Innovation and Trade Policy in a Globalizing World*

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Preliminary and Incomplete

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February 15, 2017

Abstract

We assess the role of import tariffs and R&D subsidies as policy responses to foreign technological competition. To this end, we build a general equilibrium growth model embedding a Ricardian framework of trade where firm innovation shapes endogenously the dynamics of technology and market leadership in a world with countries at different stages of development. Knowledge spillovers and decreasing returns to knowledge accumulation drive cross-country technological convergence. Firms' R&D decisions are driven by the size of the market, the effort to escape competitive pressures, domestic and international business stealing, and technology spillovers. A calibrated version of the model reproduces the foreign technological catch-up the U.S. experienced by the 1970s and early 1980s. Accounting for transitional dynamics, we show that foreign technological acceleration hurts the U.S. welfare in the short and medium run through *business stealing*, but generates long-run benefits via higher quality of imported goods and higher domestic innovation in the U.S. induced by *escape-competition effect*. The model suggests that the introduction of Research and Experimentation Tax Credit in 1981 proves to be an effective policy response to foreign competition, generating substantial welfare gains. A counterfactual exercise shows that increasing trade barriers as an alternative policy response produces gains only in the very short run, 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.

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

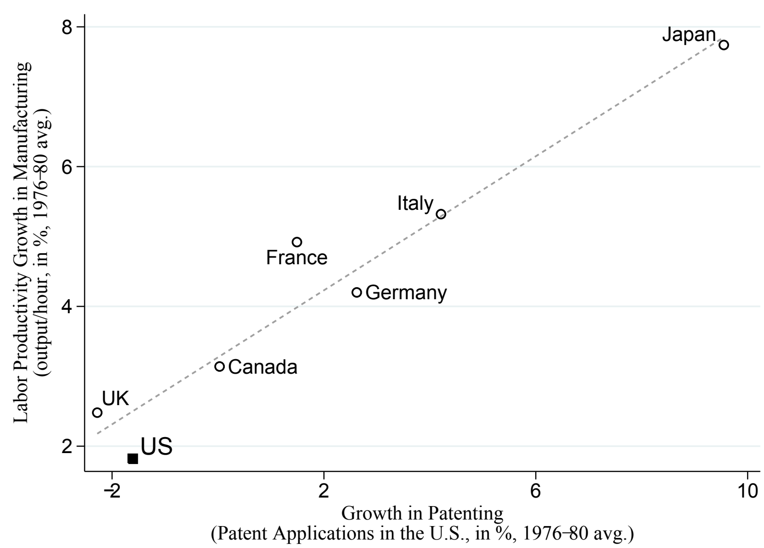
*We thank seminar and conference participants at the Bank of Italy, International Atlantic Economic Society and Italian Trade Study Group, University of Pennsylvania, CREST Paris, University of Nottingham, and Salome Baslandze, Christopher A. Laincz, and Tom Schmitz for useful comments. We are indebted to Daniel J. Wilson for sharing and helping with his data. Akcigit gratefully acknowledges the National Science Foundation, the Alfred P. Sloan Foundation, and the Ewing Marion Kauffman Foundation for financial support. The views in this paper are solely the responsibilities of the authors and should not be interpreted as reflecting the view of the Board of Governors of the Federal Reserve System or of any other person associated with the Federal Reserve System.

"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 1970s and early 1980s, the U.S. experienced a remarkable convergence in terms of productivity and technology by advanced countries such as Japan, Germany and France. This generated an alarming concern among policy circles, especially among the Reagan administration, as illustrated in the above quote. As a response to this convergence, the Reagan government, among other policies, introduced an R&D tax credit scheme in 1981 for the first time in the U.S. history. Surprisingly, similar concerns were raised in the recent presidential race. President Trump's election speeches focused on the issue that the U.S. is losing its competitiveness to other big players in the world. His policy response, though, suggests raising barriers to imports. In this paper, we ask the following important question: What are the roles of policies, especially *trade* and *innovation* policies, on the U.S. economy and welfare? This paper aims to answer this question by providing a new set of empirical evidence, proposing a new general equilibrium theory of international technology competition and economic growth, and quantifying its welfare implications.



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.

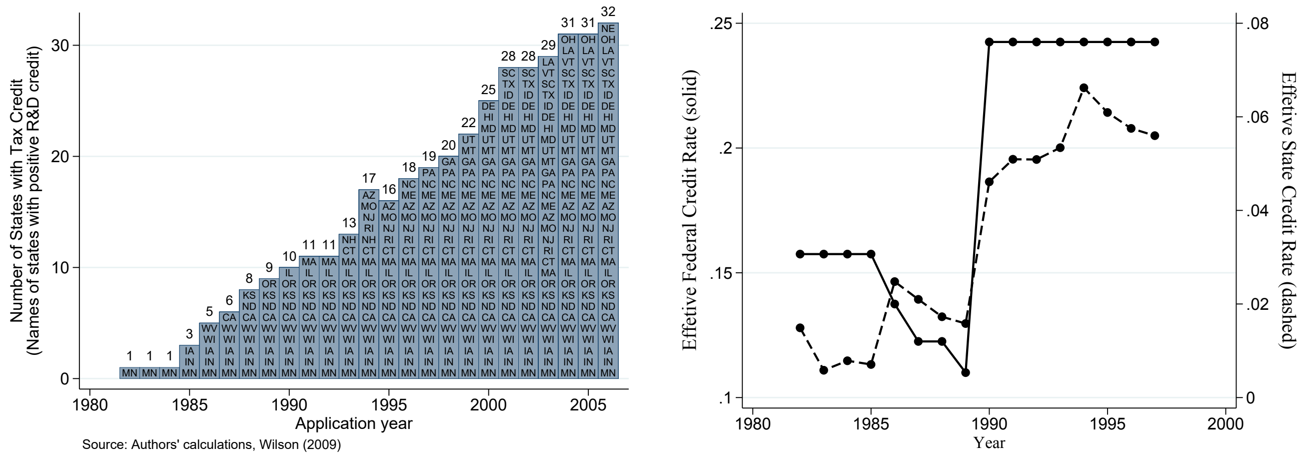
As illustrated in Figure 1, the U.S. performed poorly relative to its advanced peers in terms of labor productivity and innovation in the second half of 1970s.[2] The average growth in output per hours worked in manufacturing has been the lowest in the U.S. In tandem, new patent applications registered in the U.S. by the residents of these foreign countries expanded except from the U.K., whereas patent applications by the U.S. residents have actually shrunk. Strikingly, the largest growth rates in patent applications in the U.S. have been recorded by those countries whose labor productivity growth in manufacturing outpaced the U.S. the most.

In Section 2 we present more intriguing facts on cross-country technological convergence and innovation policy. In particular, U.S. Patent Office data show that between 1975 and 1985, the ratio of foreign patent counts to total patent counts increased steadily by 33%. While the U.S. was the global technology leader in 80% of the technology classes in 1975, measured by the share of patents registered by the U.S. residents in a given technology class, in 10 years this fraction declined to 60%.[3] 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 (Ham and Mowery (1999) and Mowery and Rosenberg (1989)). One of these policies was the introduction in 1981 of the first Federal R&D Tax Credit and starting in 1982 with Minnesota, different states began to adopt State R&D Tax Credits. Motivated by these facts, this paper provides a new quantitative investigation of gains from globalization, and contrasts the effects of R&D subsidies and protectionist policies on cross-country technology convergence, economic growth and aggregate welfare.

A sensible quantitative analysis of the dynamics presented above necessitates an open economy framework where economic growth is shaped by the interplay of innovation and international technological competition. Moreover, a careful policy evaluation needs to take into account the changes along the transition path. With these key points in mind, we build a new endogenous growth model where innovation determines the dynamics of technology and market leadership in a world economy. Our framework builds on the step-by-step innovation models of Schumpeterian creative destruction. The model features a home country and a set of foreign countries bundled into a unique rest of the world region. In both countries, final good firms produce final output combining a fixed factor and a set of intermediate goods, available from both domestic and foreign producers. In each intermediate sector of the world economy, 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 entrants creates an additional source of competitive pressure both on

[2] The relationship over a slightly longer time period is presented in Figure 21 in Appendix A.3.

[3] Similar trends can be found focusing on countries' share of global R&D at the sectoral level (Impullitti, 2010).



(A) Number of states

(B) Federal and average state R&D subsidies

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

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. While higher-quality imported intermediate goods translate into higher productivity in domestic final good production, thus increasing the domestic fixed factor income and benefiting domestic consumers, foreign technological competition affects the home economy through various other channels, especially shaping firm decisions, which we explain next.[4]

The open economy dimension of our model redefines firms' incentives to innovate that are captured by the standard step-by-step models. The key drivers of innovation in the generic step-by-step framework include: the *market size effect*, which postulates that larger markets by generating larger profits stimulate innovation; the *business-stealing effect*, according to which innovation by followers reduces the value of the incumbent firm thereby reducing its incentive to innovate; and the *escape-competition effect*, according to which incumbent firms have an incentive to move away from the follower in order to escape competition. The first difference in an open economy is that the competitive pressure on a domestic firm, which defines the escape-competition effect, is created by a foreign competitor. But more importantly, the business-stealing effect gains an international aspect: Innovation by followers and entrant foreign firms reduce the value of innovation for incumbents in the home country. Thus, foreign competition creates counteracting forces on domestic innovation. While domestic firms increase their R&D effort to escape competition, the threat of losing business to the foreign competitor affects domestic firms' innovation negatively. Finally, our model

[4]This positive effect of higher quality imported goods on domestic productivity resonates with the findings of Coe and Helpman (1995) who estimate a substantial contribution of foreign R&D to domestic total factor productivity growth of countries.

retains the domestic aspect of business stealing through domestic entry, another extension of previous step-by-step models that proves to be an important source of overinvestment in R&D, shaping the optimal level of R&D subsidies.

In line with the empirical evidence, our two economies are initially separated by a technology gap, namely, home firms have technological and market leadership in most sectors of the economy. The wider the technological distance between the two firms, the larger the number of innovation needed to catch up with the leader; but due to international knowledge spillovers, the follower never falls too far behind, and because of decreasing returns to knowledge accumulation, catching up will eventually happen. Hence, although the initial global distribution of leadership is skewed toward home firms, as the economy transitions to its steady state, foreign firms catch up and leapfrog in more and more sectors, and technological convergence attains. This cross-country convergence process echoes that in the standard Solow model where convergence is driven by decreasing returns to capital accumulation. In our model, international knowledge spillovers and decreasing returns to knowledge accumulation lead to cross-country convergence.

We parametrize the model to match key trade, innovation and growth facts in the 1970s and reproduce the structure of global leadership in those years, with the U.S. representing the technological frontier and a set of European countries plus Japan being the followers. The transitional dynamics of the model reproduces the convergence in technological leadership observed in the patent data in the 1970s and early 1980s. The calibrated model allows us to analyse the welfare consequences of foreign technological convergence, a mode of globalization that has not been widely explored in the literature, and due to the dynamic features our model we can assess these consequence across time. We find that in the short to medium run, foreign technological competition produces substantial welfare losses whose key driver is international business stealing. As foreign firms catch up and possibly leapfrog domestic incumbents, global market leadership and the related profits shift from domestic to foreign firms, reducing income and consumption in the home country. In a 20-year horizon, consumption is about 3% lower each year compared to an counterfactual economy where foreign firms are prevented from stealing businesses of domestic firms. In the long run, though, the gains from having higher-quality imports, which improve domestic productivity in final good production, compensate for the losses of profits. In contrast, in the counterfactual economy where foreign convergence does not generate business stealing, foreign firms' incentives to improve the quality of their goods, which would potentially become imported, are reduced.

Next, 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 19.2% 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 0.8% 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. Over a 100 years horizon the subsidy change raises consumption by 1.8% per year, and this is mostly due to its stimulating effect 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.

Finally, we explore the welfare implications of protectionism, i.e. raising trade barriers, as an alternative policy response to foreign catching up. Increasing the trade cost of imports generates short-run gains, as it tames international business stealing due to foreign catching up. For the first 15 years after a 40% increase in trade barriers there are gains up to 0.2% of consumption. Later the losses due to lower competition start kicking in leading to substantial drops in welfare in the long run. These losses are due to the key sources of gains from trade in this economy: First, trade allows the home country to replace low quality/productivity intermediate goods with better foreign goods; second, stronger competition generated by foreign catching up triggers an escape competition effect forcing domestic firms to innovate more. Interestingly, while the model captures large long-run gains from trade similarly to many standard trade models, its dynamic structure suggests the presence of short run losses that cannot be captured in static or steady state economies.

Taking stock, foreign technological catching up generates substantial welfare losses for a few decades due to business stealing, but the gains due to faster domestic innovation to escape competition and to the import of higher quality goods dominate in the long run. Increasing R&D subsidy during periods of accelerating foreign competition proves to be beneficial, while raising trade barriers generates only small short run gains and substantial losses in the long-run. The key message from this result is that when a country experiences fiercer foreign technological competition R&D subsidies help national firms compete without giving up gains from trade.

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), Aghion et al.

(2001) 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.

In analyzing the strategic role of R&D subsidies in open economies we provide a quantitative perspective on classical themes in the strategic trade and industrial policy literature.[5] Spencer and Brander (1983) and Eaton and Grossman (1986) analyzed 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.[6] While this literature focuses on stylized theoretical models, a few recent papers have attempted to make contact with the data. Ossa (2015) sets up a quantitative economic geography model to analyse production subsidy competition between U.S. states. Impullitti (2010) uses a multicountry version of the standard Schumpeterian growth model to assess the welfare properties of R&D subsidies in open economy. This paper is closely related in the spirit to our work, but they limit their analysis to the steady state, and do not embed a mechanism of endogenous cross-country convergence. We contribute by introducing an engine of technological convergence, exploring welfare gains from different modes of globalization and evaluating various policies both in the short and in the long run.

Our analysis of the welfare effects of trade liberalization and foreign technological catching up is related to the large literature on the gains from globalization. Classic papers such as Hicks (1953) and Samuelson (2004) have shown that in a standard Ricardian trade model a country's technological progress can not only benefit but also harm its trading partners. Foreign technical change transmits to its trading partner through the terms of trade: It benefits its trading partners if the technological improvement happens in industries where the source country has a comparative advantage and vice versa.[7] A quantitative assessment of this mechanism can be found in Eaton and Kortum (2002). In multi-country quantitative Ricardian model they show that increasing productivity in the U.S. and Germany produces sizable welfare gains for other OECD countries.[8] In intra-industry trade models, the transmission mechanism works through the "home-market effect". As recently shown by Hsieh and Ossa (2016), technological progress benefits a country's trading partners if it takes place

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

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

[7]See also Matsuyama (2007) for a simple formal illustration of this argument.

[8]Along the same line, a set of recent papers has analyzed the effects of China's technological progress on its trading partners' welfare in trade models based on comparative advantage (see e.g. Di Giovanni et al. (2014)). For a recent empirical analysis of Chinese impact on U.S. domestic innovation, see Autor et al. (2016).

in industries with high trade elasticity: The gains from lower import prices is stronger than the loss in the set of goods exported, hence the aggregate price index declines. In our Schumpeterian setting, by definition, foreign catching-up represents technological progress in sectors with home technological advantage, therefore it generates welfare losses similar to those shown by Hicks and Samuelson for a Ricardian economy. But differently from the standard Ricardian trade model, technology evolves endogenously in our economy, and the escape competition effect produces welfare gains that dominate the losses in the long run.

Our analysis of protectionism as a possible policy response to increasing foreign technology competition makes contact with the large literature on the gains from trade. Most of the literature is focused on static gains and, as Burstein and Melitz (2013) point out in a recent survey, more research is needed to understand the implications of firm and technology dynamics for the gains from trade. Recent papers have explored these gains in multi-country models of growth driven by technology diffusion.Sampson (2016) analyses an economy with heterogeneous firms where productivity growth is driven by knowledge diffusion at the entry stage. Trade-induced firm selection accelerates knowledge diffusion and growth, thereby tripling the gains from trade relative to heterogeneous-firm settings with static productivity at the firm level. Along similar lines, Perla et al. (2015) set up a model where growth is driven by knowledge diffusion between incumbent firms, and show that trade accelerates technology diffusion and growth producing substantial welfare gains. Impullitti and Licandro (2017) analyse 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. We contribute to this literature analysing the gains brought about different modes of globalization, that is reduction in trade barriers and international technology diffusion. Moreover, analysing the whole transitional dynamics, we can explore both the short and the long-run effects of globalization on national welfare.

The rest of the paper is organized as follows. Section 2 describes the empirical facts on international technology competition, Section 3 introduces the theoretical framework, Section 4 outlines the calibration procedure and provides the quantitative results, and Section 5 concludes.

2 Empirical Facts

This section presents some empirical regularities regarding trends in global technological leadership and R&D activity.

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 3 shows the yearly change in the proportion of patents registered in the U.S. by foreigners using USPTO data on patent counts.[9] 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 one in the U.S. counterpart until 1985. Interestingly, in the following years the converge process comes to a halt, and we observed an inversion of the trend.[10]

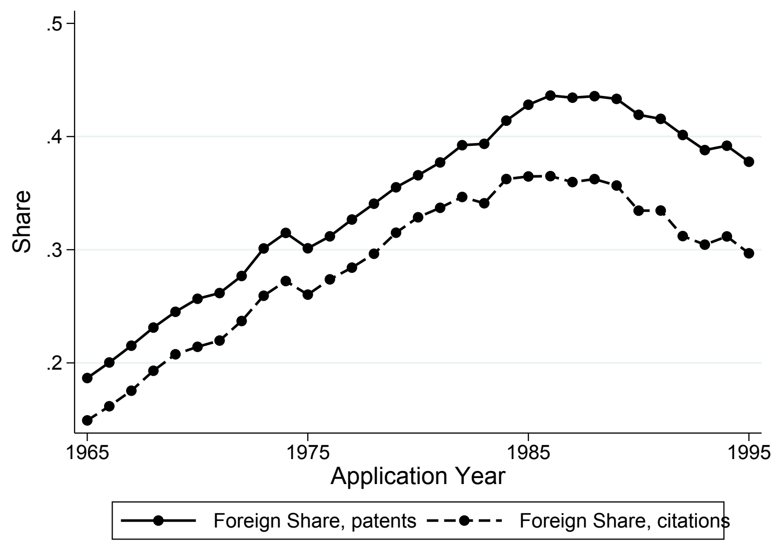


Figure 3: Share of foreign patents: 1965-1995

Figure 4 brings the analysis down to the level of patent classes (IPC4) using the same data set. What it delineates is 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

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

[10]We produce similar graphs using absolute counts in Appendix A.1. Those figures show in particular that the changes in the shares are chiefly driven by a surge in patent registrations by U.S. residents.

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.[11]

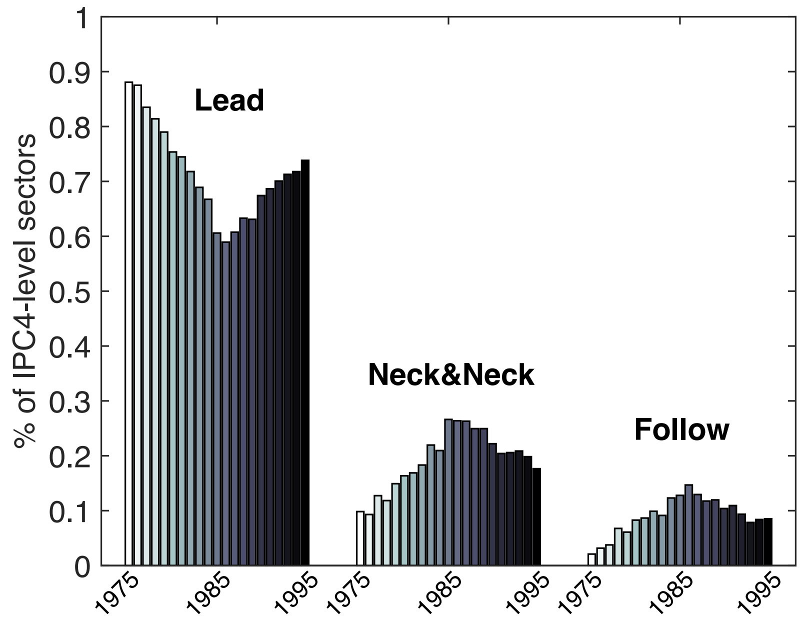


Figure 4: Leadership distribution: share of sectors with U.S. lead, neck-and-neck, foreign lead

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 to unduly substitute government for private firms in activities that the latter can naturally perform better. These policies included several programs

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

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 tax incentives to innovation which started with the Research and Experimentation Tax Credit in 1981.

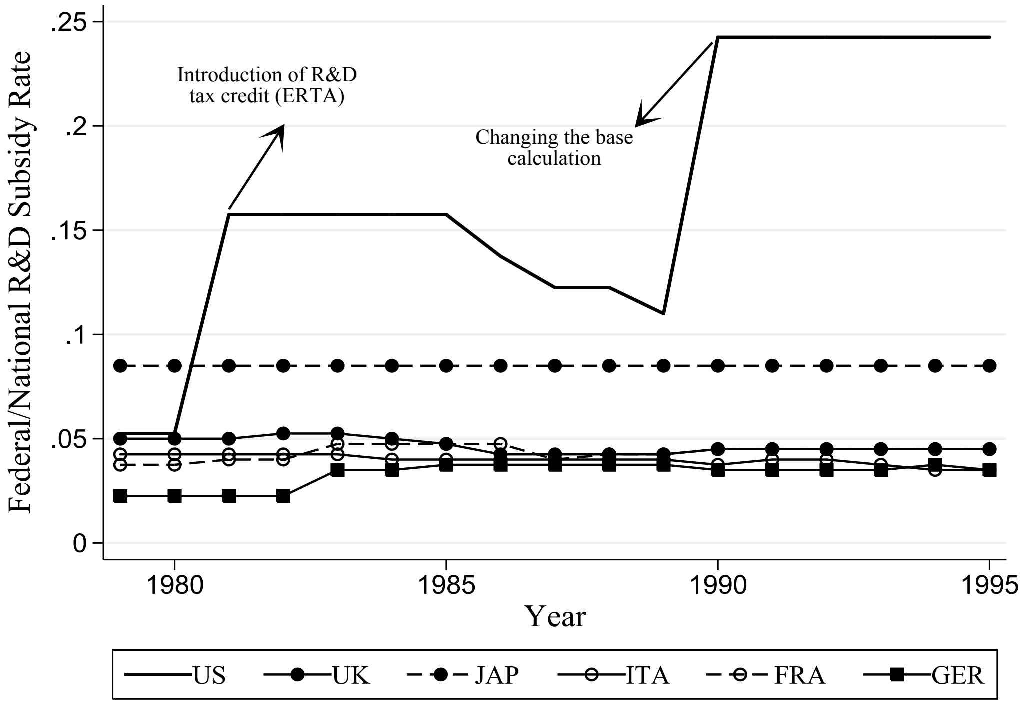


Figure 5: Effective R&D tax credit rates across countries

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 5 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 6 we report the evolution of average rate of U.S. State tax credits together with the number of the states that offer a tax credit from Wilson (2009). We can see that the average effective tax credit at the state level was about 6% in 1995, nearly half of the federal one, and the number of states following such a policy rose to 32.

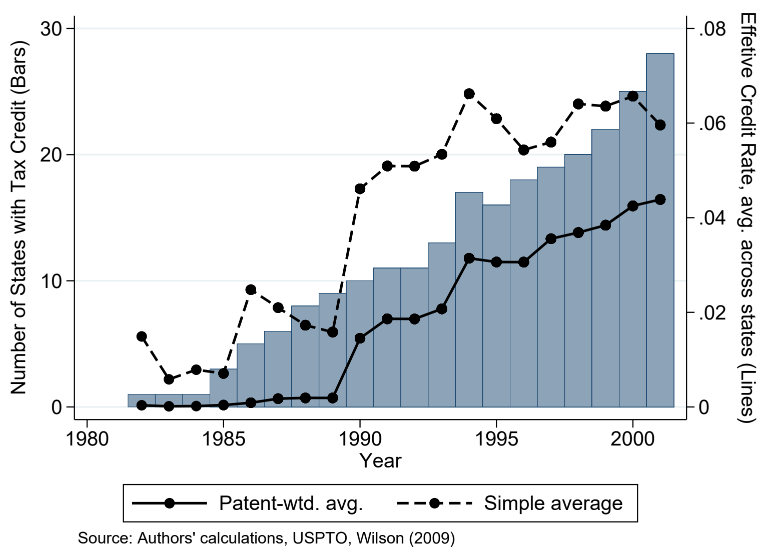


Figure 6: U.S. State-level R&D tax credit

Next we attempt to gain some additional descriptive insight about the link the between tax credits and innovative behavior of firms. At the aggregate level, Figure 7 plots the evolution of the average R&D expenditure-to-sales ratio across COMPUSTAT firms over time, juxtaposed with the annual share of patents registered by U.S. residents in total patent applications. We observe both variables picking up soon after the introduction of federal R&D subsidies.

Digging the relationship deeper, we exploit the state-level variation in the dates when credit policies came into action, and set up a simple firm level regression analysis using COMPUSTAT database. The regression specification is as follows:

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

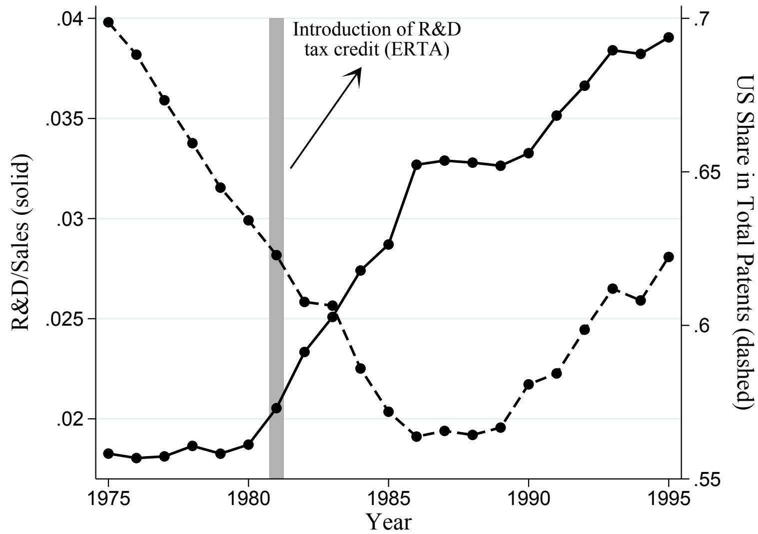


Figure 7: R&D expenditure-to-sales ratio and U.S. patent share

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 1. All versions (represented by columns of the table) reveal the positive effect of state level R&D tax credits on the firms' innovative activities. This effect is also robust to the existence of lagged values of the dependent variable in the regression.[12]

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

Dep. Var.:	$\ln(R\&D_t)$ (1)	$\ln(R\&D_t)$ (2)	$\ln(Patents_t)$ (3)	$\ln(Patents_t)$ (4)
$\ln(R\&D_{t-1})$	-	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

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

3 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 heterogeneous quality products. 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.

3.1 Preferences

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

$$U_t = \int_t^{\infty} \exp(-\rho\,(s-t))\,\frac{C_{cs}^{1-\psi} - 1}{1-\psi}\,ds \tag{2}$$

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

$$r_{ct}A_{ct} + L_c w_{ct} = P_{ct}C_{ct} + \dot{A}_{ct} \tag{3}$$

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. 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. 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)].

3.2 Technology and Market Structure

3.2.1 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 both countries according to the following technology in perfectly competitive markets:

$$Y_{ct} = \frac{L_c^{\beta}}{1-\beta} \int_0^1 \left[\sum_{c \in \{A,B\}} q_{cjt}^{\beta} k_{cjt}^{1-\beta} \right] dj \tag{4}$$

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 the quality level of k_j, and β is the share of fixed factor in total output. We assume the fixed factor L_c to be immobile across countries whereas the intermediate goods can be obtained from any country. 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 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 its input 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.

3.2.2 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 existing quality associated with the variety the incumbent indexed by cj produces increases as follows:

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

where $\lambda > 1$ and n_t is a random variable which will be specified below. We assume that initially $q_{Aj0} = q_{Bj0}\ \forall j \in [0, 1]$ holds.

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

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

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 $m_{cjt} \in \{-\bar{m}, ..., 0, ..., \bar{m}\}$.

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:

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

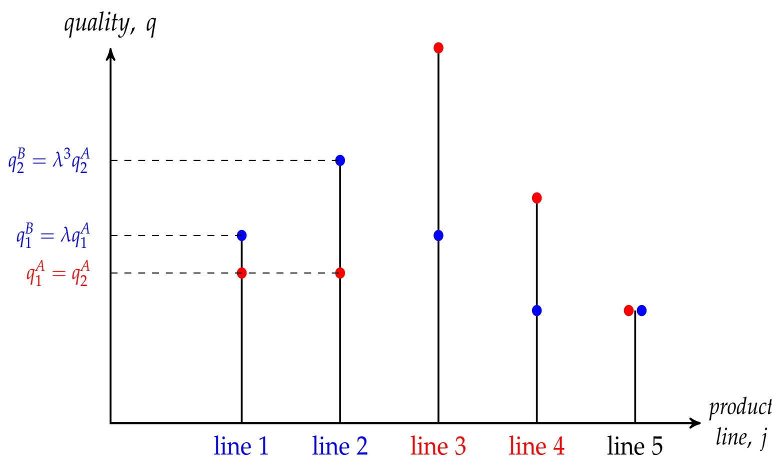
Note that q_{cjt} in the denominator captures the fact that a quality is more costly to improve if it is more advanced. This production function implies the following cost function for generating an arrival rate of x_{cjt} :

$$d\left(x_{cjt}, q_{cjt}\right) = q_{cjt} \frac{\alpha_c}{\gamma_c} x_{cjt}^{\gamma_c}. \tag{5}$$

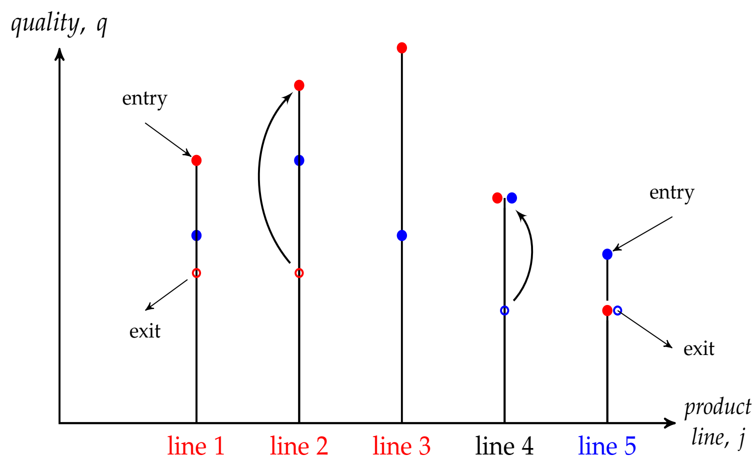
Entrants. In every product line there are potential entrants from both countries investing in innovation to enter the market. The innovation technology for entrants is

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

Notice that this innovation technology depends on the existing quality q_{cjt} of the domestic incumbent firm.



(A) Product lines



(B) Entry, Exit, and Leadership

Figure 8: Evolution of product lines

Figure 8 demonstrates the evolution of leadership in intermediate product lines due to incumbent innovation, entry and exit. In the left panel, five product lines are shown. In the first two, firms from country B, and in the next two firms from country A 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. Finally, 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.[13] 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 an innovation, it can open up the 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, $\mathbb{F}_m(\cdot)$, and therefore, the step size associated with the innovation, depend on m. We assume that it is not country-specific. 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 9a. We assume that it has the following functional form:

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

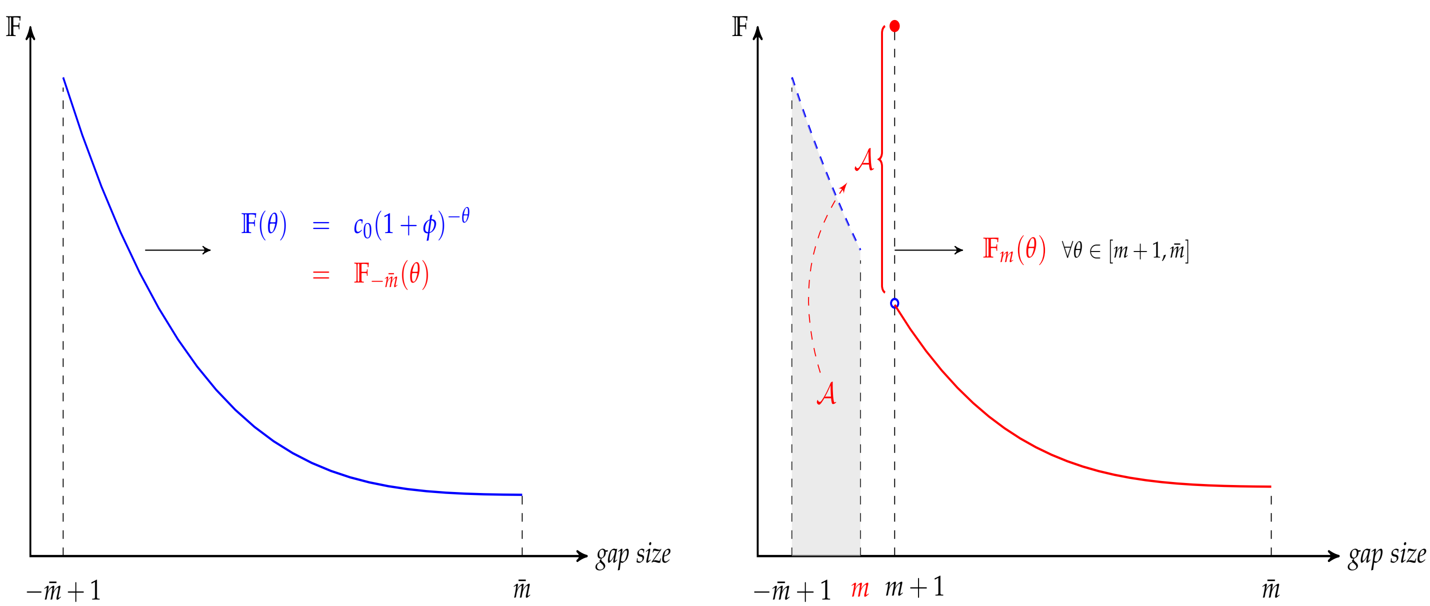
[13] Conversely, each innovation comes with an associated step size that is randomly generated by some probability mass function.

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 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:

$$\mathbb{F}_m(n) = \begin{cases} \mathbb{F}(m+1) + \mathcal{A}(m) & \textit{for } n = m+1 \\ \mathbb{F}(s) & \textit{for } n \in \{m+2, ..., \bar{m}\} \end{cases} . \tag{6}$$

As demonstrated in Figure 9b, $\mathcal{A}(m) \equiv \sum_{s=-\bar{m}+1}^{m} \mathbb{F}(s)$ 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 9: 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 by a single common step size. This feature would imply a slow process of convergence in leadership shares, in contrast to what we see in the data. Therefore, by incorporating $\mathbb{F}(n)$, we generalize this feature and equip the model with enough flexibility to replicate the catch-up process observed in the data.[14] 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, equal distribution of reaching better positions means higher chances across a few better positions that firm has ahead. Given that in the data, the initial leadership distribution is strongly in favor of the U.S., the advantage for leading firms would lead to a shift in the distribution to larger gaps, working against the convergence process in the data.

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:

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

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

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, despite improving the 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 the key fea-

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

ture in our economy generating cross-country convergence in innovation, technology, and income.

3.3 Equilibrium

Next, we will define the Markov Perfect Equilibrium of the model. 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.*

3.3.1 Household

We start with the maximization problem of the household. The Euler equation of the household problem determines the interest rate in the economy as

$$r_{ct} = g_{ct}\psi + \rho.$$

3.3.2 Final and intermediate goods production

Next, we turn to the maximization problem of the final good producer. Using the production function (4) , the final good producers generate the following demand for the fixed factor L_c and intermediate good $j \in [0,1]$

$$w_{ct} = \frac{\beta}{1-\beta} L_c^{\beta-1} \int_0^1 q_{jt}^{\beta} k_{jt}^{1-\beta} dj \tag{7}$$

$$p_{jt} = L_c^{\beta} q_{jt}^{\beta} k_{jt}^{-\beta} \tag{8}$$

where $q_{jt} \equiv \max\{q_{Ajt}, q_{Bjt}\}$ and k_{jt} is its quantity.

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

$$k_{jt} = \left[\frac{1-\beta}{\eta}\right]^{\frac{1}{\beta}} q_{jt} \text{ and } p_j = \frac{\eta}{1-\beta}. \tag{9}$$

where we used the fact that $L_c = 1$. The realized price is a constant mark-up 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 $\pi \equiv \eta^{\frac{\beta-1}{\beta}}\left(1-\beta\right)^{\frac{1-\beta}{\beta}}\beta$.

The problem when selling abroad is different due to the iceberg costs associated with trade. In line with 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 $\left(1+\kappa\right)\eta k_{cj}$. Given the iceberg costs, only the firm with higher cost-adjusted productivity will find it profitable to sell in the other country. Hence, consider the supply of intermediate j to country B, the firm from country A exports intermediate j to country B if and only if

$$\frac{q_{Ajt}}{1+\kappa} \geq q_{Bjt}.$$

In this Bertrand competition setting, the existence of a competitor with inferior quality - located in the foreign country, by definition - 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 costless case leads to the optimal quantity exported and the associated profits:

$$k_{cjt}^{*}=\left[\frac{1-\beta}{(1+\kappa)\,\eta}\right]^{\frac{1}{\beta}}L_{f}q_{cjt}\text{ and }p_{j}^{*}=\frac{(1+\kappa)\,\eta}{1-\beta}\Rightarrow\pi^{*}\left(q_{jt}\right)=\pi^{*}L_{f}q_{cjt}\tag{10}$$

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

Before we introduce aggregate quantities, let us define two additional variables that will ease the exposition. First, we define the smallest gap by which the leader needs to lead its follower in order to be able to export its good. Because there are 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 the foreign counterpart such that the firm cannot export ($q/\,(1+\kappa)<q^{*}$). 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^{*} :

$$\begin{aligned}m^{*}&\equiv\left\{m:\left[\frac{q_{mj}/\lambda}{q_{-mj}^{*}}<1+\kappa\right]\&\left[\frac{q_{mj}}{q_{-mj}^{*}}\geq1+\kappa\right]\right\}\\&\equiv\left\{m:\left[\lambda^{m-1}<1+\kappa\right]\&\left[\lambda^{m}\geq1+\kappa\right]\right\}\\&\equiv\arg\min_{m}\left\{m\in[0,\bar{m}]:\lambda^{m}\geq1+\kappa\right\}.\end{aligned}\tag{11}$$

Next 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

$$Q_{cmt}\equiv\int_{\mu_{cm}}q_{cjt}dj.$$

Using the equilibrium conditions derived previously, total output becomes

$$Y_{ct}=\sum_{m=-m^{*}+1}^{\bar{m}}\left[\frac{1-\beta}{\eta}\right]^{\frac{1-\beta}{\beta}}\frac{Q_{cmt}}{1-\beta}+\sum_{m=-\bar{m}}^{-m^{*}}\left[\frac{1-\beta}{(1+\kappa)\,\eta}\right]^{\frac{1-\beta}{\beta}}\frac{Q_{cmt}}{1-\beta}.\tag{12}$$

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

$$w_{ct}=\beta Y_{ct},\tag{13}$$

which follows from the first order condition of the final good producer given by equation (7).

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. ■

As a result of second point in Result 1, we will consider only intermediate good flows in the quantitative analysis when creating moments such as export-to-GDP ratio.

3.3.3 Firm Values and Innovation

This subsection presents equilibrium firm values and innovation decisions. When describing those we make use of our guess that a firm's innovation rate depends on the characteristics of the product line only through the firm's relative technological position m. In other words, the only product line specific statistic that affects innovation rates is m. Lemma 1 at the end of this subsection will verify this result.

Incumbent firms. We can write the value function for country A's incumbents:[15]

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

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

$$\Pi\left(m\right) = \begin{cases} \pi L_c + \pi^* L_f & if \quad \frac{q_{Aj}}{1+\kappa} \geq q_{Bj} \\ \pi L_c & if \quad \left(1+\kappa\right) q_{Bj} > q_{Aj} \geq \frac{q_{Bj}}{1+\kappa} \\ 0 & if \quad q_{Aj} < \frac{q_{Bj}}{1+\kappa} \end{cases}$$

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

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 $\Pi(m)$ we can see that exporting increases the size of the market, thereby increasing the incentives to innovate. This is the *market size effect* typical of standard Schumpeterian growth models. The second line denotes the expected gains from innovation. This expectation is over the new position that is determined probabilistically by the step size of innovation. Incumbent firms have an incentive to move away from the follower in order to escape competition: being further away from the follower reduces the chances of being caught up, thereby increasing the expected value of a patent. This is an *escape competition effect* typical of step-by-step innovation models (Aghion et al. 2001) but generalized for multiple and random number of gaps. Although its name seems to suggest that this effect only affects incumbent firms, it is indeed relevant for followers as well: the closer a firm is to the leader the higher the chance to catch up and leapfrog.

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 of creative destruction. 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 $\mathbb{F}_{-m}(\cdot)$.[16] We label this additional channel, 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):[17]

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

[16] 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.

[17] 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.

and

$$r_{At}V_{A(-\bar{m})t}\left(q\right)-\dot{V}_{A(-\bar{m})t}\left(q\right)=\max_{X_{A(-\bar{m})t}}\left\{-\left(1-\tau^{A}\right)\alpha_{A}\frac{\left(x_{A(-\bar{m})t}\right)^{\gamma_{A}}}{\gamma_{A}}q_{t}\right.$$

$$+x_{A(-\bar{m})t}\sum_{n_t=-\bar{m}+1}^{\bar{m}}\mathbb{F}_{-\bar{m}}\left(n_t\right)\left[V_{Ant}\left(\lambda^{(n_t+\bar{m})}q_t\right)-V_{A(-\bar{m})t}\left(q_t\right)\right]$$

$$+\tilde{x}_{A(-\bar{m})t}\left[0-V_{A(-\bar{m})t}\left(q_t\right)\right]$$

$$\left.+\left(x_{B\bar{m}t}+\tilde{x}_{B\bar{m}t}\right)\left[V_{A(-\bar{m})t}\left(\lambda q_t\right)-V_{A(-\bar{m})t}\left(q_t\right)\right]\right\}.$$

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 independent 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*

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

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,

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

The equilibrium innovation rates for entrants become

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

Entrants. Lastly, we formulate the entrant problem before defining the equilibrium of the system. Recall that entry is directed at individual product lines.

Assumption 2 *Entrant firms are short-lived. If the manager succeeds in the innovation attempt, the entrant firm replaces the domestic incumbent, otherwise the firm disappears. Households own these short-lived entrant firms and receive the well-defined positive value of the associated instantaneous assets.*

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:

$$\max_{\tilde{x}_{cmt}} -\frac{\tilde{\alpha}_c}{\tilde{\gamma}_c}\left(\tilde{x}_{cmt}\right)^{\tilde{\gamma}_c}q_t+\tilde{x}_{cmt}\sum_{n_t=m+1}^{\bar{m}}\mathbb{F}_m\left(n_t\right)V_{cnt}\left(\lambda^{(n_t-m)}q_t\right), \tag{14}$$

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

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

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

Lastly we define the equilibrium.

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

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

such that (i) the sequence of prices and quantities p_j, k_j, k_j^* satisfy (9)-(10) 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 (12), and (v) wages w_c and interest rates r clear the labor and asset markets at every t.

3.4 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 analyse 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, here we report the the resulting evolution of aggregate qualities. Changes in Q_{Amt} are characterized by the following expressions:[18]

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

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

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

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 by domestic incumbents or entrants at position $s < m$ with a step size λ^{m-s}, which happens with probability $\mathbb{F}_s(m)$,implies that the domestic incumbent in that product line will reach gap m. The second sum captures the addition of product lines, where the position of the domestic incumbent worsened to m from a better one. An improvement by foreign incumbents or

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

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 an 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

$$
\begin{aligned}
\dot{\mu}_{A\bar{m}t} &= \dot{\mu}_{B(-\bar{m})t} = \sum_{s=-\bar{m}}^{\bar{m}-1} \mathbb{F}_s(\bar{m})\left(x_{Ast} + \tilde{x}_{Ast}\right)\mu_{Ast} - \mu_{A\bar{m}t}\left(x_{B(-\bar{m})t} + \tilde{x}_{B(-\bar{m})t}\right) \\
\dot{\mu}_{Amt} &= \dot{\mu}_{B(-m)t} = \begin{array}{l} \sum_{s=m+1}^{\bar{m}} \mathbb{F}_{-s}(-m)\left(x_{B(-s)t} + \tilde{x}_{B(-s)t}\right)\mu_{Ast} \\ + \sum_{s=-\bar{m}}^{m-1} \mathbb{F}_s(m)\left(x_{Ast} + \tilde{x}_{Ast}\right)\mu_{Ast} \\ - \left[x_{Amt} + x_{B(-m)t} + \tilde{x}_{Amt} + \tilde{x}_{B(-m)t}\right]\mu_{Amt} \end{array} \\
\dot{\mu}_{A(-\bar{m})t} &= \dot{\mu}_{B\bar{m}t} = \sum_{s=-\bar{m}}^{\bar{m}-1} \mathbb{F}_s(\bar{m})\left(x_{Bst} + \tilde{x}_{Bst}\right)\mu_{A(-s)t} - \mu_{A(-\bar{m})t}\left(x_{A(-\bar{m})t} + \tilde{x}_{A(-\bar{m})t}\right).
\end{aligned}
\tag{15}
$$

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 since 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 for both countries.

Aggregate consumption of a country is equal to its disposable income and is given by the sum of total profits and wages minus total R&D expenditure:[19]

$$
\begin{aligned}
C_{ct} = & \sum_{s=m^*}^{\bar{m}} \left(\pi L_c + \pi^* L^* - \alpha_c x_{cst}^{\gamma_c}\right) Q_{cst} + \sum_{s=-m^*+1}^{m^*-1} \left(\pi L_c - \alpha_c x_{cst}^{\gamma_c}\right) Q_{cst} \\
& - \sum_{s=-m^*+1}^{m^*-1} \alpha_c x_{cst}^{\gamma_c} Q_{cst} - \sum_{s=-\bar{m}}^{-\bar{m}} \tilde{\alpha}_c \tilde{x}_{cst}^{\tilde{\gamma}_c} Q_{cst} + w_{ct} L_c \\
= & \sum_{s=m^*}^{\bar{m}} \left(\pi L_c + \pi^* L^*\right) Q_{cst} + \sum_{s=-m^*+1}^{m^*-1} \pi L_c Q_{cst} - \sum_{s=-\bar{m}}^{-\bar{m}} \left(\alpha_c x_{cst}^{\gamma_c} + \tilde{\alpha}_c \tilde{x}_{cst}^{\tilde{\gamma}_c}\right) Q_{cst} + w_{ct} L_c. \quad (16)
\end{aligned}
$$

Finally, government budget constraint can be written as

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

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

3.5 Aggregate growth

The growth rate of aggregate consumption is defined as

$$
g_{ct} = \frac{\dot{C}_{ct}}{C_{ct}} \quad (17)
$$

where the change in aggregate consumption at t reads as

$$
\begin{aligned}
\dot{C}_{ct} = & \sum_{s=m^*}^{\bar{m}} \left(\pi L_c + \pi^* L^*\right) \dot{Q}_{cst} + \sum_{s=-m^*+1}^{m^*-1} \pi L_c \dot{Q}_{cst} - \sum_{s=-\bar{m}}^{-\bar{m}} \left(\alpha_c x_{cst}^{\gamma_c} + \tilde{\alpha}_c \tilde{x}_{cst}^{\tilde{\gamma}_c}\right) \dot{Q}_{cst} \\
& - \sum_{s=-\bar{m}}^{-\bar{m}} \left(\alpha_c \gamma_c x_{cst}^{\gamma_c} \frac{\dot{x}_{cst}}{x_{cst}} + \tilde{\gamma}_c \tilde{\alpha}_c \tilde{x}_{cst}^{\tilde{\gamma}_c} \frac{\dot{\tilde{x}}_{cst}}{\tilde{x}_{cst}}\right) Q_{cst} + \dot{w}_{ct}. \quad (18)
\end{aligned}
$$

[19] Reciprocally, household's flow budget constraint implies that consumption is given by the sum of interest and fixed factor income minus capital gains and taxes:

$$
\begin{aligned}
C_c(t) &= r_t^c A_c(t) - \dot{A}_c(t) + w_c(t) L_c - T_c \\
&\approx r_t^c A_c(t) - \frac{A_c(t + \Delta t) - A_c(t)}{\Delta t} + w_c(t) L_c - T_c
\end{aligned}
$$

where $A_c(t) = \int \left(v_{jt}^c + \tilde{v}_{jt}^c\right) q_{jt} dj$ denotes the asset level. It follows that this expression and equation (16) imply the same level of C_c.Intuitively, the first two terms here correspond to the flow expression on the left hand side of firm value functions, summed over all firms. The right-hand side of firm value functions suggests that this amounts to sum of profits net of subsidised R&D cost, and together with lump-sum taxes, it equals to aggregate profits minus aggregate R&D cost as in the income expression. For welfare discussions in the quantitative section, we will use equation (16), as individual components of income provide a straightforward interpretation of of the sources of welfare changes.

Notice that $\dot{w}_{ct} = \beta \dot{Y}_{ct}$, which in turn depends on the changes in aggregate quality of both domestically produced and imported intermediate goods.

3.6 Welfare

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

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

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 $I_{c\tau}^{new}$ between t_0 and t_0+T satisfying the above relationship, we say that the policy change results in ς% variation in welfare over horizon T in consumption equivalent terms. This means that the representative consumer in the benchmark economy would need to receive ς% additional income at each point in time between t_0 and t_0+T in order to obtain the level of welfare it would have in the counterfactual scenario.

4 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.

4.1 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.[20] The weights

[20] These are the most innovation-intensive countries that compete with the U.S.

associated with each country, listed in Table 2, 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.[21] In the remainder of this section, country A will represent the U.S. and country B the foreign country.[22]

Table 2: Patent Weights of Countries

	1975	1981
Canada	.062	.052
France	.117	.093
Germany	.300	.274
Italy	.038	.032
Japan	.331	.448
Spain	.006	.003
UK	.146	.096

As Figures 5 shows there is a significant break in the R&D policy before and after 1981. Moreover, as shown in Figures 3 and 4, 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 test the model's explanatory power using the data from post-1981 period (1981-1995).[23]

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 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 inter-

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

[22]The abbreviation FN in figures refer to the foreign country in the model.

[23]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.

nally. We start with the external calibration.

4.1.1 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 steady state.[24] 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 3 summarizes these estimates.

Table 3: 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	$1-\beta$	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 only lack Canada (to take this into account, the patent weights used to organize this data are calculated again after dropping Canada). This 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 2.

4.1.2 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 a distribution of firms across technology gaps that we derive using USPTO patent data. We start with the discussion of the six moments, summarized in Table 4, that are not related to the gap distribution. Moments for the foreign country are weighted averages of the values for individual countries.

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

The first two moments are the average growth rates of TFP in both countries, calculated using TFP series in Coe et al. (2009). In our model, these correspond to the income growth rates of the countries as the only source of income growth is the average productivity growth. 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. There are two minor issues with this data set. First, 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. The second problem 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.[25] 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 (15), 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 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). Following a similar procedure explained in Section 2, 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.[26] Then, we divide this unit interval into 33 equally sized bins, each of which correspond to a range of approximately 3%.For instance, sectors with a fraction of U.S. patents between $(23/33, 24/33]$ would fall into bin 24. 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.[27] Figure 10 shows

[25]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.

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

[27]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.

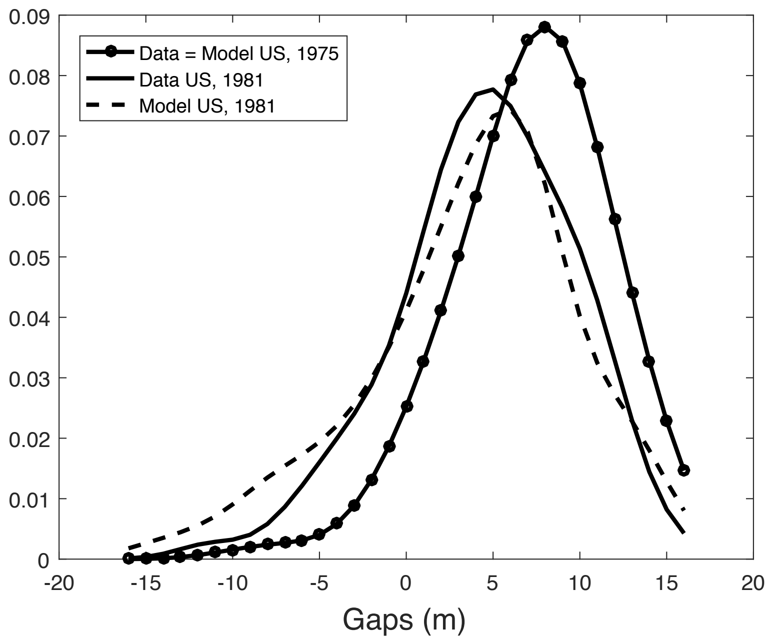


Figure 10: Gap distribution

the distribution in the data for years 1975 (dotted solid line) and 1981 (solid line).[28] The calibration of ϕ aims to match the leftward shift in the empirical gap distribution between 1975 and 1981. This shift translates into more mass of U.S. firms in relatively smaller gap sizes, and therefore, signifies a strong foreign technological catch-up.

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. $q_{Aj1975} = 1\ \forall j$.[29] 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 4 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 (15) and try to hit the empirical gap distribution in 1981 as the terminal point of the transition economy.

Solution algorithm and model fit. 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

[28] Distributions are smoothed using a kernel density function with bandwith 1.8.

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

T periods, where each period is divided into $(\Delta t)^{-1} = 2^5$ sub-periods. The algorithm is an iterative backward solution method. The main procedure of the algorithm consists of solving for the steady state and then deriving the values over the transition period going backwards from the steady state. A brief description is as follows:[30]

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 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 as the objective function.[31]

The targeted moments and the model performance in matching these moments are summarized in Table 4 and Figure 10.

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 one in Figure 10 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 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

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

[31] 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.

Table 4: Model fit

Moment	Estimate	Target	Source
TFP Growth U.S.	0.39%	0.55%	Coe et al. (2009) 1975-81
TFP Growth FN	2.13%	1.82%	Coe et al. (2009) 1975-81
R&D Share U.S.	1.59%	1.75%	OECD 1981
R&D Share FN	1.95%	1.96%	OECD 1981
Entry Rate U.S.	10%	10%	BDS 1977-81
Export Share U.S.	7.14%	7%	WB 1975-81

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 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 5. 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%.[32]

Table 5: Internally Calibrated Parameters

R&D scale		R&D scale		Step size	Iceberg	$F(n)$
α_A	α_B	$\tilde{\alpha}_A$	$\tilde{\alpha}_B$	λ	κ	ϕ
1.07	1.33	54.7	10.7	1.6%	18.8%	1.37

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

4.1.3 Validation of the model

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

Credit elasticity of R&D. The ultimate source of growth in our model is innovation. In Section 2, we presented the empirical relationship between R&D subsidies and the R&D expenditures at the firm level. In particular, the first column of Table 1 shows that, on average, the elasticity of R&D spending with respect to changes in R&D credit is 3.15. To ensure the quantitative validity of firms' response to policy changes in our model, we derive the model counterpart of the same statistic. We first compute the log-difference in R&D expenditure for incumbent firms of country A in each position m right before and after the subsidy change from 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 given by

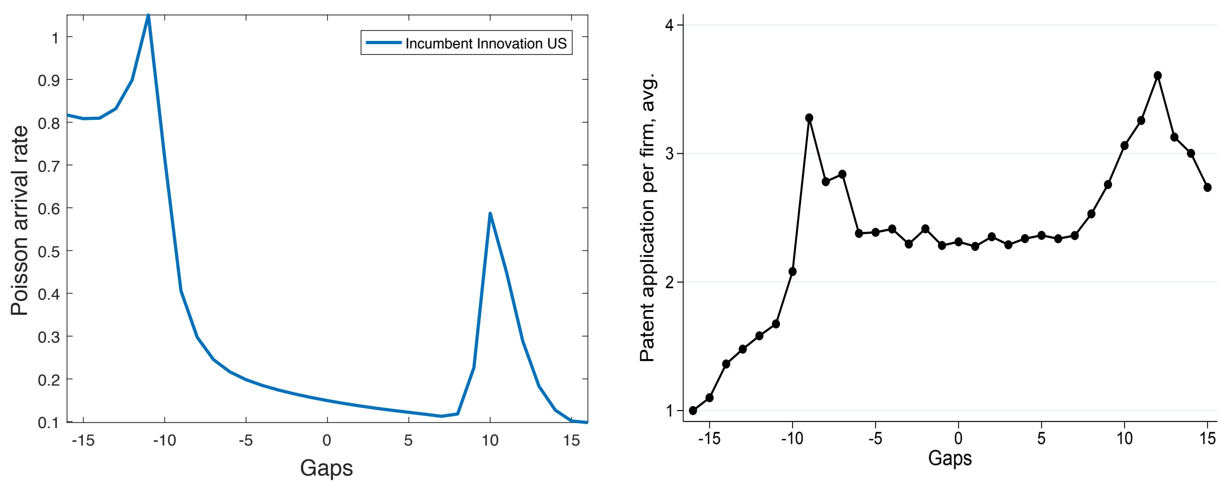
$$\int_0^1 \frac{d\log\left(\alpha_A x^{\gamma_c}_{Aj1981} q_{j1981}\right)}{d\log\left(1+\tau^A_{1981}\right)} dj = \sum_m \frac{d\log\left(\alpha_A x^{\gamma_c}_{Am1981} Q_{Am1981}\right)}{\log\left(1+\tau^A_{81-95}\right) - \log\left(1+\tau^A_{75-81}\right)}.$$

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.

Incumbent innovation vs. leadership. Figure 11 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 11a depicts incumbents' innovation intensity in balance growth path as a function of the technological gap. Figure 11b shows average patenting intensity of U.S. firms, measured by patent applications per firm, across sectors ranked according to their share of patents registered by U.S. residents, as described in Section 4.1.2.[33] In the left panel, we observe two spikes at $-m^*$ and m^*-1 which are related to cutoffs defined in equation (11). The first one happens right before the position that allows

[33] 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 4.1.2. 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. Figure 25 in Appendix C.5 shows that an alternative way of constructing the measure of our interest does not alter the key result. The difference there is that we assign technology classes to bins according to the domestic share of total patent applications after pooling all applications in that technology class across the whole time period considered.

a firm to earn domestic production as a result of firms' intense effort to reach this position. Similarly, firms producing domestically increase their innovation efforts massively close to the export cutoff with efforts peaking right before the threshold for exporting.[34] Interestingly, we observe a similar shape with two peaks also in the data, as illustrated in Figure 11b. 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 mimicing firms' innovation behavior.



(A) Incumbent innovation intensity in model (B) Patenting intensity in data

Figure 11: Innovation effort and leadership

4.2 Equilibrium properties

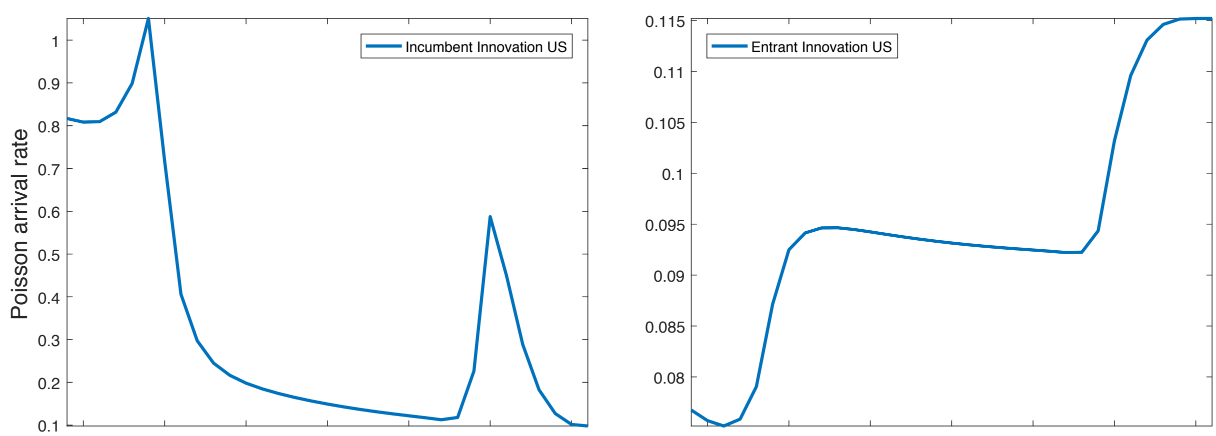
Here we show some properties of the equilibrium abstracting from policy changes and in the next section we perform the policy evaluation exercise.

Innovation cutoffs. Figure 12 illustrates the distribution of innovation effort by incumbents and entrants across the technology gaps. As described in Section 4.1.3 as part of a validity test, we observe two peaks in incumbent innovation intensities across the gap distribution. These peaks are generated by the key drivers of innovation discussed in Section 3.3.3. The market size effect 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 and this stimulates their innovation effort. As firms improve their relative position and become

[34]Subsection 4.2 explains the incentives that drive this result.

farther from cutoffs, they undertake decline less R&D. This decline is related to the escape competition mechanism described in Aghion et al. (2001), which implies that firms increase their innovative efforts as they become closer to their followers feeling more competitive pressures. In their model as well as other models of basic step-by-step mechanism [e.g. Acemoglu and Akcigit (2012)], this 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 neck-and-neck state. In contrast to the basic step-by-step models, an important difference of our model is that incumbent R&D exhibits two peaks. The reason is the existence of iceberg trade costs, which lead to a race for profits in two separate cases, domestic production and exports. 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.[35]

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 12b, reflects mainly the market size effect around the two cutoffs discussed in the previous paragraph. Entry, together with incumbent innovation below cutoffs, is the source of business stealing in the model.



(A) Incumbents

(B) Entrants

Figure 12: R&D decisions

[35]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.

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.

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. We now explore the impact on a country's welfare of foreign technological catching up. First, Figure 13 shows the resulting behavior of profits along the transition for the 1975-1981 period. Profits generated by each countries' leading firms show a clear convergence trend. This is driven by the international business-stealing effect, whereby foreign firms progressively capture leadership in more markets and formerly collected profits 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 to which we turn next.

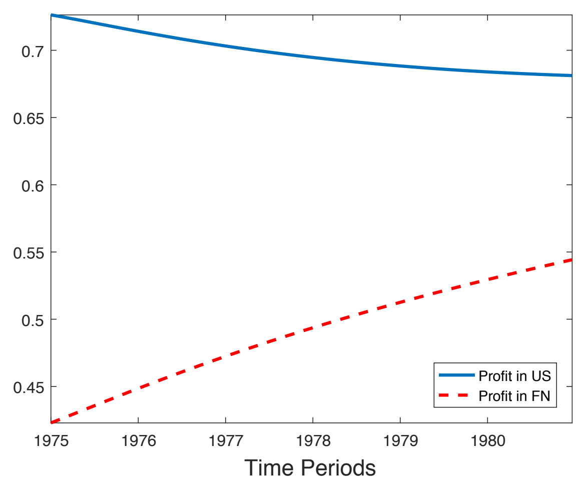


Figure 13: Profit Ratios

In order to understand the welfare effects of foreign convergence it proves useful to create a counterfactual economy where we shut down foreign business stealing. In this new setup foreign firms are allowed to innovate, however, whenever the step size of a new innovation allows them to steal the market of the U.S. competitor, we exogenously assume that the step size can only get close to the highest level that avoid capturing the profits of the competitor. For example, suppose a foreign incumbent serves only its domestic market, and to export, it needs to open the gap size between itself and its U.S. competitor by three gaps. Suppose this foreign firm receives an innovation that would make it jump four steps. In this case, we bound the step size to two so that the foreign firm cannot export and steal the U.S. market from its competitor. Next, we decompose the consumption-equivalent welfare changes into its components. First, we focus on the components of the income process in equation (16): profits, incumbent R&D expenditure, entrant R&D expenditure, wage income earned on domestically produced intermediate goods, and wage earned on imported intermediate goods. Then we replace each component of the income series in the benchmark economy one-by-one with the corresponding component generated in the counterfactual economy. This procedure enables us to measure the contribution of each component to the overall welfare change.

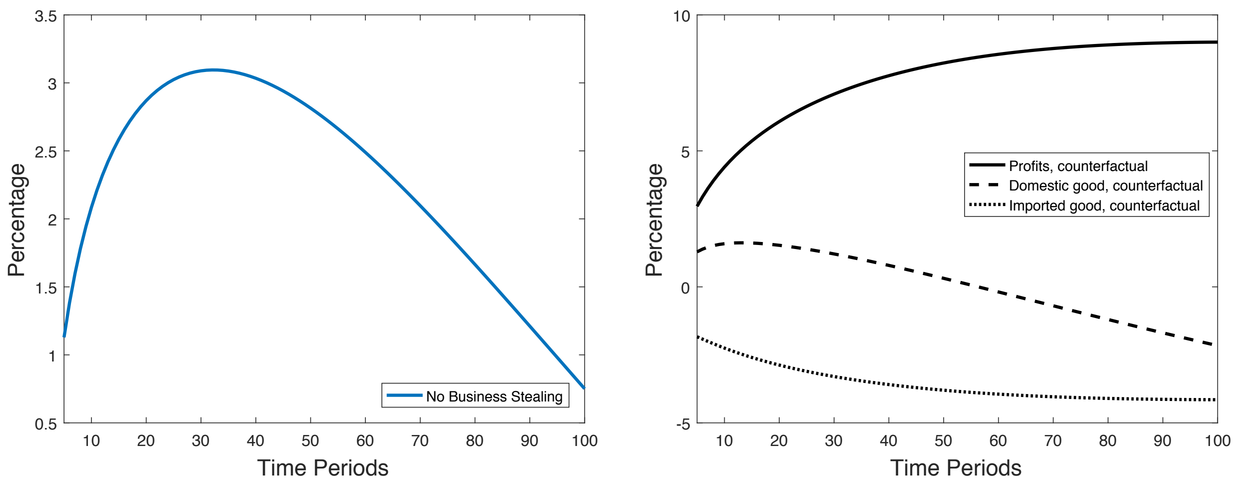
Table 6: Welfare effect of foreign catching up: 1975-95

Overall	Profits only	Inc. R&D only Escape Comp.	Ent. R&D only Business Steal.	Higher-q Domestic only	Higher-q Imports only
1.0287	1.0608	1.0018	0.9693	1.0153	0.9809

Table 6 shows that in a 20-year horizon our economy generates about 3% lower consumption each year compared to the counterfactual economy. The major driver of this loss is business-stealing: Foreign catching up shifts profits from domestic to foreign firms thereby reducing national income.[36] The gains from foreign catching up come from importing higher quality intermediate goods, but in a 20-year horizon they are not strong enough to offset the losses in profits. Finally, another driver of the overall change is the higher cost of entrant R&D. Compared to the no-business-stealing counterfactual economy, in our economy the threat of foreign business stealing reduces incumbent's value which in turn drives down entrants' R&D activity thereby increasing the resources available for consumption. These effects of changes in innovation through the resource constraint are second order, and the overall welfare losses from foreign catching up are driven by the business-stealing effect which dominates the gains from importing foreign highly productive intermediates.

In Figure 14 we show the evolution of the welfare effect of foreign catching up for a longer period of time. As can be seen in the left panel the gains from shutting down busi-

[36]Recall that aggregate profits in equation (16) are determined by both the measure of profit generating firms and the quality level of their products. This implies that the profit component of income, and thus, profit shifting as a source of welfare changes, are affected by innovations through the evolution of qualities. Nevertheless, the first-order driving force behind this component is the variation in the measure of firms that generate profits.



(A) Consumption equivalent welfare

(B) Decomposition

Figure 14: Consumption equivalent welfare

ness stealing decline over longer time horizons and they turn to losses in the very long run. The right panel provides an explanation zeroing in on the key components of national welfare driving the aggregate results.[37] In the first period of transition the profit component becomes more relevant as the years go by and its the driving force of home welfare losses due to foreign catching up. The step-size ceiling on foreign firms in the counterfactual economy prevents them from stealing business. Since a large mass of U.S. firms is just below the export cutoff and these are high innovation firms, shutting down foreign business stealing implies that more U.S. firms become exporters, and none of them lose that status, piling up on the right tail of the gap distribution. This change in the distribution at the end of the horizon is shown in Figure 24 in Appendix C.5, where we also show the related changes in the innovation distribution. Since U.S. exporters cannot be driven out of the foreign market in the counterfactual economy, they experience less competitive pressures. Less escape competition effect on firms that export but are close to the threshold result in a considerable decline in their innovation effort, as shown in the right panel of Figure 24. Hence, since more firms export and their innovation effort is lower, over time the productivity improvements generated by home firms progressively decline, and this effect dominates the profit or business-stealing component in the long run leading to welfare losses in the counterfactual economy compared to the benchmark. In other words, in our benchmark economy foreign catching up generates welfare losses in the short to medium run due to business-stealing, and welfare gains in the long-run due to the (escape) competition effect stimulating home firms to innovate more.

[37]Here we focus on the key components, the full decomposition is reported in Table 10 in Appendix C.3.

4.3 Policy Evaluation

We now introduce the observed post-81 R&D subsidy changes and assess both their effects on the global distribution of leadership and their welfare properties. We also analyze a counterfactual scenario where instead of changing R&D subsidies, the U.S. would respond to increasing foreign competition by protecting their firms with higher trade barriers.

4.3.1 R&D Subsidies

The U.S. R&D subsidy increases significantly from an average of 5.1% in the pre-1981 period to an average 19.2% in the following period, while the foreign subsidy is fairly constant, being 3.8% and 4.1% in the respective periods. Figure 15 shows the effect of the subsidy on the post-1981 distribution of technology gaps. On the left panel, the model gap distribution in 1981, which is closely calibrated to data in 1981, is the solid line. In the benchmark economy without any intervention, the transition leads us to the dashed line in 1995. If we introduce subsidies in 1981, that just becomes the solid line in 1995 on the right panel, creating a small shift to the right with respect to the dashed line representing no intervention case again. On 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.

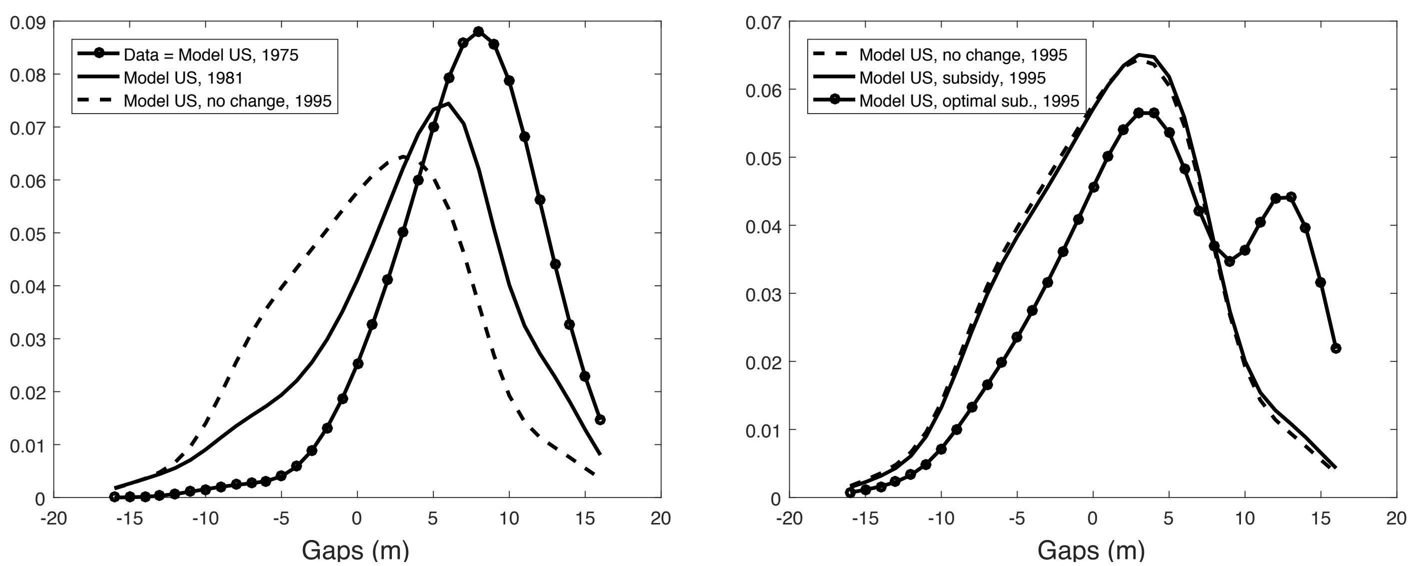


Figure 15: Gap distribution after policy changes

Now we examine the welfare properties of the R&D subsidy intervention. Table 7 reports the difference in overall U.S. welfare and in its components between a post-1981 counterfactual economy without subsidy changes and the economy embedding the subsidy changes. 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% welfare gain every year for 35 years. Income decomposition shows 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 profits. These channels contribute 1% and 0.7%, respectively, to welfare in consumption equivalent terms, more than compensating for the losses due to higher R&D spending. The economic mechanism is straightforward: By 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, and the related profits, in more sectors of the economy.[38]

Table 7: Welfare effect of U.S. R&D subsidy increase: 1981-2016

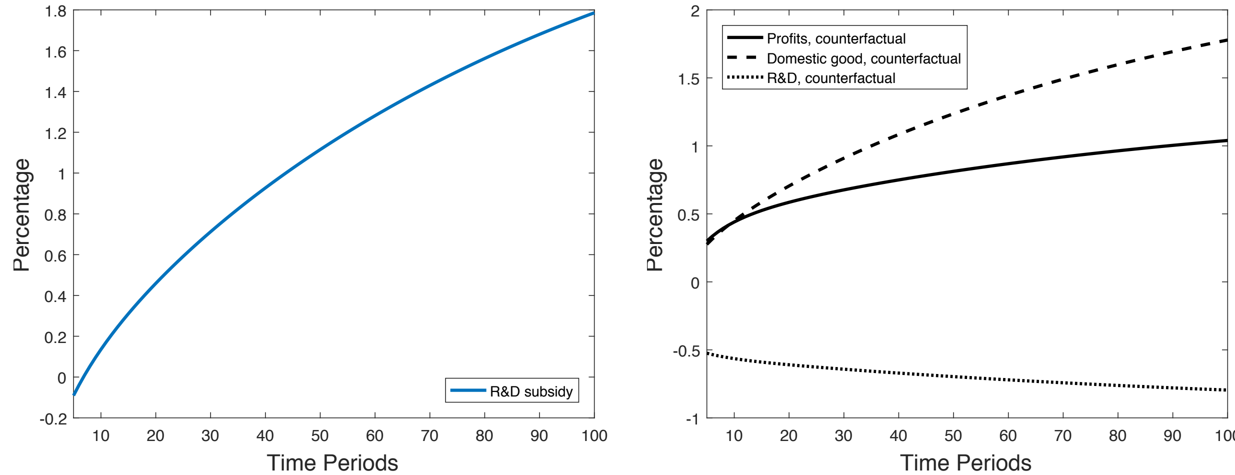
Overall	Profits only	Inc. R&D only	Ent. R&D only	Dom. Factor only	Imp. Factor only
1.0082	1.0071	0.9953	0.9981	1.0100	0.9977

In Figure 16 below we show the overall welfare gain and its components generated by the post-81 increase in U.S. subsidies over time. The left panel shows that in the short run of less than 10 years, the subsidy change leads to a welfare loss which is rapidly turned to gains as the years go by. The right panel suggests that the early loss is due to subsidy-induced shift of resources form 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.

4.3.2 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 8 reports the results.

[38]Figure 23 in Appendix C.5 illustrates the increase in steady state R&D efforts as a result of the subsidy change.



(A) Consumption equivalent welfare

(B) Decomposition

Figure 16: Consumption equivalent welfare

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

	Subsidy rate	Welfare gains 1981-2016
Observed R&D subsidy	19.2%	0.77%
Optimal R&D subsidy	69%	5.8%

The optimal subsidy is driven by a rich set of externalities typical of Schumpeterian growth models with some new twists.[39] 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 therefore it is

[39]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).

a reason to subsidize R&D, known as the *consumer surplus 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, this effect is not created through incumbents in our model, in contrast to the standard Schumpeterian model, because domestic incumbents, if successful in R&D, only replace foreign firms. In our model, the source of overinvestment is domestic entry. Because there is one firm sector from each country, any domestic entry means replacement of the domestic incumbent, which is not internalized by the entrants. Lastly, as shown in Impullitti (2010), an additional externality operates: in an open economy: Innovation by domestic incumbents or entrants that steals business from foreign firms increase national income. This *international business-stealing effect* is not taken into account by domestic innovators, hence it constitutes a reason to subsidize R&D.

Since we find that the observed subsidy is optimal for a short horizon, it follows that as time goes by and foreign catching up takes place the optimal subsidy increases. Figure 17 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, a longer period of foreign convergence can be affected by subsidies, raising the strategic or international business-stealing motive for subsidising R&D.[40]

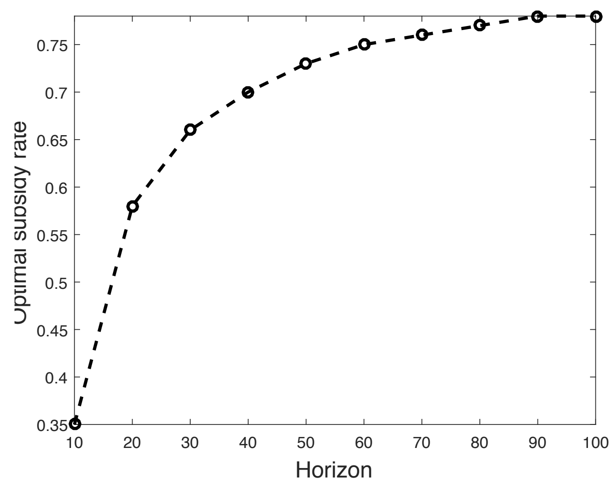
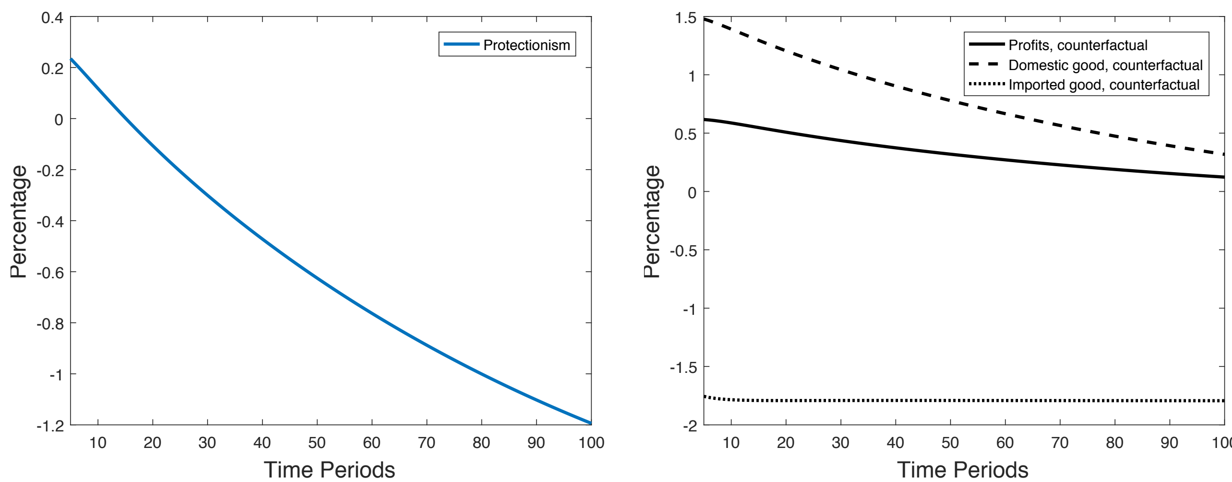


Figure 17: Optimal U.S. R&D subsidy over time

[40]A similar result is obtained in Impullitti (2010) for a standard two-country Schumpeterian model with exogenous changes in foreign technological competition.

4.3.3 Protectionist Response as Counterfactual Policy

In this subsection, we explore the implications of a unilateral increase in trade barriers as an alternative to R&D subsidies. Figure 18a shows the overall welfare gains/losses from a 40% rise in the trade cost κ after 1981 instead of increasing the R&D subsidy. In the right panel we break down the overall welfare effect into its key components. Protectionism seems to pay off in the short run, where small gains are generated from the increase in home profits and the increase in wage income coming from the use of domestic intermediate products. Over time, these gains fade away whereas losses due to the foregone high quality of foreign intermediates dominates.



(A) Consumption equivalent welfare

(B) Decomposition

Figure 18: Welfare effects of protectionism: unilateral 40% increase in trade barriers

Digging deeper, unilaterally higher trade barriers protect some sectors from import penetration initially, shifting profits 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 10. The solid line in Figure 18b shows that the initial gain from laggard firms capturing production in the domestic market is limited. Another factor that limits the profit gains is that most U.S. firms, being either exporters or solid domestic producers technologically close to or ahead of their competitors, are not affected by import protection. Figure 19 illustrates this point. Innovations decisions of this large group of firms are barely affected.

The replacement of foreign exporters by the laggard home firms has two implications on factor incomes. First, the downside is the high quality of foregone products generating a

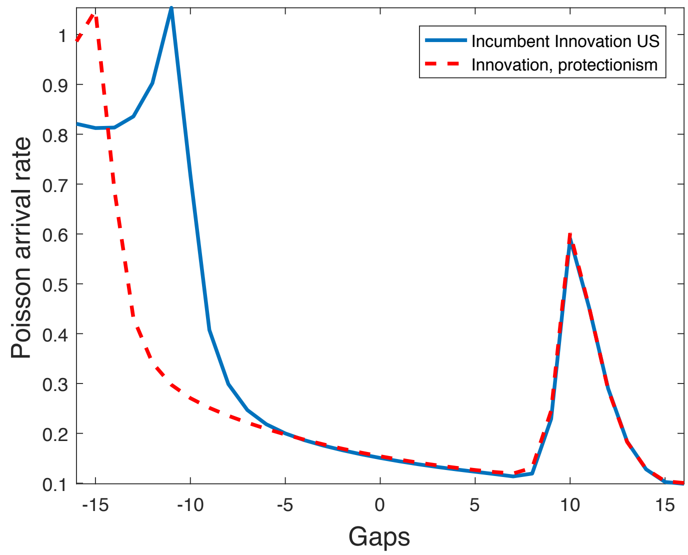


Figure 19: Innovation response to protectionism

larger welfare loss as shown by the dotted line in Figure 18b. On the positive side, though, domestic production of more goods translates into an initial rise in the welfare contribution of factor income earned using domestic goods (the dashed line). However, this is a merely one-time boost driven by the initial expansion of the mass of domestic goods used. As there is no additional innovation incentive for most domestic firms, the contribution of this component declines over time. Moreover, Figure 19 shows that innovation effort of most laggard U.S. firms that previously were not able to produce decrease substantially. As 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. Less competitive pressures lead to less innovation by these firms, making it harder to compensate for the loss of frontier imported technology. All in all, the short-run gains from profits is subdued by the loss of foreign technology over time as less domestic innovation leads to a slower pace of productivity increases.

Although this alternative policy and the counterfactual “no business stealing” world discussed earlier both make it difficult for foreign firms to export, they have stark differences in their welfare implications. This is because of the characteristics of domestic firms that are affected and their differential measures. In contrast to the protectionist response, “no business stealing” environment incentivized a large group of domestic firms to innovate in order to gain export status. This created a perpetual market size effect as those firms continued investing intensively in R&D. Furthermore, export status became permanent in that world, protecting profits from selling abroad, whereas loss of foreign market due to business stealing is still a threat in this protectionist world.

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. Realistically, firm innovation decisions in our model are motivated by the market size, escape-competition effect, and domestic and international business stealing. 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 quantitative analysis obtains several key results among various others. To start, we 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 increased foreign competition induces higher domestic innovation by U.S. incumbents through 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. 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.

References

Acemoglu, Daron and Ufuk Akcigit, "Intellectual Property Rights Policy, Competition and Innovation," *Journal of the European Economic Association*, 2012, *10* (1), 1–42.

_ , _ , Douglas Hanley, and William R Kerr, "Transition to Clean Technology," *Journal of Political Economy*, 2016, *124* (1), 52–104.

_ , _ , Nicholas Bloom, and William R Kerr, "Innovation, Reallocation and Growth," 2013.

Aghion, Philippe, Christopher Harris, and John Vickers, "Competition and Growth with Step-by-step Innovation: An Example," *European Economic Review*, 1997, *41* (3), 771–782.

_ , _ , Peter Howitt, and John Vickers, "Competition, Imitation and Growth with Step-by-step Innovation," *Review of Economic Studies*, 2001, *68* (3), 467–492.

Akcigit, Ufuk, Douglas Hanley, and Nicolas Serrano-Velarde, "Back to Basics: Basic Research Spillovers, Innovation Policy and Growth," 2016. Centre for Economic Policy Research Discussion Paper #11707.

_ , _ , and Stefanie Stantcheva, "Optimal Taxation and R&D Policies," 2016. National Bureau of Economic Research Working Paper #22908.

Autor, David, David Dorn, Gordon H. Hanson, Gary Pisano, and Pian Shu, "Foreign Competition and Domestic Innovation: Evidence from U.S. Patents," 2016. National Bureau of Economic Research # 22879.

Aw, Bee Yan, Mark J Roberts, and Daniel Yi Xu, "R&D Investment, Exporting, and Productivity Dynamics," *American Economic Review*, 2011, *101* (4), 1312–1344.

Bloom, Nick, Rachel Griffith, and John Van Reenen, "Do R&D Tax Credits Work? Evidence from A Panel of Countries 1979–1997," *Journal of Public Economics*, 2002, *85* (1), 1–31.

Burstein, Ariel and Marc J Melitz, "Trade Liberalization and Firm Dynamics," in "Advances in Economics and Econometrics Tenth World Congress. Applied Economics," Vol. 2 2013, pp. 283–328.

Capdevielle, Patricia and Donato Alvarez, "International Comparisons of Trends in Productivity and Labor Costs," *Monthly Lab. Rev.*, 1981, *104*, 14.

Coe, David T and Elhanan Helpman, "International R&D Spillovers," *European Economic Review*, 1995, *39* (5), 859–887.

_ , _ , and Alexander W Hoffmaister, "International R&D Spillovers and Institutions," *European Economic Review*, 2009, *53* (7), 723–741.

Coeurdacier, Nicolas and Helene Rey, "Home Bias in Open Economy Financial Macroeconomics," *Journal of Economic Literature*, 2013, *51* (1), 63–115.

Eaton, Jonathan and Gene M Grossman, "Optimal Trade and Industrial Policy under Oligopoly," *Quarterly Journal of Economics*, 1986, *101* (2), 383–406.

_ and Samuel Kortum, "Technology, Geography, and Trade," *Econometrica*, 2002, *70* (5), 1741–1779.

Gerschenkron, Alexander, *Economic Backwards in Historical Perspective: A Book of Essays*, Belknap Press of Harvard University Press, 1962.

Giovanni, Julian Di, Andrei A Levchenko, and Jing Zhang, "The Global Welfare Impact of China: Trade Integration and Technological Change," *American Economic Journal: Macroeconomics*, 2014, *6* (3), 153–183.

Grossman, Gene M and Edwin L-C Lai, "International Protection of Intellectual Property," *American Economic Review*, 2004, *94* (5), 1635–1653.

_ **and Elhanan Helpman**, "Quality Ladders in the Theory of Growth," *The Review of Economic Studies*, 1991, *58* (1), 43–61.

Haaland, Jan I and Hans Jarle Kind, "R&D Policies, Trade and Process Innovation," *Journal of International Economics*, 2008, *74* (1), 170–187.

Hall, Bronwyn H, Adam B Jaffe, and Manuel Trajtenberg, "The NBER Patent Citation Data File: Lessons, Insights and Methodological Tools," 2001. National Bureau of Economic Research # 8498.

Hallacher, Paul M, *Why Policy Issue Networks Matter: The Advanced Technology Program and The Manufacturing Extension Partnership*, Rowman & Littlefield, 2005.

Ham, Rose Marie and David Mowery, "The US Policy Response to Globalization: Looking for the Keys Under the Lamp Post," *Governments and Globalization*, 1999.

Hicks, John R, "An Inaugural Lecture," *Oxford Economic Papers*, 1953, *5* (2), 117–135.

Hsieh, Chang-Tai and Ralph Ossa, "A Global View of Productivity Growth in China," *Journal of International Economics*, 2016, *102*, 209–224.

Impullitti, Giammario, "International Competition and US R&D Subsidies: A Quantitative Welfare Analysis," *International Economic Review*, 2010, *51* (4), 1127–1158.

_ **and Omar Licandro**, "Trade, Firm Selection, and Innovation: The Competition Channel," *Economic Journal*, 2017.

Leahy, Dermot and J Peter Neary, "Public Policy towards R&D in Oligopolistic Industries," *American Economic Review*, 1997, pp. 642–662.

Lileeva, Alla and Daniel Trefler, "Improved Access to Foreign Markets Raises Plant-level ProductivityâĂę for Some Plants," *Quarterly Journal of Economics*, 2010, *125* (3), 1051–1099.

López, Ricardo A, "Do Firms Increase Productivity in Order to Become Exporters?," *Oxford Bulletin of Economics and Statistics*, 2009, *71* (5), 621–642.

Matsuyama, Kiminori, "Beyond Icebergs: Towards A Theory of Biased Globalization," *The Review of Economic Studies*, 2007, *74* (1), 237–253.

Mowery, David C and Nathan Rosenberg, "New Developments in US Technology Policy: Implications for Competitiveness and International Trade Policy," *California Management Review*, 1989, *32* (1), 107–124.

Ossa, Ralph, "A Quantitative Analysis of Subsidy Competition in the US," 2015. National Bureau of Economic Research Working Paper # 20975.

Perla, Jesse, Christopher Tonetti, Michael E Waugh et al., "Equilibrium Technology Diffusion, Trade, and Growth," 2015. National Bureau of Economic Research Working Paper # 20881.

Sampson, Thomas, "Dynamic Selection: An Idea Flows Theory of Entry, Trade, and Growth," *The Quarterly Journal of Economics*, 2016, *131* (1), 315–380.

Samuelson, Paul A, "Where Ricardo and Mill Rebut and Confirm Arguments of Mainstream Economists Supporting Globalization," *Journal of Economic Perspectives*, 2004, *18* (3), 135–146H.

Segerstrom, Paul S, "Endogenous Growth without Scale Effects," *American Economic Review*, 1998, pp. 1290–1310.

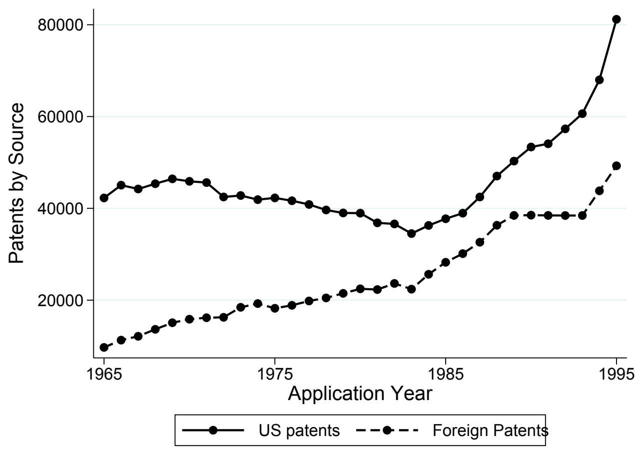
Spencer, Barbara J and James A Brander, "International R&D Rivalry and Industrial Strategy," *Review of Economic Studies*, 1983, *50* (4), 707–722.

Wilson, Daniel J, "Beggar Thy Neighbor? The In-state, Out-of-state, and Aggregate Effects of R&D Tax Credits," *The Review of Economics and Statistics*, 2009, *91* (2), 431–436.

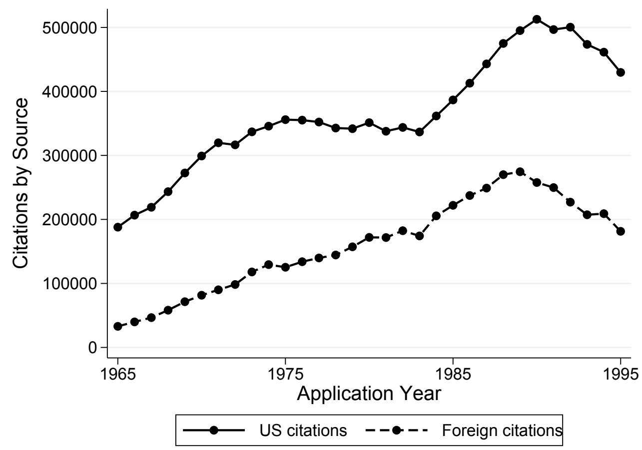
Appendices

A Additional Empirical Material

A.1 Patenting over time



(A) Patent count



(B) Citation count

Figure 20: Evolution of R&D credits in the U.S.

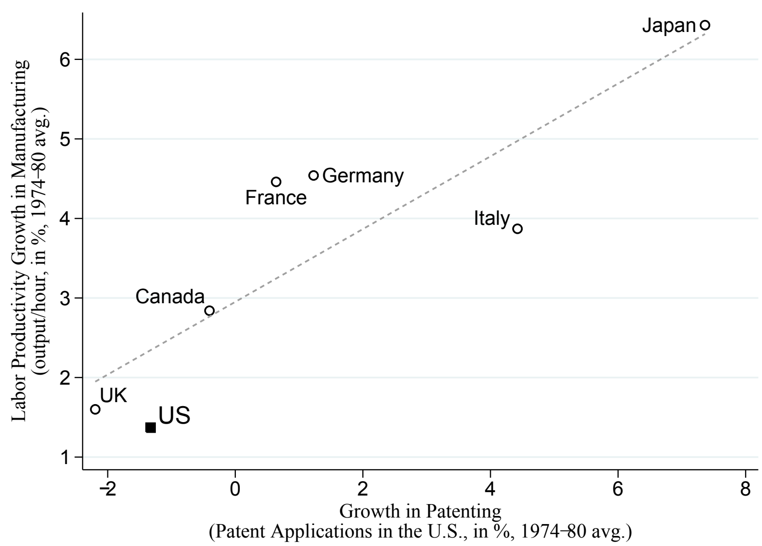
A.2 Additional regression results

This section presents the counterpart of the regression analysis in Section 2 incorporating federal tax credit. The results are shown in Table 9. 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.

Table 9: 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



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

Figure 21: 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 (9) and (10). 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 proof this lemma by guess-and-verify method. Assuming linearity we have

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

Dividing all sides by q_t we obtain that x_{Amt} does not depend on q_t. Also, linearity assumption in equation (14) 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.

B.2 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	$x_m^c \mathbb{F}_m(n)$	$\lambda^{(n-m)} Q_m^c$	n
DE innovates	$\tilde{x}_m^c \mathbb{F}_m(n)$	$\lambda^{(n-m)} Q_m^c$	n
FI innovates	$x_{-m}^f \mathbb{F}_{-m}(n)$	Q_m^c	$-n$
FE innovates	$\tilde{x}_{-m}^f \mathbb{F}_{-m}(n)$	Q_m^c	$-n$
Nothing	$1 - x_m^c - x_{-m}^f$ $- \tilde{x}_m^c - \tilde{x}_{-m}^f$	Q_m^c	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	$x_{-m}^c \mathbb{F}_{-m}(n)$	$\lambda^{(n+m)} Q_{-m}^c$	n
DE innovates	$\tilde{x}_{-m}^c \mathbb{F}_{-m}(n)$	$\lambda^{(n+m)} Q_{-m}^c$	n
FI innovates	$x_m^f \mathbb{F}_m(n)$	Q_{-m}^c	$-n$
FE leapfrogs	$\tilde{x}_m^f \mathbb{F}_m(n)$	Q_{-m}^c	$-n$
Nothing	$1 - x_{-m}^c - x_m^f$ $- \tilde{x}_{-m}^c - \tilde{x}_m^f$	Q_{-m}^c	$-m$

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	$x_{-\bar{m}}^c \mathbb{F}_{-\bar{m}}(n)$	$\lambda^{(n+\bar{m})} Q_{-\bar{m}}^c$	n
DE innovates	$\tilde{x}_{-\bar{m}}^c \mathbb{F}_{-\bar{m}}(n)$	$\lambda^{(n+\bar{m})} Q_{-\bar{m}}^c$	n
FI innovates	$x_{\bar{m}}^f \mathbb{F}_{\bar{m}}(n)$	$Q_{-\bar{m}}^c$	$-\bar{m}$
FE leapfrogs	$\tilde{x}_{\bar{m}}^f \mathbb{F}_{\bar{m}}(n)$	$Q_{-\bar{m}}^c$	$-\bar{m}$
Nothing	$1 - x_{-\bar{m}}^c - x_{\bar{m}}^f$ $- \tilde{x}_{-\bar{m}}^c - \tilde{x}_{\bar{m}}^f$	$Q_{-\bar{m}}^c$	$-\bar{m}$

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

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

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

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

where

- $\mathcal{F}_{\bar{m}}$ captures domestic firms at $s < \bar{m}$ reaching gap $\bar{m}$ with probability $\mathbb{F}_s\left(\bar{m}\right)$;
- $\mathcal{F}^1_m$ 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 $\mathbb{F}_{-s}\left(-m\right)$;
- $\mathcal{F}^2_m$ captures domestic firms at $s < m$ reaching gap m with probability $\mathbb{F}_s\left(m\right)$;
- $\mathcal{F}_{-\bar{m}}$ 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 $\mathbb{F}_s\left(\bar{m}\right)$.

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:

$$
\begin{aligned}
r_t^A v_{mt+\Delta t}^A - \frac{v_{mt+\Delta t}^A - v_{mt}^A}{\Delta t} &= \Pi\left(m\right) - \left(1-\tau^A\right)\alpha_A \frac{\left(x_{mt}^A\right)^{\gamma_A}}{\gamma_A} \\
&+ x_{mt}^A \left\{ \sum_{n=m+1}^{\bar{m}} \mathbb{F}_m\left(n\right) \lambda^{(n_t-m)} v_{nt+\Delta t}^A - v_{mt+\Delta t}^A \right\} \\
&+ \tilde{x}_{mt}^A \left[0 - v_{mt+\Delta t}^A\right] + \left(x_{-mt}^B + \tilde{x}_{-mt}^B\right) \sum_{n=-m+1}^{\bar{m}} \mathbb{F}_{-m}\left(n\right) \left[v_{-nt+\Delta t}^A - v_{mt+\Delta t}^A\right]
\end{aligned} \tag{19}
$$

$$
-\frac{\tilde{\alpha}_c}{\tilde{\gamma}_c}\left(\tilde{x}_{mt}^c\right)^{\tilde{\gamma}_c} + \tilde{x}_{mt}^c \left\{ \sum_{n=m+1}^{\bar{m}} \mathbb{F}_m\left(n\right) \lambda^{(n_t-m)} v_{nt+\Delta t}^A - 0 \right\}. \tag{20}
$$

C.2 Solution Algorithm

1. Let $\mathbb{M}$ be the set of data moments and $\mathbb{M}^m$ be the model counterpart. Define $\mathbf{R}\left(\mathbb{M} - \mathbb{M}^m\right)$ 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 $\left\{r_T^A, v_T^B\right\}^{h=0}$.
   (a) At iteration h, take $\left\{r_T^A, v_T^B\right\}^h$ 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 $\left\{v^c_{mT+\Delta t}\right\}_m = \left\{v^c_{mT}\right\}_m$ 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 $\left\{g^A_T, g^B_T\right\}^h$.

(c) Check if $\left\{r^A_T, v^B_T\right\}^h$ and $\left\{g^A_T, g^B_T\right\}^h$ meet the Euler equation. If not, set $\left\{r^A_T, v^B_T\right\}^{h+1}$ to interest rates implied by the Euler equation with $\left\{g^A_T, g^B_T\right\}^h$ and repeat until convergence.

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

   (a) At iteration h, given terminal (steady state) values $\left\{v^A_{mT}, v^B_{mT}\right\}^h_m$ compute the implied innovation rates $\left\{x^A_{mT-\Delta t}, \tilde{x}^A_{mT-\Delta t}, x^B_{mT-\Delta t}, \tilde{x}^B_{mT-\Delta t}\right\}^h_m$. Then, given terminal interest rates $\left\{r^A_T, v^B_T\right\}^h$, compute $\left\{v^A_{mT-\Delta t}, v^B_{mT-\Delta t}\right\}^h_m$. Iterate backwards using the $\left\{r^A_t, r^B_t\right\}^h_{t=\{1975,...,1975+T\}}$ until $t_0 = 1975$ to obtain the implied series $\left\{x^A_{mt}, \tilde{x}^A_{mt}, x^B_{mt}, \tilde{x}^B_{mt}\right\}^h_{mt=\{1975,...,1975+T\}}$.

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

   (c) Compute income growth rates $\left\{g^A_t, g^B_t\right\}^h_t$. Using period-by-period Euler equations, check if

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

   for $\{1975, ..., 1975 + T - 1\}$. If not, set $\left\{r^A_t, r^B_t\right\}^{h+1}_{t=\{1975,...,1975+T-1\}}$ to interest rates implied by the Euler equation with $\left\{g^A_t, g^B_t\right\}^h_{t=\{1975,...,1975+T-1\}}$ and repeat until convergence.

5. Once step 4 converges, use the final interest rates $\left\{r^A_t, r^B_t\right\}_{t=\{1975,...,1975+T\}}$ 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 10: 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 11: 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

Table 12: 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

C.4 Optimal R&D Subsidy and Trade Openness

As world becomes more closed, there is more underinvestment in innovation because innovation increases growth and does not lead firms to steal business from other domestic firms (main source of overinvestment in basic Schumpeterian models). As trade barriers get lower there is more imported goods to free ride on declining the need for higher subsidies.

Table 13: Openness and Optimal U.S. R&D subsidy: 1981-2016

	Optimal subsidy rate	Welfare gains 1981-2016
Benchmark	69%	5.8%
More open world, 0.5κ	63%	4.8%
More closed world, 1.5κ	77%	5.4%

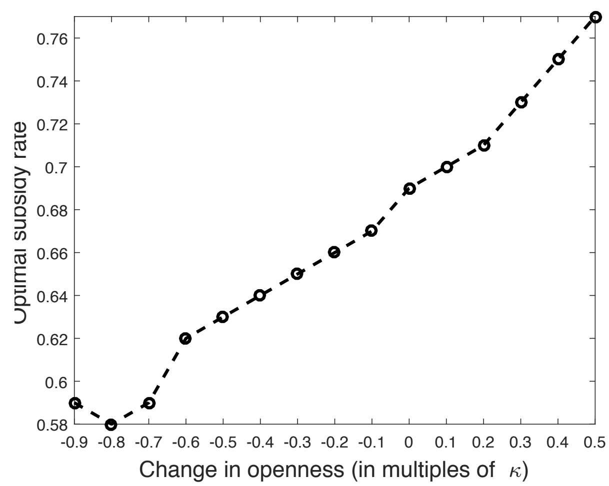
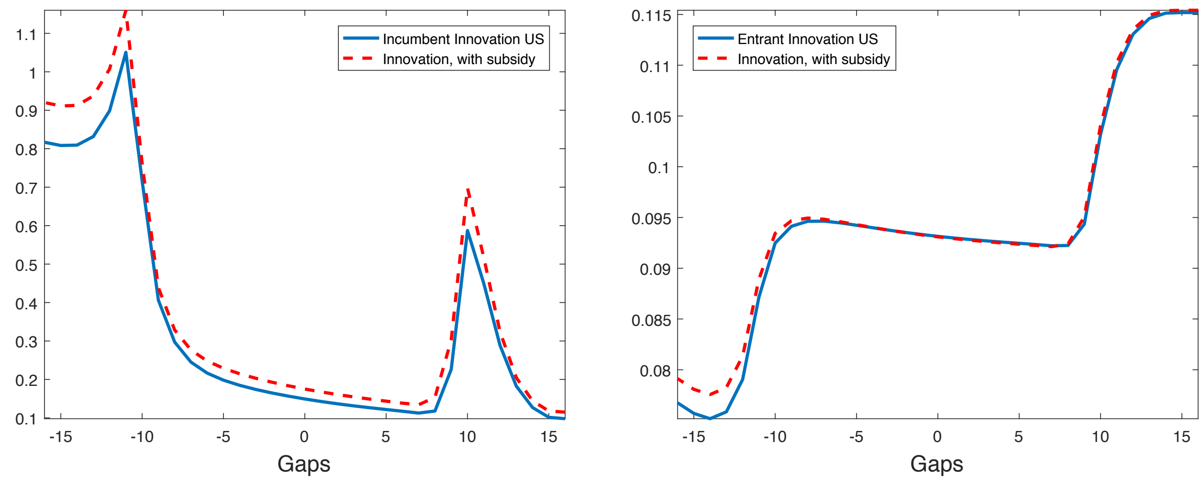


Figure 22: Optimal U.S. R&D subsidy over levels of trade openness

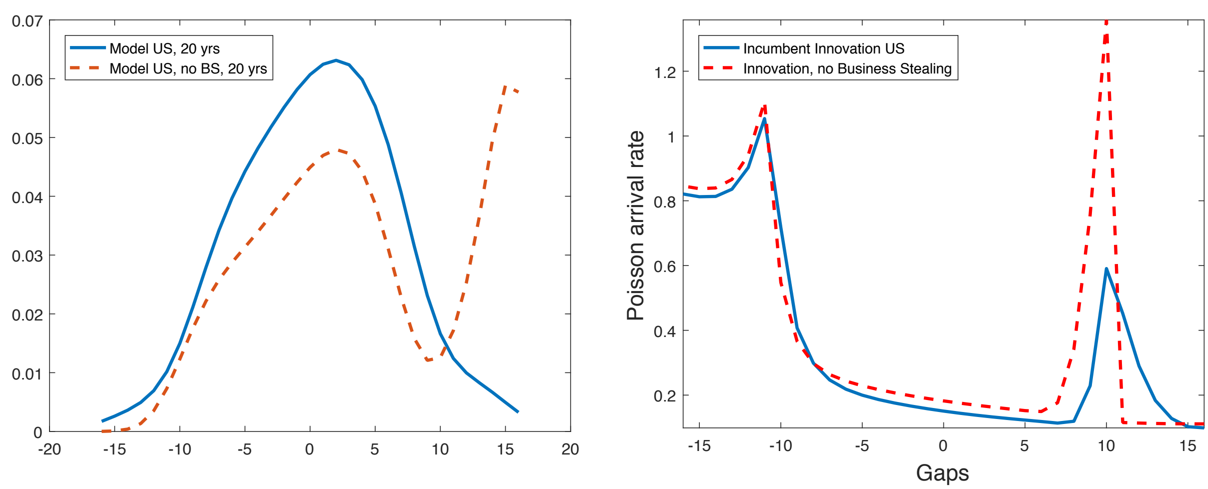
C.5 Additional Figures



(A) Incumbents

(B) Entrants

Figure 23: Changes in R&D decisions after subsidy change



(A) Gap distribution

(B) Incumbent innovation

Figure 24: U.S. leadership shares and innovation without business stealing

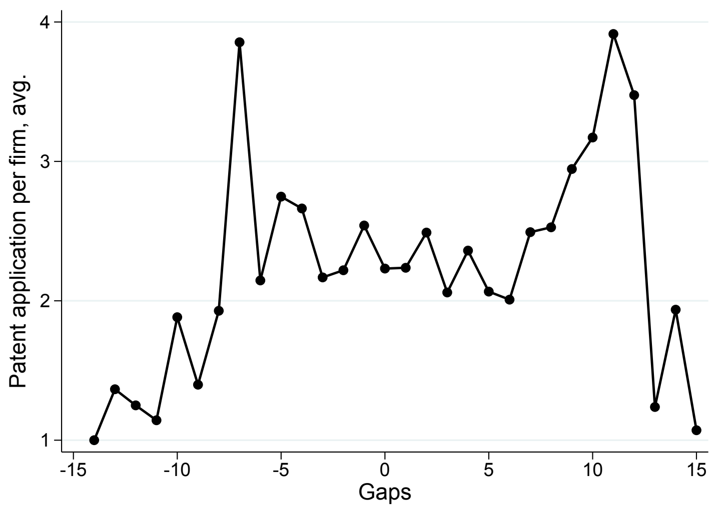


Figure 25: Patenting intensity in USPTO data