epsilon}} + \sum_{i=1}^{2} \omega_{ijFt}(z_{ijFt}y_{ijFt})^{\frac{\epsilon-1}{\epsilon}}]^{\frac{\epsilon}{\epsilon-1}}, \tag{3.5}$$

$$Y_{jFt} = [\sum_{i=1}^{2} \omega_{ijFt}(z^*_{ijFt}y^*_{ijFt})^{\frac{\epsilon-1}{\epsilon}} + \sum_{i=1}^{2} \omega_{ijHt}(z^*_{ijHt}y^*_{ijHt})^{\frac{\epsilon-1}{\epsilon}}]^{\frac{\epsilon}{\epsilon-1}}, \tag{3.6}$$

where ω_{ijct} denotes the mass of firm i in industry j and country c,[27] $z_{ijct} = \omega_{ijct}^{b\,\frac{1}{\epsilon-1}} q_{ijct}$, $z^*_{ijct} = \omega_{ijct}^{*b\,\frac{1}{\epsilon-1}} q_{ijct}$, ω^b_{ijct}, and ω^{*b}_{ijct} represent the demand shifters for Home and Foreign, respectively, q_{ijct} denotes the productivity of the firm, and $\epsilon > 1$ is the elasticity of substitution across intermediate goods within an industry.[28] Note that intermediate goods exported to Foreign are indicated with an asterisk. y_{ijHt} denotes the amount sold by a Home intermediate good firm to Home final good producers, and y^*_{ijHt} denotes the amount sold by a Home intermediate good firm to Foreign final good producers. Throughout, I indicate other variables with an asterisk in a similar fashion.

Figure 3.1: Structure of the model economy



Home final good producers buy intermediate goods from Home at prices p_{ijHt} and from Foreign at prices p_{ijFt}, and sell the final good at price P_H. Home final good producers choose intermediate quantities y_{ijHt} and y_{ijFt} to maximize profits,

$$\max_{y_{ijHt}, y_{ijFt}} P_{Ht}Y_{Ht} - \int_0^1 (\sum_{i=1}^{2} \omega_{ijHt}p_{ijHt}y_{ijHt} + \sum_{i=1}^{2} \omega_{ijFt}\tau_F p_{ijFt}y_{ijFt})dj, \tag{3.7}$$

subject to (3.4) and (3.5). The profit maximization problem gives the demand function

$$y_{ijHt} = z^{\epsilon-1}_{ijHt}(\frac{p_{ijHt}}{P_{jHt}})^{-\epsilon}\frac{P_{Ht}Y_{Ht}}{P_{jHt}}, \tag{3.8}$$

and

$$y_{ijFt} = z^{\epsilon-1}_{ijFt}(\frac{\tau_F p_{ijFt}}{P_{jHt}})^{-\epsilon}\frac{P_{Ht}Y_{Ht}}{P_{jHt}}, \tag{3.9}$$

[27] Two firms per country per industry can be considered a special case of N firms from each country – ω_{1jct} fraction of firms are identical and are treated as firm 1, and ω_{2jct} fraction of firms are identical but different from firm 1, which are treated as firm 2.

[28] The inclusion of demand shifters in the final good technology is common in trade literature, and the inclusion of productivity in the final good technology is common in the growth literature, yielding higher demand for goods with higher productivity. There is a normalization such that $\sum_i \sum_c \omega^b_{ijct} \equiv 1$ and $\sum_i \sum_c \omega^{*b}_{ijct} \equiv 1$ for each j and t.

where the aggregate price index is $P_{Ht} = \exp[\int_0^1 \ln(P_{jHt})dj]$ and the industry price index is $P_{jHt} = (\sum_{i=1}^2 \omega_{ijHt} z_{ijHt}^{\epsilon-1} p_{ijHt}^{1-\epsilon} + \sum_{i=1}^2 \omega_{ijFt} z_{ijFt}^{\epsilon-1} (\tau_F p_{ijFt})^{1-\epsilon})^{\frac{1}{1-\epsilon}}$. Likewise, Foreign final good producers' profit maximization problem gives the demand function for y^*_{ijHt}, y^*_{ijFt}, the aggregate price index P_{Ft}, and the industry price index P_{jFt}.

3.3 Intermediate Good Production

In each industry j in country c, two firms $i \in \{1, 2\}$ produce differentiated intermediate goods according to a linear production technology $y^T_{ijct} = q_{ijct} l_{ijct}$, where l_{ijct} is the labor used for producing output y^T_{ijct}, and productivity q_{ijct} is also the quality of firm i's good.

Trade costs. The intermediate good firm i sells output to final good producers in both countries. Selling to the foreign market (exporting) is subject to an iceberg trade costs $\tau_c \geq 1$. The resource constraint for Home intermediate good firms is $y^T_{ijHt} = y_{ijHt} + \tau_H y^*_{ijHt}$, so $\tau_H y^*_{ijHt}$ must be shipped for y^*_{ijHt} to be sold to Foreign. Analogously, the resource constraint for Foreign intermediate good firms is $y^T_{ijFt} = y^*_{ijFt} + \tau_F y_{ijFt}$.

Price setting. Each intermediate good firm engages in *Bertrand competition* within its industry. Intermediate good firms choose prices in the Home and Foreign markets taking as given other firms' pricing decisions. They also internalize their impact on the industry price index but are infinitesimal relative to the whole economy since the model features a continuum of industries. The constant returns production technology enables analysis of firms' production and pricing decisions in the Home and Foreign markets separately.

Each Home intermediate firm faces the following profit maximization problem in the domestic market:

$$\pi_{ijHt} \equiv \max_{p_{ijHt}} (p_{ijHt} - \frac{w_{Ht}}{q_{ijHt}}) y_{ijHt} \tag{3.10}$$

subject to the demand system above. The solution is a markup price-setting rule:

$$p_{ijHt} = \frac{\varepsilon_{ijHt}}{\varepsilon_{ijHt} - 1} \frac{w_{Ht}}{q_{ijHt}}, \quad \varepsilon_{ijHt} \equiv \epsilon - (\epsilon - 1) s_{ijHt}, \tag{3.11}$$

where ε_{ijHt} is the domestic demand elasticity faced by the Home firm and $s_{ijHt} \in [0, 1]$ is its domestic market share:

$$s_{ijHt} \equiv \frac{\omega_{ijHt} p_{ijHt} y_{ijHt}}{\sum_{i=1}^2 \omega_{ijHt} p_{ijHt} y_{ijHt} + \tau_F \sum_{i=1}^2 \omega_{ijFt} p_{ijFt} y_{ijFt}} = \omega_{ijHt} z_{ijHt}^{\epsilon-1} (\frac{p_{ijHt}}{P_{jHt}})^{1-\epsilon}. \tag{3.12}$$

The Home intermediate firm's export market problem is essentially the same. The markup-pricing-setting rule is

$$p^*_{ijHt} = \frac{\varepsilon^*_{ijHt}}{\varepsilon^*_{ijHt} - 1} \frac{w_{Ht}}{q_{ijHt}}, \quad \varepsilon^*_{ijHt} = \epsilon - (\epsilon - 1) s^*_{ijHt}, \tag{3.13}$$

where ε^*_{ijHt} is the demand elasticity facing the Home firm in its export market, and where $s^*_{ijHt} \in$

[0, 1] is the foreign market share of the firm:

$$s^*_{ijHt} \equiv \frac{\tau_H \omega_{ijHt} p^*_{ijHt} y^*_{ijHt}}{\tau_H \sum_{i=1}^2 \omega_{ijHt} p^*_{ijHt} y^*_{ijHt} + \sum_{i=1}^2 \omega_{ijFt} p^*_{ijFt} y^*_{ijFt}} = \omega_{ijHt} z^{\epsilon-1}_{ijHt} (\frac{\tau_H p^*_{ijHt}}{P_{jFt}})^{1-\epsilon}. \quad (3.14)$$

Foreign intermediate firm problems can be written analogously. Firms' production and employment decisions are then immediately obtained.

As proved in Appendix F.2, firm market shares depend only on the relative prices within each industry and are independent of prices in other industries. This implies that all firms' strategic considerations take place within an industry and are invariant to prices outside a given industry. Since firms' production and pricing decisions are essentially static, the subscript t can be omitted.

3.4 Intermediate Good Innovation

Intermediate good firms make innovation investment to compete for market leadership through improving their productivity (i.e., quality of their goods), denoted by q_{ijct}. Firms differ in their productivity and therefore have different marginal costs of production.

Technology leaders. The higher-productivity firm in each country-industry is called the *domestic leader*, paired with a lower-productivity *domestic follower* firm (*leader* and *follower* for simplicity). Domestic leaders with higher productivity than their international competition are *global leaders*. Firms are in a *neck-and-neck* position when they have the same productivity.[29] The domestic leader (follower) is denoted by $i = 1$ ($i = 2$) so that $q_{1jct} \geq q_{2jct}$. Followers are able to replace leaders by improving their productivity through innovation investments or knowledge spillovers.

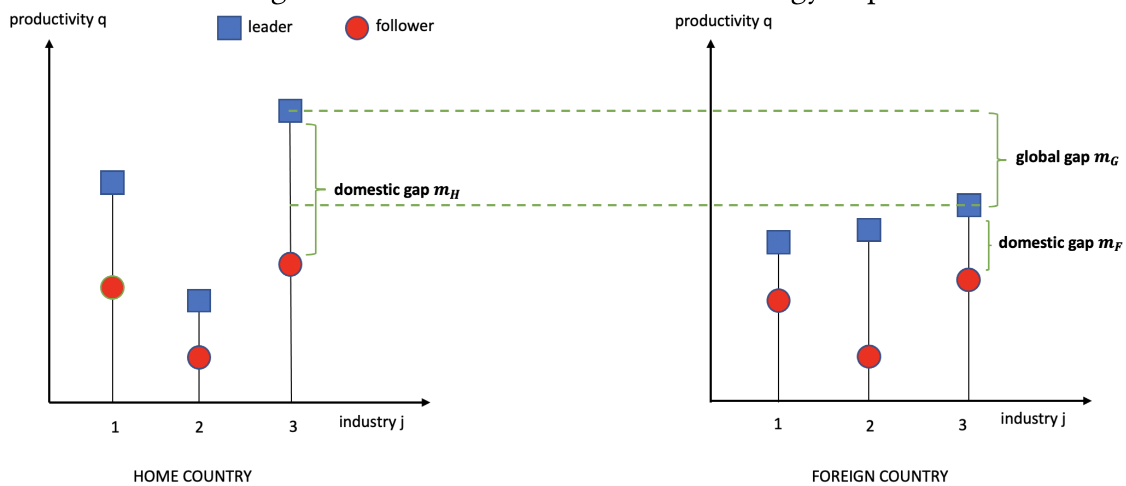
Technology gaps. Suppose that the domestic leader in industry j at time t has a technology level $q_{1jct} \equiv \lambda^{m_{1jct}}$ and that the domestic follower has a technology level $q_{2jct} \equiv \lambda^{m_{2jct}}$, where $m_{1jct} \geq m_{2jct}$ and $m_{1jct}, m_{2jct} \in \mathbb{N}$ represent the technology rungs of firms. The relative productivity between two domestic firms is then $\frac{q_{1jct}}{q_{2jct}} = \lambda^{m_{1jct}-m_{2jct}}$ and the relative productivity between domestic leaders from each country is $\frac{q_{1jHt}}{q_{1jFt}} = \lambda^{m_{1jHt}-m_{1jFt}}$. Define $m_{jct} \equiv m_{1jct} - m_{2jct}$ as the *domestic technology gap* in industry j and country c, $c \in \{H, F\}$. Define $m_{jGt} \equiv m_{1jHt} - m_{1jFt}$ as the *global technology gap* in industry j, where $m_{jGt} \geq 0$ if the Home firm is a global leader and $m_{jGt} < 0$ if the Foreign firm is a global leader. It can be shown that the technology gaps in each industry are the only industry-specific payoff-relevant state variables. Therefore, the industry subscript j for m_{jG} and m_{jc} can be dropped, and the technology gaps are sufficient to describe firms' pricing and innovation strategies. For example, as proved in Appendix F.2, firm market shares and optimal profits depend only on the technology gaps m_G and m_c and the aggregate variables P_{ct}, Y_{ct}, and w_{ct}. The total profits of Home firms across both markets can be written as $\pi_{ijHt} + \pi^*_{ijHt} \equiv \Pi_{iHt}(m_H, m_F, m_G) P_{Ht} Y_{Ht}$, where $\Pi_{iHt}(m_H, m_F, m_G) \equiv [(1 - \frac{\varepsilon_{iHt}-1}{\varepsilon_{iHt}}) s_{iHt}] + [(1 - \frac{\varepsilon^*_{iHt}-1}{\varepsilon^*_{iHt}}) s^*_{iHt}] \frac{P_{Ft} Y_{Ft}}{P_{Ht} Y_{Ht}}$.

Note that $m_H, m_F \in \mathbb{N}_0$, $m_G \in \mathbb{Z}$. The technology gap is finite for computational feasibility. I assume the domestic technology gap is bounded by $\bar{m}_c$ such that $0 \leq m_c \leq \bar{m}_c$ and that the global

[29] In a neck-and-neck position, firms typically have different parameters, although their qualities are identical.

technology gap is bounded by $\bar{m}_G$ such that $-\bar{m}_G \leq m_G \leq \bar{m}_G$. Figure 3.2 illustrates some example domestic and global technology gaps.

Figure 3.2: Domestic and Global Technology Gaps



Innovation decision. Intermediate firms' innovations follow a controlled Poisson process, with the arrival rate determined by their innovation investment. Let R_{ijct} (or $R_{ict}(m_H, m_F, m_G)$ equivalently) denote their innovation investment denominated in domestic final goods, and x_{ijct} (or $x_{ict}(m_H, m_F, m_G)$ equivalently) denote the resulting Poisson arrival rate of innovations. The specification implies that within a time interval Δt, the probability of an innovation occurring is $x_{ijct}\Delta t + o(\Delta t)$, where $o(\Delta t)$ represents terms that satisfy $\lim_{\Delta t \to 0} o(\Delta t)/\Delta t = 0$. This also implies that the probability of more than one innovation arriving within the time interval Δt is $o(\Delta t)$.

Leaders. Suppose Home leaders are also global leaders, i.e., $m_G \geq 0$. They make innovation investment to improve their productivity by $\lambda > 1$. A successful innovation of the Home leader within a time interval Δt changes both its domestic technology gap to $m_{Ht+\Delta t} = m_{Ht} + 1$ and its global technology gap to $m_{Gt+\Delta t} = m_{Gt} + 1$.[30] While when Home leaders are not global leaders, i.e., $m_G \geq 0$, they have probability $1 - \delta_H$ to improve their productivity by λ, and hence catch up with the global leaders slowly. With probability δ_H, they can directly reach global leaders' productivity level such that global technology gap $m_{Gt+\Delta t} = 0$, no matter how far away they are from the global leaders, featuring a quick catch-up in the international market. Figure F.1 and F.2 present an example of the Home leader's productivity improvement.

Followers. Suppose Home firms are global leaders, i.e., $m_G \geq 0$. The successful innovation of the Home follower changes the domestic technology gap in its country while does not change the other two technology gaps. Specifically, it can close its technology gap to $m_{Ht+\Delta t} = 0$ with probability ϕ_H regardless of its initial level of backwardness, or to improve its productivity by λ

[30] The technology gap cannot exceed the maximum/minimum of its state space. Therefore, technology gap dynamics are special at these boundaries. A successful innovation at the maximum domestic technology gap not only raises a firm's own productivity by λ but also raises its domestic competitor's productivity by λ, and similarly for other boundary cases.

such that $m_{Ht+\Delta t} = m_{Ht} - 1$ with probability $1 - \phi_H$. Therefore, follower innovations feature quick or slow catch-up in the domestic market, consistent with the specification in Akcigit and Ates (2019).[31] While if Home firms are not global leaders, i.e., $m_G < 0$, the Home follower not only has probability ϕ_H to have a quick catch-up in the domestic market, but also has probability δ_H to close the global technology gap to to $m_{Gt+\Delta t} = 0$ and overtake the Home leader such that $m_{Ht+\Delta t} = -m_{Gt}$, featuring a quick catch-up in the international market. Within probability $1 - \phi_H - \delta_H$, Home follower improve its productivity by λ and catch up with others slowly. Figure F.3 and F.4 illustrate how followers' productivity improvements change the technology gaps, through either quick catch-up or slow catch-up.

The innovation of Foreign firms can be analogously specified. Later I will discuss that the slow catch-up is a way to model the innovation disadvantage of backwardness, which captures that firms have lower innovation probability when they are more backward (consistent with, e.g., Aghion et al. (2005), Liu et al. (2022)) , and quick catch-up is a way to model the innovation advantage of backwardness, which means that firms have higher innovation probability when more left behind (consistent with the idea in Aghion et al. (2001), Akcigit et al. (2018), Peters (2020), etc). By considering both quick catch-up and slow catch-up possibilities, I am able to compare their different model implications and use the data to infer the extent to which firms have innovation disadvantage or advantage of backwardness.

Innovation costs. The function for innovation investment is

$$R_{ict}(m_H, m_F, m_G) \equiv \frac{\alpha_{ic}}{\gamma_{ic}} x_{ict}^{\gamma_{ic}}(m_H, m_F, m_G) f_{ic}(m_H, m_F, m_G) Y_{ct}, \tag{3.15}$$

where $\alpha_{ic} > 0$ represents the scale of innovation cost and $\gamma_{ic} > 1$, which implies innovation investment is convex in the arrival rate x_{ict}, and f_{ic} is a function of the technology gaps. This function indicates that innovation cost is not only scaled by the size of the total economy Y_{ct} but also dependent on technology gaps (or firm size). Different from Y_{ct} that is common to all technology gaps, f_{ic} is to capture the variation over technology gaps. As detailed in section 5, f_{ic} is a parsimonious way to represent country- and firm-specific innovation efficiency differences. For example, f_{ic} captures that larger innovation costs of more backward country or followers could be driven by poorer management skills, more severe financial frictions, or higher fixed operation costs per unit such that they face more difficulties to innovate successfully, and hence features a cost-side innovation disadvantage of backwardness. Alternative specification of f_{ic} could instead capture cost-side innovation advantage of backwardness. The introduction of f_{ic} is my departure from the literature and provides more flexibilities in quantitative analysis.

Knowledge spillovers. In each industry, within a time interval Δt, a firm receives exogenous *domestic knowledge spillovers* from its domestic competitor with probability κ or *international knowledge spillovers* from foreign competitors with probability ι as long as its productivity is lower than that of the competitors. Neck-and-neck firms are unable to receive spillovers from each other. These spillovers do not require costs and can be treated as extra probabilities of

[31] Domestic neck-and-neck situations ($m_c = 0$) are a special case. ϕ_c is assumed to be 0 so only slow catch-up exists. Successful follower innovation here changes both the domestic and global technology gaps.

increasing productivity beyond that expected from costly innovation investment. The resulting productivity improvement and technology gap change on spillover receipt are identical to the specification above.

An immediate implication is that international knowledge spillovers can take place independently from trade. Hence, similar to Cai et al. (2021), channels such as migration, FDI, or multinational production can potentially diffuse technology. These spillovers guarantee that the non-degenerate steady-state exists and that two countries will have a common growth rate along the balanced growth path, although the level of productivity across countries can be different due to different innovation intensities.[32]

Value function and innovation decision rules. The value functions of firms determine innovation decisions. A forward-looking firm invests in innovation with the hope of enhancing its relative technology position through successive innovations and reaping higher profits. Notice that some firms do not generate any positive flow profits due to high innovation costs. Nevertheless, their forward-looking nature makes them bear the innovation costs today for higher future profits.

Taking as given other firms' decisions, the value function of the Home leader for $1 \leq m_H < \bar{m}_H$, $1 \leq m_F < \bar{m}_F$, $0 < m_G < \bar{m}_G$ is

$$\begin{aligned}
r_{Ht}V_{1Ht}(m_H, m_F, m_G) - \dot{V}_{1Ht}(m_H, m_F, m_G) = \max_{x_{1Ht}\in[0,\bar{x}]}\{&\Pi_{1Ht}(m_H, m_F, m_G)P_{Ht}Y_{Ht} - P_{Ht}R_{1Ht}(m_H, m_F, m_G) \\
&+x_{1Ht}[V_{1Ht}(m_H+1, m_F, m_G+1) - V_{1Ht}(m_H, m_F, m_G)] \\
&+(x_{2Ht}+\kappa)[\phi_H V_{1Ht}(0, m_F, m_G) + (1-\phi_H)V_{1Ht}(m_H-1, m_F, m_G) - V_{1Ht}(m_H, m_F, m_G)] \\
&+(x_{1Ft}+\iota)[\delta_F V_{1Ht}(m_H, \min\{m_F+m_G, \bar{m}_F\}, 0) + (1-\delta_F)V_{1Ht}(m_H, m_F+1, m_G-1) - V_{1Ht}(m_H, m_F, m_G)] \\
&+(x_{2Ft}+\kappa+\iota)[\phi_F V_{1Ht}(m_H, 0, m_G) + \delta_F V_{1Ht}(m_H, \min\{m_G, \bar{m}_F\}, 0) + (1-\phi_F-\delta_F)V_{1Ht}(m_H, m_F-1, m_G) \\
&- V_{1Ht}(m_H, m_F, m_G)]\},
\end{aligned} \tag{3.16}$$

where $\dot{V}_{1Ht}(m_H, m_F, m_G)$ denotes the derivative of $V_{1Ht}(m_H, m_F, m_G)$ with respect to time, x_{1Ht} is short for $x_{1Ht}(m_H, m_F, m_G)$. Other firms' problems are analogously given with the corresponding firm subscript i and country subscript c. Note that these subscripts are included in the firm value function because leaders and followers in each country can have different qualities even with the same technology gaps.

The flow value of the firm in state (m_H, m_F, m_G) is composed of flow profit net of innovation investment and the change of value due to its own and its competitors' productivity improvement outcomes. The first line on the right hand side of (F.9) captures the flow profit net of innovation investment. The second line denotes the change of value due to the Home domestic leader's

[32] Klenow and Rodriguez-Clare (2004) show that international knowledge spillovers are necessary to match data patterns showing that many countries appear to share a common long-run growth rate despite persistently different rates of investment in physical capital, human capital, and research.

successful innovation. The third line denotes the change of value due to the Home domestic follower's successful innovation or knowledge spillovers from the domestic leader. The fourth line reflect the change of value due to the Foreign domestic leader's successful innovation or knowledge spillovers from the global leader, i.e., Home leader given that $m_G > 0$. The last two lines represent the change of value due to the Foreign domestic follower's successful innovation or domestic and international knowledge spillovers.

Define the normalized value v_{ict} such that

$$v_{ict}(m_H, m_F, m_G) \equiv \frac{V_{ict}(m_H, m_F, m_G)}{P_{ct} Y_{ct}}. \tag{3.17}$$

The first order conditions of the problem in (F.9) and its foreign counterpart immediately yield the following optimal innovation decisions: for $1 \leq m_H < \bar{m}_H$, $1 \leq m_F < \bar{m}_F$, $0 < m_G < \bar{m}_G$,

$$x_{1Ht} = \left(\frac{v_{1Ht}(m_H + 1, m_F, m_G + 1) - v_{1Ht}(m_H, m_F, m_G)}{\alpha_{1H} f_{1H}} \right)^{\frac{1}{\gamma_{1H}-1}}, \tag{3.18}$$

$$x_{2Ht} = \left(\frac{\phi_H v_{2Ht}(0, m_F, m_G) + (1 - \phi_H) v_{2Ht}(m_H - 1, m_F, m_G) - v_{2Ht}(m_H, m_F, m_G)}{\alpha_{2H} f_{2H}} \right)^{\frac{1}{\gamma_{2H}-1}}, \tag{3.19}$$

$$x_{1Ft} = \left(\frac{\delta_F v_{1Ft}(m_H, \min\{m_F + m_G, \bar{m}_F\}, 0) + (1 - \delta_F) v_{1Ft}(m_H, m_F + 1, m_G - 1) - v_{1Ft}(m_H, m_F, m_G)}{\alpha_{1F} f_{1F}} \right)^{\frac{1}{\gamma_{1F}-1}}, \tag{3.20}$$

$$x_{2Ft} = \left(\frac{\phi_F v_{2Ft}(m_H, 0, m_G) + \delta_F v_{1Ft}(m_H, \min\{m_G, \bar{m}_F\}, 0) + (1 - \phi_F - \delta_F) v_{2Ft}(m_H, m_F - 1, m_G) - v_{2Ft}(m_H, m_F, m_G)}{\alpha_{2F} f_{2F}} \right)^{\frac{1}{\gamma_{2F}-1}}, \tag{3.21}$$

where innovation rate $x_{ict} \in [0, \bar{x}]$, $\bar{x}$ is the maximal flow rate of innovation, and f_{ic} is short for $f_{ic}(m_H, m_F, m_G)$. The value functions and innovation decision rules are slightly different when the domestic firms are neck-and-neck since either firm can increase the global technology gap, and when firms are at boundary states where the technology dynamics are slightly modified. Details are provided in Appendix F.3.

The innovation decision rules indicate that the innovation rate depends on the extra value from successful innovation given the cost of innovation. A larger extra value from successful innovation leads to a higher innovation rate. The innovation process (quick or slow catch-up) and competitors' innovation decisions indirectly affect the firm's innovation rate via their effects on the value of the firm.

3.5 Evolution of Technology Gap Distribution

The state variables $\boldsymbol{m} \equiv (m_H, m_F, m_G)$ in each industry follow an endogenous Markov process with transition probabilities governed by the innovation rates of firms. The share of industries that have technology gaps $\boldsymbol{m}$ are denoted by $\mu_t(\boldsymbol{m}) \equiv \{\mu_t(m_H, m_F, m_G)\}_{m_c \in \{0,\ldots,\bar{m}_c\}, c \in \{H,F\}}^{m_G \in \{-\bar{m}_G,\ldots,0,\ldots,\bar{m}_G\}}$ such that $\sum \mu_t(\boldsymbol{m}) \equiv 1$. For $1 < m_H < \bar{m}_H$, $1 < m_F < \bar{m}_F$, $0 < |m_G| < \bar{m}_G$, the laws of motion that summarize the endogenous evolution of the technology gap distribution $\mu_t(\boldsymbol{m})$ can be written as follows:

$$\dot{\mu}_t(\boldsymbol{m}) = (x_{1Ht}(m_H-1, m_F, m_G-1) + \iota \cdot \mathbb{1}_{m_G-1<0})[\mathbb{1}_{m_G-1\geq 0} + \mathbb{1}_{m_G-1<0} \cdot (1-\delta_H)]\mu_t(m_H-1, m_F, m_G-1)$$

$$+(x_{2Ht}(m_H+1, m_F, m_G) + \kappa + \iota \cdot \mathbb{1}_{m_G<0})[\mathbb{1}_{m_G\geq 0} \cdot (1-\phi_H) + \mathbb{1}_{m_G<0} \cdot (1-\phi_H-\delta_H)]\mu_t(m_H+1, m_F, m_G)$$

$$+(x_{1Ft}(m_H, m_F-1, m_G+1) + \iota \cdot \mathbb{1}_{m_G+1>0})[\mathbb{1}_{m_G+1\leq 0} + \mathbb{1}_{m_G+1>0} \cdot (1-\delta_F)]\mu_t(m_H, m_F-1, m_G+1)$$

$$+(x_{2Ft}(m_H, m_F+1, m_G) + \kappa + \iota \cdot \mathbb{1}_{m_G>0})[\mathbb{1}_{m_G\leq 0} \cdot (1-\phi_F) + \mathbb{1}_{m_G>0} \cdot (1-\phi_F-\delta_F)]\mu_t(m_H, m_F+1, m_G)$$

$$-(x_{1Ht}(\boldsymbol{m}) + \iota \cdot \mathbb{1}_{m_G<0} + x_{2Ht}(\boldsymbol{m}) + \kappa + \iota \cdot \mathbb{1}_{m_G<0} + x_{1Ft}(\boldsymbol{m}) + \iota \cdot \mathbb{1}_{m_G>0} + x_{2Ft}(\boldsymbol{m}) + \kappa + \iota \cdot \mathbb{1}_{m_G>0})\mu_t(\boldsymbol{m}), \quad (3.22)$$

where $\mathbb{1}_{m_G>0}$ is an indicator function that equals one if $m_G > 0$. The measure of industries with technology gaps $\boldsymbol{m}$ increases when industries enter state $\boldsymbol{m}$ and shrinks when industries exit the state. The first line on the right-hand side in (3.22) characterizes the increase in $\mu_t(\boldsymbol{m})$ due to Home leaders' incremental increases in productivity from innovation or international knowledge spillovers, which increases the domestic technology gap from m_H-1 to m_H and global technology gap from m_G-1 to m_G. The second line represents the increase in $\mu_t(\boldsymbol{m})$ due to Home followers' incremental increases in productivity from innovation or knowledge spillovers, which reduces the domestic technology gap from m_H+1 to m_H. The third and fourth lines capture how $\mu_t(\boldsymbol{m})$ changes due to Foreign leaders and followers' incremental productivity improvements from innovations or knowledge spillovers. The last line characterizes the decrease in $\mu_t(\boldsymbol{m})$ due to firms in state $\boldsymbol{m}$ innovating or receiving knowledge spillovers who thus change state. The technology gap distribution in the steady state satisfies the property that the mass of industries entering and leaving each state is equal over time. Other cases of the evolution of distribution are relegated to Appendix F.4 for brevity.

3.6 Aggregate Growth

Define the aggregate productivity index in each country as

$$Q_{ct} \equiv \int_0^1 \ln q_{1jct} dj = \sum_{\boldsymbol{m}} \ln q_{1ct}(\boldsymbol{m})\mu_t(\boldsymbol{m}), \quad (3.23)$$

where q_{1jct} is the domestic leader's productivity in country c and industry j at period t. It is straightforward to show that the transition path of Q_{ct} defines the aggregate growth rate along the balanced growth path. The growth rates of aggregate output, consumption, and prices can also be computed. The proof is in Appendix F.5.

3.7 Market Clearing Conditions

Labor is used for the production of intermediate goods. The labor market clearing condition is

$$L_c = \int_0^1 \sum_{i=1}^{2} \omega_{ijct}(l_{ijct} + l^*_{ijct})dj. \quad (3.24)$$

The final good is used for consumption and innovation investment. Aggregate innovation investment is

$$R_{ct} = \int_0^1 \sum_{i=1}^{2} R_{ijct} dj. \tag{3.25}$$

The final goods market clearing condition is

$$Y_{ct} = C_{ct} + R_{ct}. \tag{3.26}$$

The balanced trade condition for intermediate goods is

$$\int_0^1 \sum_{i=1}^{2} (\omega_{ijFt} \tau_F p_{ijFt} y_{ijFt}) dj = \int_0^1 \sum_{i=1}^{2} (\omega_{ijHt} \tau_H p^*_{ijHt} y^*_{ijHt}) dj. \tag{3.27}$$

There is also an asset market clearing condition specified in (3.3).

3.8 Equilibrium Definition

Definition 1 (Balanced growth path equilibrium). A balanced growth path equilibrium of the two-country open economy consists of an allocation $\{y_{ict}, y^*_{ict}, l_{ict}, l^*_{ict}, x_{ict}, Y_{ct}, C_{ct}, L_c, R_{ct}, \{\mu_{\boldsymbol{m}t}, Q_{\boldsymbol{m}t}\}_{\boldsymbol{m}\equiv(m_c, m_{c'}, m_G)}\}^{c,c' \in \{H,F\}, t\in[0,\infty)}_{i\in\{1,2\}, j\in[0,1]}$, and prices $\{r_{ct}, w_{ct}, P_{ct}, p_{ict}, p^*_{ict}\}^{c\in\{H,F\}, t\in[0,\infty)}_{i\in\{1,2\}, j\in[0,1]}$ such that for any $m_c \in \{0, ..., \bar{m}_c\}$, $m_G \in \{-\bar{m}_G, ..., 0, ..., \bar{m}_G\}$ and all t,

(i) households choose C_{ct} and A_{ct} to solve their utility maximization problem;
(ii) final goods firms solve their problem to buy intermediate goods y_{ict} and y^*_{ict} optimally;
(iii) intermediate goods firms choose y_{ict}, y^*_{ict}, l_{ict}, l^*_{ict}, p_{ict}, p^*_{ict} to solve their production, employment, and pricing decisions, and x_{ict} to solve their innovation decision;
(iv) the asset market clears, pinning down r_{ct} via the household's Euler equation;
(v) the labor market clears, pinning down the wage rate w_{ct};
(vi) the final goods market clears;
(vii) trade in intermediate goods is balanced; and
(viii) $\mu_{\boldsymbol{m}t}$ and Q_{ct} evolve as specified and are consistent with firms' choices of x_{ict}.

3.9 Model Mechanism

After describing the model, I summarize some outstanding model properties to highlight the model mechanism. Intermediate firms' production and innovation decisions are keys to govern firm market shares, the distribution of technology gaps, industrial concentration, and productivity growth. To this end, I discuss how firms' production and innovation vary with technology gaps, and how globalization, modelled as declining iceberg trade costs τ_c and increasing international knowledge spillovers ι, alters firm decisions.

3.9.1 Intermediate Firm Static Production Decision

Although no closed-form solutions, it can be numerically shown that higher productivity and demand shifter of the firm lead to larger market shares, markups, and profits. Therefore, leaders have larger market share and profits than followers. Some important properties are summarized by the following propositions and the proofs are in Appendix F.6.

Proposition 1. *Given the wage rates w_{ct} and aggregate revenue $P_{ct}Y_{ct}$ in two countries, Home leaders' (followers') market share and production profits are bounded, weakly-increasing (weakly-decreasing) in the domestic technology gap, and concave (convex) in the domestic technology gap as the domestic technology gap is large enough; Home (Foreign) firms' market share and production profits are bounded, weakly-increasing (weakly-decreasing) in the global technology gap, and concave (convex) in the global technology gap as the global technology gap is high enough, given the other two technology gaps, $c \in \{H, F\}$. The Home firm's market share is increasing in the Foreign wage rates w_{Ft} and trade cost τ_F given the technology gaps.*

The bounded production profit space, a result of monopoly power, will eventually reduce the extra production profits from increasing the productivity to zero. This property also implies that a larger domestic technology gap is related to larger leader premiums in productivity, sales, and market share, while a larger global technology gap is related to a larger global market share and higher export intensity.

Proposition 2. *Larger firms' markups respond more to changes in their market share.*

Any forces that increase (decrease) firms' market shares will increase (decrease) larger firms' markups and hence production profits by more than for small firms.

3.9.2 Intermediate Firm Dynamic Innovation Decision

The complex interactions between the dynamic nature of innovation and the flexible innovation process and cost preclude analytic characterization of firms' innovation decisions. However, there is one special case in which some sharp model properties can be obtained, that is, if innovation costs are independent of technology gaps, i.e., $f_{ic}(m_H, m_F, m_G) = 0$. In this section I explain the mechanism under this special case from Home firms' perspective. For expositional simplicity, I assume probability of quick international catch-up is zero, and discuss the relaxation of the assumption later.

As shown in equations (3.18) to (3.21), the decision to innovate depends on the extra value from successful innovation, which is a function of the technology gaps. Figure 3.3 plots a numerical example for Home value functions to help explain firms' innovation decisions. The Home leader (follower) value is increasing and eventually concave (decreasing and convex) in the domestic technology gap m_H and increasing, initially convex, and eventually concave in the global technology gap m_G. Since firm value is mostly production profits, the shape of the value function is inherited from the properties related to production established above.

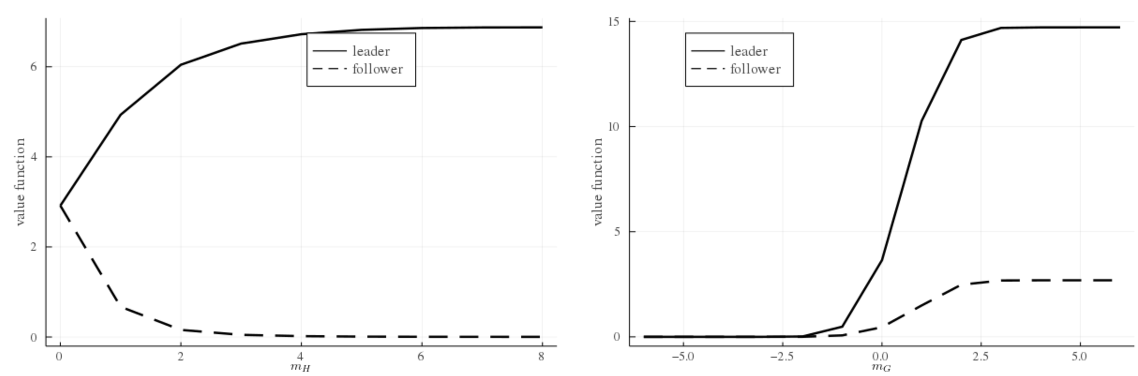
The eventual concavity of leader value functions over the domestic and global technology gaps indicates that leader innovation eventually decreases as their market share grows and they face decreasing returns to additional innovation. On the other hand, the increasing and initial convex of the value function indicates that firm innovation increases as their market share grows. For example, Figure 3.3 indicates Home firms' innovation rates first increase and then decrease over the global technology gap because their value function is increasing, initially convex, and then concave over the global technology gap.

For followers, the innovation rate is determined by the probability of quick catch-up. Consider two special cases. Case 1, quick catch-up probability $\varphi_c = 0$. The innovation decision rule of Home followers (3.19) implies that $x_{2Ht} = \left(\frac{(v_{2Ht}(m_H-1,m_F,m_G)-v_{2Ht}(m_H,m_F,m_G))}{\alpha_{2H}}\right)^{\frac{1}{\gamma_{2H}-1}}$. Given the usual parameters that $\alpha_{ic} > 0$ and $\gamma_{ic} > 1$, the innovation x_{2Ht} is increasing the difference between $v_{2Ht}(m_H - 1, m_F, m_G)$ and $v_{2Ht}(m_H, m_F, m_G)$. Since follower value is decreasing and convex in m_H, followers that are more behind (face larger m_H) have lower innovation rates. Put differently, followers, realizing that they have less extra benefits from additional innovation and are less likely to overtake leaders, innovate less. I use "innovation disadvantage of backwardness" to capture that firms have lower innovation rate when more left behind.

Case 2, quick catch-up probability $\varphi_c = 1$. The innovation decision rule of Home followers (3.19) indicates $x_{2Ht} = \left(\frac{v_{2Ht}(0,m_F,m_G)-v_{2Ht}(m_H,m_F,m_G)}{\alpha_{2H}}\right)^{\frac{1}{\gamma_{2H}-1}}$. The innovation rate x_{2Ht} is increasing in the difference between $v_{2Ht}(0, m_F, m_G)$ and $v_{2Ht}(m_H, m_F, m_G)$. Since follower value is decreasing in m_H, $(v_{2Ht}(0, m_F, m_G) - v_{2Ht}(m_H, m_F, m_G))$ is increasing in m_H. Therefore, followers that are more behind (face larger m_H) have higher innovation rates due to the larger benefits from additional innovation. This is exactly how quick catch-up characterizes the innovation advantage of backwardness: more left-behind firms innovate more due to larger benefits from innovation.

The two *opposing* results highlight that the quick catch-up probability of followers is one of the key model mechanisms, which will be disciplined by the data.

Figure 3.3: Value Functions



(a) $v_{iH}(m_H, 0, 0)$ (b) $v_{iH}(1, 0, m_G)$

Notes: This figure plots numerical Home value functions given $f_{ic}(m_H, m_F, m_G) = 0$ in terms of the domestic technology gap m_H (given $m_F = 0$, $m_G = 0$) and global technology gap m_G (given $m_H = 1$, $m_F = 0$).

3.9.3 Effects of Globalization

The two forces of globalization are modelled by *declining trade iceberg costs* τ and *increasing international knowledge spillovers* ι in the spirit of the trade and endogenous growth literature pioneered by Rivera-Batiz and Romer (1991). This section describes the effects of globalization from Home firms' perspective.

Three effects of globalization on firm production and innovation. Both globalizing forces alter firms' production profits by changing domestic and foreign market shares and the country shares of aggregate revenue, as predicted by Proposition A.1 in Appendix F.2.[33] First, the model contains the *"market size effect"* through which a larger Foreign market leads to higher Home export profits. Second, the model includes an *"import competition effect"* via lower Home domestic profits.

Two forces of globalization also alter firms' innovation decisions. On the one hand, the innovation decisions are *indirectly* affected by the changes in production profits (and hence the changes in the extra value from successful innovation), due to market size and import competition effect. Greater extra value typically leads to a larger innovation incentive. On the other hand, the increasing international knowledge spillovers *directly* alter firm innovation rates via a unique *"international business stealing effect"*. Specifically, firms consider the changing possibility of raising the global technology gap and the shifts in value at different global technology gaps. The international business stealing effect makes it harder for firms with global technological advantage to maintain their advantage.

Asymmetric response to globalization leads to uneven firm growth. The oligopolistic domestic competition joint with followers' *disadvantage* or *advantage* of backwardness leads to that leaders and followers have asymmetric responses to globalization in terms of production and innovation, giving rise to uneven firm growth.

If followers have disadvantage of backwardness. According to Proposition 2, the market size effect triggers a larger increase in Home leader export profits but a larger decrease in their domestic profits compared to followers given the technology gaps.[34] A direct implication is that when followers can only catch up with the leaders slowly, the market size effect of globalization brings a much larger increase in export profits for leaders compared to followers, while the import competition effect of globalization brings a much larger decrease in domestic profits for leaders compared to followers. This is because both leaders and followers improve their productivity step-by-step and the resulting changes in production profits are "gradual". The intuition for the international business stealing effect is similar to the import competition effect because leaders' profit loss is larger than followers. When the market size effect dominates the import competition effect and international business stealing effect, leaders have a larger increase in innovation rates

[33] The change in market share is driven by the changes in trade costs and relative wages between countries, as shown in Lemma A.1 in Appendix F.2. The relative changes in wages and aggregate revenue between countries is via the general equilibrium effect.

[34] Beyond the direct effect on market share predicted by Proposition 2, the relative increase in Foreign expenditure $\frac{P_F Y_F}{P_H Y_H}$ will also favor the export profits of large firms, as predicted by Proposition A.1 in Appendix F.2.

than followers due to the larger increase in export profits, and hence become more likely to raise the domestic technology gap.

If followers have advantage of backwardness. If followers have *advantage* of backwardness, the mechanism mentioned above can be overturned. When followers catch up with the leaders quickly, they can always improve their productivity by a larger "step size" compared to leaders. The market size effect, for example, will bring a much larger increase in export profits for followers than leaders, and hence will increase followers' innovation rates by more. The more aggressive innovation of followers will reduce the domestic technology gap.

Aggregate implications of uneven firm growth. Leaders and followers' asymmetric production and innovation response to globalization reshapes the firm distribution over technology gaps, generating changes in industrial concentration and productivity growth. A larger increase in domestic technology gap due to leaders' larger innovation increase typically increases the industrial concentration. However, the predictions on aggregate productivity growth are more subtle. The previous discussions imply that how firm innovation rates vary with different technology gaps are vital in generating model predictions for aggregate productivity growth. In particular, firms have *disadvantage* or *advantage* of backwardness have different implications on how firms' innovation rates vary with the technology gaps.

Next, I provide data evidence for *disadvantage* of backwardness and turn to quantitative analysis to discipline the model mechanism by the data. Henceforth, I interpret the Home country in the model as *an advanced OECD country* (denoted by OECD hereafter) and the Foreign country as representing *the rest of the world* (denoted by ROW hereafter).

4 Facts for Innovation Disadvantage of Backwardness

The model produces testable implications for innovation *disadvantage* of backwardness. In this section, I present and discuss the empirical patterns that are consistent with innovation disadvantage of backwardness using firm-level patent data. I first describe the data sources and variable construction that allow me to document patterns of firm innovation. I then present empirical results by means of regression with appropriate fixed effect structures.

4.1 Data

I use cross-country patent data merged with balance sheet data from ORBIS between 1999 to 2004 to represent firm-level innovation patterns in 1990s, which will be used to inform the parameterization in initial balanced growth path, as detailed in section 5.1.[35] I focus on patents that file in the U.S. patent office (USPTO) to avoid any possibility of double counting the same patents in multiple patent offices. Since existing literature (e.g., Cai et al. (2021)) usually argues that most

[35] Due to data availability issues the data starts from 1999.

important innovations from other countries have been patented in the U.S., the possibility of this causing a sample selection issue is minimally concerning. More details are in Appendix D.3.

4.2 Variable Construction

According to the model, innovation disadvantage of backwardness means firms have lower innovation rate if they are more left behind relative to domestic or foreign competitors in terms of technology distance. To test whether this prediction holds in the data, I construct two variables that are relevant for the model prediction: (i) technology gaps that measure the technology distance; (ii) innovation rate. Of note, I do not claim that a causal relationship exists. Technology gaps and innovation rate are both endogenous in the model, and their correlations in the data are what I want the model to be able to produce.

Technology gaps. Technology gaps are state variables of the model which govern firm decisions and the resulting industry mass distribution over technology gaps. Directly measuring technology gaps in the data is challenging. Because of the lack of the firm-level price information, it is extremely difficult to measure the true productivity of the firm. I instead utilize sales, which is directly observable. I use a country's industry-level leader premium in sales to measure the domestic technology gaps in OECD and other countries' leader premium in sales as a measure of domestic technology gaps in ROW. The model predicts that a larger domestic technology gap is tightly linked to a larger leader sales premium, allowing me to use this closely related moment to pin down technology gaps.[36] I use industry-level OECD global output shares to establish the global technology gaps, as the model predicts a larger global technology gap leads to a larger global output share.[37]

Innovation rate. I use patent data to measure firm innovation rates, following the literature pioneered by Griliches (1998).[38] Specifically, I compute the number of citations a firm received for patents that were applied for in year t (as opposed to granted years) to discipline the model innovation rate.[39] Ideally, the private value of the patent to the firm would discipline the model since this directly governs the firm's innovation decision. However, obtaining these privately-held patent values across many countries is challenging. The evidence documented by Kogan et al. (2017) showing that patent value is strongly correlated with the citation-weighted number of patents helps alleviate concerns over using patenting or patent citations to discipline firms' innovation decision in the model. I assign 0 for observations without patents or citations, effectively

[36] The leader premium in sales is computed as the log difference in sales between leaders and followers in both the model and the data. The data is from 12 European countries in the ORBIS data set, as shown in section 2.

[37] I measure a country's global output share using its world gross output share in an industry, with data coming from the 2021 OECD input-output tables.

[38] Griliches (1998) points out that economists have long relied on patents as an observable proxy for innovativeness. Other papers by Hall et al. (2001), Aghion et al. (2005), Cavenaile et al. (2019), and Akcigit et al. (2018) also use the number of patents or patent citations to measure innovativeness.

[39] Using application years as opposed to granted years is to capture the actual effective time of innovation, consistent with existing literature, e.g., Cai et al. (2021). This measure implies a patent is only counted once in a specific year. More details on patent data construction are relegated to Appendix D.3.

assuming that firms which do not innovate or fail to file a patent after innovation investment have 0 innovation probability.[40] Of note, this does not mean that a firm has 0 patent every year throughout all periods in the data. I observe that many firms have patents every several years. This is also consistent with the well-documented fact that patent activity is usually infrequent.

4.3 Regression with Fixed Effects

I run firm-level regressions with appropriate fixed effect structures to uncover the relationship between firm innovation and technology gaps in the data.

Motivated by patent race models (e.g., Aghion et al. (2005), Cavenaile et al. (2019)), a firm's innovation rate can be linear or quadratic in the technology gaps. To this end, I standardize the innovation measures of firms by taking the mean and then dividing by the standard deviation among all firms. I then estimate an empirical specification for the cross-country data as follows. For firm i in industry j, country c, and year t,

$$y_{ijct} = \beta_0 + \beta_1 \text{leader premium}_{jct} + \beta_2 \text{global output share}_{jct} + \beta_3 \text{leader premium}_{jc't} + \beta_4 \text{leader premium}^2_{jct} + \beta_5 \text{global output share}^2_{jct} + \beta_6 \text{leader premium}^2_{jc't} + \theta_{c,t} + \mu_j + \chi_i + \epsilon_{ijct}, \quad (4.1)$$

where y_{ijct} denotes the standardized innovation rate, leader premium$_{jct}$ represents the leader premium in sales in country c and industry j, and leader premium$_{jc't}$ represents the leader premium in sales in the other country c'. global output share$_{jct}$ is the country's gross world output share in industry j. The superscript 2 denotes the quadratic term. Country-year fixed effects, industry fixed effects, and firm fixed effects are denoted by $\theta_{c,t}$, μ_j, and χ_i, respectively. The regression is weighted by firm sales, consistent with the idea mentioned in Autor et al. (2020a).[41]

Summary of results. Table 4.1 displays the regression results in the data and Figure 4.1 uses the regression coefficients to plot the innovation rate over the two domestic technology gaps and the global technology gap, respectively, setting the other two at their means in each case. The data results show that firm innovation is mainly *decreasing* in the domestic technology gap while first *increasing* then slightly *decreasing* in the global technology gap. According to the model, the data results indicate leaders (OECD firms) have decreasing returns to innovation when their technological advantage in the domestic (international) market is high enough; followers (OECD firms) have innovation *disadvantage* of backwardness in the domestic (international) market since they have less innovation when they are more left behind.

Robustness check. I conduct several additional checks and find results are qualitatively the same. They are (i) alternative empirical specification: regressions with higher order terms and interaction terms, or with additional firm-level controls (leverage, sales); (ii) alternative measures of innovation: either scale-dependent or scale-free (number of patents of the firm, number of

[40] I drop industries in which firms rarely file patents, doing so if both leaders and followers are assigned 0.

[41] This alleviates the concern that many non-patent firms are small and do not account for a large market share and aggregate implications; taking these firms into account in the regression by assigning 0 biases the results towards small firms. The results are similar if the observations are weighted by the number of firm patents.

citations per patent of the firm) and firm-level growth rate (five-year forward growth in sales and TFPR); [42] (iii) alternative data sample: drop firms that never apply patents throughout the whole data period to address the concerns that including these non-innovative firms overestimate the followers' innovation disadvantage of backwardness; (iv) alternative measures of technology gaps: use leader market share among domestic firms and HHI to measure domestic technology gap, and OECD global export share to measure global technology gap; (v) alternative definitions of leaders and followers: leaders are top 10% number of firms per industry-country pair.

Table 4.1: Number of Citations (All Firms)

	all firms	leaders	followers
OECD leader premium	-0.495***	-0.557**	0.274***
	(0.163)	(0.243)	(0.067)
ROW leader premium	-1.803***	-1.804**	-1.516***
	(0.573)	(0.862)	(0.235)
OECD global output share	72.973**	82.235	53.052***
	(34.657)	(51.100)	(13.764)
OECD leader premium^2	0.021	0.024	-0.037***
	(0.019)	(0.028)	(0.008)
ROW leader premium^2	0.096	0.089	0.201***
	(0.065)	(0.097)	(0.029)
OECD global output share^2	-525.275**	-592.409*	-306.123***
	(216.453)	(316.514)	(89.360)
Obs.	8,908,710	434,132	8,420,064
Adjusted R^2	.75	.74	.65
Country-Year FE	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes

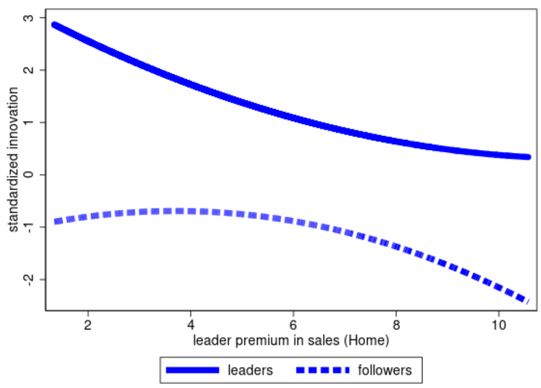
Notes: This table presents results from equation (4.1) in the data. The explanatory variable is measured by the standardized number of patent citations in 1999-2004. The regression is weighted by firm sales. * $p < 0.10$, ** $p < 0.05$,*** $p < 0.01$.

4.4 Discussion and Comparison with Existing Literature

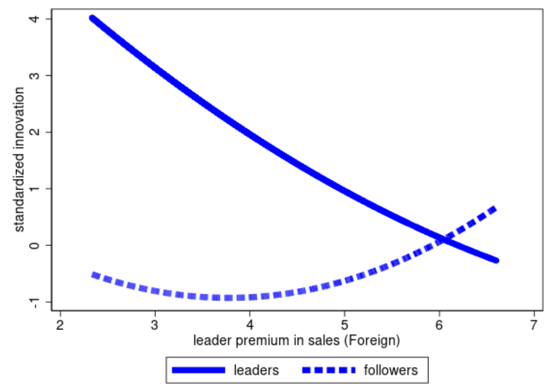
In this section, I discuss how my findings of innovation disadvantage of backwardness reconcile with the seemingly opposing findings in the existing literature, and highlight how my findings reveal that the disadvantage of backwardness is much more significant in the data than previously understood. The key relies on the "extensive margin": firms are less likely to have patents (and hence citations) when they are more left behind. I document this finding by merging the firm-level patent data with balance sheet data. While the previous studies mainly focus on the "intensive margin" due to data availibilities (see, e.g., Kogan et al. (2017), Acemoglu et al. (2018), Akcigit and

[42] For firms without patents, number of citations per patent of the firm is assigned as 0.

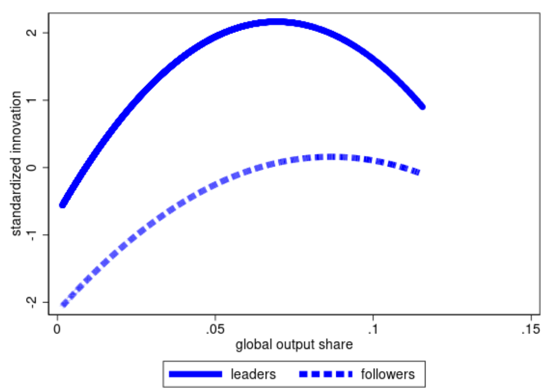
Figure 4.1: Standardized Number of Citations (All firms)



(a) OECD leader premium in sales



(b) ROW leader premium in sales



(c) OECD global output share

Notes: This figure presents the regression coefficients for all firms in the data in the 1990s. The blue solid line represents leaders and the blue dashed line represents followers. The X-axis in each panel denotes the leader premium in sales in Home (OECD) and Foreign (ROW) and the OECD global output share, respectively. The Y-axis denotes the standardized number of citations in the data.

Kerr (2018)). They focus on firms that have patents (typically large firms), and hence cannot take into account whether firms stop patenting when they are more left behind.

The pattern shown in Figure 4.1 that firms have innovation disadvantage of backwardness in the domestic market in fact highly depends on the "extensive margin". To see this, I only keep observations with patents in the sample and rerun the regression in equation (4.1).[43] The results in Figure B.1 indicate that followers' citations increase in the domestic technology gap, opposite to the findings with sample of all firms. Using the language of step-by-step innovation models (e.g., Aghion et al. (2005), Cavenaile et al. (2019)), this finding suggests that we mainly observe the increasing part of the "inverted-U". While if we focus on all firms we mainly observe the decreasing part of the "inverted-U".[44] Figure B.2 and B.3 further use the raw data to illustrate the "extensive margin". Figure B.2 plots how the fraction of firms that have patents varies with the three measured technology gaps using the raw data of all firms. Figure B.3 instead plots by dropping firms that never patent throughout the whole data sample. Both figures show that not only leaders but also followers are less likely to have patents as industrial concentration increases. The difference between the two figures also indicate that both leaders and followers are more likely to become never patent firms as industrial concentration increases.

As discussed in section 5, underestimating followers' innovation disadvantage of backwardness or not matters for the growth effects of globalization. It is not surprising why previous papers (e.g., Cavenaile et al. (2019)) often derive conclusions that increasing the industrial concentration could facilitate innovation because most firms are in the increasing part of the "inverted-U". My paper shows that increasing industrial concentration can decrease innovation since most firms are in the decreasing part of the "inverted-U" once taking into account the "extensive margin".

5 Quantitative Analysis

In this section I start from a balanced growth path equilibrium analysis. I first describe how I conduct parametrization to match the model to the data and validate the model via out-of-sample predictions. I then illustrate the parameterized model mechanism and study the aggregate implications of globalization. Next, I decompose the channels through which globalization operates and compare with other secular trends nested in the model. Finally, I highlight the role of key model elements and provide some additional discussions on policy implications, welfare analysis, transition dynamics, extra data evidence to support the model mechanism, and model assumptions and extensions.

[43] If a firm has a patent in 2010 but not in 2009, only the observation in 2010 is taken into account in this data sample.

[44] When turning to using the number of patents a firm applies to redo the exercise, I find that by focusing on the patent firms, we can still observe innovation *disadvantage* of backwardness for followers, though the extent that followers' number of patents decrease in the domestic technology gap is mitigated compared to the baseline sample with all firms. That is, more firms are in the increasing part of the "inverted-U" compared to the baseline sample.

5.1 Parameterization

I interpret the Home country in the model as *an advanced OECD country* (denoted by OECD hereafter) and the Foreign country as representing *the rest of the world* (denoted by ROW hereafter).[45] I minimize the heterogeneity between OECD and ROW for simplicity and set differences in innovation cost parameters and the market size parameter L_c to generate a realistic global technology gap and market size difference between OECD and ROW. The common parameters across countries are estimated to match to the OECD data.

I parameterize the initial balanced growth path (BGP) equilibrium to the 1995–2000 data (1990s) and reestimate all parameters to pin down the new 2010–2015 (2010s) balanced growth path equilibrium, given the data availabilities.

5.1.1 Initial Balanced Growth Path

As shown in Table 5.1, I group 25 parameters into two categories. The first category is parameterized externally. The second category is parameterized internally.

I. Externally estimated parameters. The fraction of leaders within a country-industry is set to 5 percent, consistent with the way I define leaders empirically, and all other firms are followers. All leaders (followers) are identical as if there is only one representative leader and the leader (follower) mass in industry output is 5 (95) percent. The OECD labor force is normalized to 1. The domestic and international quick catch-up probability, ϕ_c and δ_c, are taken from Akcigit and Ates (2019) and Akcigit et al. (2020). The innovation cost function is quadratic with $\gamma_{ic} = 2$, which is the common estimate in the empirical innovation literature (cf., Acemoglu et al. (2018)).

II. Internally estimated parameters. The remaining 20 parameters are jointly pinned down by the requirement that the model accounts for 22 salient aggregate, industry-level and firm-level moments in the data, as shown in Table 5.1. Although these parameters are jointly determined using the simulated method of moments (SMM) technique, some parameters are closely related to certain specific moments, as detailed below.

i. Aggregate variables. Panel A in Table 5.1 displays parameters related to aggregate moments. I first discuss parameters related to globalization and then others.

Step 1. Globalization parameters. The trade iceberg cost τ is set to target the OECD export intensity, measured by total exports as a share of GDP.[46] As standard in trade literature, a larger

[45] The advanced OECD country is defined as a GDP-weighted average of the 24 countries that joined OECD before 1974: Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Japan, Luxembourg, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom and United States. The "rest of the world" is defined as the GDP-weighted average of countries covered in the 2021 edition of the OECD input-output tables, including all 38 OECD countries and 28 non-OECD countries/regions. The GDP weight is time invariant from 1995 to 2015. The parameterization results are robust to using export-weighted averages across countries. I only consider countries that are covered in the OECD input-output tables due to the data availability required for model validation.

[46] The real interest rate and export intensity data are from the World Bank. The aggregate TFP growth rate is from the Penn World Table 9.1.

trade iceberg cost indicates a lower export intensity. The international knowledge spillover parameter ι is set to match OECD TFP relative to ROW, consistent with existing papers (see, e.g., Prato (2021)). This is because the international knowledge spillover ι in the model is closely related to the relative productivity between countries. A larger ι means less productive ROW is more likely to receive spillovers and reduce the global productivity gap. While the way to discipline international knowledge spillover parameter is standard, two potential issues arise and I address by several methods.

First, relative productivity between countries is not only affected by international knowledge spillovers, but also other forces such as financial development or labor market reforms that influence misallocation, or national policies that affect innovation. All these and more would affect productivity. Therefore, matching the relative productivity in the data without considering other potential causes leads to a biased estimate of ι. To this end, I construct country TFP by controlling for several competing channels, and use it as the date target. Details on this procedure are in Appendix E.1.

Second, though again consistent with the idea of other papers (e.g., Akcigit and Ates (2019)), using a single parameter ι to model international knowledge spillovers may not be reasonable, especially considering we change the value of ι to model the change of international knowledge spillovers.[47] Since international spillovers are a key focus of this paper, such concerns are critical. To this end, I use the industry-level variation in relative productivity between countries to show that ι can help replicate the entire distribution of relative productivity across industries (this can be treated as an out-of-sample test). Moreover, increasing ι can replicate the change of the distribution over time in the data, indicating the simple parameterization of international spillovers is not obviously lacking in depth. Specifically, Figure C.1 plots the density distribution of relative productivity across industries in the data and the model distributions using different values of ι. Relative productivity is computed as the log difference in industry TFP between OECD and ROW.[48] A relative productivity larger than 0 means OECD is more productive than ROW. A larger fraction of industries concentrated at high relative productivity levels means more OCED industries have a technological advantage. This figure shows that the initial BGP of the model matches the 1990s distribution, and increasing ι leads to a model distribution closer to the data distribution in the 2010s. A larger ι typically narrows the model industry density and shifts it to the left, indicating ROW technological catchup, while a smaller ι shifts the distribution to the right and leads to larger technology gaps.[49] I further model international knowledge spillovers in

[47] Akcigit and Ates (2019) use a single parameter to model domestic knowledge spillover and evaluate the effect of its change over time.

[48] In the data, industry TFP is constructed using the 2019 EU KLEMS data adjusting for differences in prices, capital utilization, labor quality, resource allocation, and innovation subsidies across countries. In the model, industry TFP is computed as total output over total employment. Defining industry TFP as the employment- (or sales-) weighted average of TFPQ across firms in the model leads to similar results. More details are in Appendix E.1.

[49] The changing TFP density distribution in the data indicates a technological convergence story, consistent with Kremer et al. (2021). Figure E.1 in Appendix E.1 plots the data distribution over relative productivity between OECD and ROW every five years to show that the changes in the empirical distribution are not driven by the choice of years for the initial and end periods.

different ways to establish the robustness of the model results. These discussions are in section 5.6.4.

Step 2. Other parameters. The labor force in ROW L_F is tightly linked to OECD's global output share; a larger L_F indicates a smaller OECD global output share. I estimate the within-industry elasticity of substitution across intermediate goods ϵ to target the aggregate markup estimated by the existing literature (e.g., De Loecker et al. (2020), which suggests markups for U.S. public firms in the 1990s ranged from 1.2 to 1.3).[50] I set the discount factor ρ to match the OECD interest rate along the balanced growth path. The innovation step size λ is set to target the aggregate TFP growth rate in the OECD.

ii. Industry distribution over technology gaps. Panel B in Table 5.1 further shows parameters related to the industry distribution over technology gaps. I use OECD leader sales premiums to discipline the domestic knowledge spillover parameter κ, similar to the idea in existing work (e.g., Liu et al. (2022)). A larger κ means followers are more likely to receive spillovers and hence reduce the technology gap and leader sales premium.[51] The firm-level demand shifter parameters $(\omega_{ic}^{b}, \omega_{ic}^{*b})$ are set to match the mean and standard deviation of the export intensity premium, the standard deviation of the leader sales premium and the OECD global output share, and the correlation of these latter two. In particular, a larger demand shifter of the leader relative to the follower indicates a larger leader market share and leader premiums in sales and export intensity. The demand shifters also affect the standard deviations and correlations mentioned above because firms at different technology gaps have different responses to the change of demand shifters.

iii. Innovation over technology gaps. The relationship between a firm's innovation rate and its technology gaps is a key for model mechanism. Innovation investment decisions induce a stationary distribution of technology gaps across industries and countries and correspondingly stationary industrial concentrations and productivity growth. Forces that alter firms' investment incentives will change the distribution of technology gaps, and hence change industrial concentrations and productivity growth. Therefore, empirically disciplining how innovation varies with technology gaps is crucial in quantifying the model predictions.

Step 1: Innovation cost scale and leader premium in innovation. Before disciplining how firms' innovation rate varies over technology gaps, I pin down the innovation cost scale parameter α_{1c} in equation (3.15) by matching the R&D to GDP ratio in OECD and ROW in the data. I also consider the innovation difference between leader and follower by estimating α_{2c} to match the mean and standard deviation of leader premium in innovation rate in the model and the data.[52]

Step 2: Uncover state-dependent innovation costs. As discussed in section 4, firm inno-

[50] The computation of the aggregate markup in the model is a revenue-weighted harmonic mean of firm markups, as discussed in Edmond et al. (2015).

[51] I can also use leader TFPR premiums to discipline κ, but using TFPR introduces considerably more measurement errors due to unobservable firm-level price information in the data.

[52] Leader premium in innovation in the model is computed as the difference between leaders' and followers' standardized innovation rates. In the data it is computed as the difference between leaders' and followers' standardized patent citations.

vation is mainly *decreasing* in the domestic technology gap while first *increasing* then slightly *decreasing* in the global technology gap. According to the model, it means firms have decreasing returns to innovation when their market share is large enough; firms have innovation *disadvantage* of backwardness and hence innovate less when they are more distant from the technology frontier. In existing literature, researchers use slow follower catch-up to explain this pattern in the domestic market (Aghion et al. (2005), Akcigit et al. (2018), Liu et al. (2022)). Different from existing literature, I find slow follower catch-up alone is not enough to explain the data patterns documented in section 4, after carefully matching the aggregate productivity growth (which is related to the step size of innovation), industry distribution moments, and innovation cost scale in the data like existing literature.

Therefore, I specify a flexible innovation cost function that depends on technology gaps to additionally discipline firms' innovation rates over technology gaps. In particular, $R_{ict}(m_H, m_F, m_G) \equiv \frac{\alpha_{ic}}{\gamma_{ic}} x_{ict}^{\gamma_{ic}}(m_H, m_F, m_G) f_{ic}(m_H, m_F, m_G) Y_{ct}$, where $f_{ic}(m_H, m_F, m_G) \equiv \exp(m_H)^{\bar{\varphi}_{ic}} \exp(m_F)^{\bar{\psi}_{ic}} \exp(m_G)^{\bar{\chi}_{ic}}$, $i \in \{1, 2\}, c \in \{H, F\}$. α_{ic} governs the scale of innovation costs for all firms in a country and is disciplined as detailed above. γ_{ic} matters for the innovation elasticity and is set to 2 externally as stated before. $f_{ic}(m_H, m_F, m_G)$ is the new addition to innovation costs specified in existing literature (see, e.g., Akcigit and Ates (2019)).[53] The exponential function is used to avoid non-positive costs due to non-positive technology gaps. For simplicity, let $\bar{\varphi}_{ic}$, $\bar{\psi}_{ic}$, and $\bar{\chi}_{ic}$ discipline the curvature of innovation investment along the domestic and global technology gaps. A larger $\bar{\varphi}_{ic}$ indicates firms have to pay higher innovation costs with a larger Home domestic technology gap (m_H). From a Home leader's perspective, this can be due to firm size is increasing in m_H and innovation cost is proportional to firm size, due to, e.g., the larger overhead costs faced by larger firms.[54] From a follower's perspective, a positive $\bar{\varphi}_{ic}$ can be driven by followers at higher m_H (i.e., smaller firms) who face more problems with exogenous inefficiencies, poor management skills, more severe financial frictions, or high fixed operation costs per unit such that they face more difficulties to innovate successfully. That is to say, small firms have lower innovation efficiencies due to more innovation costs when they are more left behind. A positive $\bar{\chi}_{ic}$ means OECD firms pay sufficiently higher innovation costs as the global technology gap m_G rises to ensure innovation cost is positively correlated with exports. A negative $\bar{\chi}_{ic}$ indicates ROW firms pay higher innovation costs with a larger global technology gap (lower m_G). When $\bar{\varphi}_{ic}$, $\bar{\psi}_{ic}$, and $\bar{\chi}_{ic}$ are 0, the innovation cost is independent of firm size. I run the same regression for model simulated firms as in specification (4.1) and ensure it replicates the regression coefficients in the data regression by estimating the state state-dependent innovation parameters $\bar{\varphi}_{ic}$, $\bar{\psi}_{ic}$, and $\bar{\chi}_{ic}$.

To summarize, the country and firm specific state-dependent innovation cost parameters are a parsimonious way to represent country- and firm-specific efficiency differences. These param-

[53] The papers built on dynamic patent race models typically scale innovation costs by some aggregate measure, e.g., wages, aggregate output, or firm productivity, so firm size does not affect firm innovation incentives.

[54] This is consistent with stylised facts showing that larger firms spend more on innovation but the growth rate of productivity does not scale with size. See Impullitti and Licandro (2018). Note that although setting $f_{ic}(m_H, m_F, m_G) = 0$ also generates productivity growth independent of size, it typically generates much lower innovation expenditures for large firms, inconsistent with the data, leading me to introduce a non-negligible f_{ic} function.

eters are estimated to match the observed relationship between firm innovation and technology gaps, specifically, the 6 regression coefficients (β_1 to β_6) in equation (4.1). Parameter values in Table 5.1 show that ROW firms pay higher innovation costs than OECD firms, which reflects the relatively low innovation efficiency in ROW. The large differences in the innovation cost parameters are also driven by the large market size difference between OECD and ROW.[55] On the other hand, Table 5.1 indicates that leaders' innovation costs are increasing in their domestic technological advantage (and domestic market share); followers' innovation costs are also increasing in their technology distance from domestic leaders, suggesting that followers face more innovation costs when they are more left behind. While firms pay slightly higher innovation costs if they are more left behind the global technology frontier.

III. Comparison with existing literature. In terms of parameterization, my key departure from the literature is that I introduce state-dependent innovation cost function to uncover the innovation costs faced by followers and leaders. Specifically, I pin down other parameters similar to existing papers but consider more heterogeneities between leaders and followers and carefully match the industry distribution over technology gaps in terms of sales, export intensity, and innovation. I then introduce state-dependent innovation cost function to explain the firm innovation behavior over technology gaps in the data, as suggested by section 4, joint with other parameters.

To summarize, the way to generate innovation *disadvantage* of backwardness in existing literature is to impose slow catch-up of followers. However, by adopting calibration strategies similar to the existing literature, I infer from the firm-level patent data that innovation *disadvantage* of backwardness due to slow catch-up of followers is not enough to explain the empirical observations. I therefore argue that part of innovation *disadvantage* of backwardness is from innovation costs.

IV. Model fit and discussion. Table 5.1 lists the set of parameters that achieve the best fit and the actual and simulated moments used to estimate the parameters. It shows that the model successfully captures the aggregate moments and industry distribution in the data. The model also closely matches the innovation related moments, especially the shape of innovation rate along technology gaps, as illustrated in Appendix G.3.

5.1.2 New Balanced Growth Path

After parameterizing the initial balanced growth path equilibrium to match the 1990s, I reestimate all internal parameters to pin down the new balanced growth path equilibrium representing the

[55] I the discipline innovation cost function to match the innovation rate instead of innovation expenditure in the data for two reasons. First, the innovation cost function in the model also represents efficiency differences across firms, which are not the same as innovation expenditures. Second, innovation expenditures are poorly captured in ORBIS. Although intangible assets in ORBIS is related to innovation investment, it is a stock variable instead of a flow variable. As a robustness check, I utilize firm-level R&D expenditures in the Compustat Global data set (the sample is biased towards large firms) and run similar regressions as equation (4.1). The data implied regression coefficients are qualitatively consistent with the ones estimated from patent data in ORBIS.

Table 5.1: Parameterization and Targeted Moments: Initial BGP

Parameter	Notation	Value	Identification	Targeted Moments	
				Data	Model
External Parameterization					
Fraction of leaders	ω_{1c}	0.05	Empirical facts		
Home labor force	L_H	1	Normalization		
Domestic quick catch-up prob.	ϕ_c	0.0423	Akcigit and Ates (2019)		
International quick catch-up prob.	δ_c	0.025	Akcigit et al. (2020)		
Innovation cost elasticity	γ_{ic}	2	Common estimates		
Internal Parameterization					
Panel A. Aggregate variables					
Foreign labor force	L_F	30	Mean global output share	0.06	0.06
Elasticity of substitution	ϵ	5	Aggregate markup	1.20 - 1.30	1.30
Discount factor	ρ	0.05	Real interest rate	0.05	0.05
Productivity step size	λ	1.08	TFP growth rate,%	1.05	1.05
Trade iceberg cost	τ_c	1.91	Mean export intensity	0.17	0.17
International spillover	ι	0.01	Mean OECD TFP relative to ROW	1.29	1.29
Panel B. Industry distribution					
Domestic spillover	κ	0.09	Mean leader sales premium	3.10	3.09
Demand shifter	ω^b_{1H},ω^{*b}_{1F}	0.40	St.dev. leader sales premium	0.99	0.79
	ω^b_{2H},ω^{*b}_{2F}	0.14	Mean leader export intensity premium	0.05	0.05
	ω^b_{1F},ω^{*b}_{1H}	0.40	St.dev. leader export intensity premium	0.08	0.07
			St.dev. global output share	0.05	0.04
			β(leader sales premium, global output share)	0.00	0.00
Panel C. Innovation					
Innovation cost scale	α_{1H}	18.73	R&D/GDP in OECD,%	2.27	2.30
	α_{1F}	109.56	R&D/GDP in ROW,%	1.91	1.87
	α_{2H}	2.97	Mean leader innovation premium	0.25	0.32
	α_{2F}	7.83	St.dev. leader innovation premium	0.48	0.56
Innovation cost curvature	$\bar{\varphi}_{1H}$, $\bar{\varphi}_{2H}$	0.50	β_1(innovation, OECD leader sales premium)	-0.495***	-0.435
	$\bar{\psi}_{1F}$, $\bar{\psi}_{2F}$	23.50	β_4(innovation, OECD leader sales premium^2)	0.021	0.014
	$\bar{\psi}_{1H}$, $\bar{\psi}_{2H}$	0.50	β_3(innovation, ROW leader sales premium)	-1.803***	-0.962
	$\bar{\varphi}_{1F}$, $\bar{\varphi}_{2F}$	23.50	β_6(innovation, ROW leader sales premium^2)	0.096	0.079
	$\bar{\chi}_{1H}$, $\bar{\chi}_{2H}$	-0.28	β_2(innovation, OECD global output share)	72.973**	69.986
	$\bar{\chi}_{1F}$, $\bar{\chi}_{2F}$	8.46	β_5(innovation, OECD global output share^2)	-525.275**	-340.623

Notes: The first three columns in this table presents the list of model parameters and estimated values for the Home (OECD) and Foreign (ROW) countries along the initial BGP, $i \in \{1, 2\}$, $c \in \{H, F\}$. For the internal parameterization, all parameters are estimated jointly. ROW parameters are the same as OECD unless otherwise specified. The last three columns in this table presents values of targeted moments in the data (1990s) and the model (initial BGP). The targeted moments are for the internal parameterization using the simulated method of moments technique. The data moments are computed from advanced OECD countries unless specified. All data measures are GDP-weighted across countries and obtained from ORBIS, World Bank, OECD ICIO 2021, etc.

2010s. The changes in τ_c and ι indicate the two forces of globalization. Several other parameter changes capture some secular trends: the decrease of κ indicates declining domestic knowledge spillovers as discussed in Akcigit and Ates (2019), the decrease in ρ represents a declining real interest rate as illustrated by Liu et al. (2022), and the increase in the innovation cost parameter α_{ic} captures the fall in research productivity found in Bloom et al. (2020).

Model fit and discussion. Table 5.2 lists the set of parameters that achieve the best fit and the actual and simulated moments used to estimate the parameters. To capture the observed changes in the data, the probability of international knowledge spillovers increases ($\iota' > \iota$), and the trade iceberg cost decreases ($\tau_c' < \tau_c$). Further, the new domestic spillover parameter is estimated to be larger than for international spillovers, in line with the existing literature arguing that knowledge spillovers are stronger within than across countries (see, e.g., Eaton and Kortum (1999), Keller (2002), Sampson (2020)).

5.2 Model Validation

Before discussing the mechanism of the parameterized model, I present two out-of-sample tests to assess the quantitative plausibility of the parameterization in light of empirical relationships not used in the parameterization.

5.2.1 Industry Mass Distribution

The model targets the mean and standard deviation of the industry-level leader sales premium and the global output share of OECD. Although not directly targeted, the entire distribution of OECD leader market shares among domestic firms and OECD firms' global output share closely match the data along both the initial and new BGPs. Figure 5.1 classifies market shares of leaders and global output shares into 5 groups defined by an even partition over the range of the data, and then calculating the fraction of industries in each set. Over time, more and more industries have leaders with high domestic market shares, indicating an increase in domestic concentration. At the same time, more and more OECD industries are losing global market share. Since the aggregate productivity effect of firm innovation depends on the changing distributions of firms, these changes in concentration influence growth. The successful replication of the industry mass distribution makes the model implications more convincing.

5.2.2 Shape of Innovation Rate over Technology Gaps

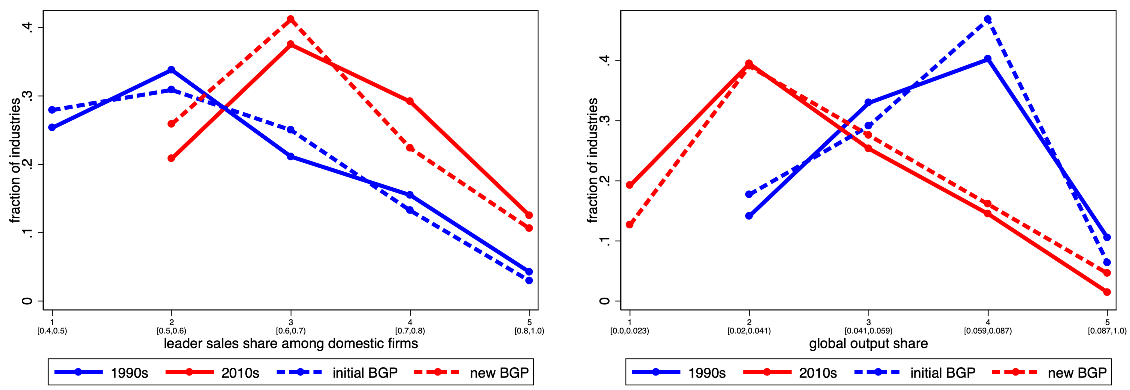
The model targets the total innovation rate of all firms, combining leaders and followers. Reassuringly, the untargeted innovation rates of leaders and followers also end up closely matched to the data. Table G.1 presents the model regression results from equation (4.1) for leaders and followers and shows that the model results are quantitatively similar to the data. Figure 5.2 uses the same industry classification as Figure 5.1 and plots the measured innovation rates of OECD

Table 5.2: Parameterization and Targeted Moments: New BGP

Parameter	Notation	Value	Identification	Targeted Moments	
				Data	Model
External Parameterization					
Fraction of leaders	ω_{1c}	0.05	Empirical facts		
Home labor force	L_H	1	Normalization		
Domestic quick catch-up prob.	φ_c	0.0423	Akcigit and Ates (2019)		
International quick catch-up prob.	δ_c	0.025	Akcigit et al. (2020)		
Innovation cost elasticity	γ_{ic}	2	Common estimates		
Internal Parameterization					
Panel A. Aggregate variables					
Foreign labor force	L_F	31.5	Mean global output share	0.03	0.03
Elasticity of substitution	ϵ	6	Aggregate markup	1.50 - 1.60	1.51
Discount factor	ρ	0.02	Real interest rate	0.02	0.02
Productivity step size	λ	1.12	TFP growth rate,%	0.27	0.26
Trade iceberg cost	τ_c	1.83	Mean export intensity	0.24	0.24
International spillover	ι	0.05	Mean OECD TFP relative to ROW	1.13	1.13
Panel B. Industry distribution					
Domestic spillover	κ	0.07	Mean leader sales premium	3.62	3.61
Demand shifter	ω^b_{1H},ω^{*b}_{1F}	0.38	St.dev. leader sales premium	1.24	1.15
	ω^b_{2H},ω^{*b}_{2F}	0.15	Mean leader export intensity premium	0.30	0.26
	ω^b_{1F},ω^{*b}_{1H}	0.38	St.dev. leader export intensity premium	0.08	0.07
			St.dev. global output share	0.03	0.03
			β(leader sales premium, global output share)	0.00	0.00
Panel C. Innovation					
Innovation cost scale	α_{1H}	35.92	R&D/GDP in OECD,%	2.46	2.46
	α_{1F}	217.37	R&D/GDP in ROW,%	2.19	2.21
	α_{2H}	5.67	Mean leader innovation premium	0.39	0.41
	α_{2F}	15.11	St.dev. leader innovation premium	0.73	0.76
Innovation cost curvature	$\bar{\varphi}_{1H}$, $\bar{\varphi}_{2H}$	0.47	β_1(innovation, OECD leader sales premium)	0.041***	0.039
	$\bar{\psi}_{1F}$, $\bar{\psi}_{2F}$	22.70	β_4(innovation, OECD leader sales premium^2)	-2.837***	-2.768
	$\bar{\psi}_{1H}$, $\bar{\psi}_{2H}$	0.47	β_3(innovation, ROW leader sales premium)	48.750***	46.435
	$\bar{\varphi}_{1F}$, $\bar{\varphi}_{2F}$	22.70	β_6(innovation, ROW leader sales premium^2)	-0.146***	-0.127
	$\bar{\chi}_{1H}$, $\bar{\chi}_{2H}$	-0.23	β_2(innovation, OECD global output share)	33.324***	35.461
	$\bar{\chi}_{1F}$, $\bar{\chi}_{2F}$	9.21	β_5(innovation, OECD global output share^2)	-622.410***	-598.753

Notes: The first three columns in this table presents the list of model parameters and estimated values for the Home (OECD) and Foreign (ROW) countries along the new BGP, $i \in \{1,2\}, c \in \{H,F\}$. For the internal parameterization, all parameters are estimated jointly. ROW parameters are the same as OECD unless otherwise specified. The last three columns in this table presents values of targeted moments in the data (2010s) and the model (new BGP). The targeted moments are for the internal parameterization using the simulated method of moments technique. The data moments are computed from advanced OECD countries unless specified. All data measures are GDP-weighted across countries and obtained from ORBIS, World Bank, OECD ICIO 2021, etc.

Figure 5.1: Industry Mass Distribution: Model vs Data

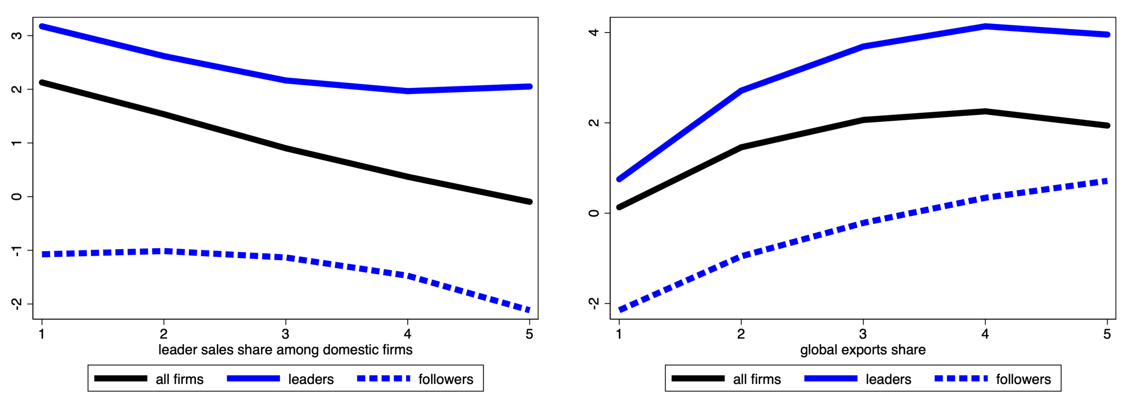


(a) OECD leader market share (b) OECD global output share

Notes: This figure presents the industry mass distribution over leader domestic market share and global market shares for OECD firms in both the model and the data. The X-axis partitions the range of X into 5 equal lengths. The Y-axis denotes the fraction of industries in each group.

leaders and followers over OECD leaders' domestic shares and OECD's global output shares in the model. Consistent with the data, the model predicts leaders have higher innovation rates than followers, that both firms innovate less as leader domestic market share increases, and that innovation first increases then slightly decreases as global output share increases.[56]

Figure 5.2: Shape of Innovation Rate in the Initial BGP



(a) OECD leader market share (b) OECD global output share

Notes: This figure presents the standardized innovation rate in terms of the leader's domestic market share and the industry's global output share for all firms, leaders, and followers, respectively, in initial BGP in the model for the OECD. The X-axis partitions the range of X into 5 equal lengths. The Y-axis denotes the fraction of industries in each group.

[56] Of note, a higher innovation rate does not mean higher innovation intensity. Innovation intensity is often measured by patents per employee (see, e.g., Akcigit and Kerr (2018)) or R&D-sales ratio (see, e.g., Acemoglu et al. (2018)).

5.3 Mechanism Discussion

Section 3.9 discusses some outstanding model properties and reveals how firm innovation rates vary with technology gaps matters for the model predictions. In this section I explain the model mechanism from the OECD perspective through the parameterization results.

As shown in Figure 5.2, along the initial BGP leader and follower innovation rates mainly *decrease* in the domestic technology gap. On the other hand, firm innovation rates first *increase* then *decrease* in the global technology gap. Taking into account the industry mass distribution over the global technology gap, most firms are concentrated in the region where their innovation rates increase in the global technology gap. The huge foreign market makes OECD firms want to increase their exports for higher profits at higher global technology gaps, and hence innovation rates mainly increase in the global technology gap.

Globalization alters firms' innovation rates and reshapes the distribution over technology gaps, and hence industrial concentration and productivity growth via three effects. Globalization increases the foreign market size, enabling firms to export more and obtain higher export profits via the *market size effect.* The larger foreign market is from both declining trade iceberg costs, which enables firms to export more, and increasing international knowledge spillovers, which improve the productivity of less productive ROW firms and hence market size via general equilibrium effects. Globalization also induces an *import competition effect* that reduces domestic profits. As indicated in section 3.9, the overall effect on the production profits of firms depends on the relative changes of export and domestic profits. Since leaders have higher export intensities than followers, leaders are more able than followers to increase export profits in response to globalization to reduce the negative effect on domestic profits.

Therefore, when globalization triggers a large enough increase in the foreign market size such that the increased leader export profits offsets their declining domestic profits, leaders have a larger increase in innovation incentives than followers, thereby increasing the domestic technology gap, their domestic market share, and profits.[57] The induced increase in industrial concentration among domestic firms in turn lowers aggregate innovation and productivity growth due to the lower innovation rates at higher domestic technology gap, which is referred to as "weaker domestic competition". On the other hand, the increasing international knowledge spillovers directly strengthen international competition and reduce the global technology gap and hence OECD firms' technological advantage relative to ROW via *international business stealing effect*, which contributes to lower aggregate productivity growth due to reduced innovation incentives at lower global technology gaps. Globalization induces "harsher foreign competition", via import competition effect and international business stealing effect, typically decreases leaders' innovation rates by more than followers because of larger reduction of value of leaders, and hence contributes to a decrease in the domestic technology gap. Therefore, an increase in the domestic technology gap and hence industrial concentration indicates market size effect dominates the

[57] What matters is the *relative* change in the innovation rates of leaders and followers. Follower innovation could decrease due to the import competition effect.

other two effects.

5.4 Implications of Globalization

In this section I investigate the implications of globalization and compare to other secular trends mentioned in section 5.1.2. I then decompose the two forces of globalization to examine their contribution to the model findings.

5.4.1 Implications of Globalization and Comparison with Other Secular Trends

Implications on OECD. The first two columns in Table 5.3 indicate that the model successfully captures key features of the OECD data, notably the slowing productivity (TFP) growth rate and the uneven firm growth in both domestic and foreign markets (measured by leader premiums in sales and exports), consistent with motivating fact 1 and 2. The larger increase in the export premium is due to the large increase in foreign market size which favors leader exports.[58]

The third-to-last column in Table 5.3 reports the effect of changing individual parameters from their initial BGP values to their new BGP values, holding the others fixed at initial values. The third column in Table 5.3 changes the globalization parameters ι and τ, showing that globalization explains approximately 80% of the increasing domestic concentration and 50% of the decrease in OECD productivity growth.[59] The increase in the domestic technology gap is consistent with the rise in industrial concentration, as well as the data evidence that the productivity gap between leaders and followers increases, as shown in Section 2. The decrease in the global technology gap is consistent with the decline in OECD TFP relative to ROW from the 1990s to the 2010s. Moreover, globalization predicts a decrease in OECD global output shares and an increase in the OECD aggregate markup, which are also secular trends documented by the literature.

Implications on ROW. For ROW, globalization decreases TFP growth because all countries share the same balanced growth path in the model. Interestingly, the increase in domestic concentration is much smaller than in OECD, as shown in Table C.1. This is because along the initial BGP, ROW is much less concentrated compared to OECD,[60] and hence follower firms have relatively strong catch-up incentives, moderating domestic concentration.

Comparison with other secular trends. The last three columns in Table 5.3 show the effect of

[58] Recall the leader premium in sales is computed from the GDP-weighted average of 12 advanced OECD countries in ORBIS. The leader premium in exports is computed from the GDP weighted average of France and Greece due to data limitations. To make these premiums comparable, the leader premium in exports reported here is relative to sales in France and Greece.

[59] Recall domestic concentration is measured as the leader sales share among domestic firms in both the model and data. The 5% mass of leaders within each industry enables me to simultaneously match the leader premium in sales and domestic concentration to the data.

[60] This is because the larger innovation cost in ROW slows down the growth of firms, especially leaders. This is consistent with the empirical findings discussed by Peters and Zilibotti (2021) that in richer economies firms are on average larger and the best firms grow more over time than in poorer countries, though our theoretical explanation is different.

each alternative trend nested in this model. The alternatives are a declining real interest rate (decrease ρ), declining domestic knowledge spillovers (decrease κ), and a fall in research productivity (increase α_{ic}).

Two interesting findings result. First, all these alternatives yield some counterfactual predictions. Although a declining real interest rate and declining domestic knowledge spillovers contribute to slower TFP growth and increasing domestic concentration, they predict a larger global technology gap and almost constant OECD global output shares, inconsistent with the observed convergence between OECD and ROW TFP. This is because OECD firms have higher innovation efficiency than ROW firms. The declining real interest rates and domestic knowledge spillovers promote the successful innovation of OECD firms by more, increasing the global technology gap. The fall in research productivity generates slower TFP growth but predicts a decrease in domestic concentration. This is because leaders are more sensitive to increases in innovation costs as shown from firms' profit function and innovation decision rule.

Second, the explanatory power of globalization in terms of the aggregate variables of interest is much stronger than all these alternatives.[61] The large explanatory power is not only from harsher foreign competition, which is absent in closed economy models, but also from larger foreign market. Globalization uniquely generates broader markets than other forces and amplifies the economies of scale due to innovation. Therefore, it is not surprising that globalization dominates other forces.

5.4.2 Decomposing the Forces of Globalization

As detailed in Section 5.1, two parameters jointly govern globalization: the iceberg cost τ and the international knowledge spillover parameter ι. The fourth and fifth columns in Table 5.3 report the implications of changing each in isolation. Increasing international spillovers play a major role in generating increasing domestic concentration and slower aggregate TFP growth. In contrast, declining trade costs predict an increase in aggregate TFP growth and a counterfactually smaller increase in the leader export premium compared to sales, driven by larger decreases in domestic leader markups relative to export markups.[62] Constant aggregate TFP growth and global output shares also indicate the tiny role of trade costs.

The dominant role of increasing international knowledge spillovers is due to two reasons. First, increasing international knowledge spillovers generate a much larger *market size effect* by costlessly increasing the productivity (and hence aggregate income and final demand) of relatively unproductive ROW firms, resulting in OECD leaders having greater innovation incentives than followers, leading to larger leader premiums in sales and exports. The induced weaker domestic competition due to higher domestic concentration leads to a decrease in aggregate TFP growth. Second, increasing international knowledge spillovers generate a unique *international business stealing effect*, facilitating the fast growth of ROW TFP and reducing the global tech-

[61] The only exception is the role of a fall in research productivity on TFP growth.

[62] This is a direct implication of Proposition 2.

Table 5.3: Implications of Globalization on OECD

	Data	Model	Decomposition					
			globalization	$\iota\uparrow$	$\tau\downarrow$	$\rho\downarrow$	$\kappa\downarrow$	$\alpha_H,\alpha_F\uparrow$
Panel A. Technology gaps								
ΔDomestic gap		1.33	1.15	1.14	0.01	0.24	0.61	-0.69
ΔGlobal gap		-1.61	-0.82	-0.82	-0.05	0.17	0.14	-0.10
Panel B. Uneven firm growth								
ΔLeader sales premium	0.52	0.52	0.44	0.39	0.01	0.09	0.15	-0.25
ΔLeader exports premium	0.91	0.92	0.81	0.81	0.002	0.26	0.49	-0.32
Panel C. Aggregates								
ΔTFP growth rate,%	-0.78	-0.79	-0.42	-0.42	0.00	-0.001	-0.07	-0.92
ΔDomestic concentration	0.08	0.08	0.07	0.06	0.01	0.01	0.03	-0.03
ΔGlobal output share	-0.03	-0.02	-0.01	-0.01	0.00	0.00	0.00	0.00
ΔAggregate markup	0.30	0.21	0.14	0.08	0.05	0.001	0.01	-0.01

Notes: The first two columns of this table present the changes of key variables within OECD and ROW from the 1990s (initial BGP) to the 2010s (new BGP) in the data and the model. The third-to-last column shows the effect of globalization (ι increase and τ decrease), increasing international knowledge spillovers (ι increase), decreasing trade iceberg costs (τ decrease), a declining real interest rate (ρ decrease), declining domestic knowledge spillovers (κ decrease), and a fall in research productivity (α increase) from the initial BGP to the new BGP. The domestic technology gap is the average $m_c, c \in \{H, F\}$, and the global technology gap is the average m_G in the model.

nological advantage of OECD firms. This harms OECD firms' innovation incentives and lowers aggregate TFP growth.

To further understand the different roles of the two forces of globalization, I examine how the distribution of OECD industries over their global market share changes in response to each force. Figure 5.3 shows increasing international knowledge spillovers shifts the initial distribution to the left, while decreasing iceberg costs disperses the initial distribution around its mean. Those different effects highlight that a dominating international knowledge spillover effect is required to shift the distribution consistently with the data, as shown in Figure 5.1.

In fact, the differential effects on the industry mass distribution exactly reflect firms' innovation responses and the changing technology gaps. In the model, the higher the global technological advantage of an industry, the higher its global market share. Increasing international spillovers makes it harder for OECD to maintain its original technological advantage, shifting the distribution left. Therefore, increasing international spillovers speak to a cross-country *technological convergence* story. Instead, the decreasing trade costs speak to a *specialization* story, which generates industry technological divergence across countries. The decreasing trade costs incentivize OECD firms with initially high global technological advantages to innovate more to reap higher export profits due to the relatively large market size effect, so we see a fatter right tail in panel (b) of Figure 5.3.[63] Similarly, ROW firms that have initially high global technological advantages innovate more to have higher sales, further reducing OECD's global market share relative to ROW, so we see a fatter left tail.

These interesting findings highlight that different globalizing forces affect firm growth and aggregate productivity growth differently. Therefore, studying the effects of globalization requires correctly identifying the forces of globalization and is a more complex undertaking than previously understood.

5.5 The Role of the Main Model Elements

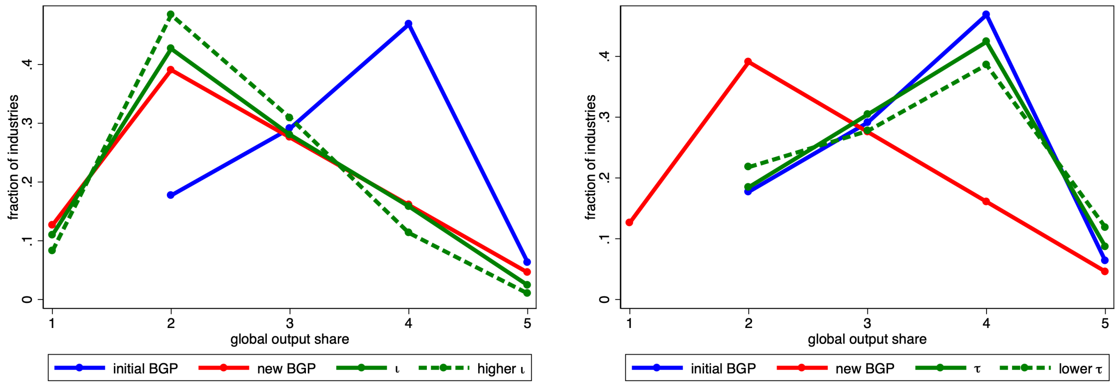
The previous analysis reveals the model mechanism hinges on two key ingredients: (i) oligopolistic domestic competition; (ii) innovation *disadvantage* of backwardness. In this section, I highlight the role of each key ingredient in driving the quantitative results and summarize in Table 5.4. I then provide analysis for other relevant model elements.

5.5.1 Oligopolistic Domestic Competition

Strategic domestic competition between heterogeneous firms, due to the oligopolistic competition, is a novel addition to existing *open economy* growth or innovation models. How does strategic domestic competition affect the model predictions compared to strategic international

[63] The model predicts the higher the global technological advantage, the more exports, and the larger the market size effect of globalization.

Figure 5.3: Industry Mass Distribution Over global output share of OECD



(a) increase ι

(b) decrease τ

Notes: Panel (a) and (b) in this figure present the industry mass distribution over OECD global output shares when separately changing the international knowledge spillover parameter ι and the iceberg cost parameter τ separately in the model. The blue line represents the initial BGP. The red line represents the new BGP. The green solid line represents changing one parameter from its initial BGP value to its new BGP value. The green dash line represents increasing (decreasing) one parameter from its initial BGP value to a value that is twice larger (smaller) than the new BGP value. The X-axis partitions the range of X into 5 equal lengths. The Y-axis denotes the fraction of industries in each group

competition? To see this, I shut down all strategic domestic competition by collapsing each industry to one firm per country. A recalibrated model indicates that strategic international competition alone plays a minor role in driving down long-run aggregate productivity growth, as shown in column (2) in Table 5.4. This is due to the larger "escape-competition" innovation incentive of OECD firms with a high technological advantages relative to the rest of the world and the larger innovation incentive of OECD firms with a technological disadvantage due to more international knowledge spillovers. Unfortunately, the one-firm-per-industry setup makes it impossible to study industrial concentration within a country.

5.5.2 Innovation Disadvantage of Backwardness

Different from the existing work, innovation *disadvantage* of backwardness is from not only the slow catch-up of firms that are distant from the technology frontier but also the more innovation costs faced by these firms. I shut down the two sources of innovation *disadvantage* of backwardness in domestic and international market, respectively, to highlight their roles.

Disadvantage of backwardness due to slow catch-up in the domestic market. In column (3) of Table 5.4, I assume quick catch-up probability of followers equals 1 in two countries and recalibrate the model such that followers have *advantage* of backwardness: they have higher innovation rate when they have larger domestic technology gap relative to the leaders. The results indicate that the predictions on domestic concentration and aggregate productivity growth are opposite to the predictions with innovation *disadvantage* of backwardness of followers. This is because market size effect of globalization still dominates and triggers a larger innovation increase of followers than leaders. Due to quick catch-up, followers expect a much larger increase in export profits from globalization once they close the technology gap with the leaders, and hence innovate more. To summarize, innovation *disadvantage* of backwardness of followers is critical to predict that globalization contributes to a rising industrial concentration and a slower productivity growth.

Disadvantage of backwardness due to innovation costs in the domestic market. According to the parameterization of the baseline model, the innovation *disadvantage* of backwardness is from not only slow catch-up of followers but also more innovation costs faced by more left-behind followers. A natural follow-up question is, do two sources of innovation *disadvantage* of backwardness have different implications of globalization? To see this, in column (4) of Table 5.4, I fix the slow catch-up probability of followers to the baseline model level, recalibration the model, especially the state-dependent innovation cost function, to match the same magnitude of *advantage* of backwardness as in column (3). The results indicate two sources of innovation *disadvantage* of backwardness have qualitative similar predictions.

Disadvantage of backwardness in the international market. According to the parameterization of the baseline model, the innovation *disadvantage* of backwardness in the international market is from slow catch-up of firms. In particular, leaders in two countries can only innovate step-by-step. In column (5) of Table 5.4, I shut down innovation *disadvantage* of backwardness in the international market by changing the state-innovation cost parameter $\bar{\chi}_{ic}$ such that firms pay lower innovation cost if they have larger global technology gap relative to the global leader. At the same time, I keep innovation *disadvantage* of backwardness in the domestic market as in the baseline model. The results indicate that by allowing *advantage* of backwardness in the international market, the negative productivity growth effect of globalization is mitigated (compare column (5) and (1)). This is because after globalization reduces global technological advantage of OECD countries due to the "harsher foreign competition", OECD firms have higher innovation rate due to *advantage* of backwardness in the international market.

In column (6), I keep *advantage* of backwardness in the international market and further shut down the strategic domestic competition by collapsing each industry to one firm per country. The recalibration results indicate that globalization has positive productivity growth effect. Without globalization-induced "weaker domestic competition", the "harsher foreign competition" predicts a faster productivity growth. To summarize, innovation *disadvantage* of backwardness in the international market contributes to the prediction that globalization generates a slower productivity growth.

5.5.3 Other Model Elements

Two other model elements are also relevant for the model mechanism and differ from many existing trade models with or without innovation. They are (i) international knowledge spillover and (ii) endogenous productivity of firms. Their roles highlight the interaction between global-

Table 5.4: The Role of the Main Model Elements

	(1)	(2)	(3)	(4)	(5)	(6)
	Globalization	No domestic	*Advantage* of backwardness			
		competition	in domestic market		in int'l market	
	(benchmark)	(1 firm per j, c)	($\phi_c = 1$)	($\bar{\varphi}_c < 0$)	($\bar{\chi}_c < 0$)	(1 firm per j, c)
Panel A. Technology gaps						
ΔDomestic gap	1.15		-0.43	-0.11	0.19	
ΔGlobal gap	-0.82	-0.20	-0.65	-0.49	-0.53	-0.15
Panel B. Uneven firm growth						
ΔLeader sales premium	0.44		-0.07	-0.01	0.21	
ΔLeader exports premium	0.81		-0.19	-0.03	0.26	
Panel C. Aggregates						
ΔTFP growth rate,%	-0.42	-0.09	0.45	0.20	-0.11	0.08
ΔDomestic concentration	0.07		-0.04	-0.01	0.05	
ΔGlobal output share	-0.01	-0.004	-0.008	-0.007	-0.007	-0.003
ΔAggregate markup	0.14	-0.02	-0.02	-0.01	0.09	-0.01

Notes: This table presents the effect of globalization on OECD in the baseline model and counterfactuals by shutting down the model elements.

ization (especially international knowledge spillover force) and firm innovation generates a much larger effect than either one alone, as indicated in Table C.2. More detailed analysis is relegated to Appendix C.3.

5.6 Additional Discussion

In this section, I provide discussions of policy implications, transition dynamics and welfare, additional empirical evidence on the model mechanism, and model assumptions and extensions.

5.6.1 Policy Implications

The negative productivity growth effect of globalization discussed above is depressing. Are there policies that could mitigate this adverse effect? I introduce a set of unilateral policies for OECD during globalization to assess the potential remedies.

Specifically, I compare the productivity growth change from the initial BGP to the new BGP. In the new BGP, I introduce globalization (as in the baseline model) and a policy in OECD. The policy can be an innovation policy (subsidy to follower or all firms), trade policy (export subsidy to follower, tariff increase), or corporate tax policy (profit tax on leader). All policies have the same balanced government transfer (equivalent to a 20% tariff increase). Policies that favor followers (i.e., subsidy to followers or tax on leaders) are to intensify domestic competition, given that globalization weakens domestic competition. Policies that favor all firms (i.e., subsidy to all firms or tariff increase) are to reduce globalization-induced foreign competition.

Panel B in Table 5.5 indicates three interesting findings. First, an innovation policy that aims to intensify domestic competition is more effective in boosting productivity growth than one that aims to reduce foreign competition. The underlying economic reason is exactly highlighted in section 5.5.1. Second, an innovation policy is more effective than a trade or corporate tax policy in raising productivity growth. This is because innovation policy can directly affect firms' innovation incentives. In contrast, other policies can only indirectly affect firms' innovation via the production profits change, and firms' innovation is less sensitive to the indirect effect. Third, tariff increases that reduce foreign competition negatively affect productivity growth. This is because the tariff increases further weaken domestic competition and reduce firms' innovation incentives, suggesting policymakers should consider the interplay between foreign and domestic competition in designing productivity-enhancing policies.

Besides the policies discussed above, policymakers consider other policies, e.g., technology transfer policies. These policies can be intellectual property right protection and other defensive R&D policies that establish barriers to technology transfer. In Panel C of Table 5.5, I consider the policy that facilitates domestic technological transfers from leaders to followers in OECD. Similar to Panel B, I compare the initial BGP to the new BGP with globalization and domestic technology transfer policy (impose a domestic knowledge spillover κ twice larger than the baseline model). The results indicate that this domestic technology transfer policy can undo the negative growth effect of globalization. Followers benefit from the domestic technological transfer, become less negatively affected by the globalization-induced weaker domestic competition, and grow faster.

I also consider the international technology transfer policy that reduces technological transfers from OECD to ROW by reducing the international knowledge spillover ι to half its baseline level. The results show that lowering international technology transfer can also mitigate the negative growth effect of globalization. This is because of a smaller market size effect and international business stealing effect, mitigating both the weaker domestic competition and harsher foreign competition induced by globalization. Though these technology transfer policies seem promising, I assume these transfers are costless in this exercise. Hence, it is unclear how costly these policies are to achieve the desired results. Pricing these technology transfer policies is left for future research.

5.6.2 Transition Dynamics and Welfare

In the above, I conduct quantitative analysis based on steady state comparative statics. However, it often takes a long time for the economy to transition between steady states. Therefore, it is unclear whether the long-run productivity growth prediction of the model is consistent with the productivity growth slowdown we observe in the data. Further, advanced OECD countries experienced a burst of productivity growth from the 1990s to the early 2000s before productivity growth slowed. Productivity growth in the rest of the world, especially emerging markets, is

Table 5.5: Unilateral Policy Implications

	productivity growth change, %
Panel A. Globalization	
baseline model	-0.42
Panel B. Globalization + balanced government transfer	
innovation policy	
subsidy to follower	-0.13
subsidy to all firms	-0.20
trade policy	
export subsidy to follower	-0.42
tariff increase	-0.43
corporate tax policy	
profit tax on leader	-0.42
Panel C. Globalization + costless technology transfer	
increase domestic transfer $\kappa \times 2$	0.01
decrease int'l transfer $\iota/2$	-0.21

Notes: In this table, Panel A shows the long-run productivity growth effect of globalization in the baseline model. Panel B presents the long-run productivity growth effect of globalization with policies that have the same balanced government transfer. Panel C shows the long-run productivity growth effect of globalization with costless technology transfers.

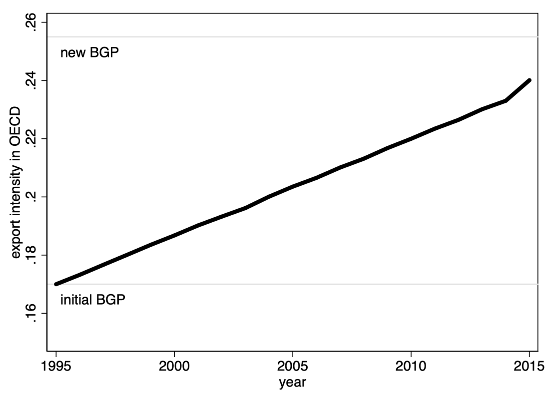
faster than in advanced OECD countries. The steady state analysis makes it impossible to analyze non-linear changes in productivity growth or asymmetric productivity growth across countries. To this end, I compute the model's transition dynamics in response to globalization to further examine the dynamics of productivity and concentration. Specifically, I consider a gradual decrease in trade iceberg costs and a gradual increase in international knowledge spillovers to match the export intensity in OECD and relative TFP between OECD and ROW in the first 20 years of a transition episode. The detailed computational algorithm is relegated to Appendix G.1.

Figure 5.4 plots the first 20 years of the transition dynamics, showing that during the transition productivity growth initially surges and then after 7 years quickly declines towards to the new steady state value. The productivity growth of ROW is higher than OECD. These transition patterns of productivity growth are fairly consistent with what we observe in the data. Intuitively, OECD firms realize that globalization will create larger foreign markets and hence larger profits especially for leaders, which leads to surges in innovation investment and productivity growth. But over time, the general equilibrium forces that decrease innovation materialize, leading to a slowdown in productivity growth. The higher productivity growth of ROW is due to more knowledge spillovers from a more productive OECD. On the other hand, the gradual change in relative productivity due to infrequent innovation between domestic leaders and followers leads to slowly rising industrial concentration that does not fully reach its new steady state after 20 years.

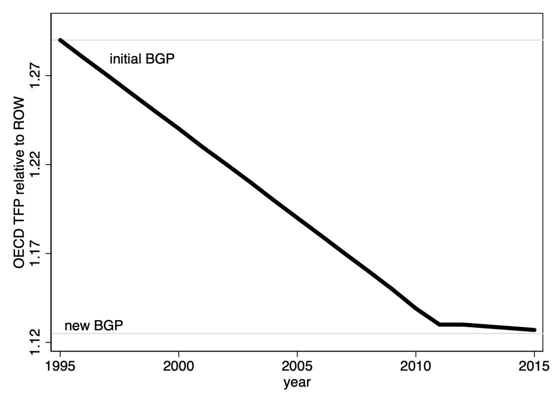
A direct implication is that though the productivity growth of ROW benefits from globalization in the short-run, in the mid-run and long-run productivity growth slows down globally. Therefore, the growth rate of all countries in the long-run depends on the innovation of global leaders.

In terms of welfare implications of globalization, I find OECD increases by 1 percent and ROW increases by 9 percent, in consumption equivalence terms, starting from the transition towards the new BGP. Moreover, the welfare gains are front-loaded, driven by the slower productivity growth in the long run.

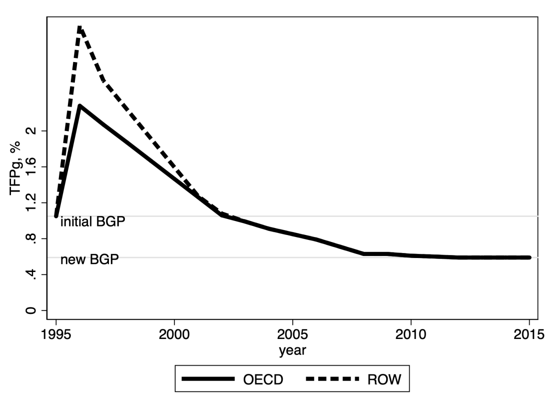
Figure 5.4: Transition Dynamics



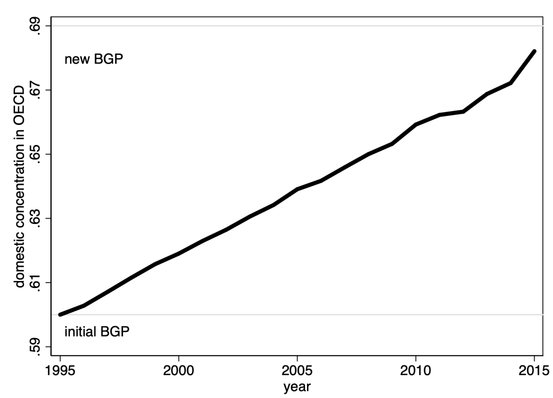
(a) export intensity



(b) relative TFP



(c) TFP growth



(d) domestic concentration

Notes: Panel (a) and (b) in this figure present the evolution of TFP growth in OECD and ROW, along with the domestic concentration in OECD for the first 20 years of the transition dynamics. The initial and new BGP values induced solely by globalization are also added in the figure.

5.6.3 Additional Evidence of the Model Mechanism

Market size effect generates innovation slowdown. According to the model, globalization creates larger foreign market sizes and induces differential innovation responses across leaders and followers. Firms, especially leaders, want to innovate to acquire larger export profits from successful innovation. The larger innovation incentive of leaders relative to followers translates into larger domestic technology gaps and higher domestic concentration, which then decreases both leaders' and followers' innovation incentives. Therefore, industries with larger increases in export openness first generate bigger changes in leaders' innovation incentives and correspondingly larger declines later. To show this, I track firms through the 20-year transition dynamics and use the model simulated data to run regressions using the initial and end periods of the transition. I then run similar regressions in the data to verify this mechanism holds. Table 5.6 displays that the model results are qualitatively consistent with the data. Table A.4 provide additional empirical evidence using alternative measures of innovation in the data.

Table 5.6: Export Openness and Innovation Response

	Data (ΔNumber of Patents$_{t-5,t}$)				Model (ΔInnovation Rate$_{t-5,t}$)			
	initial period		end period		initial period		end period	
	leader	follower	leader	follower	leader	follower	leader	follower
$\Delta EXO_{t-5,t}$	4.897**	-9.407***	-6.041***	-0.255	11.352	-1.233	-18.463	-0.056
	(2.114)	(2.181)	(1.734)	(0.505)				
Obs.	145,914	2,547,403	547,586	8,770,004				
Adjusted R^2	.8	.77	.76	.83	.53	.38	.62	.37
Country-Year FE	Yes	Yes	Yes	Yes				
Year FE					Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes				
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Notes: This table presents regression results of firms' innovation responses from year $t-5$ to t to a change in export intensity from year $t-5$ to t in the data and in the model simulated transition dynamics. The initial periods denote years before 2005 in the data and the first 10 years in the model. The end periods denote years after 2005 in the data and the last 10 years in the model. The innovation measures are standardized number of patents in the data and standardized innovation rate in the model. Controls include industry-level export intensity and firm-level innovation measures at year $t-5$. * $p<0.10$, ** $p<0.05$, *** $p<0.01$.

5.6.4 Discussion of Model Assumptions and Extensions

Several assumptions simplified the model. This section shows that the model mechanism and results do not hinge on these assumptions and provide some modelling extensions. More details are in Appendix F.7.

Restricted exporting. In the baseline model all firms export. However, the data indicates not all do. I assume leaders export while followers do not to capture how large firms are more likely to export. The recalibration results under this alternative setup suggest higher domestic concentration and slower productivity growth. This is because the market size effect of globalization no longer works for followers. The harsher foreign competition lowers followers' market share and innovation incentives, contributing to weaker domestic competition compared to the baseline model. Therefore, the mechanism is strengthened by assuming not all firms export.

Endogenous entry and exit. In the baseline model there is no entry and exit for simplicity. I introduce endogenous entry and exit into the baseline model and find that globalization explains not only the increasing industrial concentration and lower productivity growth, but also the declining entry rate and the share of young firms in the whole economy.[64] Specifically, I model in each period there is a potential entrant in each industry-country pair that make innovation decisions such that with some probability the entrant can replace the domestic follower. The key idea is to capture realistic firm life-cycle dynamics so entrants cannot directly become leaders. Globalization depresses follower values and innovation as described above, so potential entrants realize lower expected values after entering the market, reducing entry.

Knowledge spillovers via lower innovation costs. Knowledge spillovers are notoriously difficult to measure and hence most papers model them indirectly (e.g., see discussion in Perla et al. (2021)).[65] Though sensitivity analysis on spillover parameters has been conducted, I provide an alternative way to model knowledge spillovers to further establish robustness. Specifically, increasing international knowledge spillovers operate through lowering innovation costs of firms without global technological advantage (Home (Foreign) firms with global technology gap $m_G < 0$ ($m_G > 0$)). The decreasing domestic knowledge spillovers operate through higher follower innovation costs.[66] The recalibration results indicate this alternative generates similar predictions as the baseline model. The market size effect remains large enough and the quick catch-up probability of followers is small enough such that increasing international spillovers generates a strong market size effect and leads to a rise in industrial concentration and slower productivity growth.

International knowledge spillovers endogenously vary with trade. In the baseline model, international knowledge spillovers can be from trade flows, FDI, migration, etc. Quite a few papers instead empirically and theoretically focus on one specific channel, trade flows (see, e.g., Aghion et al. (2019a) and Buera and Oberfield (2020)). One may want to know whether setting international knowledge spillovers endogenously vary with trade alters the model implications. To this end, I model that firms have to pay per-period fixed export costs to export and that domestic firms can only get international knowledge spillovers from foreign firms that sell in the domestic market. The declining trade iceberg costs endogenously increase international knowledge spillovers by generating that more firms are able to export. The model mechanism and results are fairly robust under this alternative specification.[67]

[64] The declining entry rate and the share of young firms are secular trends in recent decades in advanced OECD countries, see, e.g., Akcigit and Ates (2019).

[65] In the baseline model, knowledge spillovers affect firms' probability to increase their productivity but do not affect firms' innovation costs.

[66] I decrease the innovation cost $\exp(m_G)^{\bar{\chi}_{ic}}$ for firms without global technological advantage by percentage points to represent more international spillovers and increase the innovation cost $\exp(m_H)^{\bar{\varphi}_{2c}}$ for followers by percentage points to represent fewer domestic spillovers, recalibrating to the same data moments as the benchmark model.

[67] The key idea is that lower trade iceberg costs trigger that OECD firms with technological advantage, especially with relatively low technological advantage over ROW are more able to export compared to other OECD firms, and hence these firms are more likely to generate spillovers to ROW; OECD firms with technological disadvantage

6 Conclusion

In this paper, I develop a two-country endogenous growth model to study how globalization increases leader innovation relative to followers and accounts for a significant portion of both the increasing industrial concentration and the aggregate productivity growth slowdown observed in recent decades. Strikingly, I show that globalization's increasing international knowledge spillovers are crucial, not its declining trade iceberg costs. Importantly, the main mechanism is weaker domestic competition induced by the market size effect of globalization, as opposed to harsher foreign competition via import competition or international business stealing effects.

The main mechanism relies on the two new model features compared to existing open economy growth and innovation models, strategic domestic competition and an innovation *disadvantage* of backwardness, generating a decrease in mid-run and long-run productivity growth due to the backwardness of followers and decreasing innovation returns of leaders. In another contribution to the endogenous growth literature, I provide empirical facts on the innovation disadvantage of backwardness and use the model to infer that part of the disadvantage is from innovation costs, which are generally ignored by the existing endogenous growth models but have non-trivial effects on aggregate outcomes.

My model provides a useful framework for studying the interplay between trade policy, innovation policy, and antitrust policy in an open economy environment. Analyzing optimal policy is left for future research, though the previous policy discussion provided insights into the intratemporal trade-offs between reducing foreign competition and facilitating domestic competition, and the intertemporal trade-offs between reallocating resources to more or less productive firms given their future growth potential. On the other hand, optimal policy analysis requires that international knowledge spillovers are properly accounted for. For example, whether trade policy is welfare-improving depends on whether the international knowledge spillovers are primarily embodied or disembodied in trade flows. Therefore, identifying the magnitudes of the different channels of international knowledge spillovers would be a promising avenue for future research.

My findings also provide several other important topics for future research. One is micro-founding innovation costs in the model and providing more direct empirical evidence of how different innovation costs impact productivity growth. The other topic is to study the nature of innovation. For example, in this paper, globalization only affects firms' innovation probability. Still, it can also change the nature of innovation, e.g., globalization may induce leaders to buy patents or to apply for patents to protect their market share and prevent the catch-up of followers instead of improving their productivity. Understanding these issues can help us better understand how different types of firms innovate facing different costs or frictions, and how to mitigate followers' innovation disadvantage of backwardness to facilitate productivity growth.

instead get more spillovers from ROW due to more ROW firms export to OECD. These mechanisms are similar to the baseline model. More discussions are in Appendix F.7.

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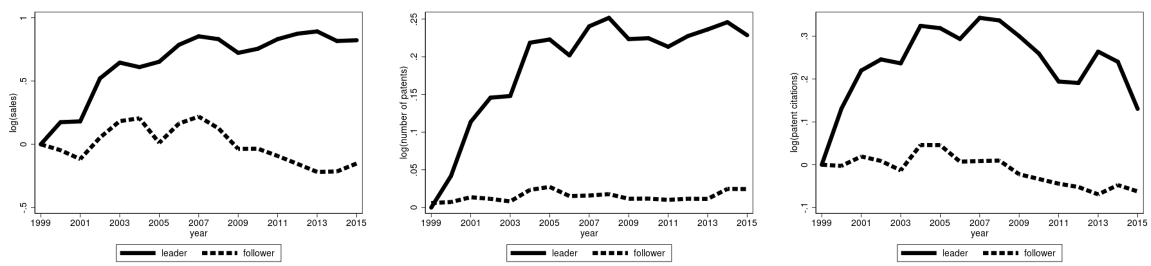
A Additional Motivating Facts

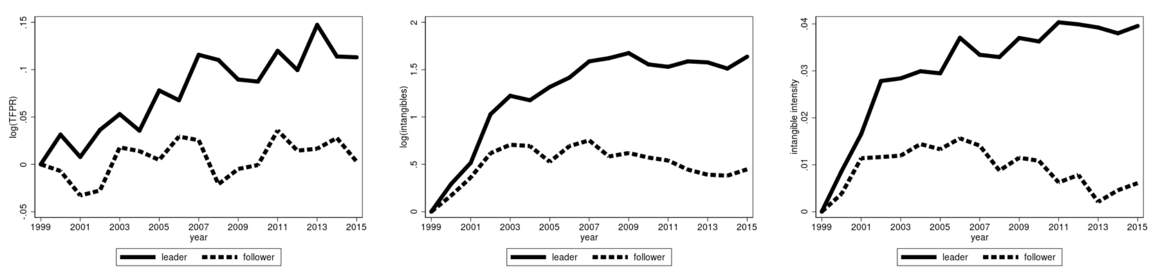
A.1 Fact 1 and 2. Level of Leaders and Followers with the Raw Data

In the main text I demonstrate the divergence between leaders and followers by means of regression with appropriate fixed effect structures. This captures the relative changes between leaders and followers but fails to show any overall level changes. Figure A.1 uses the raw data to plot average sales, number of patents, number of patent citations, TFPR, intangibles, and intangible intensity of leaders and followers in twelve countries. The figure shows the divergence is driven by the (slowing) increase of leaders and the stagnation of followers.

Figure A.1: Raw Data: Uneven Firm Growth



(a) sales (b) number of patents (c) patent citations



(d) TFPR (e) intangibles (f) intangible intensity

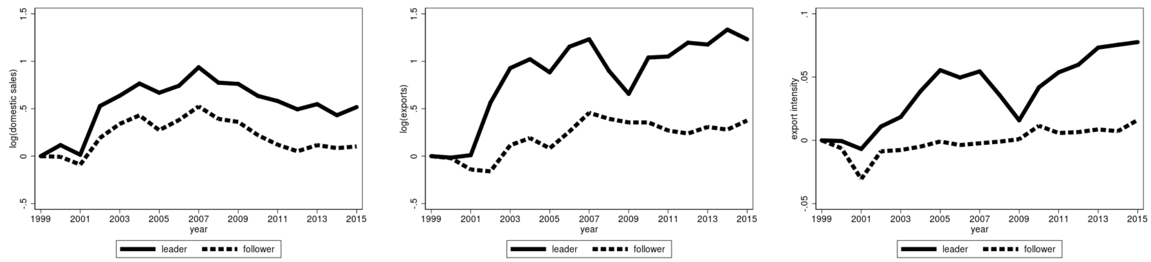
Notes: The figure plots averages of each variable for leaders and followers over time using ORBIS data in twelve countries between 1999 and 2015, with the initial year normalized to 0. It uses unweighted averages across countries and industries.

Figure A.2 plots average domestic sales, exports, and export intensity of leaders and followers in France and Greece, showing that the divergence in exports is driven by larger increases in exports and export intensity among leaders.

A.2 Import Openness and Uneven Firm Growth

Table A.1 and A.2 use two measures of import openness common in existing literature to show the increase in import openness is insignificantly or negatively correlated with the divergence between industry leaders and followers.

Figure A.2: Raw Data: Uneven Firm Growth in Domestic Market and Foreign Market



(a) domestic sales (b) exports (c) export intensity

Notes: The figure plots averages of each variable for leaders and followers over time using ORBIS data in France and Greece between 1999 and 2015, with the initial year normalized to 0. It uses unweighted averages across countries and industries. Firms can be exporters or non-exporters. Non-exporters have 0 exports.

Table A.1: Import Intensity Increase and Uneven Firm Growth

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Δsale	Δpatents^N	Δcitations	ΔTFPR	Δint.	Δints^{int}	Δsale^{do}	Δsale^{ex}	Δints^{exp}
ΔIMO	-0.027	0.012	-0.054	-0.042	-0.241**	-0.218***	0.136	0.102	0.039
	(0.042)	(0.093)	(0.126)	(0.041)	(0.102)	(0.062)	(0.406)	(0.245)	(0.156)
Adjusted R^2	.13	.05	.09	.0041	.032	.013	.22	.058	.04
Country-Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Obs.	15,866	1,225	1,225	9,927	15,866	15,866	3,331	3,331	3,331

Notes: This table presents regression results based on import intensity (IMO) using the empirical specification in equation (2.2). Standard errors are clustered at the 2-digit industry level. The regression is weighted by time-invariant industry output in each country. Import intensity is computed as the imports-output ratio. Columns (1) to (6) use data from twelve countries. "patents^N" denotes the number of patents applied for by the firm, "citations" denotes patent citations received by the firm, "int." denotes intangible capital, and "ints^{int}" denotes intangible intensity. Column (7) to (9) use data from France and Greece. "sale^{do}" denotes domestic sales, "sale^{ex}" denotes exports, and "ints^{exp}" denotes export intensity. * $p < 0.10$, ** $p < 0.05$,*** $p < 0.01$.

Table A.2: Import Penetration Increase and Uneven Firm Growth

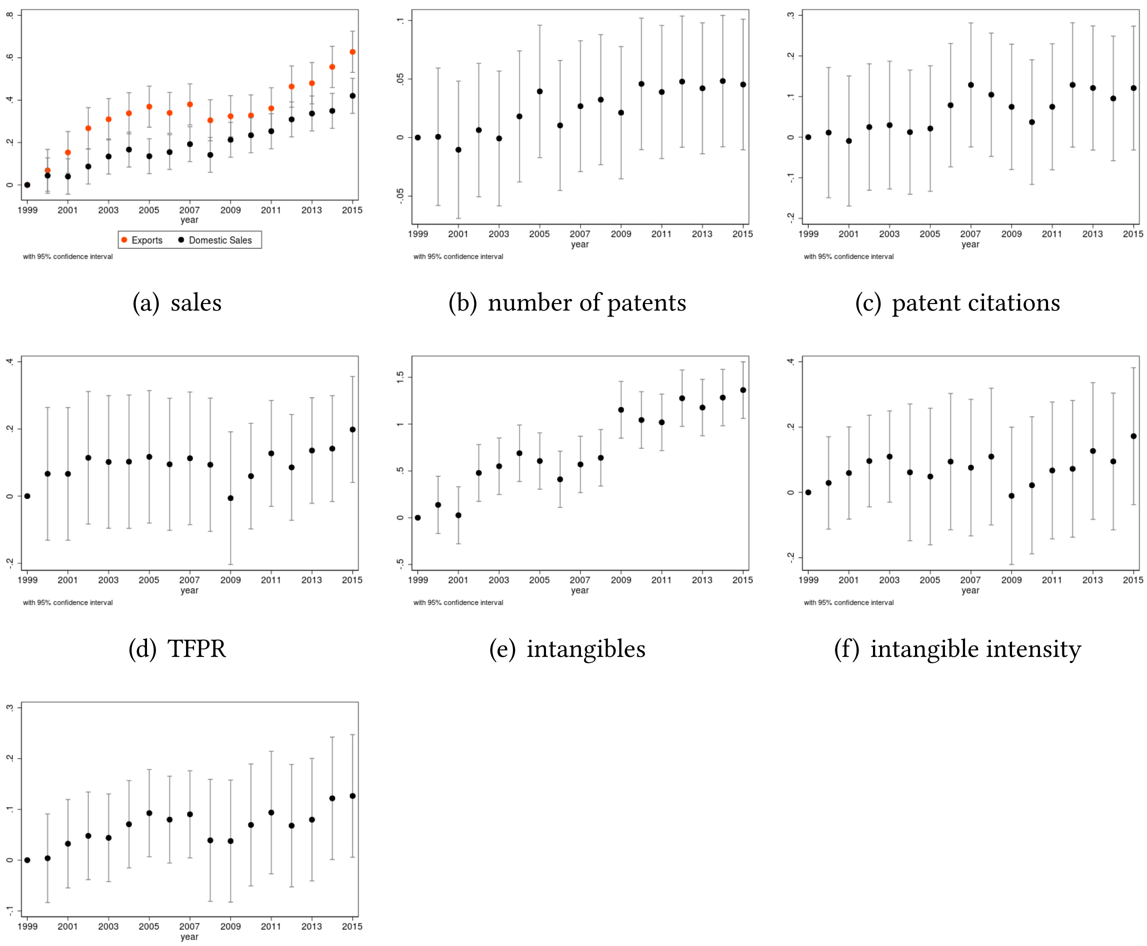
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Δsale	Δpatents^N	Δcitations	ΔTFPR	Δint.	Δints^{int}	Δsale^{do}	Δsale^{ex}	Δints^{exp}
ΔIMP	0.519	0.091	0.100	0.276	-0.408	-0.024	0.750	0.097	-0.001
	(0.831)	(0.090)	(0.070)	(0.345)	(0.708)	(0.601)	(0.560)	(0.797)	(0.098)
Adjusted R^2	.19	.01	.02	.04	.076	.0081	.23	.11	.19
Country-Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Obs.	15,866	1,225	1,225	9,927	15,866	15,866	3,331	3,331	3,331

Notes: Similar to Table A.1, this table presents regression results based on import penetration (IMP) instead of import intensity (IMO). Import penetration is computed as imports divided by domestic absorption. Domestic absorption = output + imports - exports.

A.3 Uneven Firm Growth Among Always Exporters

Figure A.3 documents divergences in sales, patenting, patent citations, TFPR, intangibles, intangible intensity, and export intensity between leaders and followers among firms that continuously export throughout the whole period.

Figure A.3: Uneven Firm Growth Among Always Exporters



(a) sales

(b) number of patents

(c) patent citations

(d) TFPR

(e) intangibles

(f) intangible intensity

(g) export intensity

Notes: The figure plots the coefficient $\beta_{1,t}$ in equation (2.1) over time for firms that have positive exports throughout all years in France and Greece. The confidence intervals are defined at 5%. The coefficient in year 1999 is normalized to 0.

A.4 Export Openness and Heterogeneous Innovation Response

Table A.3 and A.4 show that the increase in export intensity triggers an increase (decrease) among leaders (followers) in patents and citations in the early 2000s but a reduction in patents and citations for all firms afterward.

Table A.3: Export Openness and ΔNumber of Patents$_{t-5,t}$ (Data)

	initial period		end period	
	leader	follower	leader	follower
ΔEXO$_{t-5,t}$	4.897**	-9.407***	-6.041***	-0.255
	(2.114)	(2.181)	(1.734)	(0.505)
EXO$_{t-5}$	4.261	-3.327	-12.485***	-0.193
	(2.853)	(2.085)	(1.828)	(0.592)
Number of Patents$_{t-5}$	-1.269***	-1.311***	-0.897***	-1.176***
	(0.066)	(0.144)	(0.022)	(0.038)
Obs.	145,914	2,547,403	547,586	8,770,004
Adjusted R^2	.8	.77	.76	.83
Country-Year FE	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes

Notes: This table presents regression results of firms' standardized number of patents from year $t-5$ to t against the change in export intensity from year $t-5$ to t in the data. The initial period denotes years before 2005 and the end period denotes years after 2005. Controls include industry-level export intensity and firm-level standardized number of patents at year $t-5$. * $p < 0.10$, ** $p < 0.05$,*** $p < 0.01$.

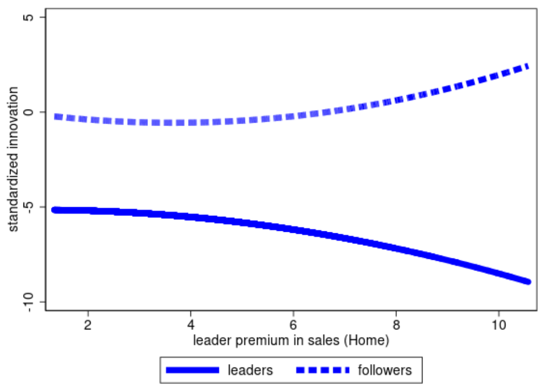
Table A.4: Export Openness and ΔPatent Citations$_{t-5,t}$ (Data)

	initial period		end period	
	leader	follower	leader	follower
ΔEXO$_{t-5,t}$	6.834**	-1.411***	-12.311***	-0.184***
	(2.890)	(0.183)	(1.800)	(0.023)
EXO$_{t-5}$	18.274***	-1.499***	-14.631***	-0.146***
	(3.701)	(0.204)	(2.075)	(0.025)
Patent Citations$_{t-5}$	-0.992***	-1.013***	-0.934***	-0.916***
	(0.005)	(0.001)	(0.002)	(0.000)
Obs.	145,914	2,547,403	547,586	8,770,004
Adjusted R^2	.45	.49	.44	.67
Country-Year FE	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes

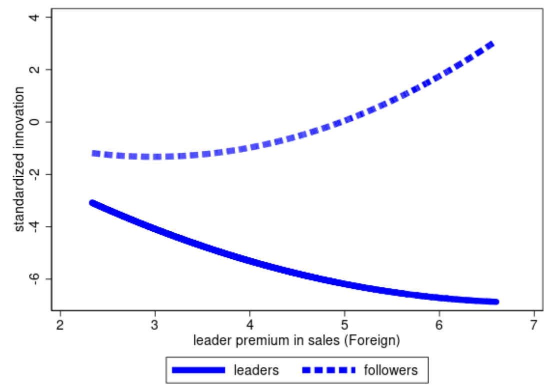
Notes: This table presents regression results of firms' standardized number of patent citations from year $t-5$ to t against changes in export intensity from year $t-5$ to t in the data. The initial period denotes years before 2005 and the end period denotes years after 2005. Controls include industry-level export intensity and firm-level standardized number of patent citations at year $t-5$. * $p < 0.10$, ** $p < 0.05$,*** $p < 0.01$.

B Additional Facts for Innovation Disadvantage of Backwardness

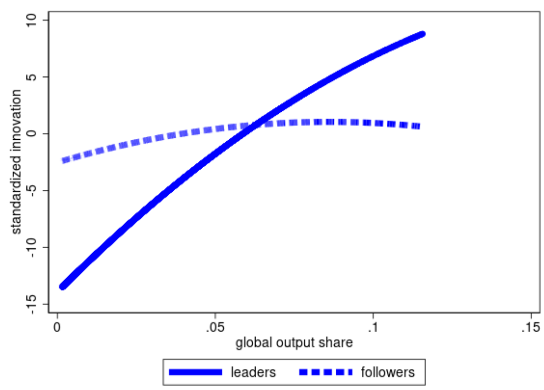
Figure B.1: Standardized Number of Citations (Patent Firms)



(a) OECD leader sales premium



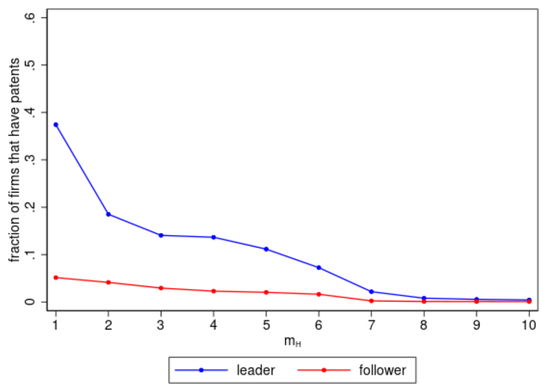
(b) ROW leader sales premium



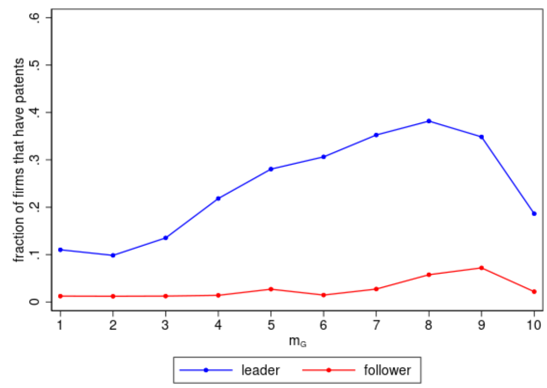
(c) OECD global output share

Notes: This figure presents the regression coefficients for patent firms in the data in the 1990s. The blue solid line represents leaders and the blue dashed line represents followers. The X-axis in each panel denotes the leader premium in sales in Home (OECD) and Foreign (ROW) and the OECD global output share, respectively. The Y-axis denotes the standardized number of citations in the data.

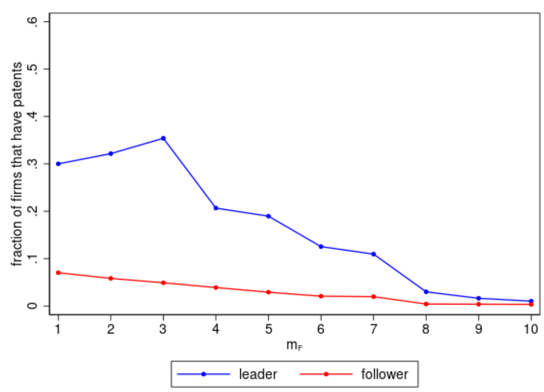
Figure B.2: Fraction of Firms that Have Patents (Among All Firms)



(a) OECD leader sales premium



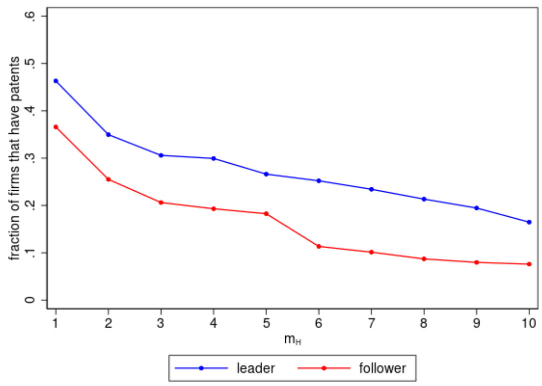
(b) OECD global output share



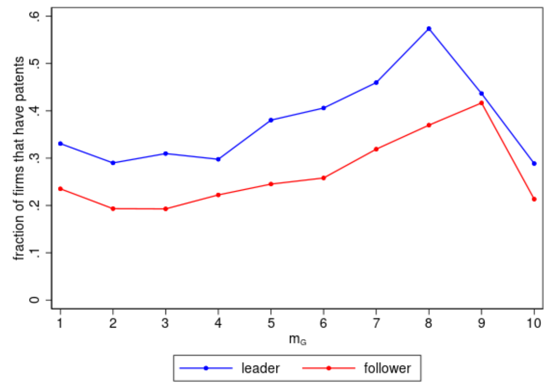
(c) ROW leader sales premium

Notes: This figure plots how patent probability varies with the three measured technology gaps in the data in the 1990s. The blue line represents leaders and the red line represents followers. The X-axis in each panel denotes the leader premium in sales in Home (OECD) and Foreign (ROW) and the OECD global output share, respectively. The Y-axis denotes the the fraction of firms that have patents in the data sample of all firms.

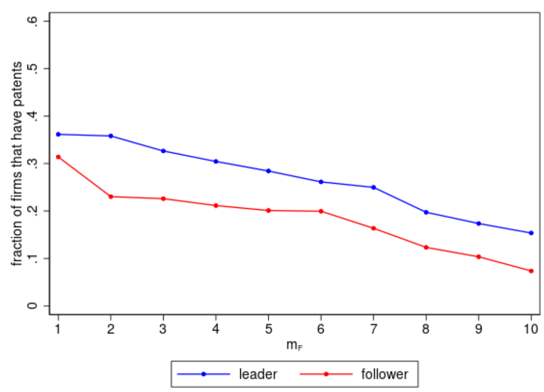
Figure B.3: Fraction of Firms that Have Patents (Drop Never Patent Firms)



(a) OECD leader sales premium



(b) OECD global output share



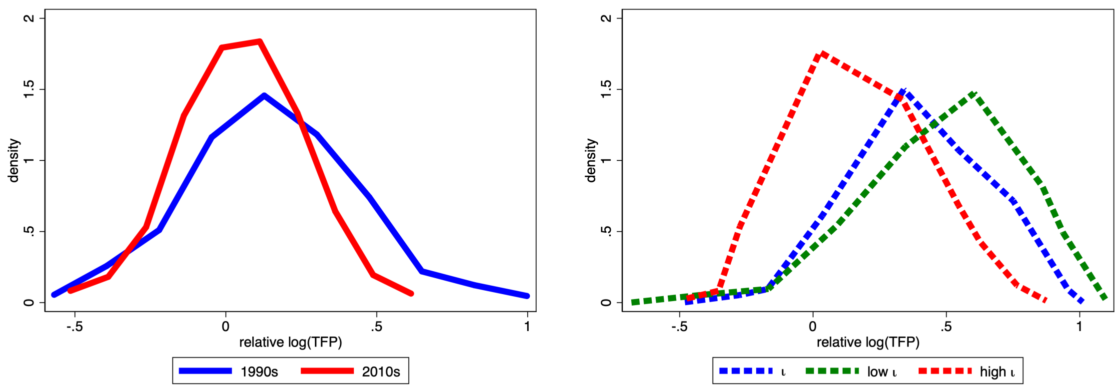
(c) ROW leader sales premium

Notes: This figure plots how patent probability varies with the three measured technology gaps in the data in the 1990s. The blue line represents leaders and the red line represents followers. The X-axis in each panel denotes the leader premium in sales in Home (OECD) and Foreign (ROW) and the OECD global output share, respectively. The Y-axis denotes the the fraction of firms that have patents in the data sample of firms that have at least one patent throughout the whole data period.

C Additional Quantitative Results

C.1 Model Validation for International Knowledge Spillover Parameter

Figure C.1: Industry Density Distribution Over Relative Productivity



(a) Data (b) Model

Notes: Panel (a) and (b) in this figure present the industry density distribution over relative productivity between OECD and ROW in the data and model. The X-axis denotes the log difference in industry TFP between OECD and ROW. The Y-axis denotes the industry density. In panel (a), the blue solid line represents the 1990s data. The red solid line represents the 2010s data. In panel (b), the blue dashed line represents the density distribution along the initial BGP. The red (green) dashed line represents increasing (decreasing) ι by a factor of 3 keeping all other parameters at their initial BGP level.

C.2 Implications of Globalization on ROW

Table C.1: Implications of Globalization on ROW

	globalization ($\iota \uparrow$, $\tau \downarrow$)		$\iota \uparrow$		$\tau \downarrow$	
	OECD	ROW	OECD	ROW	OECD	ROW
Panel A. Technology gaps						
ΔDomestic gap	1.15	0.27	1.14	0.27	0.01	0.01
ΔGlobal gap	-0.82	-0.82	-0.82	-0.82	-0.05	-0.05
Panel B. Uneven Firm Growth						
ΔLeader sales premium	0.44	0.07	0.39	0.07	0.01	0.002
ΔLeader exports premium	0.81	0.13	0.81	0.15	0.002	-0.02
Panel C. Aggregates						
ΔTFP growth rate,%	-0.42	-0.42	-0.42	-0.42	0.00	0.00
ΔDomestic concentration	0.07	0.02	0.06	0.02	0.01	0.00
ΔAggregate markup	0.14	-0.08	0.08	-0.06	0.05	-0.03

C.3 The Role of Other Model Elements

Table C.2 presents the role of international knowledge spillover and endogenous productivity of firms in the model.

International knowledge spillover. A large set of papers typically build trade models with innovation without considering international knowledge spillovers (see, e.g., Atkeson and Burstein (2010), Aghion et al. (2018)) and mainly focus on the effect of declining trade iceberg costs or exogenous increases in foreign market size. What value do the international knowledge spillovers in my model add? To this end, I recalibrate the model with a small enough ι to shut down international spillovers while preserving the existence of a non-degenerate BGP with two asymmetric countries. The results indicate import competition induced by declining iceberg costs is so strong that we see counterfactully decreases in leader premiums.

Endogenous productivity. I recalibrate a model with fixed firm-level productivity by shutting down firm innovation and knowledge spillovers. The model is reduced to a static trade model à la Atkeson and Burstein (2008) and the key mechanism left is the endogenous markup of firms. This static framework makes it impossible to study productivity growth, and counterfactually predicts leader export growth is smaller than that of followers in response to declining trade costs due to the larger increases in markup on exports.

Table C.2: The Role of the Other Model Elements

	Globalization (benchmark)	No int'l spillover (tiny ι)	Fixed productivity (static)
Panel A. Technology gaps			
ΔDomestic gap	1.15	-0.21	
ΔGlobal gap	-0.82	-0.29	
Panel B. Uneven firm growth			
ΔLeader sales premium	0.44	-0.14	0.04
ΔLeader exports premium	0.81	-0.15	-0.05
Panel C. Aggregates			
ΔTFP growth rate,%	-0.42	-0.01	
ΔDomestic concentration	0.07	-0.02	0.01
ΔGlobal output share	-0.01	-0.005	-0.001
ΔAggregate markup	0.14	-0.03	-0.001

Notes: This table presents the effect of globalization on OECD in the baseline model and two simplified models.

D Firm-Level Data Appendix

The details of procedures relating to ORBIS data processing and the robustness of empirical facts are presented in this section.

D.1 Data Cleaning Procedure

1. Delete observations with missing BvD ID or BvD Account number (the main account identifier) and the observations with just a company name and no other information.
2. Keep unconsolidated accounts only.
3. Drop observations with missing year information.
4. Drop firm-year observations with missing information regarding their industry of activity.
5. Drop firm-year observations with missing or negative operating revenue.

D.2 Balance Sheet Variable Construction

In this section, I document all the balance sheet variables I need and their definitions.

D.2.1 Construct Variable

Following Gopinath et al. (2017), I measure sales by operating revenue to maximize data coverage.[68] Exports is obtained from the variable "export revenue" in ORBIS. I measure domestic sales as the difference between sales and exports.[69] Export intensity is defined as the exports-sales ratio of the firm. Intangible capital is obtained from the variable "intangible fixed assets" in ORBIS. Intangible capital includes all intangible assets such as formation expenses, research expenses, goodwill, development expenses and all other expenses with a long term effect. Intangible intensity is computed as the fraction of intangible fixed assets as a share of total fixed assets (total fixed assets = intangible fixed assets + tangible fixed assets + other fixed assets). I use the Wooldridge (2009) method of production function estimation to estimate revenue based total factor productivity (TFPR).

To estimate TFPR, I measure value added as the difference between gross output (operating revenue) and materials. I measure the capital stock using the book value of fixed assets, including both tangible and intangible fixed assets. I use the costs of employees instead of the number of employees to represent labor input in the production function to control for differences in the quality of the workforce across firms.

[68] Operating revenue has slightly better data coverage than sales of firms. I rechecked all empirical facts and find similar results.

[69] The data shows more than 99.99% of firms in France and Greece have positive domestic sales. Therefore, most exporters sell in the domestic market.

D.2.2 Deflate Nominal Variable

Since variables in the raw data are nominal, I deflate them. Given that we do not observe prices at the firm level, I use two-digit industry level gross output price deflators from EU KLEMS (2017 release).[70] In particular, I deflate sales, exports, domestic sales, and costs of employees by the output price deflators. I deflate the capital stock and intangible capital with the price of capital goods.[71]

D.3 Patent Variable Construction

The patent data is obtained from the ORBIS intellectual property data set, which provides a direct linkage between patent data and ORBIS balance sheet data via firm ID. I assign patents to their current owners and only keep patents that file in the U.S. patent office (USPTO) to avoid any possibility of double counting the same patents in multiple patent offices. Since existing literature (e.g., Cai et al. (2021)) usually argues that most important innovations from other countries have been patented in the U.S., the possibility of this causing a sample selection issue is minimally concerning.

After matching the patent data with firm-level balance sheet data, I construct two measures of firm innovativeness: number of patents and number of patent citations received. Specifically, firm i's total patents in year t is the total number of patents p applied for in year t; the number of citations some patent p received from year t onwards is citation_{pt}. I define the number of patent citations for the firm in year t as $\sum_p \text{citation}_{pt}$, and the number of citations in year $t' = \sum_{p'} \text{citation}_{p't'}$, where $p' \neq p, t' \neq t$.

There are concerns that patent citations have systematic differences across industries and earlier patents have more years during which they can receive citations (truncation bias). Since the focus of the paper is within-industry differences between leaders and followers, these concerns do not contaminate the analysis. Using the alternative measure, number of patents, as a robustness check is reassuring, and I also follow Hall et al. (2001) to use truncation correction weights to establish robustness, which further helps alleviate the concern.

[70] variable name: *VA_P*.

[71] Price of capital goods is from Eurostat's total output price index series [*sts_inpp_a*].

E Industry-Level Data Appendix

E.1 Industry TFP Construction

In this section, I discuss how I construct industry TFP that is comparable across countries. Industry TFP is used to validate the distribution of relative productivity between OECD and ROW in the model.

To the best of my knowledge, the only publicly available data set that provides detailed 2-digit industry TFP information across countries from the 1990s to now is EU KLEMS, however, this data set only provides TFP growth, not TFP level.[72] To this end, I utilize the labor input, capital input, and value added in this data set to construct industry TFP that is comparable across countries.[73]

Methodology. I use the multilateral TFP index suggested by Caves et al. (1982), which is widely adopted by existing literature (see, e.g., Keller (2002), Cameron et al. (2005), Inklaar and Timmer (2008), Feenstra et al. (2015)). For industry j in country c and year t, consider $\ln(\frac{Z_{cjt}}{Z_{Fjt}}) = \ln(\frac{Y_{cjt}}{Y_{Fjt}}) - \bar{\alpha}_{cjt} \ln(\frac{L_{cjt}}{L_{Fjt}}) - (1 - \bar{\alpha}_{cjt}) \ln(\frac{K_{cjt}}{K_{Fjt}})$, where $\bar{\alpha}_{cjt} = \frac{\alpha_{cjt}+\alpha_{Fjt}}{2}$. Z is TFP, Y is value added, L is labor input, and K is capital input. The country F represents the reference country, i.e., the U.S. in this case. The variable $\bar{\alpha}_{cjt}$ is the average labor share in industry j between the U.S. and country c . Therefore, the level of TFP of country c in sector j is relative to the U.S.. Normalizing the U.S. TFP level to 1 in all industries, the TFP level in other countries can be pinned down. These index number measures of TFP are consistent with a translog production technology, which provides an arbitrarily close local approximation to any underlying constant returns to scale production technology, and are more general than those commonly derived from the Cobb–Douglas production function.

Practical Implementation. To ensure the measured TFP reflects productivity differences across countries instead of price differences across countries, a common practice in the literature is to use aggregate economy purchasing power parity (PPP) exchange rates to convert value-added and factor inputs into common currency units. To this end, I use aggregate economy PPP data from the OECD (USA ≡ 1) to convert value-added and factor inputs in EU KLEMS (in national currency) into common currency units. The labor input is measured by compensation of employees. Compared to hours worked or number of employees, the benefit of using compensation of employees is it takes into account country-industry variation in the skill composition of the workforce. The capital input is measured by the capital stock adjusted for cyclical differences in capacity utilization. Specifically, I regress the capital stock in the country-industry level annual panel on the U.S. capital utilization index (TCU in FRED), and keep the residual term as the capital input adjusted for cyclical differences in capacity utilization.

[72]Relatedly, Inklaar and Timmer (2008) only provides data in 1987, 1997 and 2005.

[73]Note that EU KLEMS 2019 only provides data for all European Union member states, Japan, and the US. Therefore, some countries that are covered in OECD input-output tables are not covered in EU KLEMS. The classifications of OECD and ROW countries are the same as section 5.1.

Controlling for alternative stories. Besides considering capital utilization over the business cycle and labor quality differences across countries, I also control for TFP improvements due to improving allocation or innovation subsidies. This paper shows increasing international knowledge spillovers lead to faster improvement in TFP in the less developed world. However, motivated by the misallocation literature (Hsieh and Klenow (2009)), this catch-up growth could be due to improving allocation of resources across heterogeneous firms over time instead of productivity increases, possibly driven by domestic reforms. Alternatively, national innovation subsidy policies could also affect innovation investment and TFP growth. To control for these alternative stories, I regress measured TFP on a financial development index (directly obtained from the IMF), a labor quality improvement index (measured by expenditure on tertiary education as a share of government expenditure on education), the ease of doing business index (directly obtained from the World Bank) and the R&D-GDP ratio (directly obtained from the World Bank). I take the residual term from these regressions as a measure of TFP. This TFP, controlling for capital utilization, labor quality composition, better allocation, and innovation policy differences is the benchmark TFP used for the analysis in the main text.[74]

Robustness. I also consider a number of extensions to the benchmark measure to establish the robustness of the results. I conduct two particular robustness tests. First, I consider industry heterogeneity in relative output prices across countries. In the benchmark, I use the aggregate economy PPP to control for price differences across countries. However, there is a concern that cross-country relative prices may vary substantially across industries, so using aggregate PPP could lead to a biased measure of TFP. To address this concern, I use time-invariant industry-specific PPP data from Inklaar and Timmer (2014) instead of aggregate PPP to reconstruct TFP.[75] Second, I control for measurement errors in the share of labour in value-added. There is a concern that if the labor share over time is volatile, it indicates potential measurement errors. However, the labor share in the data is stable, which alleviates the concern. Moreover, I follow Harrigan (1997) in using the properties of the translog production technology to smooth the observed labour shares. Specifically, I regress the labor share on industry-country fixed effects and capital-labor ratios, and use the fixed effect part as the one without measurement errors. In both robustness tests, I find the resulting distribution of relative productivity between OECD and ROW to be fairly consistent.

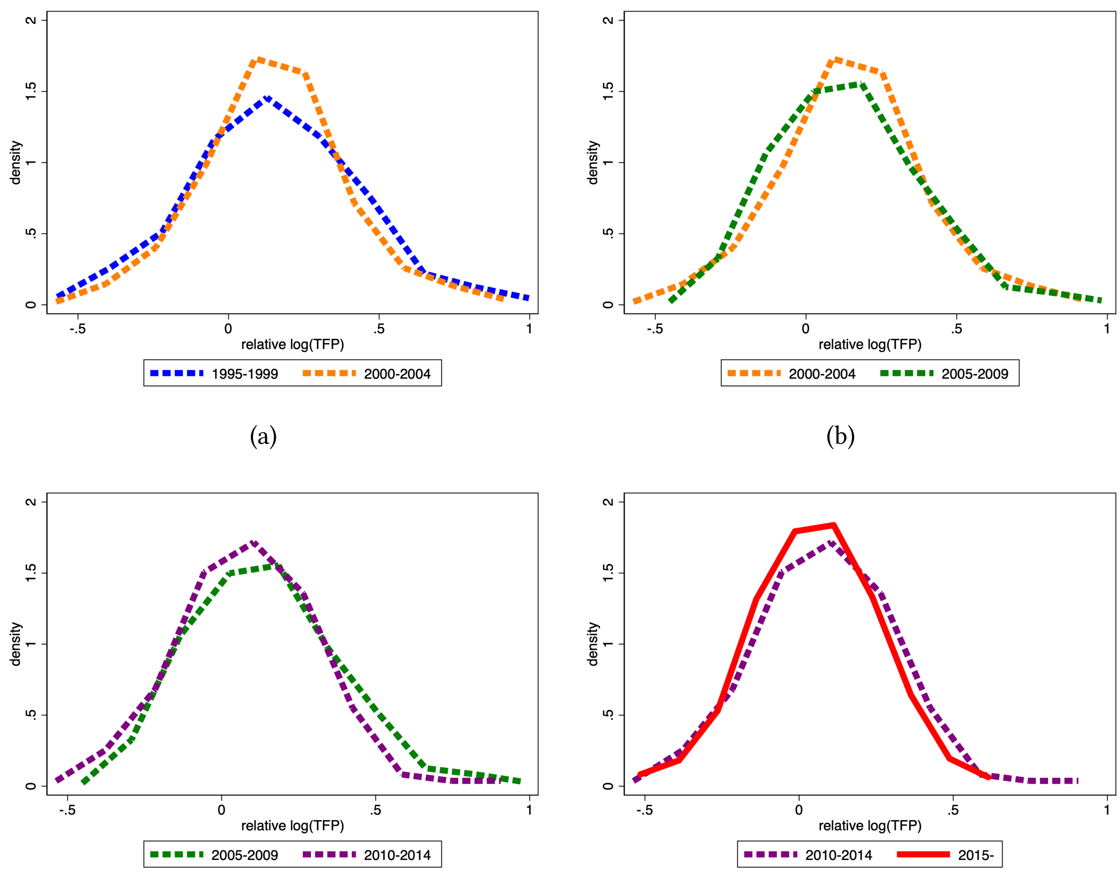
Distribution of relative TFP across industries. Figure E.1 presents the industry density distribution over relative productivity between OECD and ROW every five years, using the constructed TFP data. Relative productivity is computed as the log difference in industry TFP between OECD and ROW. A relative productivity larger than 0 means OECD is more productive

[74]Recently the increasing innovativeness of China raises a concern that the decrease in relative TFP between OECD and ROW is not from increasing international knowledge spillovers but from increasing Chinese innovativeness due to government subsidies for innovation and possibly other reasons. However, three points are worth mentioning. First, the industry-level TFP data set I construct excludes China and is primarily European. Second, the existing literature agrees on substantial and increasing international knowledge spillovers from the OECD to China as detailed in section 1. Third, controlling for the R&D-GDP ratio when constructing TFP helps alleviate this concern.

[75]The industry-specific data is time-invariant since the data is just for 2005.

than ROW. The larger the relative productivity, the more productive is OECD than ROW. A larger density concentrated in high relative productivity levels means more OECD industries have a technological advantage. As indicated by Figure E.1, the distribution in the 1990s is more concentrated in regions where OECD has technological advantage over ROW, while over time this distribution gradually shifts to the left and becomes more constrained, indicating OECD is losing its technological advantages over ROW.

Figure E.1: Industry Density Distribution Over Relative Productivity in the Data



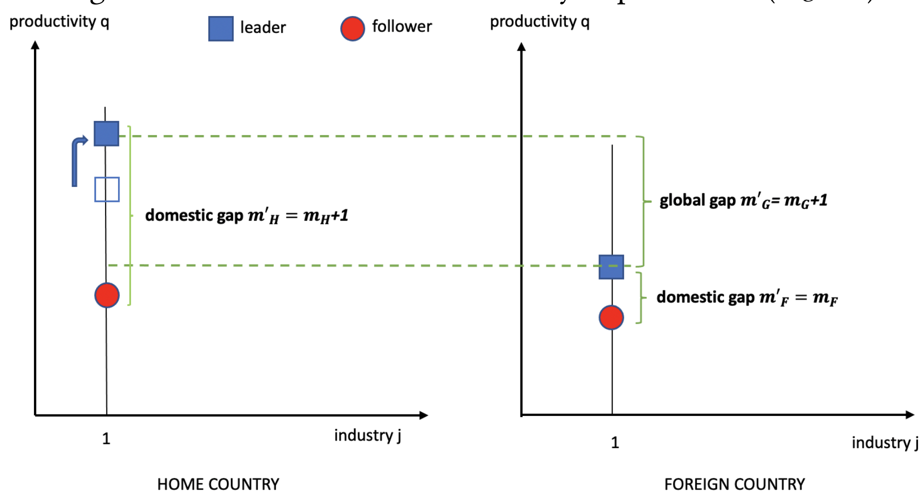
(a) (b) (c) (d)

Notes: Panel (a) to (d) in this figure present snapshots of the industry density distribution over relative productivity between OECD and ROW every five years. The X-axis denotes the log difference in industry TFP between OECD and ROW. The Y-axis denotes industry density.

F Model Appendix

F.1 Productivity Improvement Due to Innovation or Knowledge Spillovers

Figure F.1: Home Leader's Productivity Improvement ($m_G \geq 0$)



F.2 Proofs for Intermediate Firms' Static Decisions

This section proves technology gaps are sufficient statistics for characterizing industry variation. Specifically, intermediate goods firms' market shares, markups, sales, and profits are functions solely of technology gaps, aggregate variables, and exogenous parameters.

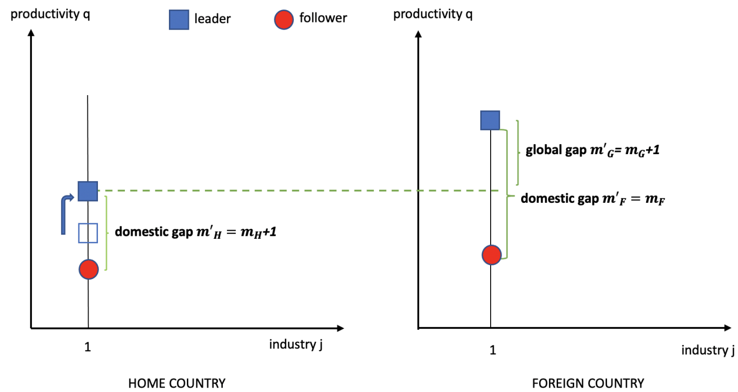
Lemma A.1. *Intermediate good firms' market share (s_{ijHt}, s^*_{ijHt}, s_{ijFt}, and s^*_{ijFt}), and markup (mu_{ijHt}, mu^*_{ijHt}, mu_{ijFt}, and mu^*_{ijFt}) are a function of technology gaps m_{Gt}, m_{ct}, wage w_{ct}, and parameters (τ_c, etc), where $i \in \{1, 2\}$, $j \in [0, 1]$, and $c \in \{H, F\}$.*

Proof Let i and i' denote the two firms in industry j from each country. We have $p_{ijHt} = \frac{\varepsilon_{ijHt}}{\varepsilon_{ijHt}-1}\frac{w_{Ht}}{q_{ijHt}} = \frac{\epsilon-(\epsilon-1)s_{ijHt}}{\epsilon-(\epsilon-1)s_{ijHt}-1}\frac{w_{Ht}}{q_{ijHt}} \equiv mu_{ijHt}\frac{w_{Ht}}{q_{ijHt}}$. Using demand function for y_{ijct}, we have s_{ijHt} as a function of relative prices and relative productivity:

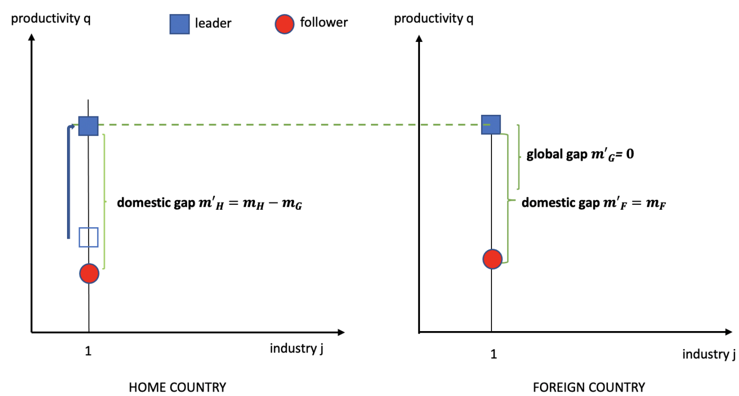
$$s_{ijHt} = \frac{1}{1 + \frac{\omega_{i'jHt}\omega^b_{i'jHt}}{\omega_{ijHt}\omega^b_{ijHt}}(\frac{q_{i'jHt}}{q_{ijHt}})^{\epsilon-1}(\frac{p_{i'jHt}}{p_{ijHt}})^{1-\epsilon} + \frac{\omega_{ijFt}\omega^b_{ijFt}}{\omega_{ijHt}\omega^b_{ijHt}}(\frac{q_{ijFt}}{q_{ijHt}})^{\epsilon-1}(\frac{\tau_F p_{ijFt}}{p_{ijHt}})^{1-\epsilon} + \frac{\omega_{i'jFt}\omega^b_{i'jFt}}{\omega_{ijHt}\omega^b_{ijHt}}(\frac{q_{i'jFt}}{q_{ijHt}})^{\epsilon-1}(\frac{\tau_F p_{i'jFt}}{p_{ijHt}})^{1-\epsilon}}. \tag{F.1}$$

The expression for s^*_{ijHt}, s_{ijFt}, and s^*_{ijFt} can be analogously given. It is straightforward to see the relative price is a function of market share, relative wage, and relative productivity. The relative productivity can be written as a function of m_G and m_c, $c \in \{H, F\}$. Given exogenous parameters ω_{ijct}, ω^b_{ijct}, τ_c, and ϵ and wage w_{ct}, there is a mapping from technology gaps to market shares. Since markup is a function of market share, a direct implication is markup also depends on technology gaps. □

Figure F.2: Home Leader's Productivity Improvement ($m_G < 0$)



(a) slow international catch-up



(b) quick international catch-up

Figure F.3: Home Follower's Productivity Improvement ($m_G \geq 0$): quick or slow catch-up

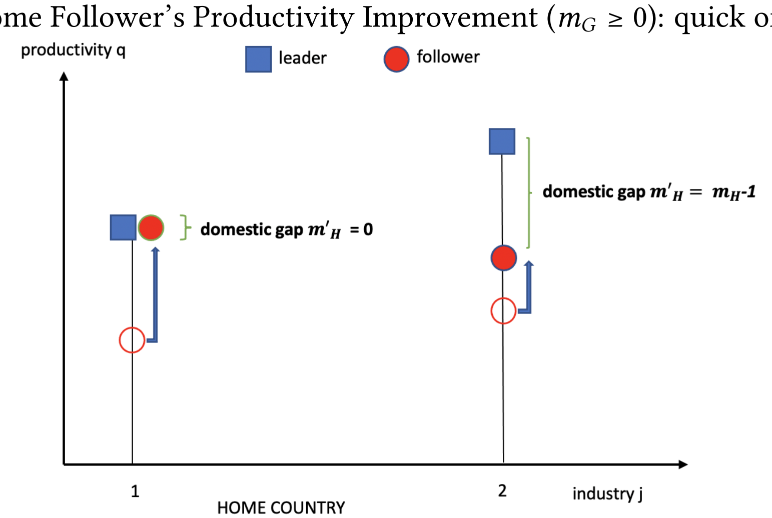
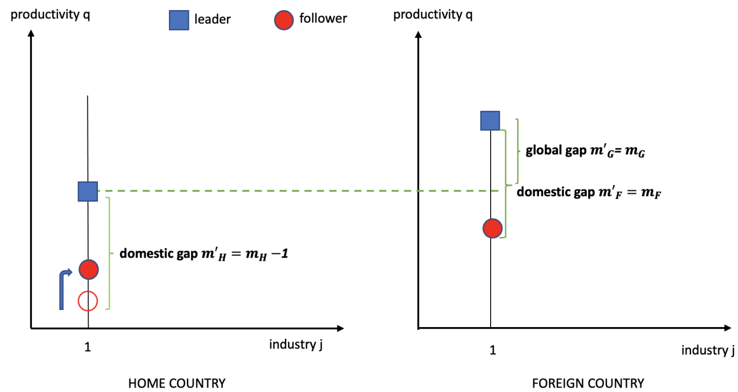
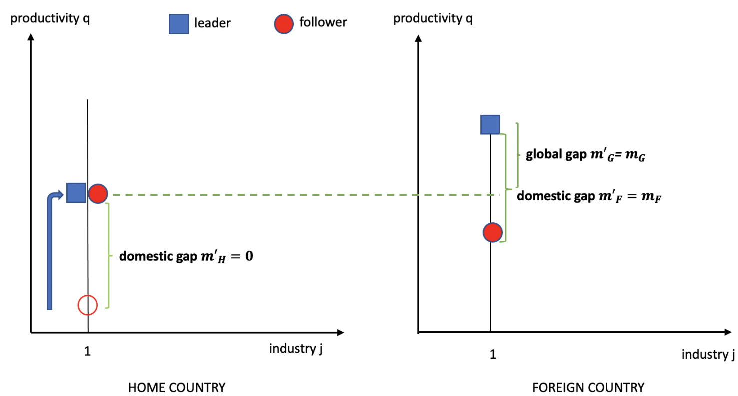


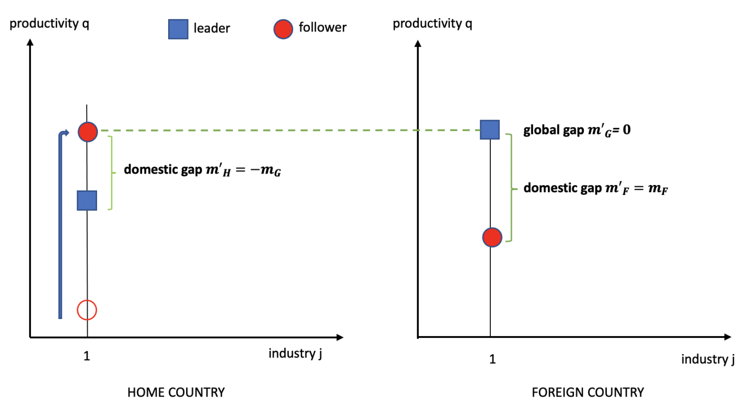
Figure F.4: Home Follower's Productivity Improvement ($m_G < 0$)



(a) slow catch-up



(b) quick domestic catch-up



(c) quick international catch-up

Proposition A.1. *Intermediate good firms' optimal profits (π_{ijHt}, π^*_{ijHt}, π_{ijFt}, and π^*_{ijFt}) and sales py_{ijHt}, py^*_{ijHt}, py_{ijFt}, and py^*_{ijFt}) are a function of technology gaps m_{Gt}, m_{ct}, wage w_{ct}, aggregate price P_{ct}, and aggregate output Y_{ct}, where $i \in \{1,2\}$, $j \in [0,1]$, and $c \in \{H,F\}$.*

Proof let us prove from Home country's perspective in two steps. First, in Home market, using demand function for y_{ijct}, optimal profits can be written as

$$\pi_{ijHt} = \frac{1}{\omega_{ijHt}}[(1-\frac{1}{mu_{ijHt}})s_{ijHt}]P_{Ht}Y_{Ht} \tag{F.2}$$

where $mu_{ijHt} \equiv \frac{\epsilon-(\epsilon-1)s_{ijHt}}{\epsilon-(\epsilon-1)s_{ijHt}-1}$. Second, in Foreign market, optimal profits can be written as

$$\pi^*_{ijHt} = \frac{1}{\omega_{ijHt}}[(1-\frac{1}{mu^*_{ijHt}})s^*_{ijHt}]P_{Ft}Y_{Ft} \tag{F.3}$$

where $mu^*_{ijHt} \equiv \frac{\epsilon-(\epsilon-1)s^*_{ijHt}}{\epsilon-(\epsilon-1)s^*_{ijHt}-1}$. Profits in Foreign Country can be analogously derived. So profits are a function of market share s_{ijct}, s^*_{ijct}, P_{ct}, Y_{ct}, and w_{ct}. From Lemma A.1, we know market shares are a function of m_{Gt}, m_{ct} and w_{ct}. So profits are a function of m_{Gt}, m_{ct}, P_{ct}, Y_{ct} and w_{ct}. For future convenience, define $\Pi_{ijHt}(m_H, m_F, m_G) \equiv [(1-\frac{1}{mu_{ijHt}})s_{ijHt}] + [(1-\frac{1}{mu^*_{ijHt}})s^*_{ijHt}]\frac{P_{Ft}Y_{Ft}}{P_{Ht}Y_{Ht}}$ such that the total profit of the leader firm (mass adjusted) is $\Pi_{ijHt}(m_H, m_F, m_G)P_{Ht}Y_{Ht}$. Analogously, mass adjusted sales of Home firms are $(s_{ijHt} + s^*_{ijHt}\frac{P_{Ft}Y_{Ft}}{P_{Ht}Y_{Ht}})P_{Ht}Y_{Ht}$. Similar definitions can be given for Foreign. Note that the subscript j can be omitted since m_H, m_F, and m_G are sufficient to describe the industry. □

F.3 Value Function and Innovation Decision

In the main text I only specify the value function of Home firms for states $1 \le m_H < \bar{m}_H$, $1 \le m_F < \bar{m}_F$, $0 < m_G < \bar{m}_G$. In this section I characterize other states.

Other Non-boundary states: $1 \le m_H < \bar{m}_H$**,** $1 \le m_F < \bar{m}_F$**,** $-\bar{m}_G < m_G \le 0$**.** The value functions and innovation decisions are similar to the main text but Home firms get international knowledge spillovers from Foreign firms given that $-\bar{m}_G < m_G < 0$. By adding some indicators, these states can be written together. That is, the value function of the Home leader for $1 \le m_H < \bar{m}_H$, $1 \le m_F < \bar{m}_F$, $-\bar{m}_G < m_G < \bar{m}_G$ is

$$r_{Ht}V_{1Ht}(m_H, m_F, m_G) - \dot{V}_{1Ht}(m_H, m_F, m_G) = \max_{x_{1Ht}\in[0,\bar{x}]}\{\Pi_{1Ht}(m_H, m_F, m_G)P_{Ht}Y_{Ht} - P_{Ht}R_{1Ht}(m_H, m_F, m_G)$$

$$+(x_{1Ht} + \iota\cdot\mathbb{1}_{m_G<0})[\mathbb{1}_{m_G\ge0}\cdot V_{1Ht}(m_H+1, m_F, m_G+1) + \mathbb{1}_{m_G<0}\cdot(\delta_H V_{1Ht}(\min\{m_H - m_G, \bar{m}_H\}, m_F, 0)$$

$$+(1-\delta_H)V_{1Ht}(m_H+1, m_F, m_G+1)) - V_{1Ht}(m_H, m_F, m_G)]$$

$$+(x_{2Ht}+\kappa+\iota\cdot\mathbb{1}_{m_G<0})[\mathbb{1}_{m_G\ge0}\cdot(\phi_H V_{1Ht}(0, m_F, m_G)+(1-\phi_H)V_{1Ht}(m_H-1, m_F, m_G))+\mathbb{1}_{m_G<0}\cdot(\phi_H V_{1Ht}(0, m_F, m_G)$$

$$+\delta_H V_{2Ht}(\min\{-m_G, \bar{m}_H\}, m_F, 0) + (1-\phi_H-\delta_H)V_{1Ht}(m_H-1, m_F, m_G)) - V_{1Ht}(m_H, m_F, m_G)]$$

$$+(x_{1Ft} + \iota \cdot \mathbb{1}_{m_G>0})[\mathbb{1}_{m_G>0} \cdot (\delta_F V_{1Ht}(m_H, \min\{m_F + m_G, \bar{m}_F\}, 0) + (1 - \delta_F) V_{1Ht}(m_H, m_F + 1, m_G - 1))$$

$$+\mathbb{1}_{m_G \le 0} \cdot V_{1Ht}(m_H, m_F + 1, m_G - 1) - V_{1Ht}(m_H, m_F, m_G)]$$

$$+(x_{2Ft}+\kappa+\iota \cdot \mathbb{1}_{m_G>0})[\mathbb{1}_{m_G>0} \cdot (\phi_F V_{1Ht}(m_H, 0, m_G)+\delta_F V_{1Ht}(m_H, \min\{m_G, \bar{m}_F\}, 0)+(1-\phi_F-\delta_F) V_{1Ht}(m_H, m_F-1, m_G))$$

$$+ \mathbb{1}_{m_G \le 0} \cdot (\phi_F V_{1Ht}(m_H, 0, m_G) + (1 - \phi_F) V_{1Ht}(m_H, m_F - 1, m_G)) - V_{1Ht}(m_H, m_F, m_G)]\}, \tag{F.4}$$

where $\mathbb{1}_{m_G>0}$ ($\mathbb{1}_{m_G<0}$) is an indicator function that equals one if $m_G > 0$ ($m_G < 0$).

The optimal innovation decisions are

$$x_{1Ht} = \begin{cases} \left(\frac{v_{1Ht}(m_H+1, m_F, m_G+1) - v_{1Ht}(m_H, m_F, m_G)}{\alpha_{1H} f_{1H}} \right)^{\frac{1}{\gamma_{1H}-1}} & \text{if } m_G \ge 0, \\ \left(\frac{\delta_H v_{1Ht}(\min\{m_H - m_G, \bar{m}_H\}, m_F, 0) + (1-\delta_H) v_{1Ht}(m_H+1, m_F, m_G+1) - v_{1Ht}(m_H, m_F, m_G)}{\alpha_{1H} f_{1H}} \right)^{\frac{1}{\gamma_{1H}-1}} & \text{if } m_G < 0. \end{cases} \tag{F.5}$$

$$x_{2Ht} = \begin{cases} \left(\frac{\phi_H v_{2Ht}(0, m_F, m_G) + (1-\phi_H) v_{2Ht}(m_H-1, m_F, m_G) - v_{2Ht}(m_H, m_F, m_G)}{\alpha_{2H} f_{2H}} \right)^{\frac{1}{\gamma_{2H}-1}} & \text{if } m_G \ge 0, \\ \left(\frac{\phi_H v_{1Ht}(0, m_F, m_G) + \delta_H v_{2Ht}(\min\{-m_G, \bar{m}_H\}, m_F, 0) + (1-\phi_H-\delta_H) v_{1Ht}(m_H-1, m_F, m_G) - v_{1Ht}(m_H, m_F, m_G)]}{\alpha_{2H} f_{2H}} \right)^{\frac{1}{\gamma_{2H}-1}} & \text{if } m_G < 0. \end{cases} \tag{F.6}$$

$$x_{1Ft} = \begin{cases} \left(\frac{\delta_F v_{1Ft}(m_H, \min\{m_F + m_G, \bar{m}_F\}, 0) + (1-\delta_F) v_{1Ft}(m_H, m_F+1, m_G-1) - v_{1Ft}(m_H, m_F, m_G)}{\alpha_{1F} f_{1F}} \right)^{\frac{1}{\gamma_{1F}-1}} & \text{if } m_G > 0, \\ \left(\frac{v_{1Ft}(m_H, m_F+1, m_G-1) - v_{1Ft}(m_H, m_F, m_G)}{\alpha_{1F} f_{1F}} \right)^{\frac{1}{\gamma_{1F}-1}} & \text{if } m_G \le 0. \end{cases} \tag{F.7}$$

$$x_{2Ft} = \begin{cases} \left(\frac{\phi_F v_{2Ft}(m_H, 0, m_G) + \delta_F v_{1Ft}(m_H, \min\{m_G, \bar{m}_F\}, 0) + (1-\phi_F-\delta_F) v_{2Ft}(m_H, m_F-1, m_G) - v_{2Ft}(m_H, m_F, m_G)}{\alpha_{2F} f_{2F}} \right)^{\frac{1}{\gamma_{2F}-1}} & \text{if } m_G > 0, \\ \left(\frac{\phi_F v_{2Ft}(m_H, 0, m_G) + (1-\phi_F) v_{2Ft}(m_H, m_F-1, m_G) - v_{2Ft}(m_H, m_F, m_G)}{\alpha_{2F} f_{2F}} \right)^{\frac{1}{\gamma_{2F}-1}} & \text{if } m_G \le 0. \end{cases} \tag{F.8}$$

where innovation rate $x_{ict} \in [0, \bar{x}]$, $\bar{x}$ is the maximal flow rate of innovation.

Domestic neck-and-neck states. The domestic neck-and-neck firms can both increase the domestic and global technology gap. Taking as given other firms' decisions, the value function of neck-and-neck firm $i \in \{1, 2\}$ in Home country for $m_H = 0$, $1 \le m_F < \bar{m}_F$, $0 < m_G < \bar{m}_G$ is

$$r_{Ht} V_{iHt}(0, m_F, m_G) - \dot{V}_{iHt}(0, m_F, m_G) = \max_{x_{iHt} \in [0, \bar{x}]} \{\Pi_{iHt}(0, m_F, m_G) P_{Ht} Y_{Ht} - P_{Ht} R_{iHt},$$

$$+x_{1Ht}[V_{iHt}(1, m_F, m_G + 1) - V_{iHt}(0, m_F, m_G)]$$

$$+x_{2Ht}[V_{i'Ht}(1, m_F, m_G + 1) - V_{iHt}(0, m_F, m_G))]$$

$$+(x_{1Ft} + \iota)[\delta_F V_{iHt}(0, \min\{m_F + m_G, \bar{m}_F\}, 0) + (1 - \delta_F) V_{iHt}(0, m_F + 1, m_G - 1) - V_{iHt}(0, m_F, m_G)]$$

$$+(x_{2Ft} + \kappa + \iota)[\phi_F V_{iHt}(0, 0, m_G) + \delta_F V_{iHt}(0, \min\{m_G, \bar{m}_F\}, 0) + (1 - \phi_F - \delta_F) V_{iHt}(0, m_F - 1, m_G)$$

$$- V_{iHt}(0, m_F, m_G)]\}, \tag{F.9}$$

where $V_{i'Ht}(1, m_F, m_G + 1)$ represents the change of the status, i.e., the successful innovation of the competitor makes the firm become a follower, $\dot{V}_{iHt}(0, m_F, m_G)$ denotes the derivative of $V_{iHt}(0, m_F, m_G)$ with respect to time, x_{ict} is short for $x_{ict}(0, m_F, m_G)$. Notice that $V_{iH}(-1, m_F, m_G + 1) = V_{i'H}(1, m_F, m_G + 1)$, while $V_{iF}(-1, m_F, m_G + 1) = V_{iF}(1, m_F, m_G + 1)$, that is, Foreign firms are only affected by the relative technology gap in Home country, and are indifferent to who is the Home domestic leader. Because of the difference in parameters, two neck-and-neck firms in Home country are not identical even though their productivity are the same. For simplicity, I assume two neck-and-neck firms have different innovation behaviors. This assumption does not affect the key model mechanism and predictions.

The corresponding optimal innovation decisions are

$$x_{1Ht} = \left(\frac{v_{1Ht}(1, m_F, m_G + 1) - v_{1Ht}(0, m_F, m_G)}{\alpha_{1H} f_{1H}} \right)^{\frac{1}{\gamma_{1H}-1}}, \tag{F.10}$$

$$x_{2Ht} = \left(\frac{v_{1Ht}(1, m_F, m_G + 1) - v_{2Ht}(0, m_F, m_G)}{\alpha_{2H} f_{2H}} \right)^{\frac{1}{\gamma_{2H}-1}}, \tag{F.11}$$

$$x_{1Ft} = \left(\frac{\delta_F v_{1Ft}(0, \min\{m_F + m_G, \bar{m}_F\}, 0) + (1 - \delta_F) v_{1Ft}(0, m_F + 1, m_G - 1) - v_{1Ft}(0, m_F, m_G)}{\alpha_{1F} f_{1F}} \right)^{\frac{1}{\gamma_{1F}-1}}, \tag{F.12}$$

$$x_{2Ft} = \left(\frac{\phi_F v_{2Ft}(0, 0, m_G) + \delta_F v_{1Ft}(0, \min\{m_G, \bar{m}_F\}, 0) + (1 - \phi_F - \delta_F) v_{2Ft}(0, m_F - 1, m_G) - v_{2Ft}(0, m_F, m_G)}{\alpha_{2F} f_{2F}} \right)^{\frac{1}{\gamma_{2F}-1}}, \tag{F.13}$$

where $x_{ict} \in [0, \bar{x}]$ and $\bar{x}$ is the maximal flow rate of innovation. The states for $m_F = 0$ can be analogously characterized.

Boundary states. When solving the model numerically, the state space is assumed to be finite. Specifically, $m_H \in \{0, ..., \bar{m}_H\}$, $m_F \in \{0, ..., \bar{m}_F\}$, and $m_G \in \{-\bar{m}_G, ..., \bar{m}_G\}$. Firms in the boundary state cannot change the technology gap, so these firms' innovation decisions should be separately considered.

For $m_H = \bar{m}_H$, $1 \leq m_F < \bar{m}_F$, $-\bar{m}_G < m_G < \bar{m}_G$, the value function of Home leader is

$$r_{Ht} V_{1Ht}(\bar{m}_H, m_F, m_G) - \dot{V}_{1Ht}(\bar{m}_H, m_F, m_G) = \max_{x_{1Ht} \in [0, \bar{x}]} \{\Pi_{1Ht}(\bar{m}_H, m_F, m_G) P_{Ht} Y_{Ht} - P_{Ht} R_{1Ht}(\bar{m}_H, m_F, m_G)$$

$$+ (x_{1Ht} + \iota \cdot \mathbb{1}_{m_G<0})[\mathbb{1}_{m_G \geq 0} \cdot V_{1Ht}(\bar{m}_H, m_F, m_G + 1) + \mathbb{1}_{m_G<0} \cdot (\delta_H V_{1Ht}(\min\{\bar{m}_H - m_G, \bar{m}_H\}, m_F, 0)$$

$$+ (1 - \delta_H) V_{1Ht}(\bar{m}_H, m_F, m_G + 1)) - V_{1Ht}(\bar{m}_H, m_F, m_G)]$$

$$+ (x_{2Ht} + \kappa + \iota \cdot \mathbb{1}_{m_G<0})[\mathbb{1}_{m_G \geq 0} \cdot (\phi_H V_{1Ht}(0, m_F, m_G) + (1 - \phi_H) V_{1Ht}(\bar{m}_H - 1, m_F, m_G)) + \mathbb{1}_{m_G<0} \cdot (\phi_H V_{1Ht}(0, m_F, m_G)$$

$$+ \delta_H V_{2Ht}(\min\{-m_G, \bar{m}_H\}, m_F, 0) + (1 - \phi_H - \delta_H) V_{1Ht}(\bar{m}_H - 1, m_F, m_G)) - V_{1Ht}(\bar{m}_H, m_F, m_G)]$$

$$+(x_{1Ft} + \iota \cdot \mathbb{1}_{m_G>0})[\mathbb{1}_{m_G>0} \cdot (\delta_F V_{1Ht}(\bar{m}_H, \min\{m_F + m_G, \bar{m}_F\}, 0) + (1 - \delta_F) V_{1Ht}(\bar{m}_H, m_F + 1, m_G - 1))$$

$$+\mathbb{1}_{m_G\leq 0} \cdot V_{1Ht}(\bar{m}_H, m_F + 1, m_G - 1) - V_{1Ht}(\bar{m}_H, m_F, m_G)]$$

$$+(x_{2Ft}+\kappa+\iota\cdot\mathbb{1}_{m_G>0})[\mathbb{1}_{m_G>0}\cdot(\phi_F V_{1Ht}(\bar{m}_H, 0, m_G)+\delta_F V_{1Ht}(\bar{m}_H, \min\{m_G, \bar{m}_F\}, 0)+(1-\phi_F-\delta_F) V_{1Ht}(\bar{m}_H, m_F-1, m_G))$$

$$+ \mathbb{1}_{m_G\leq 0} \cdot (\phi_F V_{1Ht}(\bar{m}_H, 0, m_G) + (1 - \phi_F) V_{1Ht}(\bar{m}_H, m_F - 1, m_G)) - V_{1Ht}(\bar{m}_H, m_F, m_G)]\}, \qquad \text{(F.14)}$$

which implies that Home leaders want to increase global technology gap to gain higher market share and profits despite being unable to gain larger technological advantage over Home followers.

For $1 \leq m_H < \bar{m}_H$, $1 \leq m_F < \bar{m}_F$, $m_G = \bar{m}_G$, the value function of Home leader is

$$r_{Ht} V_{1Ht}(m_H, m_F, \bar{m}_G) - \dot{V}_{1Ht}(m_H, m_F, \bar{m}_G) = \max_{x_{1Ht}\in[0,\bar{x}]} \{\Pi_{1Ht}(m_H, m_F, \bar{m}_G) P_{Ht} Y_{Ht} - P_{Ht} R_{1Ht}(m_H, m_F, \bar{m}_G)$$

$$+x_{1Ht}[V_{1Ht}(m_H + 1, m_F, \bar{m}_G) - V_{1Ht}(m_H, m_F, \bar{m}_G)]$$

$$+(x_{2Ht} + \kappa)[(\phi_H V_{1Ht}(0, m_F, \bar{m}_G) + (1 - \phi_H) V_{1Ht}(m_H - 1, m_F, \bar{m}_G)) - V_{1Ht}(m_H, m_F, \bar{m}_G)]$$

$$+(x_{1Ft}+\iota)[(\delta_F V_{1Ht}(m_H, \min\{m_F+\bar{m}_G, \bar{m}_F\}, 0)+(1-\delta_F) V_{1Ht}(m_H, m_F+1, \bar{m}_G-1))-V_{1Ht}(m_H, m_F, \bar{m}_G)]$$

$$+(x_{2Ft}+\kappa+\iota)[(\phi_F V_{1Ht}(m_H, 0, \bar{m}_G)+\delta_F V_{1Ht}(m_H, \min\{\bar{m}_G, \bar{m}_F\}, 0)+(1-\phi_F-\delta_F) V_{1Ht}(m_H, m_F-1, \bar{m}_G))$$

$$- V_{1Ht}(m_H, m_F, \bar{m}_G)]\}, \qquad \text{(F.15)}$$

which implies that Home leaders want to increase domestic technology gap to gain higher market share and profits than Home followers when they reach the largest global technology gap.

For $1 \leq m_H < \bar{m}_H$, $1 \leq m_F < \bar{m}_F$, $m_G = -\bar{m}_G$, the value function of Home leader is

$$r_{Ht} V_{1Ht}(m_H, m_F, -\bar{m}_G)-\dot{V}_{1Ht}(m_H, m_F, -\bar{m}_G) = \max_{x_{1Ht}\in[0,\bar{x}]} \{\Pi_{1Ht}(m_H, m_F, -\bar{m}_G) P_{Ht} Y_{Ht}-P_{Ht} R_{1Ht}(m_H, m_F, -\bar{m}_G)$$

$$+(x_{1Ht}+\iota)[\delta_H V_{1Ht}(\min\{m_H+\bar{m}_G, \bar{m}_H\}, m_F, 0)+(1-\delta_H) V_{1Ht}(m_H+1, m_F, -\bar{m}_G+1))-V_{1Ht}(m_H, m_F, -\bar{m}_G)]$$

$$+(x_{2Ht}+\kappa+\iota)[\phi_H V_{1Ht}(0, m_F, -\bar{m}_G)+\delta_H V_{2Ht}(\min\{\bar{m}_G, \bar{m}_H\}, m_F, 0)+(1-\phi_H-\delta_H) V_{1Ht}(m_H-1, m_F, -\bar{m}_G)-V_{1Ht}(m_H, m_F, -\bar{m}_G)]$$

$$+x_{1Ft}[V_{1Ht}(m_H, m_F + 1, -\bar{m}_G) - V_{1Ht}(m_H, m_F, -\bar{m}_G)]$$

$$+ (x_{2Ft} + \kappa + \iota)[\phi_F V_{1Ht}(m_H, 0, -\bar{m}_G) + (1 - \phi_F) V_{1Ht}(m_H, m_F - 1, -\bar{m}_G)) - V_{1Ht}(m_H, m_F, -\bar{m}_G)]\}, \qquad \text{(F.16)}$$

which specifies the case when Foreign leaders reach the largest global technology gap.

Other special cases can be written analogously. In sum, there are 27 cases for value functions, taking into account the cases for non-boundary and boundary states with the specification of the state indicators (e.g., $\mathbb{1}_{m_G>0}$).[76]

[76] 3 cases for m_H, m_F, and m_G respectively.

The assumption on the boundary is innocuous since I check robustness by using alternative ways of modelling boundaries, e.g., firm value can be increased by $\lambda > 1$ on the boundary and find that the quantitative results are almost the same.

F.4 Evolution of Technology Gap Distribution

In the main text I only characterize the evolution of distribution for states $1 < m_H < \bar{m}_H$, $1 < m_F < \bar{m}_F$, $0 < |m_G| < \bar{m}_G$ for brevity. In this section I characterize other cases.

Domestic neck-and-neck states. Note that leaders from with $m_c - 1$ can enter the state m_c via successful innovation, $c \in \{H, F\}$. Therefore, the case for $m_c = 1$ is special since both leaders and followers from $m_c - 1 = 0$ can change the global technology gap. The case for $m_c = 0$ is also special since leaders with $m_c - 1 = -1$ is not well defined. Moreover, the possibility of quick catch-up of followers also allow firms with any m_c to transit to state $m_c = 0$. Despite complex specialties, adding some indicator functions can nest the special cases for $m_c = 0, 1$ such that there is a uniform evolution of distribution for all non-boundary states: for $0 \le m_H < \bar{m}_H$, $0 \le m_F < \bar{m}_F$, $0 < |m_G| < \bar{m}_G$,

$$
\begin{aligned}
\dot{\mu}_t(\boldsymbol{m}) = {} & \mathbb{1}_{m_H>0} \cdot [(x_{1Ht}(m_H-1, m_F, m_G-1) + \iota \cdot \mathbb{1}_{m_G-1<0})[\mathbb{1}_{m_G-1\ge 0} + \mathbb{1}_{m_G-1<0} \cdot (1-\delta_H)]\mu_t(m_H-1, m_F, m_G-1) \\
& + (x_{2Ht}(m_H+1, m_F, m_G) + \kappa + \iota \cdot \mathbb{1}_{m_G<0})[\mathbb{1}_{m_G\ge 0} \cdot (1-\phi_H) + \mathbb{1}_{m_G<0} \cdot (1-\phi_H-\delta_H)]\mu_t(m_H+1, m_F, m_G)] \\
& + \mathbb{1}_{m_H=1} \cdot (x_{2Ht}(m_H-1, m_F, m_G-1) + \iota \cdot \mathbb{1}_{m_G-1<0})[\mathbb{1}_{m_G-1\ge 0} + \mathbb{1}_{m_G-1<0} \cdot (1-\delta_H)]\mu_t(m_H-1, m_F, m_G-1) \\
& \qquad + \mathbb{1}_{m_H=0} \cdot \sum_{m'_H>0}^{\bar{m}_H} \phi_H (x_{2Ht}(m'_H, m_F, m_G) + \kappa \cdot \mathbb{1}_{m'_H>0} + \iota \cdot \mathbb{1}_{m_G<0})\mu_t(m'_H, m_F, m_G) \\
& + \mathbb{1}_{m_F>0} \cdot [(x_{1Ft}(m_H, m_F-1, m_G+1) + \iota \cdot \mathbb{1}_{m_G+1>0})[\mathbb{1}_{m_G+1\le 0} + \mathbb{1}_{m_G+1>0} \cdot (1-\delta_F)]\mu_t(m_H, m_F-1, m_G+1) \\
& + (x_{2Ft}(m_H, m_F+1, m_G) + \kappa + \iota \cdot \mathbb{1}_{m_G>0})[\mathbb{1}_{m_G\le 0} \cdot (1-\phi_F) + \mathbb{1}_{m_G>0} \cdot (1-\phi_F-\delta_F)]\mu_t(m_H, m_F+1, m_G)] \\
& + \mathbb{1}_{m_F=1} \cdot (x_{2Ft}(m_H, m_F-1, m_G+1) + \iota \cdot \mathbb{1}_{m_G+1>0})[\mathbb{1}_{m_G+1\le 0} + \mathbb{1}_{m_G+1>0} \cdot (1-\delta_F)]\mu_t(m_H, m_F-1, m_G+1) \\
& \qquad + \mathbb{1}_{m_F=0} \cdot \sum_{m'_F>0}^{\bar{m}_F} \phi_F (x_{2Ft}(m_H, m'_F, m_G) + \kappa \cdot \mathbb{1}_{m'_F>0} + \iota \cdot \mathbb{1}_{m_G>0})\mu_t(m_H, m'_F, m_G) \\
& - (x_{1Ht}(\boldsymbol{m}) + \iota \cdot \mathbb{1}_{m_G<0} + x_{2Ht}(\boldsymbol{m}) + \kappa + \iota \cdot \mathbb{1}_{m_G<0} + x_{1Ft}(\boldsymbol{m}) + \iota \cdot \mathbb{1}_{m_G>0} + x_{2Ft}(\boldsymbol{m}) + \kappa + \iota \cdot \mathbb{1}_{m_G>0})\mu_t(\boldsymbol{m}),
\end{aligned}
\tag{F.17}
$$

where the last line represents the mass of firms that leave state $\boldsymbol{m}$ and the other lines represent the mass of firms that enter state $\boldsymbol{m}$.

Global neck-and-neck states. Compared to states with $0 \le m_H < \bar{m}_H$, $0 \le m_F < \bar{m}_F$, $0 < |m_G| < \bar{m}_G$, when $0 \le m_H < \bar{m}_H$, $0 \le m_F < \bar{m}_F$, $m_G = 0$, there are four extra inflows into the current state $\boldsymbol{m} = (m_H, m_F, m_G)$ as leaders and followers from both countries can reduce the global technology gap to zero by doing successful innovation or getting knowledge spillovers. The extra inflow due to Home leaders' productivity increase is $\sum_{m'_H=m_H+m'_G \& m'_H\geq 0}\sum_{m'_G<0}(x_{1Ht}(m'_H,m_F,m'_G)+\iota)\delta_H\mu_t(m'_H,m_F,m'_G))$. The extra inflow due to Home followers' productivity increase is $\sum_{0\leq m'_H\leq \bar{m}_H}\sum_{m'_G=\max\{-m_H,-\bar{m}_G\}\& m'_G<0}(x_{2Ht}(m'_H,m_F,m'_G)+\iota+\kappa\cdot\mathbb{1}_{m'_H>0})\delta_H\mu_t(m'_H,m_F,m'_G)$. The extra inflow due to Foreign leaders' productivity increase is $\sum_{m'_F=m_F-m'_G\& m'_F\geq 0}\sum_{m'_G>0}(x_{1Ft}(m_H,m'_F,m'_G)+\iota)\delta_F\mu_t(m_H,m'_F,m'_G))$. The extra inflow due to Foreign followers' productivity increase is $\sum_{0\leq m'_F\leq \bar{m}_F}\sum_{m'_G=\min\{m_F,\bar{m}_G\}\& m'_G>0}(x_{2Ft}(m_H,m'_F,m'_G)+\iota+\kappa\cdot\mathbb{1}_{m'_F>0})\delta_F\mu_t(m_H,m'_F,m'_G)$.

Boundary states. For boundary states with $|m_G|=\bar{m}_G$ or $m_c=\bar{m}_c$, $c\in\{H,F\}$, we need to consider extra inflows into the current state $\boldsymbol{m}=(m_H,m_F,m_G)$ as firms cannot leave the boundary states through successful innovation or getting knowledge spillovers. We also need to remove some states that are not well defined from the evolution of the distribution.[77]

For state $0\leq m_H<\bar{m}_H, 0\leq m_F<\bar{m}_F, m_G=\bar{m}_G$, compared to equation (F.17), there are extra inflows into current state: $\mathbb{1}_{m_H>0}\cdot[x_{1Ht}(m_H-1,m_F,\bar{m}_G)\mu_t(m_H-1,m_F,\bar{m}_G)+\mathbb{1}_{m_H=1}\cdot x_{2Ht}(m_H-1,m_F,\bar{m}_G)\mu_t(m_H-1,m_F,\bar{m}_G)$. While some inflows disappear since they are no longer well defined: $+\mathbb{1}_{m_F>0}\cdot[(x_{1Ft}(m_H,m_F-1,\bar{m}_G+1)+\iota\cdot\mathbb{1}_{\bar{m}_G+1>0})[\mathbb{1}_{\bar{m}_G+1\leq 0}+\mathbb{1}_{\bar{m}_G+1>0}\cdot(1-\delta_F)]\mu_t(m_H,m_F-1,\bar{m}_G+1)$ $+\mathbb{1}_{m_F=1}\cdot(x_{2Ft}(m_H,m_F-1,\bar{m}_G+1)+\iota\cdot\mathbb{1}_{\bar{m}_G+1>0})[\mathbb{1}_{\bar{m}_G+1\leq 0}+\mathbb{1}_{\bar{m}_G+1>0}\cdot(1-\delta_F)]\mu_t(m_H,m_F-1,\bar{m}_G+1)$.

For another example, for state $m_H=\bar{m}_H, 0\leq m_F<\bar{m}_F, m_G=\bar{m}_G$, compared to equation (F.17), there are three extra inflows into current state: $x_{1Ht}(\bar{m}_H,m_F,\bar{m}_G-1)\mu_t(\bar{m}_H,m_F,\bar{m}_G-1)$, $x_{1Ht}(\bar{m}_H-1,m_F,\bar{m}_G)\mu_t(\bar{m}_H-1,m_F,\bar{m}_G)$, and $x_{1Ht}(\bar{m}_H,m_F,\bar{m}_G)\mu_t(\bar{m}_H,m_F,\bar{m}_G)$. While some inflows disappear since they are no longer well defined: $(x_{2Ht}(\bar{m}_H+1,m_F,\bar{m}_G)+\kappa+\iota\cdot\mathbb{1}_{\bar{m}_G<0})[\mathbb{1}_{\bar{m}_G\geq 0}\cdot(1-\phi_H)+\mathbb{1}_{\bar{m}_G<0}\cdot(1-\phi_H-\delta_H)]\mu_t(\bar{m}_H+1,m_F,\bar{m}_G)]$ and $(x_{1Ft}(\bar{m}_H,m_F-1,\bar{m}_G+1)+\iota\cdot\mathbb{1}_{\bar{m}_G+1>0})[\mathbb{1}_{\bar{m}_G+1\leq 0}+\mathbb{1}_{\bar{m}_G+1>0}\cdot(1-\delta_F)]\mu_t(\bar{m}_H,m_F-1,\bar{m}_G+1)+\mathbb{1}_{m_F=1}\cdot(x_{2Ft}(\bar{m}_H,m_F-1,\bar{m}_G+1)+\iota\cdot\mathbb{1}_{\bar{m}_G+1>0})[\mathbb{1}_{\bar{m}_G+1\leq 0}+\mathbb{1}_{\bar{m}_G+1>0}\cdot(1-\delta_F)]\mu_t(\bar{m}_H,m_F-1,\bar{m}_G+1)$.

Other boundary states can be analogously characterized. In sum, there are originally 48 cases for the law of motion of the distribution across all non-boundary and boundary states ($m_c=0,1,\bar{m}_c$ or others, $c\in\{H,F\}$ $m_G=-\bar{m}_G,\bar{m}_G$ or others) but by adding a set of indicators the 48 cases are reduced to 12 cases ($m_c=\bar{m}_c$ or others, $c\in\{H,F\}$ $m_G=-\bar{m}_G,\bar{m}_G$ or others), greatly simplifying the problem. The detailed analysis on all cases is available upon request.

F.5 Proofs for Aggregate Growth

Proposition A.2. *Along the balanced growth path the growth rate of aggregate Home productivity is* $g_H=\{\sum_{0\leq m_H\leq\bar{m}_H}\sum_{0\leq m_F\leq\bar{m}_F}\sum_{m_G\geq 0}[x_{1H}(\boldsymbol{m})\cdot\mu(\boldsymbol{m})+x_{2H}(\boldsymbol{m})\cdot\mathbb{1}_{m_H=0}\cdot\mu(\boldsymbol{m})]+\sum_{0\leq m_H\leq\bar{m}_H}\sum_{0\leq m_F\leq\bar{m}_F}\sum_{m_G\leq 0}[x_{1F}(\boldsymbol{m})\cdot\mu(\boldsymbol{m})+x_{2F}(\boldsymbol{m})\cdot\mathbb{1}_{m_F=0}\cdot\mu(\boldsymbol{m})]\}\cdot\ln(\lambda)$, *where* $\boldsymbol{m}$ *is short for* (m_H,m_F,m_G), *and the growth rate of aggregate productivity in Home and Foreign are the same, i.e.,* $g_H=g_F$.

Proof The aggregate Home productivity index is defined by Home leaders' productivity: $Q_{Ht}\equiv\int_0^1\ln q_{1jHt}dj$. Home leaders' productivity increases because of innovations or from international knowledge spillovers from the Foreign. Along the balanced growth path the aggregate growth

[77] For example, Foreign leaders are able to reduce m_G, while no Foreign leaders can transit to state $(m_H,m_F,\bar{m}_G)$ with $\bar{m}_G+1$.

due to international spillovers from the Foreign is identical to the aggregate growth due to Foreign leaders' innovation.

To see it more clearly, define the aggregate world productivity index by the global technology frontier in each industry j: $\tilde{Q}_t \equiv \int_0^1 \ln q_{1jHt} \cdot \mathbb{1}_{m_G \geq 0} dj + \int_0^1 \ln q_{1jFt} \cdot \mathbb{1}_{m_G < 0} dj$. It is straightforward to show that $Q_{Ht} = \tilde{Q}_t + \int_0^1 m_G \ln(\lambda) \mathbb{1}_{m_G < 0} dj$ given that $Q_{Ht} = \int_0^1 \ln q_{1jHt} \mathbb{1}_{m_G \geq 0} dj + \int_0^1 \ln(q_{1jFt} \frac{q_{1jHt}}{q_{1jFt}}) \mathbb{1}_{m_G < 0} dj$. So $g_{Ht} \equiv \dot{Q}_{Ht} = \dot{\tilde{Q}}_t$ along a stationary equilibrium. $\dot{\tilde{Q}}_t$ is determined by the innovation of the global technology frontier in each industry j.[78]

Within a time interval of Δt, the mass of productivity improvement realized in industries with $m_G > 0$ due to successful innovation of Home leaders is $\Delta t[\sum_{m_H=0}^{\bar{m}_H} \sum_{m_F=0}^{\bar{m}_F} \sum_{m_G=0}^{\bar{m}_G} x_{1Ht}(\boldsymbol{m})\mu_t(\boldsymbol{m})]$. Notice that when two Home firms are in neck-and-neck status, both firms can drive up the aggregate productivity through successful innovation. So the mass of productivity improvement realized in industries with $m_G \geq 0$ due to successful innovation of the other neck-and-neck Home firm within a time interval of Δt is $\Delta t[\sum_{m_H=0}^{0} \sum_{m_F=0}^{\bar{m}_F} \sum_{m_G=0}^{\bar{m}_G} x_{2Ht}(\boldsymbol{m})\mu_t(\boldsymbol{m})]$.

The mass of productivity improvement realized in industries with $m_G < 0$ due to successful innovation of Foreign leaders can be symmetrically characterized. When $m_G = 0$, both Home leaders and Foreign leaders can drive up the aggregate productivity through successful innovation.

Since the productivity improvement has step size λ, we have $\tilde{Q}_{t+\Delta t} - \tilde{Q}_t$
$= \Delta t[\sum_{m_H=0}^{\bar{m}_H} \sum_{m_F=0}^{\bar{m}_F} \sum_{m_G=0}^{\bar{m}_G} x_{1Ht}(\boldsymbol{m})\mu_t(\boldsymbol{m})$
$+ \sum_{m_H=0}^{0} \sum_{m_F=0}^{\bar{m}_F} \sum_{m_G=0}^{\bar{m}_G} x_{2Ht}(\boldsymbol{m})\mu_t(\boldsymbol{m})$
$+ \Delta t[\sum_{m_H=0}^{\bar{m}_H} \sum_{m_F=0}^{\bar{m}_F} \sum_{m_G=-\bar{m}_G}^{0} x_{1Ft}(\boldsymbol{m})\mu_t(\boldsymbol{m})$
$+ \sum_{m_H=0}^{\bar{m}_H} \sum_{m_F=0}^{0} \sum_{m_G=-\bar{m}_G}^{0} x_{2Ft}(\boldsymbol{m})\mu_t(\boldsymbol{m})] \cdot \ln(\lambda)$.

Rearranging and taking the limit $\Delta t \longrightarrow 0$, along the balanced growth path we have $g_{Ht} = \dot{\tilde{Q}}_t = \{\sum_{0 \leq m_H \leq \bar{m}_H} \sum_{0 \leq m_F \leq \bar{m}_F} \sum_{m_G \geq 0} [x_{1H}(\boldsymbol{m}) \cdot \mu(\boldsymbol{m}) + x_{2H}(\boldsymbol{m}) \cdot \mathbb{1}_{m_H=0} \cdot \mu(\boldsymbol{m})] + \sum_{0 \leq m_H \leq \bar{m}_H} \sum_{0 \leq m_F \leq \bar{m}_F} \sum_{m_G \leq 0} [x_{1F}(\boldsymbol{m}) \cdot \mu(\boldsymbol{m}) + x_{2F}(\boldsymbol{m}) \cdot \mathbb{1}_{m_F=0} \cdot \mu(\boldsymbol{m})]\} \cdot \ln(\lambda)$, where $\boldsymbol{m}$ is short for (m_H, m_F, m_G).

Foreign country can be proved similarly. Moreover, $g_F = g_H$. This can be seen from $Q_{Ft} \equiv \int_0^1 \ln q_{1jFt} dj = \int_0^1 \ln(\frac{q_{1jFt}}{q_{1jHt}} q_{1jHt}) dj = \int_0^1 \ln(q_{1jHt}) dj + \int_0^1 \ln(\frac{q_{1jFt}}{q_{1jHt}}) dj = Q_{Ht} + \int_0^1 \ln(\frac{q_{1jFt}}{q_{1jHt}}) dj$. Notice that $\int_0^1 \ln(\frac{q_{1jFt}}{q_{1jHt}}) dj = \sum_{\boldsymbol{m}} \ln(\frac{q_{1jFt}}{q_{1jHt}}) \mu_{\boldsymbol{m}}$ depends on the distribution of firms and relative productivity between Home leaders and Foreign leaders, and is constant in balanced growth path equilibrium. Therefore, the growth rate of Q_{Ft} equals the growth rate of Q_{Ht} in balanced growth path equilibrium, i.e., $g_F = g_H$. □

Proposition A.3. *Along the balanced growth path the growth rate of aggregate output Y_c and consumption C_c is $2g_c$, the growth rate of aggregate price index P_c is $-2g_c$, and the growth rate of wage w_c and interest rate r_c is 0, where g_c is the growth rate of aggregate productivity, $c \in \{H, F\}$.*

Proof The proof is written two steps from Home country's perspective. First derive the expression for aggregate output, consumption, and prices, and then compute the aggregate growth

[78] It is obvious that $\dot{Q}_{Ht}$ remains the same if define Q_{Ht} by Home followers.

rate.

Plugging in intermediate firms' production function, we have

$$\ln(Y_{Ht}) = \int_0^1 \ln(Y_{jHt})dj = 2Q_{Ht} + \text{CON1} \tag{F.18}$$

where $\text{CON1} = \frac{\epsilon}{\epsilon-1}\int_0^1 \ln[\omega_{1jHt}{\omega^b_{1jHt}}^{\frac{1}{\epsilon}} l_{1jHt}^{\frac{\epsilon-1}{\epsilon}} + \omega_{2jHt}{\omega^b_{2jHt}}^{\frac{1}{\epsilon}} l_{2jHt}^{\frac{\epsilon-1}{\epsilon}}(\frac{q_{2jHt}}{q_{1jHt}})^{\frac{2(\epsilon-1)}{\epsilon}} + \omega_{1jFt}{\omega^b_{1jFt}}^{\frac{1}{\epsilon}}(l_{1jFt}/\tau_F)^{\frac{\epsilon-1}{\epsilon}}(\frac{q_{1jFt}}{q_{1jHt}})^{\frac{2(\epsilon-1)}{\epsilon}} + \omega_{2jFt}{\omega^b_{2jFt}}^{\frac{1}{\epsilon}}(l_{2jFt}/\tau_F)^{\frac{\epsilon-1}{\epsilon}}(\frac{q_{2jFt}}{q_{1jHt}})^{\frac{2(\epsilon-1)}{\epsilon}}]dj$. We also have

$$\ln(P_{Ht}) = \int_0^1 \ln(P_{jHt})dj = -2Q_{Ht} + \text{CON2} \tag{F.19}$$

where $\text{CON2} = \frac{1}{1-\epsilon}\int_0^1 \ln(\omega_{1jHt}\omega^b_{1jHt}(mu_{1jHt}w_{Ht})^{1-\epsilon} + \omega_{2jHt}\omega^b_{2jHt}(mu_{2jHt}w_{Ht})^{1-\epsilon}(\frac{q_{2jHt}}{q_{1jHt}})^{2(\epsilon-1)} + \omega_{1jFt}\omega^b_{1jFt}(mu_{1jFt}w_{Ft}\tau_F)^{1-\epsilon}(\frac{q_{1jFt}}{q_{1jHt}})^{2(\epsilon-1)} + \omega_{2jFt}\omega^b_{2jFt}(mu_{2jFt}w_{Ft}\tau_F)^{1-\epsilon}(\frac{q_{2jFt}}{q_{1jHt}})^{2(\epsilon-1)})dj$.

Since in the balanced growth path equilibrium, the distribution of firms, labor demand, markup, and wage rate are invariant across technology gaps, the terms CON1 and CON2 are constant. Therefore, the aggregate growth rate of Y_{Ht} and P_{Ht} depends on Q_{Ht}. Differentiating equation (F.18) and (F.19) with respect to time yields the following expressions for the growth rate:

$$(\ln(Y_{Ht}))'_t = \frac{\dot{Y}_{Ht}}{Y_{Ht}} = 2\dot{Q}_{Ht} \equiv 2g_{Ht}, \quad (\ln(P_{Ht}))'_t = \frac{\dot{P}_{Ht}}{P_{Ht}} = -2\dot{Q}_{Ht} \equiv -2g_{Ht}. \tag{F.20}$$

From the final goods market clearing condition, it is straightforward to show that $\frac{C_{Ht+\Delta t}-C_{Ht}}{C_{Ht}} = \frac{Y_{Ht+\Delta t}(1-\frac{R_{Ht+\Delta t}}{Y_{Ht+\Delta t}})-Y_{Ht}(1-\frac{R_{Ht}}{Y_{Ht}})}{Y_{Ht}(1-\frac{R_{Ht}}{Y_{Ht}})}$. Since $\frac{R_{Ht}}{Y_{Ht}}$ is stationary in balanced growth path, $\frac{\dot{C}_{Ht}}{C_{Ht}} = \frac{\dot{Y}_{Ht}}{Y_{Ht}}$.

The equilibrium conditions also directly imply that growth rte of wage w_{Ht} and interest rate r_{Ht} are 0 along balanced growth path. The Foreign is analogous. □

F.6 Proofs for Model Mechanism

Proposition 1. *Given the wage rates w_{ct} and aggregate revenue $P_{ct}Y_{ct}$ in two countries, Home leaders' (followers') market share and profits are bounded, weakly-increasing (weakly-decreasing) in the domestic technology gap, and concave (convex) in the domestic technology gap as the domestic technology gap is large enough; Home (Foreign) firms' market share and profits are bounded, weakly-increasing (weakly-decreasing) in the global technology gap, and concave (convex) in the global technology gap as the global technology gap is high enough, given the other two technology gaps, $c \in \{H, F\}$. The Home firm's market share is increasing in the Foreign wage rates w_{Ft} and trade cost τ_F given the technology gaps.*

Proof The proof is written in three steps from Home market's perspective.[79]

First, define three relative prices. $\rho_1(m_H, m_F, m_G) \equiv \frac{p_{2jHt}}{p_{1jHt}}$, $\rho_2(m_H, m_F, m_G) \equiv \frac{\tau_F p_{1jFt}}{p_{1jHt}}$, $\rho_3(m_H, m_F, m_G) \equiv \frac{\tau_F p_{2jFt}}{p_{1jHt}}$.

[79] This is essentially a two-country version proof of Lemma 1 and 2 in Liu et al. (2022).

Second, write down market share, markup and profit as a function of relative prices. From Lemma A.1, we have $s_{ijct} \equiv \frac{1}{1+B_{ijct}}$, $mu_{ijct} = \frac{1+\epsilon B_{ijct}}{(\epsilon-1)B_{ijct}}$, $\pi_{ijct} = \frac{1}{1+\epsilon B_{ijct}} \frac{P_{Ht}Y_{Ht}}{\omega_{ijct}}$, where $B_{1jHt} = \frac{\omega_{2jHt}\omega^b_{2jHt}}{\omega_{1jHt}\omega^b_{1jHt}}(\lambda^{-m_H})^{\epsilon-1}\rho_1^{1-\epsilon} + \frac{\omega_{1jFt}\omega^b_{1jFt}}{\omega_{1jHt}\omega^b_{1jHt}}(\lambda^{-m_G})^{\epsilon-1}\rho_2^{1-\epsilon} + \frac{\omega_{2jFt}\omega^b_{2jFt}}{\omega_{1jHt}\omega^b_{1jHt}}(\lambda^{-(m_F+m_G)})^{\epsilon-1}\rho_3^{1-\epsilon}$;

$B_{2jHt} \equiv \frac{\omega_{1jHt}\omega^b_{1jHt}}{\omega_{2jHt}\omega^b_{2jHt}}(\lambda^{m_H})^{\epsilon-1}\rho_1^{\epsilon-1} + \frac{\omega_{1jFt}\omega^b_{1jFt}}{\omega_{2jHt}\omega^b_{2jHt}}(\lambda^{m_H-m_G})^{\epsilon-1}(\rho_2\rho_1^{-1})^{1-\epsilon} + \frac{\omega_{2jFt}\omega^b_{2jFt}}{\omega_{2jHt}\omega^b_{2jHt}}(\lambda^{m_H-(m_F+m_G)})^{\epsilon-1}(\rho_3\rho_1^{-1})^{1-\epsilon}$;

$B_{1jFt} \equiv \frac{\omega_{1jHt}\omega^b_{1jHt}}{\omega_{1jFt}\omega^b_{1jFt}}(\lambda^{m_G})^{\epsilon-1}\rho_2^{\epsilon-1} + \frac{\omega_{2jHt}\omega^b_{2jHt}}{\omega_{1jFt}\omega^b_{1jFt}}(\lambda^{m_G-m_H})^{\epsilon-1}(\rho_1\rho_2^{-1})^{1-\epsilon} + \frac{\omega_{2jFt}\omega^b_{2jFt}}{\omega_{1jFt}\omega^b_{1jFt}}(\lambda^{-m_F})^{\epsilon-1}(\rho_3\rho_2^{-1})^{1-\epsilon}$;

$B_{2jFt} \equiv \frac{\omega_{1jHt}\omega^b_{1jHt}}{\omega_{2jFt}\omega^b_{2jFt}}(\lambda^{m_G+m_F})^{\epsilon-1}\rho_3^{\epsilon-1} + \frac{\omega_{2jHt}\omega^b_{2jHt}}{\omega_{2jFt}\omega^b_{2jFt}}(\lambda^{m_F-m_G-m_H})^{\epsilon-1}(\rho_1\rho_3^{-1})^{1-\epsilon} + \frac{\omega_{1jFt}\omega^b_{1jFt}}{\omega_{2jFt}\omega^b_{2jFt}}(\lambda^{m_F})^{\epsilon-1}(\rho_2\rho_3^{-1})^{1-\epsilon}$.

Third, solve relative prices as a function of technology gaps.

$\rho_1 = \frac{1+\epsilon B_{2jHt}}{1+\epsilon B_{1jHt}}\frac{B_{1jHt}}{B_{2jHt}}\lambda^{m_H}$; $\rho_2 = \frac{1+\epsilon B_{1jFt}}{1+\epsilon B_{1jHt}}\frac{B_{1jHt}}{B_{1jFt}}\lambda^{m_G}\frac{\tau_F w_{Ft}}{w_{Ht}}$; $\rho_3 = \frac{1+\epsilon B_{2jFt}}{1+\epsilon B_{1jHt}}\frac{B_{1jHt}}{B_{2jFt}}\lambda^{m_G+m_F}\frac{\tau_F w_{Ft}}{w_{Ht}}$. These three equations jointly pin down the three relative prices. From the algebra, $\lim_{m_H\to\infty}\rho_1 = \infty$, $\lim_{m_G\to\infty}\rho_2 = \infty$, $\lim_{m_G\to\infty}\rho_3 = \infty$. Therefore, for large enough m_H, π_{1jHt} is bounded given any finite m_F and m_G. It directly follows that π_{1jHt} is concave as $m_H \longrightarrow \infty$. Moreover, π_{1jHt} is weakly-increasing in m_H. For large enough m_G, π_{ijHt} is bounded given any finite m_H and m_F. It directly follows that π_{ijHt} is concave as $m_G \longrightarrow \infty$. Moreover, π_{ijHt} is weakly-increasing in m_G. On the other hand, π_{2jHt} is weakly-decreasing and convex in m_H and π_{ijFt} is weakly-decreasing and convex in m_G, s_{ijct} is increasing in w_{Ft} and τ_F, which are directly from the algebra.

Similarly, we can define three relative prices from Foreign market's perspective and derive similar properties. □

Proposition 2. *Larger firms' markups respond more to changes in their market share.*

Proof $-\frac{\partial\ln(\varepsilon_{ijct})}{\partial\ln(s_{ijct})} = \frac{s_{ijct}(\epsilon-1)}{\epsilon-s_{ijct}(\epsilon-1)} \geq 0$, where ε_{ijct} is the demand elasticity governing firm's markup, s_{ijct} is market share in domestic or foreign market, and ϵ is the elasticity of substitution. $\frac{\partial\ln(mu_{ijct})}{\partial\ln(\varepsilon_{ijct})} = \frac{1}{1-\varepsilon_{ijct}} < 0$. Therefore, firm's elasticity of the markup with respect to the market share is increasing in its market share is immediate. □

F.7 Model Extensions

In this section, I provide the detailed model setup and equilibrium conditions of model extensions discussed in section 5.6.4. It is straightforward to model followers do not export and make knowledge spillovers operate via lower innovation costs. Therefore, I discuss the other two extensions, endogenous entry and exit and international knowledge spillovers endogenously vary with trade.

F.7.1 Endogenous Entry and Exit

In each period there is a potential entrant in each industry-country pair that make innovation decisions such that with some probability the entrant can replace the follower. Potential entrants pay innovation cost $\tilde{R}_{ct}(m_H, m_F, m_G) = \frac{\tilde{\alpha}_c}{\tilde{\gamma}_c}\tilde{x}_{ct}(m_H, m_F, m_G)^{\tilde{\gamma}_c}$ to have Poisson arrival rate of innovation $\tilde{x}_{ct}(m_H, m_F, m_G)$. Once the innovation is successful, the entrant replaces the follower and the follower exits the market with zero value. Otherwise, the entrant disappears with zero value. With probability $1 - \phi_c$, the entrant closes the domestic technology gap with the leader (quick catch-up); with probability ϕ_c, the entrant reduces the domestic technology gap with the leader by 1 (slow catch-up).

Representative consumers own firms (incumbents and potential entrants). The sum of firm value $A_{ct} = \sum_{\boldsymbol{m}}[\sum_{i=1}^{2} V_{ict}(m_H, m_F, m_G) + \tilde{V}_{ct}(m_H, m_F, m_G)]\mu(\boldsymbol{m})$, where V_{ict} is the value of incumbent, $\tilde{V}_{ct}$ is the value of entrant, and $\boldsymbol{m} \equiv (m_H, m_F, m_G)$.

The Home entrant's innovation problem is as follows.

$$\tilde{V}_{Ht}(m_H, m_F, m_G) = \max_{\tilde{x}_{Ht}}\{\tilde{x}_{Ht}[\phi_H V_{2Ht}(0, m_F, m_G) + (1 - \phi_H)V_{2Ht}(m_H - 1, m_F, m_G)] - \frac{\tilde{\alpha}_H}{\tilde{\gamma}_H}\tilde{x}_{Ht}^{\tilde{\gamma}_H}\} \quad \text{(F.21)}$$

where $\tilde{x}_{Ht}$ is short for $\tilde{x}_{Ht}(m_H, m_F, m_G)$. The innovation decision rule is hence

$$\tilde{x}_{Ht} = (\frac{\phi_H V_{2Ht}(0, m_F, m_G) + (1 - \phi_H)V_{2Ht}(m_H - 1, m_F, m_G)}{\tilde{\alpha}_H})^{\frac{1}{\tilde{\gamma}_H - 1}}. \quad \text{(F.22)}$$

The innovation problem of Home incumbents is extended with two additional terms compared to the baseline model. For Home leaders, there are two extra terms on the RHS of VFI: $\tilde{x}_{Ht}[\phi_H V_{1Ht}(0, m_F, m_G) + (1 - \phi_H)V_{1Ht}(m_H - 1, m_F, m_G) - V_{1Ht}(m_H, m_F, m_G)] + \tilde{x}_{Ft}[\phi_F V_{1Ht}(m_H, 0, m_G) + (1 - \phi_F)V_{1Ht}(m_H, m_F - 1, m_G) - V_{1Ht}(m_H, m_F, m_G)]$. The innovation problem of Home followers is also extended with two additional terms on the RHS of VFI: $\tilde{x}_{Ht}[0 - V_{1Ht}(m_H, m_F, m_G)]$ $+\tilde{x}_{Ft}[0 - V_{1Ht}(m_H, m_F, m_G)]$. The Foreign is analogous. In this alternative setup, though the value of incumbents is reshaped, the innovation decision rules do not change.

For the evolution of technology gap distribution and aggregate growth, any terms that are associated with followers will be added an extra $\tilde{x}_c$. The aggregate innovation expenditure now also includes the entrants' innovation cost.

It is straightforward that if globalization drives down the value of followers, entrants decrease innovation rate since the value from entering the market decreases. Therefore, globalization contributes to declining entry. Though there is a subtle effect that less entry increases the follower's value since it is less likely to be replaced, the quantitative magnitude of this effect is small.

F.7.2 International Knowledge Spillovers Endogenously Vary with Trade

Consider international knowledge spillovers via the firm interactions. Firms have to pay per-period fixed export cost f_c^{ex} in units of labor to export. Therefore, only a fraction of firms export. Only firms that export can exert international knowledge spillovers to firms in the other country as long as their productivity is higher than firms in the other country. Conditional on exporting, leaders (followers) give international knowledge spillovers with probability ι^l (ι^f). The Home intermediate firms' production decision now incorporates export decision $\zeta_{iHt}^*(\boldsymbol{m})$. It can be shown that $\zeta_{iHt}^*(\boldsymbol{m}) = 1$ if $(p_{iHt}^*(\boldsymbol{m}) - \frac{w_{Ht}}{q_{iHt}(\boldsymbol{m})})y_{iHt}^*(\boldsymbol{m}) \geq w_{Ht}f_H^{ex}$, where $\boldsymbol{m} = (m_H, m_F, m_G)$. The VFI, evolution of technology gap distribution and aggregate growth in this alternative setup replace the

$\iota \cdot \mathbb{1}_{m_G<0}$ in the baseline model with $\underbrace{\iota^l \cdot \mathbb{1}_{m_G<0} \cdot \mathbb{1}_{\zeta^*_{1H}=1}}_{\textbf{int'l spillover from F leader}} + \underbrace{\iota^f \cdot \mathbb{1}_{m_G+m_F<0} \cdot \mathbb{1}_{\zeta^*_{2H}=1}}_{\textbf{int'l spillover from F follower}}$ for Home firms. The Foreign is analogous.

The declining trade iceberg costs induce more Home firms become exporters, especially firms with relatively low global technological advantage ($m_G > 0$ but m_G relatively low). Therefore, there is more international knowledge spillovers for firms with relatively low global technological advantage. Symmetrically, Foreign firms with relatively low global technological advantage ($m_G < 0$ but close to 0) are more able to become exporters and exert knowledge spillovers to Home firms. Therefore, declining trade iceberg costs generate more spillovers around $m_G = 0$, consistent with the baseline model. In contrast, the firms with high global technological advantage face much less increase in international spillovers since the exporting probability increases by less.

G Numerical Appendix

G.1 Computation Algorithm for BGP

There are two key challenges in numerically solving the model. First, the presence of three technology gaps makes it complicated to solve compared to other models with only one technology gap, especially due to the special cases for the domestic neck-and-neck states and boundary states when computing the value function iteration and the evolution of the distribution of technology gaps. Second, the asymmetric country setup, rich innovation process, multi-firm production, and nonlinear relationships due to endogenous markups and strategic innovation behaviors make it challenging to pin down the equilibrium. I overcome these difficulties by using certain techniques (choice of state space and numeraire, indicator functions, etc) and provide a tractable computation algorithm.

G.1.1 Solution Method

Given parameter values, the computational algorithm for solving a stationary balanced growth path equilibrium involves seven steps.

First, set up the technology gap space $\boldsymbol{m} = (m_H, m_F, m_G)$. I set up the state space to be sufficiently large such that further enlarging the state space does not significantly change the quantitative results. Specifically, $\bar{m}_c = 8, c \in \{H, F\}, \bar{m}_G = 6$. Unlike existing papers that set $-\bar{m}_c \leq m_c \leq \bar{m}_c$, I set $0 \leq m_c \leq \bar{m}_c$ and characterize the problems of the leader and follower separately, which helps reduce the computational burden significantly in the setup with multiple state variables.

Second, set initial guesses for Foreign wages w_F^{old}, plus aggregate expenditure $P_c Y_c^{old}$ and interest rates r_c^{old} in each country. There are two tricks in this step. The first is choosing the Home wage as the numeraire in the model instead of using aggregate prices like most existing papers. This helps generate $r_{ct} = \rho$ in balanced growth path equilibrium such that interest rate r_{ct} is directly pinned down without any iteration. The second trick is to iterate $P_c Y_c^{old}$ as a single object instead of iterating each term separately.

Third, solve the static decisions (production and pricing) of firms given the initial guesses. Then solve the value functions jointly for both countries by backward induction and the uniformization method developed by Acemoglu and Akcigit (2012). This process yields the optimal innovation policies as well as static decisions of firms in each state. I ensure that $\max_{\boldsymbol{m}} \|v_{\boldsymbol{m}}^{new} - v_{\boldsymbol{m}}^{old}\| \leq$ 1e-06. The trick here is the uniformization method, which helps ensure the convergence of the value function iteration and greatly reduces the time required to find the convergence. More details are available upon request.

Fourth, compute the stationary distribution of firms over technology gaps. I impose that the total mass of industries is one. Initially guess a mass of industries and solve the distribution of firms by using the "evolution equations" across the technology gaps, and adjust the mass of industries such that the total mass of industries is one, and keep iterating until the distribution becomes stationary. The trick here is to add a set of indicator functions to reduce the special cases as discussed in Appendix F.4. I then compute the aggregate growth rate using innovation decisions and the stationary distribution.

Fifth, impose market clearing conditions. Given firms' static decisions and the stationary distribution of firms, compute $P_c Y_c^{new}$ and w_F^{new} by imposing labor market clearing conditions and the balanced trade condition. Check whether $w_F^{new} - w_F^{old} \le$ 1e-06, $P_c Y_c^{new} - P_c Y_c^{old} \le$ 1e-06, $c \in \{H, F\}$. If not, update w_F^{old} and $P_c Y_c^{old}$, and restart from the third step until they converge.

Sixth, after solving the model, I simulate a discrete time version of the model with 10 subperiods per year for a panel of 10000 firms in each country for 300 years after the model reaches the steady state distribution over technology gaps. I then compute firm-level variables of interest.

Finally, compare model moments to targeted data moments. Search over the parameter space to minimize the objective function $\min_{\boldsymbol{\theta}} \sum_{k=1}^{K} p_k \frac{|\text{model}_k(\boldsymbol{\theta}) - \text{data}_k|}{\frac{1}{2}|\text{model}_k(\boldsymbol{\theta}) + \text{data}_k|}$. More details are in Appendix G.1.2.

G.1.2 Estimation Routine

I estimate the parameters of the model via Simulated Method of Moments (SMM). Specifically, I choose a vector of parameters $\boldsymbol{\theta}^*$ to minimize the objective function

$$\min_{\boldsymbol{\theta}} \sum_{k=1}^{K} p_k \frac{|\text{model}_k(\boldsymbol{\theta}) - \text{data}_k|}{\frac{1}{2}|\text{model}_k(\boldsymbol{\theta}) + \text{data}_k|},$$

where k denotes the kth moment in the model and the data, K denotes the total number of moments, and p_k denotes the weight of moment k. I set the weights p_k such that the productivity growth rate, leader premium in sales, relative productivity between two countries, and export intensity are weighted 5 times more than the other moments.

G.2 Computation Algorithm for Transition Dynamics

I assume that the economy begins in the initial balanced growth path. At period $t = 1$, it is hit by a permanent and unexpected decrease in trade iceberg costs and an increase in international knowledge spillovers. Eventually, the economy will converge to a new balanced growth path at period T, for some T large enough. I solve a discrete version of the model with small time increments $\Delta t = 0.1$ and proceed in five steps.

First, solve the initial balanced growth path and the new balanced growth path.

Second, guess a wage path $w_{Ft} = \{w_{F1}, w_{F1+\Delta t}, w_{F1+2*\Delta t}, ..., w_{FT}\}$, aggregate revenue path for PY_{Ht}, PY_{Ft}, and interest rate path r_{Ht}, r_{Ft}, with $w_{Ht} \equiv 1$.

Third, solve the firm static problems in each period given the guesses. Given the steady state values $v_{m,T}$ assumed at T (new balanced growth path values), solve for innovation policies at

$T - \Delta t$. For example, for $1 < m_H < \bar{m}_H$, $1 < m_F < \bar{m}_F$, $0 < m_G < \bar{m}_G$ and assume $\delta_c = 0, c \in \{H, F\}$,

$$x_{1HT-\Delta t} = \left(\exp(-r_{HT}\Delta t) \frac{V_{1HT}(m_H + 1, m_F, m_G + 1) - V_{1HT}(m_H, m_F, m_G)}{\alpha_{1H} f_{1H} P_H Y_H} \right)^{\frac{1}{\gamma_{1H}-1}}, \tag{G.1}$$

$$x_{2HT-\Delta t} = \left(\exp(-r_{HT}\Delta t) \frac{\phi_H V_{2HT}(0, m_F, m_G) + (1 - \phi_H) V_{2HT}(m_H - 1, m_F, m_G) - V_{2HT}(m_H, m_F, m_G)}{\alpha_{2H} f_{2H} P_H Y_H} \right)^{\frac{1}{\gamma_{2H}-1}}, \tag{G.2}$$

$$x_{1FT-\Delta t} = \left(\exp(-r_{FT}\Delta t) \frac{V_{1FT}(m_H, m_F + 1, m_G - 1) - V_{1FT}(m_H, m_F, m_G)}{\alpha_{1F} f_{1F} P_F Y_F} \right)^{\frac{1}{\gamma_{1F}-1}}, \tag{G.3}$$

$$x_{2FT-\Delta} = \left(\exp(-r_{FT}\Delta t) \frac{\phi_F V_{2FT}(m_H, 0, m_G) + (1 - \phi_F) V_{2FT}(m_H, m_F - 1, m_G) - V_{2FT}(m_H, m_F, m_G)}{\alpha_{2F} f_{2F} P_F Y_F} \right)^{\frac{1}{\gamma_{2F}-1}}. \tag{G.4}$$

Then given the policy functions at $T - \Delta t$ and guessed variables, solve for the value functions:

$$\begin{aligned}
&V_{icT-\Delta t}(m_H, m_F, m_G) \\
&= \max_{x_{icT-\Delta t} \in [0, \bar{x}]} \{ \Delta t [\Pi_{icT-\Delta t}(m_H, m_F, m_G) P_{cT-\Delta t} Y_{cT-\Delta t} - P_{cT-\Delta t} R_{ijcT-\Delta t}] + \exp(-r_{HT}\Delta t) \{ \\
&\Delta t \cdot [(x_{1HT-\Delta t} + \iota \cdot \mathbb{1}_{m_G<0})(V_{icT}(m_H + 1, m_F, m_G + 1) - V_{icT}(m_H, m_F, m_G)) \\
&+(x_{2HT-\Delta t} + \kappa + \iota \cdot \mathbb{1}_{m_G<0})(\phi_H V_{icT}(0, m_F, m_G) + (1 - \phi_H) V_{icT}(m_H - 1, m_F, m_G) - V_{icT}(m_H, m_F, m_G)) \\
&+(x_{1FT-\Delta t} + \iota \cdot \mathbb{1}_{m_G>0})(V_{icT}(m_H, m_F + 1, m_G - 1) - V_{icT}(m_H, m_F, m_G)) \\
&+(x_{2FT-\Delta t} + \kappa + \iota \cdot \mathbb{1}_{m_G>0})(\phi_F V_{icT}(m_H, 0, m_G) + (1 - \phi_F) V_{icT}(m_H, m_F - 1, m_G) - V_{icT}(m_H, m_F, m_G))] \\
&+ V_{icT}(m_H, m_F, m_G) \}.
\end{aligned} \tag{G.5}$$

Repeat the above and solve innovation decision and value function of firms backwards until $t = 1$.

Fourth, suppose at $t = 1$, $Q_{H1} \equiv \bar{Q}_1$. Given the sequence of innovation decisions and the evolution of the firm distribution, start from $t = 1$ to obtain the distribution of firms over technology gaps and the sequence of growth rates $g_{ct}, c \in \{H, F\}$ over the transition as well as aggregate variables. Of note, the aggregate productivity growth rate in a non-stationary equilibrium is a weighted average of firm-level productivity growth rate.

Fifth, check if the guessed path of wages, interest rate, and PY are consistent with the labor market clearing condition in each country, balanced trade condition, and household Euler equations in each country. If not, update the paths of wages, interest rate, and PY using the implied sequence of paths the from market clearing conditions. Repeat from step 3 until the guessed paths converge.

G.3 Targeted and Non-Targeted Moments

This section lists the regression results in the data and model for disciplining how firms' innovation rates vary with the domestic technology gap and global technology gap in the model. The regression coefficients for all firms are targeted moments, and those for leaders and followers separately are non-targeted moments.

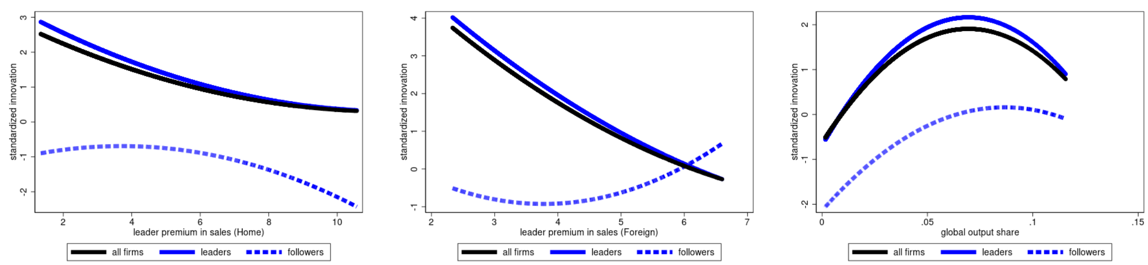
Table G.1 shows the regression results in the model are quantitatively similar to the data. Figure G.1 uses the data regression coefficients in Table G.1 to plot how the standardized number of patent citations varies with the revealed domestic technology gap (leader premium in sales of a country (denoted by OECD) and other countries (denoted by ROW)), as well as the revealed global technology gap (country's global output share), given the average level of the other two measures. This shows that as the revealed domestic technology gap increases, both leaders and followers have less patents while there is an inverted-U shape over the revealed global technology gap. Leaders have higher standardized number of patent citations than followers.

Table G.1: Number of Patent Citations (Data) and Innovation Rate (Model)

	Targeted		Non-Targeted			
	all firms		leaders		followers	
	data	model	data	model	data	model
OECD leader premium	-0.495***	-0.435	-0.557**	-0.545	0.274***	0.226
	(0.163)		(0.243)		(0.067)	
ROW leader premium	-1.803***	-0.962	-1.804**	-1.018	-1.516***	-1.919
	(0.573)		(0.862)		(0.235)	
OECD global output share	72.973**	69.986	82.235	99.717	53.052***	54.480
	(34.657)		(51.100)		(13.764)	
OECD leader premium^2	0.021	0.014	0.024	0.034	-0.037***	-0.029
	(0.019)		(0.028)		(0.008)	
ROW leader premium^2	0.096	0.079	0.089	0.077	0.201***	0.123
	(0.065)		(0.097)		(0.029)	
OECD global output share^2	-525.275**	-340.623	-592.409*	-583.952	-306.123***	-215.354
	(216.453)		(316.514)		(89.360)	
Obs.	8,908,710		434,132		8,420,064	
Adjusted R^2	.75	0.66	.74	0.73	.65	0.49
Country-Year FE	Yes		Yes		Yes	
Industry FE	Yes		Yes		Yes	
Firm FE	Yes		Yes		Yes	

Notes: This table presents results from equation (4.1) in both the data and the model. The explanatory variable is the standardized innovation rate. In the data it is measured by the standardized number of patent citations in 1999-2004. In the model it is measured by the standardized innovation rate in initial BGP. The regression is weighted by firm sales. * $p < 0.10$, ** $p < 0.05$,*** $p < 0.01$.

Figure G.1: Standardized Number of Patent Citations (Data)



(a) OECD leader premium in sales (b) ROW leader premium in sales (c) OECD global output share

Notes: This figure presents the targeted and non-targeted regression coefficients for all firms, leaders, and followers in the data in the 1990s. The black solid line represents all firms. The blue solid line represents leaders and the blue dashed line represents followers. The X-axis in each panel denotes the leader premium in sales in Home (OECD) and Foreign (ROW) and the OECD global output share, respectively. The Y-axis denotes the standardized number of patent citations in the data.