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Innovation and Trade Policy in a Globalized World

Ufuk Akcigit, Sina T. Ates and Giammario Impullitti

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Centre for Economic Policy Research
33 Great Sutton Street, London EC1V 0DX, UK
Tel: +44 (0)20 7183 8801
www.cepr.org

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JEL Classification: F13, F43, F60, O40

Keywords: economic growth, innovation policy, Open economy, trade policy

Ufuk Akcigit - uakcigit@uchicago.edu
University of Chicago and CEPR

Sina T. Ates - sina.t.ates@frb.gov
Federal Reserve Board

Giammario Impullitti - giammario.impullitti@nottingham.ac.uk
University of Nottingham and CEPR

Innovation and Trade Policy in a Globalized World*†

Ufuk Akcigit
University of Chicago, NBER, CEPR

Sina T. Ates
Federal Reserve Board

Giammario Impullitti
University of Nottingham, CEP, CEPR

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†E-mail addresses: uakcigit@uchicago.edu, sina.t.ates@frb.gov, Giammario.Impullitti@nottingham.ac.uk.

1 Introduction

During the past presidential term in the United States, a heated debate centered on the position of the United States in its trade relationships. President Donald J. Trump's speeches focused, among other issues, on the United States losing its security and competitiveness to other major economic players in the world. A favored, and widely discussed, policy suggestion was raising barriers to international trade. Finally, on March 9, 2018, the United States imposed tariffs on certain imports. Only three weeks after the implementation of U.S. tariffs, on April 2, China retaliated by imposing tariffs on various U.S. products.

Similar concerns were raised three decades ago, during the 1970s and early 1980s, following the U.S. exposure to a remarkable convergence by advanced countries such as Japan, Germany, and France, in terms of technology and productivity (see Figure 1). This generated extreme concern in U.S. policy circles, most notably the Ronald Reagan administration. As opposed to the recent focus on protectionist measures, the policy mix adopted by the Reagan government introduced a research and development (R&D) tax credit scheme in 1981 for the first time in U.S. history.[1] Part of a broader set of industrial policies aimed at improving the competitiveness and innovativeness of U.S. firms in a more challenging global economy, these subsidies lasted for the full length of Reagan's administration and beyond (Mowery and Rosenberg, 1993).[2]

Why should countries respond to increasing foreign competition? What is the scope for domestic innovation policy? To shed light on these questions at the center of recurring political and academic debates, this paper presents a new open-economy endogenous growth model and employs it to perform policy analysis. The key theoretical goal is to analyze the impact of globalization, both as foreign technological catching up and an increase in trade openness, on the scope for domestic innovation policy. The analysis unveils new links between globalization and the key market distortions motivating policy intervention in support of innovation. The framework is then used for an evaluation of the Research and Experimentation Tax Credit introduced in 1981. A counterfactual protectionist scenario is also considered to present a comparison of between *trade* and *innovation* policies as alternative responses to stronger foreign competition.

We begin providing a new set of empirical facts that motivate our analysis and guide the model construction. As illustrated in Figure 1, the United States performed poorly relative to its main competitors in terms of labor productivity and innovation in the second half of the 1970s. The average growth in output-per-hours-worked in manufacturing was the lowest in the

[1] In his first term, Ronald Reagan also passed some protectionist measures in the face of a severe recession, a significant appreciation of the dollar, and increasing foreign competition from Japanese and European firms (e.g., an emblematic 49% duty on Japanese motorcycles). But at the same time, Reagan implemented policies to open borders, and in his second term, his trade policy agenda had shifted drastically away from protectionism (Irwin, 2017).

[2] Similar measures included the reinforcement of the protection of intellectual property rights, the promotion of the transfer of military technologies to commercial applications, and the extension of procurement contracts by agencies from NASA to the Department of Defense, aimed at creating markets of an appropriate size to encourage firms to make risky investments in innovation.

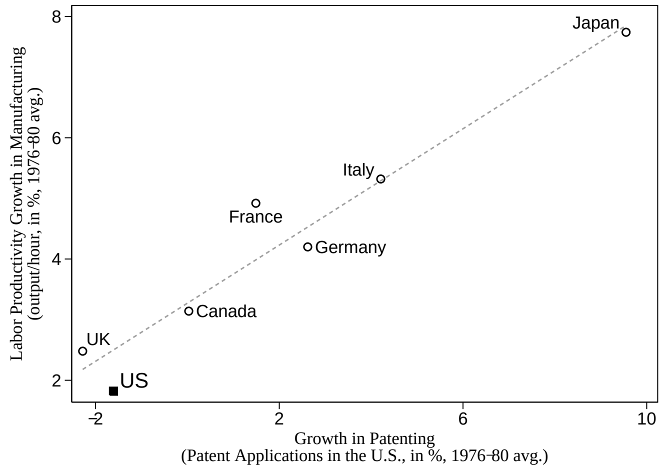


Figure 1: Convergence between the United States and its peers

Notes: The figure shows the relationship between growth of average labor productivity in the manufacturing sector and growth in the number of patent applications for the United States and its major trading partners between 1976 and 1980. We obtain data on patent applications in the United States from the USPTO and on international productivity comparisons from Capdevielle and Alvarez (1981).

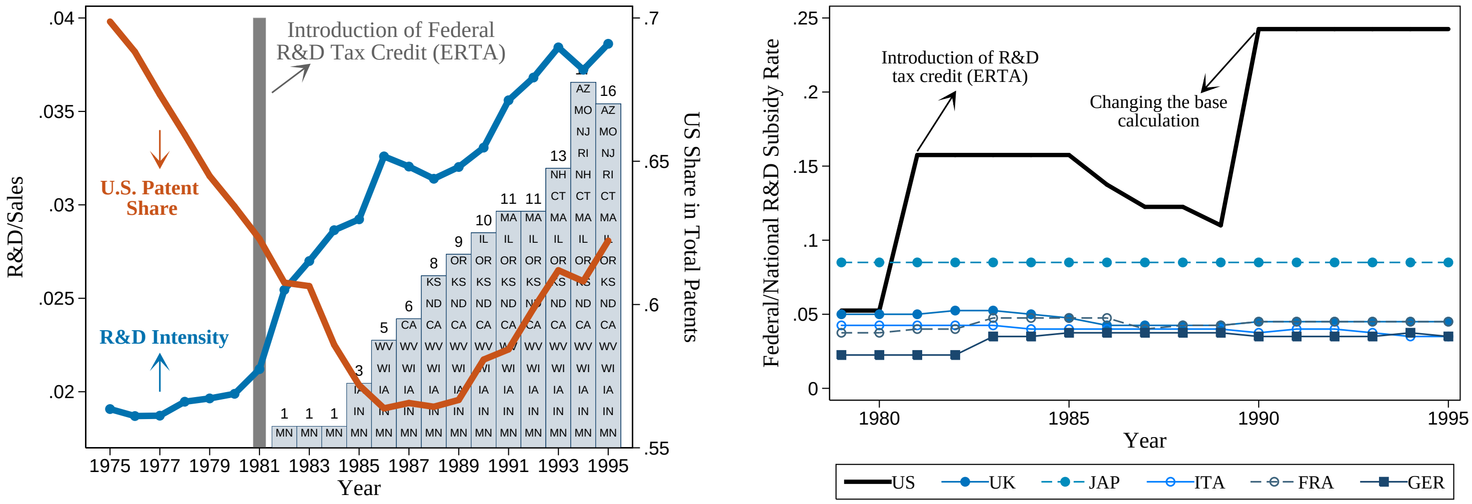
United States. Moreover, foreign innovation, proxied by new patent applications registered in the United States by the residents of these foreign countries, expanded substantially except for the United Kingdom. The figure also reveals that the largest growth rates in patent applications have been recorded by those countries whose labor productivity growth in manufacturing most outpaced the United States. Strikingly, patent applications by U.S. residents actually declined in absolute terms during the same period. United States Patent and Trademark Office (USPTO) data reveal that the ratio of foreign patents to total patents doubled between 1975 and 1985.[3] While the United States held 70 percent of the patent applications in 1975, ten later years this share declined to around 55 percent.[4]

Concerns over U.S. competitiveness in those years led to the introduction of a set of demand- and supply-side policies explicitly targeting incentives for innovation. One of those was the introduction of the R&D tax credits at the federal level in 1981, immediately followed by individual states' actions. Upon these policy changes, aggregate R&D intensity of U.S. public firms showed a dramatic increase, indicated by the blue line in Figure 2a. With an expected delay, the annual share of patents registered by U.S. residents in total patent applications increased as well, as denoted by the orange line in the same figure.[5] Starting in 1982 with Minnesota, several states followed suit by introducing state-level R&D tax credits (Figure 2a). In contrast, there was no significant action in R&D policies for the other major countries (Figure 2b).

[3]See Figure A.1 in Appendix A.1. This section gives a further account of the empirical findings on international technological competition and the relevant policies during the period of interest.

[4]Similar trends are found in countries' share of global R&D at the sectoral level (see Impullitti, 2010). For a historical account of the dynamics of the U.S. technological leadership and the Japanese and European convergence, see Nelson (1990).

[5]Information on sales and R&D expenditures of U.S. public firms are obtained from the Compustat database.



A) R&D and innovation intensity of the U.S. firms

B) Effective R&D tax credit rates across countries

Figure 2: Dynamics of the gap distribution and the identification of ϕ

Notes: Panel A shows the evolution of aggregate R&D intensity (defined as the ratio of total R&D spending over total sales) of the public U.S. firms listed in the Compustat database, and the share of patents registered by U.S. residents in total patents registered in the USPTO database from 1975 to 1995. The ratios are calculated annually. The bars show the total number of U.S. states with a provision of R&D tax credits, along with their names, for every year since the first adoption of such a measure in 1982. Panel B depicts effective R&D subsidy rates in the United States and its major trading partners from 1979 to 1995 (unavailable for Canada). Following Impullitti (2010), R&D subsidies are calculated using corporate tax data from Bloom et al. (2002), who take into account different tax and credit systems. The subsidies reflect key features of the tax system aimed at reducing the cost of R&D, particularly depreciation allowances and tax credits for R&D expenditures. This structure is responsible for the positive value of our subsidy measure initially. For more details, see Impullitti (2010).

A sensible quantitative analysis of the economic processes presented above necessitates an open-economy framework where economic growth is shaped by the interplay of innovation and technological convergence. Accordingly, we build a two-country framework featuring innovation-driven growth and technological convergence. Our framework builds on the *step-by-step* innovation models of Schumpeterian creative destruction, which allow for strategic interaction among competitors. In both countries, final-good firms produce output by combining a fixed factor and a set of intermediate goods, sourced from domestic and foreign producers. In each intermediate sector, a home and a foreign firm compete for global market shares and invest in R&D to improve the quality of their product. Endogenous entry by a fringe of domestic and foreign firms creates an additional source of competitive pressure on both leaders and followers in each product line.

The open-economy dimension of our model redefines firms' incentives to innovate that are typical of the standard step-by-step models. The key driver of innovation in the closed-economy step-by-step framework is the *escape-competition effect*, in which the leader firm has an incentive to move away from the follower in order to escape competition. One of the novel implications of our open-economy model is that two such effects arise in a similar spirit. In each line, firms from both countries compete to serve the domestic and foreign market. Innovation generates a ranking of the product lines based on the quality difference between the home firm and the foreign firm. Trade costs generate quality cutoffs that partition the product space into exporting and non-exporting firms, and export status is regulated by firms' productivity *relative* to their foreign competitors. When the (cost-adjusted) quality of domestic intermediate goods in country c is too inferior relative to its foreign counterpart, final-good producers in country c decide to source their intermediate goods from abroad, which determines country c's *import cutoff*. Likewise, if the relative quality of the domestic producer in country c is above a certain threshold, the foreign final-good producers decide to import from the intermediate-good producer in country c, which specifies the *export cutoff* on the relative quality for country c. As in the standard Ricardian model, the presence of variable trade costs (iceberg and tariffs) regulates the set of non-traded goods between the two cutoffs. Differently from the standard framework, comparative advantage is endogenous and driven by quality-improving innovation.

The key feature of these two cutoffs is that innovation efforts intensify around them due to increased competition. Just below the import cutoff, domestic firms exert additional effort to gain their leadership in the home market; hence, we name it the *defensive R&D* effort. Likewise, when a domestic firm is just below the export cutoff, it exerts additional effort to improve its lead and conquer the foreign market. We call this effort the *expansionary R&D* effort. These two new effects generate a double-peaked R&D effort distribution over the relative quality space that, remarkably, is also supported in the USPTO patent data. From a policy point of view, the distinction between defensive and expansionary R&D is crucial, as they generate different responses to alternative industrial policies.

In our setting, countries are structurally similar, except for policy choices, and for historical reasons there is an initial technology gap which skews the distribution of technology and market leadership in favor of a country. Decreasing returns to R&D drive cross–country convergence in leadership along the transition to the steady state. Countries' incentives to subsidize or tax R&D depend on the typical distortions present in Schumpeterian growth models. The presence of *intertemporal knowledge spillovers* implies that the current innovators do not internalize the benefit of their success for future innovators, causing an underinvestment in innovation, and thus provide a motive for subsidies. Unlike in the standard closed-economy model, though, *business-stealing effect* does not necessarily cause an overinvestment in innovation: domestic firms steal from foreign firms, not domestic competitors. These motives and the effect of policies on innovation incentives of domestic firms shape the optimal policy implications of our analysis.

We parameterize the model to match key trade, innovation, and growth facts in the late 1970s and reproduce the evolution of global leadership in those years, with the United States initially representing the technological frontier in most sectors, while a set of European countries plus Japan lag behind. The transitional dynamics of the model reproduces the convergence in technological leadership observed in the patent data during the 1970s and early 1980s. We validate our model's mechanism with a rich set out-of-sample tests. Simulating the model beyond the calibration period, we examine the dynamics of foreign technological convergence—a mode of globalization not widely explored in the literature—in the absence of policy interventions. In particular, we demonstrate the significant deterioration in the positions of U.S. firms in international technological competition that would have arisen in the absence of any policy intervention. With loss in technological leadership comes loss in profits that shift from U.S. to foreign firms.

In regards to policy evaluation, we first feed the model the increase in R&D subsidies observed in the U.S. in the early 1980s and assess its welfare properties over a period of intensifying foreign competition. The average effective U.S. R&D subsidy increases from about 5 percent in the 1970s to approximately 19 percent in the post-1981 period. This subsidy increase generates small losses in the short to medium run and substantial gains in the long run. The losses are due to the cost of the subsidy and the positive effect on wages which worsens firms' competitiveness along that margin. The gains stem from the reduced cost of R&D for U.S. firms stimulating their innovation and thereby accelerating productivity growth. In addition, the resulting acceleration of U.S. firms' product quality improvements boosts their competitiveness, helping them recoup global leadership and thereby shifting profits back home. Over the three decades following the subsidy increase, there is 0.4 percent consumption equivalent welfare gain per year, driven by profit shifting and especially by innovation-induced productivity growth.

Next, we consider a counterfactual scenario where in the period of growing foreign competition the U.S. raises import tariffs instead of introducing the subsidy to R&D. A rise in tariffs has the benefit of taming the profit shifting caused by foreign catching-up. This benefit is overturned by mainly two counteracting forces. First, there is the negative effect on aggregate productivity of replacing better-quality imported goods with inferior domestic counterparts. Second, protective measures reduce incentives for domestic firms in import-competing sectors to innovate, as lower foreign competition makes survival on their own market easier. As time goes by, this force becomes more dominant and leads to substantial drops in welfare in the long run.

Further qualitative and quantitative results emerge from our analysis of the optimal innovation and trade policy. To begin, the optimal R&D subsidy is increasing with the horizon of the policy maker. The main reason for this result is that the benefits of R&D subsidies in terms of higher product quality levels materialize over time. Firms do not internalize the intertemporal spillovers that their innovations create: future domestic innovation builds on the quality level improved by current innovations, which determines both the aggregate productivity and the competitiveness of domestic firms in the future. Since the gains from R&D subsidies, which stimulate innovation and correct for the underinvestment, materialize and cumulate as time passes, the optimal level of R&D subsidies rises as the horizon of the policy maker lengthens. Indeed, we find that the optimal subsidy rate is substantially higher than the observed change if the horizon in consideration is about three decades.

A salient finding is that the optimal R&D subsidy is decreasing in trade openness, measured by a multilateral reduction in import tariffs. In our model, foreign competition induces firms to increase their innovation, in order to either protect their turf (defensive) or expand into export markets (expansionary). Around the domestic and export cutoff the private incentive to innovate is stronger. Away from these cutoffs, conquering a market is harder, keeping it is easier; thus, innovation is discouraged and the need for public support is stronger. Trade liberalization decreases the distance between these cutoffs, making a larger set of domestic firms subject to stiffer foreign competition and incentivizing them to innovate. If the mass of these firms around the new cutoffs is large enough, trade liberalization has a strong effect on aggregate innovation thereby improving the alignment between private and public incentives to R&D and reducing the need for aggressive subsidies.[6] That said, while the effect of trade on innovation and growth is positive in our benchmark calibration, counterfactual analysis provides examples of the non-monotonicity of this relationship.

Finally, the optimal unilateral tariff is zero in both the short and the long run. As discussed above, trade protection slows down productivity growth weakening the incentives to innovate. The dynamic welfare losses produced by lower growth more than offset the potential gains via terms of trade manipulation, relocation, and profit-shifting, which motivate unilateral tariff protection in static trade models. We also show that the joint optimal U.S. trade and innovation policy requires positive R&D subsidies, increasing in the policy horizon, and zero tariff at any horizon.

Literature Review

The endogenous technical change framework that we use as the backbone of our economy is a model of growth through step-by-step innovation as in Aghion et al. (2001, 2005) and the latest developments by Acemoglu and Akcigit (2012). Because of the strategic interaction among firms, this framework proves particularly useful to study the nexus of competition and innovation. Yet the extant applications are analyzed in steady state, also abstracting from free entry. We propose the first open-economy version, introduce free entry, solve for its transition path, and perform policy analysis.

The paper is closely related to the literature on innovation policy and R&D subsidies in particular. Bloom et al. (2019) provide a recent survey of the empirical work in this literature. The econometric estimates reviewed uncover large positive gaps between social and private returns to R&D, motivating government intervention to correct the relevant market failures. Segerstrom

[6] This result connects our paper to another recent policy event. After the Brexit vote, the UK government has launched a new "industrial strategy" aimed at boosting productivity via investment in innovation and skilled workforce UK-Government (2017). Our finding provides an economic rationale for this decision to complement the increased trade barriers that any Brexit deal will entail with an industrial policy to prop up innovation and productivity growth. However, replacing the innovation incentive that is produced by market openness with tax cuts and other subsidies has important implications for the public finances. Trade openness has a small impact on the budget of the government, as the remaining trade barriers are mostly non-tariff, while tax cuts and subsidies can be very costly and less affordable for economies facing larger debt burdens.

(1998) and Jones and Williams (2000) isolate the key distortions leading to sub-optimal innovation in endogenous growth models: non-appropriability of knowledge, (intertemporal) knowledge spillovers, business stealing (or creative destruction), and congestion externalities. Jones and Williams (2000) show that intertemporal knowledge spillovers dominate quantitatively, suggesting that it is optimal to subsidize R&D. Bloom et al. (2013), using a panel of U.S. firms, estimate the business stealing and the knowledge spillover externalities showing that the latter quantitatively dominates, so that the gross social returns to R&D are at least twice as high as the private returns.

The recent quantitative analysis of innovation policy in a closed economy is also a relevant reference for our work. Acemoglu et al. (2018) study the effect of taxes and R&D subsidies in a version of the Klette and Kortum (2004) model where firms have heterogeneous innovation efficiency. Akcigit et al. (2016a) analyze optimal subsidies to basic and applied research in this class of models. Akcigit et al. (2016b) study the optimal design of corporate taxation and R&D subsidies when firms' heterogeneous R&D productivity is private information. Atkeson and Burstein (2019) analyze aggregate implications of innovation policy in a general model of endogenous growth that nests earlier canonical frameworks. In a closed economy version of step-by-step models, whose broader applications receive attention more recently, Akcigit and Ates (2019) analyze the effects of R&D subsidies along with other factors on business dynamism and market power. We contribute to this line of work analyzing the impact of globalization, both as foreign technological catching up and increase in trade openness, on the effectiveness and optimality of innovation subsidies.

We make contact with theoretical literature on trade and growth. Our paper is particularly related to the work on endogenous comparative advantage. Grossman and Helpman (1990) show that in an open economy version of Romer (1990), trade liberalization increases growth if it promotes innovation in the country with comparative advantage in R&D. If knowledge spillovers are stronger domestically, comparative advantage can be acquired and there is scope for R&D policy intervention.[7] Eaton and Kortum (2001) nest the Ricardian trade model of Eaton and Kortum (2002) into the semi-endogenous growth model of Kortum (1997).[8] In this particular model, innovation is efficient and trade leaves both the growth rate and the innovation level unaffected. In a multi-sector version of this class of models and replacing random research with research directed to a particular sector, Somale (forthcoming) obtains level effects of trade on innovation which generate a positive, albeit small, welfare contribution to the gains from trade. In Cai et al. (forthcoming), trade increases long-run growth via technology diffusion (as in Eaton and Kortum, 1999), producing substantial dynamic welfare gains.[9]

[7] In a related framework, Sampson (2020) analyzes the role of cross-country differences in R&D efficiency and cross-sectoral difference in knowledge spillovers in shaping global income inequality.

[8] Semi-endogenous refers to a class of models where long-run growth is exogenous and shocks and policies can only have level effects in the long run. See Jones (2005) for a recent review of this literature.

[9] Technology diffusion is also the main driver of the dynamic gains from trade in the exogenous growth model of

Our first contribution to this literature is to consider the transitional dynamics, which allow for a rigorous computation of the welfare effects of policies and the analysis of optimal policies across different horizons of the policy maker.[10] Second, unlike these models, in our step-by-step framework, the effect of trade on innovation and growth can be non-monotonic. As such, our framework provides a more flexible ground for the quantitative analysis of changes in foreign competition, with both the sign and the size of the effect of trade on growth being disciplined by the data. Using sector-level UK data, Aghion et al. (2005) find an inverted-U relationship between competition and innovation.[11] Bloom et al. (2016) find a positive effect of Chinese import penetration on innovation and technical change in 12 European countries. Autor et al. (2020) show that Chinese import penetration has a negative impact on U.S. firms' patenting, especially for less profitable firms. Aghion et al. (2017) instead analyze the effect of an export shock on French firms patenting decisions and find on average a positive impact of export on innovation. Building on the step-by-step models of innovation, our framework encompasses the nexus of competition, innovation, and trade openness reflected by this broad set of empirical findings.

Despite the tight link between trade and growth, little research has been devoted to analyze innovation policies in open economy. Here lies the key contribution of our paper. Grossman and Helpman (1990) show that R&D subsidies are more effective if used in countries with comparative advantage in innovation. But when knowledge spillovers are partially local, R&D subsidies can be used to generate comparative advantage in R&D. Grossman and Helpman (1991a) use a similar framework to characterize the optimal R&D subsidy for a small open economy, as well as analyzing the growth and welfare effects of trade policy. We contribute to this literature analyzing the *interaction* between changes in trade openness and optimal innovation policy.[12]

Finally, our counterfactual analysis of the import tariffs contributes to the optimal trade policy literature. In standard trade models, the typical motives for a country to unilaterally impose an import tariff are: terms of trade manipulation (e.g. Gross, 1987), relocation effects (e.g. Ossa, 2011), and profit shifting (e.g. Ossa, 2012). In our model, all these distortions justifying

Buera and Oberfield (2020). Perla et al. (forthcoming) and Sampson (2016) find large dynamic gains from trade due to the effect of openness on technology adoption and domestic knowledge diffusion, respectively. Innovation, instead, is the main driver of substantial dynamic gains from trade in Impullitti and Licandro (2018).

[10] Most of the extant literature focuses on the steady state, as the state space in multi-country, multi-sector models is very large making the transitional dynamics computationally challenging. A rare recent exception is Perla et al. (forthcoming), who analyze transitional dynamics in a one-sector, symmetric-country, model.

[11] A similar analysis for the U.S. reports a negative relationship (Hashmi, 2013). Other firm-level analyses confirm the inverted U-shape relationship for large firms in France (Askenazy et al., 2013), while a positive relationship is found in Spanish data (Beneito et al., 2015). Aghion et al. (2009) suggest that foreign entry encourages innovation for firms in technological advanced industries and discourages it for firms in laggard sectors.

[12] Impullitti (2010) analyzes the link between foreign technological competition and optimal R&D subsidies in the steady state of a two-country quality ladder model without trade costs. In a New Economic Geography model, Baldwin and Krugman (2004) show that as trade costs fall agglomeration forces become stronger thus making tax competition to attract firms/capital less fierce. In our model, the key force shaping the interaction between trade integration and public policy is not agglomeration but knowledge spillovers.

a positive optimal tariff are present, but a key additional dynamic distortion drives this result. Tariff protection produces large welfare losses via its discouraging effects on innovation and productivity growth. The growth channel dominates all the standard static channels, leading to a zero optimal unilateral tariff. To the best of our knowledge, this is the first paper studying optimal trade policy in an endogenous growth framework.

The rest of the paper is organized as follows. Section 2 introduces the theoretical framework. Section 3 outlines the calibration procedure and provides out-of-sample tests. Section 4 discusses policy implications and optimal policies and previews the results of sensitivity and robustness analyses. Section 5 presents the model's implications in regard to import competition and domestic innovation. Section 6 concludes.

2 Model

We present a model of international technological competition in which firms from two countries, indexed by $c \in \{A, B\}$, compete over the ownership of intermediate-good production. Each country has access to the same final-good production technology. There is a continuum of intermediate goods indexed by $j \in [0, 1]$ used in final-good production. The final good is used for consumption and innovation. There is no trade in assets, which rules out international borrowing and lending and enables the two countries to grow at different rates during the transition.

In each production line of intermediate goods there are two active firms—one from each country—engaging in price competition to obtain a monopoly of production. In this competition, Ricardian forces of comparative advantage are at play, as intermediate-good firms produce using labor, and relative wages influence their competitiveness. Moreover, trade of intermediate goods is costly due to a combination of iceberg costs and tariffs. The firm that produces the variety of better quality after adjusting for trade and relative production costs holds a price advantage. Firms innovate by investing resources to improve the quality of their product in the spirit of step-by-step models. If the quality difference between the products of two firms is large enough, then the firm with the leading technology can cover the trade cost and export to the foreign country. Because innovation success is random, the global economy features a distribution of firms supplying products of heterogeneous quality. In addition to incumbents, there is an outside pool of entrant firms. These firms engage in research activity to obtain a successful innovation that enables them to replace the domestic incumbent in a particular product line. Introducing the entry margin allows the model to distinguish the effects of domestic and foreign competition.

Finally, our main goal is to investigate the quantitative policy implications of our model. For interested readers, we provide a theoretical discussion of a simplified version of the model and present analytical expressions and results of the main static and dynamic forces in Appendix C.

2.1 Preferences

Consider the following economy in continuous time. Both countries admit a representative household with the following CRRA utility:

$$U_t = \int_t^\infty \exp(-\rho\,(s-t))\,\frac{C_{cs}^{1-\psi}-1}{1-\psi}\,ds, \tag{1}$$

where C_{ct} represents consumption at time t in country c, ψ is the curvature parameter of the utility function, and $\rho > 0$ is the discount rate. The budget constraint of a representative household in country c at time t is

$$r_{ct}A_{ct} + L_c w_{ct} + F_c f_{ct} = P_{ct}C_{ct} + \dot{A}_{ct} + G_{ct}, \tag{2}$$

where L_c is labor that is supplied inelastically for intermediate-good production, F_c is the fixed factor (e.g., land) in country c, and G_{ct} is the lump-sum taxes/transfers.[13] The associated prices are r_{ct}, the return to asset holdings of the household, w_{ct}, the wage level, f_{ct}, the fixed factor income, and P_{ct}, the price of the consumption good in country c. Households in country c own all the firms in the country; therefore, the asset market clearing condition requires that the asset holdings have to be equal to the sum of firm values

$$A_{ct} = \int_0^1 \tilde{V}_{cjt} + V_{cjt}dj,$$

where tilde "~" denotes values pertaining to entrant firms. We assume full *home bias* in asset holding, which is robustly supported by the empirical evidence in the 1980s and 1990s.[14]

2.2 Technology and Market Structure

2.2.1 Final Good

The final good, which is to be used for consumption and R&D expenditure is produced in perfectly competitive markets in both countries according to the following technology:

$$Y_{ct} = \frac{F_c^\beta}{1-\beta}\int_0^1 \left(q_{Ajt}^{\frac{\beta}{1-\beta}}k_{Ajt} + q_{Bjt}^{\frac{\beta}{1-\beta}}k_{Bjt}\right)^{1-\beta} dj. \tag{3}$$

Here, k_j refers to the intermediate good $j \in [0,1]$, q_j is the quality of k_j, and β is the share of fixed factor in total output. Intermediate goods can be obtained from any country, whereas the fixed factor F_c is assumed to be immobile across countries. We normalize the supply of the fixed factor

[13] F_c pins down the scale of the economy and ensures constant returns to scale in the final–good production.

[14] In 1989, 92 percent of the U.S. stock market was held by U.S. residents. Japan, the U.K., France, and Germany show similar patterns, at 96 percent, 92 percent 89 percent, and 79 percent, respectively. A similar picture can be observed until the early 2000s, when the home bias started to decline (see, for example, Coeurdacier and Rey, 2013).

$F_c = 1$ in both countries.

Firms in both countries may potentially produce each variety j. In the absence of trade frictions they are perfect substitutes in the final-good production, once adjusted for their qualities. As a result, final-good producers will choose to buy their inputs from the firm that offers a higher quality of the same variety (after adjusting for relative prices).[15] When trade costs exist, final-good producers buy the intermediate good of higher quality, once the prices are adjusted to reflect the trade costs. Final good producers in both countries have access to the same technology, which will allow us to focus on the heterogeneity of the intermediate-good sector. Both countries produce the same identical final good, which under the maintained assumption of frictionless trade in final goods, implies that the price of the final output in both countries will be the same.[16] We normalize that price to be the numeraire without any loss of generality.

2.2.2 Intermediate Goods and Innovation

Incumbents. In each product line j, two incumbent firms—one from each country—compete for the market leadership à la Bertrand. These firms produce differentiated varieties of the same intermediate good using domestic labor. As such, firms differ in two aspects: (i) the quality of their output, denoted by q_{cj}, and (ii) their marginal costs of production because of differences in productivity and aggregate wages. We first describe the former margin and discuss the latter when formulating the equilibrium.

We say that country A is *the technological leader* in industry j if $q_{Ajt} > q_{Bjt}$ and *the technological follower* if $q_{Ajt} < q_{Bjt}$. Firms are in a *neck-and-neck* position when $q_{Ajt} = q_{Bjt}$. The quality q_{Ajt} improves through successive innovations in A or spillovers from B (detailed later). When there is an improvement in country c specific to product line j during an interval of time Δt, the quality increases proportionally such that $q_{cj(t+\Delta t)} = \lambda^{n_t} q_{cjt}$, where $\lambda > 1$ and $n_t \in \mathbb{N}$ is a random variable, which will be specified below. We assume that initially $q_{cj0} = 1$, $\forall j \in [0, 1]$.

Let us denote by $N_t = \int_0^t n_s ds$ the number of quality jumps up to time t. Hence, the quality of a firm at time t is $q_{cjt} = \lambda^{N_{cjt}}$. The relative state of a firm with respect to its foreign competitor is called the technology gap between two countries (in the particular product line) and can be summarized by a single integer $m_{Ajt} \in \mathbb{N}$ such that

$$\frac{q_{Ajt}}{q_{Bjt}} = \frac{\lambda^{N_{Ajt}}}{\lambda^{N_{Bjt}}} = \lambda^{N_{Ajt} - N_{Bjt}} \equiv \lambda^{m_{Ajt}}.$$

[15] Even in the absence of trade frictions, the prices of intermediate goods from different countries can differ reflecting relative labor costs.

[16] Frictionless trade in final good serves only the purpose of equilibrating the trade balance in both countries. Consequently, there is no trade in final good in autarky—i.e., when there is no trade in intermediate goods (if, e.g, tariffs are prohibitively high). Alternatively, one could assume no trade in final good with the additional equilibrium condition that aggregate trade is balanced, which would determine the relative prices of final goods. However, that would bring an additional level of complexity without much further insight for the core of our analysis, which focuses on the link between the endogenous growth of an economy and its trade openness.

As we shall see, m_{cjt} is a sufficient statistic for describing line-specific values, and we will therefore drop the subscript j when a line-specific value is denoted by m. We assume that there is a sufficiently large but exogenously given limit in the technology gap, $\bar{m}$, such that the gap between two firms is $m_{ct} \in \{-\bar{m}, ..., 0, ..., \bar{m}\}$.[17]

Firms invest in R&D in order to obtain market leadership through improving the quality of their products. Let R^d_{cj} and x_{cj} denote the amount of R&D investment and the resulting Poisson arrival rate of innovation by country c in j, respectively. The production function of innovations takes the following form: $x_{cjt} = \left(\gamma_c \frac{R^d_{cjt}}{\alpha_c q_{cjt}}\right)^{\frac{1}{\gamma_c}}$. Note that q_{cjt} in the denominator captures the fact that a quality is more costly to improve if it is more advanced. This production function implies the following convex cost for generating an arrival rate x_{cjt} :

$$R^d\left(x_{cjt}, q_{cjt}\right) = q_{cjt}\frac{\alpha_c}{\gamma_c}x^{\gamma_c}_{cjt}. \tag{4}$$

Entrants. Every period, a new entrepreneur in each product line and from each country invests in innovation to enter the market. If an entrepreneur succeeds in her attempt, the entrant firm replaces the domestic incumbent; otherwise, the firm disappears. The innovation technology for entrants is $\tilde{x}_{cjt} = \left(\tilde{\gamma}_c \frac{\tilde{R}^d_{cjt}}{\tilde{\alpha}_c q_{cjt}}\right)^{\frac{1}{\tilde{\gamma}_c}}$, which implies the following convex cost function:

$$\tilde{R}^d\left(\tilde{x}_{cjt}, q_{cjt}\right) = q_{cjt}\frac{\tilde{\alpha}_c}{\tilde{\gamma}_c}x^{\tilde{\gamma}_c}_{cjt}. \tag{5}$$

We demonstrate the evolution of leadership in intermediate product lines as a result of incumbent innovation, entry, and exit in Appendix B.1 (see Figure A.4).

Innovations and Step Size. Each innovation improves the relative position of the firm in the technological competition. Conditional on innovation, the new position at which the firm will end up is determined randomly by a certain probability mass distribution $\mathbb{F}_m(\cdot)$.[18] Because the maximum number of gaps is capped by $\bar{m}$, there is a different number of potential gaps that each firm may reach depending on its current position in the technological competition. For instance, if a firm is leading by ten gaps, with a single innovation it can potentially open up the advantage to $\{11, ..., \bar{m}\}$, whereas for a neck-and-neck firm, an innovation can help it reach $\{1, ..., \bar{m}\}$. Hence, the probability mass function that determines the new position, $\mathbb{F}_m(\cdot)$, is a function of m.

In order to keep the model parsimonious, we assume there exists a fixed given distribution $\mathbb{F}(\cdot)$, and we derive $\mathbb{F}_m(\cdot)$ from this distribution in the following way. First, we define the

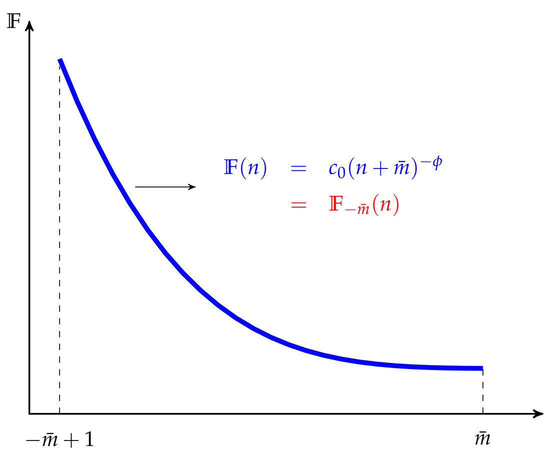
[17] In the baseline calibration, we set $\bar{m} = 16$. In Appendix H, we test the sensitivity of our results to a lower $\bar{m}$ and show that our baseline results remain almost unchanged.

[18] Conversely, each innovation comes with an associated step size that is randomly generated by some probability mass function.

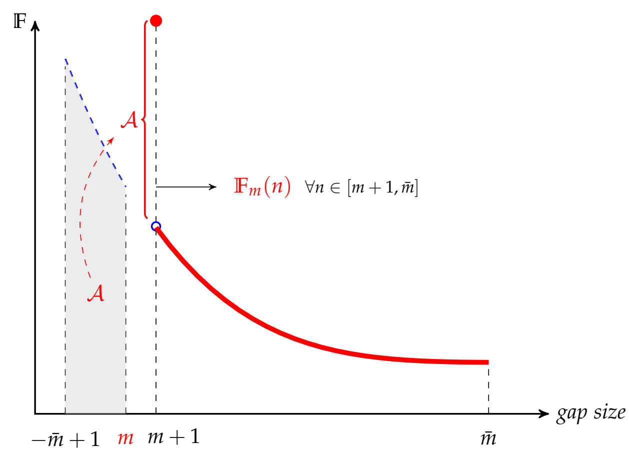
benchmark distribution over positions larger than $-\bar{m}$, the most laggard position, as depicted in Figure 3a. We assume that it has the following functional form:

$$\mathbb{F}(n) \equiv \; c_0 (n + \bar{m})^{-\phi} \quad \forall \, n \in \{-\bar{m}+1, ..., \bar{m}\} \; . \tag{6}$$

This parametric structure is defined by only two parameters: a curvature parameter $\phi > 0$, and a shifter c_0 that ensures $\sum_n \mathbb{F}(n) = 1$. It implies a decaying probability in the new position n. As such, the probability that an innovation generates larger technological jumps is lower.



A) Benchmark



B) At position m

Figure 3: Probability mass function for new position

Notes: Panel A illustrates the function $\mathbb{F}(\cdot)$, defined in equation (6), which we use to generate the position-dependent distributions of innovation size. Thus, it describes also the probability distribution over potential positions, where an innovation can take the most laggard incumbent, denoted by $\mathbb{F}_{\bar{m}}(\cdot)$. Similarly, Panel B illustrates $\mathbb{F}_m(\cdot)$ for a generic position m.

The highest gap size a firm can reach is $\bar{m}$. Therefore, the step size distribution specific to the firm's position, $\mathbb{F}_m(\cdot)$, is defined over positions $n \in \{m+1, ..., \bar{m}\}$ and is derived as follows:

$$\mathbb{F}_m(n) = \begin{cases} \mathbb{F}(m+1) + \mathcal{A}(m) & for \; n = m+1 \\ \mathbb{F}(s) & for \; n \in \{m+2, ..., \bar{m}\} \end{cases} . \tag{7}$$

As demonstrated in Figure 3b, $\mathcal{A}(m) \equiv \sum_{s=-\bar{m}+1}^{m} \mathbb{F}(s)$ is an additional probability of improving the current quality only one more step, on top of what $\mathbb{F}(\cdot)$ would imply for that event, which is given by $\mathbb{F}(m+1)$. This specification for position-specific distributions implies that as firms become technologically more advanced relative to their competitors, it is relatively harder to open up the gap more than one step at a time. Moreover, their derivation comes at no additional cost in terms of parameters thanks to the additive nature of $\mathcal{A}$. Finally, notice that $\mathbb{F}_{-\bar{m}}(n) = \mathbb{F}(n)$.[19]

[19]Reflecting "the advantage of backwardness" (Gerschenkron, 1962), this building block introduces a flexible structure that helps the model mimic the technological convergence between the United States and its competitors observed

During a small time interval $\Delta t \to 0$, the resulting law of motion for the quality level of an incumbent from A that operates in product line j can be summarized as follows. For $m > -\bar{m}$ the law of motion becomes

$$q_{Aj(t+\Delta t)} = \begin{cases} \lambda^n q_{Ajt} \text{ with probability } \left(x_{Ajt} + \tilde{x}_{Ajt}\right) \mathbb{F}_m(n) \Delta t + o(\Delta t) & \text{for } n \in \{m+1, ..., \bar{m}\} \\ q_{Ajt} \quad \text{ with probability } 1 - \left(x_{Ajt} + \tilde{x}_{Ajt}\right) \mathbb{F}_m(n) \Delta t + o(\Delta t) & \end{cases},$$

and for $m = -\bar{m}$ the law of motion follows

$$q_{Aj(t+\Delta t)} = \begin{cases} \lambda^n q_{Ajt} \text{ with probability } \left(x_{Ajt} + \tilde{x}_{Ajt}\right) \mathbb{F}_{-\bar{m}}(n) \Delta t + o(\Delta t) & \text{for } n \in \{-\bar{m}+1, ..., 2\bar{m}\} \\ q_{Ajt} \quad \text{ with probability } 1 - \left(x_{Ajt} + \tilde{x}_{Ajt}\right) \mathbb{F}_{-\bar{m}}(n) \Delta t + o(\Delta t) & \\ \lambda q_{Ajt} \text{ with probability } \left(x_{Bjt} + \tilde{x}_{Bjt}\right) \mathbb{F}_m(n) \Delta t + o(\Delta t) & \end{cases},$$

where $o(\Delta t)$ denotes the second-order terms. In a product line where the incumbent from A is in position m, the quality improves when either the domestic incumbent or entrant innovates. Moreover, the quality in a product line where the firm from A is at the highest possible lag $-\bar{m}$ improves not only with innovations by the domestic incumbent and entrant, but also with those by the foreign incumbent or entrant. In other words, when the leader at gap $\bar{m}$ innovates, the technology at gap $-\bar{m}+1$ becomes freely available to the follower in this product line.

2.3 Equilibrium

In this section, we solve for the Markov Perfect Equilibrium of the model where the strategies are functions of the payoff relevant state variable m. We start with the static equilibrium. Then we build up the value functions for the intermediate producers and entrants and derive their closed form solutions along with the R&D decisions. These variables help us characterize the evolution of the world economy over time. Henceforth, we will drop the time index t unless it causes confusion and denote export-related variables by an asterisk.

2.3.1 Households

We start with the maximization problem of the household. The Euler equation of the household problem determines the interest rate in the economy as: $r_{ct} = g_{ct}\psi + \rho$.

2.3.2 Final and Intermediate Good Production

Next, we turn to the maximization problem of the final good producer in country $c \in \{A, B\}$. Using the production function (3), the final-good producers generate the following demand for

in the data. For a detailed theoretical discussion of this feature, see Appendix B.2.

the fixed factor F_c and intermediate good $j \in [0,1]$:

$$f_{ct} = \frac{\beta}{1-\beta} F_c^{\beta-1} \left(q_{Ajt}^{\frac{\beta}{1-\beta}} k_{Ajt} + q_{Bjt}^{\frac{\beta}{1-\beta}} k_{Bjt} \right)^{1-\beta} \tag{8}$$

$$p_{cjt} = F_c^{\beta} q_{cjt}^{\frac{\beta}{1-\beta}} \left(q_{Ajt}^{\frac{\beta}{1-\beta}} k_{Ajt} + q_{Bjt}^{\frac{\beta}{1-\beta}} k_{Bjt} \right)^{-\beta}. \tag{9}$$

Now we consider the intermediate-good producers' problem. In our open-economy setting, producers can sell their goods both domestically and internationally. However, as trade is subject to iceberg costs, the producer faces different demand schedules on domestically sold and exported goods. Therefore, the producer earns different levels of profits on these goods depending on the destination country. Let us start with the case of domestic business. Intermediate firms produce using labor under the following production function:

$$k_{cjt} = \frac{\bar{q}_{ct}}{\eta} l_{cjt}, \tag{10}$$

where $\bar{q}_{ct}$ denotes the economy-wide productivity level (defined below) and η is a constant. Then, the profit maximization problem of the monopolist in product line j becomes[20]

$$\pi\left(q_{jt}\right) = \max_{k_{jt}\geq 0} \left\{ L_c^{\beta} q_{jt}^{\beta} k_{jt}^{1-\beta} - \frac{\eta}{\bar{q}_{ct}} w_{ct} k_{jt} \right\} \ \forall j \in [0,1].$$

We will denote the wage rate relative to the productivity level as $\bar{\omega}_{ct} = \frac{w_{ct}}{\bar{q}_{ct}}$, which will be an important object in determining prices, quantities, and terms of trade. The optimal quantity and price for intermediate variety j follow from the first order conditions:

$$k_{jt} = \left[\frac{1-\beta}{\eta} \bar{\omega}_{ct}^{-1} \right]^{\frac{1}{\beta}} q_{jt} \quad \text{and} \quad p_j = \frac{\eta}{1-\beta} \bar{\omega}_{ct}, \tag{11}$$

with F_c set to 1. The realized price is a time-varying markup over the marginal cost and is independent of the individual product quality. Thus, the profit earned by selling an intermediate good domestically is

$$\pi_{ct}\left(q_{jt}\right) = \pi \bar{\omega}_{ct}^{\frac{\beta-1}{\beta}} q_{jt},$$

where $\pi \equiv \eta^{\frac{\beta-1}{\beta}} (1-\beta)^{\frac{1-\beta}{\beta}} \beta$. Notice that in deriving profits, we assumed that the monopolist is able to charge the unconstrained monopoly price. Assumption 1 specified below ensures that the leaders are able to act as unconstrained monopolists.

The problem when selling abroad is different due to trade costs. In line with the trade

[20]The monopolist's maximization problem assumes the equilibrium property that a final-good producer buys an intermediate input from one firm only. Therefore, the monopolist producer's demand k_j is given by equation (9) with the amount supplied by the other firm k_{-j} set to zero (see Assumption 1).

literature, we assume that in order to export one unit of an intermediate good, the exporting firm needs to ship $1+\kappa$ units of that good ($\kappa \geq 0$). Moreover, a firm in country A exporting to country B pays import tariffs at rate τ^B, which we model as a cost-shifter à la Costinot and Rodriguez-Clare (2014). This means that when the firm considers meeting the foreign demand, it will take into account that its marginal cost will be $(1+\kappa)\left(1+\tau^B\right)\eta$. Given the trade costs, only the firm with the higher cost-adjusted quality will find it profitable to sell in the other country. Hence, the firm from country A exports intermediate good j to country B if and only if

$$\frac{q_{Ajt}}{\left[(1+\kappa)\left(1+\tau^B\right)\omega_{At}\right]^{\frac{1-\beta}{\beta}}} \geq q_{Bjt},$$

where $\omega_{At} = \frac{\bar{w}_{At}}{\bar{w}_{Bt}}$ denotes the relative productivity-adjusted wage levels in both countries. This condition implies that iceberg costs, the foreign country's tariff rate, and a relatively higher level of productivity-adjusted wage rate at home affect the home country's terms of trade adversely, making it harder for its firms to export. As such, the model features Ricardian comparative advantage, whereby a country that is laggard in most product lines and thus exhibits a low wage rate obtains a relative price advantage.

In this Bertrand competition setting, the existence of a competitor with inferior quality—by definition, located in the foreign country—could potentially push the leader to limit pricing. To simplify the analysis we make the following assumption:

Assumption 1 *In every product line, incumbents enter a two-stage game where each incumbent pays an arbitrarily small fee $\varepsilon > 0$ in the first stage in order to bid prices in the second stage.*

Assumption 1 ensures that only the incumbent with the highest cost-adjusted quality pays the fee and is therefore able to set the monopoly price in the second stage. Under this assumption, similar derivations as in the case of domestic sales lead to the following optimal quantity of exports and associated profits:

$$k^*_{cjt} = \left[\frac{1-\beta}{(1+\kappa)\left(1+\tau^{c'}\right)\eta}\bar{w}_{ct}^{-1}\right]^{\frac{1}{\beta}} L_{c'}q_{cjt} \quad \text{and} \quad p^*_{cj} = \frac{(1+\kappa)\left(1+\tau^{c'}\right)\eta}{1-\beta}\bar{w}_{ct} \Rightarrow \pi^*_{ct}\left(q_{jt}\right) = \pi^*_c \bar{w}_{ct}^{\frac{\beta-1}{\beta}} L_{c'}q_{cjt}, \tag{12}$$

with $c \in \{A, B\}$, $c \neq c'$, and $\pi^*_c = \left[(1+\kappa)\left(1+\tau^{c'}\right)\eta\right]^{\frac{\beta-1}{\beta}}(1-\beta)^{\frac{1-\beta}{\beta}}\beta$.

We denote by m^X_c the smallest gap by which a leader from country $c \in \{A, B\}$ needs to lead its follower in order to be able to export its good.[21] Due to trade costs and differences in production costs, it is possible that an intermediate-good producer has a higher-quality product compared to its foreign competitor (e.g., $q_c > q_{c'}$), but in cost-adjusted terms the quality of its good is lower than the foreign counterpart such that the firm cannot export

[21] Appendix B.3 discusses how positive trade costs determine which goods are traded, and thus, shape the technology frontier of two competing countries.

$\left(q_c/q_{c'} < \left[(1+\kappa)\left(1+\tau^{c'}\right)\omega_{ct}\right]^{\frac{1-\beta}{\beta}}\right)$. To secure a quality advantage even after trade costs are accounted for, the technology gap between a leader and its follower has to reach the threshold

$$m^X_{ct} \equiv \arg\min_m \left\{ m \in [0,\bar{m}] : \lambda^m \geq \left[(1+\kappa)\left(1+\tau^{c'}\right)\omega_{ct}\right]^{\frac{1-\beta}{\beta}} \right\}. \tag{13}$$

It is worth emphasizing that this cutoff depends on ω_{ct}. Therefore, the relative (productivity-adjusted) wage levels of both countries affects the cutoff for exports, capturing the role of comparative advantage. As the relative wage ratio varies over time, so does the cutoff. Reciprocally, the cutoff for imports—conversely, the export cutoff for the foreign country firms—is defined as

$$m^M_{ct} \equiv \arg\max_m \left\{ m \in [-\bar{m},0] : \lambda^m < \left[(1+\kappa)\left(1+\tau^{c}\right)\omega_{ct}^{-1}\right]^{\frac{1-\beta}{\beta}} \right\}. \tag{14}$$

The cutoffs for exports and imports are almost always asymmetric—i.e., $m^X_{ct} \neq |m^M_{ct}|$ almost always holds.

Now we define the quality index of sectors where firms from country c are in state m. Denote the measure of product lines where firms from c are m-steps ahead by μ_{cm}. Then the aggregate quality across these product lines is given by

$$Q_{cmt} \equiv \int q_{cjt} \mathbb{I}_{\{j \in \mu_{cm}\}} dj,$$

with the domestic technology frontier—i.e., the average quality of goods that can be produced domestically—being defined as

$$Q_{ct} \equiv \int_0^1 q_{cjt} dj = \sum_{-\bar{m}}^{\bar{m}} Q_{cmt}. \tag{15}$$

Using the equilibrium conditions derived previously, total output is given as

$$Y_{ct} = \sum_{m=m^M_{ct}+1}^{\bar{m}} \left[\frac{1-\beta}{\eta}\varpi_{ct}^{-1}\right]^{\frac{1-\beta}{\beta}} \frac{Q_{cmt}}{1-\beta} + \sum_{m=-\bar{m}}^{m^M_{ct}} \left[\frac{1-\beta}{(1+\kappa)(1+\tau^c)\eta}\varpi_{c't}^{-1}\right]^{\frac{1-\beta}{\beta}} \frac{Q_{c'mt}}{1-\beta}. \tag{16}$$

The first sum denotes the contribution of domestic intermediate goods. The second sum, which is across product lines where foreign exporters lead domestic firms by at least $|m^M_{ct}|$ gaps, denotes the contribution of imported goods. Equation (8) implies that the fixed factor price is $f_{ct} = \beta Y_{ct}$.

Finally, we assume that the domestic technology frontier determines the aggregate labor productivity in intermediate good production, such that $\bar{q}_{ct} = Q_{ct}$. With that, the labor market condition implies the following wage rate:

$$1=\frac{\eta}{\bar{q}_{ct}}\left[\int\mathbb{I}\left\{m>m_{ct}^{M}\right\}k_{cjt}dj+\int\mathbb{I}\left\{m>m_{ct}^{X}\right\}(1+\kappa)\,k_{cjt}^{*}dj\right]\Rightarrow$$

$$\bar{w}_{ct}^{\frac{1}{\beta}}=\frac{\eta}{\bar{q}_{ct}}\left[\frac{1-\beta}{\eta}\right]^{\frac{1}{\beta}}\underbrace{\left[\sum_{m_{ct}^{M}}^{\bar{m}}Q_{cmt}+\frac{(1+\kappa)}{\left[(1+\kappa)\left(1+\tau^{c'}\right)\right]^{\frac{1}{\beta}}}\sum_{m_{ct}^{X}}^{\bar{m}}Q_{cmt}\right]}_{denote\ \mathcal{Q}_{ct}}\Rightarrow\bar{w}_{ct}=\frac{1-\beta}{\eta}\eta^{\beta}\left[\frac{\mathcal{Q}_{ct}}{Q_{ct}}\right]^{\beta}. \tag{17}$$

We complete the description of equilibrium properties of goods' production with their implications for trade flows. The final good is freely traded and it absorbs possible imbalances in intermediate-goods trade. Hence, trade in this economy is balanced, and the changes in the relative prices w_{At}/w_{Bt} and f_{At}/f_{Bt} drive the adjustment.

2.3.3 Firm Values and Innovation

We can write the value function for country A's incumbents in the following way:[22]

$$\begin{aligned}r_{At}V_{Amt}(q_t)-\dot{V}_{Amt}(q_t)=\max_{x_{Amt}}\Bigg\{&\Pi_t\left(m;\tau^{A},\tau^{B}\right)\bar{w}_{ct}^{\frac{\beta-1}{\beta}}q_t-\left(1-s^{A}\right)\alpha_A\frac{(x_{Amt})^{\gamma_A}}{\gamma_A}q_t\\&+x_{Amt}\sum_{n_t=m+1}^{\bar{m}}\mathbb{F}_m(n_t)\left[V_{Ant}\left(\lambda^{(n_t-m)}q_t\right)-V_{Amt}(q_t)\right]+\tilde{x}_{Amt}\left[0-V_{Amt}(q_t)\right]\\&+\left(x_{B(-m)t}+\tilde{x}_{B(-m)t}\right)\sum_{n_t=-m+1}^{\bar{m}}\mathbb{F}_{-m}(n_t)\left[V_{A(-nt)}(q_t)-V_{Amt}(q_t)\right]\Bigg\},\end{aligned} \tag{18}$$

where $\Pi\left(m;\tau^{A},\tau^{B}\right)$ is defined as

$$\Pi_t\left(m;\tau^{A},\tau^{B}\right)=\begin{cases}\pi L_A+\pi^{*}L_B & if\quad m\geq m_{At}^{X}\\ \pi L_A & if\quad m_{At}^{X}>m>m_{At}^{M}\\ 0 & if\quad m\leq m_{At}^{M}\end{cases}.$$

Note that the profit level depends on foreign tariffs because profits from exports, derived in equation (12), are affected by it. Also, domestic tariffs affect profits protecting some firms.

The first line on the right-hand side denotes the operating profits net of R&D costs, where s^{A} is the R&D subsidy. Profits are linear in product quality, creating an incentive for innovation even for firms at the largest lead. As is evident from the definition of $\Pi_t\left(m;\tau^{A},\tau^{B}\right)$, capturing the domestic market or expanding into foreign markets adds to profits, thereby intensifying the incentives to innovate. Expansion of markets through exports reflects the *market-size effect*. The second line denotes the expected gains from innovation. This expectation is over potential new

[22] In equilibrium, m is a sufficient statistic for firm value. Lemma 1 at the end of this subsection verifies this result. Accordingly, we replace subscript j with m unless otherwise necessary.The problem for incumbent firms from country B is defined reciprocally.

positions. The exact position is determined probabilistically by the step size of innovation. For firms that are close to their rivals and, thus, feel the competition at its most intense, the innovation effort reflects a dominant incentive for taking over the competitor in order to gain market power. This is an *escape-competition effect* typical of step-by-step innovation models. A distinguishing feature of our model, however, is that this force emerges at two distinct positions instead of a single one as is typical of closed-economy versions. The first case is when a laggard firm is one-step behind short of beating the foreign exporter and gaining access to domestic production. This leads to an intense innovation activity by the laggard firm, which we label as *defensive R&D*. Second, a similar intensification happens when a domestic producer is one step short of gaining access to export markets, in which case *expansionary R&D* is observed. We further discuss this extension of the *escape-competition* effect across multiple stages of competition—in particular, over domestic and foreign markets—in Section 3.2 by confronting the model with the data.

The remaining components capture the creative destruction by domestic and foreign competitors. The second part of the second line reveals that entry by domestic firms forces the incumbent to exit with probability one, as by construction every product line is forced to have one firm from each country. This domestic *business-stealing effect* reduces the value of an incumbent firm and therefore its incentive to innovate. Moreover, in an open economy, there is an additional channel through business stealing. The last line explains the changes as a result of innovation in the foreign country. Any innovation there, regardless of the source being an entrant or an incumbent, deteriorates the position and the value of the domestic incumbent; and the size of the deterioration is again determined probabilistically by $\mathbb{F}_{-m}(\cdot)$.[23] We label this additional channel as the *international business-stealing effect*.[24]

The firms' problems are characterized by an infinite-dimensional space of intermediate-good qualities. The following lemma renders the firm environment independent of the current quality of their products, reducing the state space to finite dimensions.

Lemma 1 *The value functions are linear in quality such that $V_{cm}(q) = qv_{cm}$ for $m \in \{-\bar{m}, ..., \bar{m}\}$. This ensures that the innovation decision of the firm is independent of j once controlled for m.*

Proof. See Appendix B.4 for the derivation and the definition of v_{cm}. ■

The first order conditions of the problems defined above yield the following equilibrium

[23] The distribution function is labeled with the subscript $-m$ because it is associated with the competitor's position. Note that there is no threat of exit posed by the foreign entrant, as that entrant replaces the incumbent of its own country.

[24] We define the value functions for the two boundary cases where the incumbent is $\bar{m}$-steps ahead (behind) in Appendix B.5. As discussed there, the *international knowledge spillover* manifests itself in the value function of $\bar{m}$-step-behind incumbent.

R&D decisions for an incumbent in state m:

$$x_{cmt}=\begin{cases}\max\left\{\left[\frac{1}{\alpha_c(1-s^c)}\sum_{n=m+1}^{\bar{m}}\mathbb{F}_m(n)\left\{\lambda^{(n_t-m)}v_{cnt}-v_{cmt}\right\}\right]^{\frac{1}{\gamma_c-1}},0\right\} & if\ \ m<\bar{m}\\ \max\left\{\left[\frac{1}{\alpha_c(1-s^c)}(\lambda-1)\,v_{c\bar{m}t}\right]^{\frac{1}{\gamma_c-1}},0\right\} & if\ \ m=\bar{m}\end{cases}. \tag{19}$$

Similarly, the equilibrium innovation rates for entrants become[25]

$$\tilde{x}_{cmt}=\begin{cases}\max\left\{\left[\lambda v_{c\bar{m}t}\cdot\tilde{\alpha}_c^{-1}\right]^{\frac{1}{\tilde{\gamma}_c-1}},0\right\} & if\ m=\bar{m}\\ \max\left\{\left[\tilde{\alpha}_c^{-1}\sum_{n=m+1}^{\bar{m}}\mathbb{F}_m(n)\,\lambda^{(n_t-m)}v_{cnt}\right]^{\frac{1}{\tilde{\gamma}_c-1}},0\right\} & if\ m<\bar{m}\end{cases}. \tag{20}$$

Closing the model, aggregate consumption is derived from the budget constraint in equation (2). Aggregate R&D spending R_{ct} is derived combining equations (4), (5), (19), and (20):

$$R_{ct}=\sum_{m=-\bar{m}}^{\bar{m}}\left(\alpha_c x_{cmt}^{\gamma_c}+\tilde{\alpha}_c\tilde{x}_{cmt}^{\tilde{\gamma}_c}\right)Q_{cmt}. \tag{21}$$

The net government spending reads as

$$G_{ct}=s^c\sum_{m=-\bar{m}}^{\bar{m}}\alpha_c x_{cmt}^{\gamma_c}Q_{cmt}-\tau^c\sum_{m=-\bar{m}}^{m_{ct}^M}\left[\frac{1-\beta}{(1+\kappa)(1+\tau^c)\,\eta}\varpi_{c't}^{-1}\right]^{\frac{1-\beta}{\beta}}\frac{Q_{c'mt}}{1-\beta}, \tag{22}$$

where the first part accounts for the bill of R&D subsidies, and the second part accounts for the revenue from tariffs.

Finally, we present the law of motions that summarize the endogenous evolution of the gap distribution. The change in μ_{Amt}, the share of product lines where the firm from country A is at position m, is given by

$$\dot{\mu}_{Amt}=\dot{\mu}_{B(-m)t}=\begin{array}{l}\sum_{s=m+1}^{\bar{m}}\mathbb{F}_{-s}(-m)\left(x_{B(-s)t}+\tilde{x}_{B(-s)t}\right)\mu_{Ast}\\ +\sum_{s=-\bar{m}}^{m-1}\mathbb{F}_s(m)\left(x_{Ast}+\tilde{x}_{Ast}\right)\mu_{Ast}\\ -\left[x_{Amt}+x_{B(-m)t}+\tilde{x}_{Amt}+\tilde{x}_{B(-m)t}\right]\mu_{Amt}\end{array}. \tag{23}$$

Notice that the change in μ_{Amt} also defines reciprocally the change in $\mu_{B(-m)t}$. The measure μ_{Amt} grows when the gap difference in some product lines reach m, and it shrinks when existing lines with difference m reach another position. The first line on the right-hand side refers to the increase in μ_{Amt} due to innovations by foreign firms in lines where the gap difference is larger than m, which bring the gap difference in those lines to m. The second line refers to the increase

[25] See Appendix B.6 for the derivation of entrant firm values.

in μ_{Amt} due to domestic innovations in lines where the gap difference is smaller than m. The last line refers to the decrease in μ_{Amt} due to any innovation in those lines with gap difference in m. We leave further details and the discussion of the evolution of Q_{cmt} to Appendix B.7. Finally, we provide the formal equilibrium definition in Appendix B.8.

2.4 Welfare

Aggregate welfare in economy c over horizon T calculated at time t_0 is given by

$$\mathbb{W}_{t_0}^{c} = \int_{t_0}^{t_0+T} \exp(-\rho\,(s-t))\,\frac{C_{cs}^{1-\psi}-1}{1-\psi}\,ds.$$

In the quantitative section, we will report the welfare differences between a counterfactual and the baseline economy in consumption equivalent terms using the following relationship:

$$\int_{t_0}^{t_0+T} \exp(-\rho\,(s-t_0))\,\frac{\left(C_{cs}^{new}\right)^{1-\psi}-1}{1-\psi}\,ds = \int_{t_0}^{t_0+T} \exp(-\rho\,(s-t_0))\,\frac{\left((1+\varsigma)\,C_{cs}^{base}\right)^{1-\psi}-1}{1-\psi}\,ds.$$

If a policy change at time t_0 yields a new income sequence C_{ct}^{new} between t_0 and t_0+T satisfying the above relationship, we say that the policy change results in ς% variation in consumption-equivalent welfare over horizon T. This means that the representative consumer in the baseline economy would need to receive ς% additional income at each point in time between t_0 and t_0+T in order to obtain the level of welfare it would have in the counterfactual scenario.

2.5 Taking Stock

Before completing this section, we think that a brief discussion on some central features of our model is worthwhile.

Analytical Results: Static and Dynamic Forces

While deriving analytical results in the full-fledged model is exceedingly difficult, we are able to provide a theoretical characterization of important forces in our model in Appendix C by making use of a simplified environment. In particular, we characterize the static and dynamic forces that shape the main mechanisms in our analysis. First, we show that relative to the autarky, opening to trade benefits the home country statically by raising the fixed factor income making better-quality foreign intermediates available for domestic final-good production. However, the attendant loss in profit income of domestic firms renders the total static effect ambiguous. Next, we discuss the dynamic forces. We show that as foreign competition intensifies, foreign firms respond by increasing their innovation effort. In our model, the competition between firms has an international aspect, and the intensification of competition arises in two regions across technology gaps between firms owing to trade costs. Consequently, firms' innovation effort intensifies for similar but distinct motives, both of which relate to a market size effect: defensive R&D to capture domestic profits and expansionary R&D to capture export markets. We refer the interested reader to Appendix C for a detailed discussion of these theoretical results.

Discussion on Domestic Competition

Our model has an oligopolistic competition between a domestic and a foreign firm. A potential extension of the framework would be the addition of domestic competition among incumbent firms. This new feature would generate another competitive force, intensifying firms' innovation efforts at the technological neck-and-neck state (i.e., when $m = 0$). As a result, the innovation effort profile (see Figure 6a below) would reflect an intensification based on three forces—defensive R&D, expansionary R&D, and domestic escape-competition—resulting in three innovation effort peaks instead of two. Because the competitive force exerted by other domestic incumbents would be a supplement to rather than a replacement of the current forces, our policy results on international competition should remain largely intact. However, this addition would generate substantial technical complexity, expanding the state space of firms to include both the domestic and foreign technology gaps. To the best of our knowledge, our paper is the first to solve these duopoly models with strategic interaction in an open economy setting, while also computing the transition, and we believe that the tools that we provide in our analysis will be useful for further extensions such as the addition of strategic interaction among domestic competitors.

3 Quantitative Analysis

In this section, we study the quantitative implications of our theoretical framework. After calibrating the model, we first discuss its performance in terms of out-of-sample predictions. Then, we focus on the implications of R&D subsidies and tariff policies for technological competition. We evaluate alternative scenarios including the simultaneous use of both policy measures and tariff retaliation by trade partners in terms of their welfare consequences. We start our exploration with the calibration of our model.

3.1 Calibration

When mapping our two-country model to the data, we envision a world that consists of the United States and a foreign country, which is a weighted combination of the six countries employed in the empirical section: Canada, France, Germany, Italy, Japan, and the U.K.[26] The weights associated with each country, listed in Table 1, reflect the count of patents registered in the United States by the residents of a specific country in the initial year of the sample (1975) as

[26]These are the most innovation-intensive countries competing with the United States, measured by their share of patent applications in the USPTO patent data.

a fraction of all foreign patents registered in the United States in that year.[27] In the remainder of this section, country A will represent the United States and country B the foreign country.

Table 1: Patent weights of countries

Canada	France	Germany	Italy	Japan	U.K.
6.2%	11.7%	30.0%	3.8%	33.1%	14.6%

As Figure 2b shows, there is a significant break in the R&D policy before and after 1981. Moreover, there is a strong convergence in the relative shares of domestic and foreign patents registered in the United States prior to 1981, which also holds true for the share of sectors led by domestic and foreign firms (see Figure A.1 in Appendix A.1). A key objective of our calibration strategy is to reproduce this convergence in order to conduct our policy evaluation exercises in an environment that mimics the intensification of the foreign technological competition faced by U.S. firms in those years. Therefore, we match the model to a set of moments that we obtain from the data that span 1975 to 1981. Then, we impose the changes in R&D policy observed in the data to the calibrated model and analyze their implications for the post-1981 period (1981 to 2016).

In the calibrated model, we try to keep the least amount of heterogeneity across countries, other than subsidy levels, in order to focus solely on the effect of policy differences. The two large open economies share symmetric technologies except the scale parameters of R&D cost functions and the imposed R&D subsidies. These assumptions leave us with the following 16 structural parameters to be determined:

$$\theta \equiv \left\{ \alpha_A, \alpha_B, \tilde{\alpha}_A, \tilde{\alpha}_B, \gamma, \tilde{\gamma}, \rho, \psi, \beta, \kappa, \eta, \lambda, \phi, \tau_{75-81}, s^A_{75-81}, s^B_{75-81} \right\}.$$

Some of these parameters are calibrated externally and the remaining are calibrated internally. We start with the external calibration.

3.1.1 External Calibration

We take the CRRA parameter of the utility function $\psi = 2$, a standard value in the macroeconomics literature. We set the time discount parameter $\rho = 1\%$. These preference parameters imply a 3.11 percent interest rate in the balanced growth path and an average rate of 2.46 percent between 1975 and 1981 for the United States. We set $\beta = 0.5$, which leads to a roughly 75 percent share of fixed factor and wage income in U.S. GDP in the balanced growth path, with η set equal to $1 - \beta$.[28] We assume R&D cost functions to have a quadratic shape such that $\gamma = \tilde{\gamma} = 2$, which is the common estimate in the empirical R&D literature (see Acemoglu et al. (2017) for a

[27] Weights may not sum to 1 because of rounding.

[28] By income approach, GDP is equal to the sum of profits, wages, and fixed factor income earned.

thorough discussion). We set the tariff rate, which we take to be common for both countries, to 5.5 percent, a value that is consistent with U.S. International Trade Commission (2009). The left panel of Table 2 lists these values.

A crucial set of parameters is the R&D subsidy rates. The numbers we use are those calculated in Impullitti (2010), which lack only Canada.[29] These data go back to 1979. Given that the rates in the sample countries do not markedly fluctuate before the mid-1980s, we assume the values before 1979 to be the same as in 1979. For the calibration part, the subsidy rates for both countries are 1975-1981 averages, which are again weighted for the foreign countries. When we simulate the model for the post-1981 period, we will recalculate the subsidy rates to match the averages across 1982 to 1995.[30] We also recalculate the weights of foreign countries the same way, but use 1981 patent counts.

Table 2: List of parameter values

Panel A: Externally calibrated			**Panel B: Internally calibrated**		
Parameter	Value	Description	Parameter	Value	Description
ψ	2	Elasticity of substitution	α_A	1.97	R&D scale, incumbents US
$\gamma, \tilde{\gamma}$	2	R&D cost curvature	α_B	3.16	R&D scale, incumbents FN
ρ	1%	Rate of time preference	$\tilde{\alpha}_A$	56.9	R&D scale, entrants US
β	0.5	Factor income share	$\tilde{\alpha}_B$	18.4	R&D scale, entrants FN
s^A_{75-81}	5.3%	R&D subsidy US, 75-81	ϕ	1.21	Curvature of $\mathbb{F}(n)$
s^B_{75-81}	3.8%	R&D subsidy FN, 75-81	λ	1.60%	Innovation step size
τ_{75-81}	5.50%	Tariff rate	κ	6.19%	Iceberg trade cost

3.1.2 Internal Calibration and Identification

We have seven remaining parameters: $\{\alpha_A, \alpha_B, \tilde{\alpha}_A, \tilde{\alpha}_B, \lambda, \phi, \kappa\}$. One of these, ϕ, determines the shape of the generic step-size distribution. In order to calibrate them, we use six data points and the distribution of firms across technology gaps that we derive using USPTO patent data. We start with the discussion of the six moments, summarized in Table 3, that are not directly related to the gap distribution. Again, moments pertaining to the foreign country are weighted averages of the values for individual countries.

The first two moments are the average growth rates of total factor productivity (TFP) in both countries, calculated using TFP series in Coe et al. (2009). The next two moments are aggregate non-defense R&D expenditure as a percentage of GDP, which we obtain from the Main Science

[29] We address this issue by recalculating the patent weights after dropping Canada.

[30] We focus our calibration on the period before 1995 for several reasons. First, we want to avoid the run-up to the U.S. dot-com bubble and the crisis that followed in the early 2000s. Second, we isolate our period from heightened competition exerted by China. Although valuable in itself, this would introduce a second period of exogenous variation to our analysis, making it more complicated for no apparent benefit. Finally, our theoretical assumption of home bias is better suited for this relatively earlier period of financial globalization.

and Technology Indicators (MSTI) database of the OECD.[31] As a fifth target, we include the birth rate of new establishments for the United States, computed using the BDS database.[32] The sixth moment is the ratio of U.S. manufacturing exports to GDP, which we derive using World Bank data. These moments allow us to determine six parameters as follows. Aggregate R&D shares discipline the scale parameters of the incumbent R&D cost functions $\{\alpha_A, \alpha_B\}$. The scale parameter of the entrant R&D cost function for country A $(\tilde{\alpha}_A)$ is determined by the U.S. establishment birth rate. Then, TFP growth rates pin down the basic step size λ and the entrant R&D cost for country B $(\tilde{\alpha}_B)$. The U.S. export-to-GDP ratio determines the iceberg cost κ, as κ drives m^X, the minimum gap a firm needs to open up in order to export, given τ and λ.

The last parameter to be internally calibrated is ϕ, which controls the curvature of the generic probability function over technology gaps, $\mathbb{F}(n)$. As manifested by equations (A.2), this function, by forming the basis of position-specific $\mathbb{F}_m(n)$, becomes an integral determinant of the model dynamics that govern the evolution of firms' measure across technology gaps $(\mu_{cm}\text{'s})$. We make use of this relationship to discipline the shape of $\mathbb{F}(n)$. To this end, we first derive the empirical distribution of sectors across technology gaps using the information on patents provided by the USPTO data. This procedure, illustrated in Figure 4, provides us with the data counterpart of firms' measure across technology gaps (gap distribution) in the model.

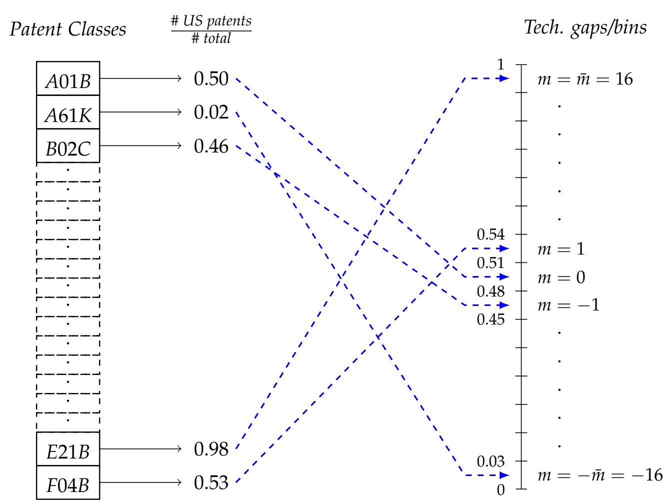


Figure 4: Mapping USPTO patent data to the model

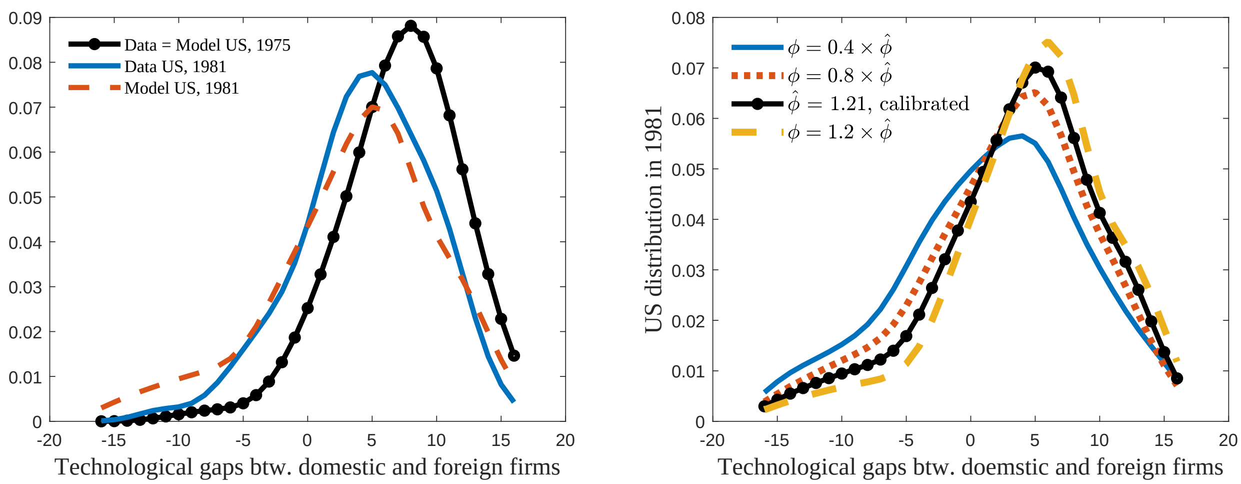
Notes: The figure illustrates how patent classes in the USPTO data are assigned to equally sized bins on a unit measure according to the share of patents owned by U.S. residents, obtaining an empirical distribution of technology gaps.

We start with sorting sectors in a given year according to the fraction of patents in each sector

[31]Non-defense R&D spending data do not include Japan. However, Science and Engineering Indicators reports of the National Science Foundation, based on MSTI data, provide estimates for Japan, which we use to amend our calculations with the OECD data. Also, MSTI data start in 1981, which is why we use the initial values of this variable.

[32]We prefer entry by establishments instead of firms because while in the data firms enter at different sizes, in our model every firm operates in one product line.

that are registered by U.S.-based entities in that year.[33] Then, we divide this unit interval into 33 equally spaced bins, each of which corresponding to a range of approximately 3 percent. For instance, sectors with a fraction of U.S. patents between 0 and 3 percent would fall into $m = -16$, sectors with a fraction between 4 and 6 percent would fall into $m = -15$, and so on. Sectors in the data correspond to product lines in our model, and thus, the measure of sectors across bins (normalized to sum to 1) corresponds in our model to μ_m's for country A across 33 gap levels from $-\bar{m} = -16$ to $\bar{m} = 16$.[34] Figure 5a shows the distribution in the data for years 1975 (circled black line) and 1981 (solid blue line).[35] It reveals that, initially, a substantial mass of U.S. firms are technological leaders, with a mean gap close to seven; however, subsequently, their distribution has shifted leftward, with the mean gap falling to around four in 1981. This shift translates into a larger mass of U.S. firms in relatively smaller gap sizes and, therefore, signifies a strong foreign technological catch-up. The calibration of ϕ aims to match the dynamics of this catch-up process that occurred between 1975 and 1981, as described later.



A) Technological gap distribution: data and calibration

B) Identification of ϕ

Figure 5: Dynamics of the gap distribution and the identification of ϕ

Notes: Panel A depicts three technology gap distributions and demonstrates the model's performance (positive values on the horizontal axis denote U.S. technological leadership). The dotted solid line is the empirical distribution in 1975, which also defines the initial distribution for the model simulation in the calibration. The solid blue line is the empirical distribution in 1981 and defines the target distribution of the simulation. The dashed red line is the model-generated distribution in 1981, simulated at the calibrated parameters. Panel B illustrates the effect of ϕ (the curvature parameter of the step-size distribution function) on the simulated gap distribution, the variation in which enables the identification of ϕ. It exhibits various model-generated distributions in 1981 that result from simulations with varying levels of ϕ as other parameters being held at their calibrated values.

In order to obtain the model counterparts of our data targets, we simulate the two economies

[33] The total mass of patents in a given year consists of patents by registrants from the United States and the other six foreign countries that we used throughout the paper. For the robustness of our results to a method where sectoral country shares are calculated based on cumulative patent counts over a number of years, see Section H.4.

[34] We chose the maximum gap to allow for a realistic catch-up process for laggard firms while having enough observations in each bin of the empirical distribution.

[35] Distributions are smoothed using a kernel density function with a bandwidth of 1.8.

between 1975 and 1981, initializing the model at the empirical gap distribution in 1975. Initially, we normalize the quality of U.S. intermediate goods to one—i.e., $q_{Aj1975} = 1 \ \forall j$.[36] We solve the transition path of the model over 1975 to 1981 as described below. We derive the model counterparts of the seven moments presented in Table 3 by taking averages of the simulated series over the relevant period. We also compute the evolution of the gap distribution in the model using equations (A.2) defined in Appendix B.7 and try to hit the empirical gap distribution in 1981 as the terminal point of the economy in transition.

Solution Algorithm and Model Fit. In order to solve the model, we first discretize it. The solution algorithm assumes that the economy starts in 1975 and transitions to the balanced growth path in T periods, where each period is divided into $(\Delta t)^{-1} = 2^5$ sub-periods. The algorithm is an iterative backward solution method. The main procedure of the algorithm consists of solving for the balanced growth path and then deriving the values over the transition period going backward from the balanced growth path. A detailed explanation of the solution steps is presented in Appendix D.[37]

The targeted moments and the model performance in matching these moments are summarized in Table 3 and Figure 5a.

Table 3: Model fit

Moment	Estimate	Target	Source
TFP Growth U.S.	0.47%	0.55%	Coe et al. (2009) 1975-81
TFP Growth FN	1.98%	1.73%	Coe et al. (2009) 1975-81
R&D/GDP U.S.	1.65%	1.75%	OECD 1981
R&D/GDP FN	1.90%	1.96%	OECD 1981
Entry Rate U.S.	9.98%	10.0%	BDS 1977-81
Export Share U.S.	7.06%	7.00%	WB 1975-81

Along the transition, the catching-up country exhibits higher R&D-to-GDP ratios growing faster than the leading country. The model captures these differences between the two economies observed in the data quite successfully. The entry rate and the export shares are also well fitted. Finally, the position of the dashed red line relative to the solid blue one in Figure 5a indicates the strong performance of the model in matching the 1981 distribution of technology gaps.

[36] The quality levels of firms from B are initialized accordingly with respect to their position in technological competition. Mathematically, this normalization implies that if in product line j the firm from A is at position m, then $q_{Bj1975} = \lambda^{-m}$, $m \in \{-\bar{m}, ..., \bar{m}\}$.

[37] To avoid any numerical instability, we introduce a small extension to the relationship between the gap structure and the trade of goods in the computations. We assume that the quality of the foreign good is observed with an iid error around its true value—i.e., the final–good producers observe the foreign good's quality imperfectly. Appendix D provides a detailed account. Effectively, the additional structure comes into play only around the cutoffs and, thus, affects only a small mass of firms. Therefore, it is inconsequential for the aggregates but is still useful in ensuring a smooth numerical solution.

In the model, the forces of cross-country convergence that enable the reproduction of the catch-up observed in the data are chiefly governed by the curvature of the step-size distribution ϕ. Figure 5b illustrates how different values of ϕ lead to various shapes of technology gap distribution. Each line in the figure represents a distribution that emerges in 1981 once the model is simulated between 1975 and 1981 at the calibrated parameter values except ϕ, which takes a different value in each iteration. Lower values of ϕ mean a flatter probability distribution $\mathbb{F}(n)$ over step sizes (or, equivalently, positions ahead), allowing technologically laggard firms to catch up more quickly. Therefore, a low value of ϕ would imply a larger leftward shift in the initial gap distribution of U.S. firms. The position of the solid blue line in Figure 5b relative to the circled black line, which represents the calibration result, illustrates this case. The converse happens for larger values of ϕ, as demonstrated by the relative position of the yellow dashed line, which is generated by a value that is 20 percent higher than the calibrated one.

The distribution across new positions, $\mathbb{F}(n)$, facilitates technological convergence, helped by the international knowledge spillovers, which keep laggard firms from the foreign country in the global innovation race, preventing them from falling too far behind.[38] Importantly, an innovation can generate an improvement of multiple steps for laggard firms, whereas the number of potential steps to improve becomes smaller as a firm opens up the technological gap with its follower. In the words of Gerschenkron (1962), this structure creates an "advantage of backwardness" for followers—i.e., laggard firms have an advantage in the number of steps they can improve with each innovation, while far-ahead leaders cannot open further their lead quickly. Thus, foreign firms catch up with domestic firms along the transition, generating a cross-country technological convergence. This convergence in our economy echoes that in the Solow model with a key difference. In Solow convergence is driven by decreasing returns in capital accumulation; in our economy endogenous innovation together with an "advantage of backwardness" drives the convergence.

The internal calibration results are listed in the right panel of Table 2. They imply that in the BGP, $m_A^X = 8$ and $|m_A^M| = 6$—i.e., a firm from A (B) needs to lead by at least 8 (6) technological gaps to export.[39] The level of ϕ generates a considerable chance of improving multiple steps with a single innovation for laggard firms. For instance, the probability that an innovation by the most laggard firm brings a multi-step improvement is 67 percent.[40]

[38]In addition, Ricardian comparative advantage helps firms from a technologically laggard country remain competitive in product markets. The adjustment in relative wages preclude the case in which no firm from a particular country generates profits.

[39]Notice that the introduction of imperfect observability of the foreign good quality in the numerical solution implies that some firms at these cutoffs may fail to export with a certain probability.

[40]Conversely, the probability that the most laggard firm receives a single-step innovation is 33 ($= 100 - 67$) percent.

3.2 Validation of the Model

Before discussing the properties and the policy implications of the calibrated model, we present four out-of-sample tests to assess the quantitative plausibility of the integral mechanism of our model, in light of empirical relationships not used in the calibration process.

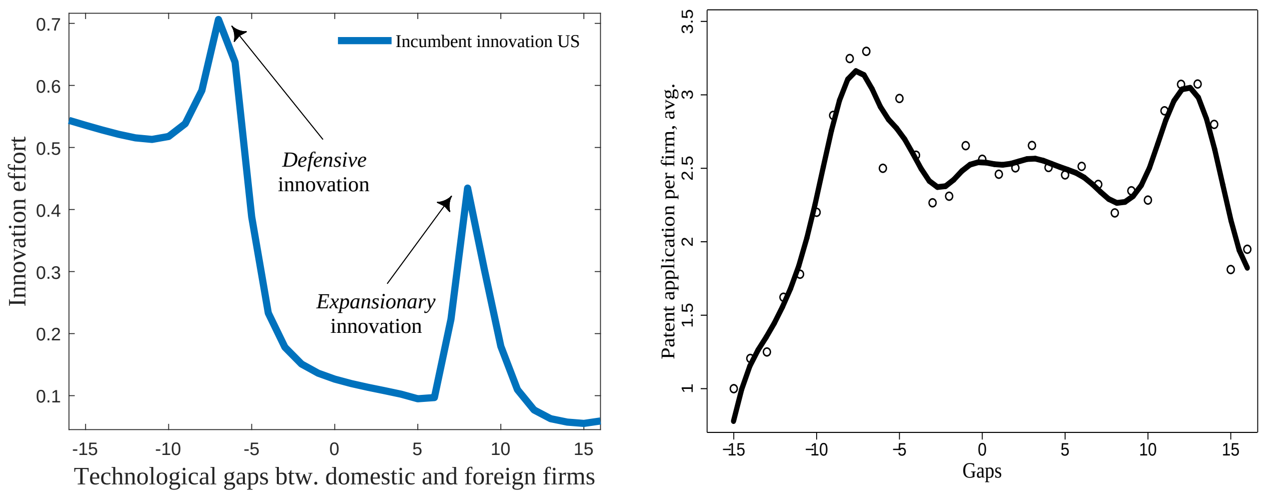
Validation Exercise I: Incumbent Innovation vs. Leadership

Figure 6 compares the relationship between innovation efforts of incumbent firms and their technological position relative to their competitors in the model and in the data. Figure 6a displays incumbents' innovation intensity as a function of the technology gap. Figure 6b shows average patenting intensity of U.S. firms in the USPTO data, measured by patent applications per firm, across sectors ranked according to their share of patents registered by U.S. residents, as described in Section 3.1.2.[41] In Figure 6a, we observe two spikes at $-m^M = -6$ and $m^X = 8$ that are related to cutoffs defined in equations (13) and (14).[42] The left one emerges because of the *defensive R&D* effort, as the firm increases its innovation to improve its position and capture domestic production. Similarly, the right peak emerges because of the *expansionary R&D* effort of firms that sell domestically. They increase their innovation efforts massively when closer to the export cutoff, as a new innovation right before that threshold enables the domestic firm to expand into the export market. Interestingly, we observe a similar shape with two peaks also in the data, as illustrated in Figure 6b. Again, the peaks emerge in sectors where U.S. firms hold a strong technological advantage, or disadvantage, as measured by the sectoral share of total patents registered by U.S. residents. The remarkable performance of the model in capturing the innovation intensity observed in the data provides further evidence for our model's ability to mimic firms' innovation behavior.

The jump in innovation in the proximity of the export cutoff is consistent with a large body of evidence showing that firms innovate in order to enter the export market. Using Chilean plant-level data, López (2009) finds that productivity and investment increase before plants begin to export. Estimating a dynamic structural model with Taiwanese plant-level data, Aw et al. (2011) show that the decisions of firms to innovate and to enter the export market are highly correlated—i.e., firms entering the export market are more likely to speed up their investment in

[41] We create the empirical measure of average innovation intensity across technology gaps as follows. First, we calculate the total number of domestic patent applications and unique domestic owners of those patents for each pair of technology class and year. Next, we rank these class-year pairs according to the share of domestic applications in total applications and assign them to technology bins as in Figure 4. Then, in each bin, we sum the total domestic patents and unique domestic assignees across class-year pairs. The ratio of those is the average patenting intensity per assignee in a given bin, which proxies for innovation intensity in our model. The exercise considers applications between 1975 and 1995, a long span of time, as the comparison is to the balance growth path in the model. To generate the figure, we also drop patents assigned to the assignee id "0", as most of the other assignee values have more than six digits. Figure A.9 in Appendix F shows that including those patents leads to sharper spikes in the data.

[42] Owing to the random term associated with the observed foreign good quality, some domestic firms retain profits from the domestic market, event though the true comparison of cost-adjusted qualities would not allow it. Therefore, while the peak innovation effort happens at the aforementioned cutoffs, the innovation rate is also noticeably high at the adjacent gap.



A) Model: Incumbent innovation intensity

B) Data: Patenting intensity of U.S. incumbents

Figure 6: Incumbent innovation effort and leadership

Notes: Panel A shows the innovation intensity of U.S. incumbent firms in the balance growth path of the calibrated economy. Panel B shows the average number of patents applied for by the U.S. firms in the USPTO data across technology gaps (the creation of the technology gaps is illustrated in Figure 4). The hollow markers designate actual data points, and the line is fit by smoothing splines.

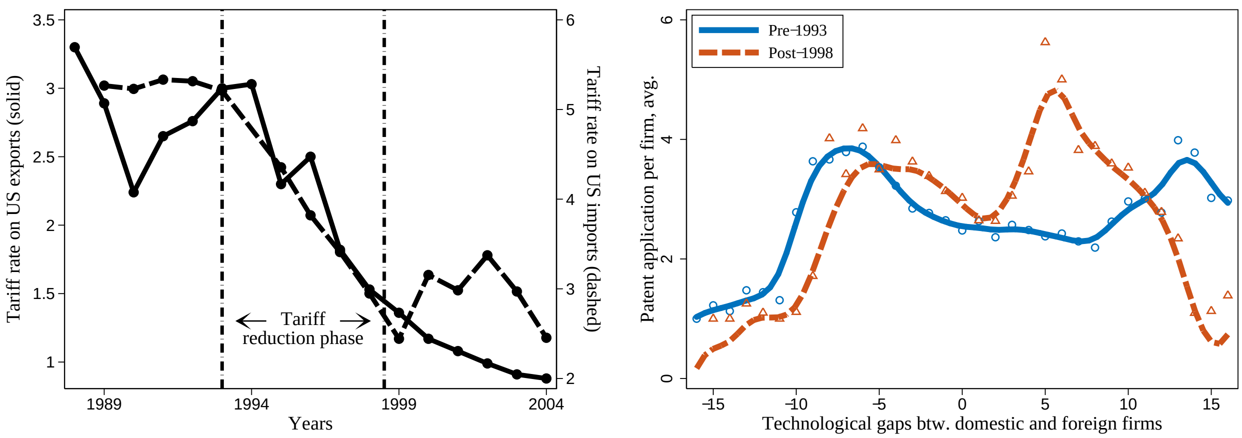
R&D. Lileeva and Trefler (2010) find that Canadian plants that were induced by the U.S. tariff cuts to start exporting (i) increased their labor productivity, (ii) engaged in more product innovation, and (ii) had higher adoption rates for advanced manufacturing technologies.

Validation Exercise II: Tariff Reduction and Shift in Innovation Intensity

As another test, we present a case study on the link between trade barriers and firms' innovation efforts. Our model implies that because of intensified competition around trade thresholds, which are determined by trade costs, firms increase their innovation efforts in these regions. One way to detect this relationship in the data is to focus on firms' innovation behavior in a specific sector and its evolution over time with respect to changes in trade barriers in that sector. To perform such an analysis, we map USPTO patent data to Standard International Trade Classification (SITC) industries (revision 2) and concentrate on the manufacturing sector, which makes up about half of patenting activity, over a period with substantial reductions in tariff rates.[43] Data on tariffs are available from the World Integrated Trade Solution (WITS) database of the World Bank. Studying tariff reductions in a specific sector instead of a cross-industry comparison allows us to proceed without resorting to using a reliable estimate of industry-specific trade costs—known to be notoriously difficult to obtain [Anderson and van Wincoop (2004), Hummels and Lugovskyy (2006)]—as long as non-tariff barriers are not rising over time.

Figure 7a shows the decline in the tariff rates to which U.S. manufacturing imports and

[43] We obtain crosswalks for mapping USPTO data to SITC industry level from Lybbert and Zolas (2014).



A) Tariff rates over time

B) Incumbent innovation before 1993 and after 1998

Figure 7: Tariffs and incumbents' innovation intensity across technology gaps in manufacturing

Notes: Panel A shows the reduction in the average effective tariff rates applied to U.S. imports and exports of manufactured goods following the Uruguay round of the GATT. Tariff rates applied by or to goods of individual countries are obtained from WITS and are weighted by the patenting intensity of the trade partners in the USPTO data. Panel B shows the change in the innovation intensity of incumbent U.S. patentees in the manufacturing sector across technology gaps. The hollow markers designate actual data points (circles for the earlier period and triangles for the later), and the lines are fit using smoothing splines.

exports were subject over the 1990s.[44] On average, both barriers were 2 percent lower between 1997 and 2004 than between 1989 and 1993, in part as a result of the Uruguay round of the General Agreement on Tariffs and Trade completed in 1994 and other bilateral trade agreements. In parallel, Figure 7b depicts the innovation intensity of incumbent patentees in the U.S. manufacturing sector with respect to their technological position relative to foreign competitors, again before and after the mid-1990s.[45] Noticeably, incumbent-innovation intensity in the manufacturing sector exhibits a double-peaked profile in line with our findings for the complete set of patents in the USPTO data. Moreover, we observe that the period of tariff reductions coincides with an inward shift of peaks in incumbents' innovation intensity profile across technology gaps. This observation mirrors the predictions of our model: Lower bilateral trade barriers imply that firms with a lesser technology advantage over their competitors start exporting, making the competition for markets stiffer at smaller technology gaps and thereby resulting in peaks closer to (purely technological) neck-and-neck position (which occurs at zero).

[44] The tariff data on WITS go back to 1989. The United States is one of the few countries that reports tariffs on imports reliably across time and trade partners. We use the same sample of trade partners as in the original analysis (Canada, Germany, France, Italy, Japan, and the U.K.) and weight the average effective tariff to manufacturing imports from each of them by their patent share in the USPTO data in 1988. Similar reductions in tariffs are observed when accounting for larger groups of countries as well. Tariffs on U.S. manufacturing exports are more limited, reported only by Canada and Japan. We use the Japanese series, as Japan constitutes about half of foreign patents registered in the United States by the late 1980s. Finally, we use the broad sector grouping for manufacturing in WITS data, which comprises chapters 6 (manufactured products) and 8 (miscellaneous manufactured articles) of the SITC classification (excluding non-ferrous metals with the code 68).

[45] We constructed the innovation intensity of incumbents in the manufacturing sector over technology gaps following similar steps to those described in Section 3.1.2, except that we used SITC subindustries instead of patent classes as the unit of analysis. To be in line with the WITS data, we used the same specification of the manufacturing sector, which consists of SITC chapters 6 and 8.

Appendix E discusses two more exercises, which compare the model's implications for entrants' innovation intensity and the elasticity of firm innovation to policy changes to empirical counterparts. Having provided empirical support for the model's key implication, we now turn to policy analysis.

4 Policy Evaluation

In this section, we first demonstrate the foreign catch-up process that the United States would experience in the absence of policies. Then we perform a quantitative investigation of various policy alternatives and assess their welfare implications. We also discuss the design of optimal policies considering different horizons for policy and accounting for the transition period.

4.1 Technological Convergence and Foreign Catching-Up

Foreign technological catch-up is a key implication of the model. Improvements in a country's trade partners' technology is a mode of globalization that has received less attention in the literature than the reduction of trade and offshoring barriers. To explore this relationship in our model, we focus on how foreign technological catch-up manifests itself in the technological advantage of the leading country, which again represents the United States. In particular, Figure 8 shows the evolution of the average technological lead that U.S. firms would have over their foreign competitors in the absence of any policy intervention. In line with the leftward shift of the gap distribution displayed in Figure 5, Figure 8 suggests that the average technological lead that U.S. firms would have would continue to decline drastically.

This dramatic decline implies a strong international business-stealing effect, whereby foreign

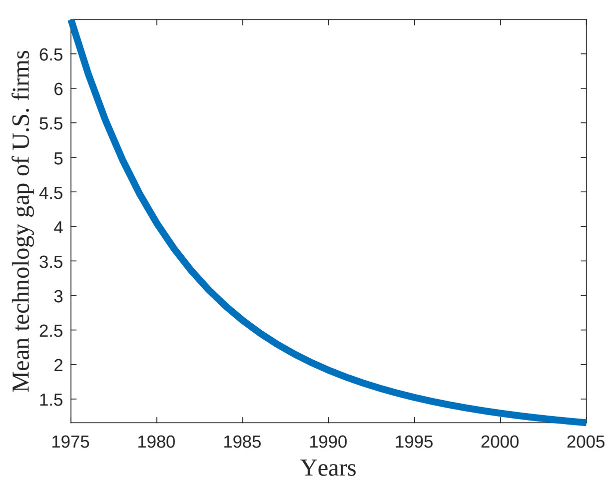


Figure 8: Average technology lead of the U.S. firms, no policy intervention

Notes: The figure exhibits the evolution of the average technology lead that the U.S. firms have over their foreign competitors across years along the transition of the calibrated economy.

firms progressively capture leadership in more and more markets, and profits collected previously by the U.S. firms are now going into the pockets of foreign firms. Notice that, while losing a domestic market to foreign exporters brings about a productivity gain from better-quality imports, the same is not true when the U.S. exporters lose their technological leadership, and thus, profits from abroad, but continue to serve the domestic market—the case for a large set of U.S. firms. As such, international business stealing suggests that foreign technological convergence indeed hurt the U.S. economy. In addition, our model implies that this convergence has dynamic effects. With the technological advantage of the U.S. firms shrinking as a result of the foreign catch-up, as time passes, they find themselves further away from the export cutoff and decrease their innovation effort in response (as would be implied by Figure 6a).[46] As we discuss below, this dynamic change in innovation incentives and its effect through intertemporal spillovers are key margins that shape the policy implications of our analysis. Now we turn to the analysis of industrial policies that could potentially help the economy tackle foreign technological catch-up.

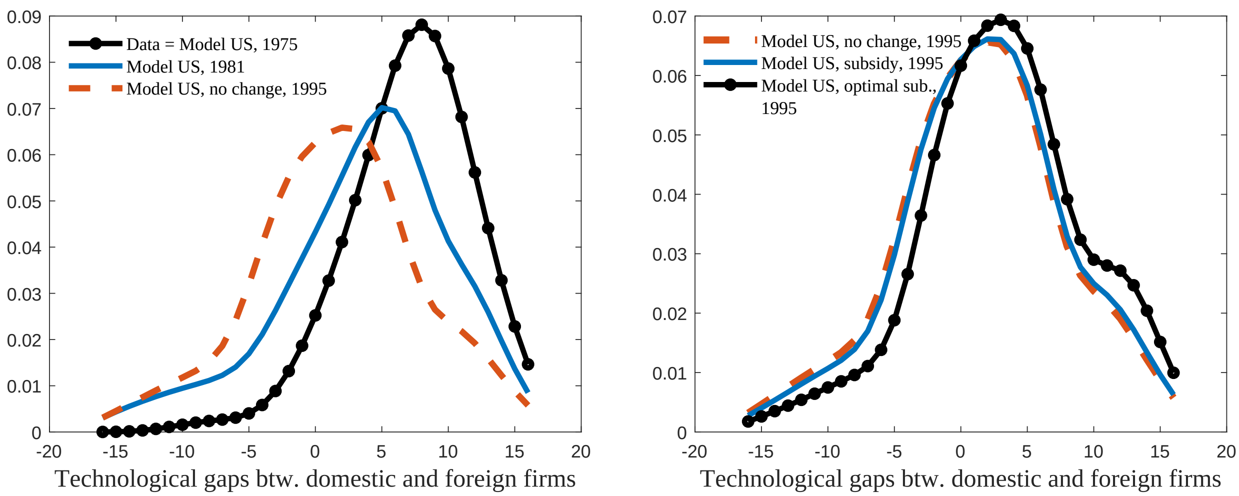
4.2 The Research and Experimentation Tax Credit

Policy intervention in the early 1980s to improve the competitiveness of U.S. companies pushed up the level of R&D subsidies from an average of 5.1 percent in the pre-1981 period to an average of 19.2 percent in the subsequent period. The subsidy level in the foreign country remained fairly constant, with 3.8 percent and 4.1 percent in the respective periods. Figure 9 shows the effect of the subsidy to incumbents' R&D spending on the post-1981 distribution of technology gaps.

In the left panel, the model gap distribution in 1981 is the solid blue line, which is closely calibrated to data in 1981 (not shown). In the benchmark economy with no policy intervention, the transition after 1981 results in a large leftward shift, leading to the red dashed line distribution by 1995 on both panels. By contrast, in the alternative economy, where subsidies were introduced in 1981, the resulting distribution in 1995 becomes the solid blue line in the right panel. The effect of higher subsidies is a small shift to the right relative to the no-intervention benchmark case represented by dashed lines. This positive shift would have been drastic had the optimal level of R&D subsidy been introduced in 1981 (circled solid line). We will discuss optimal subsidies in Section 4.4.

Now we examine the welfare properties of the R&D subsidy intervention. We compute the welfare difference for a 35-year horizon from 1981 until 2016. The result is reported in the first row of Table 4. We find that the U.S. subsidy increase generates a 0.4 percent consumption gain every year over a span of 35 years. Decomposing the overall welfare change into variations in individual sources of income (not shown), we find that these gains are driven by an increase in

[46] In theory, foreign technological convergence can potentially support domestic innovation temporarily if, as a consequence, a large set of domestic exporters, who were comfortably above the export cutoff are now closer to that cutoff, are induced to increase their innovation effort in the face stiffer foreign competition. However, in the baseline model, the dominant effect stems from domestic firms falling further below cutoff, a force that strengthens over time. We discuss these dynamic effects in more detail below.



A) Data and the calibrated model

B) Model and counterfactual subsidies

Figure 9: Gap distribution after policy changes

Notes: Panel A exhibits the technology gap distributions in the calibrated model at three points in time: initially in 1975 (dotted solid line, the same as in the data), in 1981 (solid blue line), and in 1995 (dashed red line) assuming there was no policy change. Positive values on the horizontal axis denote U.S. technological leadership. Panel B exhibits the resulting gap distributions in 1995 under three different scenarios: under no policy change (dashed red line, the same as in Panel A), under the actual R&D policies after 1981 (solid blue line), and under the model-implied optimal R&D policy rate for the horizon between 1981 and 1995 (dotted solid line).

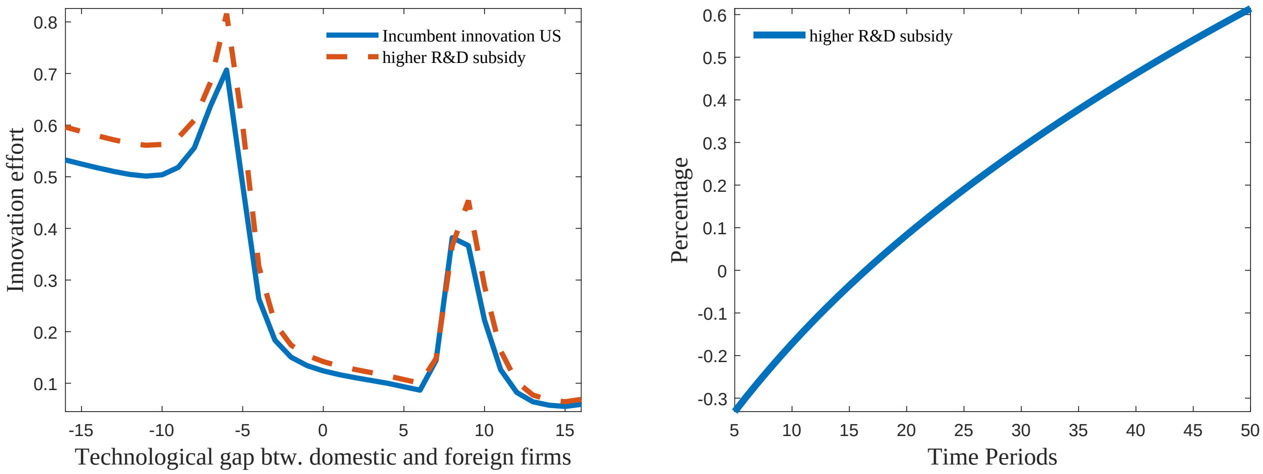
innovation by U.S. firms, which in turn leads to faster growth in both U.S. factor productivity and profit income. As illustrated in Figure 10a, the underlying economic mechanism is straightforward: By reducing the cost of R&D, subsidies stimulate innovation in U.S. incumbent firms, thereby accelerating productivity growth and allowing U.S. firms to obtain market leadership, and the related profits, in a large share of sectors in the economy. The gains from these channels more than offset the resources devoted to the higher aggregate R&D spending.[47]

Table 4: Observed R&D Subsidy: 1981-2016

	Subsidy rate	Welfare gains (1981-2016)
Observed R&D Subsidy	19.2%	0.38%
Optimal R&D Subsidy	54%	1.17%

In Figure 10b, we show the evolution of welfare gains over time generated by the increase in U.S. subsidies. The figure shows that in the shorter run—when a horizon of up to approximately 17 years is considered—the subsidy change leads to a welfare loss, which turns to gains as years go by. This early loss means that the consumption path in the economy with higher subsidies is below the baseline path for some time following the policy change. This loss reflects two factors. First, an increase in subsidies shifts resources from consumption to innovation. Second, a

[47]Figure A.8b demonstrates the positive effect of higher subsidies on the time path of average technology lead of the U.S. firms, resulting in a significantly higher path than the one in the "no-intervention" case in Figure 8.



A) Change in innovation by incumbents

B) Consumption equivalent welfare

Figure 10: Consumption equivalent welfare

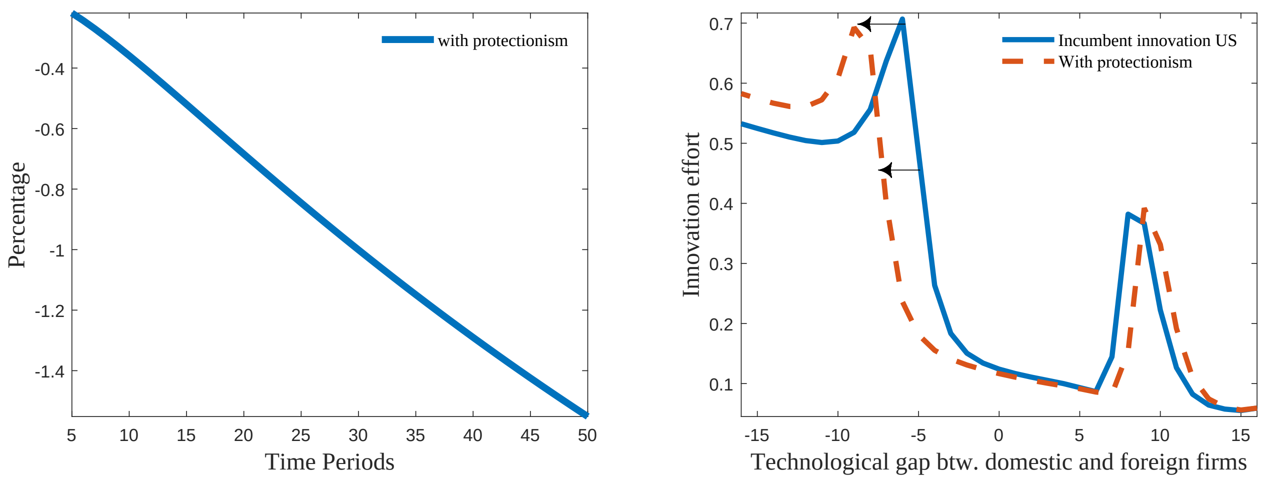
Notes: The figure illustrates the effects of a unilateral R&D-subsidy increase in the United States (replicating actual policy changes). Panel A shows the shift in the innovation-effort profile of U.S. incumbent firms over technology gaps (averages over the first 15 years after the policy change). Panel B shows the welfare change in consumption equivalent terms over different time horizons.

relatively faster growth in qualities as a result of higher innovation effort pushes up the wages in home country relative to the wages in the foreign country, hurting the home country's competitiveness and dampening the profit-shifting channel. Over time, the profit shifting and, even more importantly, the increase in labor productivity generated by higher domestic innovation, offset the losses, leading to sizable gains.

4.3 A Unilateral Increase in Import Tariffs

In this subsection, we explore the implications of a unilateral increase in tariffs as an alternative policy response. Figure 11a shows the consumption-equivalent welfare gains/losses for the representative household generated by a 100 percent rise in tariffs τ^{US} in 1981 (equivalent to a 5.5-percentage-point change). Compared to the path in a counterfactual economy that does not experience any policy intervention, protectionism hurts consumers in both the short and the long run, despite gains from an increase in home profits. The loss in welfare grows over time.

Digging deeper, unilaterally higher trade barriers initially generate a small increase in profit income by protecting some sectors from import penetration and shifting profits toward home firms. Recall, though, that the measure of relatively most laggard firms that can benefit from trade protection is relatively small for the United States, as indicated by the left tail of the dashed line in Figure 5a. Therefore, the initial gain from laggard firms recapturing production in the domestic market is limited. Moreover, the replacement of foreign exporters by the laggard home firms means that the high-quality foreign products are foregone and replaced by inferior domestic alternatives. This foregone intermediate-good quality leads to substantial welfare losses. The



a) Consumption equivalent welfare

b) Innovation response to protectionism

Figure 11: Welfare effects of protectionism: unilateral 100 percent (5.5 ppts) increase in tariffs

Notes: The figure illustrates the effects of a unilateral 100 percent increase in U.S. tariffs (without retaliatory response). Panel A shows the welfare change in consumption equivalent terms over different time horizons. Panel B shows the shift in the innovation-effort profile of U.S. incumbent firms over technology gaps (averages over the first 15 years after the policy change).

combined effect is negative regardless of the horizon over which the welfare is computed, and the magnitude grows over time.

As time goes by, the factor that governs variations in welfare is the decline in competitive pressures on domestic firms, which leads to a drop in their innovative activity. Figure 11b shows that innovation efforts by most of the laggard U.S. firms decrease substantially. Because the protectionist policy shifts the threshold for losing the domestic market to a foreign competitor further to the left, more firms move further from such an immediate threat. This weakens the defensive innovation motive and leads to lower innovation efforts by these firms, making it harder to compensate for the loss of imported frontier technology. Moreover, most U.S. firms, being either exporters or solid domestic producers that are technologically close to or ahead of their competitors, do not benefit from higher domestic tariffs.[48] As shown in Figure 11b, innovation decisions of this large group of firms barely change, implying that they do not contribute any additional boost to profit income or factor productivity in response to the policy move.[49] All in all, the short-run gains from profit shifting are subdued by the loss of foreign technology, which grows over time as weaker defensive innovation incentives lead to less domestic innovation, and thus, to a slower growth of productivity and profit income.

[48]In fact, the unilateral tariff increase has a small negative effect on these firms, as the export cutoff shifts slightly to the right, as depicted in Figure 11b. This shift reflects the effect on wages of protecting import-competing firms. Protected domestic firms start production and increase their labor demand, and the ensuing increase in wages reduces the competitiveness of U.S. exporters, which requires them to have a slightly larger technological lead over their competitors before being able to export.

[49]Evidently, the time path of the average technology lead of the U.S. firms is lower than the one in the "no-intervention" case in Figure 8, implying a faster loss in average U.S. leadership (see Figure A.8a in Appendix F).

4.4 Optimal Policies

Next we discuss the implications for optimal policy starting with R&D subsidies.

4.4.1 Optimal R&D Subsidies

We compute the optimal R&D subsidies for the home country and compare them with the U.S. subsidy observed in the data in the post-1981 period (reported in Table 4). Precisely, we compute the subsidy rate that maximizes the present discounted value of welfare in a 35-year horizon from 1981 to 2016 and calculate the welfare gains from the optimal subsidy with respect to the benchmark scenario, where the U.S. subsidy does not change in 1981. We also compare these welfare gains under optimal subsidy with those obtained under the observed post-1981 subsidy. The second row in Table 4 reports the results for the optimal policy.

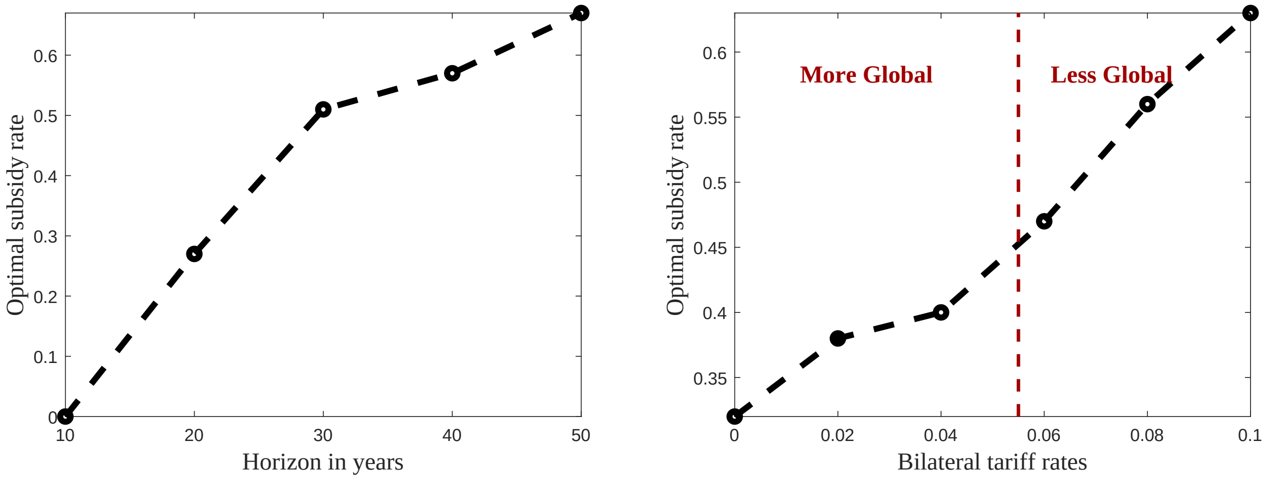
The comparison of the two rows in Table 4 indicates that although U.S. policymakers went in the right direction by increasing the subsidy rate in response to accelerating foreign catching-up in the 1980s, they did not go far enough. According to our model, the subsidy rate should have increased to 54 percent, about three times the observed one. This high subsidy would have pushed up welfare by a notable 1.17 percent every year in the 35-year period considered. In fact, the observed post-1981 subsidy is only optimal for a time horizon of about 15 years.

In our model, the optimal subsidy is determined by a rich set of externalities typical of Schumpeterian growth models, albeit with some novel twists.[50] To start, future innovations build on the stock of current innovations, but current innovators do not take into account that their activity will benefit future innovators. This *intertemporal spillover effect* leads to underinvestment in R&D and provides a reason to subsidize R&D. Second, entrant innovation destroys domestic incumbents' business, exerting a negative externality on domestic incumbent innovation. This *business-stealing effect* leads to overinvestment in R&D and rationalizes a tax on R&D. In addition, the international aspect of our model generates a third externality that misses in standard closed-economy models of Schumpeterian creative destruction. Through catching up or leapfrogging, a laggard domestic firm can steal the foreign leader's business (or part of it). This effect, which we label as the *international business-stealing effect*, can encourage or discourage innovation, depending on the technology gap between the competing firms. By increasing innovation, R&D subsidies help domestic firms compete in the global market, thereby shifting profits from foreign firms to national ones and increasing national income.[51]

Figure 12a shows optimal subsidy levels for different horizons. The optimal subsidy increases with the length of the policy horizon, because a longer horizon allows larger gains from

[50] Closed-form expressions defining these externalities in standard versions of the quality-ladder model can be found in Grossman and Helpman (1991b), Segerstrom (1998) and Jones and Williams (2000).

[51] This strategic role of subsidies was first analyzed with static partial equilibrium models in the strategic trade and industrial policy literature (e.g., Eaton and Grossman, 1986; Spencer and Brander, 1983).



A) Over different horizons

B) Over openness (over the fixed horizon of 35 years)

Figure 12: Optimal U.S. R&D subsidy, over different horizons and levels of openness

Notes: Panel A exhibits the profile of the optimal R&D policy for the United States over various policy horizons. Panel B exhibits optimal R&D policy rate for the United States over a fixed horizon of 35 years subject to varying degrees of globalization. Zero means the calibrated level of tariffs for both countries, and negative numbers mean a more global world.

policy-induced innovation and growth to materialize. The intertemporal knowledge spillovers motive for subsidies plays a key role here, as it springs from the failure of current innovators to internalize the benefit of their success for future innovators. A long-sighted policy maker wants to subsidize innovation more as she recognizes that this market failure is stronger when future innovation and growth is taken into account.

Another interesting result is shown in Figure 12b, where we plot the level of optimal subsidy for a fixed 35-year horizon in economies with varying degrees of openness, measured by the level of import tariff. In a more open world with smaller trade costs, the level of optimal R&D subsidy is lower, implying that a less aggressive policy is appropriate. In other words, the underinvestment in R&D in the home country is lower in a more open world, and the policy maker can correct it with a smaller subsidy.

This result is again driven by the innovation-boosting effect of foreign competition. As we discussed above, around the import and export cutoffs, the private incentive to innovate is stronger, because competition is stiffer. In between these cutoffs lies a region where competition is weak and innovation is scarce. Each domestic firm produces comfortably only for its domestic market, and being far from the cutoffs, it has neither a big risk of losing its market nor a big drive to gain new ones. As a result, the incentives to innovate are low. Trade liberalization decreases the distance between these cutoffs, shrinking the set of non-traded goods (goods sold only domestically), where competition and innovation are at their lowest.[52] If the mass of firms that are

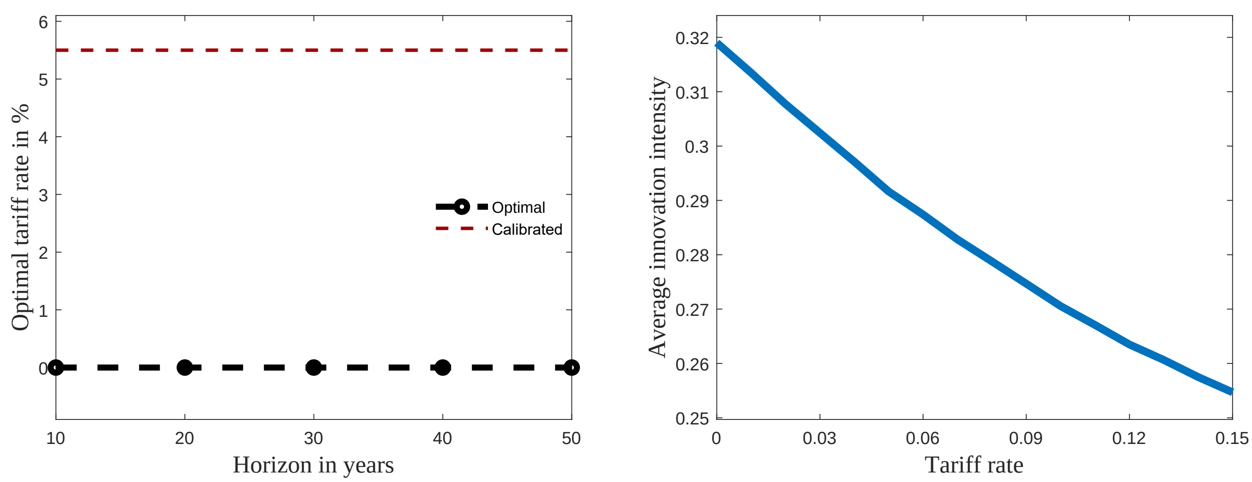
[52]Figure 11b shows that a tariff hike shifts the import cutoff left. Conversely, a reduction in tariffs would shift the import cutoff to the right. When the tariff reduction is bilateral, it pulls the two cutoffs toward each other.

exposed to higher competition as a result of the inward shift in cutoffs is large enough, trade liberalization has a strong positive effect on aggregate innovation incentivizing those firms to increase their effort. As such, trade liberalization helps to align private and public incentives for R&D. This is indeed the case in our benchmark economy, allowing the policy maker to pursue a less aggressive R&D policy in a more global world with lower bilateral tariffs.[53] This complementarity is a novel implication of our analysis, underscoring the relevance of investigating R&D policy in an open-economy setting that captures the essence of foreign competition.

An interesting observation is that this finding speaks closely to a recent policy event. After the Brexit vote, which will likely raise trade barriers between the UK and the European partners, the U.K. government introduced a new "industrial strategy" to boost productivity via investment in innovation and skilled workforce UK-Government (2017). Our finding on the interaction between optimal R&D subsidies and the level of trade openness provides an economic rationale for this policy decision—that is to compensate for the increased trade barriers with industrial policy that supports innovation.

4.4.2 Optimal Unilateral Tariffs

The negative relationship between the aggregate innovation effort and protection also plays an important role for the design of optimal tariff policy. As shown in Figure 13a, the optimal tariff policy, where the United States unilaterally sets the tariffs on goods imported to the United States, is to have zero tariffs for any horizon over which the policymaker calculates the welfare.



A) Optimal tariff policy over time horizons

B) Average innovation over openness

Figure 13: Optimal tariff policy and innovation over openness

Notes: Panel A shows the optimal unilateral tariff policy for the United States over various policy horizons. Horizontal dashed line denotes the calibrated tariff level. Panel B shows the negative effect of unilaterally higher U.S. tariff rates on average innovation intensity of U.S. firms.

[53] Figure A.10 (Appendix F) shows the increase in aggregate domestic innovation with lower bilateral trade barriers.

As Figure 13b demonstrates, the reason is the damping effect of tariffs on domestic aggregate innovation. This negative dynamic effect dominates static gains from tariffs including profit-shifting, which are typically found in standard static models, as elaborated below. As such, the policy maker optimally chooses to reduce tariffs to zero at any horizon under consideration.

To be sure, several motives for positive tariffs typical of standard static trade models are also at play in our framework. As is typical in intra-industry trade models (e.g., Ossa, 2011), countries can use tariffs to increase the mass of good produced at home, as shown in Figure 11b. This benefits home consumers as the related saving in trade costs lower their average price. If these benefits are larger than the losses produced by the effect of tariffs on the price of imported goods, countries have incentives to set positive import tariffs. The incentives are even stronger in frameworks with positive equilibrium profits, like ours, as the above "relocation" effect also carries a profit-shifting effect, which adds to the motivation for tariffs (e.g. Ossa, 2012). Finally, there is the terms of trade motive, typical of neoclassical trade models. An import tariff increases the profits of domestic firms, which in turn, raises the labor demand, domestic wages, and therefore, domestic prices. As a result, the country's terms of trade, defined as the ratio of ex-factory prices of export and import, improve. The fact that, in our model, the optimal tariff level is zero despite these motives for positive levels, emphasizes the significance of accounting for dynamic implications of tariffs. This new channel plays the key role in shaping the welfare effect of a tariff, driving the policy maker to optimally choose free trade at any policy horizon.

A caveat is in order. In a version of this model without Ricardian comparative advantage, the optimal tariff policy turns out to be positive in the short to medium run (Akcigit et al., 2018). There, the gains from profit–shifting are large enough to more than offset other losses generated by protectionist policies when relatively shorter horizons are considered. By contrast, a key margin in this model is the adjustment of the relative wage. As higher protection improves the home country's terms of trade, the induced increase in domestic production pushes up labor demand. This higher demand raises the cost of production in the home country relative to the foreign, generating a counteracting force to the competitiveness of domestic firms (see Figure A.12 in Appendix F). That force, in turn, limits the effective outward shift of the import cutoff in response to higher tariffs, and thus, the actual mass of firms that are protected. Consequently, the gains in aggregate profit income from higher tariffs are attenuated, falling short of offsetting the negative productivity effects of higher tariffs discussed above even in the short run.

4.4.3 Joint Policy Analysis: Optimal Innovation and Trade Policy

Having analyzed the implications of individual policy options, we now focus on the optimal joint policy in which the United States could use both R&D subsidy and one-sided tariff policy in tandem. Figure 14 plots the optimal R&D subsidy under this scenario over different horizons with a solid blue line, and the optimal tariff rate with a dashed blue line. The figure reveals that the optimal tariff level is again zero across all horizons as in the single policy experiment.

Similarly, the optimal R&D-policy profile is also rising with the length of the policy horizon under consideration, mimicking earlier results. However, an important difference is that the level of the optimal R&D subsidies is lower than the path obtained in the single policy experiment. The reason is that the concurrent large reduction in tariffs changes the incentives of a significant share of U.S. firms, with the attendant intensification of foreign competition inducing these firms to increase their innovation effort. This increase in overall innovation effort, in turn, reduces the need for aggressive R&D subsidies, underlining again the complementarity between the two policy tools. Yet, it is worth noting that when considering optimal policies, we assumed away any reaction from the foreign country and focused only on one-sided tariff policies. Appendix G discusses the implications of such foreign response.

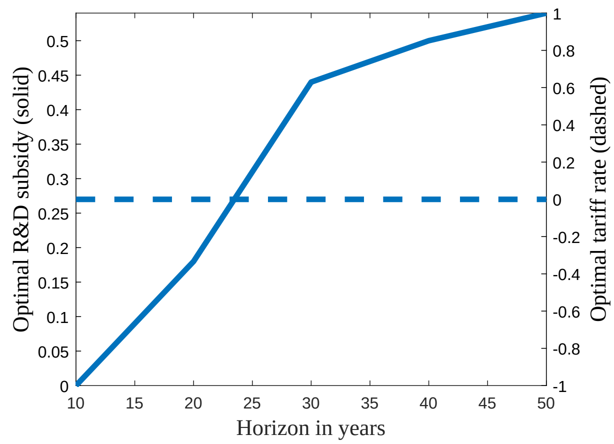


Figure 14: Optimal joint policy with unilateral tariff changes

Notes: The figure compares horizon-dependent optimal joint policy under the assumption of no foreign retaliation.

4.4.4 Sensitivity and Robustness

We provide various robustness checks for our main results, which we discuss in detail in Appendix H.[54] In each experiment, we recalibrate the model to accommodate a different assumption and compute the optimal policies implied by the re-calibrated models in each experiment along with the welfare implications. A common observation across different experiments is that for reasons discussed in Section 4.3, the optimal unilateral trade policy is the same as in the baseline calibration, which is zero tariffs regardless of the policy horizon. The optimal R&D subsidy rate is again increasing across longer policy horizons as in the baseline result, but with some quantitative differences depending on the experiment. All told, our main results remain robust to the alternative assumptions considered in this analysis.

[54]We consider the following six experiments: (i) lower maximum technology gap ($\bar{m}$), (ii) revisiting the calibration excluding the U.K. from the sample, (iii) revisiting the calibration using the distribution of quality-adjusted patents, (iv) revisiting the calibration using the distribution of cumulative patent counts, (v) a higher discount rate (ρ), and (vi) a higher price elasticity (lower β).

5 Foreign Competition and Domestic Innovation

A recent strand of papers in the empirical trade and firm dynamics literature has drawn notable attention thanks to their important, and seemingly contradictory, contributions to a heated topic: the effect of foreign competition on domestic firms and industries and, in particular, their innovative activity. Bloom et al. (2016) argue that Chinese import competition induced innovative activity in exposed domestic sectors in Europe [see also Coelli et al. (2016), Gorodnichenko et al. (2010), and Iacovone (2012)], whereas Autor et al. (2020) argue the opposite, using data on U.S. firms and sectors [see also Hashmi (2013) and Hombert and Matray (2015)], and yet a third set of papers including Aghion et al. (2017) find ambiguous results.

In this section, we show that our framework can help reconcile these seemingly contradictory observations in the literature. In particular, we present an exercise on rising import competition and illustrate that its effect on aggregate innovation crucially depends on the sectoral composition of domestic firms in terms of their technological competence relative to the foreign competitors. As a result, import competition has a non-monotonic impact on aggregate innovation, given the innovation profile in Figure 6a.

Our exercise considers three economies that differ in their technology position relative to the foreign competitor. One economy is in a relatively laggard initial condition—i.e., in most sectors, their firms are distant followers—another one is in a relatively frontier position, and the third one is an intermediate case. To generate intensifying import competition in our model, we consider a 50 percent decline in tariffs. As is evident from the earlier discussion of unilateral protectionist policies, this change shifts the defensive-R&D cutoff inwards, creating heterogeneous effects on firm innovation: Firms that fall further behind the defensive-R&D cutoff decrease their innovation effort, while firms that become closer to the cutoff intensify theirs. The overall effect at the aggregate level depends on the distribution of sectors across relative technological positions in foreign competition. Figure 15 illustrates this point. The values in the figure show the percentage change in the industry-level innovation rate in response to lower tariffs one year after the tariff change. In the economy with the largest mass of the relatively most laggard sectors, the effect is negative, while it becomes positive as the technological gap distribution shifts to the right. The reason is that the economy with less negatively skewed distribution includes relatively more firms that happen to be around the new defensive-R&D cutoff, feeling the more intense threat of losing markets and therefore exerting more innovative effort.

The comparison of the intermediate and the frontier economy, however, reveals that more advanced economies are not necessarily poised to benefit from intensifying foreign competition. The result hinges again on the share of firms in each economy that increase their innovative activity the most with intensifying competition. Even though the economy on the right is the most advanced one—its average technological lead over its trade partner is highly positive—a relatively large mass of laggard firms is responsible for an overall decline in aggregate innovation.

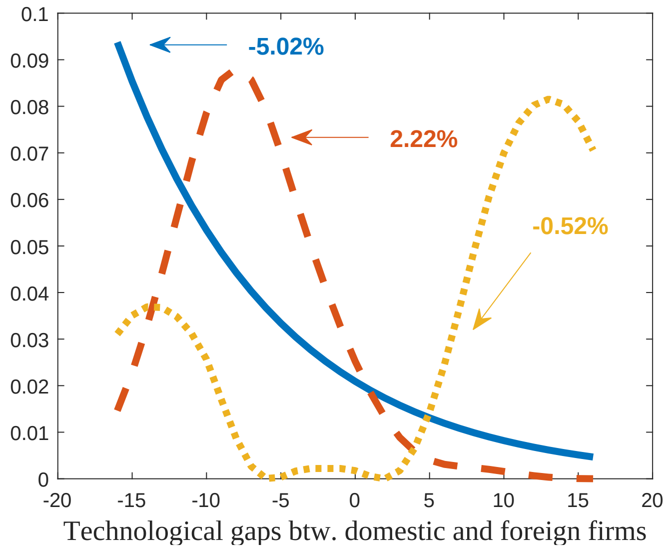


Figure 15: Effect of trade liberalization on aggregate innovation

Notes: The figure contrasts the change in aggregate innovation caused by trade liberalization in various sectors defined by different initial technological gap distributions. Specified values show percentage change in aggregate innovation in each sector.

These firms, now with their chances of capturing a market being diminished, become discouraged and decrease their innovation efforts in response to the intensified foreign competition, and in this case, this decline becomes the dominant force.

In sum, our analysis indicates that the impact of trade liberalization might have a positive or negative impact on the liberalizing economy's aggregate innovation level depending on the initial relative technology gap between the competing countries. Moreover, even a relatively very advanced economy might experience a reduction in aggregate innovation, if it has an enough number of sectors that are getting discouraged by foreign competition.

6 Conclusion

Motivated by a set of novel facts on advanced foreign countries catching up with the United States during the 1970s and 1980s, we build a general equilibrium framework of endogenous growth and trade to evaluate the effectiveness of innovation and trade policies in open economy. While realistically mimicking an extensive set of empirical relationships, our machinery is still tractable enough to allow for the analysis of transitional dynamics, which proves to be crucial for policy evaluation.

Our quantitative analysis shows that foreign technological catching-up hurts U.S. welfare by stealing away business and profits of U.S. firms. We find that the introduction of R&D subsidies in the U.S. in the early 1980s was an effective response to restore the technological competitiveness of U.S. firms, with a notable welfare contribution in the medium term. Moreover, the optimal subsidy is increasing over time horizons and decreasing in openness. The latter is an intriguing result, which owes again to the dynamic innovation-stimulating effect of foreign competition on domestic firms. In our model economy, future ideas leading to productivity improvements build on the stock of existing ideas, but companies do not account as to whether and to what extent their idea will benefit future innovators. The fact that current firms do not internalize these potential benefits generate underinvestment in R&D and provide a motive for R&D subsidies. Lower trade barriers—generating more competition in the domestic market and facilitating access to foreign markets—increase private companies' incentives to innovate and thereby diminish the necessity for government intervention. Finally, we consider a counterfactual protectionist response to foreign catching-up. We find that, increasing trade barriers for imports unilaterally is always detrimental fro welfare. The driving force of this result is again the link between trade and innovation. Despite helping national firms retain their market shares and profits in the short run, protectionism purges their incentives to innovate, thereby making consumers worse off over any horizon in consideration, and increasingly so over longer term.

Our new dynamic model, with its rich competition structure, provides a useful framework for future research on the effect of trade openness on firm dynamics. First, an intriguing question in this agenda is the impact of foreign direct investment on innovation incentives in the receiving country. Second, in regards to innovation policy, our framework can be used to analyze quantitatively the optimal policy design on intellectual property rights in open economies. Finally, the framework can shed new light on the design of optimal corporate tax policies in open economies, accounting for their broader dynamic implications on firms' innovation decisions. These are some exciting avenues for future research.

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For Online Publication: Appendices

A Additional Empirical Material

A.1 Empirical Facts

This section presents empirical regularities in global technological competition and describes the technological convergence between the United States and other major economies. An account of federal- and state-level R&D tax credit policies follows. The section concludes with suggestive evidence on the positive effect of R&D tax credits on firm-level performance.

Fact 1: Technological Convergence

There is a striking change in the relative position of foreign countries relative to the United States in the worldwide technological competition over the course of 1970s until the mid-1980s. At both aggregate and sectoral levels, we observe a clear pattern of catching-up, which we measure using patent and citation counts.

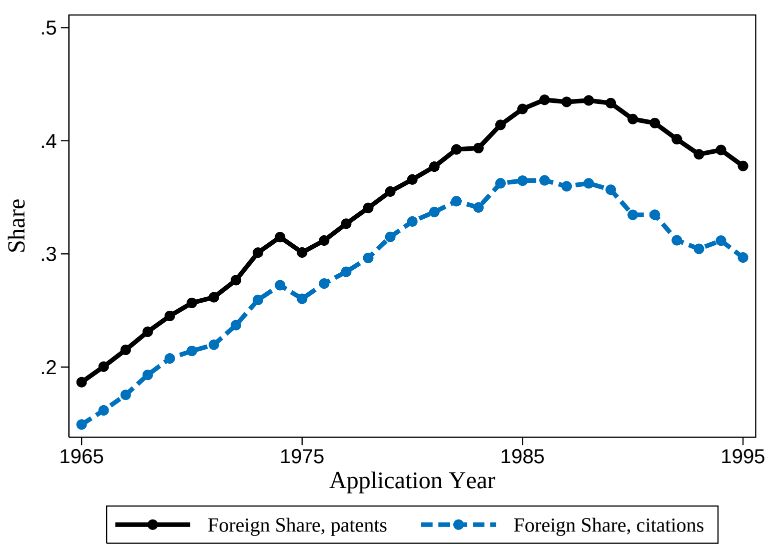


Figure A.1: Share of foreign patents: 1965-1995

Using USPTO data on patent counts, Figure A.1 shows the yearly change in the proportion of patents registered in the United States by foreign entities (solid line).[55] It also depicts the same ratio for the citations received by those patents (dashed line). Both lines display an obvious, increasing trend, which means that the growth in the number of foreign-based patents is higher than the growth in U.S.-based ones. Interestingly, the convergence process comes to a halt around the mid-1980s, and we observe a reversal of the trend.

[55]The distinction between domestic and foreign patents is by geographic location of registry. For more detail, see Hall et al. (2001).

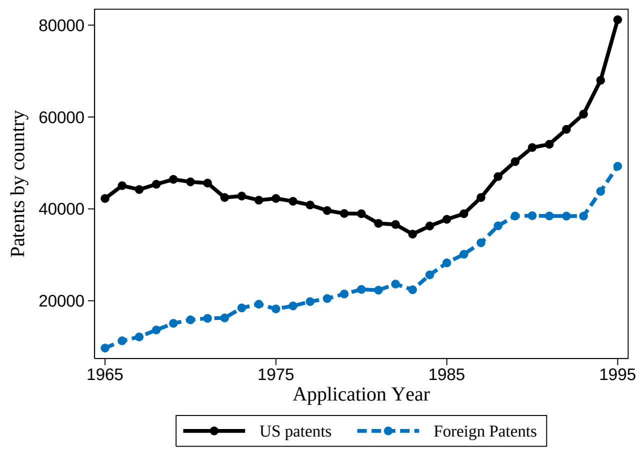


Figure A.2: Patent Counts

Fact 2: R&D Tax Incentives

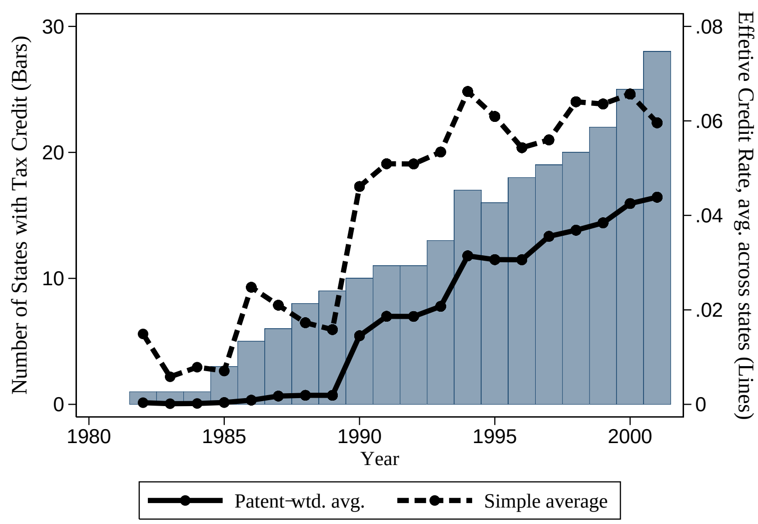
Concerns about the strength of the U.S. industries and their ability to compete in a fast-moving global economy increased dramatically in the late 1970s. The key discussions focused on whether the new technologies arising from federally funded R&D were being fully and effectively exploited for the benefit of the national economy, whether there were barriers slowing down private firms in creating and commercializing innovations and new technologies, and whether public-private collaboration in research and innovation could help the U.S. economy in facing these new challenges. Several new policy measures were introduced in those years, with particular attention to avoiding unduly substitution of government for private firms in activities that the latter can naturally perform better. These actions included several programs to facilitate the transfer of the outcome of the federal R&D to private businesses (e.g., the National Cooperative Research Act of 1984, and the Technology Transfer Act of 1986), policies to strengthen intellectual property rights such as the Bayh-Dole Act (1980), and in particular, tax incentives to innovation that started with the Research and Experimentation Tax Credit (R&E) in 1981.

The R&E Tax Credit introduced a 25 percent tax deduction on the increase in R&D spending over the average of the past three years. In 1985, the statutory rate was reduced to 20 percent, and in 1990 the base for eligibility was defined as the average of the 1984–88 R&D to sales ratio (with a maximum of 16 percent) times current sales. The U.S. competitors in high-tech industries—Japan and the large European economies—introduced, or already had in place, tax incentives for innovation. Using corporate tax data, Bloom et al. (2002) estimate the R&D subsidy produced by tax policies in the United States, Japan, and key European countries. The data take into account the different tax and tax credit systems used in each country and measure the reduction in the cost of $1 of R&D investment produced by the tax system. Figure 2b of the main text shows the R&D tax subsidy for the set of countries we are interested in.

The variations across countries are mainly due to the presence and effectiveness of a specific tax credit for R&D. The sudden increase in U.S. subsidies, for instance, takes place with the introduction of the R&E Tax Credit in 1981 and with the revision of the base defining incremental

R&D in 1990. We can see that in 1980 the reduction in innovation cost attributable to the tax system was about 5 percent; it jumps to about 15 percent in 1981, and further increases to more than 25 percent in 1990. In Japan, there is a fixed tax credit of limited effectiveness for the period considered. In the rest of the countries there are no special tax provisions or credits given on R&D expenditures, and the positive and fairly constant subsidy rates are produced by tax credits common to all assets.

In 1982, starting with Minnesota, U.S. states also introduced tax subsidies for R&D. In Figure A.3 we report the evolution of the average rate of U.S. state tax credits together with the number of states offering a tax credit each year, using tax credit data of Wilson (2009). The simple average of effective tax credits across states offering a credit was about 6 percent in 1995, nearly one-fourth of the federal one, and the number of states following such a policy rose to 32. Figure A.3 also shows the average R&D credit level weighted by the state-level patent production, whose evolution over time is parallel to the simple average.[56]



Source: Authors' calculations, USPTO, Wilson (2009)

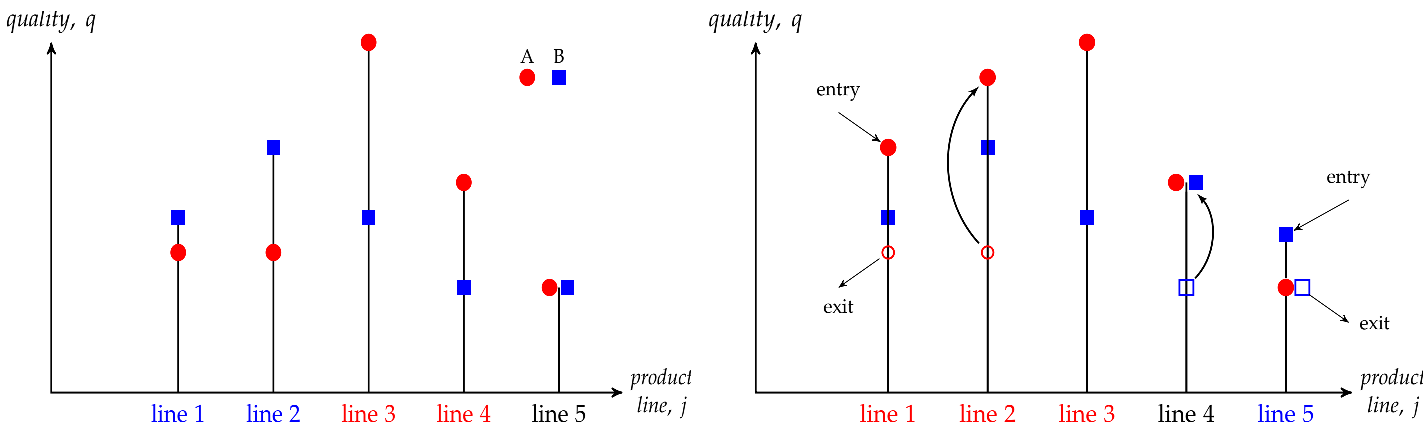
Figure A.3: U.S. state-level R&D tax credit

B Model Details and Derivations

B.1 Innovation and Firm Dynamics

Figure A.4 demonstrates the evolution of leadership in intermediate product lines as a result of incumbent innovation, entry, and exit. In the left panel, five product lines with heterogeneous technology gaps are shown. In the first two lines, firms from country B (designated by a square) lead, and in the next two lines, firms from country A (designated by a circle) lead. In the last line, firms are in neck-and-neck position. The right panel exhibits how these positions evolve. Country A seizes technological leadership in the first two lines in two different ways. In line 1, an

[56] As opposed to the simple average, the weighted average multiplies the state-level effective credit by the fraction of total U.S.-based patents registered in that state.



A) Product lines

B) Entry, exit, and leadership

Figure A.4: Evolution of product lines

Notes: Panel A exhibits the positions of competing incumbent firms with heterogeneous quality gaps in a set of product lines. Firms from country B (designated by blue squares) are technological leaders in the first two lines, firms from country A (red circle) are leaders in the next two lines, and firms are in neck-and-neck position in the last line. Panel B illustrates the effects of innovation by incumbents and entrants and the resulting dynamic of entry, exit, and technological leadership. Empty squares or circles denote the previous position of firms that innovate or exit.

entrant from A enters with a large enough quality improvement, moving ahead of the previous leader, who is from B, and also driving the previous domestic incumbent out of business. In line 2, the incumbent from A generates an innovation with a step size that is larger than the existing gap, which enables it to surpass the previous leader. While there is no change in line 3, firms become neck-and-neck in line 4 as a result of a successful innovation by the incumbent from B. In line 5, an entrant innovation from B breaks the neck-and-neck competition and brings the technological leadership to B, while also forcing the country's previous incumbent to exit.

Lastly, notice that changes in technological leadership may not result in business stealing when trade costs exist. Consider line 2, where country B's final-good producers initially buy domestic inputs from the technologically superior domestic intermediate producer. Even if technological leadership changes hands in this line, country B's final good producers may still prefer buying domestic intermediate inputs instead of importing the better-quality foreign input if trade costs make it unprofitable despite the quality advantage of country A's firm.

B.2 Discussion of the Distribution $\mathbb{F}(\cdot)$

In closed-economy step-by-step models, each innovation improves the existing quality of the follower either by a single step or by making the follower catch up with the leader no matter how big the initial gap is. The former is dubbed "slow catch-up regime," while the latter is dubbed "quick catch-up regime" in Acemoglu and Akcigit (2012). A slow catch-up regime would imply a slow process of convergence in leadership shares in contrast to what is observed in the data, and yet the quick catch-up regime would have the opposite effect. Therefore, by incorporating $\mathbb{F}(n)$, we generalize the modeling of firms' catching up and equip the model with enough flexibility to replicate the convergence process observed in the data. Note that this specification converges to the standard step-by-step model as $\phi \to \infty$.

The treatment of $\mathcal{A}(m)$ in the derivation of position-specific distributions serves the same purpose. An alternative could assume equal distribution of the truncated probability mass $\mathcal{A}(m)$ across potential positions $\{m+1, ..., \bar{m}\}$. This alternative would imply a relatively fatter right tail in $\mathbb{F}_m(n)$ and, thus, a higher chance of climbing up the position ladder. However, this structure would favor the United States, most of whose firms are technological leaders in their products, as opposed to the foreign countries, whose firms are lagging in most product lines. Even though a laggard firm can close the gap by multiple steps, a leading firm in this alternative setup could easily open up the gap again. It happens because for a leading firm, equal allocation of $\mathcal{A}(m)$ across the few better positions the firm may reach entails a higher chance of reaching better positions quickly again (as compared to the current specification where the probability of one-step improvements is disproportionately higher at larger leads). Because of this advantage of the leading firms, the model, once initiated at the empirical distribution, would have a strong force working against the shift in the leadership distribution toward smaller gaps, as the empirical distribution strongly favors the United States in the early years of the sample period. This feature would contrast with the convergence process in the data. By contrast, our current structure with innovations of heterogeneous step sizes helps the model generate the correct speed of convergence as in the data, while the distributional assumptions capture the idea of "advantage of backwardness" as in Gerschenkron (1962), as relatively more laggard firms are in a more advantageous position to receive multiple-step innovations.

B.3 Illustration of Trade Costs and the Technology Frontiers

Without loss of generality and abstracting from wage differentials, Figure A.5 illustrates a special case where the quality frontiers of the two economies align perfectly in a descending order of qualities across sectors. The solid lines define the quality frontier of the domestic intermediate producers, where A and B denote the home and the foreign country, respectively. The dashed lines show the level of these qualities when adjusted by trade and relative input costs. Firms of the home country can export a product as long as the cost-adjusted quality, denoted by the dashed line A', is higher than the domestic quality of that product available in the foreign country, denoted by the solid B line. When the reverse occurs, the home country imports the higher-quality product. Otherwise, firms serve only their domestic markets. Two intersections of dashed and solid lines determine two cutoffs that define three regions of product lines according to their position in trade.

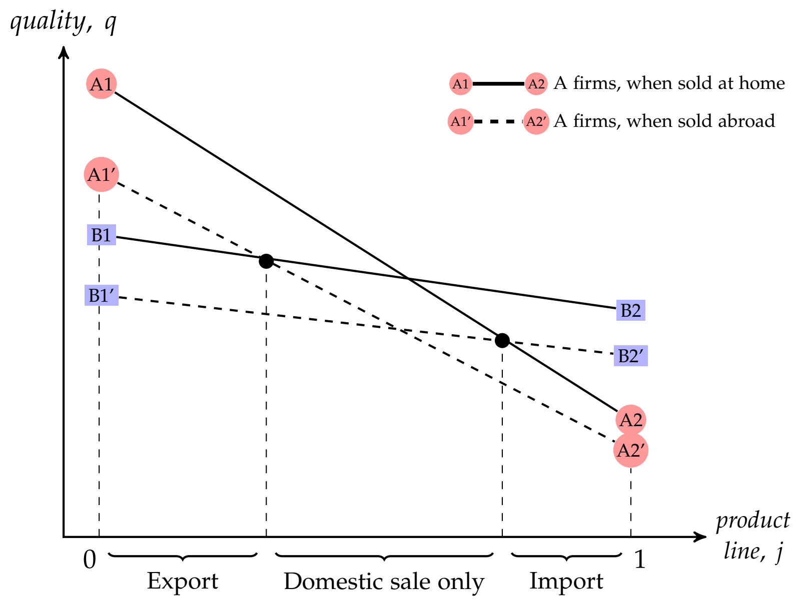


Figure A.5: Effect of trade costs on quality and trade flows

Notes: The figure exhibits the technology frontiers, defined as the product qualities of incumbent firms over all product lines, of two countries in an example economy (shown by the solid lines). When exporting, the effective technology frontiers (given by the dashed lines) are lower than the actual ones because the exporters need to incur trade costs.

B.4 Proofs

Lemma 1 We confirm this lemma by guess-and-verify method. Conjecture the following form: $V_{cmt} = qv_{mt}$. Substituting this expression into equation (18), we get:

$$
\begin{aligned}
r_{At}v_{Amt}q - \dot{v}_{Amt}q = \max_{x_{Amt}} \Pi(m)\, q - \left(1 - s^A\right) \alpha_A \frac{(x_{Amt})^{\gamma_A}}{\gamma_A} q \\
+ x_{Amt} \left[\sum_{n_t = m+1}^{\bar{m}} \mathbb{F}_m(n_t)\, v_{Ant} \lambda^{(n_t - m)} q - v_{Amt} q \right] \\
+ \tilde{x}_{Amt} \left[0 - v_{Amt} q \right] \\
+ \left(x_{B(-m)t} + \tilde{x}_{B(-m)t} \right) \sum_{n_t = -m+1}^{\bar{m}} \mathbb{F}_{-m}(n_t) \left[v_{A(-nt)} q - v_{Amt} q \right].
\end{aligned}
$$

Dividing all sides by q, we obtain the desired result:

$$
r_{At}v_{Amt} - \dot{v}_{Amt} = \max_{x_{Amt}} \left\{ \begin{array}{c} \Pi_t\left(m; \tau^A, \tau^B\right) \bar{w}_{ct}^{\frac{\beta-1}{\beta}} - \left(1 - s^A\right) \alpha_A \frac{(x_{Amt})^{\gamma_A}}{\gamma_A} \\ + x_{Amt} \sum_{n_t = m+1}^{\bar{m}} \mathbb{F}_m(n_t) \left[\lambda^{(n_t - m)} v_{Ant} - v_{Amt} \right] + \tilde{x}_{Amt} \left[0 - v_{Amt} \right] \\ + \left(x_{B(-m)t} + \tilde{x}_{B(-m)t} \right) \sum_{n_t = -m+1}^{\bar{m}} \mathbb{F}_{-m}(n_t) \left[v_{A(-nt)} - v_{Amt} \right] \end{array} \right\}.
$$

B.5 Value Functions for Boundary Gaps

To complete the exposition of incumbents' problem we present the two boundary cases where the incumbent is $\bar{m}$-steps ahead (behind):[57]

$$r_{At}V_{A\bar{m}t}(q) - \dot{V}_{A\bar{m}t}(q) = \max_{x_{A\bar{m}t}} \Bigg\{ (\pi L_A + \pi^* L_B)\, q - \left(1 - s^A\right) \alpha_A \frac{(x_{A\bar{m}t})^{\gamma_A}}{\gamma_A} q + x_{A\bar{m}t}\left[V_{A\bar{m}t}(\lambda q) - V_{A\bar{m}t}(q)\right] + \tilde{x}_{A\bar{m}t}\left[0 - V_{A\bar{m}t}(q)\right] + \left(x_{B(-\bar{m})t} + \tilde{x}_{B(-\bar{m})t}\right) \sum_{n_t=-\bar{m}+1}^{\bar{m}} \mathbb{F}_{-\bar{m}}(n_t)\left[V_{A(-n)t}(q) - V_{A\bar{m}t}(q)\right] \Bigg\},$$

and

$$r_{At}V_{A(-\bar{m})t}(q) - \dot{V}_{A(-\bar{m})t}(q) = \max_{x_{A(-\bar{m})t}} \Bigg\{ - \left(1 - s^A\right) \alpha_A \frac{\left(x_{A(-\bar{m})t}\right)^{\gamma_A}}{\gamma_A} q + x_{A(-\bar{m})t} \sum_{n_t=-\bar{m}+1}^{\bar{m}} \mathbb{F}_{-\bar{m}}(n_t)\left[V_{Ant}\left(\lambda^{(n_t+\bar{m})} q\right) - V_{A(-\bar{m})t}(q)\right] + \tilde{x}_{A(-\bar{m})t}\left[0 - V_{A(-\bar{m})t}(q)\right] + \left(x_{B\bar{m}t} + \tilde{x}_{B\bar{m}t}\right)\left[V_{A(-\bar{m})t}(\lambda q) - V_{A(-\bar{m})t}(q)\right] \Bigg\}.$$

The last term in the value function of $\bar{m}$-step-behind incumbent captures the knowledge spillovers. When a leader at the maximum gap $\bar{m}$ innovates, the follower in this sector automatically sees its technology jump by a measure λ, reflecting a form of international knowledge spillovers. In each period this spillover keeps laggard firms in the innovation race, preventing them from falling too far behind. Because the innovation technology is the same for all firms, laggards always have a chance to catch up.

B.6 Entrant Firm Value

Recall that entry is directed at individual product lines and a successful entrant improves on the active domestic incumbent's technology. The problem of an entrant that aims at a product line where the domestic incumbent is $m > 0$ ($m < 0$) steps ahead (behind) is as follows:

$$\tilde{V}_{cmt}(q_t) = \max_{\tilde{x}_{cmt}} \left\{ -\frac{\tilde{\alpha}_c}{\tilde{\gamma}_c}\left(\tilde{x}_{cmt}\right)^{\tilde{\gamma}_c} q_t + \tilde{x}_{cmt} \sum_{n_t=m+1}^{\bar{m}} \mathbb{F}_m(n_t)\, V_{cnt}\left(\lambda^{(n_t-m)} q_t\right) \right\}. \tag{A.1}$$

Again, $\mathbb{F}_m(\cdot)$ denotes the probability distribution of potential step sizes, from which a random step will realize conditional on having an innovation. An entrant who fails to innovate exits the

[57] These value functions assume that $\bar{m}$-step ahead leader captures both the domestic and the foreign market—i.e., the quality advantage at the largest gap is enough to cover the trade costs.

economy. Solving this problem leads to the following equilibrium value of the entrant firm:

$$\tilde{V}_{cmt}(q_t) = \left(1 - \frac{1}{\tilde{\gamma}_c}\right)\tilde{\alpha}_c\left(\tilde{x}_{cmt}\right)^{\tilde{\gamma}_c} q_t > 0,$$

which is independent of the production line's index j and is determined by the current gap size.

B.7 Aggregation and the Distribution of Leadership

The growth rate of this economy is determined by the changes in aggregate quality across intermediate goods, Q_{cmt}. In order to analyze the evolution of aggregate quality and breaking it down into its various sources we need to consider all possible scenarios of innovation outcomes and keep track of the resulting changes in quality levels across product lines at each gap size. Changes in Q_{Amt} are characterized by the following expressions:[58]

$$\begin{aligned}\dot{Q}_{Amt} = &\sum_{s=-\bar{m}}^{m-1}\mathbb{F}_s(m)\left(x_{Ast}+\tilde{x}_{Ast}\right)\lambda^{m-s}Q_{Ast} + \sum_{s=m+1}^{\bar{m}}\mathbb{F}_{-s}(-m)\left(x_{B(-s)t}+\tilde{x}_{B(-s)t}\right)Q_{Ast}\\ &-\left[x_{Amt}+x_{B(-m)t}+\tilde{x}_{Amt}+\tilde{x}_{B(-m)t}\right]Q_{Amt}\end{aligned}$$

$$\dot{Q}_{A\bar{m}t} = \left[\left(x_{A\bar{m}t}+\tilde{x}_{A\bar{m}t}\right)(\lambda-1) - x_{B(-\bar{m})t} - \tilde{x}_{B(-\bar{m})t}\right]Q_{A\bar{m}t} + \sum_{s=-\bar{m}}^{\bar{m}-1}\mathbb{F}_s(\bar{m})\left(x_{Ast}+\tilde{x}_{Ast}\right)\lambda^{\bar{m}-s}Q_{Ast}$$

$$\dot{Q}_{A(-\bar{m})t} = \left[\left(x_{B\bar{m}t}+\tilde{x}_{B\bar{m}t}\right)(\lambda-1) - x_{A(-\bar{m})t} - \tilde{x}_{A(-\bar{m})t}\right]Q_{A(-\bar{m})t} + \sum_{s=-\bar{m}}^{\bar{m}-1}\mathbb{F}_s(\bar{m})\left(x_{Bst}+\tilde{x}_{Bst}\right)Q_{A(-s)t}.$$

The first equation is the generic expression that describes the change in the aggregate quality of intermediate goods produced by firms from country c at position m. The first sum captures the addition of new incumbents improving to gap m. An innovation with step size λ^{m-s} by a domestic incumbent or entrant at position $s < m$ happens with probability $\mathbb{F}_s(m)$, and it implies that the domestic incumbent in that product line will reach gap m. The second sum captures the addition of product lines, where the position of the domestic incumbent worsens to m from a better one. An improvement by foreign incumbents or entrants from position $-s < -m$ to $-m$, which occurs with probability $\mathbb{F}_{-s}(-m)$, hits the domestic incumbent in that product line enjoying the position $s > m$ and brings it down to gap m. The third component in the equation captures the fact that any innovation in a product line where the domestic incumbent is at position m causes a change in its position and, thus, a negative change in the aggregate quality index across product lines of position m. The other two equations describe the boundary cases. In case of $\bar{m}$, notice that innovation by the domestic incumbent or entrants does not change the gap between the domestic incumbent and the foreign follower due to spillover effects, but raises the average quality by the step size. Reciprocally, any innovation by the foreign incumbent or entrant improves the quality of the good that the most laggard domestic incumbents produce

[58]The evolution of the variables for country B is given reciprocally.

because of spillover effects.

The laws of motion that determine the measure of product lines where the incumbent from country c is at position m are described by

$$
\begin{aligned}
\dot{\mu}_{A\bar{m}t} &= \dot{\mu}_{B(-\bar{m})t} = \textstyle\sum_{s=-\bar{m}}^{\bar{m}-1} \mathbb{F}_s(\bar{m})\left(x_{Ast}+\tilde{x}_{Ast}\right)\mu_{Ast} - \mu_{A\bar{m}t}\left(x_{B(-\bar{m})t}+\tilde{x}_{B(-\bar{m})t}\right) \\
\dot{\mu}_{Amt} &= \dot{\mu}_{B(-m)t} = \textstyle\sum_{s=m+1}^{\bar{m}} \mathbb{F}_{-s}(-m)\left(x_{B(-s)t}+\tilde{x}_{B(-s)t}\right)\mu_{Ast} \\
&\quad + \textstyle\sum_{s=-\bar{m}}^{m-1} \mathbb{F}_s(m)\left(x_{Ast}+\tilde{x}_{Ast}\right)\mu_{Ast} \\
&\quad - \left[x_{Amt}+x_{B(-m)t}+\tilde{x}_{Amt}+\tilde{x}_{B(-m)t}\right]\mu_{Amt} \\
\dot{\mu}_{A(-\bar{m})t} &= \dot{\mu}_{B\bar{m}t} = \textstyle\sum_{s=-\bar{m}}^{\bar{m}-1} \mathbb{F}_s(\bar{m})\left(x_{Bst}+\tilde{x}_{Bst}\right)\mu_{A(-s)t} - \mu_{A(-\bar{m})t}\left(x_{A(-\bar{m})t}+\tilde{x}_{A(-\bar{m})t}\right).
\end{aligned} \tag{A.2}
$$

The drivers of the dynamics are the same as in the case of aggregate quality indices, except that step sizes are not relevant in determining the changes in μ. Notice that the change in the measure of position-m product lines in a country corresponds to the change in the measure of position-$(-m)$ product lines in the other country. Moreover, because there is a unit measure of intermediate product lines we have $\sum_m \mu_{cm} = 1$. Therefore, information on $2\bar{m}-1$ measures is enough to describe the distribution of product lines according to the technological gap size between the two active incumbents from each country.

B.8 Definition of the Equilibrium

Definition 1 (Equilibrium) *Let the world economy consist of two countries $c \in \{A, B\}$. A Markov Perfect Equilibrium is an allocation*

$$\left\{r_{ct}, w_{ct}, f_{ct}, p_j, k_{jt}, k^*_{jt}, x_{cjt}, \tilde{x}_{cjt}, Y_{ct}, C_{ct}, R_{ct}, G_{ct}, L_c, \left\{\mu_{cmt}, Q_{cmt}\right\}_{m\in\{-\bar{m},\ldots,\bar{m}\}}\right\}_{c\in\{A,B\}, j\in[0,1]}^{t\in[0,\infty)}$$

such that (i) the sequence of prices and quantities p_j, k_{jt}, k^*_{jt} satisfy equations (11)-(12) and maximize the operating profits of the incumbent firm in the intermediate-good product line j; (ii) the R&D decisions $\left\{x_{cjt}, \tilde{x}_{cjt}\right\}$ are defined in equations (19) and (20), and R_{ct} is given in equation (21); (iii) supply of fixed factor L_c is equal to the profit-maximizing demand by the final-good producers defined by equation (8); (iv) Y_{ct} is as given in equation (16); (v) C_{ct} is as derived from equation (2); (vi) fixed factor compensations f_{ct} clears the markets for the fixed factor at every t; (vii) wages w_{ct} clear the labor markets at every t; (viii) interest rates r_{ct} satisfies the households' Euler equation; (ix) government has a balanced budget at all times in line with equation (22); (x) and $\left\{\mu_{cmt}, Q_{cmt}\right\}_{m\in\{-\bar{m},\ldots,\bar{m}\}}$ are consistent with optimal R&D decisions.

C Analytical Results in a Simplified Model

In this appendix, we discuss some of the key economic forces of our model in more detail providing analytical characterizations. We split the discussion into two parts: static and dynamic. Even though it is not possible to express the equilibrium objects in a fully analytical form in transition, we make significant progress in that direction by focusing on a simplified version here. One departure from the full–fledged model that we will maintain in the theoretical exposition for the sake of clarity is that the intermediate goods are produced using the final good at a constant marginal cost η.[59] We start with the discussion of static forces.

C.1 Static Effects of Openness

In this subsection, we will abstract from iceberg costs and we will consider two extreme economies: open economy (i.e., no tariffs) versus autarky (i.e, prohibitive tariffs). We can solve for the static equilibrium for these two alternative economies and show that income of the fixed factor is always bigger in an open economy—i.e., $f^{autarky} < f^{open}$. This result is intuitive. In a world with open economies, more productive intermediate-good producers sell to the final-good producers in both countries. This selection channel facilitates the transfer of better-quality intermediate goods across countries, increasing the productivity of the fixed factor utilized in the production of domestic final output. Therefore, this channel, labeled as *direct transfer of technology* in Keller (2004), leads to a higher fixed factor income in both countries.

However, the impact of openness on profits is not obvious. In contrast to the state of autarky, the open economy allows relatively more productive firms to sell to a larger market by providing the opportunity to export. Yet, at the firm level the selection channel implies that less productive domestic firms lose their profits to foreign competitors, which they would earn otherwise in autarky, causing a decline in aggregate profit income. As a result, the net effect of openness on total profits remains ambiguous. Proposition 1 summarizes these findings.

Proposition 1 *In the environment without iceberg trade costs described above:*

A) *Opening the economy to international trade increases the income of the fixed factor, i.e., $f^{autarky} < f^{open}$. However, the total change in profits of the domestic business owners is ambiguous and depends on the initial composition of the technology gaps between two countries, i.e., $\int_0^1 \Pi_j^{autarky} dj \lesseqgtr \sum_{m=-\bar{m}}^{\bar{m}} \mu_m \Pi_m^{open}$.*

B) *The static effect of unilateral trade policy liberalization (reduction in tariffs) on aggregate income is shaped by the loss of profits to foreign exporters and the gain in fixed factor income and, therefore, has an ambiguous direction.*

Before presenting the proof of the proposition, let us describe the static effects of opening up to trade in more detail. At the aggregate level, the static effects of openness on the income

[59] For the description of the version without labor input in intermediate good production, see Akcigit et al. (2018). This assumption simplifies the analytical exposition by eliminating the general equilibrium adjustment through wages. In the quantitative analysis, we discuss how this channel affects the results.

and welfare of consumers stem from three main channels, with two of them having a positive direction and one having a negative direction. To show this, we consider a closed economy and analyze the effects of it opening up. In autarky, the total output in country c is

$$Y_c^C = \left[\frac{1-\beta}{\eta}\right]^{\frac{1-\beta}{\beta}} (1-\beta)^{-1} \int_0^1 q_{cj} dj \equiv \varphi \int_0^1 q_{cj} dj,$$

which is produced using only domestic intermediates. Likewise, the fixed factor and profit incomes are

$$w_c^C = \beta Y_c^C \quad \text{and} \quad \Pi_c^C = \pi \int_0^1 q_{cj} dj = \beta (1-\beta) Y_c.$$

The gross national income, sum of profits and fixed factor income, is given by

$$NI_c^C = \beta (1-\beta) Y_c^C + \beta Y_c^C = (2-\beta) \beta \varphi \int_0^1 q_{cj} dj.$$

When this economy opens to trade (subject only to tariffs) the same expressions become

$$\begin{aligned} Y_c^O &= \left[\frac{1-\beta}{\eta}\right]^{\frac{1-\beta}{\beta}} (1-\beta)^{-1} \left[\int_0^1 \mathbb{I}_{q_{cj} > \hat{q}_{c'j}} q_{cj} dj + \int_0^1 \mathbb{I}_{q_{cj} < \hat{q}_{c'j}} \hat{q}_{c'j} dj\right] \\ &= Y_c^C + \varphi \int_0^1 \mathbb{I}_{q_{cj} < \hat{q}_{c'j}} \left[(1+\tau)^{-\frac{1-\beta}{\beta}} q_{c'j} - q_{cj}\right] dj, \end{aligned}$$

where we define $\hat{q} \equiv q / (1+\tau)^{\frac{1-\beta}{\beta}}$, abstracting from iceberg costs for now. Similarly,

$$w_c^O = \beta Y_c^O \quad \text{and} \quad \Pi_c^O = \pi \int_0^1 \mathbb{I}_{q_{cj} > \hat{q}_{c'j}} q_{cj} dj + \pi^* \int_0^1 \mathbb{I}_{\hat{q}_{cj} > q_{c'j}} q_{cj} dj,$$

with gross income given by

$$NI_c^O = \pi \int_0^1 \mathbb{I}_{q_{cj} > \hat{q}_{c'j}} q_{cj} dj + \pi^* \int_0^1 \mathbb{I}_{\hat{q}_{cj} > q_{c'j}} q_{cj} + \beta Y_c^O. \tag{A.3}$$

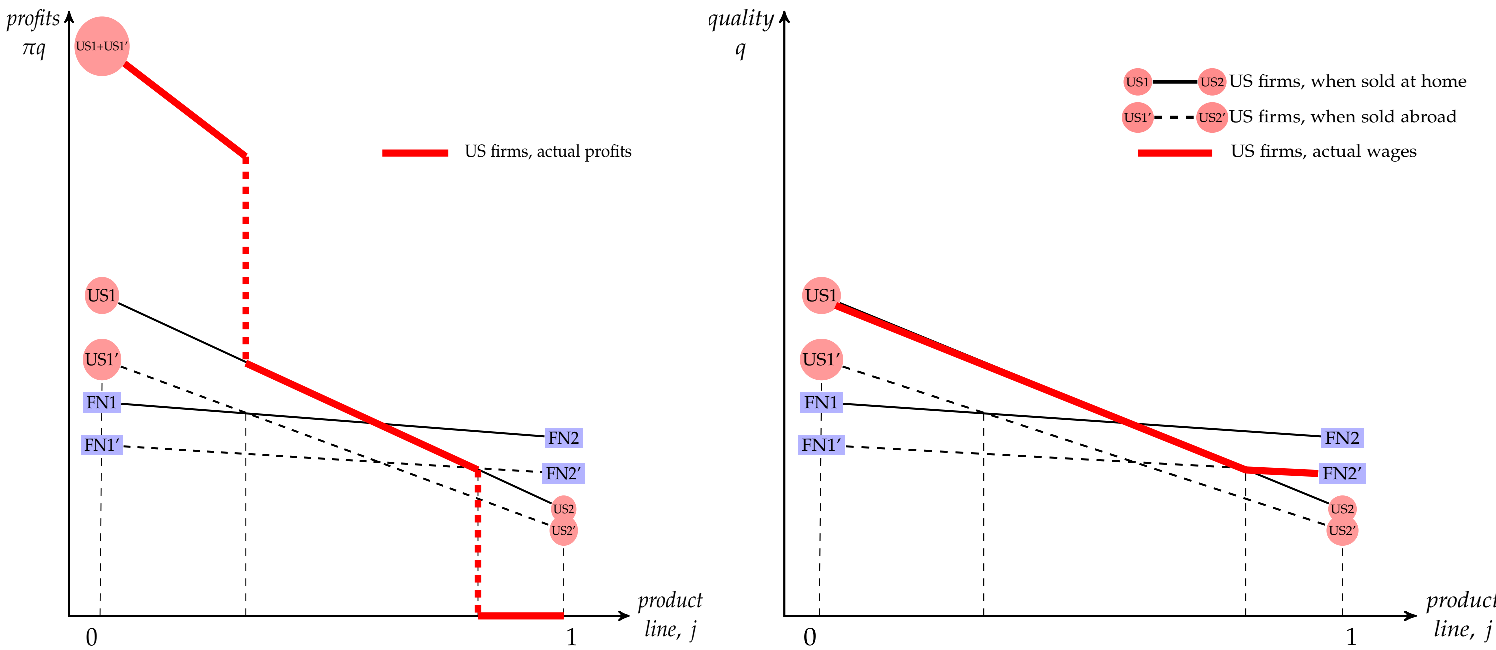
Thus, the comparison between incomes in autarky and the open economy boils down to the comparison of

$$\int_0^1 q_{cj} dj \;\; \text{and} \;\; \int_0^1 \mathbb{I}_{q_{cj} > \hat{q}_{c'j}} q_{cj} dj + (1+\tau)^{-\frac{1-\beta}{\beta}} \int_0^1 \mathbb{I}_{\hat{q}_{cj} > q_{c'j}} q_{cj} dj,$$

determining the profit component, and to the comparison of

$$\int_0^1 q_{cj} dj \;\; \text{and} \;\; \int_0^1 \mathbb{I}_{q_{cj} > \hat{q}_{c'j}} q_{cj} dj + (1+\tau)^{-\frac{1-\beta}{\beta}} \int_0^1 \mathbb{I}_{q_{cj} < \hat{q}_{c'j}} q_{c'j} dj,$$

determining fixed factor income. Figure A.6 illustrates these comparisons. As in Figure A.5, solid lines determine the domestic technology frontier, whereas dashed lines show the iceberg cost-adjusted levels of these frontiers that emerge when engaging in trade. The left panel shows the product lines and the associated qualities that determine aggregate profit income for the



A) Effect on profits

B) Effect on fixed factor income

Figure A.6: Static effects of openness

Notes: Panel A illustrates the profits generated by the U.S. incumbents in an example economy. In autarky, profits are given by the solid line US1-US1′, whereas in an open economy, profits are given by the thick red line starting at (US1+US1′). When the economy is open, exporters earn the sum of profits from selling both domestically, based on their actual product quality (solid line US1-US2), and abroad, based on their trade-cost-adjusted quality (dashed line US1′-US2′). Firms that cannot export and sell only domestically generate profits based on their actual product quality. Incumbents in sectors where the U.S. imports the specific good have zero profits. Panel B illustrates the relevant quality frontier that determines the labor productivity and, thus, the domestic fixed factor income paid in the final-good sector. In autarky, the relevant frontier is given by the product qualities of all domestic firms (US1-US1′). In an open economy, the relevant quality frontier (thick red line US1-FN2) is the upper envelope of product qualities available in both countries, taking into account the quality of imported intermediate goods.

home country in an open world. The right panel shows the technology frontier that determines the productivity of the domestic fixed factor.

First, compared to the state of autarky, the open economy allows relatively more productive firms to sell to a larger market by providing the opportunity to export. This positive effect of *market size* on aggregate income is evident from the first component in equation (A.3), as profits of leading firms increase proportionally by π^*. This increase corresponds to the upward expansion of the red line in Figure A.6a, determined by the additional income from exporting. Note that the effective quality when exporting is reduced by trade costs. The second static effect of openness works through the *selection* of more productive intermediate-good producers due to increased competition exerted by foreign competitors. This selection channel facilitates the transfer of better-quality intermediate goods across countries, increasing the productivity of the fixed factor utilized in the production of domestic final output. Figure A.6b illustrates this selection mechanism, which indicates that the fixed factor productivity is a function of the upper envelope of product qualities available in the international market. Therefore, this channel, labeled as *di-*

rect transfer of technology in Keller (2004), leads to a higher fixed factor income in both countries.[60] However, the selection channel implies at the firm level that less productive domestic firms lose the profits to foreign competitors, which they would earn otherwise in autarky, resulting in a decline of aggregate profit income. As illustrated in Figure A.6a, some product lines fail to generate profits, as they are substituted by imports.

Next we present the proof of Proposition 1.[61]

Proof of Proposition 1 The effect of opening up on fixed factor income is given by $\Delta f = \beta\phi\Delta_f$, where Δ_f is defined as the following difference:

$$\begin{aligned}\Delta_w &\equiv \int_0^1 \mathbb{I}_{q_{cj}>\hat{q}_{c'j}} q_{cj} dj + (1+\tau)^{-\frac{1-\beta}{\beta}} \int_0^1 \left[1 - \mathbb{I}_{q_{cj}>\hat{q}_{c'j}}\right] q_{c'j} dj - \int_0^1 q_{cj} dj \\ &= \int_0^1 \mathbb{I}_{q_{cj}<\hat{q}_{c'j}} \left(\hat{q}_{c'j} - q_{cj}\right) dj \\ &> 0.\end{aligned}$$

The transfer of better technology affects this component positively. The total effect on profits given by $\Delta\Pi = \pi\Delta_\Pi$, where Δ_Π is defined as the following difference:

$$\begin{aligned}\Delta_\Pi &\equiv \int_0^1 \mathbb{I}_{q_{cj}>\hat{q}_{c'j}} q_{cj} dj + (1+\tau)^{-\frac{1-\beta}{\beta}} \int_0^1 \mathbb{I}_{\hat{q}_{cj}>q_{c'j}} q_{cj} dj - \int_0^1 q_{cj} dj \\ &= \int_0^1 \mathbb{I}_{\hat{q}_{cj}>q_{c'j}} \hat{q}_{cj} dj - \int_0^1 \mathbb{I}_{q_{cj}<\hat{q}_{c'j}} q_{cj} dj \\ &\lesseqgtr 0.\end{aligned}$$

The first component is the gain from exports, and the second component is the loss of profits from firms that are laggard in international competition. The direction of the difference depends on the measure of leading firms in country c as well as on the difference between the average quality of country c's leading and laggard firms.

Therefore, the combined effect on national income, which reads as

$$\Delta f + \Delta\Pi = \beta\varphi\Delta_f + \pi\Delta_\Pi,$$

is ambiguous.

In the case of unilateral tariff reduction, domestic exporters are not affected, as the unilateral tariff reduction only affects the cutoff for imports. Therefore, its effect is determined by the loss of domestic profits and the gains from technology transfer driven by the higher import volume. Conversely, in an extreme case where a country is lagging in all sectors by a very small margin, opening to trade from autarky may decrease national income initially, as the small productivity gain from transferring slightly better technology may not compensate for the loss of profits in all

[60] Notice that iceberg costs prevent the trade of some better-quality foreign goods available in the market.

[61] Additionally, scale effects arise in a setting where competing countries are of different sizes. For a discussion, see Chapter 15 in Aghion and Howitt (2009).

sectors.

C.2 Dynamic Effects of Openness and Escape Competition

In order to emphasize the dynamic strategic interaction between intermediate producers introduced by foreign competition, we focus on a special case of our model. In particular, we consider a standard step-by-step open-economy setting with two symmetric countries that abstracts from firm entry, features quick catch-up by followers, and minimizes the incentives for quality improvements. First, we take $\tilde{\alpha}_c \to \infty$ implying zero entry in both countries. Second, innovations improve a leader's position by a single step—i.e. $\mathbb{F}_m(n = m+1) = 1$, $\forall m \geq 0$. Third, we set $\mathbb{F}_m(n = 0) = 1$, $\forall m < 0$, to allow any innovating follower to reach neck-and-neck position. Fourth, we assume that $\lambda = 1 + \varepsilon$ where ε is arbitrarily close to zero, implying that quality improvements from innovations are minuscule.[62] The following proposition argues that, in this environment, firms in neck-and-neck position have the highest innovation intensity.

Proposition 2 *The above assumptions imply that*

1. *the innovation intensity becomes the highest at neck-and-neck position;*
2. *the followers innovate at the same intensity and strictly less than the neck-and-neck firms;*
3. *the leaders do not innovate.*

Formally, $x_0 > x_{-m} = x_{-\bar{m}} > x_{\bar{m}} = x_m = 0$ *for* $m > 0$.

Proof. In this environment firm values can be written as

$$
\begin{aligned}
rv_{-\bar{m}} &= -\frac{x_{-\bar{m}}^2}{2} + x_{-\bar{m}}\left[v_0 - v_{-\bar{m}}\right] \\
rv_{-m} &= -\frac{x_{-m}^2}{2} + x_{-m}\left[v_0 - v_{-m}\right] + x_m\left[v_{-m-1} - v_{-m}\right] \\
rv_0 &= -\frac{x_0^2}{2} + x_0\left[v_1 - v_0\right] + x_0\left[v_{-1} - v_0\right] \\
rv_m &= 2\pi - \frac{x_m^2}{2} + x_m\left[v_{m+1} - v_m\right] + x_{-m}\left[v_0 - v_m\right] \\
rv_{\bar{m}} &= 2\pi - \frac{x_{\bar{m}}^2}{2} + x_{\bar{m}}\left[v_{\bar{m}} - v_{\bar{m}}\right] + x_{-\bar{m}}\left[v_0 - v_{\bar{m}}\right]
\end{aligned}
$$

with $m \in \{1, ..., \bar{m} - 1\}$.[63] Note that $v_{-m} = v_{-\bar{m}}$ and $v_m = v_{\bar{m}}$ satisfy the set of equation for $m > 0$. This implies that we have three distinct firm values and innovation rates, and that $x_{\bar{m}} = x_m = 0$.

Now we show $x_0 > 0$, $x_{-\bar{m}} > 0$ and $x_0 > x_{-m} = x_{-\bar{m}}$.

1. $v_{\bar{m}} > v_0$: Assume not such that $v_0 \geq v_{\bar{m}} = v_1$. Then $[v_1 - v_0] \leq 0$, and $x_0 = 0$. This implies $v_0 = 0 \geq v_{\bar{m}} = v_1$. But $v_0 = 0$ would mean $rv_{\bar{m}} = 2\pi - x_{-\bar{m}}v_{\bar{m}}$ and thus $v_{\bar{m}} > 0$, a contradiction. Therefore $x_0 > 0$.

[62] Therefore, innovation incentives are driven by business-stealing and escape-competition effects.

[63] Lemma 1 applies also in this environment. For the sake of the argument, we assume that neck-and-neck firms have zero profits. We also drop country identifiers thanks to symmetry.

2. $v_0 > v_{-\bar{m}}$: Assume not such that $v_{-\bar{m}} \geq v_0$. Then $x_{-\bar{m}} = 0$ implying that $v_{-\bar{m}} = 0 \geq v_0$. This is possible only if $x_0 = 0$. But since $v_{\bar{m}} > v_0$ as shown above, $x_0 > 0$, a contradiction. Therefore $x_{-\bar{m}} > 0$.

3. $[v_{\bar{m}} - v_0] > [v_0 - v_{-\bar{m}}]$: Assume not such that $[v_0 - v_{-\bar{m}}] \geq [v_{\bar{m}} - v_0]$ .This means $v_0 < 0$ unless $x_0 = 0$. If $v_0 < 0$, it is a contradiction by step 2. If $x_0 = 0$ meaning that $v_0 = 0$ it is a contradiction by step 1. Therefore $[v_{\bar{m}} - v_0] > [v_0 - v_{-\bar{m}}]$ and $x_0 > x_{-m} = x_{-\bar{m}} > x_{\bar{m}} = x_m = 0$.

■

Proposition 2 formalizes the fact that the positive effect of foreign competitive pressures on innovation incentives becomes the strongest when firms compete against rivals producing goods of similar quality. This effect is analogous to the one in closed-economy step-by-step models—namely, the "escape-competition" effect—but it gains an international aspect in the context of a small open economy. Moreover, notice that in our general model, the international structure modifies the escape-competition effect in more subtle ways than merely shifting the origin of the competitive pressure from domestic to foreign. In fact, the intensification of innovation as a result of international competition arises at two points in our generalized model instead of one because of trade costs. Firms have an incentive to escape competition for two similar yet distinct reasons: to capture domestic profits (defensive R&D); and to capture export markets (expansionary R&D). These important dynamic effects, reflecting again market size and selection channels, are completely absent in a static comparison.

D Solution Algorithm

1. Let $\mathbb{M}$ be the set of data moments and $\mathbb{M}^m$ be the model counterpart. Define $\mathbf{R}(\mathbb{M} - \mathbb{M}^m)$ as the function that calculates a weighted sum of the difference between data and model moments.

2. Guess a set of values for the internally calibrated parameters θ_{guess}.

3. Calculate the balanced growth path (BGP), where time derivatives are zero by definition. Start iteration $h = 0$ with the guess $\{r_T^A, r_T^B, \omega_T\}^{h=0}$.

   (a) At iteration h, take $\{r_T^A, r_T^B, \omega_T\}^h$ given and solve incumbent firm values jointly for both countries by backward iteration.

      i. Given ω_T, compute the implied import and export cutoffs $\{m_{AT}^M, m_{AT}^X\}^h$.

      ii. Guess $\{v_{AmT+\Delta t}, v_{BmT+\Delta t}\}_{m\in\{-\bar{m},..,\bar{m}\}}$. Assuming these to be the true BGP values compute innovation rates $\{x_{AmT}, \tilde{x}_{AmT}, x_{BmT}, \tilde{x}_{BmT}\}_{m\in\{-\bar{m},..,\bar{m}\}}$. Notice that these are innovation rates at one period before, as innovation is a forward looking decision and thus depends on the next period value in discrete time.

      iii. Compute $\{v_{AmT}, v_{BmT}\}_m$ using the value function equations. By the definition of BGP, values at $T + \Delta t$ and T should be the same.

iv. Check if

$$\max_{m,c} \|v_{cmT+\Delta t} - v_{cmT}\| < \varepsilon.$$

If not met, set $\{v_{cmT+\Delta t}\}_m = \{v_{cmT}\}_m$ and repeat.

(b) Take the BGP innovation rates and set $Q_{Am0} = 1\ \forall m$. Iterate forward on aggregate quality indices Q_{cmt} using the transition equations until growth rates of the implied income processes for both countries and the relative wage stabilize. Call these $\{g_T^A, g_T^B, \omega'_T\}^h$.

(c) Check if (i) $\{r_T^A, r_T^B\}^h$ and $\{g_T^A, g_T^B\}^h$ meet the Euler equation; and (ii) ω_T^h and $\omega_T'^h$ converge. If not, set $\{r_T^A, r_T^B\}^{h+1}$ to interest rates implied by the Euler equation with $\{g_T^A, g_T^B\}^h$ and ω_T^h to $\omega_T'^h$. Repeat until convergence.

4. Next calculate the equilibrium over the transition. Start iteration $h = 0$ by guessing a time path for interest rates $\{r_t^A, r_t^B, \omega_t\}_{t=\{1975,...,1975+T\}}^{h=0}$. The terminal values are set to the BGP at every iteration.

   (a) At iteration h, given the guess for relative wages $\omega_{t=\{1975,...,1975+T\}}^h$, compute the implied import and export cutoffs $\{m_{At}^M, m_{At}^X\}_{t=\{1975,...,1975+T\}}^h$.

   (b) Given the terminal (BGP) values $\{v_{AmT}, v_{BmT}\}_m^h$ compute the implied innovation rates $\{x_{AmT-\Delta t}, \tilde{x}_{AmT-\Delta t}, x_{BmT-\Delta t}, \tilde{x}_{BmT-\Delta t}\}_m^h$. Then, given terminal interest rates $\{r_T^A, r_T^B\}^h$, compute $\{v_{AmT-\Delta t}, v_{BmT-\Delta t}\}_m^h$. Iterate backwards using the $\{r_t^A, r_t^B\}_{t=\{1975,...,1975+T\}}^h$ until $t_0 = 1975$ to obtain the implied series $\{x_{Amt}, \tilde{x}_{Amt}, x_{Bmt}, \tilde{x}_{Bmt}\}_{mt=\{1975,...,1975+T\}}^h$.

   (c) Set $Q_{Am0} = 1\ \forall m$. Using the implied innovation rates, compute the endogenous evolution of Q_{cmt} and μ_{cmt} for $t = \{1975, ..., 1975 + T\}$ by forward iteration and back up the implied income processes.

   (d) Compute the implied income growth rates and the relative wages $\{g_t^A, g_t^B, \omega'_t\}_t^h$. Using period-by-period Euler equations, check if

$$\max_{c,t} \left\{ \left\| \{g_t^c\}^h - \frac{\{r_t^c\}^h - \rho}{\psi} \right\| + \left\| \{\omega'_t\}^h - \{\omega_t\}^h \right\| \right\} < \varepsilon.$$

   for $\{1975, ..., 1975 + T - 1\}$. If not, set $\{r_t^A, r_t^B\}_{t=\{1975,...,1975+T-1\}}^{h+1}$ to interest rates implied by the Euler equation with $\{g_t^A, g_t^B\}_{t=\{1975,...,1975+T-1\}}^h$ and $\{\omega_t\}_{t=\{1975,...,1975+T-1\}}^{h+1}$ to $\{\omega'_t\}_{t=\{1975,...,1975+T-1\}}^h$. Repeat until convergence.

5. Once step 4 converges, use the final interest rates and relative wages $\{r_t^A, r_t^B, \omega_t\}_{t=\{1975,...,1975+T\}}$ to compute equilibrium firm decisions, the aggregate variables and the model counterparts of the data moments.

6. Minimize $\mathbf{R}\left(\mathbb{M} - \mathbb{M}^m\left(\theta_{guess}\right)\right)$ using an optimization routine.

As discussed in footnote 37, the final–good producer observes the quality of the foreign good only imperfectly. Therefore, she may choose to produce using one variety (domestic or foreign) even if the true effective quality gap implies the other one is the better option. This assumption ensures a smooth transition path. Let us provide an example to show how this assumption works.

Recall that the export cutoff was defined by the following relationship:

$$m \log \lambda \geq (1-\beta)\left[\frac{1}{\beta}\log(1+\kappa) - \log\left(\frac{\bar{Q}_{Bt}}{\bar{Q}_{At}}\frac{Q_{At}}{Q_{Bt}}\right)\right].$$

The smallest integer $m^X \in \mathbb{N}$ that satisfies this relationship is the export cutoff. First, notice that the *iid* error has a bearing on the optimal variety decision of the final–good producer only around the export/import cutoffs. Suppose that the true effective technology gap between two firms is m. If $m^X \notin [m-1/2, m+1/2]$, the imperfectly observed quality of the foreign variety would not alter the decision of the final good producer. Now let us consider the other case. Suppose that $m^* = 13.7$ makes the expression above hold with equality. Then, a firm would need to open the gap at least 14 steps to be able to export, if the true quality was observed by the foreign buyer with certainty. But in the setting with imperfect observability, even if a foreign firm is 14 steps ahead, the observed technology gap may fall anywhere in [13.5,14.5] with equal probability. Consequently, there is a 20 percent chance that the quality of the foreign good was observed at a value that makes the observed gap below 13.7. In that event, importing would become seemingly unprofitable for the final-good producer, and the foreign firm would not be able to export its good.

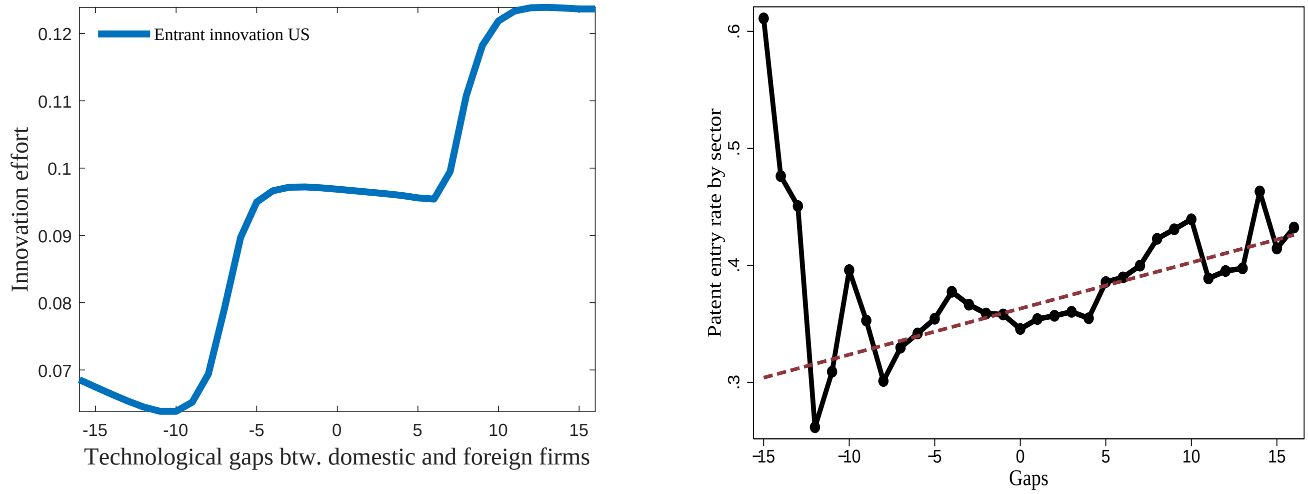
This adjustment ensures a smooth numerical transition, removing any discontinuity in the solution—especially, in the implied equilibrium wage rates—that may arise when the export/import cutoffs change endogenously from one integer to another.

E Additional Validation Exercises

Validation Exercise III: Entrant Innovation vs. Leadership

Entry is another source of business stealing in the model. However, in contrast to incumbents, potential entrants are not subject to immediate competitive pressures from the other country's firms. Therefore, the shape of entrants' R&D effort profile, demonstrated in Figure A.7a, reflects mainly the market size effect around the two cutoffs and not a direct effect of foreign competition.

Because entry to the highest gaps implies access to export markets, it is more profitable, leading to a higher entry effort aimed at these positions. Figure A.7b shows that this is indeed the case in the USPTO patent data, where we again classified sectors into bins according to the technological lead, as in Figure 6b. The solid black line in the figure depicts the flow of new patents (normalized by the number all U.S. patents in that sector-year observation to eliminate sectoral differences in patenting intensity) registered by U.S. residents that appear for the first



A) Entrant innovation intensity in model

B) Patenting intensity of U.S. entrants in data

Figure A.7: Entrant innovation effort and leadership

Notes: Panel A shows the innovation intensity of U.S. entrant firms in the balance growth path of calibrated economy. Panel B shows the average entry rate of patents applied for by the U.S. firms that appear in a sector in the USPTO data for the first time across technology gaps (for the creation of the technology gaps, see Figure 4). Number of patents by new patentees is weighted by the number of all patents registered by U.S. residents. The fitted line shows predicted values from a weighted linear regression of average entry rate on bins weighted by the number of sector-year observations in each bin.

time in a sector, averaged out across sector-year observations between 1975 and 1995 in each bin.[64] The dashed line shows the density-weighted regression line for 33 technology gaps. We observe that the entry intensity is higher for sectors where existing U.S. firms have larger technological leads over their foreign competitors.

Validation Exercise IV: Credit Elasticity of R&D

The ultimate source of growth in our model is innovation. Therefore, when analyzing the effect of policies on aggregate outcomes, a correct measurement of the responsiveness of innovative activity to policy changes is of utmost importance. In order to evaluate our estimated model's implications in that regard, we now investigate the empirical elasticity of innovative activity to R&D credits and compare it with its model counterpart.

In order to measure the credit-elasticity of innovation, we exploit the state-level variation in the dates when credit policies came into action and conduct a simple firm level regression analysis using the Compustat database. The regression specification is as follows:

$$\ln Y_{jst} = \beta_0 + \beta_1 \ln SC_{st} + \beta_2 \ln Y_{jst-1} + \psi_j + \psi_t + u_t \,, \qquad \text{(A.4)}$$

where ψ_j and ψ_t represent firm and year dummies, respectively, and u_t is the error term. SC_{st} is the tax credit level in state s where firm j operates. For the dependent variable Y we use both $R\&D$ and patent counts. We utilize two different specifications for this regression that differ in

[64]Observations of the same sector over different years are treated as separate entries in Figure A.7b.

the inclusion of the lagged value of the dependent variable. The results are summarized in Table A.1. All versions (represented by columns of the table) reveal the positive effect of state level R&D tax credits on the firms' innovative activities. This effect is also robust to the existence of lagged values of the dependent variable in the regression.

Table A.1: The effect of R&D tax credit on innovation (excl. federal credits)

Dep. Var.:	$\ln(R\&D_t)$ (1)	$\ln(R\&D_t)$ (2)	$\ln(Patents_t)$ (3)	$\ln(Patents_t)$ (4)
$\ln(State\ credit_t)$	3.153	0.524	2.948	1.203
	(10.92)***	(2.12)**	(10.93)***	(4.28)***
$\ln(R\&D_{t-1})$	-	0.631	-	-
	-	(106.67)***	-	-
$\ln(Patent_{t-1})$	-	-	-	0.499
	-	-	-	(72.83)***
Year Dummy	Yes	Yes	Yes	Yes
Firm Dummy	Yes	Yes	Yes	Yes

Notes: The table lists the results obtained from different OLS specifications that illustrate the effect of (U.S. state-level) tax credits on U.S. firms' innovation. t-statistics are provided in parentheses. ***, **, and * denote significance at 1 percent, 5 percent, and 10 percent, respectively.

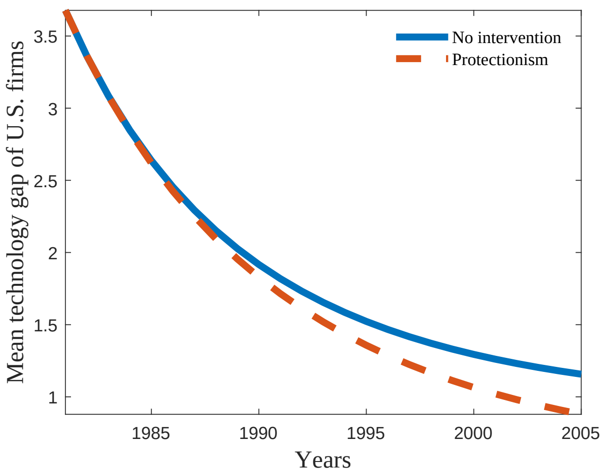
The first column of Table A.1 shows that, on average, the elasticity of R&D spending with respect to changes in R&D credit is 3.15. To ensure the quantitative validity of firms' response to policy changes in our model, we derive the model counterpart of the same statistic. We first compute the log-difference in R&D expenditure for incumbent firms of country A in each position m right before and after the subsidy change from s^A_{75-81} to s^A_{81-95}. Following the same steps used to create empirical variables, the average elasticity of R&D spending to subsidy is given by

$$\int_0^1 \frac{d\log\left(\alpha_A x^{\gamma_c}_{Aj1981} q_{j1981}\right)}{d\log\left(1+s^A_{1981}\right)} dj = \sum_m \frac{d\log\left(\alpha_A x^{\gamma_c}_{Am1981} Q_{Am1981}\right)}{\log\left(1+s^A_{81-95}\right) - \log\left(1+s^A_{75-81}\right)}.$$

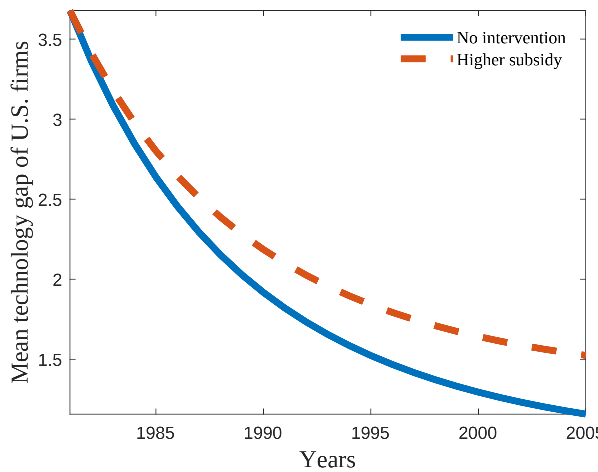
This model statistic has a value of 2.29 in contrast to 3.15 in the data. It implies that in the model, an increase in R&D subsidy induces a solid response of R&D expenditure, in line with its empirical counterpart, although its strength is somewhat weaker than in the data. Note that the empirical economy-wide elasticity is likely to be lower than state-level elasticity due to reallocation of resources across states; therefore, it is also reassuring to see that our simulated macro elasticity is below the state-level empirical estimate.

F Additional Figures

Figure A.8 demonstrates the effect of tariff and R&D policies on the model-implied time path of average technological lead of U.S. firms over their competitors. Increasing unilateral protection leads to a relatively lower path, while higher subsidies result in a uniformly higher path relative to the one in the case of no policy intervention.



A) 5.5-percentage-point unilateral tariff hike



B) Actual R&D policy

Figure A.8: Average technology lead of the U.S. firms, after policy intervention

Figure A.9 replicates 6b incorporating patents with assignee id "0" in the analysis. The inclusion of these patents lead to sharper peaks.

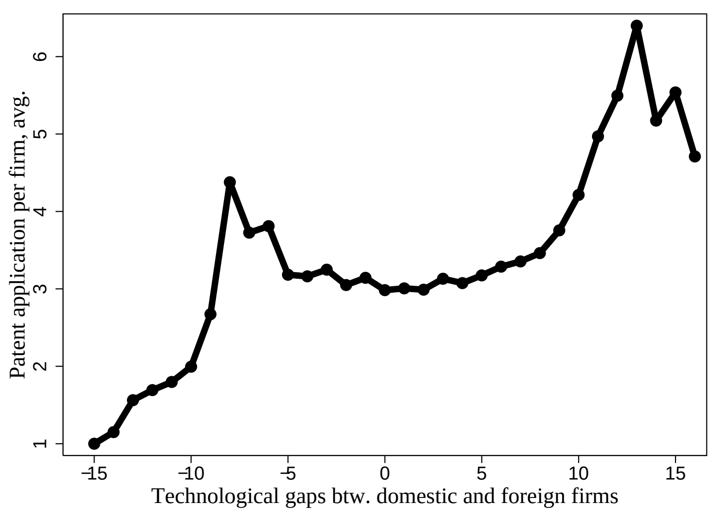


Figure A.9: Patenting intensity in USPTO data, including assignee id "0"

Figure A.10 demonstrates the negative effect of bilateral tariffs on aggregate U.S. innovation. Notice that the slope (in absolute terms) is higher when tariffs are raised bilaterally, implying a stronger effect on innovation than that of unilateral tariff increases (see Figure 13b).

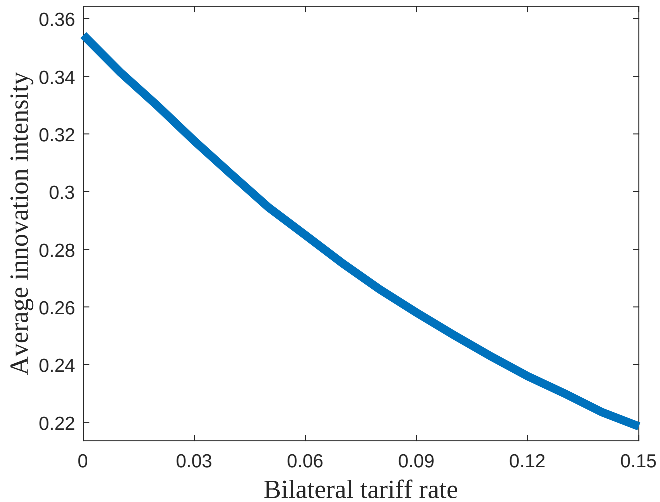


Figure A.10: Aggregate U.S. innovation over bilateral tariff levels

Notes: The figure shows the weakening effect of bilateral tariffs on domestic aggregate innovation in the US.

Figure A.11 shows the welfare loss in response to a bilateral 5.5-percent increase in tariffs. Retaliatory tariff measures lead to a substantial welfare loss in the United States, which is rising over time (about 2.9% over a 50-year horizon).

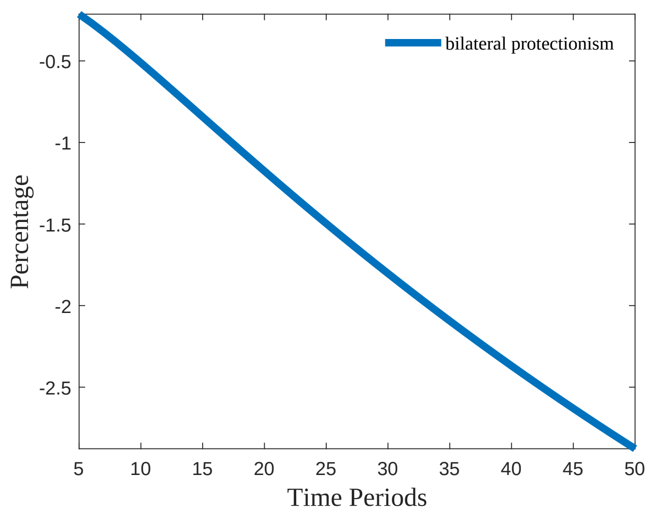


Figure A.11: Welfare under protectionism with foreign retaliation

Notes: The figure illustrates the consumption–equivalent change in welfare over different time horizons in response to a bilateral 5.5-percentage-point tariff increase.

Figure A.12 compares the time path of the relative wages ($\omega_{At} \equiv \bar{w}_{At}/\bar{w}_{Bt}$) in the baseline environment (the solid line) and in the alternative economy with higher unilateral tariffs in country A after 1981 (the dashed line). The unilateral tariff increase clearly pushes up ω_{At}, decreasing the competitiveness of the domestic firms (see equations 13 and 14).

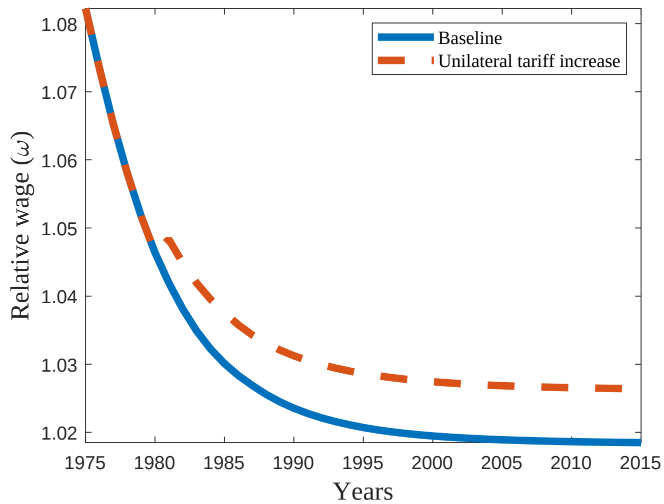


Figure A.12: Relative wages

Notes: Figure A.12 compares the time path of the relative wages ($\omega_{At} \equiv \bar{w}_{At}/\bar{w}_{Bt}$) in the baseline environment (the solid line) and in the alternative economy with higher unilateral tariffs in country A after 1981 (the dashed line).

G Effect of Foreign Retaliation and Optimal Joint Policy Revisited

In order to understand the effect of foreign retaliation on the design of trade policy, we analyze our policy alternatives under the assumption that any change in tariffs imposed by the home country is perfectly matched by the foreign one.[65] Figure A.13 shows the optimal joint policy in this modified setting with bilateral tariff changes (circled black lines), in juxtaposition with the results obtained in the benchmark setting (blue lines).

Again, the optimal policy liberalizes the economy's trade regime as much as possible, removing tariffs irrespective of the length of the policy horizon under consideration. This finding would be expected, as there are stronger incentives for this choice when the foreign country retaliates. In this setting, protectionist policies limit not only the market for imports to the home country, but also exports from the home country, because the tariff changes are replicated by the foreign trade partner. The effects of retaliatory tariff increases on the U.S. incumbents are demonstrated in Figure A.14. As opposed to Figure 11b, the cutoff for exports increases, making them accessible to only a small group of firms. With the export cutoff rising as a result of higher trade barriers, a reduction in innovative activity—driven by similar reasons explained in the analysis of unilateral policies—occurs now for a wider range of firms.[66] Conversely, liberal policies expand the export market of the home country and stimulate innovation for a large set

[65]The introduction of the Smoot-Hawley Tariff Act in the United States during the early stages of the Great Depression provides an example of how the unilateral introduction of trade policies could trigger retaliatory responses from trade partners, potentially harming the domestic economy.

[66]Figure A.11 in Appendix F illustrates the associated welfare losses when trade policy is analyzed alone but subject to the threat of foreign retaliation. Retaliatory tariff measures lead to a substantial welfare loss in the United States, which is rising over time (about 2.9% over a 50-year horizon for a 5.5 percent bilateral tariff increase). Similarly, bilateral tariffs also hurt foreign households, leading to a 2.6% decline in welfare in consumption-equivalent terms over a 50-year horizon.

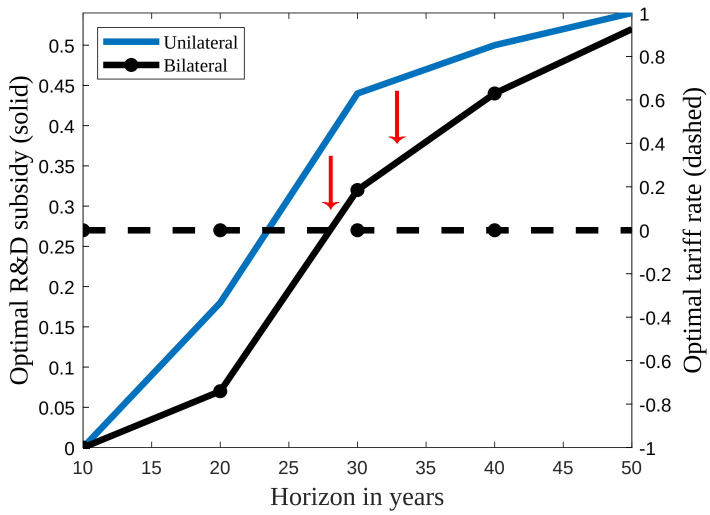


Figure A.13: Optimal joint policy in unilateral and bilateral tariff changes

Notes: The figure compares horizon-dependent optimal joint policy in case of (trade-policy) retaliation to that in the baseline.

of firms via a more intense expansionary R&D motive. Given that most U.S. incumbents are in technologically leading positions, the optimal trade policy under the assumption of retaliation favors these firms by opening up their markets to export, at the expense of a few more laggard firms losing their markets to foreign importers.

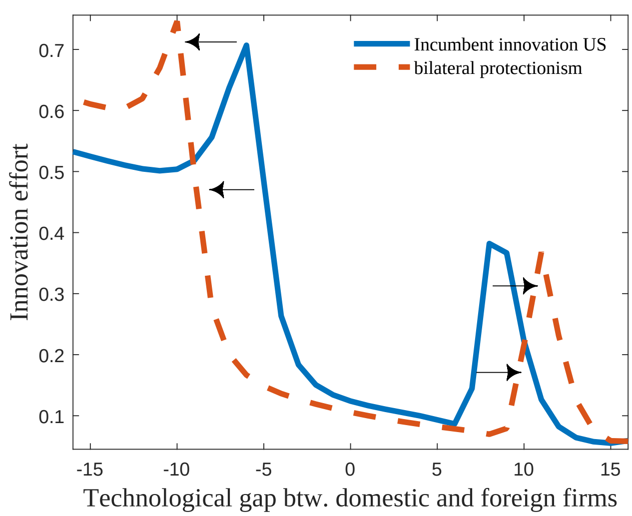


Figure A.14: Innovation response to protectionism with foreign retaliation

Notes: The figure illustrates the effect of a bilateral increase in tariffs on the the innovation-effort profile of U.S. incumbent firms over technology gaps in BGP.

While there are no significant qualitative differences in the schedule of optimal R&D subsidy levels, quantitatively, the optimal levels are lower than in the previous experiment (no retaliation of trade policy). The rationale behind this finding is again the innovation–boosting effect of more open economies, which we discussed in relation to our findings illustrated in Figure 12b. When both countries reduce tariff levels, competition intensifies for a large chunk of firms, incentivizing them to innovate, which, in turn, reduces the magnitude of underinvestment in R&D and the need for aggressive R&D subsidies.

H Sensitivity and Robustness

We provide various robustness checks for our main results, and Table A.2 summarizes the optimal policies implied by the re-calibrated models in each experiment. The resulting optimal unilateral trade policies are the same as in the baseline calibration, which is zero tariffs regardless of the policy horizon (Panel B of Table A.2). Therefore, in the remainder, we will focus on the sensitivity of optimal R&D subsidies to alternative calibrations, which are summarized in Panel A of Table A.2. The welfare implications of optimal policies are shown in Table A.3.

Table A.2: Policy experiments in alternative scenarios

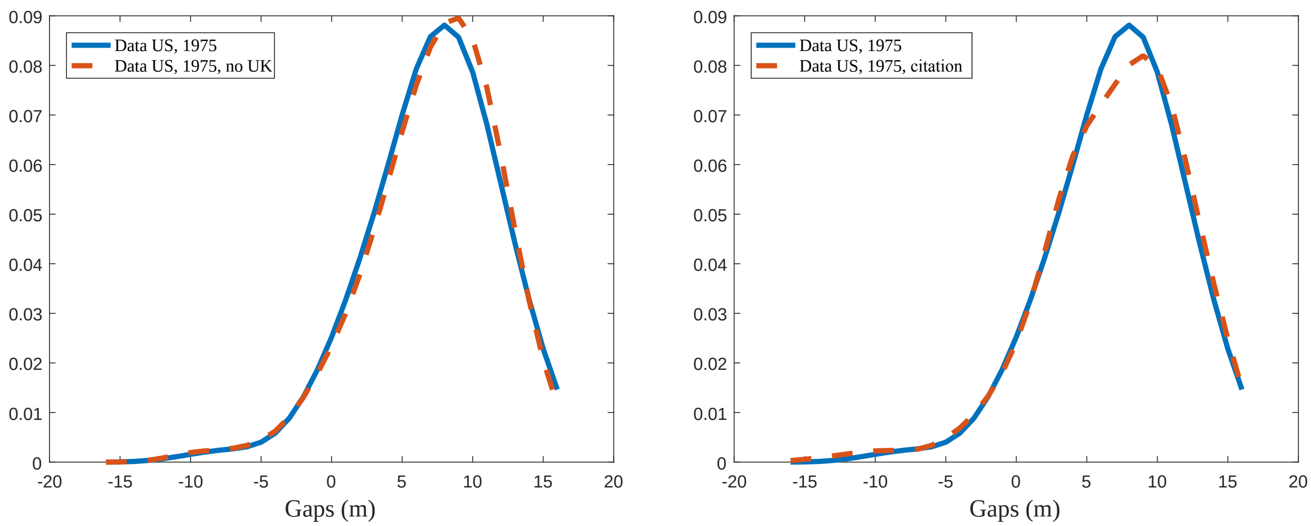
Panel A	Optimal subsidy levels				
Horizon in years	10	20	30	40	50
Baseline	0%	27%	51%	57%	67%
Lower $\bar{m}$	0%	27%	49%	60%	65%
Cumulative patents	19%	55%	65%	72%	72%
Higher discount	0%	23%	47%	52%	63%
Higher price elasticity	0%	35%	56%	64%	70%
Panel B	Optimal unilateral tariff levels				
Horizon in years	10	20	30	40	50
Baseline	0%	0%	0%	0%	0%
Alternative scenarios	0%	0%	0%	0%	0%

H.1 Lower Maximum Technology Gap $\bar{m}$

Our first exercise considers the robustness of the baseline results to the value of the maximum technology gap that can separate two incumbent firms. In our baseline, this value is set to $\bar{m} = 16$. As a robustness check, we calculate the empirical gap distribution by setting $\bar{m} = 10$ and recalibrate our model accordingly. The second row in Panel A of Table A.2 presents the profile of optimal unilateral R&D policy over different horizons. A comparison to the first row, which replicates the baseline results, shows that the results are very similar to those found in the baseline calibration. Hence, we conclude that our original findings are robust to the values of $\bar{m}$.

H.2 Dropping the U.K.

As illustrated in Figure 1, the U.K. has a similar productivity and innovation performance to the United States in the late 1970s, in stark contrast with the other advanced competitors of the United States. Conjecturing that idiosyncratic factors may have negatively separated the performance of the U.K. from its peers, we recalibrate our model using data that exclude the U.K. For this exercise, we re-weight our targets using data on the remaining five foreign countries and re-compute the empirical gap distribution. Figure A.15a shows that the shift in the initial distribution caused by dropping the U.K. is minuscule, which is also the case with the other targets. Consequently, the parameter values obtained by this alternative calibration, as well as the quantitative results, barely differ from the baseline; hence, we do not repeat them here.



A) Dropping the U.K. B) Citation-weighted patents

Figure A.15: Alternative initial technological gap distribution

Notes: The figure contrasts alternative initial technological gap distributions (red dashed lines) with the baseline (solid blue lines). Panel A depicts the version omitting the U.K., while panel B shows the version based on citation-weighted patents.

H.3 Quality-adjusted Patents

In this exercise, we test the robustness of our analysis to the use of citation-weighted patent counts when forming moments from the data, as well as the empirical technology gap distribution. Using citation-weighted patents implies about a 4-percent higher share for Japan among all countries in 1975 at the expense of Germany, the share of which declines by the same amount. As illustrated in Figure A.15b, this reshuffling leads to only minimal changes in the empirical technology gap distribution, which also holds true for other moments. As a result, the calibration output is very similar to baseline, as one would expect, when using the alternative measure. Therefore, we skip the rest of the results generated by this alternative calibration.

Table A.3: Welfare implications of optimal policies in alternative scenarios

	Welfare change with									
	optimal subsidy rate					optimal tariff rate				
Horizon in years	10	20	30	40	50	10	20	30	40	50
Baseline	0.0%	0.1%	0.7%	1.7%	2.8%	0.3%	0.7%	1.1%	1.4%	1.8%
Lower $\bar{m}$	0.0%	0.1%	0.7%	1.8%	2.9%	0.3%	0.6%	0.9%	1.2%	1.4%
Cumulative patents	0.%	1.0%	3.0%	5.5%	8.0%	0.2%	0.4%	0.5%	0.6%	0.7%
Higher discount	0.0%	0.1%	0.6%	1.2%	1.8%	0.3%	0.7%	1.1%	1.4%	1.6%
Higher price elasticity	0.0%	0.2%	1.1%	2.4%	3.8%	0.5%	1.3%	2.0%	2.7%	3.3%

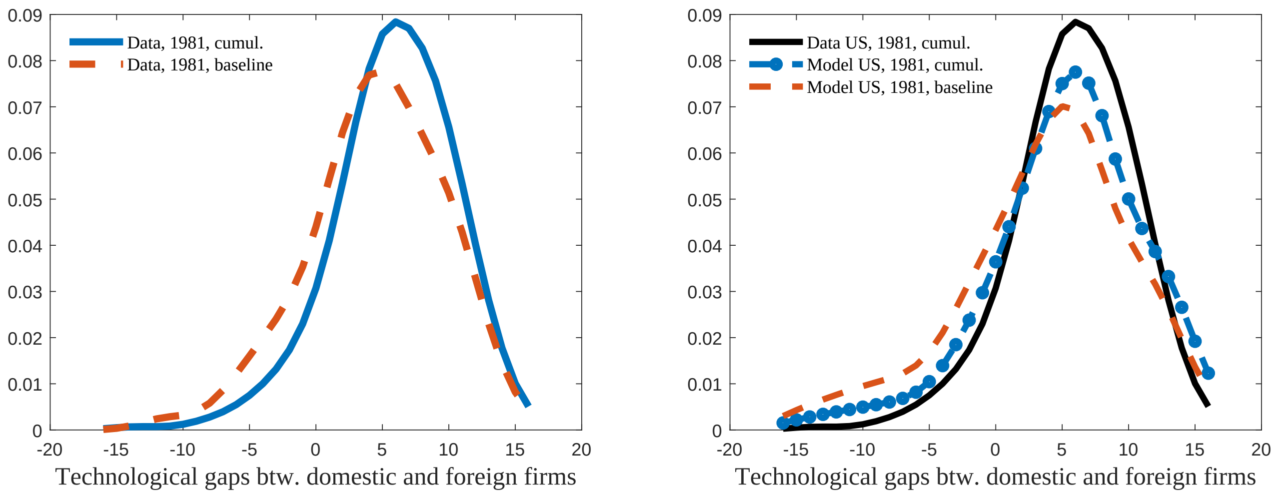
Notes: The table presents the consumption-equivalent change in welfare in alternative scenarios for different horizons. For the optimal policy levels, see Table A.2.

H.4 Gap Distribution Based on Cumulative Patent Count

In our baseline calibration, we match the shift in the empirical gap distribution from 1975 to 1981, where we generate the distributions using patent counts in individual years.[67] In this exercise, we test the robustness of our results to computing the empirical gap distributions based on the cumulative patent counts starting from 1965. Doing so, we measure the evolution of technological leadership based on the cumulative patent stock. In particular, when we compute the U.S. patent share in a sector in a certain year, as in Figure 4, we use the patents registered in that sector between 1965 and the particular year of interest. For example, to generate the empirical gap distribution in 1975, we rank sectors using information from patents registered between 1965 and 1975 instead of 1975 alone. As can be expected, the shift in the empirical gap distribution is less pronounced in this method, because the country shares of patent stocks vary more slowly. Therefore, in Figure A.16a in Appendix F, the distribution in 1981 is to the right of the baseline one. This slower shift in the gap distribution leads to some changes in the values of calibrated parameters. Notably, the calibration yields a higher ϕ—implying a relatively smaller chance of large–step innovations—and a higher λ. Consequently, the implied optimal R&D subsidy profile (row 3 in Panel A) is noticeably higher than that in the baseline calibration. The reason for this result is that with a higher step size λ, the magnitude of underinvestment is larger in this economy, calling for higher R&D subsidies.[68] Consequently, the implied change in welfare is also considerably larger than in the baseline economy. All told, while this experiment suggests higher optimal subsidy, our main results are robust to the use of the alternative empirical gap distribution.

[67] One reason for starting in 1975 is that in the raw USPTO data, the number of patents that are assigned to a technology class is much smaller before the mid-1970s compared to subsequent years.

[68] As is the case with Schumpeterian creative destruction models, the existence of intertemporal spillovers—the fact that an innovation raises the quality level permanently—creates a wedge between the social and private discount rates, as the private firm internalizes these benefits only partially (to the extent of the rents it can capture over the course of its life). Intertemporal spillovers imply that the social planner cares more about the future than the owner of the private firm, and the wedge between the discount rates increases in the step size λ—the parameter that determines the proportional quality gain from innovation.



A) Baseline and alternative 1981 distributions (data)

B) Calibrated 1981 distributions

Figure A.16: Calibration and comparison to baseline with the alternative empirical gap distribution

Notes: Panel A contrasts empirical 1981 technological gap distributions in the alternative method (solid blue line) and the baseline (red dashed line). Panel B contrasts model-generated 1981 technological gap distributions.

H.5 Higher Discount Rate ρ

In the baseline calibration, we fixed the discount rate of the households to 1 percent. In order to test the sensitivity of our results to this parameter, we also ran an alternative calibration, setting the discount rate to 2 percent. Our calibration outcome as well as the optimal policies in this exercise differ from the baselines results only slightly. As shown in row 4 of Panel A Table A.2, the level of optimal R&D subsidies is slightly lower, which would be expected given the higher rate with which households discount the future. Not surprisingly, the higher discount rate also implies a somewhat smaller welfare gain from increased subsidies, as shown in Table A.3. Given the relatively minor differences from the baseline, we conclude that our baseline findings are robust to the choice of the discount rate.

H.6 Higher Price Elasticity (lower β)

In our model, the price elasticity of demand for intermediate goods is β^{-1}, which also shapes the trade elasticity. In this exercise, we test the robustness of our results to this elasticity. In particular, we increase this elasticity setting $\beta = 0.4$ and recalibrate the model. The final row in Panel A of Table A.2 presents the implications of the re-calibrated model for optimal R&D policy. Again, the findings are similar to the baseline, except for some difference in subsidy levels. The higher level of optimal subsidies reflects the fact that a lower level of β increases the share of profits in aggregate income, leading to a larger extent of underinvestment in the face of technological convergence.[69] As would be expected, these higher optimal subsidy levels imply larger welfare gains than those obtained in the baseline economy.

[69] Similarly, a specific increase in subsidies generates a larger (smaller) welfare gain (loss) over the same period in this version relative to the baseline. For instance, the consumption-equivalent welfare gain from the subsidy increase discussed in Section 4.2 is 0.45 percent as opposed to a 0.38 percent gain in the baseline.