Innovation and Trade Policy in a Globalized World*

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***** STILL PRELIMINARY & COMMENTS WELCOME *****

Abstract

We assess the effects of import tariffs and R&D subsidies as policy responses to foreign technological competition. To this end, we build a dynamic general equilibrium growth model where firm innovation shapes the dynamics of technology endogenously, and, therefore, market leadership and trade flows, in a world with two large open economies at different stages of development. The model accounts for competitive pressures exerted by both entrant and incumbent firms. Firms' R&D decisions are driven by (i) the *defensive innovation motive*, (ii) the *expansionary innovation motive*, and (iii) technology *spillovers*. The theoretical investigation illustrates that, statically, globalization (defined as reduced trade barriers) has ambiguous effect on welfare, while, dynamically, intensified globalization boosts domestic innovation through induced international competition. A calibrated version of the model reproduces the foreign technological catch-up the U.S. experienced during the 1970s and early 1980s. Accounting for *transitional dynamics*, we use our model for policy evaluation and compute optimal policies over different time horizons. The model suggests that the introduction of the Research and Experimentation Tax Credit in 1981 proves to be an effective policy response to foreign competition, generating substantial welfare gains in the long run. A counterfactual exercise shows that increasing trade barriers as an alternative policy response produces gains only in the very short run, and only when introduced unilaterally, while leading to large losses in the medium and long run. Protectionist measures generate large dynamic losses from trade, distorting the impact of openness on innovation incentives and productivity growth. Finally, we show that less government intervention is needed in a globalized world, thanks to intensified international competition as a result of lower trade barriers.

Keywords: Economic growth, short and long-run gains from globalization, foreign technological catching up, innovation policy, trade policy, competition.

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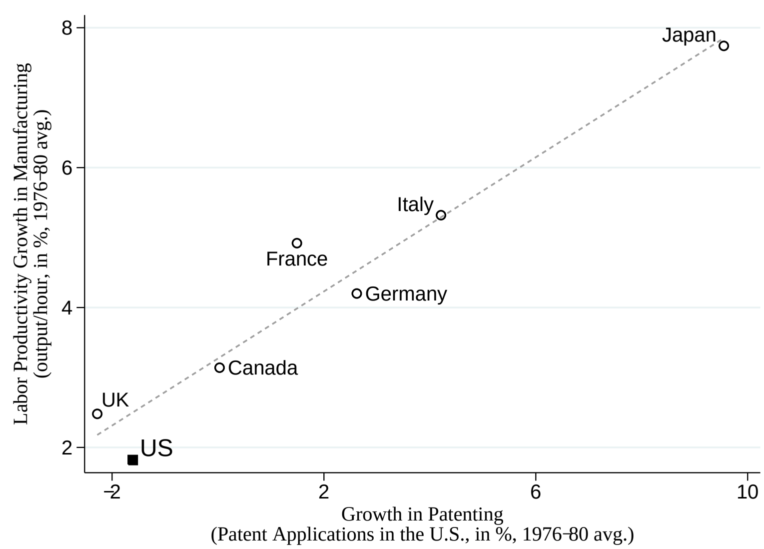
"Foreign competition in the technology intensive industries poses a more serious threat to our country's position in the international marketplace than ever before in our history."

John P. McTague (1985)[1]

1 Introduction

During the last presidential race a heated debate centered around the position of the U.S. in its trade relationships. President Trump's speeches focused on the issue that the U.S. is losing its competitiveness to other big players in the world. A favored and widely-discussed policy suggestion was raising barriers to international trade. Interestingly, similar concerns were raised also three decades ago, following the exposure of the U.S. during 1970s and early 1980s to a remarkable convergence by advanced countries such as Japan, Germany and France in terms of technology and productivity (see Figure 1). This generated an alarming concern among policy circles, including the Reagan administration, as illustrated in the above quote. As opposed to the recent focus on protectionist measures, the Reagan government, among other policies, introduced an R&D tax credit scheme in 1981 for the first time in the U.S. history. In this paper, we evaluate policy responses to international technology competition, focusing on *trade* and *innovation* policies. We first provide a new set of empirical facts which are used to motivate to construction of a new dynamic general equilibrium theory of international technology competition specifically crafted to perform quantitative policy analysis.



Source: USPTO, Capdevielle and Alvarez (1981), and authors' own calculation

Figure 1: Convergence between the U.S. and its peers

[1] Associate Director of the Office of Science and Technology Policy of the Reagan Administration. Hallacher (2005), pp.2.

As illustrated in Figure 1, the U.S. performed poorly relative to its advanced peers in terms of labor productivity and innovation in the second half of 1970s.[2] The average growth in output per hours worked in manufacturing has been the lowest in the U.S. Moreover, innovation rate, proxied by new patent applications registered in the U.S. by the residents of these foreign countries, expanded substantially except for the U.K. Strikingly, patent applications by the U.S. residents have actually shrunk in absolute terms during the same period. In addition to that, we find that the largest growth rates in patent applications have been recorded by those countries whose labor productivity growth in manufacturing outpaced the U.S. the most. In parallel, the U.S. Patent and Trademark Office (USPTO) data show that between 1975 and 1985, the ratio of foreign patent to total patent count recorded a solid 50% increase.[3] While the U.S. held 70% of the patent applications in 1975, in 10 years this fraction declined to around 55%.[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 these policies was the introduction of the R&D Tax Credit, both at the federal and state levels. The first federal-level R&D Tax credit was introduced in 1981. Upon these policy changes, aggregate R&D intensity of U.S. public firms showed a dramatic increase as shown by the solid black line in Figure 2a. After the expected delay, the annual share of patents registered by U.S. residents in total patent applications picked up as well (see the dashed line in the same figure).[5] Starting in 1982 with Minnesota, several states followed suit as well and introduced state-level R&D tax credits, as shown in Figure 2b. By contrast, there was no significant action in R&D policies of the other major countries, as depicted in Figure 2c.[6] Motivated by these facts, this paper provides a new quantitative investigation of the effects of R&D subsidies in open economy and compares them to the effects of raising trade barriers as a response to rising foreign technology competition. This policy comparison also allows us to provide new theoretical insights and quantitative perspectives on the gains from globalization.

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 international technological competition. Moreover, global R&D races and international trade are dominated by large firms whose choices can affect market aggregates, giving rise to strategic market power. The aircraft industry provides an example for a technology-intensive sector dominated by two firms, Airbus and Boeing, who compete strategically for global market leadership

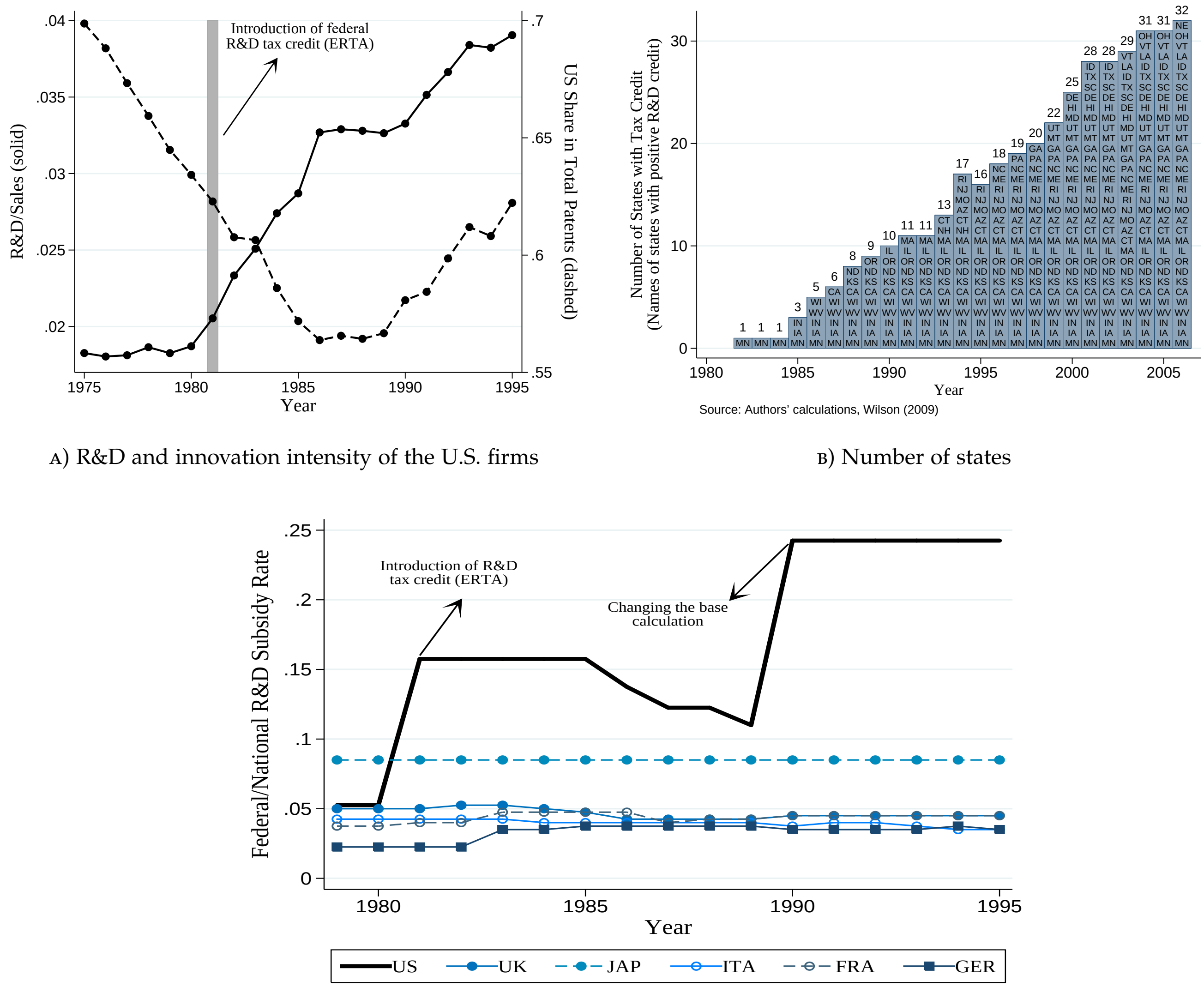
[2]The relationship over a longer time period is presented in Figure A.5 in Appendix A.3.

[3]See Figure A.1 in Appendix A.1. This section gives 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)].

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

[6]Following Impullitti (2010), R&D subsidies are calculated using corporate tax data from Bloom et al. (2002), which take into account different tax and credit systems. The subsidies reflect features of the tax system aimed at reducing cost of R&D, in particular, 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) R&D and innovation intensity of the U.S. firms

b) Number of states

c) Effective R&D tax credit rates across countries

Figure 2: Evolution of R&D credits in the U.S.

[Irwin and Pavcnik (2004), Baldwin and Krugman (1988)]. The top one percent of US trading firms account for about 80 percent of total US trade and their large market shares allow them to affect market prices [Bernard et al. (2017), Hottman et al. (2016)]. Hence, a model that allows for strategic interaction between the competing firms is needed to analyse our facts and to generate new insights on trade and innovation policies. Moreover, since our facts are intrinsically dynamic, a careful policy evaluation exercise needs to take into account the changes along the transition path.

With these key points in mind, we build a new two-country dynamic endogenous growth model where innovation determines the dynamics of technology and global market leadership. Our framework builds on the *step-by-step* innovation models of Schumpeterian creative destruction that allows for strategic interaction among competitors. In both countries, final good firms produce output 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. Free entry by a fringe of domestic and foreign firms creates an additional source of competitive pressure both on leaders and followers in each product line. International markets are characterized by trade costs and international diffusion of ideas in the form of knowledge spillovers. A theoretical investigation of this setting shows that, statically, openness to trade benefits the fixed factor in the final goods production via higher-quality intermediate good imports, which translate into higher productivity in domestic final good production. By contrast, the effect on business owners, which operates through a combination of larger markets size and loss of markets to foreign rivals, is ambiguous. In addition to this, trade openness impacts the economies' dynamics by affecting motives for innovation.

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 generic step-by-step framework is the *escape-competition effect*, according to which incumbent firms have an incentive to move away from the follower in order to escape competition. A novel implication of our model is that two such effects arise in a similar spirit. The main difference in an open economy with trade frictions is that vertical competition within each product line assumes an international dimension, as firms are from different countries. In each line, firms in both countries compete to serve the domestic and foreign market. Innovation generates a ranking of the product lines based of the quality/productivity difference between the home and the foreign firm. As in models of trade with firm heterogeneity (e.g. Melitz, 2003), trade costs generate quality cutoffs that partition the product space into exporting and non-exporting firms. But differently from these models where competition takes place horizontally between firms producing different goods and firms are ranked based on their absolute productivity level, in our model the ranking and therefore the cutoffs are pinned down by the productivity of firms relative to their foreign competitors. When the domestic intermediate good quality is too inferior relative to its foreign counterpart, domestic final good producers decide to source their intermediate goods from abroad and this generates the first *import cutoff* of the quality. Likewise, if the relative quality of the domestic producer is above a certain threshold, foreign final good producer decides to import from the domestic intermediate good producer and this generates the *export cutoff* of the relative quality.

The key feature of these two cutoffs is that innovation efforts are intensified around them. 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 to the export cutoff, it exerts additional effort in order 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 which, 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, as discussed below.

Another important feature of our model is the free entry of new firms. Both in the domestic and foreign economies, new entrants try to replace incumbents. The entry rate is state dependent in that there will be more domestic entry into those sectors where the domestic incumbents maintain a larger lead over their foreign rivals. This is another prediction of the model for which we find empirical support in the patent data. We observe more patents coming from new entrants in patent classes where U.S. incumbents have a larger fraction of the patents.

We parametrize the model to match key trade, innovation and growth facts in late 1970s and reproduce the evolution of global leadership in those years, with the U.S. initially representing the technological frontier in most sectors while a set of European countries plus Japan leading in a few. The transitional dynamics of the model reproduces the convergence in technological leadership observed in the patent data in the 1970s and early 1980s. We validate our model's mechanism with out-of-sample tests concerning the link between innovative activity and technological leadership, and the elasticity of firm-level R&D spending to policy changes. In particular, we lay out striking similarities between the model and the data as to the innovation patterns of firms at different technological positions vis-a-vis their foreign competitors. Furthermore, simulating the calibrated model beyond the calibration period, we examine the dynamics of foreign technological convergence, a mode of globalization that has not been widely explored in the literature, in absence of policy interventions. In particular, we demonstrate the significant deterioration in the position of U.S. firms in international technological competition that would have arisen in absence of any policy intervention.

Next, we continue with policy analysis. First, we analyze welfare implications of protectionism, i.e., raising trade barriers *unilaterally*. The welfare implications of the policy change depend on the *time horizon* over which the policy is evaluated. Increasing the trade cost generates short-run gains, as it tames international business stealing due to foreign catching up. These gains more than compensate for the negative effect on aggregate productivity of replacing better-quality imported goods with inferior domestic counterparts. Over the first decade after a 20% increase in trade barriers there are gains up to 0.2% of consumption. However, protective measures reduce incentives for domestic firms to do defensive innovation, weakening the foreign competitive pressures domestic firms are exposed to. As time goes by, this force dominates, leading to substantial drops in welfare in the long run. It operates through the key sources of gains from trade in this economy. First, declining defensive innovative effort limits the ability of the economy to make up for the foregone productivity that would otherwise be generated by the high-quality imports. Second, it reduces the growth of aggregate profit income. Weaker foreign competition, and the following reduction in defensive innovative activity, generated by protectionism also shapes the optimal trade policy, calling for a more liberal regime when the welfare impact is evaluated over a longer time horizon.

As an alternative policy option to protectionism, we feed the model the increase in U.S. R&D subsidies that took place in the early 1980s and assess the welfare properties of this policy during a period of growing foreign competition. The effective average U.S. R&D subsidy increases from about 5% in the 1970s to approximately 19% in the post-1981 period. Feeding the model this subsidy change generates non-negligible gains both in the short and in the long run. During more than three decades after the subsidy increase, consumption is about 0.9% higher, and this gain is driven by both business stealing and innovation. Reducing the cost of innovation, subsidies stimulate both U.S. entrants and incumbent firms' R&D, thereby accelerating productivity growth and allowing U.S. firms to obtain market leadership. With a 50-year horizon, consumption-equivalent welfare gain rises to 1.1% per year thanks to the stimulating effect of subsidies on innovation. We also show that the optimal subsidy level for the same horizon is much higher than the observed change. In fact, the observed increase in subsidies is an optimal response when only a horizon shorter than 10 years is considered, as the growth-stimulating impact of subsidies, which becomes stronger over time, calls for higher subsidies over longer horizons.

Next, we analyze the optimal policy design when both options are available to the policymaker. A key result is that, especially the direction of the trade policy component, crucially depends on the assumption about the response of the trade partners. When the policymaker creates the policy under the assumption that unilateral changes are possible, the optimal policy favours protectionist trade measures combined with aggressive R&D subsidies. This is due to the fact that protectionist policies protect domestic profits yet lower the innovation incentives. Hence, aggressive R&D subsidies are needed to make up for the reduced innovation efforts. However, if the trade partners *retaliate*, the optimal policy reverses and calls for a regime as liberal as possible. The risk of losing the export market plays the key role in this reversal.

Finally, our analysis shows that less policy intervention is needed as the world becomes more globalized through reduced trade costs. This interesting result emerges due to the fact that lower trade costs intensify competition in the global market place. More competitive markets induce more innovation, both defensive and expansionary. In other words, as globalization takes place, markets take care of the innovation incentives and eliminate the need for policy intervention.

Taking stock, foreign technological catching up has taken its toll on the technological leadership of U.S. firms and led to significant losses in their profits through business stealing. Increasing R&D subsidies during periods of accelerating foreign competition proves to be an effective response to foreign competition, while raising trade barriers generates only small short run gains and substantial losses in the long run. The key message of our analysis is that when a country experiences fiercer foreign technological competition R&D subsidies help national firms compete without giving up gains from trade. Finally, optimal trade policy design crucially depends on the possibility of foreign retaliation, in which case potential loss of export markets calls for a more liberal trade regime.

Literature Review This paper is related to several lines of research in the literature. 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. (1997, 2001, 2005) and in the latest developments by Acemoglu and Akcigit (2012) and Acemoglu et al. (2016). We propose the first open economy version of this class of models, and provide a quantitative exploration of the gains from globalization and the role of innovation subsidies in open economies.

On modeling the trade side, our setting draws similarities to the theoretical literature that analyzes the impact of trade exposure on (industry-level) aggregate productivity in models with heterogeneous firm productivities, pioneered by Melitz (2003).[7] Our structural general equilibrium framework incorporates several forces such as competition and market size, whose impact on firm innovation is highlighted by recent empirical work that focuses on the nexus of innovation and trade [see Muendler (2004), Bustos (2011), Iacovone et al. (2011), Autor et al. (2016), Chen and Steinwender (2016) and in particular, Bloom et al. (2016), Aghion et al. (2017) among others].[8] It also encompasses technology transfer alongside with firm innovation as sources of productivity growth, in line with the empirical findings of Cameron et al. (2005). We contribute to this literature by formalizing and quantifying a new theory of endogenous firm decisions and openness to trade.

Building on the seminal contributions of Rivera-Batiz and Romer (1991) and Grossman and Helpman (1993), our analysis emphasizes the role of firms' innovation decisions in shaping policy-induced aggregate dynamics, and thus, makes contact with a growing literature on dynamic gains from trade.[9] A set of recent papers introduced knowledge diffusion into trade models as a source that shapes dynamic gains [Perla et al. (2015), Buera and Oberfield (2016), Sampson (2016) among others]. Impullitti and Licandro (2017), on the other hand, analyze gains from trade in a model of firm heterogeneity, variable markups and innovation-driven productivity growth. They find that the growth effects of trade liberalization doubles the welfare gains obtainable in a static version of the model. Analyzing various extensions of the canonical Melitz (2003) frame-

[7] In the fashion of these models, firms with heterogeneous productivities select the markets to serve in our model. Conversely, openness to trade may affect the input-sourcing decisions of firms. For an analysis of this effect in a setup of heterogeneous firms, see Antràs and Helpman (2004).

[8] While Bloom et al. (2016) show the positive effect of Chinese import penetration on the technical change in twelve European countries, Aghion et al. (2017) examine the differential impact of market size and competition effects on innovation decisions of exporting French firms with heterogeneous initial productivity levels. They find that the market size effect is the dominant force for firms that have higher productivity at times of increased demand. On a related note, Mayer et al. (2014) and Mayer et al. (2016) look at the product range and mix of multi-product firms as another source of within-firm productivity variations. They document the positive effect of increased export market competition on firm productivity through adjustments in these margins.

[9] In this regard, our attempt advances the literature in the direction pointed out by Burstein and Melitz (2013). In their recent chapter, the authors stress the need for more research dynamic gains from trade, as opposed to extensively-studied static ones, and on the implications of firm and technology dynamics as a potential source.

work, Burstein and Melitz (2013) discuss the effects of trade liberalization on firm dynamics. In parallel to our findings, they highlight how firms' innovation responses determine transitional dynamics induced by trade liberalization. Bloom et al. (2013) develop a trapped-factor model to show that trade liberalization with low wage country could reduce the opportunity cost of innovation. Our work contributes to this literature by emphasizing the role of strategic interaction between firms in shaping their innovation responses, and thereby, the dynamic gains from trade. We also examine these gains along the transition path, thanks to our framework that is capable of tracking the endogenous evolution of competition and innovation patterns in a tractable fashion. Last but not least, endogenous productivity growth and transitional dynamics provide further channels through which trade liberalization and policy may affect aggregate welfare, in addition to those considered by Atkeson and Burstein (2010) and Arkolakis et al. (2012).[10]

Finally, industrial policies in open economies have been studied by a large body of work.[11] Spencer and Brander (1983) and Eaton and Grossman (1986) explored theoretically the strategic motive to use tariffs and subsidies (to production and innovation) to protect the rents and the market shares of domestic firms in an imperfectly competitive global economy.[12] Ossa (2015) sets up a quantitative economic geography model to study production subsidy competition between U.S. states. In the spirit of our work, Impullitti (2010) uses a multi-country version of the standard Schumpeterian growth model to assess the welfare properties of R&D subsidies in open economy, although his work is confined to steady state.[13] Considering the trade policy, Demidova and Rodríguez-Clare (2009) find that an import tariff can be welfare enhancing in a static small open economy with firm heterogeneity and product differentiation. Recent work of Costinot et al. (2015) and Costinot et al. (2016) provide intriguing insights on the type-dependent formulation of optimal policy design in static Ricardian and monopolistic competition environments, respectively.[14] In contrast to these studies, a distinct feature of our model is the link between different modes of foreign competition and innovation at the firm level. We show that in this setting, different policies affect different types of innovations: For instance, unilateral protectionism distorts incentives for *defensive* R&D whereas retaliation by trade partners distorts incentives for *expansionary* R&D. This relationship, and the resulting dynamic gains from trade and transitional dynamics, are central to the design of optimal trade and innovation policy. Dif-

[10]Considering a simple model of sequential production in intermediate goods, Melitz and Redding (2014) also point to trade-induced changes in domestic productivity as a source of departure from the findings of Arkolakis et al. (2012), which state that welfare gains from trade in a group of standard models can be derived from a few aggregate statistics, and thus, are fairly modest. Alessandria and Choi (2014) emphasizes the significance of accounting for transition in this regard.

[11]Institutional challenges in applying appropriate industrial polices are beyond the scope of this paper. Interested readers can see Rodrik (2004) for an extensive discussion.

[12]See Leahy and Neary (1997) and Haaland and Kind (2008) for recent contributions. While the literature focuses on static models, Grossman and Lai (2004) analyze strategic IPR policy in a multi-country endogenous growth model.

[13]The paper also relates to the recent quantitative analyzes of R&D subsidies in closed economy. See Acemoglu et al. (2013) and Akcigit et al. (2016a,b).

[14] Analyzing trade policies over the business cycle, the recent work by Barattieri et al. (2017) explores the recessionary effects of protectionism in a DSGE framework.

ferentiating between the short and long run, we demonstrate the crucial dependence of policy implications on the horizon considered along the transition.

The rest of the paper is organized as follows. Section 2 introduces the theoretical framework and presents analytical results. Section 3 outlines the calibration procedure and provides out-of-sample tests. Section 4 discusses policy implications and optimal policies, and Section 5 concludes.

2 Model

In this section, 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. Final good is used for consumption, production of intermediate goods and innovation. There is free trade in intermediate goods and final goods sectors and no trade in assets. Lack of trade in assets rules out international borrowing and lending and make the two countries grow in different rates during the transition.

In each production line for intermediate goods there are two active firms, one from each country, engaging in price competition to obtain monopoly power of production. The firm that produces the variety of better quality after adjusting for the trade 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. Since innovation success is a random process the global economy features a distribution of firms supplying products of heterogeneous quality. In addition to trade in intermediate and final goods, there is a second channel of interdependency linking the countries: trade in ideas. The exchange of ideas consists in technology diffusion through international knowledge spillovers.

In addition to incumbent firms, there is an outside pool of entrant firms. These firms engage in research activity to obtain a successful innovation which 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. Understanding these distinct forces is particularly important once we use our model for the evaluation of different policies.

2.1 Preferences

Consider the following continuous time economy. 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, 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

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

where r_{ct} is the return to asset holdings of the household, L_c is the amount of fixed factor (could be labor or land) in country c, w_{ct} is the fixed factor income, P_{ct} is the price of the consumption good in country c, and T_{ct} is the lump-sum tax. Household in country c owns all the firms in c, therefore the asset market clearing condition requires that the asset holdings has to be equal to the sum of firm values:

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

where tilde "~" denotes values referring to entrant firms. We assume full *home bias* in asset holding, an assumption that is robustly supported by the empirical evidence in the 1980s and 1990s.[15]

2.2 Technology and Market Structure

2.2.1 Final good

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

$$Y_{ct} = \frac{L_c^{\beta}}{1-\beta} \int_0^1 q_{sjt}^{\beta} k_{sjt}^{1-\beta} dj; \; s \in \{A, B\} \tag{3}$$

Here, L_c is the amount of fixed factor in c, k_j refers to the intermediate good $j \in [0,1]$ and q_j is the quality level of k_j, and β is the share of fixed factor in total output. This production function implicitly imposes that in each sector j only the highest quality (after adjusting for trade costs) intermediate good will be used by the final good producer. Intermediate goods can be obtained

[15] For instance, in 1989, 92% of the U.S. stock market was held by U.S. residents, and Japan, UK, France and Germany show similar shares, 96%, 92% 89% and 79% respectively. A similar picture can be observed till the early 2000s when the home bias started to decline [see e.g. Coeurdacier and Rey (2013)].

from any country, whereas the fixed factor L_c is assumed to be immobile across countries. We normalize $L_c = 1$ in both countries to reduce notation.

Imports of intermediate goods are subject to iceberg trade costs. We assume that in order to export one unit of an intermediate good, the exporting country needs to ship $(1+\kappa)$ units of that good, $\kappa > 0$. Note that firms in both countries may potentially produce each variety j and in absence of trade frictions, they are perfect substitutes after adjusting 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, once the prices are adjusted to reflect the trade costs. Final good producers in both countries have access to the same technology and this will allow us to focus on the heterogeneity of the intermediate goods sector. Both countries produce the same identical final good, which, under the assumption of frictionless trade in final goods, implies that the price of the final output in both countries will be the same. We normalize that price to 1 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 $c \in \{A, B\}$, compete for the market leadership à la Bertrand. Each one of these infinitely-lived firms has the same marginal cost of production η, yet they differ in terms of their quality of output, q_{cj}. We say that country A is *the leader* in j if

$$q_{Ajt} > q_{Bjt}$$

and *the 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 - we will shortly detail the process of spillovers. Each time there is an improvement in country c specific to product line j, the quality increases as follows:

$$q_{cj(t+\Delta t)} = \lambda^{n_t} q_{cjt},$$

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

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

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

Firms invest in R&D in order to obtain market leadership through improving the quality of their products. Let 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. The production function of innovations takes the following form:

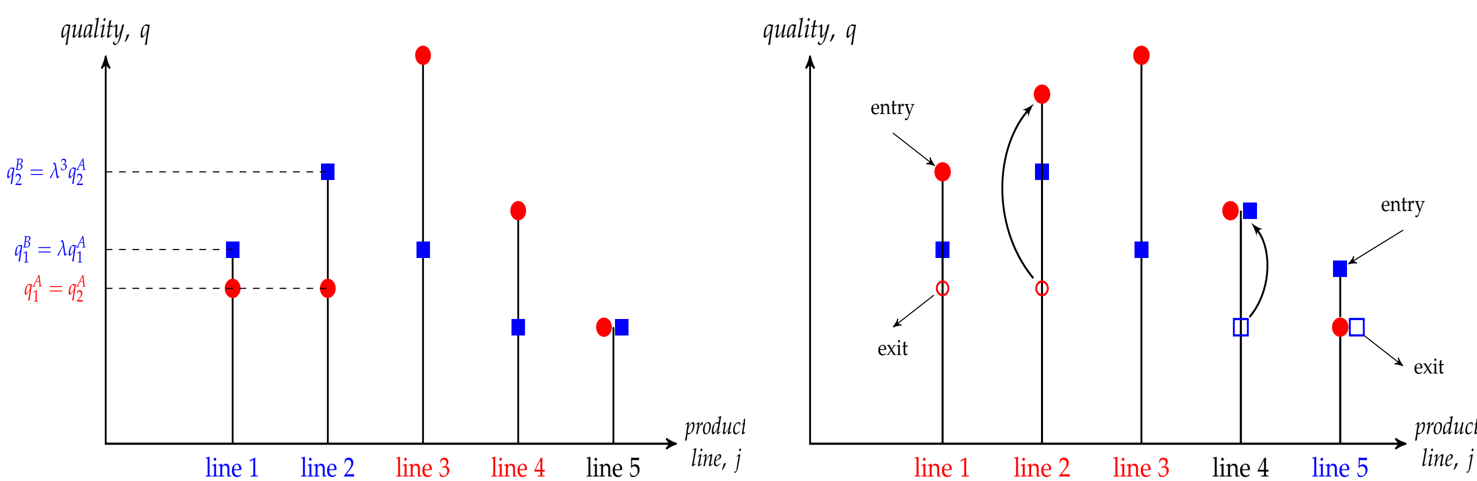
$$x_{cjt} = \left(\gamma_c \frac{d_{cjt}}{\alpha_c q_{cjt}}\right)^{\frac{1}{\gamma_c}}.$$

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 cost function for generating an arrival rate of x_{cjt} :

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

Entrants. In every product line there are potential entrants from both countries investing in innovation to enter the market. The innovation technology for entrants is

$$\tilde{x}_{cjt} = \left(\tilde{\gamma}_c \frac{\tilde{d}_{cjt}}{\tilde{\alpha}_c q_{cjt}}\right)^{\frac{1}{\tilde{\gamma}_c}}.$$



A) Product lines

B) Entry, Exit, and Leadership

Figure 3: Evolution of product lines

Figure 3 demonstrates the evolution of leadership in intermediate product lines driven by incumbent innovation, entry and exit. In the left panel, five product lines are shown. In the first two, firms from country B (designated by a square) and in the next two firms from country A (designated by a circle) lead. In the last one, firms are in neck-and-neck position. Notice that technology gaps are heterogeneous across lines. For instance, in line 1, the incumbent firm from B $\left(f_1^B\right)$ leads its competitor from A $\left(f_1^A\right)$ by one gap whereas f_2^B leads f_2^A by three. The right panel exhibits how these positions evolve. Country A seizes technological leadership in the first two lines in two different ways. In the first line, an entrant from A enters driving the previous incumbent f_1^A out of business. Moreover, it enters with a large enough quality improvement moving ahead of the previous leader f_1^B. In the second line, f_2^A generates an innovation of a step size larger than three, which enables it to more than close the gap and to capture the technological leadership. While in line three, there is no change, in line four firms become neck-and-neck as a result of successful innovation by f_4^B. In line five, an entrant from B brings the technological leadership to its country while driving out its country's previous incumbent.

Lastly, notice that changes in technological leadership may not result in business stealing in existence of trade costs. A firm steals the business of its foreign competitor in two cases: either, when a domestic incumbent, which is so technologically laggard that the product it can produce is imported, improves its quality enough so that the domestic final good producer finds it profitable to buy the domestic good, or, when a domestic incumbent improves enough to penetrate the foreign market.

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 $\mathbb{F}_m(\cdot)$.[16] Because the maximum number of gaps is capped by $\bar{m}$, there is a different number of potential gaps for each firm to reach depending on their current position in the technological competition. For instance, if a firm is leading by 10 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 that 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 benchmark distribution over positions larger than $-\bar{m}$, the most laggard position, as depicted in Figure 4a. We assume that it has the following functional form:

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

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. This decay translates into a decay in the probability of an innovation generating larger technological

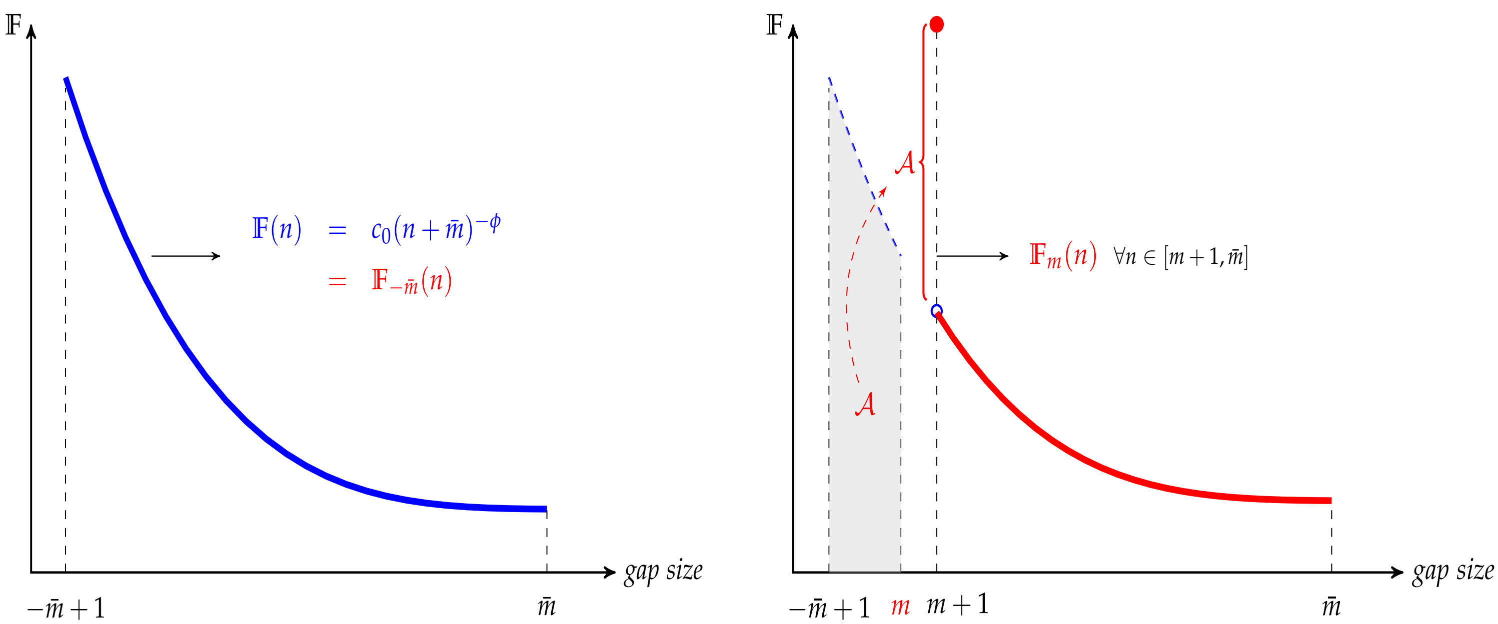
[16]Conversely, each innovation comes with an associated step size that is randomly generated by some probability mass function.

jumps.

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:

$$\mathbb{F}_m(n) = \begin{cases} \mathbb{F}(m+1) + \mathcal{A}(m) & for\ n = m+1 \\ \mathbb{F}(s) & for\ n \in \{m+2, ..., \bar{m}\} \end{cases}. \tag{5}$$

As demonstrated in Figure 4b, $\mathcal{A}(m) \equiv \sum_{s=-\bar{m}+1}^{m} \mathbb{F}(s)$ 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 due to the additive nature of $\mathcal{A}$. Finally notice that $\mathbb{F}_{-\bar{m}}(n) = \mathbb{F}(n)$.



A) Benchmark

B) At position m

Figure 4: Probability mass function for new position

An explanation for this particular way of modeling innovation step sizes is in order. In the basic step-by-step model, each innovation improves the existing quality of the follower either by a single step or it makes the follower catch-up with the leader no matter how big the initial gap is. Hence the former is dubbed "slow catch-up regime," while the latter is dubbed "quick catch-up regime" in Acemoglu and Akcigit (2012). 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 this feature and equip the model with enough flexibility to replicate the catch-up process found in the data.[17] The treatment of $\mathcal{A}(m)$ in the derivation of position-specific distributions serves the same purpose. An alternative could involve an equal distribution of the truncated probability $\mathcal{A}(m)$ across potential positions $\{m+1, ..., \bar{m}\}$. This alternative would imply a relatively fatter right tail in $\mathbb{F}_m(n)$, thus higher chances of climbing up the position ladder. However, this structure would favor the U.S., most of whose firms are technological leaders in their products, more than the foreign countries, whose firms are lagging in most product lines. Even though a laggard firm can close the gap by a few steps, a leading firm in this alternative setup could easily open up the gap. This happens because, for a leading firm, equally distributing $\mathcal{A}(m)$ across a few better positions the firm has ahead means higher chances of quickly reaching these positions again. Given that, in the data, the initial leadership distribution is strongly in favor of the U.S., this advantage for the leading firms would result in a shift of the distribution towards larger gaps, operating against the convergence process in the data.

After 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 at position m $(-\bar{m})$ can be summarized as follows:

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

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

Consider the quality levels associated with the incumbent firms from country A. In a product line where the firm from A is in position m the quality improves if either the domestic incumbent or entrant innovates. Moreover, the quality in a product line where the firm from A is in the highest possible lag, $-\bar{m}$, improves not only if the domestic incumbent and entrant innovates, but also if either the foreign incumbent or entrant innovates. The assumption of maximum number of gaps implies that, in industries where this maximum is reached, an additional innovation by the leader, despite improving its quality, cannot widen the gap further. The underlying economic intuition is that 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. Since in this economy the leader and the follower belong to different countries by construction, this *knowledge spillover* implies a technology flow across the countries' borders. This spillover is a key feature in our economy generating cross-country convergence in innovation, technology, and income.

[17] Note that this specification approaches to the standard step-by-step model as $\phi \to \infty$.

2.3 Equilibrium

In this section, we will solve for the Markov Perfect Equilibrium of the model where the strategies are functions of the payoff relevant state variable m. We will first start with the static equilibrium. Then we will build up the value functions for the intermediate producers and entrants and derive their closed form solutions along with the R&D decisions. These will help us characterize the evolution of the world economy over time. Henceforth we will drop the time index t when it causes no confusion.

Definition 1 (Allocation) *An allocation for this world economy consists of interest rate r, country specific fixed factor price w_c, country specific aggregate output, consumption, R&D expenditure and intermediate input expenditure $\{Y_c, C_c, D_c, K_c\}$ and last, intermediate good prices, quantities, and innovation arrival rate $\{p_j, k_j, k_j^*, x_{cj}, \tilde{x}_{cj}\}$ in country c, product line j.*

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 goods production

Next, we turn to the maximization problem of the final good producer. Using the production function (3) , the final good producers generate the following demand for the fixed factor L_c and intermediate good $j \in [0, 1]$:

$$w_{ct} = \frac{\beta}{1-\beta} L_c^{\beta-1} \int_0^1 q_{jt}^{\beta} k_{jt}^{1-\beta} dj \tag{6}$$

$$p_{jt} = L_c^{\beta} q_{jt}^{\beta} k_{jt}^{-\beta}. \tag{7}$$

Now we consider the intermediate producer's problem. In our open economy setting, producers can sell their goods both domestically and internationally. However, since trade is subject to iceberg costs the producer faces different demand schedules on domestically sold and exported goods. Therefore it earns different levels of profits on these goods depending on the destination country. Let us start with the case of domestic business. We denote the constant marginal cost of producing an intermediate variety by η. Then, the profit maximization problem of the monopolist in product line j becomes

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

The optimal quantity and price for intermediate variety j follows from the first order conditions

$$k_{jt}=\left[\frac{1-\beta}{\eta}\right]^{\frac{1}{\beta}}q_{jt}\text{ and }p_j=\frac{\eta}{1-\beta}\tag{8}$$

give that L_c is set to 1. The realized price is a constant markup over the marginal cost and is independent of the individual product quality. Thus, the profit earned by selling each intermediate good domestically is

$$\pi\left(q_{jt}\right)=\pi q_{jt},$$

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 potent to charge the unconstrained monopoly price. Assumption 1 introduced below ensures that the leaders are able to act as unconstrained monopolists.

The problem when selling abroad is different because of the iceberg costs associated with trade. In line with the trade literature, we define the iceberg cost as the proportional unit to be shipped additionally in order to sell one unit of good abroad. This means that when the firm considers to meet the foreign demand it will take into account that its marginal cost will be $(1+\kappa)\eta$. Given the iceberg costs, only the firm with the higher cost-adjusted productivity will find it profitable to sell in the other country. Hence, the firm from country A exports intermediate j to country B if and only if

$$\frac{q_{Ajt}}{(1+\kappa)^{\frac{1-\beta}{\beta}}}\geq q_{Bjt}.$$

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 implies that only the incumbent with the highest cost-adjusted quality pays the fee, and therefore sets the monopoly price in the second stage. Under this assumption, following similar steps as in the case of domestic sales leads to the following optimal quantity exported and the associated profits:

$$k_{cjt}^{*}=\left[\frac{1-\beta}{(1+\kappa)\eta}\right]^{\frac{1}{\beta}}L_f q_{cjt}\text{ and }p_j^{*}=\frac{(1+\kappa)\eta}{1-\beta}\Rightarrow\pi^{*}\left(q_{jt}\right)=\pi^{*}L_f q_{cjt}\tag{9}$$

with $\pi^* = ((1+\kappa)\,\eta)^{\frac{\beta-1}{\beta}}\,(1-\beta)^{\frac{1-\beta}{\beta}}\,\beta < \pi$, where the star indicates the equilibrium in the export market.

Figure 5 summarizes the effect of iceberg costs on the technology frontier of two competing countries.

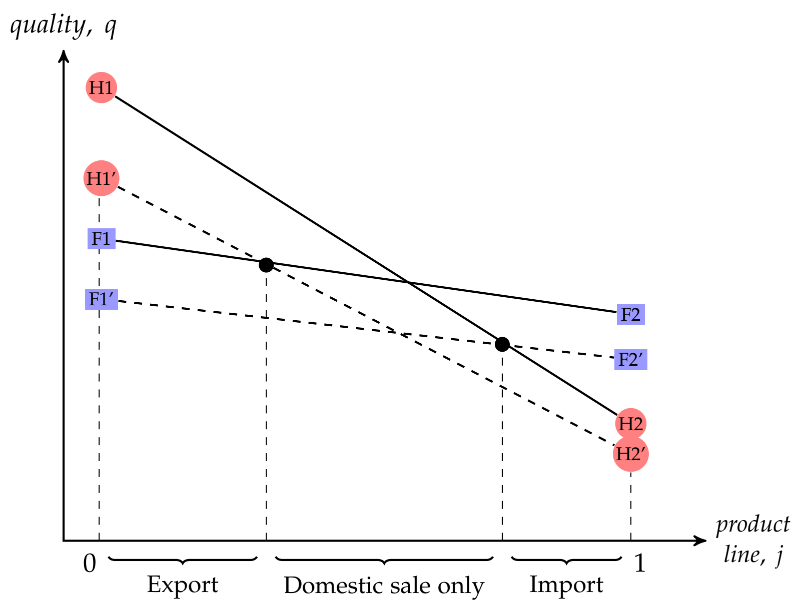


Figure 5: Effect of iceberg cost on quality and trade flows

Just to fix ideas, in this figure product lines are (re)ordered according to the level of qualities in a descending order. The solid lines define the quality frontier of the domestic intermediate producers, where H and F denote the home and the foreign country. The dashed lines show the level of these qualities when adjusted by the iceberg cost. Firms of the home country can export a product as long as the cost-adjusted quality, denoted by the dashed line H', is higher than the domestic quality of that product available in the foreign country, denoted by the solid F line. When the reverse happens, the home country imports the higher-quality product. Otherwise, firms serve only their domestic markets. Two intersections of dashed lines and solid lines determine two cutoffs that define three regions of product lines according to their position in trade. Next, we define mathematically these cutoffs along with another auxiliary variable that will ease the exposition.

We denote the smallest gap by which the leader needs to lead its follower in order to be able to export its good by m^*. Because of iceberg costs, it is possible that an intermediate good producer has a higher quality product compared to its foreign competitor (e.g. $q > q^*$), but in cost-adjusted terms the quality of its good is lower than the foreign counterpart such that the firm cannot export ($q/\,(1+\kappa)^{\frac{1-\beta}{\beta}} < q^*$). To secure a quality advantage even after iceberg costs are accounted for, the technology gap between a leader and its follower has to reach the threshold

$$m^* \equiv \arg\min_m \left\{ m \in [0, \bar{m}] : \lambda^m \geq (1+\kappa)^{\frac{1-\beta}{\beta}} \right\} \tag{10}$$

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

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

Using the equilibrium conditions derived previously, total output becomes

$$Y_{ct} = \sum_{m=-m^*+1}^{\bar{m}} \left[\frac{1-\beta}{\eta} \right]^{\frac{1-\beta}{\beta}} \frac{Q_{cmt}}{1-\beta} + \sum_{m=-\bar{m}}^{-m^*} \left[\frac{1-\beta}{(1+\kappa)\,\eta} \right]^{\frac{1-\beta}{\beta}} \frac{Q^*_{mt}}{1-\beta}. \tag{11}$$

The first sum denote the contribution of domestic intermediate goods. The second sum, which is across product lines where domestic firms lag foreign leaders by at least $-m^*$ gaps, denote the contribution of imported goods. Finally the fixed factor price is

$$w_{ct} = \beta Y_{ct}, \tag{12}$$

which follows from the first order condition of the final good producer given by equation (6).

We complete the description of equilibrium properties of goods' production with their implications for trade flows. Result 1 summarizes key points.

Result 1 *The following results hold in equilibrium:*

1. *The final good price is equalized across countries.*
2. *When the flow of final goods is accounted for, trade is balanced for both countries.*

Proof. See Appendix B.1. ■

2.3.3 Firm Values and Innovation

This subsection presents equilibrium firm values and innovation decisions.[18]

[18] In equilibrium, m is a sufficient statistic for firm value. Lemma 1 at the end of this subsection will verify this result. Accordingly, we replace subscript j with m unless otherwise is necessary.

Incumbent firms. We can write the value function for country A's incumbents:[19]

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

where $\Pi\left(m\right)$ is defined as

$$
\Pi\left(m\right)=\begin{cases}\pi L_c+\pi^{*}L_f & if \quad m\geq m^{*}\\ \pi L_c & if \quad m^{*}>m>-m^{*}\\ 0 & if \quad m\leq -m^{*}\end{cases}.
$$

The first line on the right hand side denotes the operating profits net of R&D costs, where τ^{A} is the R&D subsidy. From the definition of $\Pi\left(m\right)$ we can see that exporting increases the size of the market, thereby increasing the incentives to innovate. This is the *market-size effect*. The second line denotes the expected gains from innovation. This expectation is over potential new 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 when rivals are apart by two distinct gaps of technology, 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 *escape-competition* effect across multiple stages of competition, in particular, over domestic and foreign markets, further in Section 3.2, by confronting the model with the data.

The last two lines on the right hand side capture the creative destruction by domestic and foreign competitors. The third 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 *business-stealing effect* reduces the value of an incumbent firm and therefore its incentive to innovate. In open economy, there is an additional channel through business

[19] The problem for incumbent firms from country B is defined reciprocally.

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 $\mathbb{F}_{-m}(\cdot)$.[20] We label this additional channel as the *international business-stealing effect*.

To complete the exposition of incumbents' problem we introduce two boundary cases where the incumbent is $\bar{m}$-steps ahead (behind):[21]

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

and

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

The last term in the value function of $\bar{m}$-step-behind incumbent captures the knowledge spillovers. When a leader at the maximum gap m innovates, the follower in this sector automatically sees its technology jumping by a measure λ, in order for to maintain the maximum gap between the two firms at m. Together with the market-size, the escape-competition and the business-stealing effects described above, the *international knowledge spillover* is the last key feature driving innovation in our framework. In each period the spillover keeps the laggard firms in the innovation race, avoiding that they fall too far behind. Since the innovation technology is the same for all firms laggards always have a chance to catch up.

The firms' problems are characterized by an infinite-dimensional space as a result of the quality levels of intermediate goods. The following lemma renders the firm environment inde-

[20]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.

[21]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.

pendent of the current quality of their products.

Lemma 1 *The value functions are linear in quality such that* $V_{cm}(q) = qv_{cm}$ *for* $m \in \{-\bar{m}, ..., \bar{m}\}$ *where*

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

This ensures that firm innovation decision does not depend on j once controlled for m.

Proof. See Appendix B.1. ∎

The first order conditions of the problems defined above yield the following equilibrium condition for an incumbent in state m,

$$x_{cmt} = \left\{ \begin{array}{cc} \left[\frac{1}{\alpha_c(1-\tau^c)} (\lambda - 1) v_{c\bar{m}t}\right]^{\frac{1}{\gamma_c - 1}} & if \;\; m = \bar{m} \\ \left[\frac{1}{\alpha_c(1-\tau^c)} \sum_{n=m+1}^{\bar{m}} \mathbb{F}_m(n) \left\{\lambda^{(n_t-m)} v_{cnt} - v_{cmt}\right\}\right]^{\frac{1}{\gamma_c - 1}} & if \;\; m < \bar{m} \end{array} \right. .$$

The equilibrium innovation rates for entrants become

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

Entrants. Lastly, we formulate the entrant problem before defining the equilibrium of the system. Recall that entry is directed at individual product lines. Every period, a unit mass of entrepreneurs in each product line attempt to innovate and enter the business. If the entrepreneur succeeds in her attempt, the entrant firm replaces the domestic incumbent, otherwise the firm disappears.

An entrant improves on the domestic technology. The problem of an entrant that aims at a product line where the current domestic incumbent is $m > 0$ ($m < 0$) steps ahead (behind) is as follows:

$$\tilde{V}_{cmt}(q_t) = \max_{\tilde{x}_{cmt}} -\frac{\tilde{\alpha}_c}{\tilde{\gamma}_c} (\tilde{x}_{cmt})^{\tilde{\gamma}_c} q_t + \tilde{x}_{cmt} \sum_{n_t=m+1}^{\bar{m}} \mathbb{F}_m(n_t) V_{cnt}\left(\lambda^{(n_t-m)} q_t\right), \tag{13}$$

where $\mathbb{F}_m(\cdot)$ 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 economy. Solving this problem leads to the following equilibrium value of the entrant firm:

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

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

Before finally defining the equilibrium of the model, government budget constraint can be written as

$$T_c = \tau^c \sum_{s=-\bar{m}}^{\bar{m}} \alpha_c x_{cst}^{\gamma_c} Q_{cst}, \tag{14}$$

implying that the total expenditure on subsidies is equal to the lump-sum tax.

Lastly we define the equilibrium.

Definition 2 (Equilibrium) *A Markov Perfect Equilibrium of this world economy is an allocation*

$$\{r_c, w_c, p_j, k_j, k_j^*, x_{cj}, \tilde{x}_{cj}, Y_c, C_c, D_c, K_c\}_{c\in\{A,B\}, j\in[0,1]}^{t\in[0,\infty)}$$

such that (i) the sequence of prices and quantities p_j, k_j, k_j^* satisfy (8)-(9) and maximize the operating profits of the incumbent firm in the intermediate good product line j; (ii) the R&D decisions $\{x_{cj}, \tilde{x}_{cj}\}$ maximizes the expected profits of firms taking wages w_c, aggregate output Y_c, the R&D decisions of other firms and government policy $[\tau_c]_{t\geq 0}$ as given; (iii) labor allocation L_c is the profit maximizing labor choice of the final good producers; (iv) Y_c is as given in equation (11), (v) wages w_c and interest rates r clear the labor and asset markets at every t, and (vi) government budget constraint (14) holds at all times.

Next, we introduce the term for aggregate consumption and the measurement of aggregate welfare. We leave the analytical discussion of the evolution of the aggregate quantities such as Q_{cmt} and Q_{cmt}, which summarize the dynamics of the model, to Appendix B.2.

2.4 Welfare

Aggregate consumption of a country is equal to its disposable income and is given by the sum of total profits and wages net of total R&D expenditure:

$$C_{ct} = \sum_{s=m^*}^{\bar{m}} (\pi L_c + \pi^* L^*) Q_{cst} + \sum_{s=-m^*+1}^{m^*-1} \pi L_c Q_{cst} - \sum_{s=-\bar{m}}^{-\bar{m}} \left(\alpha_c x_{cst}^{\gamma_c} + \tilde{\alpha}_c \tilde{x}_{cst}^{\tilde{\gamma}_c}\right) Q_{cst} + w_{ct} L_c. \tag{15}$$

Aggregate welfare in economy c over a 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 welfare differences between a counterfactual and the benchmark economy in consumption equivalent terms using the following relationship:

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

If a policy change at time t_0 yields a new income sequence $C_{c\tau}^{new}$ between t_0 and t_0+T satisfying the above relationship, we say that the policy change results in $\varsigma\%$ variation in welfare over horizon T in consumption equivalent terms. This means that the representative consumer in the benchmark economy would need to receive $\varsigma\%$ 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 Discussion of the Main Forces and Taking Stock

Before proceeding to the quantitative investigation of the model, we find it worthwhile to discuss some of the key economic forces of our model in more detail. 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 can make significant progress in that direction by focusing on a slightly simplified version in this section.[22]

2.5.1 Static Effects of Openness

At the aggregate level, the static effects of openness on the income and welfare of consumers stem from three main channels, with two having a positive and one having a negative direction. To show this, we consider a closed economy and analyze the effects of its 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

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

[22] For a thorough discussion of similar channels in the context of a basic Schumpeterian creative destruction model, see Chapter 15 in Aghion and Howitt (2009).

When this economy opens to trade the same expressions become

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

where we define $\hat{q} \equiv q/\,(1+\kappa)$. Similarly,

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

with gross income given by

$$
\begin{aligned}
NI_c^O &= \pi \int_0^1 \mathbb{I}_{q_{cj}>\hat{q}_j^*} q_{cj} dj + \pi^* \int_0^1 \mathbb{I}_{q_{cj}>\hat{q}_j^*} q_{cj} dj + \beta Y_c^O \qquad (16) \\
&= \beta\varphi \left[(1-\beta)\left(1+(1+\kappa)^{-\frac{1-\beta}{\beta}}\right) \int_0^1 \mathbb{I}_{q_{cj}>q_{cj}^*} q_{cj} dj + \int_0^1 \mathbb{I}_{q_{cj}>\hat{q}_j^*} q_{cj} dj + (1+\kappa)^{-\frac{1-\beta}{\beta}} \int_0^1 \mathbb{I}_{q_{cj}<\hat{q}_j^*} \hat{q}_j^* dj\right].
\end{aligned}
$$

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

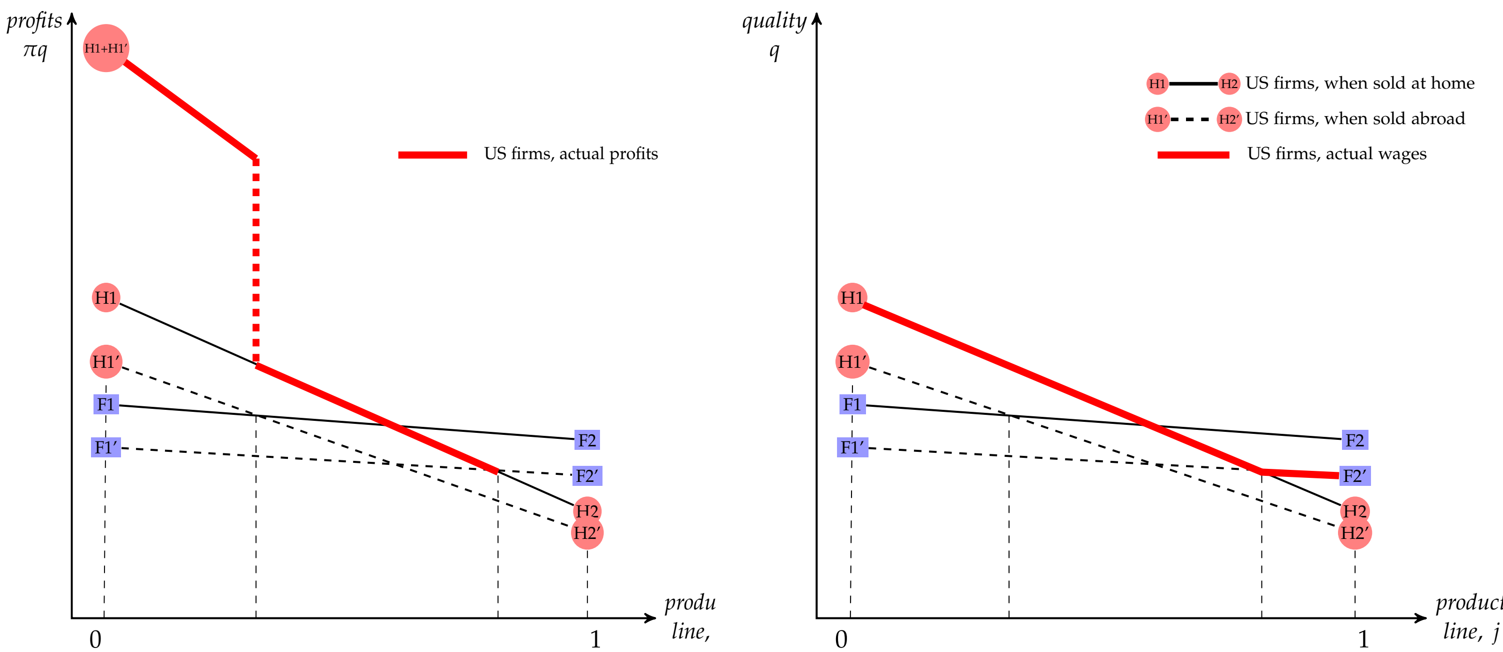
$$
\int_0^1 q_{cj} dj \quad \text{and} \quad \left(1+(1+\kappa)^{-\frac{1-\beta}{\beta}}\right) \int_0^1 \mathbb{I}_{q_{cj}>\hat{q}_j^*} q_{cj} dj
$$

determining the profit component, and to the comparison of

$$
\int_0^1 q_{cj} dj \quad \text{and} \quad \int_0^1 \mathbb{I}_{q_{cj}>\hat{q}_j^*} q_{cj} dj + (1+\kappa)^{-\frac{1-\beta}{\beta}} \int_0^1 \left[1-\mathbb{I}_{q_{cj}>\hat{q}_j^*}\right] \hat{q}_j^* dj
$$

determining fixed factor income. Figure 6 illustrates these comparisons. As in Figure 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 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 (16), as profits of leading firms increase proportionally by π^*. This increase corresponds to the upward expansion of the red line in Figure 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 fixed factor utilized



A) Effect on profits

B) Effect on wages

Figure 6: Static effects of openness

in the production of domestic final output. Figure 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 *direct transfer of technology* in Keller (2004), leads to a higher fixed factor income in both countries.[23] 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 6a, some product lines fail to generate profits as they are substituted by imports. Proposition 1 summarizes the static effects of openness.[24]

Proposition 1 *In the simplified environment described above:*

A) the static change in income in the open economy relative to autarky is determined by the following forces: i) exports / market size expansion; ii) technology transfer; iii) import penetration / destruction of laggard firms' markets. The combined impact of these forces is ambiguous.

B) the static effect of unilateral trade policy liberalization (reduction in tariffs) on aggregate income is determined by the second and third channels. Therefore, the direction of its effect is ambiguous.

Proof. See Appendix B.1. ■

[23] Notice that iceberg costs prevent the flow of all better-quality foreign goods available.

[24] 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).

For instance, 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 a tad better technology may not compensate for the loss of profits in all sectors.

2.5.2 Dynamic Effects of Openness and Escape Competition

As explained in Section 2.3.3, market size and selection channels affect not only the aggregate values, but also firm decisions, introducing a dynamic component. A larger market size increases incentives for innovation whereas the threat of international business stealing, which is the loss of profits to better-quality foreign competitors underlying the selection effect, decreases the value of a firm. However, an important dynamic channel whose impact is completely absent in a static comparison is *escape competition,* the incentive of firms producing goods of similar qualities to escape foreign competition and gain market dominance. In the remainder, we focus on this relatively less standard effect.

In order to emphasize the strategic interaction between intermediate producers introduced by the 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 and minimizes the incentives for quality improvements. First we take $\tilde{\alpha}_c \to \infty$ implying zero entry in both countries. Second, we assume that $\lambda = 1 + \varepsilon$ where ε is arbitrary close to zero, implying that quality improvements from innovations are minuscule. Lastly, we also abstract from subsidies and trade costs, and focus on the balance growth path for the sake of exposition. 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 $m \in \{1, ..., \bar{m} - 1\}$.[25] 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*

[25] 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.

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. See Appendix B.1. ■

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, but it gains an international aspect in the context of a small open economy. However, 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 model instead of one. A combination of market size effect and trade costs drives this result. First, firms have an incentive to escape competition for two similar yet distinct reasons: to capture domestic profits and to capture export markets. In both cases, firms attempt to gain market power and expand profits; but in the first one, competition is against a foreign exporter over the domestic market whereas, in the second, competition is against a foreign firm over their domestic market. Furthermore, because of iceberg trade costs, these challenges do not arise when actual product qualities are similar, as it would happen in the simplified model in Proposition 2. Instead, they arise when trade-cost-adjusted qualities are close, which happens at two distinct positions depending on the market to be captured, i.e. if it is about the domestic market or exports. If home market is at stake, a laggard home firm tries to escape the competitive pressure exerted by a more advanced foreign competitor, whose product has a similar quality once adjusted for trade costs. If an export market is at stake, a relatively more advanced home firm tries to overcome a laggard foreign firm, whose product quality is competitive once trade costs are taken into account.

In the analysis above, firm entry was absent in order to highlight the incentives of interest. However, openness can indeed alter entrant incentives through its effect on the value of incumbents. This is another way that openness affects firm decisions dynamically, as domestic entry leads to the destruction of domestic incumbents creating a source of underinvestment to innovation by incumbents. In the quantitative section, which follows next, we remove the restrictive feature of absence of entry, as well as other simplifying assumptions used in this subsection, such as quick catch-up by the followers and zero iceberg costs.

3 Quantitative Analysis

In this section, we study the quantitative implications of our theoretical framework. In particular, we focus on different channels of technological progress and quantify the welfare implications of the U.S. R&D policies. We also consider implications of alternative policy options that could have been introduced. We start our exploration with the calibration of our the model.

3.1 Calibration

When mapping our two-country model to the data, we envision a world that consists of the U.S. and a weighted combination of the following 7 countries, which we also employed in the empirical section: Canada, France, Germany, Italy, Japan, Spain and UK.[26] The weights associated with each country, listed in Table 1, reflect the count of patents registered in the U.S. by the residents of a specific country in the initial year of the sample (1975) as a fraction of all foreign patents registered in the U.S. in that year.[27] In the remainder of this section, country A will represent the U.S. and country B the foreign country.

Table 1: Patent Weights of Countries

Canada	France	Germany	Italy	Japan	UK
6.2%	11.7%	30.0%	3.8%	33.1%	14.6%

As Figures 2c shows there is a significant break in the R&D policy before and after 1981. Moreover, as shown in Figures A.1 and A.3 in Appendix A.1, there is a strong convergence in the relative shares of domestic and foreign patents registered in the U.S. as well as in the share of sectors led by domestic and foreign firms prior to this date. Therefore, our calibration strategy is to match the model to a set of moments which we obtain from the data that span over 1975-1981. Then, we impose to the calibrated model the changes in R&D policy observed in the data and analyze their implications for the post-1981 period (1981-1995).[28]

In the calibrated model, we try to keep the least amount of heterogeneity across countries in addition to 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 17

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

[27] Weights may not sum up to one due to rounding.

[28] We focus our analysis on the period before 1995 for several reasons. First of all, we want to avoid the run up to the U.S. dot-com bubble and the crisis that followed in 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.

structural parameters to be determined:

$$\theta \equiv \left\{\alpha_A, \alpha_B, \tilde{\alpha}_A, \tilde{\alpha}_B, \gamma, \tilde{\gamma}, \rho, \psi, \beta, \kappa, \eta, \lambda, \phi, \tau^A_{75-81}, \tau^B_{75-81}, \tau^A_{81-95}, \tau^B_{81-95}\right\}.$$

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

3.1.1 External Calibration

For the CES parameter of the utility function, we take the standard macro value $\psi = 2$. We set the time discount parameter $\rho = 1\%$. These preference parameters imply 2.8% interest rate in steady state, and an average rate of 1.8% between 1975-1981 for the U.S. We set $\beta = 0.6$, which leads to a 70% share of fixed factor income in U.S. GDP in balanced growth path, and take η equal to $1 - \beta$.[29] 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. (2013) for a thorough discussion). Table 2 summarizes these estimates.

Table 2: Externally Calibrated Parameters

ψ	$\gamma, \tilde{\gamma}$	β	η	ρ	τ^A_{75-81}	τ^B_{75-81}	τ^A_{81-95}	τ^B_{81-95}
2	2	0.6	0.4	1%	5.3%	3.8%	19.2%	4.1%

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.[30] These data go back until 1979. Given that the rates do not fluctuate much for the countries in the sample before mid-80s, we take the numbers before 1979 be the same with the one in 1979. For the calibration part, the subsidy rates for both countries are 1975-1981 averages which is again weighted for the foreign countries. When we simulate the model for the post-81 period, we will recalculate the subsidy rates to match the averages across 1982-1995. Doing these, we also recalculate the weights of foreign countries the same way but using 1981 patent counts and the weights are shown in Table 1.

3.1.2 Internal Calibration

We have seven parameters remaining: $\{\alpha_A, \alpha_B, \tilde{\alpha}_A, \tilde{\alpha}_B, \kappa, \lambda, \phi\}$, one of which, 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 derived using USPTO patent data. We start with the discussion of the six moments, summarized in Table 3, that are not related to

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

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

the gap distribution. Moments for the foreign country are weighted averages of the values for individual countries.

The first two moments are the average growth rates of TFP in both countries, calculated using TFP series in Coe et al. (2009). The next two moments are aggregate R&D as a percentage of GDP, which we obtain using the Main Science and Technology Indicators (MSTI) database of OECD. We use the non-defense R&D intensity numbers and these miss for Japan. However, Science and Engineering Indicators reports of NSF, based on MSTI data, provide estimates of this variable for Japan which we use to amend our calculations with the OECD data. One issue to note is that MSTI starts in 1981. That is why for this variable we use the values in this starting year. As a fifth target, we include the birth rate of new establishments for the U.S. computed using BDS database.[31] 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 help determine scale parameters of the incumbent R&D cost functions $\{\alpha_A, \alpha_B\}$. The scale parameter of the entrant R&D cost 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 $(\tilde{\alpha}_B)$. Finally, the U.S. export-to-GDP ratio determines the iceberg cost κ as κ sets m^*, the minimum gap a firm needs to open up in order to export, given λ.

The last parameter to be calibrated internally, ϕ, controls the curvature of the generic probability function over technology gaps, $\mathbb{F}(n)$. As manifested by equations (A.1), 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 distribution of sectors across technology gaps using the information on patents provided by the USPTO data as the data counterpart of firms' measure across technology gaps (gap distribution) as shown in Figure 7.

Following a similar procedure explained in Section A.1, we first sort sectors in a given year according to the fraction of patents by a U.S. registrant in total patents in each sector.[32] Then, we divide this unit interval into 33 equally spaced bins, each of which correspond to a range of approximately 3%. For instance, sectors with a fraction of U.S. patents between 0% to 3% would fall into $m = -16$ and 4% to 6% would fall into $m = -15$. Sectors in the data correspond to product lines in our model, and thus, the measure of sectors across bins (normalized to sum up to 1) corresponds to μ_m's for country A in our model across $\bar{m} = 16$ gaps.[33] Figure 8a shows the

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

[32] The total consist of patents by registrants from the U.S. and the other seven foreign countries that we used throughout the paper.

[33] 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.

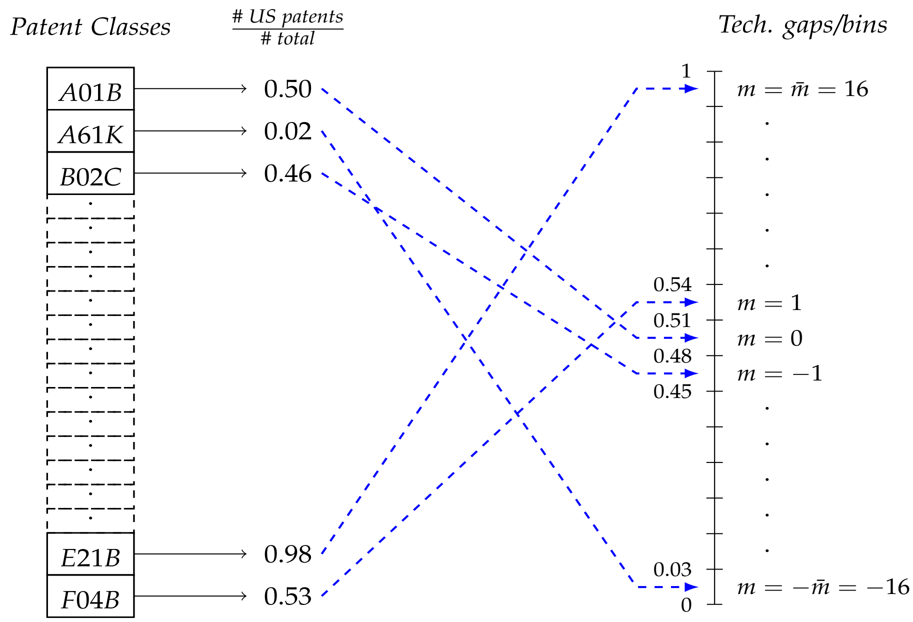


Figure 7: Mapping USPTO patent data to the model

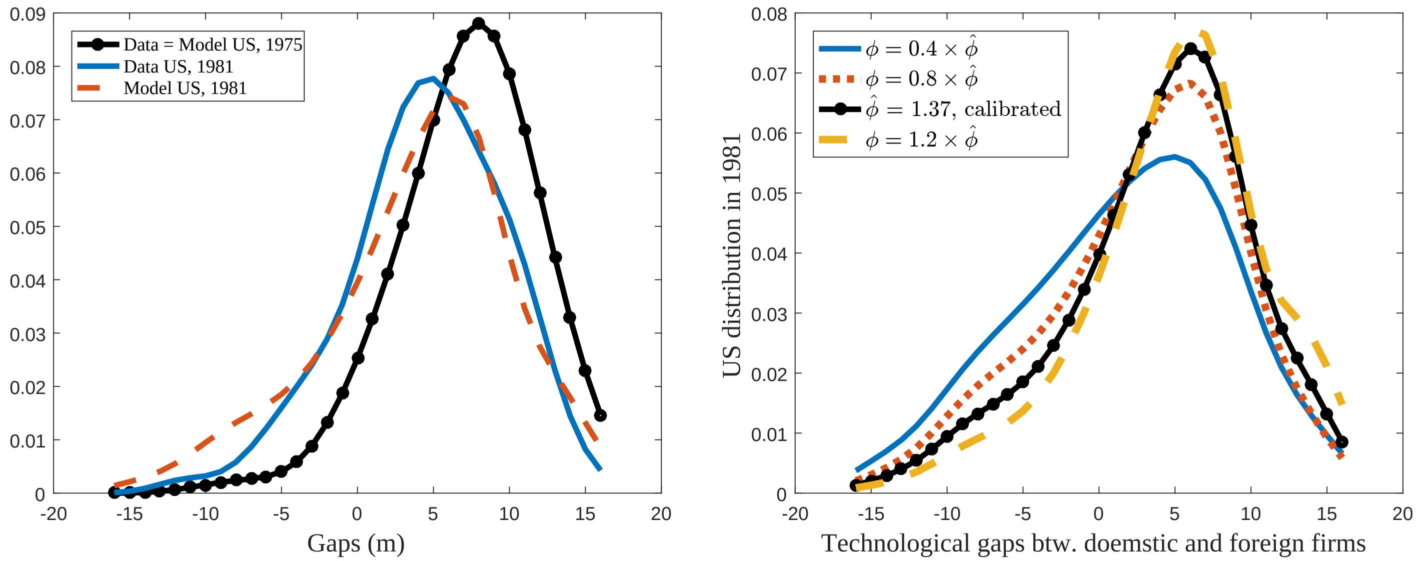
distribution in the data for years 1975 (circled black line) and 1981 (solid blue line).[34] It reveals that initially, a substantial mass of U.S. firms are technological leaders, with the mean gap being close to 7; but subsequently, their distribution has shifted leftward, with the mean gap falling to around 4 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 in the discussion of the model fit below.

In order to obtain the model counterparts of our data targets, we simulate the two economies between 1975-1981, initializing the model at the empirical gap distribution in 1975. Initially, we normalize the quality of U.S. intermediate goods to one, i.e. $q_{Aj1975} = 1\ \forall j$.[35] We solve the transition path of the model over 1975-1981 as described below. We derive the model counterparts of the six moments presented in Table 3 by taking averages of the simulated series over the relevant period. We also compute the the evolution of the gap distribution in the model using equations (A.1) and try to hit the empirical gap distribution in 1981 as the terminal point of the transition economy.

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 steady state in T

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

[35]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 $q_{Bj1975} = \lambda^{-m}$, $m \in \{-\bar{m}, ..., \bar{m}\}$.



A) Technological gap distribution: data and calibration

B) Identification of ϕ

Figure 8: Gap distribution after policy changes

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 steady state and then deriving the values over the transition period going backwards from the steady state. A brief description is as follows:[36]

1. Let $\mathbb{M}$ be the set of data moments and $\mathbb{M}^m$ be the model counterpart. Define $\mathbf{R}\left(\mathbb{M} - \mathbb{M}^m\right)$ as the objective 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 steady state, where time derivatives are zero by definition. Compute the innovation rates, the implied growth rates and finally the steady state interest rates.

4. Next calculate the equilibrium over the transition. Guess a time path for interest rates with the terminal values being set to steady state at every iteration. Solve for firm values and innovation rates backwards in time starting from the steady state. Using the resulting sequences, simulate the income path and its growth rate. Use the Euler equation to derive the implied interest rates and compare them to the series fed initially.

5. Once step 4 converges, use the final interest rate series to compute 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 a minimization routine. We use sum of squared errors

[36] A detailed explanation of steps is presented in Appendix C.2.

as the objective function.[37]

The targeted moments and the model performance in matching these moments are summarized in Table 3 and Figure 8a.

Table 3: Model fit

Moment	Estimate	Target	Source
TFP Growth U.S.	0.45%	0.55%	Coe et al. (2009)1975-81
TFP Growth FN	2.13%	1.82%	Coe et al. (2009) 1975-81
R&D/GDP U.S.	1.65%	1.75%	OECD 1981
R&D/GDP FN	1.85%	1.96%	OECD 1981
Entry Rate U.S.	10%	10%	BDS 1977-81
Export Share U.S.	7.11%	7%	WB 1975-81

Along the transition the catching up country grows faster and has higher R&D to GDP ratios than the leading country. The model captures well these difference between the two economies observed in the data. The entry rate and the export shares are also well fitted. Finally, the position of the dashed line relative to the solid blue one in Figure 8a indicates that the model performs well in matching the 1981 distribution of technology gaps. Hence, the cross-country convergence mechanism built in the model reproduces the catching up observed in the data. The mechanism in the model is largely governed by the curvature of the step-size distribution, ϕ, and Figure 8b illustrates how different ϕ values result in varying shapes of technology gap distribution. Each line in the figure represents the resulting distribution in 1981, after the model is simulated at the calibrated parameter values except for different values of ϕ, starting from 1975. Lower values of ϕ mean a flatter probability distribution $\mathbb{F}(n)$ over step-sizes (or equivalently, gaps 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 distribution of U.S. firms over technology gaps. The position of the solid blue line in Figure 8b 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 a value that is 20% higher than the calibrated one.

The distribution across new positions, $\mathbb{F}(n)$, is the engine of convergence. More precisely, the international knowledge spillover allows laggard firms from the foreign country to stay in the global innovation race. More importantly, an innovation can potentially 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 Gerschenkron (1962)'s

[37] The moments that pertain to the gap distribution are weighted by the number of bins matched to make the total weight of the distribution-related moments the same as the other targets.

terms, 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 their lead further quickly. Thus, foreign firms catch up with domestic firms along the transition generating convergence. The cross-country convergence in our economy echoes that in the Solow model with the key difference that, while in Solow convergence is driven by decreasing returns in capital accumulation, in our economy knowledge spillovers and an 'advantage of backwardness' drive the convergence.

The internally calibrated parameters resulting from this procedure are listed in Table 4. The combination of the iceberg cost κ and the step size λ imply $m^* = 11$, i.e., a firm needs to lead by at least 11 technological gaps to export. The level of ϕ generates a considerable chance of improving multiple steps with a single innovation for laggard firms. For example, the probability that an innovation the most laggard firm receives helps the firm improve multiple steps is 60%.[38]

Table 4: Internally Calibrated Parameters

R&D scale		R&D scale		Step size	Iceberg	$\mathbb{F}(n)$
α_A	α_B	$\tilde{\alpha}_A$	$\tilde{\alpha}_B$	λ	κ	ϕ
0.69	1.14	44.6	8.77	1.49%	19.4%	1.35

3.2 Validation of the model

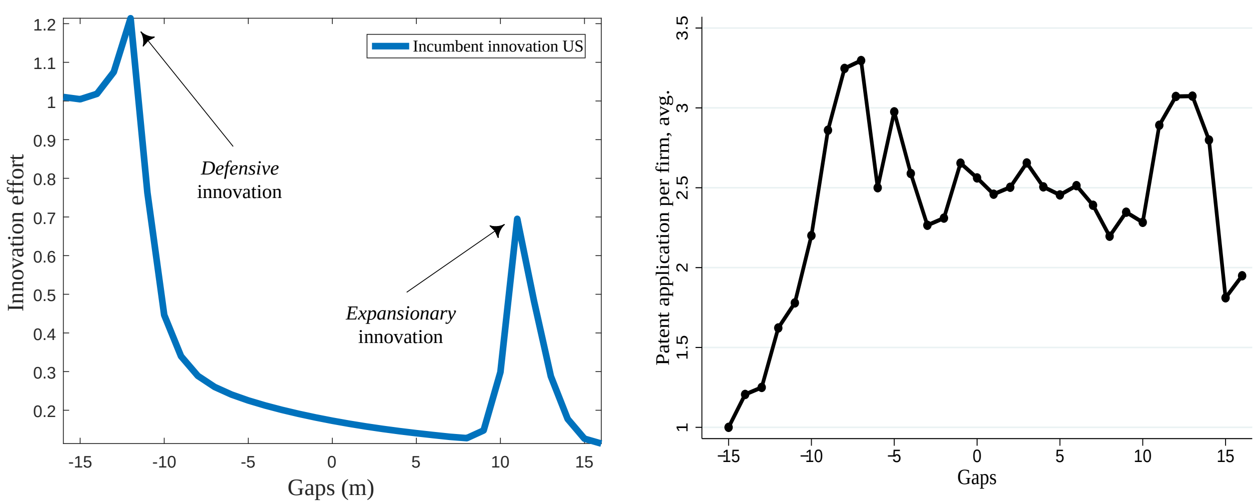
Before discussing the properties and the policy implications of the calibrated model, we present three out-of-sample tests to assess the quantitative plausibility of the integral mechanism of our model, in light of empirical relationships not used in the calibration process.

Incumbent innovation vs. leadership. Figure 9 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 9a depicts incumbents' innovation intensity as a function of the technology gap. Figure 9b 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.[39] In the left panel, we

[38]Conversely, the probability that an innovation the most laggard firm receives is a single-step one is 40%.

[39]We create the 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. Then we rank these class-year pairs according to the share of domestic applications in total applications, and assign them to technology bins as in 3.1.2. Then, in each bin, we sum 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 1975-95, 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 other assignee values have more than six digits. Figure A.8 in Appendix C.4 shows that including those patents leads to sharper spikes in the data.

observe two spikes at $-m^*$ and $m^* - 1$ which are related to cutoffs defined in equation (10). The first one happens right before the position that allows a firm to earn domestic production as a result of firms' intense effort to reach this position. This generates the *defensive innovation* incentive in order to maintain the leadership in the domestic market. Similarly, firms producing domestically increase their innovation efforts massively close to the export cutoff with efforts peaking right before the threshold for exporting. A new innovation right before that threshold enables the domestic firm to export and this generates *expansionary innovation* incentive right before m^*. Interestingly, we observe a similar shape with two peaks also in the data, as illustrated in Figure 9b. Again, the peaks emerge in sectors where U.S. firms hold a strong technological advantage or disadvantage. The striking performance of the model in capturing the innovation intensity observed in the data provides further evidence for our model's ability in mimicking firms' innovation behavior.

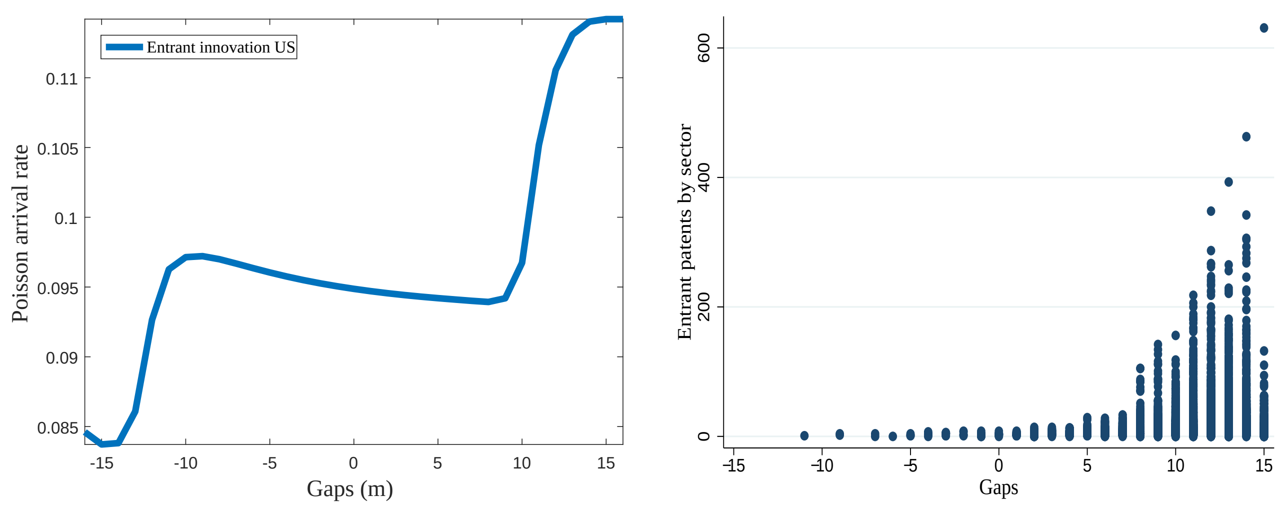


A) Incumbent innovation intensity in model B) Patenting intensity of U.S. incumbents in data

Figure 9: Innovation effort and leadership

The peaks observed in equilibrium incumbent innovation are generated by the key drivers of innovation discussed in Section 2.3.3. The defensive innovation motive is the main incentive to increase innovation before entering the domestic market. A few more steps ahead allow these firms to conquer the domestic market by escaping their rival, and this stimulates their innovation effort. As firms improve their relative position and become farther from cutoffs, they feel less competitive pressures and decrease their R&D efforts. In the basic step-by-step mechanism [e.g. Aghion et al. (2001), Acemoglu and Akcigit (2012) among others], the competition is most intense in the technological neck-and-neck position above which a leader generates profits. Therefore, leaders closer to that position undertake relatively more R&D, and R&D effort exhibits a single peak at the neck-and-neck state. In contrast to the basic step-by-step models, an important feature of our model is that incumbent R&D exhibits two peaks. The reason is the open economy structure with iceberg trade costs, which leads to a race for profits in two separate cases: domestic production and exports. In our model, openness to trade introduces an additional expansionary innovation motive, for which the relevant cutoff is different than the one that determines domestic sales because of iceberg costs. Finally, another contributor to the declining R&D of incumbents at higher gaps is the fact that bigger leads limit the number of quality jumps an innovation can potentially provide to the leader.[40]

Entrant innovation vs. leadership. Entry, together with incumbent innovation just below cutoffs to enter domestic or foreign markets, is the source of business stealing in the model. However, in contrast to incumbents, entrants are not subject to immediate competitive pressures from other country's firms. Therefore, the shape of R&D effort of entrants, demonstrated in Figure 10a, reflects mainly the market size effect around the two cutoffs discussed in the previous subsection. Moreover, because entry to the highest gaps implies access to export markets, it is more profitable, and this leads to a higher entry effort to enter to these positions. Figure 10b 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 done previously for Figure 9b. Each dot in the figure represents a sector in the patent data between 1975-1995, and the value shows the number of patents assigned to U.S. (entrant) firms that patent in that sector for the first time.[41] We observe that the entry intensity is higher for sectors where existing U.S. firms have larger technological lead over their foreign competitors.



A) Entrant innovation intensity in model B) Patenting intensity of U.S. entrants in data

Figure 10: Innovation effort and leadership

[40]This effect arises again because of the shape of $\mathbb{F}_m(n)$. It again resonates with a similar effect in basic step-by-step models. In those setups, leaders' R&D effort decrease as they open up their lead because every new innovation generates a smaller increment in profits.

[41]Observations of the same sector over different years are treated as separate entries.

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. López (2009) using Chilean plant-level data, find that productivity and investment increase before plants begin to export. Aw et al. (2011) using Taiwanese plat-level data estimate a dynamic structural model of the decisions of firms to innovate and to enter the export market. They found that these two decisions are highly correlated, that is firms entering the export market are more likely to also speed up their investment in R&D. Lileeva and Trefler (2010) find that Canadian plants that were induced by the U.S. tariff cuts to start exporting (a) increased their labor productivity, (b) engaged in more product innovation, and (c) had higher adoption rates for advanced manufacturing technologies.

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 COMPUSTAT database. The regression specification is as follows:

$$\ln Y_{jst} = const. + \ln Y_{jst-1} + \ln SC_{st} + \psi_j + \psi_t + u_t \tag{17}$$

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 the 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 which differ in the inclusion of the lagged value of the dependent variable. The results are summarized in Table 5. 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.[42]

The first column of Table 5 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 τ^A_{75-81} to τ^A_{81-95}. Following the same steps used to create empirical variables, the average elasticity of R&D spending to subsidy is

[42] A version of the regression analysis which includes also the federal credits can be found in the Appendix A.2.

Table 5: 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)
$\ln(R\&D_{t-1})$	-	0.631	-	-
	-	(106.67)***	-	-
$\ln(Patent_{t-1})$	-	-	-	0.499
	-	-	-	(72.83)***
$\ln(State\ credit_t)$	3.153	0.524	2.948	1.203
	(10.92)***	(2.12)**	(10.93)***	(4.28)***
Year Dummy	Yes	Yes	Yes	Yes
Firm Dummy	Yes	Yes	Yes	Yes

given by

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

This model statistic has a value of 2.27 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, albeit 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.

3.3 Technological convergence and foreign catching up

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. Now we briefly explore how foreign technological catching up manifests itself in the leading country in our model, which again represents the U.S. Figure 11 shows the evolution of the average technological lead the U.S. firms would have over their foreign competitors in absence of any policy intervention.

The dramatic decline is the symptom of a strong international business-stealing effect, whereby foreign firms progressively capture leadership in more and more markets, and profits that were collected by the U.S. firms are now collected by the foreign firms. This business-stealing effect is crucial in shaping the welfare effects of foreign catching up. In fact, shutting down the business stealing by foreign firms by allowing them to improve the quality of their products at most up to a step behind the U.S. incumbents generates substantial welfare gains in the U.S.

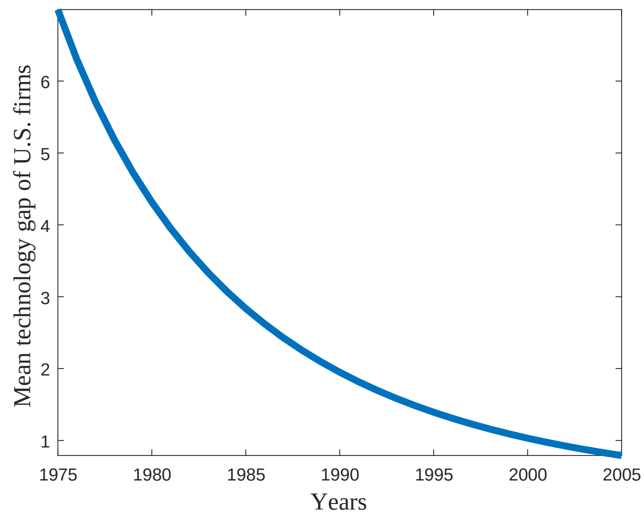


Figure 11: Average technology lead of the U.S. firms, no policy intervention

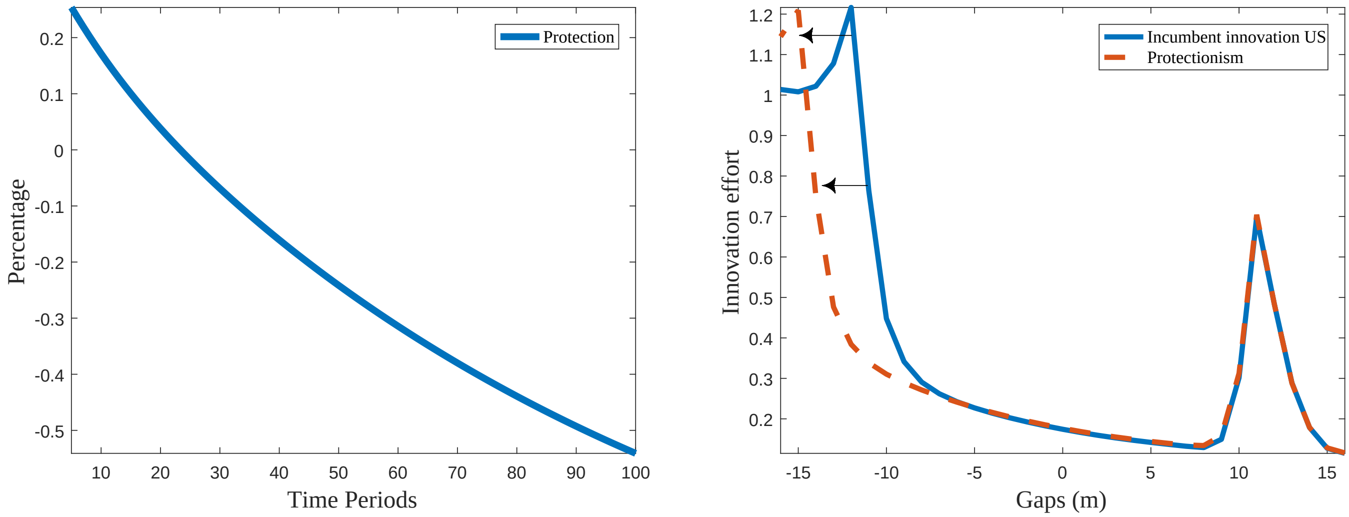
Concluding that the technological convergence hurt the U.S. economy, we now turn to policy analysis.

4 Policy Evaluation

In this section we perform a quantitative investigation of various policies and assess their welfare implications. We discuss the design of optimal policies considering different horizons for policy, also taking into account the transition period. We start the discussion with protectionist measures. Then, we continue with R&D policies, analyzing both the observed post-81 R&D subsidy changes and the optimal subsidy levels. We also consider the design of optimal joint policy, and conclude with a discussion of how retaliation for domestic trade policies by trade partners can alter the design of optimal policies.

4.1 Protectionist Response

In this subsection, we explore the implications of a unilateral increase in trade barriers as an alternative to R&D subsidies and discuss how the optimal tariff policy varies over time horizons. Figure 12a shows the consumption-equivalent welfare gains/losses for the representative household generated by a 20% rise in the trade cost κ in 1981. Compared to the path in a counterfactual economy that does not experience any policy intervention, protectionism seems to pay off in the short run, where small gains are generated from the increase in home profits. However, over time, the gains are declining and turn to negative after two decades.



a) Consumption equivalent welfare

b) Innovation response to protectionism

Figure 12: Welfare effects of protectionism: unilateral 20% increase in trade barriers

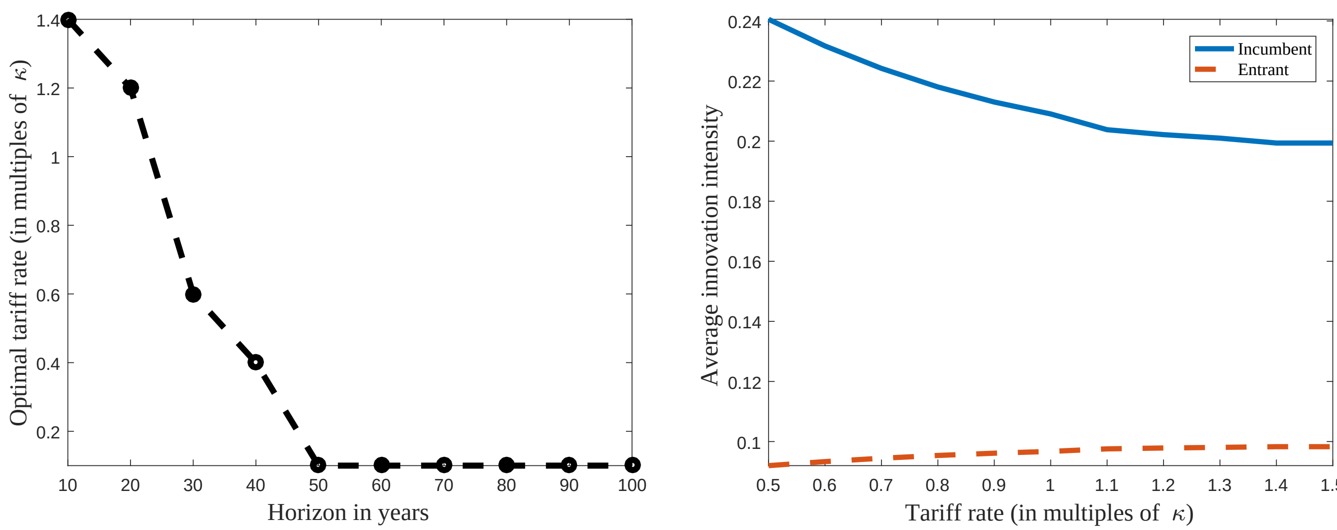
Digging deeper, unilaterally higher trade barriers generate initially a small increase in profit income by protecting some sectors from import penetration shifting market ownership towards home firms. Recall though that the measure of most laggard firms who can benefit from trade protection is relatively small for the U.S., as indicated by the left tail of the dashed line in Figure 8a. 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 significant welfare losses. Overall, the combined welfare effect is nevertheless positive over short-to-medium run.

As time passes, the factor that governs variations in welfare is the decline in competitive pressures on domestic firms, which leads to a decline innovative activity. Figure 12b shows that innovation efforts of most laggard U.S. firms decrease substantially. Because the protectionist policy shifts the threshold for losing the domestic market to a foreign competitor to the left, more firms become farther from such immediate threat. This weaker defensive innovation motive leads to less innovation by these firms, making it harder to compensate for the loss of frontier imported technology. Moreover, most U.S. firms, being either exporters or solid domestic producers that are technologically close to or ahead of their competitors, are not affected by import protection. As shown in Figure 12b, 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.[43] All in all, the short-run gains from profits are subdued over

[43] Evidently, the time-path of average technology lead of the U.S. firms is lower than the one in the "no-intervention" case (see Figure A.7a in Appendix C.4).

time by the loss of foreign technology, while weaker defensive innovation incentive leads to less domestic innovation, and thus, to a slower growth of productivity and profit income.

The negative relationship between the aggregate innovation effort and protection plays an important role also for the design of optimal tariff policy. As shown in Figure 13a, the optimal tariff policy, where the U.S. sets the tariffs imported goods are subject to unilaterally, is effectively to close the borders to imports, when the relevant horizon over which the policymaker calculates the welfare is a very short one like a decade. However, the preferred level of tariffs decreases as the relevant horizon becomes longer, and suggests a more liberal tariff regime with respect to the calibrated economy when the horizon considered extends beyond two decades. As figure 13b demonstrates, the reason is the dampening effect of higher tariff rates imposed by the home country on domestic aggregate innovation. This dynamic negative effect dominates static gains over time, and therefore, implies lower tariffs for optimal policy when longer time horizons considered.



A) Optimal tariff policy over time horizons

B) Average innovation over openness

Figure 13: Innovation over openness and optimal tariff policy over horizon

4.2 R&D Subsidies

As a result of the policy intervention to improve the competitiveness of U.S. companies, the level of R&D subsidies in the U.S. increased significantly from an average of 5.1% in the pre-1981 period to an average 19.2% in the subsequent period, while the foreign subsidy remained fairly constant, being 3.8% and 4.1% in the respective periods. Figure 14 shows the effect of the subsidy on the post-1981 distribution of technology gaps. On both panels, the model gap distribution in 1981, which is closely calibrated to data in 1981, is the solid blue line. In the benchmark economy, which experiences no policy intervention, the transition leads to the dashed line in the left panel by the year 1995. By contrast, in the economy where subsidies were introduced instead in 1981, the resulting distribution in 1995 just becomes the solid blue line in the right panel. The effect of higher subsidies is a small shift to the right relative to the dashed line, which represents no intervention case.[44]

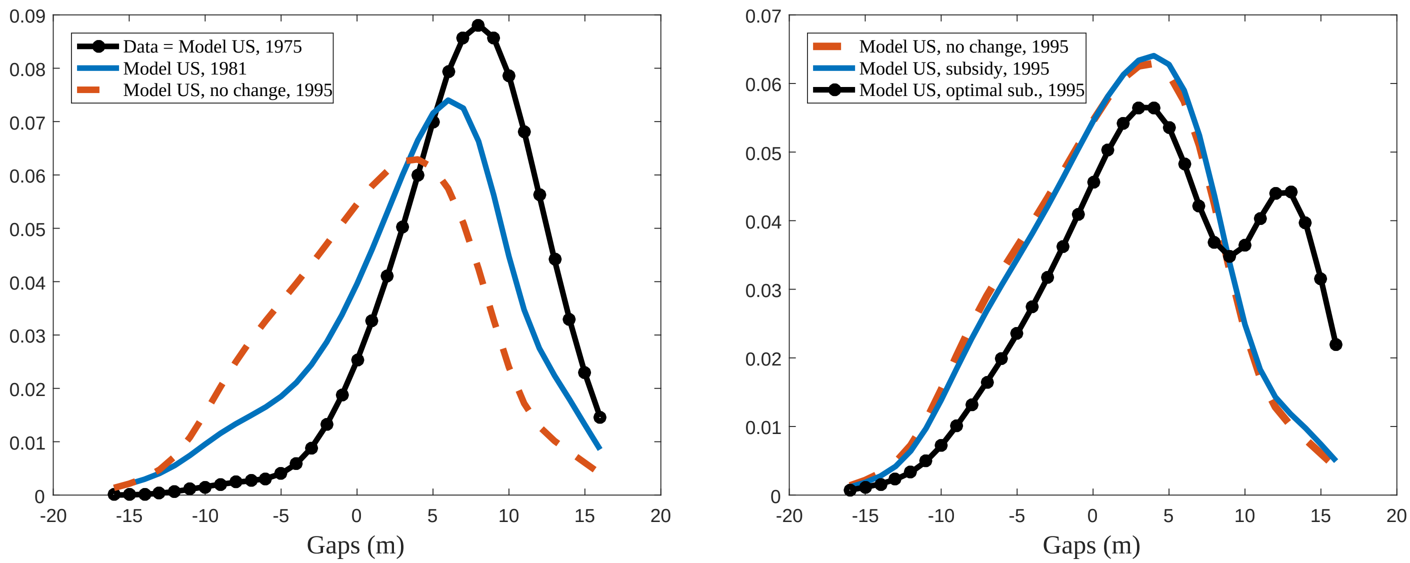


Figure 14: Gap distribution after policy changes

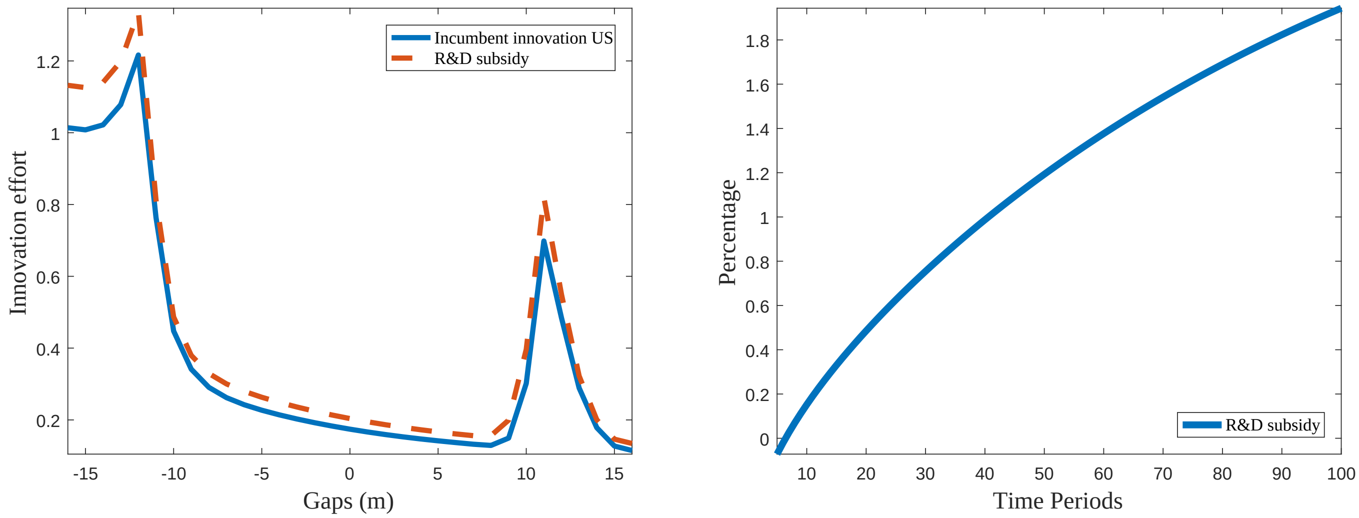
Now we examine the welfare properties of the R&D subsidy intervention. We compute the welfare difference for a 35 years horizon from 1981 until the present year 2016. We find that the U.S. subsidy increase generates a 0.8% consumption gain every year over a span of 35 years. Decomposing the overall welfare change into variations in individual sources of income (not shown), we find that these gains are driven by an increase in innovation by U.S. firms, which in turn leads to a faster growth in both the U.S. factor productivity and profit income. As illustrated in Figure 15a, the underlying economic mechanism is straightforward: By reducing the cost of R&D, subsidies stimulate innovation U.S. incumbent firms, thereby accelerating productivity growth and allowing U.S. firms to obtain market leadership, and the related profits, in more sectors of the economy. The gains from these channels more than offset the resources devoted to the higher aggregate R&D spending.[45]

In Figure 15b, we show the evolution of welfare gains over time generated by the increase

[44]In the right panel, we also show by the circled line the drastic shift that would have arisen had the optimal level of R&D subsidy introduced in 1981. We will discuss optimal subsidies in the next subsection.

[45]Figure A.7b shows how higher subsidies result in a time-path of average technology lead of the U.S. firms that is significantly higher than the one in the "no-intervention" case. Furthermore, higher subsidies stimulate also entrant innovation in an implicit way, although to a significantly lower extent, by increasing the value of entering the business Figure A.6 in Appendix C.4 illustrates the increase in steady state R&D effort of entrants following the subsidy change.

in U.S. subsidies. The figure shows that in the short run of less than 10 years, the subsidy change leads to a welfare loss, which rapidly turns to gains as years go by. This early loss is due to subsidy-induced shift of resources from consumption to innovation. 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.



A) Change in innovation by incumbents

B) Consumption equivalent welfare

Figure 15: Consumption equivalent welfare

4.3 Optimal R&D Subsidies

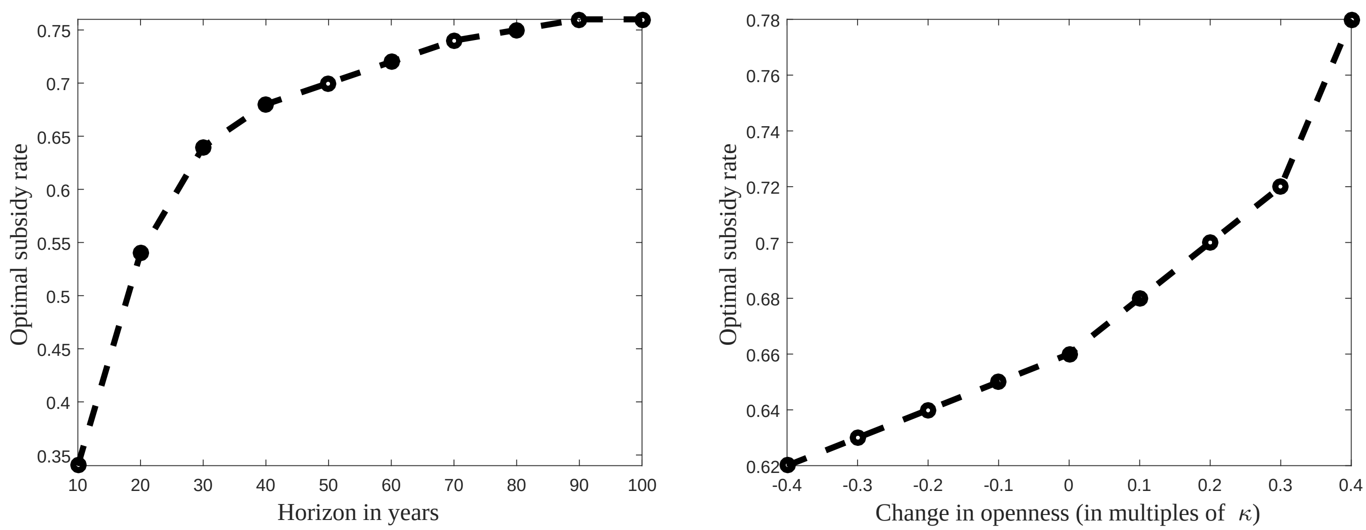
Next we compute the optimal R&D subsidies for the home country and compare it with the U.S. subsidy observed in the data in the post-81 period. Precisely we compute the subsidy rate that maximizes the present discounted value of welfare in a 35 years horizon from 1981 to 2016 and calculate the welfare gains with the optimal subsidy compared to a situation 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-81 subsidy. Table 6 reports the results.

Although U.S. policy makers went in the right direction by increasing the subsidy rate as foreign catching up was accelerating in the 1980s, they did not go far enough. The optimal subsidy response to increasing foreign technological competition suggests that the subsidy rate should have been about 70%, more than three times higher than the observed one. This high subsidy would have increased welfare by a striking 5.8% every year in the 35-year period considered. Moreover, we have also calculated the optimal subsidy for shorter time horizons and we find that the observed post-81 subsidy is only optimal for a time horizon of about 8 years.

Table 6: Observed and optimal U.S. R&D subsidy: 1981-2016

	Subsidy rate	Welfare gains 1981-2016
Observed R&D subsidy	19.2%	0.87%
Optimal R&D subsidy	66%	5.49%

In our model, the optimal subsidy is determined by a rich set of externalities typical of Schumpeterian growth models with some novel twists.[46] First, since future innovations build on the stock of current innovations, innovators do not take into account that their activity will benefit current and future consumers. This leads to underinvestment in R&D and creates a reason to subsidize R&D, known as the *intertemporal spillover effect*. Through catching up or leapfrogging a laggard steals incumbent's business (or part of it), and this is not taken into account in his investment choice. This external effect of innovation leads to overinvestment in R&D and therefore it is a reason to tax R&D, known as the *business stealing effect*. However, in contrast to the standard closed-economy Schumpeterian model, this effect is now created by both domestic entrants and foreign competitors.



A) Over different horizons

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

Figure 16: Optimal U.S. R&D subsidy, over different horizons and levels of openness

As we find that the observed subsidy is optimal for a short horizon, it follows that as time horizon gets longer, the optimal subsidy rate increases. Figure 16a shows optimal subsidy levels for several horizons. This implies that the potential growth gain from innovation induced by higher subsidies increases as longer time horizons considered. Intuitively, optimal R&D sub-

[46]Closed form expressions for these externalities for versions of the standard quality ladder model can be found in Grossman and Helpman (1991) and Segerstrom (1998).

sidies are trading-off the current reduction in consumption with future gains in growth rates. The longer is the horizon, the larger becomes the perceived gain from increased growth rate of aggregate consumption.

Another interesting result is shown in Figure 16b, where we plot the level of optimal subsidy in economies with varying degrees of openness over the same 35-year horizon. It is evident that, in a more open economy with smaller iceberg costs, the level of optimal subsidies is lower, implying that a less aggressive policy is suitable. This result is again driven by the innovation-boosting effect of foreign competition through intensification of escape-competition channel.

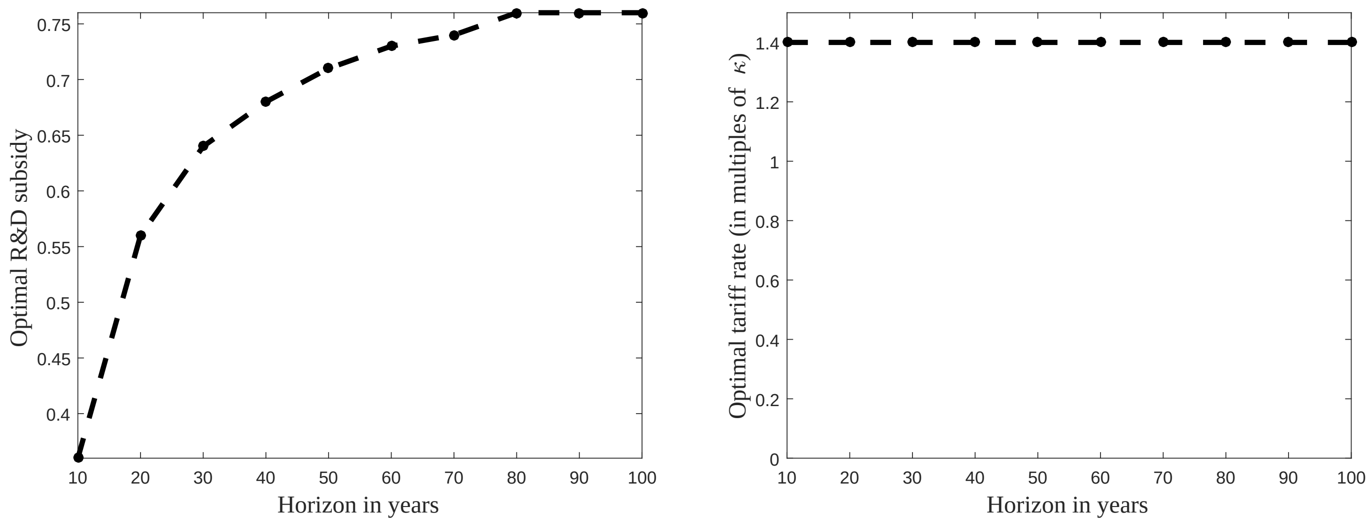
4.4 Optimal Innovation and Trade Policy

Having analyzed the implications of individual policy options, we now focus on the optimal joint policy where the U.S. could use both R&D subsidy and one-sided tariff policy in tandem. Figure 17 plots the optimal levels of these policies over different horizons. The left panel shows that the optimal subsidy levels are close to the ones found when R&D subsidies were considered in isolation, being only slightly higher in some horizons. The right panel, however, shows that strongly protectionist policies are preferred over any horizon, effectively closing the borders to any import penetration. This is in stark contrast with 13a, which shows that optimal tariffs are declining with longer horizon, when considered in isolation. The reason is that, being allowed to set subsidy levels freely, the home country can incentivize its firms to innovate at higher rates, compensating for the loss of innovative efforts as a result of lower competitive pressure that protectionism causes. Therefore, allowing the economy to adjust both margins freely, the joint policy alternative leads to a highly protectionist regime. However, it is crucial to note that when considering optimal policies, we assumed away any reaction from the foreign country and focused only on one-sided tariff policies. Next, we delve into the implications of such foreign response.

4.5 Effect of Foreign Retaliation on Optimal Policy

Until now, we analyzed the trade policy in a unilateral fashion: The home country could set its tariff rates freely, without facing a response from the foreign country. Although this analysis serves as a helpful benchmark, such unilateral moves would be unlikely the case in reality. Then the natural question follows: What would be the effect of foreign retaliation on the design of trade policy?[47] To answer this question, 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.

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



A) Optimal R&D subsidy

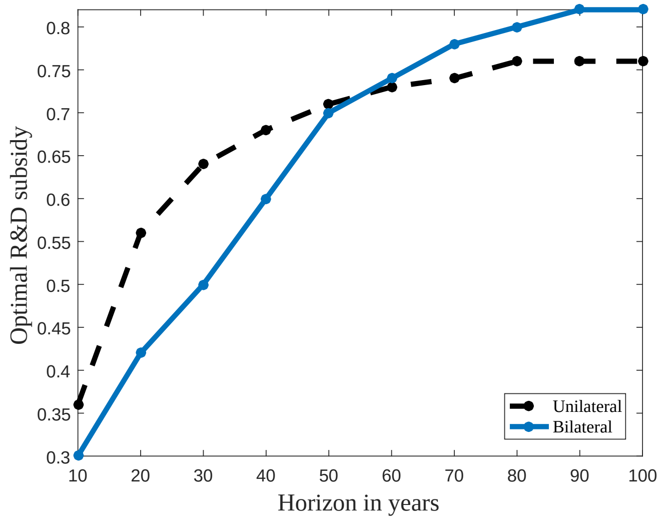
B) Optimal tariff rate

Figure 17: Optimal joint policy

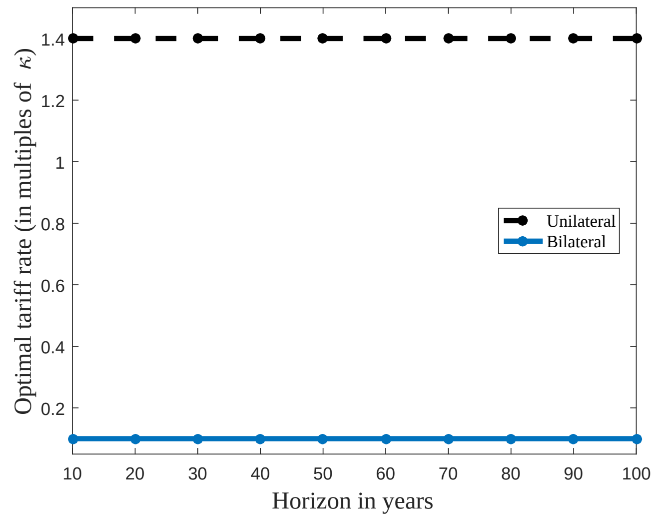
Figure 18 shows the optimal joint policy in this modified setting of bilateral tariff changes (solid blue lines), in juxtaposition with the results obtained in the benchmark setting (dashed black lines).

While there are no significant qualitative differences in the optimal R&D subsidy levels, shown in Figure 18b, there is a complete reversal in the trade policy. Now, the optimal policy becomes to liberalize the economy's trade regime as much as possible. This result arises because 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 case for the U.S. incumbents is demonstrated in Figure 18c for a 20% increase in bilateral tariff rates. As opposed to 12b, the cutoff for exports increases, making it accessible to only a small group of firms. Moreover, the reduction in innovative activity, for similar reasons to what has been explained in the analysis of unilateral policies, now happens for a wider range of firms. Conversely, liberal policies expand the export market of the home country, and stimulate innovation via more intense escape-competition effect. Given that most of 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.[48]

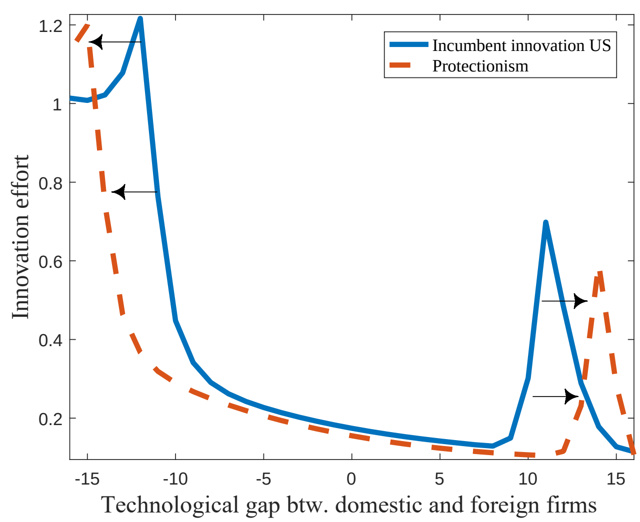
[48]A similar reversal happens when individual trade policy is applied in the case of foreign retaliation, with full liberalization being preferred even when the shortest horizons are concerned.



A) Optimal R&D subsidy



B) Optimal tariff rate



C) Innovation response in case of retaliation

Figure 18: Optimal joint policy in unilateral and bilateral tariff changes

5 Conclusion

In this paper, we shed light on a recurring debate about the competitiveness of U.S. firms relative to their foreign competitors and how to improve their position. Motivated by a set of novel facts on foreign catching-up of the U.S. by other advanced countries during 1970-80s, we build an open economy general equilibrium framework of endogenous growth and trade to evaluate the effectiveness of innovation and trade policies in improving competitiveness of U.S. firms. Firm innovation decisions in our model are motivated by the defensive and expansionary innovation motives, and domestic and international business stealing effects. While knowledge spillovers and decreasing returns to knowledge accumulation lead to cross-country convergence, productivity differences drive trade flows. While incorporating an extensive set of realistic relationships, our machinery is still well-suited for the analysis of transitional dynamics, which proves to be crucial in policy evaluation.

Our theoretical and quantitative analysis obtains several key results among various others. Theoretically, we show that, in the static sense, increased openness benefits the fixed factor in production via higher quality intermediate imports raising its compensation, while the impact on business owners is ambiguous, as larger export demand and loss of markets to better foreign rivals exert opposing forces. In the dynamic sense, increased openness, and thus foreign competition, encourages more domestic innovation through an intensified escape-competition channel on defensive and expansionary margins. Quantitatively, we first show that foreign technological catching-up hurts the U.S. welfare by stealing away business and profits of U.S. firms. However, over the longer run, the positive dynamic effect of increased foreign competition on domestic innovation dominate by intensifying the escape-competition effect. Second, we assess that the introduction of R&D subsidies in the U.S. was a viable response to restore technological competitiveness of U.S. firms, with a notable welfare contribution in medium term. Moreover, we show that the optimal subsidy is increasing over time horizons and decreasing in openness. The latter is an intriguing result, which owes again to the positive effect of foreign competition on domestic innovation through escape-competition channel. Finally, we consider a counterfactual protectionist response to foreign catching-up. We find that increasing trade barriers for imports unilaterally increases U.S. welfare only in the short run, chiefly through the substitution of imports with domestic production leading to higher domestic profits. However, failing to incentivize U.S. firms to accelerate technological improvement, the protectionist policy cannot compensate for the loss of high quality imports and leads to substantial welfare losses in medium to long run. Therefore, protectionist policies, despite helping businesses to retain profits in the short run, make consumers worse off over longer terms.

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Appendices

A Additional Empirical Material

A.1 Empirical Facts

This section presents empirical regularities regarding the trends in global technological leadership and illustrates technological convergence between the U.S. and other major economies. A description of federal- and state-level R&D tax credit policies follows. The section concludes with suggestive evidence of the 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 U.S. in the worldwide technological competition over the course of 1970s until mid-80s. Both in the aggregate and sectoral level, we observe a clear pattern of catching-up which we measure using patent and citation counts.

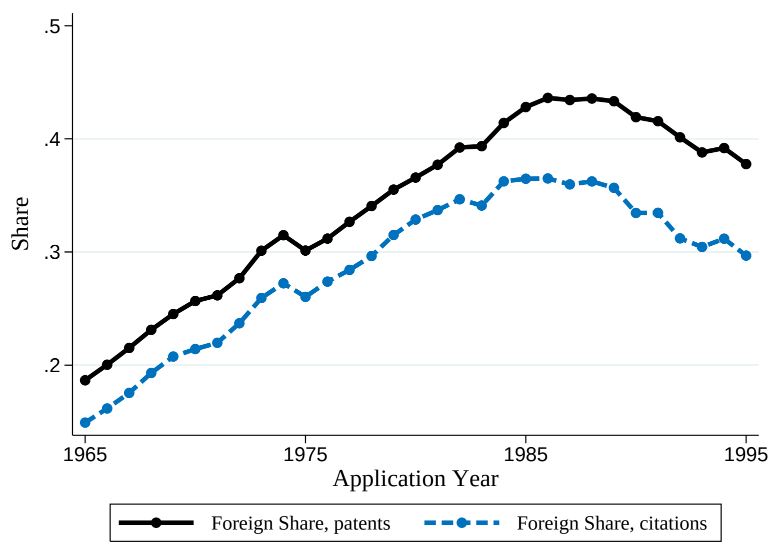
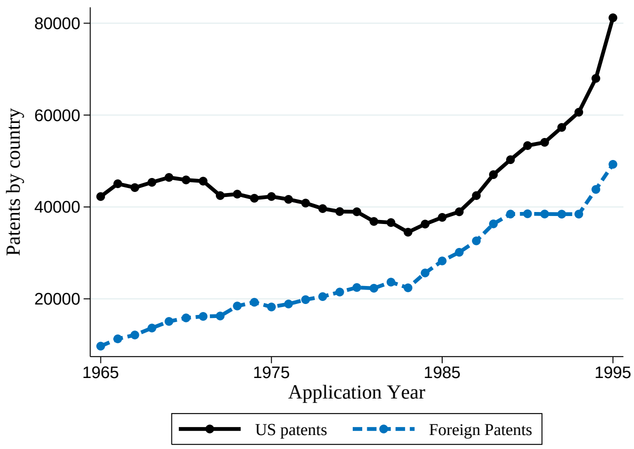


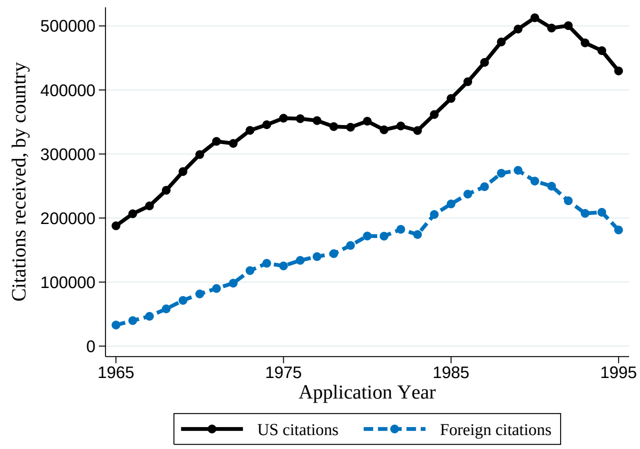
Figure A.1: Share of foreign patents: 1965-1995

Figure A.1 shows the yearly change in the proportion of patents registered in the U.S. by foreigners using USPTO data on patent counts.[49] It also depicts a similar ratio for the citations those patents received. Both lines show 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, in the following years the converge process comes to a halt, and we observed an inversion of the trend. Moreover, a glance at the absolute counts, shown in A.2, reveals that the changes in the shares are chiefly driven by a surge in patent registrations by U.S. residents.

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



A) Patent count



B) Citation count

Figure A.2: Evolution of R&D credits in the U.S.

Figure A.3 brings the analysis down to the level of patent classes (IPC4) using the same data set. It delineates the percentage of sectors (broadly defined by patent classes) "owned" by the U.S.- and foreign-based firms over years as well as the percentage of sectors where they are in a "neck-and-neck" position. The ownership of a sector is defined by having more patents than a certain share of patents registered for the particular sector. The situation we call neck-and-neck arises when the difference of the shares of patents held by two countries is less than a threshold, which is 15% in this case. This implies that a sector is dominated (owned) by the firms of a country if their share is above 57.5%, and it is neck-and-neck if their share is between 42.5% and 57.5%. The figure shows the declining trend in the percentage of all sectors where U.S. firms are dominating until the mid-1980s. This observation demonstrates the relative strengthening of foreign competitors in the technological competition. Notice that, in line with the aggregate trends, we observe an inversion of the trend after 1985 also at the sectoral level.[50]

Fact 2: R&D Tax Incentives

Partly motivated by these and other similar facts, in the late 1970s concerns about the strength of U.S. industry and its ability to compete in a fast moving global economy increased dramatically. The key issues 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 (NSF, 2016, Tassey, 2007). Several new policy measures were introduced in those years with a particular attention at avoiding unduly substitution of government for private firms in activities that the latter can naturally perform better. These policies included several programs to facilitate transfer of the outcome of the federal R&D to private business (e.g. the National Cooperative Research act in 1984, the Technology Transfer Act, 1986), policies strengthening intellectual property rights such as the Bayh-Dole Act (1980), and

[50]The results are unchanged when patents are weighted by citations received.

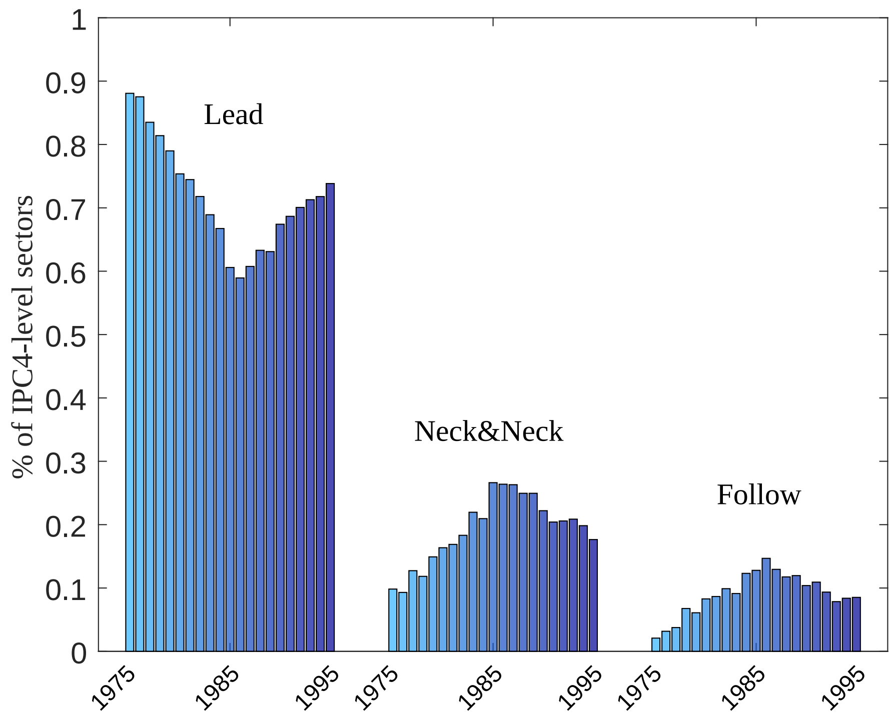


Figure A.3: Leadership distribution: share of sectors with U.S. lead, neck-and-neck, foreign lead

tax incentives to innovation which started with the Research and Experimentation Tax Credit 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 1984–1988 R&D to sales ratio (with a maximum of 16%) times current sales. The U.S. competitors in high-tech industries, Japan and the large European economies, introduced or had already 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 U.S., 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 2c 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% in 1981 and further increase up to more than 25% 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.4 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% in 1995, nearly a quarter of the federal one, and the number of states following such a policy rose to 32. Figure A.4 also shows average R&D credit level weighted by the state-level patent production, whose evolution over time is parallel to the simple average.[51]

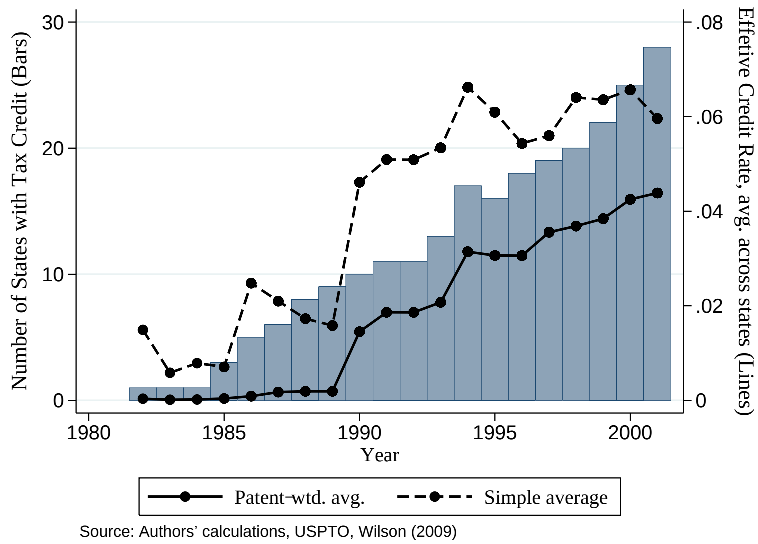


Figure A.4: U.S. State-level R&D tax credit

A.2 Additional regression results

This section presents the counterpart of the regression analysis in Section 2 incorporating federal tax credit. The results are shown in Table A.1. In all specifications except the last one, federal credits have positive and significant coefficients as expected. The results are qualitatively the same with the exception of last regression.

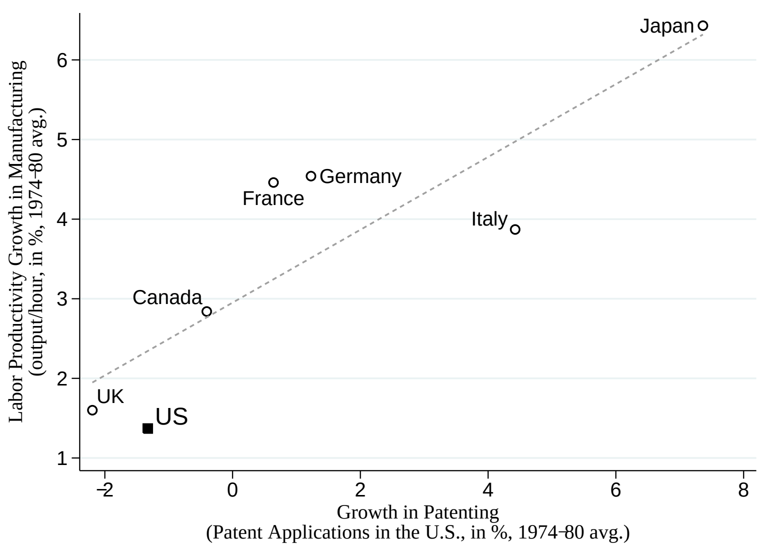
[51] As opposed to the simple average, the weighted average multiplies the state-level effective credit by the fraction of total U.S.-based patents registered in that state.

Table A.1: The Effect of R&D Tax Credit on Innovation (incl. Federal Credits)

Dep. Var.:	$\ln(R\&D_t)$ (5)	$\ln(R\&D_t)$ (6)	$\ln(Patents_t)$ (7)	$\ln(Patents_t)$ (8)
$\ln(R\&D_{t-1})$	-	0.641	-	-
	-	(113.16)***	-	-
$\ln(Patent_{t-1})$	-	-	-	0.559
	-	-	-	(77.22)***
$\ln(State\ credit_t)$	7.555	0.731	4.255	0.148
	(28.72)***	(3.26)**	(16.74)***	(0.55)
$\ln(Federal\ credit_t)$	3.940	1.930	0.563	-0.341
	(28.26)***	(16.61)**	(4.18)***	(-2.41)**
Year Dummy	No	No	No	No
Firm Dummy	Yes	Yes	Yes	Yes

A.3 Miscellaneous

Figure A.5 replicates Figure 1 over the slightly longer time period 1974-80. The message remains intact.



Source: USPTO, Capdevielle and Alvarez (1981), and authors' own calculation

Figure A.5: Convergence between the U.S. and its peers

B Model and Derivations

B.1 Proofs

Result 1

1. *Final Good Price Equality*
   Intuitively, trade in final good, which is not subject to iceberg costs, equates the final good price in both countries (to be 1 as the numeraire). The reason why it is economically viable for competitive final good producers in both countries to operate, even when there is no factor price equalitzation for intermediate goods due to trade costs, is that wages adjust accordingly. Thus, adjustments in the prices of two factors of production guarantee that the final good production takes place in both countries at the break even point.
   To see this consider the profit of the representative final good producer:

$$P_c\left(t\right)Y_c(t) - w_c(t)L_c - \int_0^1 p_j(t)k_j(t)dj = P_c\left(t\right)Y_c(t) - w_c(t)L_c - \left[\int_{\Omega^c} \frac{\pi}{\beta} q_j(t)dj + \int_{\Omega^*} \frac{\pi^*}{\beta} q_j^*(t)dj\right].$$

   Here we plugged in intermediate good price from equations (8) and (9). The final good producer buys some intermediate goods domestically and and exports some others. We group intermediate goods according to their production location, denoting the measure of domestic and imported intermediate products by Ω^c and Ω^*. Referring to the total expenditure on domestically bought and imported intermediate goods by Z_c^K and M_c^K, respectively, we decompose further:

$$\begin{aligned} P_c\left(t\right)Y_c(t) - w_c(t)L_c - \int_0^1 p_j(t)k_j(t)dj &= P_c\left(t\right)Y_c(t) - w_c(t)L_c - \left(Z_c^K + M_c^K\right) \\ &= P_c\left(t\right)Y_c(t) - \beta Y_c(t) - \left(1-\beta\right)Y_c(t) \\ &= \left(P_c\left(t\right) - 1\right)Y_c(t). \end{aligned}$$

   For the competitive equilibrium in final good production to hold $P_c\left(t\right) = 1$ must hold at all times.

2. *Trade Balance*
   We will show this result in two steps. First, by production approach, GDP equals the sum of value added in final and intermediate good sectors:

$$\begin{aligned} GDP_c &= \left(Y_c - \left(Z_c^K + M_c^K\right)\right) + \left(\left(Z_c^K + X_c^K\right) - K_c\right) \\ &= Y_c - K_c + \left(X_c^K - M_c^K\right) \end{aligned}$$

   where K_c is the final good used in intermediate good production, X_c^K and M_c^K represent the value of exports and imports of intermediate goods, respectively. Then, the national accounting identity becomes

$$\begin{aligned} Y_c - K_c + \left(X_c^K - M_c^K\right) &= C_c + R_c + (X_c - M_c) \\ &= C_c + R_c + \left(X_c^K - M_c^K\right) + \left(X_c^Y - M_c^Y\right) \end{aligned}$$

where C_c is disposable income/consumption, D_c is investment in R&D, and the $(X_c - M_c)$ is net exports which we decompose into net exports of intermediate and final goods in the bottom line. Equivalently, the aggregate resource constraint follows as

$$Y_c = C_c + R_c + K_c + \left(X_c^Y - M_c^Y\right).$$

It implies that that the final output in excess of consumption, intermediate input and R&D expenditures becomes

$$(Y_c - D_c - K_c) - C_c = \left(X_c^Y - M_c^Y\right).$$

For the second step, denote aggregate sales and profits of domestic firms by S_c and Π_c, respectively. We can write total profits as $\Pi_c \equiv S_c - K_c = \left(Z_c^K + X_c^K\right) - K_c$. Total income available for consumption is the sum of intermediate firm profits net of R&D expenditures and wages:

$$C_c = \Pi_c - D_c + \beta Y_c.$$

Substituting this expression for C_c implies that the final output in excess of consumption, intermediate input and R&D expenditures is equal to minus net exports of intermediate goods:

$$\begin{aligned} (Y_c - R_c - K_c) - C_c &= (Y_c - D_c - K_c) - (\Pi_c - D_c + \beta Y_c) \\ &= (1-\beta)\, Y_c - (\Pi_c + K_c) \\ &= (1-\beta)\, Y_c - S_c \\ &= \left(Z_c^K + M_c^K\right) - \left(Z_c^K + X_c^K\right) \\ &= -\left(X_c^K - M_c^K\right). \end{aligned}$$

By the equality established previously we obtain

$$\begin{aligned} (Y_c - R_c - K_c) - C_c = \left(X_c^Y - M_c^Y\right) = -\left(X_c^K - M_c^K\right) \Rightarrow \\ \left(X_c^Y - M_c^Y\right) + \left(X_c^K - M_c^K\right) = 0. \end{aligned}$$

Lemma 1 We confirm this lemma by guess-and-verify method. Assuming linearity we have

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

Dividing all sides by q_t we obtain that x_{Amt} does not depend on q_t. Also, linearity assumption in equation (13) implies that $\tilde{x}_{Amt}$ is independent of q_t. Reciprocally, innovation decisions of foreign firms are independent of the quality level. It follows that v_{Amt} is independent of q_t such that $V_{Amt}(q_t) = v_{Amt} q_t$ holds.

Proposition 1 The effect of opening up on wage income is determined by the following difference:[52]

$$
\begin{aligned}
\Delta_w &= \int_0^1 \mathbb{I}_{q_{cj} > \hat{q}_j^*} q_{cj} dj + (1+\kappa)^{-\frac{1-\beta}{\beta}} \int_0^1 \left[1 - \mathbb{I}_{q_{cj} > \hat{q}_j^*}\right] \hat{q}_j^* dj - \int_0^1 q_{cj} dj \\
&= (1+\kappa)^{-\frac{1-\beta}{\beta}} \int_0^1 \mathbb{I}_{q_{cj} < \hat{q}_j^*} \hat{q}_j^* dj - \int_0^1 \mathbb{I}_{q_{cj} < \hat{q}_j^*} q_{cj} dj.
\end{aligned}
$$

The transfer of better technology affects this component positively. The total effect on profits is determined by

$$
\begin{aligned}
\Delta_\Pi &= \left(1 + (1+\kappa)^{-\frac{1-\beta}{\beta}}\right) \int_0^1 \mathbb{I}_{q_{cj} > \hat{q}_j^*} q_{cj} dj - \int_0^1 q_{cj} dj \\
&= (1+\kappa)^{-\frac{1-\beta}{\beta}} \int_0^1 \mathbb{I}_{q_{cj} > \hat{q}_j^*} q_{cj} dj - \int_0^1 \left[1 - \mathbb{I}_{q_{cj} > \hat{q}_j^*}\right] q_{cj} dj.
\end{aligned}
$$

The first component is the gain from exports and the second component is the loss of profits from firms which 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

$$
\Delta w + \Delta \Pi = \beta \varphi \Delta_w + \pi \Delta_\Pi,
$$

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.

[52] A strong sufficient condition for this component to be positive is that $\beta > 1/2$, meaning that the labor share in the economy is larger than one half, a condition met by almost all quantitative work.

Proposition 2 First, 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 $x_0 > 0$.

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 $x_0 > x_{-m} = x_{-\bar{m}} > x_{\bar{m}} = x_m = 0$.

B.2 Aggregation and the distribution of leadership

The growth rate of this economy is determined by the changes in aggregate quality/productivity 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. In the Appendix we describe all possible cases, and here we only report the resulting evolution of aggregate qualities. Changes in Q_{Amt} are characterized by the following expressions:[53]

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

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

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

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

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

the addition of product lines, where the position of the domestic incumbent worsened to m from a better one. An improvement by foreign incumbents or entrants from position $-s < -m$ to $-m$, which happens 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 entrants improves the quality of the good that the most laggard domestic incumbents produce due to 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

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

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 levels. 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.3 Derivation of Quality Dynamics

Here we introduce the changes in m in different scenarios and the derivation of Q_{cmt} as result of these changes.Tables below summarize different scenarios (DI (FI): Domestic (Foreign) Incumbent, DE (FE): Domestic (Foreign) entrant, DN (FN): Domestic (Foreign) competitor in neck&neck). The interpretation of a row in the following tables is "in Case X, which happens with Innov. probability Y, the Effect W is carried into New Position Z".

The case of $\bar{m}$-step-ahead Leader is in country c :

$\bar{m}$-step-ahead Leader is in country c

Case	Innov.	Effect	New Position
DI innovates	$x^c_{\bar{m}}$	$\lambda Q^c_{\bar{m}}$	$\bar{m}$
DE innovates	$\tilde{x}^c_{\bar{m}}$	$\lambda Q^c_{\bar{m}}$	$\bar{m}$
FI innovates	$x^f_{-\bar{m}}\mathbb{F}_{-\bar{m}}(n)$	$Q^c_{\bar{m}}$	$-n$
FE innovates	$\tilde{x}^f_{-\bar{m}}\mathbb{F}_{-\bar{m}}(n)$	$Q^c_{\bar{m}}$	$-n$
Nothing	$1 - x^c_{\bar{m}} - x^f_{-\bar{m}}$ $-\tilde{x}^c_{\bar{m}} - \tilde{x}^f_{-\bar{m}}$	$Q^c_{\bar{m}}$	$\bar{m}$

The case when m-step-ahead Leader $(0 \leq m < \bar{m})$ is in country c :

m-step-ahead Leader is in country c

Case	Innov.	Effect	New Position
DI innovates	$x^c_m\mathbb{F}_m(n)$	$\lambda^{(n-m)}Q^c_m$	n
DE innovates	$\tilde{x}^c_m\mathbb{F}_m(n)$	$\lambda^{(n-m)}Q^c_m$	n
FI innovates	$x^f_{-m}\mathbb{F}_{-m}(n)$	Q^c_m	$-n$
FE innovates	$\tilde{x}^f_{-m}\mathbb{F}_{-m}(n)$	Q^c_m	$-n$
Nothing	$1 - x^c_m - x^f_{-m}$ $-\tilde{x}^c_m - \tilde{x}^f_{-m}$	Q^c_m	m

The case when $-m$-step-behind Follower $(0 < m < \bar{m})$ is in country c :

m-step-behind Follower is in country c

Case	Innov.	Effect	New Position
DI innovates	$x^c_{-m}\mathbb{F}_{-m}(n)$	$\lambda^{(n+m)}Q^c_{-m}$	n
DE innovates	$\tilde{x}^c_{-m}\mathbb{F}_{-m}(n)$	$\lambda^{(n+m)}Q^c_{-m}$	n
FI innovates	$x^f_m\mathbb{F}_m(n)$	Q^c_{-m}	$-n$
FE leapfrogs	$\tilde{x}^f_m\mathbb{F}_m(n)$	Q^c_{-m}	$-n$
Nothing	$1 - x^c_{-m} - x^f_m$ $-\tilde{x}^c_{-m} - \tilde{x}^f_m$	Q^c_{-m}	$-m$

The case when $-\bar{m}$-step-behind Follower is in country c :

$-\bar{m}$-step-behind Follower is in country c

Case	Innov.	Effect	New Position
DI innovates	$x^c_{-\bar{m}}\mathbb{F}_{-\bar{m}}(n)$	$\lambda^{(n+\bar{m})}Q^c_{-\bar{m}}$	n
DE innovates	$\tilde{x}^c_{-\bar{m}}\mathbb{F}_{-\bar{m}}(n)$	$\lambda^{(n+\bar{m})}Q^c_{-\bar{m}}$	n
FI innovates	$x^f_{\bar{m}}\mathbb{F}_{\bar{m}}(n)$	$Q^c_{-\bar{m}}$	$-\bar{m}$
FE leapfrogs	$\tilde{x}^f_{\bar{m}}\mathbb{F}_{\bar{m}}(n)$	$Q^c_{-\bar{m}}$	$-\bar{m}$
Nothing	$1-x^c_{-\bar{m}}-x^f_{\bar{m}}$ $-\tilde{x}^c_{-\bar{m}}-\tilde{x}^f_{\bar{m}}$	$Q^c_{-\bar{m}}$	$-\bar{m}$

The shifts, and the resulting changes in Q^c_m, can be summarized analytically:

$$
\begin{aligned}
Q^c_{\bar{m}}(t+\Delta t) &= \lambda Q^c_{\bar{m}}\left(x^c_{\bar{m}}+\tilde{x}^c_{\bar{m}}\right)\Delta t + Q^c_{\bar{m}}\left(1-x^c_{\bar{m}}\Delta t - x^f_{-\bar{m}}\Delta t - \tilde{x}^c_{\bar{m}}\Delta t - \tilde{x}^f_{-\bar{m}}\Delta t\right)\\
&\quad + \Delta t\sum_{s=-\bar{m}}^{\bar{m}-1}\mathbb{F}_s(\bar{m})\left(x^c_s+\tilde{x}^c_s\right)\lambda^{\bar{m}-s}Q^c_s\\
\Rightarrow \dot{Q}^c_{\bar{m}} &= \left[\left(x^c_{\bar{m}}+\tilde{x}^c_{\bar{m}}\right)(\lambda-1) - x^f_{-\bar{m}} - \tilde{x}^f_{-\bar{m}}\right]Q^c_{\bar{m}} + \underbrace{\sum_{s=-\bar{m}}^{\bar{m}-1}\mathbb{F}_s(\bar{m})\left(x^c_s+\tilde{x}^c_s\right)\lambda^{\bar{m}-s}Q^c_s}_{\mathcal{F}_{\bar{m}}}
\end{aligned}
$$

$$
\begin{aligned}
Q^c_m(t+\Delta t) &= \Delta t\sum_{s=m+1}^{\bar{m}}\mathbb{F}_{-s}(-m)\left(x^f_{-s}+\tilde{x}^f_{-s}\right)Q^c_s + \Delta t\sum_{s=-\bar{m}}^{m-1}\mathbb{F}_s(m)\left(x^c_s+\tilde{x}^c_s\right)\lambda^{m-s}Q^c_s\\
&\quad + Q^c_m\left(1-x^c_m\Delta t - x^f_{-m}\Delta t - \tilde{x}^c_m\Delta t - \tilde{x}^f_{-m}\Delta t\right)\\
\Rightarrow \dot{Q}^c_m &= \underbrace{\sum_{s=m+1}^{\bar{m}}\mathbb{F}_{-s}(-m)\left(x^f_{-s}+\tilde{x}^f_{-s}\right)Q^c_s}_{\mathcal{F}^1_m} + \underbrace{\sum_{s=-\bar{m}}^{m-1}\mathbb{F}_s(m)\left(x^c_s+\tilde{x}^c_s\right)\lambda^{m-s}Q^c_s}_{\mathcal{F}^2_m}\\
&\quad - \left[x^c_m + x^f_{-m} + \tilde{x}^c_m + \tilde{x}^f_{-m}\right]Q^c_m
\end{aligned}
$$

$$
\begin{aligned}
Q^c_{-\bar{m}}(t+\Delta t) &= \lambda Q^c_{-\bar{m}}\left(x^f_{\bar{m}}+\tilde{x}^f_{\bar{m}}\right)\Delta t + Q^c_{-\bar{m}}\left(1-x^c_{-\bar{m}}\Delta t - x^f_{\bar{m}}\Delta t - \tilde{x}^c_{\bar{m}}\Delta t - \tilde{x}^f_{\bar{m}}\Delta t\right)\\
&\quad + \Delta t\sum_{s=-\bar{m}}^{\bar{m}-1}\mathbb{F}_s(\bar{m})\left(x^f_s+\tilde{x}^f_s\right)Q^c_{-s}\\
\Rightarrow \dot{Q}^c_{-\bar{m}} &= \left[\left(x^f_{\bar{m}}+\tilde{x}^f_{\bar{m}}\right)(\lambda-1) - \tilde{x}^c_{\bar{m}} - x^c_{-\bar{m}}\right]Q^c_{-\bar{m}} + \underbrace{\sum_{s=-\bar{m}}^{\bar{m}-1}\mathbb{F}_s(\bar{m})\left(x^f_s+\tilde{x}^f_s\right)Q^c_{-s}}_{\mathcal{F}_{-\bar{m}}}.
\end{aligned}
$$

where

- $\mathcal{F}_{\bar{m}}$ captures domestic firms at $s<\bar{m}$ reaching gap $\bar{m}$ with probability $\mathbb{F}_s(\bar{m})$;

- $\mathcal{F}_m^1$ captures foreign firms at $-s < -m$ reaching gap $-m$, thus hitting domestic incumbents at $s > m$ and bringing them down to gap m, with probability $\mathbb{F}_{-s}(-m)$;
- $\mathcal{F}_m^2$ captures domestic firms at $s < m$ reaching gap m with probability $\mathbb{F}_s(m)$;
- $\mathcal{F}_{-\bar{m}}$ captures foreign firms at $s < \bar{m}$ reaching gap $\bar{m}$, thus hitting domestic incumbents at $-s > -\bar{m}$ and bringing them down to gap $\bar{m}$, with probability $\mathbb{F}_s(\bar{m})$.

C Quantitative Appendix

C.1 System in Discrete Time

The discretized system is the system written in terms of instantaneous rate of changes, right before we take the limit as $\Delta t \to 0^+$ (discarding the terms with $(\Delta t)^2$). For incumbents and entrants, it is described as follows:

$$
\begin{aligned}
r_t^A v_{mt+\Delta t}^A - \frac{v_{mt+\Delta t}^A - v_{mt}^A}{\Delta t} &= \Pi(m) - \left(1-\tau^A\right)\alpha_A \frac{\left(x_{mt}^A\right)^{\gamma_A}}{\gamma_A} \\
&+ x_{mt}^A \left\{ \sum_{n=m+1}^{\bar{m}} \mathbb{F}_m(n)\,\lambda^{(n_t-m)} v_{nt+\Delta t}^A - v_{mt+\Delta t}^A \right\} \\
&+ \tilde{x}_{mt}^A \left[0 - v_{mt+\Delta t}^A\right] + \left(x_{-mt}^B + \tilde{x}_{-mt}^B\right) \sum_{n=-m+1}^{\bar{m}} \mathbb{F}_{-m}(n) \left[v_{-nt+\Delta t}^A - v_{mt+\Delta t}^A\right]
\end{aligned}
\tag{A.2}
$$

$$
-\frac{\tilde{\alpha}_c}{\tilde{\gamma}_c}\left(\tilde{x}_{mt}^c\right)^{\tilde{\gamma}_c} + \tilde{x}_{mt}^c \left\{ \sum_{n=m+1}^{\bar{m}} \mathbb{F}_m(n)\,\lambda^{(n_t-m)} v_{nt+\Delta t}^A - 0 \right\}. \tag{A.3}
$$

C.2 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 steady state, where time derivatives are zero by definition. Start iteration $h = 0$ with the guess $\left\{r_T^A, r_T^B\right\}^{h=0}$.
   (a) At iteration h, take $\left\{r_T^A, r_T^B\right\}^h$ given and solve incumbent firm values jointly for both countries by backward iteration.
      i. Guess $\left\{v_{mT+\Delta t}^A, v_{mT+\Delta t}^B\right\}_{m\in\{-\bar{m},..,\bar{m}\}}$. Assuming these to be true steady state values compute innovation rates $\left\{x_{mT}^A, \tilde{x}_{mT}^A, x_{mT}^B, \tilde{x}_{mT}^B\right\}_{m\in\{-\bar{m},..,\bar{m}\}}$. Notice that these are

innovation rates at one period before as innovation is a forward looking decision and thus, depends on next period value in discrete time.

ii. Compute $\left\{v_{mT}^{A}, v_{mT}^{B}\right\}_{m}$ using the value function equations. By the definition of the steady state, values at $T+\Delta t$ and T should be the same.

iii. Check if

$$\max_{m,c}\left\|v_{mT+\Delta t}^{c}-v_{mT}^{c}\right\|<\varepsilon.$$

If not met, set $\left\{v_{mT+\Delta t}^{c}\right\}_{m}=\left\{v_{mT}^{c}\right\}_{m}$ and repeat.

(b) Take the steady state 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 stabilize. Call these $\left\{g_{T}^{A}, g_{T}^{B}\right\}^{h}$.

(c) Check if $\left\{r_{T}^{A}, r_{T}^{B}\right\}^{h}$ and $\left\{g_{T}^{A}, g_{T}^{B}\right\}^{h}$ meet the Euler equation. If not, set $\left\{r_{T}^{A}, r_{T}^{B}\right\}^{h+1}$ to interest rates implied by the Euler equation with $\left\{g_{T}^{A}, g_{T}^{B}\right\}^{h}$ and repeat until convergence.

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

(a) At iteration h, given terminal (steady state) values $\left\{v_{mT}^{A}, v_{mT}^{B}\right\}_{m}^{h}$ compute the implied innovation rates $\left\{x_{mT-\Delta t}^{A}, \tilde{x}_{mT-\Delta t}^{A}, x_{mT-\Delta t}^{B}, \tilde{x}_{mT-\Delta t}^{B}\right\}_{m}^{h}$. Then, given terminal interest rates $\left\{r_{T}^{A}, r_{T}^{B}\right\}^{h}$, compute $\left\{v_{mT-\Delta t}^{A}, v_{mT-\Delta t}^{B}\right\}_{m}^{h}$. Iterate backwards using the $\left\{r_{t}^{A}, r_{t}^{B}\right\}_{t=\{1975,\ldots,1975+T\}}^{h}$ until $t_{0}=1975$ to obtain the implied series $\left\{x_{mt}^{A}, \tilde{x}_{mt}^{A}, x_{mt}^{B}, \tilde{x}_{mt}^{B}\right\}_{mt=\{1975,\ldots,1975+T\}}^{h}$.

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

(c) Compute income growth rates $\left\{g_{t}^{A}, g_{t}^{B}\right\}_{t}^{h}$. Using period-by-period Euler equations, check if

$$\max_{m,c,t}\left\|\left\{g_{t}^{c}\right\}^{h}-\frac{\left\{r_{t}^{c}\right\}^{h}-\rho}{\psi}\right\|<\varepsilon.$$

for $\{1975,\ldots,1975+T-1\}$. If not, set $\left\{r_{t}^{A}, r_{t}^{B}\right\}_{t=\{1975,\ldots,1975+T-1\}}^{h+1}$ to interest rates implied by the Euler equation with $\left\{g_{t}^{A}, g_{t}^{B}\right\}_{t=\{1975,\ldots,1975+T-1\}}^{h}$ and repeat until convergence.

5. Once step 4 converges, use the final interest rates $\left\{r_{t}^{A}, r_{t}^{B}\right\}_{t=\{1975,\ldots,1975+T\}}$ to compute 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.

C.3 Consumption Equivalent Welfare

Table A.2: Welfare effect of "No Business Stealing"

Year	Overall	Profits only	Inc. R&D only	Ent. R&D only	Dom. Factor only	Imp. Factor only
10	1.0208	1.0440	0.9995	0.9779	1.0159	0.9832
20	1.0287	1.0608	1.0018	0.9693	1.0153	0.9809
30	1.0309	1.0746	1.0033	0.9620	1.0101	0.9800
50	1.0281	1.0823	1.0042	0.9577	1.0031	0.9797
100	1.0075	1.0900	1.0058	0.9526	0.9784	0.9793

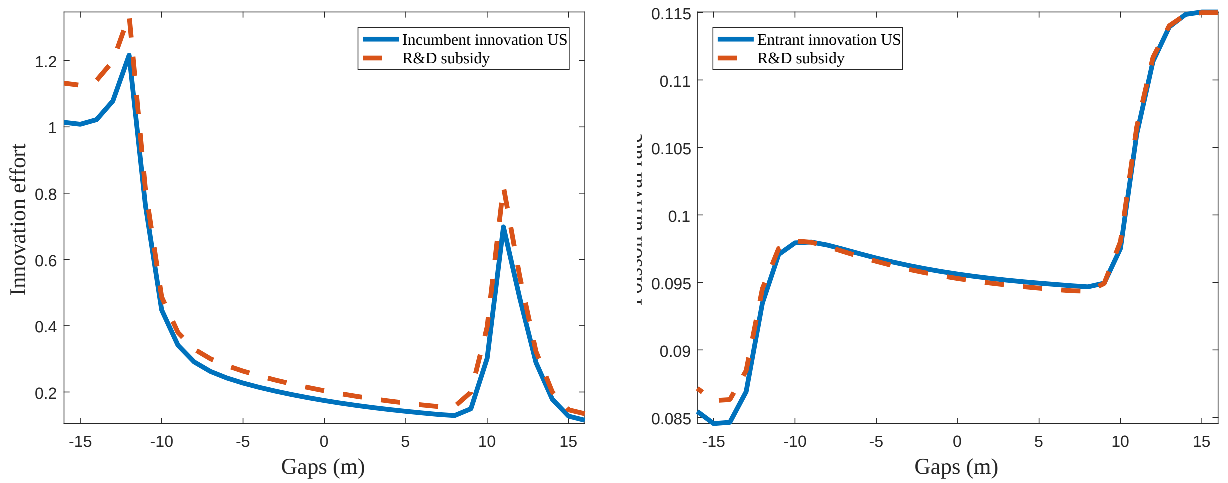
Table A.3: Welfare effect of U.S. R&D subsidy increase

Year	Overall	Profits only	Inc. R&D only	Ent. R&D only	Dom. Factor only	Imp. Factor only
10	1.0014	1.0044	0.9950	0.9994	1.0045	0.9981
20	1.0046	1.0059	0.9952	0.9987	1.0071	0.9978
30	1.0071	1.0068	0.9953	0.9983	1.0091	0.9977
50	1.0112	1.0081	0.9954	0.9977	1.0124	0.9976
100	1.0179	1.0104	0.9954	0.9967	1.0178	0.9977

Table A.4: Welfare effect of protectionism: 40% increase

Year	Overall	Profits only	Inc. R&D only	Ent. R&D only	Dom. Factor only	Imp. Factor only
10	1.0012	1.0059	1.0046	0.9947	1.0139	0.9822
20	0.9989	1.0051	1.0047	0.9950	1.0121	0.9821
30	0.9970	1.0044	1.0048	0.9953	1.0104	0.9821
50	0.9937	1.0032	1.0049	0.9958	1.0078	0.9821
100	0.9881	1.0012	1.0050	0.9966	1.0032	0.9821

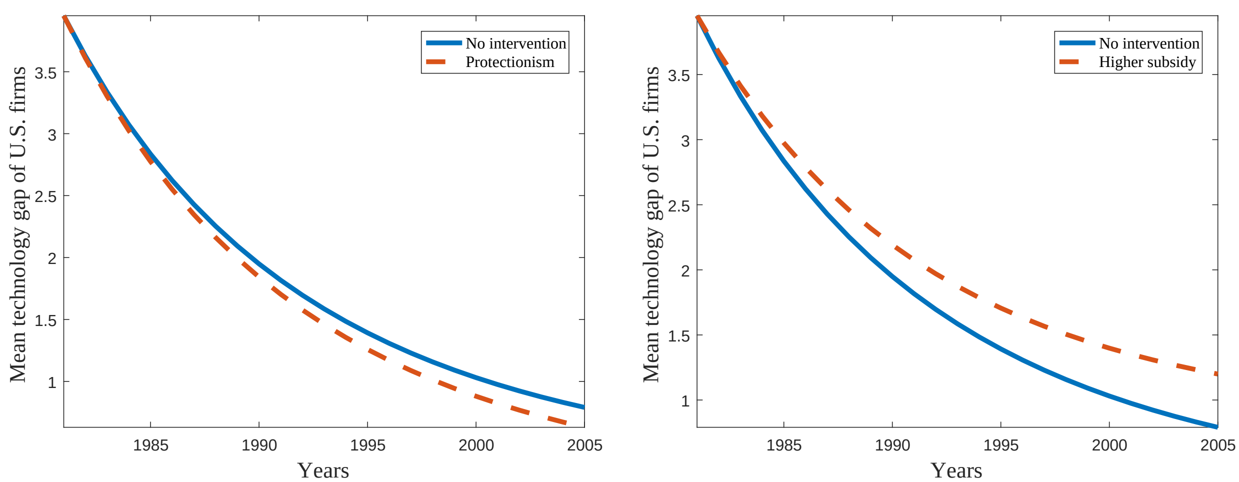
C.4 Additional Figures



A) Incumbents

B) Entrants

Figure A.6: Changes in R&D decisions after subsidy change



A) 20% tariff hike

B) Actual R&D policy

Figure A.7: Average technology lead of the U.S. firms, after policy intervention

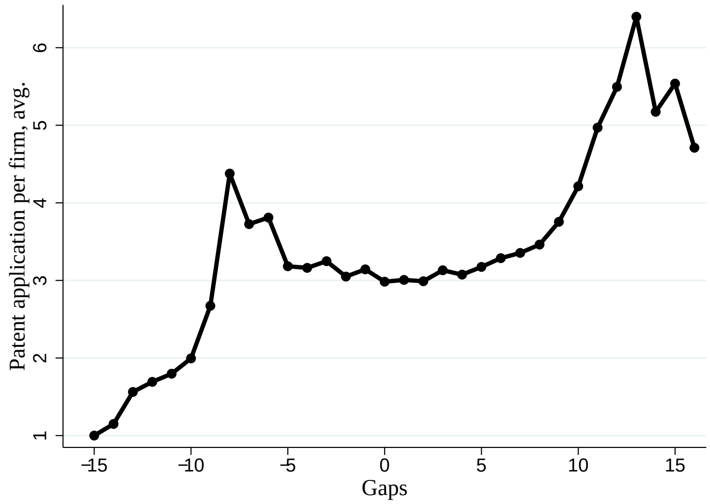


Figure A.8: Patenting intensity in USPTO data

D Robustness

D.1 Modeling Labor in the Intermediate Goods Sector

A central concern in the debate on gains from trade is the potential harm that import penetration can cause to domestic workers by stealing the market of the domestic firms [Autor et al. (2013)]. In our baseline model, labor, which is used in the final good sector, benefits from trade liberalization thanks to the higher labor productivity, which is brought about by better-quality imports replacing inferior domestic counterparts. In this section, we modify the baseline model in order to allow trade to have an adverse impact on labor. In this version, labor is utilized in the production of intermediate goods; therefore, foreign catch-up leads to a wage loss as a by-product of business stealing. We re-estimate this new version of the model, and compare its key policy implications with the ones of the baseline model.

Assume that final goods are produced by combining a fixed factor (again normalized to 1 for both countries), while intermediate goods are produced using labor:

$$k_{jt} = \frac{\bar{q}_{ct}}{\eta} l_{jt}.$$

Here, $\bar{q}_{ct}$ denotes the economy-wide labor productivity in intermediate good production, which is common across all sectors. Equilibrium profits from domestic sales and exports become

$$\pi\left(q_{jt}\right) = \left[\frac{1-\beta}{\eta}\frac{\bar{q}_{ct}}{w_{ct}}\right]^{\frac{1-\beta}{\beta}} \beta q_{jt} \quad \textit{and} \quad \pi^*\left(q_{jt}\right) = \left[\frac{1-\beta}{(1+\kappa)\,\eta}\frac{\bar{q}_{ct}}{w_{ct}}\right]^{\frac{1-\beta}{\beta}} \beta L_f q_{cjt}.$$

Market clearing condition for labor reads as $L_c = \int_0^1 l_{cjt}\, dj$. Normalizing the size of the labor force to 1 and solving for the wage yields

$$\frac{w_{ct}}{\bar{q}_{ct}} = \chi \bar{q}_{ct}^{-\beta} \left[\underbrace{Q_{ct}^{D} + Q_{ct}^{X} + (1+\kappa)^{\frac{\beta-1}{\beta}} Q_{ct}^{X}}_{\text{denote } \bar{Q}_{ct}} \right]^{\beta} \equiv \chi \left[\frac{\bar{Q}_{ct}}{\bar{q}_{ct}} \right]^{\beta}.$$

Here, $\bar{Q}_{ct}$ can be interpreted as the average quality of sales of all active domestic firms, adjusted for trade costs exported goods are subject to. In the special case where $\bar{q}_{ct} = \bar{Q}_{ct}$ we have

$$w_{ct} = \chi \bar{Q}_{ct}.$$

Therefore, $w_{ct} L_{ct} = w_{ct}$ enters the aggregate consumption term given in equation (**??**) as another source of income:

$$C_{ct} = \sum_{s=m^*}^{\bar{m}} \pi^* F^* Q_{cst} + \sum_{s=-m^*+1}^{\bar{m}} \pi F_c Q_{cst} - \sum_{s=-\bar{m}}^{-\bar{m}} \alpha_c x_{cst}^{\gamma_c} Q_{cst} - \sum_{s=-\bar{m}}^{-\bar{m}} \tilde{\alpha}_c \tilde{x}_{cst}^{\tilde{\gamma}_c} Q_{cst}$$
$$+ \beta \sum_{m=-m^*+1}^{\bar{m}} \left[\frac{1-\beta}{\eta} \right]^{\frac{1-\beta}{\beta}} \frac{Q_{cmt}}{1-\beta} + \beta \sum_{m=-\bar{m}}^{-m^*} \left[\frac{1-\beta}{(1+\kappa)\,\eta} \right]^{\frac{1-\beta}{\beta}} \frac{Q_{mt}^{*}}{1-\beta} + \chi \bar{Q}_{ct} \qquad \text{(A.4)}$$

where $\{F_c, F^*\}$ denote the fixed factor used in the final good production in home and foreign countries, respectively.

D.1.1 Calibration

We recalibrate this model following similar steps as with the baseline version. This time we set β to 0.2, allowing us to get a reasonable share of labor income around 65%. The rest of the external parameters share the baseline values. Internally calibrated parameters are presented in Table A.5. As summarized in Table A.6, this model also performs well in matching the data targets.

Table A.5: Internally Calibrated Parameters

R&D scale		R&D scale		Step size	Iceberg	$\mathbb{F}(n)$
α_A	α_B	$\tilde{\alpha}_A$	$\tilde{\alpha}_B$	λ	κ	ϕ
0.16	0.69	21.0	31.2	0.82%	2.69%	0.77

Table A.6: Model fit

Moment	Estimate	Target	Source
TFP Growth U.S.	0.45%	0.45%	Coe et al. (2009)1975-81
TFP Growth FN	1.79%	1.82%	Coe et al. (2009) 1975-81
R&D/GDP U.S.	1.83%	1.75%	OECD 1981
R&D/GDP FN	1.95%	1.96%	OECD 1981
Entry Rate U.S.	10%	10%	BDS 1977-81
Export Share U.S.	7%	7%	WB 1975-81

D.1.2 Policy Implications

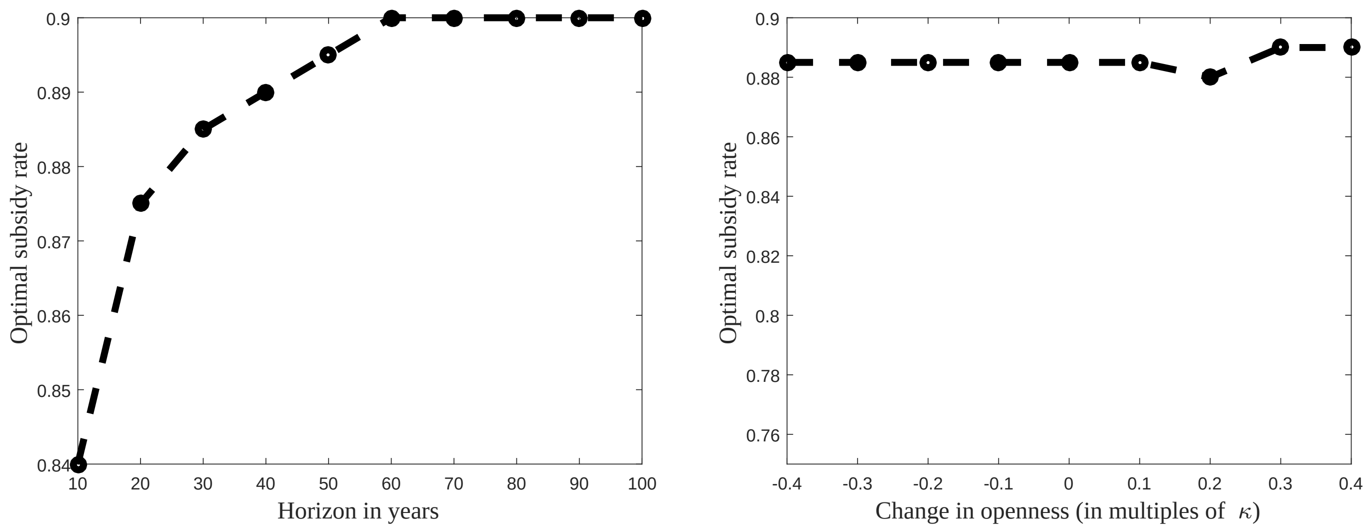
In terms of R&D subsidies, Table A.7 reveals that subsidies lead to larger welfare gains compared to the baseline model. This is an intuitive result because in this setting, the acceleration in domestic innovation increases the productivity of labor in intermediate good production, in addition to the effects present in the baseline model. This mechanism also leads to a higher level of optimal R&D subsidy.

Table A.7: Observed and optimal U.S. R&D subsidy: 1981-2016

	Subsidy rate	Welfare gains 1981-2016
Observed R&D subsidy	19.2%	2.33%
Optimal R&D subsidy	89%	45.3%

Figure A.9a implies that the policy function for optimal R&D subsidy over different horizons of time is qualitatively similar to what has been found in the baseline setting. Again, the level of optimal subsidies are much higher. However, Figure A.9b, which shows optimal subsidies over trade openness (again, considering a horizon of 35 years), is at odds with the original result that less aggressive R&D policies are preferred with a more liberal trade regime. In the new framework, very high subsidies are preferred at all levels of openness when a fixed span of 35 years is the relevant horizon. This result indicates that, as far as R&D subsidies are considered, the domestic labor productivity gains in intermediate good production are the primary determinant of the welfare gains, and thus, optimal subsidy levels.

Next, we analyze the effects of protectionist policies. Figure A.10 presents the consumption-equivalent welfare change and the change in optimal innovation effort of incumbent firms following a unilateral 20% increase in US tariffs. First, Figure A.10a, demonstrates the decline in innovation efforts of laggard US firms, again due to less foreign competition they face thanks to higher protection. Although the aggregate domestic innovation does not decrease noticeably, as shown in Figure A.11a, the steady level of innovation cannot compensate for the loss of foregone technology of imported goods, and therefore, leads to a declining trend in welfare gains



A) Over different horizons

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

Figure A.9: Optimal U.S. R&D subsidy, over different horizons and levels of openness

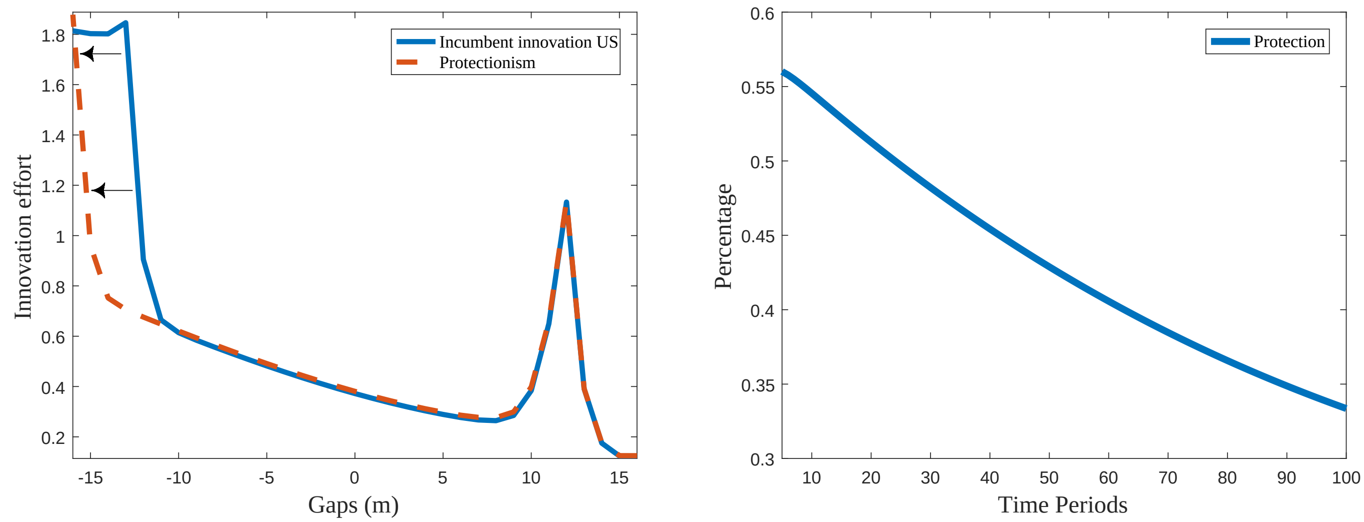
over longer time periods.[54] However, in sharp contrast with the baseline, the protectionist policy leads to welfare gains over all time horizons in this modified setting. The reason is that now protectionist polices prohibit not only business stealing, but also "wage stealing", i.e. the decline in wages because of the loss of domestic activity to foreign importers. This mechanism strengthens the positive effect of protectionist policies.

Turning to optimal unilateral tariffs over different time horizons, shown in Figure A.11b, we observe that over any time horizon, a high enough tariff rate is preferred such that the economy closes its borders to any import penetration. This boundary result is again very different than its baseline counterpart of a declining optimal tariff policy over longer time horizons. Again, this is an intuitive result given that protectionist policies protect domestic wage income in this setting. Moreover, as opposed to the baseline model, the impact of protectionist policies on innovation is muted in this setting, although we observe the negative effect on individual firms due to weaker competition. This result arises because of the transitional dynamics of mass of firms affected by the policy.[55]

Finally, Figure A.12 shows the optimal joint policy response, both in cases of unilateral (dashed black lines) and bilateral (solid blue lines) tariff changes. In the former setting, optimal levels of individual policies closely follow their counterparts obtained when policy alternatives are considered in isolation. Furthermore, as in the baseline model, the reversal in the trade policy when the foreign country retaliates arises also in this modified model. This result implies that the gains from wider export markets for the home firms dominate the additional negative effect of import penetration on domestic wages.

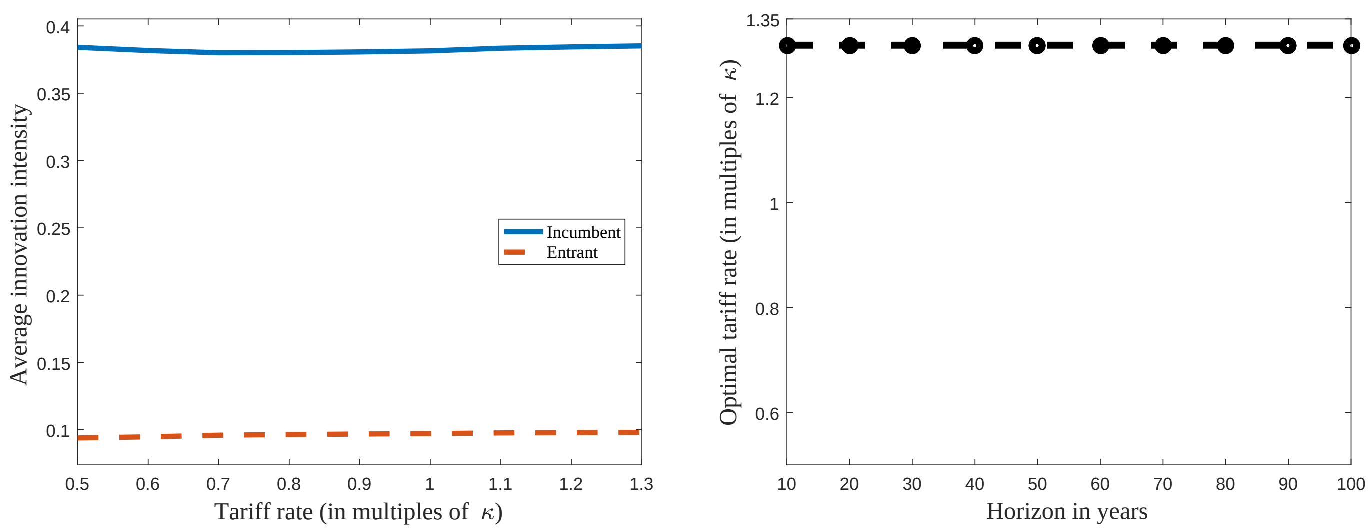
[54]Aggregate incumbent innovation is little affected by the changes in innovation efforts fo individual firms as a result of protectionist policies because of the limited mass of firms affected.

[55]These dynamics limit the fall in welfare gains over time in Figure A.10b.



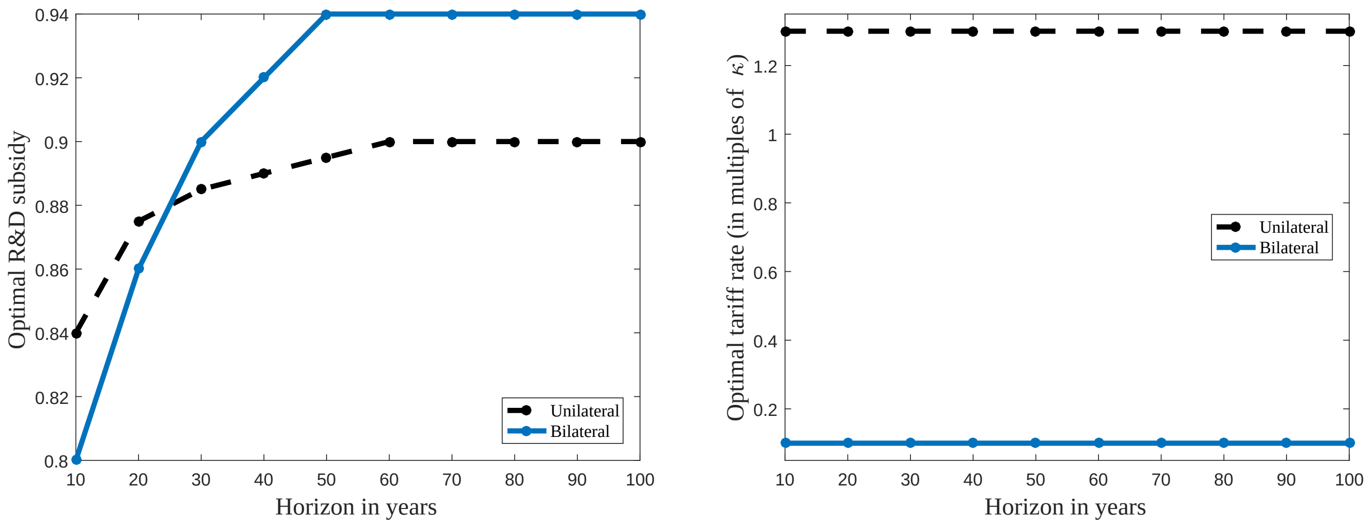
A) Consumption equivalent welfare   B) Innovation response of incumbents

Figure A.10: Welfare effects of protectionism: unilateral 20% increase in trade barriers



A) Optimal innovation response to tariffs   B) Optimal tariff policy

Figure A.11: Innovation response to tariffs and optimal tariff rate



A) Optimal R&D subsidy

B) Optimal tariff rate

Figure A.12: Optimal joint policy