Technology Dynamics, Innovation Policy and the Gains from Globalization*

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Abstract

This paper is motivated by two novel observations on global innovative activity: First, there is a clear convergence in the number of patents issued by US and non-US based firms over the course of the 1970s until the mid- 1980s. Second, in the first half of the 1980s, R&D subsidies and tax credits were introduced both at the federal and state level in the US and a halt of the technological convergence followed. Motivated by these facts we build a model of endogenous technical change to analyze the effects of openness and the welfare consequences of innovation policies in open economy. We analyze openness both in the classical form of lower trade barriers and in the less explored form of fiercer foreign technological competition. In our model firms from two asymmetric countries compete in innovation for global market leadership. The asymmetry, defined by an initial technology gap, implies that firms from the lagging country must first catch-up before leapfrogging and becoming leaders. International knowledge spillovers facilitate technology diffusion and promote cross-country income convergence. Trade frictions hinder convergence. Fiscal incentives to innovation, R&D subsidies, are used strategically by policy makers to affect the speed of convergence and the geographical structure of innovation and technological leadership. Calibrated to match key innovation, growth, and trade statistics the model is able to replicate the convergence observed in the data. Foreign catching-up results in sizable short run and long-run losses for the leading economy, the US in our quantitative application. Trade liberalization, leads to long-run run gains that are roughly double those obtained in the short run. Feeding the model the increase in US R&D subsidies in the 1980s replicates about $1/4^{th}$ of the recovery of US leadership shown in the patent data since the mid-1980s. Moreover, this aggressive innovation policy generates welfare gains of about 1% of consumption equivalent in a 25-years horizon.

Keywords: Dynamic gains from globalization, technology competition, innovation policy, convergence, endogenous growth, .

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"Some past scholars have wondered whether cheapening of transportation costs and speedier spreading of knowledge across national boundaries might in the future decimate comparative advantages ... They have also wondered whether, when all peoples are as productive as Americans, some of their new benefits might come out of reduced U.S. well-being." Paul Samuelson (2004), p.142.

1 Introduction

Technological progress and innovation are key engines of economic growth and market leadership. In open economies the effects of innovation diffuse globally through trade in goods and knowledge flows. The relation between openness, innovation and welfare has been analyzed in several contests in which openness referred to different but not necessarily unrelated aspects of globalization. It can be related to the absence of barriers to trade in good and services, but also to the free flow of ideas across national borders. As Eaton and Kortum (2007) point out, the implications of innovation for consumers and firms can vary depending on the feature of openness we consider. Lower trade barriers allow consumers and firms to benefit from foreign innovation importing the good that embeds that idea, while faster diffusion of ideas allows firms to produce and sell them locally. Policies supporting national competitiveness through innovation have different welfare implications according to the feature of openness we consider.

Governments around the world have been trying to support their national companies in the race for global technological leadership. A look at the geographic distribution of innovation investments and output in recent decades unveils interesting dynamics of this leadership. U.S. Patent Office data show that between 1975 and 1985, the ratio of foreign patent counts to the sum of US and foreign patent counts increased steadily by 33%. While the US was the global technology leader in 80% of the technology classes in 1975, in 10 years this fraction went down to 60%. In the meantime, the fraction of technology classes in which the US held a neck-and-neck position with foreigners increased from 10% to 20% and the fraction of technology classes in which the US was a lagging increased from 10% to 20%. Similar trends can be found focusing on countries' share of global R&D at the sectorial level (Impullitti, 2010). Concerns over U.S. competitiveness in those years led to the introduction of a set of policies explicitly targeting incentives for business innovation (Ham and Mowery, 1999, and Mowery and Rosernberg, 1989). One of these policies was the introduction in 1981 of the first Federal R&D Tax Credit (FRDC) and starting in 1982 with Minnesota, different states began to adopt State R&D Tax Credits (SRTC). Beginning in the mid-1980s the convergence in the ratio of patent counts stopped and the US inventors regained the world leadership in a variety of technology fields. By the end of 1995, US restored its leadership in 65% of the technology classes.

Motivated by these facts and by the debate on the role of innovation in the global economy, we build a trade model with dynamic comparative advantage to analyze the gains from openness and the welfare consequences of innovation policies. Innovation shapes the dynamics of technology and market leadership in a world economy with two countries at different development stages. International markets are characterized by trade costs and lags in the diffusion of ideas taking the form of knowledge spillovers. Diffusion lags shape the dynamic process of cross-country convergence.

We calibrate the model to match key trade, innovation ad growth facts in the 1970s and reproduce the structure of global leadership in those years, with the US representing the technological frontier and a set of European countries plus Japan being the followers. Abstracting from any changes in innovation policy, we explore the transitional dynamics triggered by the process of knowledge diffusion which leads the lagging country to progressively catch up with the leader. This allows us to study the effects on the leading country's (U.S.) welfare, of foreign technological convergence and of reduction in trade barriers. We find that the U.S. experiences sizable short and long-run losses from foreign catching up amounting to about 3% of consumption equivalent. Technological convergence yields positive welfare gains for the leading country by allowing import goods embedding innovation produced abroad. At the same time, when a domestic firm loses its technological leadership to a foreign firm, profit shifts abroad and national welfare declines. This *business-stealing* effect of foreign competition prevails in our calibrated model, thus leading to welfare losses. The robustness analysis of this result reveals that a combination of entry barriers and the diffusion speed pins down the balance between the positive innovation effect and the negative business-stealing effect of foreign competition. Trade liberalization, leads to long-run run gains that are roughly double those obtained in the short run. This result highlights the importance of accounting for the transitional dynamics when evaluating welfare gains from trade. In our economy a reduction in trade costs produces static efficiency gains due to the lower price of imported intermediate goods, and dynamic gains due to a *market-size* effect on the incentives to innovate.

Next, we feed the model the increase in US R&D subsidies that took place in the 1980s as a consequence of the introduction of the Federal and State-level R&D tax credit. Our findings suggest that about $1/4^{th}$ of the recovery of US leadership shown in the patent data since the mid-1980s can be attributed to R&D subsidies. We then analyze the welfare implication of this policy response to international competition. Although on impact the welfare effect of higher subsidies is negative, a few years down the line it turns positive and the long run gains are substantial, in the range of $1.2 - 2\%$ of consumption equivalent. Finally we decompose the effect of U.S. subsidies on the growth of national income into its innovation and business stealing component, and we find that the latter accounts for about 80% of the overall increase in income.

The rest of the paper is organized as follows. Section 2 reviews the related literature, section 3 describes the empirical facts on international technology competition, section 4 introduces the theoretical framework, section 5 outlines the calibration procedure, section 6 provides the quantitative results and section 7 concludes.

2 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 model of growth through step-by-step innovation as in Aghion, Harris, and Vickers (1997), Aghion et al. (2001) and in the latest developments by Acemoglu and Akcigit (2012). In these models two firms compete strategically for market leadership in each product line through an innovation race aimed at improving the quality of the goods produced. There is a technology/quality gap between the leader and the follower in each product line that can be filled by successful innovation. Reversals of market leadership takes place in separate steps, first the follower catches up with the leader and then further innovation allows leapfrogging. We depart from this literature in several ways. First, while the present literature focuses on closed economies, we introduce costly *international trade* and competition between domestic and foreign producers in each product line.[1] Second, a key limitation of the step-by-step model is the absence of *entry*, in each product line there are two incumbent firms and no competition from new entrants is allowed. We overcome this limitation introducing an outside pool of domestic entrant firms. These firms target a particular product line investing resources in innovation potentially enabling them the domestic incumbent firm. Introducing the entry margin allows the model to distinguish the effects of domestic and foreign competition. Finally, while the current literature focuses on the analysis to the steady state, we consider the entire *transition path* generated by technological convergence and innovation policies. This feature enables us to study both the transitional and long-run effect of international competition triggered by foreign catching up and trade liberalization, the two dimension of globalization we focus on. Moreover, since we focus on optimal innovation policy, a complete characterization of the dynamic path of welfare is needed.

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 it's trading partners. Foreign technical change transmits to its trading partner through the terms of trade: it benefits it's trading partners if the technological improvement happens in the source country comparative advantage industries and vice versa. 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 US and Germany produces sizable welfare gains for other OECD countries.[2] In intra-industry trade models, the transmission mechanism works through the "home-market effect". As recently shown by Hsie and Ossa (2011), technological progress benefits a country's trading partners if it takes place 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 model Schumpeterian competition for innovation yields endogenous comparative advantages and shapes market leadership across industries similarly to the home-market effect. Hence our framework contains traces of both classical transmission mechanisms, and add to the existing works the endogeneity of technology, the full welfare analysis along the dynamic transition path generated by foreign technological catching up, and assesses the role of innovation policy. We also look at a different, and more canonical, feature of globalization, the fall in trade costs. Our exploration of the static and dynamic gains from trade, makes contact with the vast literature on welfare gains from trade. Most of the literature is focused on static gains, and as Ariel Burstein and Marc Meliz point out in a recent survey, more research is needed for understanding the implications of firm and technology dynamics for the gains from trade (Burnstein and Melitz, 2013).

Finally our paper contributes to the theoretical and empirical literature on R&D subsidies in open economies and closed economies. The strategic trade and industrial policy literature

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[1] Aghion and Howitt (2009) consider two-country version of the step-by-step model similar to ours to analyze the effects on profits, wages and growth of moving from autarky to free trade. They focus on the steady state and since they have linear utility they do not perform welfare analysis.

[2] Along the same line, a set of recent papers has analyzed the effects of China's technological catch-up on its trading partners' welfare in trade models based on comparative advantage (see e.g. Di Giovanni, Levchenko, and Zhang, 2012, and Levchenko and Zhang, 2011).

pioneered by Spencer and Brander (1983) and Grossman and Eaton (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 a imperfectly competitive global economy.[3] While these classic papers are based on static partial equilibrium models, Grossman and Lai (2004) extend the analysis to a two-country endogenous growth model and use it explore strategic interaction in the optimal design of intellectual property rights (IPR) policy. Impullitti (2010) introduces technological asymmetry across country and innovation dynamics to study the impact of increasing foreign competition on the incentives to subsidize R&D in the leading country. Both these papers limit their analysis to the steady state. We depart from the existing literature by exploring the whole transition path of welfare to changes in innovation policy. Related papers analyzing optimal R&D subsidies in closed economies are Hall (2001), Bloom, Griffith and Van Reenen (2002), Guenther (2005), Laincz (2009), Akcigit, Hanley and Serrano-Velarde (2013), and Acemoglu et al (2013).

3 Empirical Facts

This section presents some empirical regularities regarding trends in global technological leadership and R&D activity. The facts related to the former, which motivate our paper, show the trends in patenting activity of foreign countries relative to the US. Before going into the policy analysis, we want our model to explain these trends so that they provide an *external validity* check for our model. Then, we will examine the R&D activity in the US to provide a causal relationship between this and the overall performance of a country in the technological race. This will explain why changes in R&D policies might be a valid channel to analyze the shifts in international patterns of technological competition.

Fact 1: Technological Convergence until mid-80s

There is a striking change in the relative position of foreign countries relative to the US 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 (1) shows the yearly change in the proportion of patents registered in the US by foreigners using NSF data on patent counts. 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 US counterpart.

The right panel in Figure (2) 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 US- and foreign-based firms over years as well as the percentage of sectors where they are in a “neck&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&neck arises when the difference of the shares of patents held by two countries is less than a threshold. When generating this picture, we term sectors where the difference is less than 15% as neck&neck sectors. This implies that a sector is dominated (owned) by the firms of a country if their share is above 57.5%, and it is neck&neck if their

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[3] See Neary and Leahy (2000) and Haaland and Kind (2008) for recent contributions.

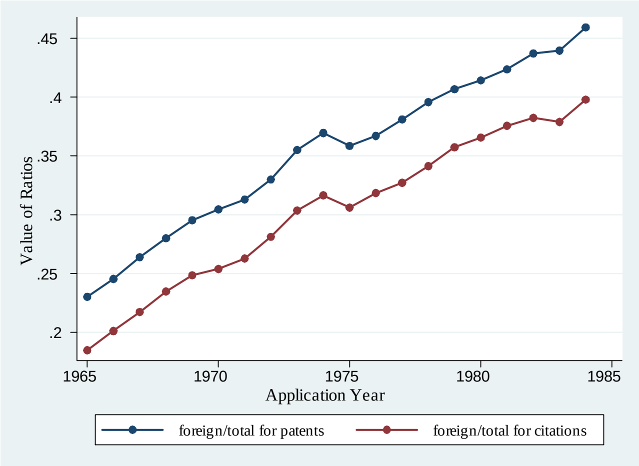
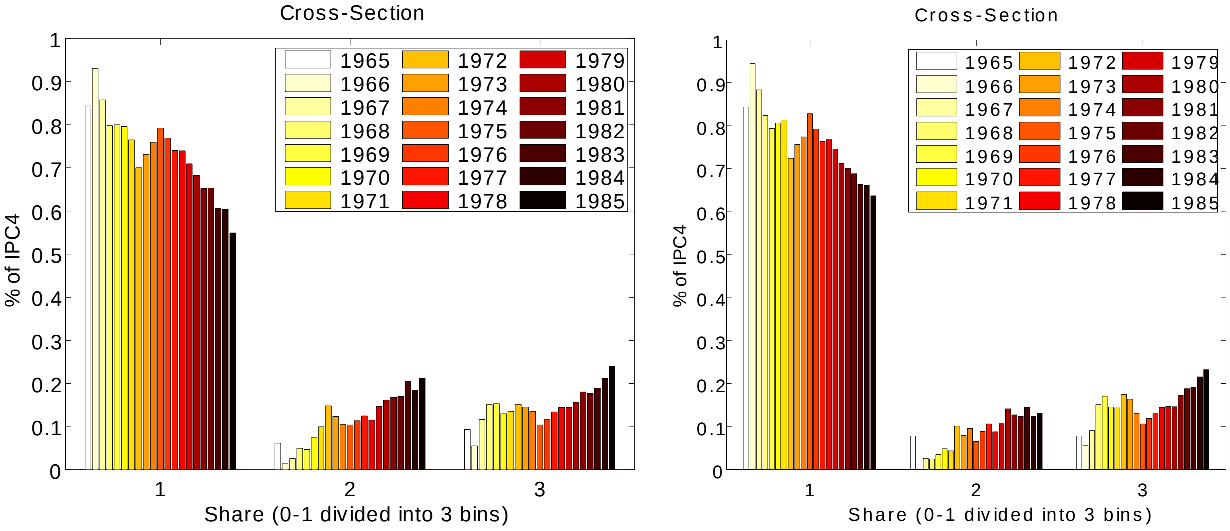


Figure 1: Ratio of patents and associated citations registered in the US by foreigners over the total, 1965-1985

share is between 42.4% and 57.5%. The second panel replicates the similar figure using the number of citations attached to those patents in the left panel.



by patents

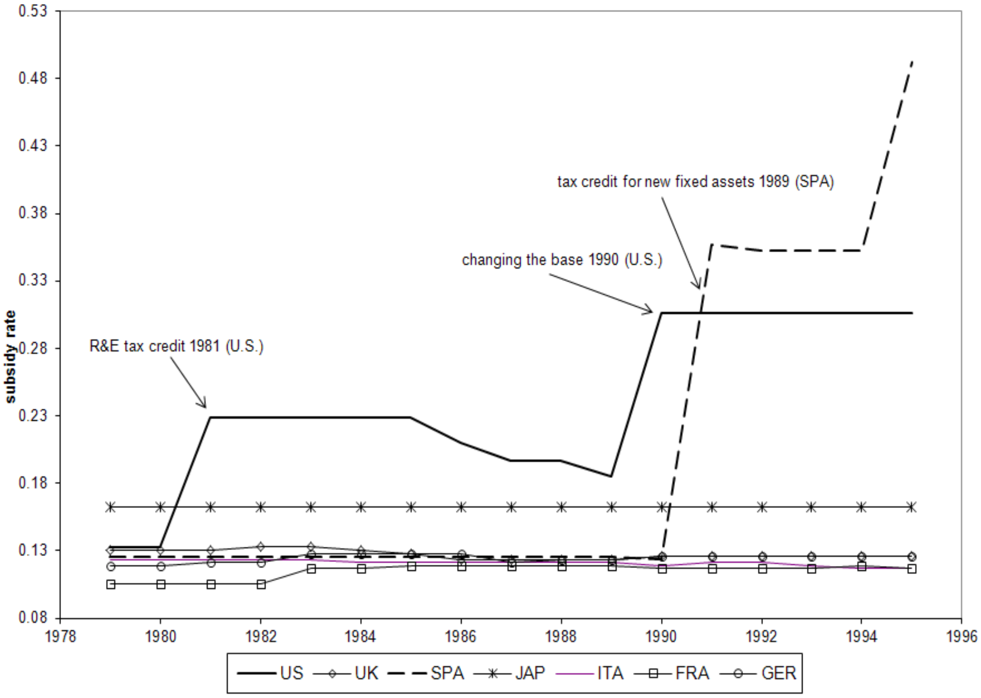
by citations

Figure 2: Proportion of sectors owned by the US and foreigners, resp., 1965-1985

Both panels show the declining trend in the percentage of all sectors where US firms are dominating. This observation demonstrates the relative strengthening of foreign competitors in the technological competition.

Fact 2: R&D Tax Credit during 80s and the Halt of Convergence

Before analyzing how the trends presented above changed after the introduction of R&D tax credits (on both state and federal level), let us give some details about this policy which started with the Federal Research and Experimentation Tax credit established in 1981. Figure (3) shows the R&D subsidy produced by tax policies in the US, Japan and key European countries obtained Bloom, Griffith, and Van Reenen (2002)'s corporate tax data. 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.[4] Following Impullitti (2010) the subsidy rate obtained here from Bloom et al. (2002) is computed to obtain a measure of the subsidy consistent with that in the model.



Source: Bloom, Griffith, Van Reenen (2002) and Impullitti (2010)

Figure 3: R&D tax credits across countries

The variations across countries are mainly due to the presence and effectiveness of a specific tax credit for R&D. The sudden increase in US subsidies, for instance, takes place with the introduction of the R&D 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 13% percent, it jumps to about 23% in 1981 and further increase up

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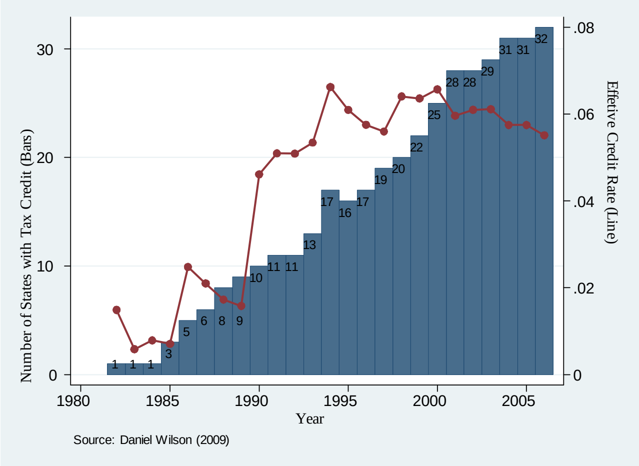
[4] The tax subsidy is the sum of depreciation allowances for R&D investment and of tax credits specifically aimed at reducing the cost of R&D. In all countries in the data there are depreciation allowances for R&D, and in most of the countries R&D costs are fully expensed; that is, depreciation allowances imply a complete write-off of R&D costs for tax purposes. Specific R&D tax credits, instead, are active in only a few countries.

to more than 30% in 1990. In the case of Spain, the other country that show variation, there was an introduction of a tax credit for all new fixed assets in 1989. 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.

Figure (4) shows the evolution of average rate of U.S. State tax credits together with the number of the states that offer a tax credit. We can see that the average effective tax credit at the state level reached a little more than 6% as of 2006, nearly half of the federal one, and the number of states following such a policy rose to 32.



Source: Daniel Wilson (2009)

Figure 4: State level evolution of R&D tax credits

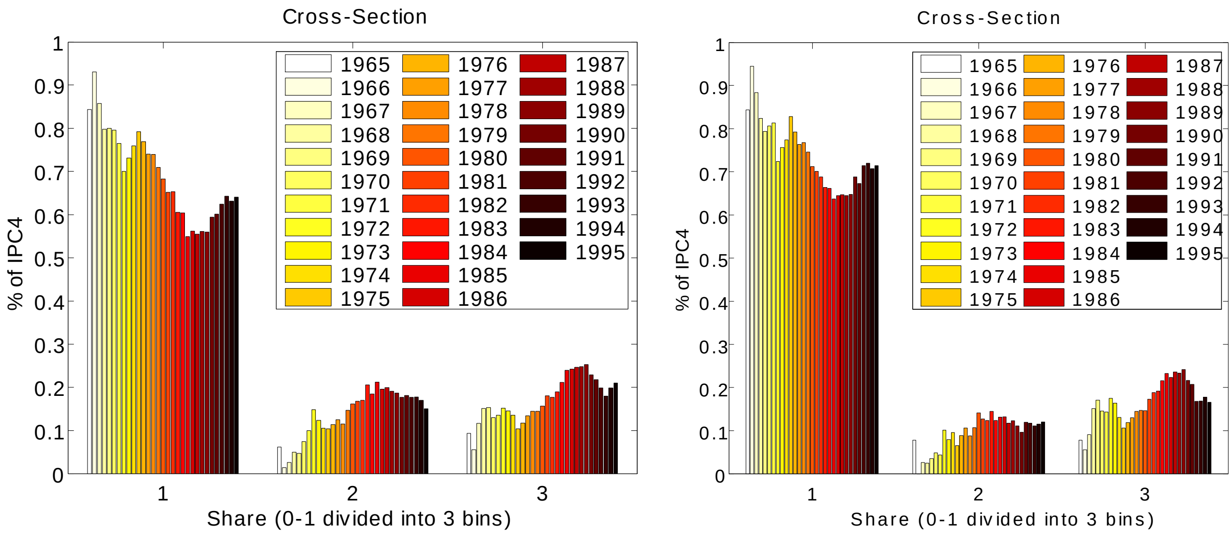
We can return to the evolution of technological leadership. Figures (5) and (6) suggest that the ratio of sectors dominated by the US-owned patents stopped decreasing and started to show a reversal of the trend. The same change can be observed in citation counts.

Figure (6) depicts a related pattern: ratio of patents (and citations) by foreign registrars in total patents registered comes to a halt and starts to decrease. These turns in innovation patterns taking place fairly soon after the introduction of tax credits in the US suggest that there could be a link between these two facts.

Next we attempt to gain some additional descriptive insight about the link the between tax credits and innovative behavior of firms. 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 data. The regression specification is as follows:

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

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



by patents by citations

Figure 5: Proportion of sectors owned by the US and foreigners, resp., 1965-1995

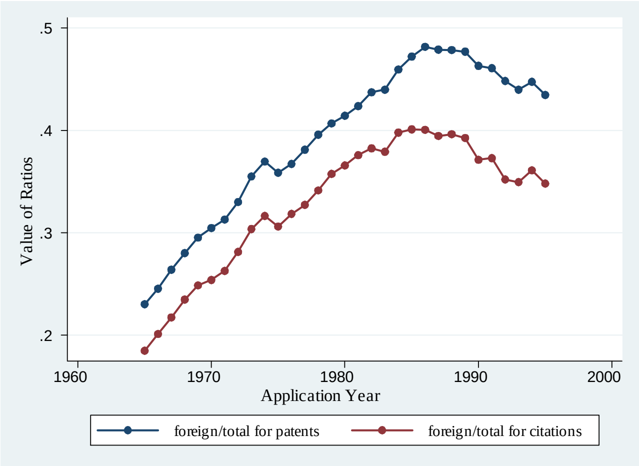


Figure 6: Ratio of patents and associated citations registered in the US by foreigners over the total, 1965-1995

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.[5]

So far we have motivated our analysis using relative measures of innovation output. Looking at figure (6) one might wonder whether the U.S. lost ground because foreign patenting

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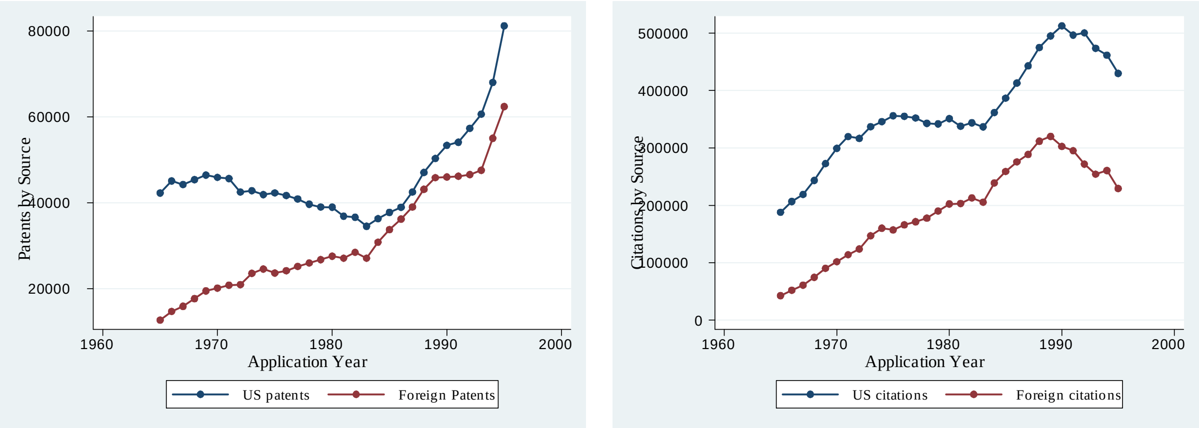
[5] A version of the regression analysis which includes also the federal credits can be found in the appendix.

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 (10.92)***	0.524 (2.12)**	2.948 (10.93)***	1.203 (4.28)***
Year Dummy	Yes	Yes	Yes	Yes
Firm Dummy	Yes	Yes	Yes	Yes

accelerated or because their own patenting declined. Figure (7) addresses this question.



by patents by citations

Figure 7: Evolution of Absolute Volumes in Patents and Citations, US vs. Foreign

As we can see, in the pre-tax-credit period there is a considerable increase in the number of patents of foreign applicants while the US-counterpart did not change sizably. In the aftermath of policy changes, patenting activity in the US starts accelerating so that, although we foreign patenting kept growing we obtain the reversal of the trend in the shares observed above.

4 Model

The model consists of two countries indexed by $c \in \{A, B\}$. 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 firms, one domestic and one foreign, competing in quality for global technology leadership. Firms innovate by investing resources to improve the quality of their product and in equilibrium only the firm producing the top quality of a product will supply it to the world economy. Since innovation success is a random process the global economy features a distribution of firms supplying heterogeneous quality products. There are two channels of interdependency linking the countries: trade in intermediate goods and trade in ideas. The latter 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 enabling 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.

4.1 Preferences

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

$$U\left(t\right) = \int_t^\infty \exp(-\rho\left(\tau - t\right)) \frac{C_c(\tau)^{1-\psi} - 1}{1-\psi}\, d\tau \tag{2}$$

where $C_c(t)$ 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

$$r_c\left(t\right) A_c\left(t\right) + L_c w_c\left(t\right) = p_c\left(t\right) C_c\left(t\right) + \dot{A}_c\left(t\right) \tag{3}$$

where $r_c\left(t\right)$ 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, $w_c\left(t\right)$ is the fixed factor income, $p_c\left(t\right)$ 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 sum of firm values has to be equal to the asset holdings

$$A_c\left(t\right) = \int_0^1 V_{cj}\left(t\right) dj$$

where j indexes the firms (and the product lines; see below). 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 US stock market was held by US 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, 2012).

4.2 Technology and Market Structure

4.2.1 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:

$$Y_c\left(t\right)=\frac{L_c^{\beta}}{1-\beta}\int_0^1\left[\sum_{c\in\{A,B\}}q_{cj}\left(t\right)^{\beta}k_{cj}\left(t\right)^{1-\beta}\right]dj \tag{4}$$

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 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 $(1+\zeta)$ units of that good, $\zeta>0$. Note that both countries 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 country that has 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 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.

4.2.2 Intermediate Goods and Innovation

In each product line j, two incumbent firms, one from each country $c\in\{A,B\}$ (indexed by cj), 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

$$q_{Aj}(t)>q_{Bj}(t)$$

and *the follower* if

$$q_{Aj}(t)<q_{Bj}(t).$$

Firms are in a *neck-and-neck* position when $q_{Aj}(t)=q_{Bj}(t)$. The quality $q_{Aj}(t)$ improves through successive innovations in A or spillovers from B - we will be more precise about this last feature in moment. Each time there is an improvement, the existing quality increases by $\left(\lambda-1\right)q_{Aj}$, i.e.

$$q_{Aj}(t+\Delta t)=\lambda q_{Aj}(t).$$

We assume the following initial condition for qualities, $q_{Aj}(0)=q_{Bj}(0)$. As a result, the state of a firm can be summarized by a single integer m_A such that

$$\text{Technology gap between } A \text{ and } B \text{ in } j=\frac{q_{Aj}(t)}{q_{Bj}(t)}=\frac{\lambda^{n_A(t)}}{\lambda^{n_B(t)}}=\lambda^{m_A(t)},$$

where $n_A(t)$ is the total number of quality improvements that has taken place in country A and $m_A(t) = n_A(t) - n_B(t)$ is the difference between the two countries in terms of those occurrences. Note that $m_A(t) = 0$ when the two firms are neck and neck. To preserve tractability, following Aghion et al (2006) we assume that the maximum technology gap between the countries cannot be more than 1 step due to technology spillovers.[6] Thus

$$m_c(t) \in \{-1, 0, 1\} \text{ for } c\{A, B\}.$$

Firms invest in R&D in order to obtain market leadership through improving the quality of their products. Let z_{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,

$$x_{cj}(t) = \left(\gamma_c \frac{z_{cj}(t)}{\alpha_c q_{cj}(t)}\right)^{\frac{1}{\gamma_c}}, \quad c \in \{A, B\}.$$

Note that q_{cj} 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_{cj}

$$C(x_{cj}, q_j(t)) = q_j(t) \frac{\alpha_c}{\gamma_c} x_{cj}^{\gamma_c}. \tag{5}$$

Note that country indices can be replaced by the technology gap (m) in every sector. Let us denote the innovation arrival rates of the leader, follower and neck-and-neck firm by $x_{1j}(t)$, $x_{-1j}(t)$ and $x_{0j}(t)$, respectively. We adopt similar notation for the quality levels $q_{1j}(t)$, $q_{-1j}(t)$ and $q_{0j}(t)$. Then the law of motion for the firm level qualities can be summarized as

$$q_{1j}(t+\Delta t) = \begin{cases} \lambda q_{1j}(t) & \text{with probability } x_{1j}(t)\Delta t \\ q_{1j}(t) & \text{with probability } 1 - x_{1j}(t)\Delta t \end{cases}$$

$$q_{-1j}(t+\Delta t) = \begin{cases} \lambda q_{-1j}(t) & \text{with probability } x_{-1j}(t)\Delta t + x_{1j}(t)\Delta t \\ q_{-1j}(t) & \text{with probability } 1 - x_{-1j}(t)\Delta t - x_{1j}(t)\Delta t \end{cases}$$

$$q_{0j}(t+\Delta t) = \begin{cases} \lambda q_{0j}(t) & \text{with probability } x_{0j}(t)\Delta t \\ q_{0j}(t) & \text{with probability } 1 - x_{0j}(t)\Delta t \end{cases}$$

Note that when a firm is the leader or neck and neck, then its quality improves only through its own R&D whereas a follower also benefits from the leader's innovation due to spillovers. Here the assumption is that when an innovation arrives the previous leading technology becomes obsolete and freely available to the follower in the product line. Since in this economy the leader and the follower belong to different countries by construction, the *knowledge spillover* implies a technology flow across the countries' boarders.

Outside firms invest in innovative activity to become the new incumbent of their country in a given product line. We assume that entry is *directed* to a particular product line. The result of R&D is stochastic such that it can lead to two types of innovations. Either the entrant replaces the domestic incumbent with a product of the same quality level or it "leapfrogs" the

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[6] Acemoglu and Akcigit (2011), extends the step-by-step model to multiple step gaps but limit the analysis to the steady-state. Focusing one a single step gap improves the numerical tractability of the transitional dynamics, at the cost of oversimplifying the structure of the economy.

incumbent, i.e. it improves the quality level of the product of the domestic incumbent by λ. We denote the probability of "leapfrogging" by ϕ.

For an entrant firm that tries to enter product line j in country c, the cost of generating a Poisson arrival rate $\tilde{x}_{cj}(t)$ of innovation is given by the following linear function:[7]

$$C\left(\tilde{x}_{cj}(t), q_j(t)\right) = \eta_m \tilde{x}_{cj}(t)\, q_{cj}(t). \tag{6}$$

Two remarks are worth at this point. It is natural to think that the cost on entry in a country and industry could depend on both the absolute level of the domestic industry (q_{cj}) and the relative position of the industry in the global scale (m_{cj}). Therefore we introduce two terms in (6) to allow for this flexibility: First, having $q_{cj}(t)$ as in (5), removes an artificial scale effects by ensuring that both returns and costs are scaling over time. Second, we introduce the parameter η_m is specific to state m. Note that the scale parameter depends only on the state, but not on the specific country. Paying this cost, the entrant expect to replace the incumbent at the rate $\tilde{x}_{cj}(t)$ with the expected quality $\left[\phi\lambda q_{cj}(t) + (1-\phi)\, q_{cj}(t)\right]$.

4.3 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 $\{Y_c, C_c, Z_c, K_c\}$ and last, intermediate good prices, quantities, and innovation arrival rate $\{p_j, k_j, x_{cj}\}$ in country c, product line j.*

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

$$g_c = \frac{r_c - \rho}{\psi}.$$

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

$$\begin{aligned} w_c &= \frac{\beta}{1-\beta} L_c^{\beta-1} \int_0^1 q_j^{\beta} k_j^{1-\beta} dj \\ p_j &= L_c^{\beta} q_j^{\beta} k_j^{-\beta}, \forall j \in [0,1]. \end{aligned}$$

where $q_j \equiv \max\left\{q_{cj}, q_{c'j}\right\}$ and k_j 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

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[7] Variables that pertain to entrants are denoted by the same letters as their counterparts for incumbents, with a "~" on top.

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

$$\pi\left(q_j\right)=\max_{k_j\geq 0}\left\{L^{\beta}q_j^{\beta}k_j^{1-\beta}-\eta k_j\right\}\ \forall j\in[0,1].$$

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

$$k_j^*=\left[\frac{1-\beta}{\eta}\right]^{\frac{1}{\beta}}q_j \text{ and } p_j^*=\frac{\eta}{1-\beta}. \tag{7}$$

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 for each intermediate good is

$$\pi^*\left(q_j\right)=\pi q_j,$$

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 $\left(1+\zeta\right)\eta k_{cj}$. 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 assume that the competitors play a stage game: In the first stage, the leader and the follower pays a small fee to participate in the price bidding game. In the second stage, only those firms that paid participate in the pricing bidding game. Clearly, this game ensures that the follower will never pay this entry fee into the price bidding, therefore in the second stage, the market leader will be left alone and will charge a monopoly price no matter how close the competitor is. Hence the quality leader can charge the unconstrained monopoly price both in the domestic and foreign market regardless of the size of the iceberg export cost.[8]

Following similar steps as in the costless case, the optimal quantity regarding exports becomes

$$k_{c'j}^*=\left[\frac{1-\beta}{\left(1+\zeta\right)\eta}\right]^{\frac{1}{\beta}}q_j\Rightarrow\pi^*\left(q_j\right)=\hat{\pi}_m q_j \tag{8}$$

with $\hat{\pi}=\left(\left(1+\zeta\right)\eta\right)^{\frac{\beta-1}{\beta}}\left(1-\beta\right)^{\frac{1-\beta}{\beta}}\beta<\pi$ and $L_{c'}=1$. Here, $c'\neq c$ denotes the foreign country, and we take c as the home country such that $k_{c'j}^*$ is the optimal quantity supplied to the destination c' by the source country c.

Under these equilibrium conditions, total output becomes

$$Y_c=\left[\frac{1-\beta}{\eta}\right]^{\frac{1-\beta}{\beta}}\frac{Q_{1c}+Q_{0c}}{1-\beta}+\left[\frac{1-\beta}{\left(1+\zeta\right)\eta}\right]^{\frac{1-\beta}{\beta}}\frac{Q_{1c'}}{1-\beta}, \tag{9}$$

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[8] For a similar use of this simplifying assumption, see Acemoglu, Gancia, Zilibotti (2012).

where Q_{mc} denotes the average quality index of sectors in state m and country c:

$$Q_{mc} \equiv \int_{j \in \Gamma_{mc}} q_j dj,$$

with Γ_{mc} being the measure of such product lines. Finally the fixed factor price is

$$w_c = \beta Y_c. \tag{10}$$

Below, the asterisk indicates an equilibrium value.

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

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

such that (i) the sequence of prices and quantities p_j^*, k_j^* *satisfy (7)-(8) and maximize the operating profits of the incumbent firm in the intermediate good product line* j*; (ii) the R&D decisions* $\left\{x_{cj}^*, \tilde{x}_{cj}^*\right\}$ *maximizes the expected profits of firms taking wages* w_c^**, aggregate output* Y_c^**, the R&D decisions of other firms* $\left\{x_{c'j}^*, \tilde{x}_{c'j}^*\right\}$ *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 (9), and (v) wages* w_c^* *and interest rates* r^* *clear the labor and asset markets at every* t*.*

4.4 Value Functions

We start this section with the problem of the entrant firms that are relatively straightforward. Remember that entry is directed at particular product lines. Let the incumbent firm's quality be $q_j = q$. Then, the optimization problems of the entrants are as follows:[9]

$$\begin{aligned}
&\max_{\tilde{x}_{-1A}} \left\{-q\tilde{x}_{-1A}\eta_{-1} + \tilde{x}_{-1A}\left[\phi V_{0c}(\lambda q) + (1-\phi) V_{-1c}(q)\right]\right\} \\
&\max_{\tilde{x}_{0A}} \left\{-q\tilde{x}_{0A}\eta_{0} + \tilde{x}_{0A}\left[\phi V_{1c}(\lambda q) + (1-\phi) V_{0c}(q)\right]\right\} \\
&\max_{\tilde{x}_{1c}} \left\{-q\tilde{x}_{1A}\eta_{1} + \tilde{x}_{1A}\left[\phi V_{1c}(\lambda q) + (1-\phi) V_{1c}(q)\right]\right\}
\end{aligned}$$

in sectors in which the domestic incumbent is a leader, neck&neck or a follower respectively. In each maximization, the first term reflects the cost of R&D, and the second term is the expected return. Notice that in case of leapfrogging, which happens with probability $\phi > 0$, the entrant receives the value of a product with quality λq, thus embedding a quality improvement.

Now, we can turn to the value functions for the leader, neck-and-neck and laggard firms, which are denoted by the subscripts $1, 0, -1$, respectively. For expositional concerns, we will abstract from the inclusion of R&D tax credits for now. To begin with, the value function of the leader in j that has a quality $q_j = q$ is expressed as follows:

$$\begin{aligned}
r_A V_{1A}(q) - \dot{V}_{1A}(q) = &(\pi + \hat{\pi}) q - \alpha_A \frac{(x_{1A})^{\gamma_A}}{\gamma_A} q + x_{1A}\left[V_{1A}(\lambda q) - V_{1A}(q)\right] \\
&+ \tilde{x}_{1A}\left[0 - V_{1A}(q)\right] + \left(x_{-1B} + \phi\tilde{x}_{-1B}\right)\left[V_{0A}(q) - V_{1A}(q)\right].
\end{aligned}$$

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[9] All these value functions are written for the firms which produce in country A. The counterparts for the ones in country B is found just by switching the country subscripts.

This value function is very intuitive. There is a discounting at the rate r_A. The first term on the right is the profit collected at every instant by the leader (note that it sells to final good producers in both countries). It earns πq on domestic sales and $\hat{\pi} q$ on exported goods where we again made use of $L = 1$. The second term is the R&D cost by the leader. As a result, the leader innovates at the rate x_{1A} which generates a change in firm value of $V_{1A}(\lambda q) - V_{1A}(q)$. The terms on the second line reflect the different sources of competition faced by the leader. First, a domestic entrant can replace it, in which case the leader goes out of business. Second, the international competition can drive the leader into neck&neck position in two ways. Either the follower firm in country B innovates at the rate x_{-1B} or an entrant in country B enters the line by leapfrogging the foreign incumbent. Remember that since the quality gap is assumed to be at most 1, leapfrogging the domestic follower would imply that the entrant in country B starts business with the same quality as the leader of the line which is located in country A. This would drive the leader again into neck&neck position.

Similarly the value function for the follower firm in A is equal to

$$\begin{aligned} r_A V_{-1A}(q) - \dot{V}_{-1A}(q) = & - \alpha_A \frac{(x_{-1A})^{\gamma_A}}{\gamma_A} q + x_{-1A}\left[V_{0A}(\lambda q) - V_{-1A}(q)\right] \\ & + \tilde{x}_{-1A}\left[0 - V_{-1A}(q)\right] + (x_{1B} + \phi \tilde{x}_{1B})\left[V_{-1A}(\lambda q) - V_{-1A}(q)\right]. \end{aligned}$$

This value function has similar interpretation as before. However two additional points are worth emphasizing. First, the follower firm makes zero profit due to Bertrand competition. Second, when the leader firm innovates in country B, or when an entrant in country B leapfrogs their own domestic firm, the quality of the follower in country A also increases from q to λq due to spillovers.

Finally the value function for the neck and neck firms can be expressed as

$$\begin{aligned} r_A V_{0A}(q) - \dot{V}_{0A}(q) = & \pi q - \alpha_A \frac{(x_{0A})^{\gamma_A}}{\gamma_A} q + x_{0A}\left[V_{1A}(\lambda q) - V_{0A}(q)\right] \\ & + \tilde{x}_{0A}\left[0 - V_{0A}(q)\right] + (x_{0B} + \phi \tilde{x}_{0B})\left[V_{-1A}(q) - V_{0A}(q)\right]. \end{aligned}$$

Note that in the neck&neck situation, firms only serve the domestic market because final good producers optimally choose not to import and pay a higher price for the foreign good of the same quality.

Lemma 1 *The value functions are linear in quality such that* $V_{mA}(q) = q v_{mA}$ *and* $\dot{V}_{mc} = \partial V_{mc}/\partial t = 0$ *for* $m \in \{-1, 0, 1\}$ *where*

$$r v_{1A} = \max_{x_{1A}} \left\{ \begin{array}{c} (\pi + \hat{\pi}) - \alpha_A \frac{(x_{1A})^{\gamma_A}}{\gamma_A} + x_{1A} v_{1A}(\lambda - 1) \\ -\tilde{x}_{1A} v_{1A} + (x_{-1B} + \phi \tilde{x}_{-1B})\left[v_{0A} - v_{1A}\right] \end{array} \right\}, \tag{11}$$

$$r v_{0A} = \max_{x_{0A}} \left\{ \begin{array}{c} L_A \pi - \alpha_A \frac{(x_{0A})^{\gamma_A}}{\gamma_A} + x_{0A}\left[\lambda v_{1A} - v_{0A}\right] \\ -\tilde{x}_{0A} V_{0A}(q) + (x_{0B} + \phi \tilde{x}_{0B})\left[v_{-1A} - v_{0A}\right] \end{array} \right\}, \tag{12}$$

$$r v_{-1A} = \max_{x_{-1A}} \left\{ \begin{array}{c} -\alpha_A \frac{(x_{-1A})^{\gamma_A}}{\gamma_A} + x_{-1A}\left[\lambda v_{0A} - v_{-1A}\right] \\ -\tilde{x}_{-1A} v_{-1A} + (x_{1B} + \phi \tilde{x}_{1B}) v_{-1A}(\lambda - 1) \end{array} \right\}. \tag{13}$$

Proof. See the appendix.

■

Lemma (1) has the implication that the quality level q drops out of the value functions. This, in turn, indicates that the values of incumbent firms do not change over time. Embedding this lemma into the entrant problems we have the following optimality conditions due to the linear structure:

$$\begin{gathered}
\left[\phi \lambda v_{1c} + (1-\phi)\, v_{1c}\right] = \eta_1 \\
\left[\phi \lambda v_{1c} + (1-\phi)\, v_{0c}\right] = \eta_0 \\
\left[\phi \lambda v_{0c} + (1-\phi)\, v_{-1c}\right] = \eta_{-1}
\end{gathered}$$

given that there is positive entry. These conditions uniquely determine the values of the incumbents.

Another implication of Lemma 1 is that the optimal R&D levels are independent of q and constant. Thus, the optimal R&D levels are as follows:

$$x_{-1A} = \left(\frac{\lambda v_{0A} - v_{-1A}}{\gamma_A \alpha_A}\right)^{\frac{1}{\gamma_A - 1}}, \quad x_{0A} = \left(\frac{\lambda v_{1A} - v_{0A}}{\gamma_A \alpha_A}\right)^{\frac{1}{\gamma_A - 1}} \text{ and } x_{1A} = \left(\frac{(\lambda - 1)\, v_{1A}}{\gamma_A \alpha_A}\right)^{\frac{1}{\gamma_A - 1}}. \tag{14}$$

Having the incumbent innovation intensities we can back up the entrant intesities using the incumbent value functions. As a result we obtain

$$\begin{aligned}
\tilde{x}_{1A}(t) = {} & \frac{(\pi + \hat{\pi})}{v_{1A}} + \frac{\gamma_A - 1}{\gamma_A} \left(\frac{1}{\alpha_A (1 - \tau^A)}\right)^{\frac{1}{\gamma_A - 1}} \frac{\left[v_{1A} (\lambda - 1)\right]^{\frac{\gamma_A}{\gamma_A - 1}}}{v_{1A}} \\
& - \frac{\left[x_{-1B} + \phi \tilde{x}_{-1B}(t)\right] (v_{1A} - v_{0A})}{v_{1A}} - r_A(t)
\end{aligned} \tag{15}$$

$$\tilde{x}_{0A}(t) = \frac{\pi}{v_{0A}} + \frac{\gamma_A - 1}{\gamma_A} \left(\frac{1}{\alpha_A (1 - \tau^A)}\right)^{\frac{1}{\gamma_A - 1}} \frac{\left[(\lambda v_{1A} - v_{0A})\right]^{\frac{\gamma_A}{\gamma_A - 1}}}{v_{0A}} - \frac{\left[x_{0B} + \phi \tilde{x}_{0B}(t)\right] (v_{0A} - v_{-1A})}{v_{0A}} - r_A(t) \tag{16}$$

$$\tilde{x}_{-1A}(t) = \frac{\gamma_A - 1}{\gamma_A} \left(\frac{1}{\alpha_A (1 - \tau^A)}\right)^{\frac{1}{\gamma_A - 1}} \frac{\left[\lambda v_{0A} - v_{-1A}\right]^{\frac{\gamma_A}{\gamma_A - 1}}}{v_{-1A}} + \left[x_{1B} + \phi \tilde{x}_{1B}(t)\right] (\lambda - 1) - r_A(t). \tag{17}$$

Notice that since interest rates fluctuate along the transition path the entrant innovation intensities move over time as opposed to their incumbent counterparts.

4.5 Transitional Dynamics

The decisions of firms will affect the leadership of a country in product lines. Let μ_{mc} denote the share of product lines in which the state of country c is $m \in \{-1, 0, 1\}$ such that

$$\mu_{-1c} + \mu_{0c} + \mu_{1c} = 1. \tag{18}$$

For instance, μ_{1A} measures the portion of the intermediate product lines where the firms of country A are leaders. The low of motions for these values are:

$$\begin{aligned}
\dot{\mu}_{1A} &= \dot{\mu}_{-1B} = \mu_{0A} \left(x_{0A} + \phi \tilde{x}_{0A}\right) - \mu_{1A} \left(x_{-1B} + \phi \tilde{x}_{-1B}\right) \\
\dot{\mu}_{0A} &= \dot{\mu}_{0B} = \begin{array}{l} \mu_{-1A} \left(x_{-1A} + \tilde{x}_{-1A} \phi\right) + \mu_{1A} \left(x_{-1B} + \tilde{x}_{-1B} \phi\right) \\ - \mu_{0A} \left[x_{0A} + x_{0B} + \tilde{x}_{0A} \phi + \tilde{x}_{0B} \phi\right] \end{array}
\end{aligned} \tag{19}$$

Note that it is sufficient to express the low of motion for μ_{1A} and μ_{0A} because of (18). These flow equations have very simple intuitions. Country A will gain more leadership when its neck&neck firms in μ_{0A} of the product lines innovate at the rate x_{0A}, or when entrants in neck&neck product lines start business by leapfrogging. Similarly, country A will loose leadership when the follower firms in μ_{1A} product lines innovate at the rate x_{-1B}, or when entrants from the other country enter by leapfrogging with $\tilde{x}_{-1B}$. In the second line, country A will become neck&neck with country B in μ_{-1A} product lines when the followers in country A are successful or when the successful entrants leapfrog. Country A is pulled to neck&neck position in μ_{1A} product lines if the followers in country B are successful or if the foreign entrants improve on the incumbent quality. On the other hand, country A will loose its neck&neck product lines if the neck&neck firm in A or B is successful, or if the entrants into these product lines enter by leapfrogging. We compute the transition path by summarizing these equations in the form of a multivariate ordinary differential equation whose details we provide in the Appendix.

4.6 Aggregate Variables

In this section, we characterize the evolution of consumption of households in country c. We use the budget constraint of the representative household in country c to pin down its consumption level

$$C_c = r_c A_c + w_c - \dot{A}_c. \tag{20}$$

Determining consumption requires the determination of A and $\dot{A}$. We turn to the asset market clearing condition to determine these values

$$A_c = \int_0^1 V_{cj} dj = v_{1c} Q_{1c} + v_{0c} Q_{0c} + v_{-1c} Q_{-1c} \tag{21}$$

and

$$\dot{A}_c = v_{1c} \dot{Q}_{1c} + v_{0c} \dot{Q}_{0c} + v_{-1c} \dot{Q}_{-1c}. \tag{22}$$

Thus, using (20), (10), (21) and (22) we find the consumption in country c as

$$C_c = \left\{ \begin{array}{c} r_c \left[v_{1c} Q_{1c} + v_{0c} Q_{0c} + v_{-1c} Q_{-1c} \right] \\ +\beta \left\{ \left[\frac{1-\beta}{\eta} \right]^{\frac{1-\beta}{\beta}} \frac{Q_{1c}+Q_{0c}}{1-\beta} + \left[\frac{1-\beta}{(1+\zeta)\eta} \right]^{\frac{1-\beta}{\beta}} \frac{Q_{1c'}}{1-\beta} \right\} \\ - \left[v_{1c} \dot{Q}_{1c} + v_{0c} \dot{Q}_{0c} + v_{-1c} \dot{Q}_{-1c} \right] \end{array} \right\}, \tag{23}$$

the total income as

$$I_c = \left\{ \begin{array}{c} \left[\left((\pi + \hat{\pi}) - \alpha_c x_{1c}^{\gamma_c} \right) Q_{1c} - \left(L_c \pi - \alpha_c x_{0c}^{\gamma_c} \right) Q_{0c} - \alpha_c x_{-1c}^{\gamma_c} Q_{-1c} \right] \\ - \left[\eta_1 \tilde{x}_{1c} Q_{1c} + \eta_0 \tilde{x}_{10c} Q_{0c} + \eta_{-1} \tilde{x}_{-1c} Q_{-1c} \right] + w_c \end{array} \right\}, \tag{24}$$

and the total R&D expenditure as

$$RnD_c = \left\{ \begin{array}{c} \left[\alpha_c x_{1c}^{\gamma_c} Q_{1c} + \alpha_c x_{0c}^{\gamma_c} Q_{0c} + \alpha_c x_{-1c}^{\gamma_c} Q_{-1c} \right] + \\ \left[\eta_1 \tilde{x}_{1c} Q_{1c} + \eta_0 \tilde{x}_{10c} Q_{0c} + \eta_{-1} \tilde{x}_{-1c} Q_{-1c} \right] \end{array} \right\}. \tag{25}$$

Finally, consider the evolution of average quality levels. Without loss of generality, we have for country A

$$\dot{Q}_{1A} = \left[x_{1A}(\lambda-1) + \tilde{x}_{1A}\phi(\lambda-1) - \tilde{x}_{-1B}\phi - x_{-1B}\right] Q_{1A} + \left(x_{0A} + \tilde{x}_{0A}\phi\right)\lambda Q_{0A} \tag{26}$$

$$\dot{Q}_{0A} = \left(x_{-1B} + \tilde{x}_{-1B}\phi\right) Q_{1A} + \left(x_{-1A} + \tilde{x}_{-1A}\phi\right)\lambda Q_{-1A} - \left[x_{0A} + x_{0B} + \tilde{x}_{0A}\phi + \tilde{x}_{0B}\phi\right] Q_{0A} \tag{27}$$

$$\dot{Q}_{-1A} = \left[x_{1B}(\lambda-1) + \tilde{x}_{1B}\phi(\lambda-1) - \tilde{x}_{-1A}\phi - x_{-1A}\right] Q_{-1A} + \left(x_{0B} + \tilde{x}_{0B}\phi\right) Q_{0A}. \tag{28}$$

Proposition 1 *Let* $Q \equiv Q_{1c} + Q_{0c} + \lambda Q_{-1c}$ *denote the average quality across all intermediate products. The common growth rate of production for the two economies is* $g = \dot{Q}/Q$*, which in steady state becomes*

$$g^* = (\lambda-1)\left[\mu^*_{1A}\left(x^*_{1A} + \phi\tilde{x}^*_{1A}\right) + \mu^*_{-1A}\left(x^*_{1B} + \phi\tilde{x}^*_{1B}\right) + \mu^*_{0A}\left[\begin{array}{c} x^*_{0A} + x^*_{0B} + \\ \phi\left(\tilde{x}^*_{0A} + \tilde{x}^*_{0B}\right) \end{array}\right]\right]$$

or more precisely

$$g^* = \frac{\dot{Q}}{Q} = (\lambda-1)\frac{Q_{1A}\left(x^*_{1A} + \phi\tilde{x}^*_{1A}\right) + \lambda Q_{-1A}\left(x^*_{1B} + \phi\tilde{x}^*_{1B}\right) + Q_{0A}\left[\begin{array}{c} x^*_{0A} + x^*_{0B} + \\ \phi\left(\tilde{x}^*_{0A} + \tilde{x}^*_{0B}\right) \end{array}\right]}{Q_{1A} + Q_{0A} + \lambda Q_{-1A}}.$$

Proof. See appendix (straightforward from Acemoglu-Akcigit, 2012). ■

4.7 R&D Subsidy Policies

In this section, we describe the effect of R&D subsidies on both countries.[10] We assume that country c provides a subsidy of τ_c on firm's R&D spending. It finances this amount through the lump sum tax imposed on household. Then the value functions in (11) – (13) are modified as

$$r_A v_{1A} = \max_{x_{1A}}\left\{\begin{array}{c} (\pi + \hat{\pi}) - (1-\tau_A)\,\alpha_A\frac{(x_{1A})^{\gamma_A}}{\gamma_A} + x_{1A}v_{1A}(\lambda-1) \\ -\tilde{x}_{1A}v_{1A} + \left(x_{-1B} + \phi\tilde{x}_{-1B}\right)\left[v_{0A} - v_{1A}\right] \end{array}\right\},$$

$$r_A v_{0A} = \max_{x_{0A}}\left\{\begin{array}{c} \pi - (1-\tau_A)\,\alpha_A\frac{(x_{0A})^{\gamma_A}}{\gamma_A} + x_{0A}\left[\lambda v_{1A} - v_{0A}\right] \\ -\tilde{x}_{0A}V_{0A}(q) + \left(x_{0B} + \phi\tilde{x}_{0B}\right)\left[v_{-1A} - v_{0A}\right] \end{array}\right\},$$

$$r_A v_{-1A} = \max_{x_{-1A}}\left\{\begin{array}{c} -(1-\tau_A)\,\alpha_A\frac{(x_{-1A})^{\gamma_A}}{\gamma_A} + x_{-1A}\left[\lambda v_{0A} - v_{-1A}\right] \\ -\tilde{x}_{-1A}v_{-1A} + \left(x_{1B} + \phi\tilde{x}_{1B}\right)v_{-1A}(\lambda-1) \end{array}\right\}.$$

The resulting budget balance of the government implies

$$T_A = \tau_A\left\{\alpha_A\left[x^{\gamma_A}_{1A}Q_{1A} + x^{\gamma_A}_{0A}Q_{0A} + x^{\gamma_A}_{-1A}Q_{-1A}\right]\right\}$$

and the household budget in that case is expressed as

$$r_c A_c + w_c - T_A = C_c + \dot{A}_c.$$

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[10] When solving and simulating our model we use R&D subsidy rates, a measure which captures the changes in R&D tax credits but enters the value functions conveniently. The details about their calculation is provided in section 5.

Therefore the new consumption level is expressed as

$$C_c = \left\{ \begin{array}{c} -T_A + w_c \\ r_c \left[v_{1c} Q_{1c} + v_{0c} Q_{0c} + v_{-1c} Q_{-1c} \right] \\ - \left[v_{1c} \dot{Q}_{1c} + v_{0c} \dot{Q}_{0c} + v_{-1c} \dot{Q}_{-1c} \right] \end{array} \right\}. \tag{29}$$

The government subsidies will now affect consumption and welfare in several directions. There is a negative effect of R&D subsidies on consumption which comes from the fact that R&D subsidies have to be financed through taxation which in turn lowers the current consumption as it is indicated in the first line of (29). However, R&D subsidies generate two positive gains through innovation dynamics: First, an increase in the subsidy rates encourages more innovation and hence increases the speed of quality improvements. Second, and somewhat more interestingly, it also generates a compositional gain since county A starts to have more leadership in the world after the subsidy. In the following section, we will analyze these effects quantitatively.

5 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 US R&D policies. Our task is to build a mapping between the model and the data. For this purpose, we consider a world that consists of the US and a weighted combination of the following 7 countries: Canada, France, Germany, Italy, Japan, Spain and UK.[11] The computed weights are listed in Table 2

To weight the data for these countries we use the patents registries by these countries in the US in 1975. The weight of a particular country corresponds to the share of patents, whose owner belongs to this country, in the total foreign-based patent registries in the US. In the following analysis, country A will represent the US and country B the foreign country.[12]

Table 2. Country Weights

	1975	1985
Canada	.062	.046
France	.117	.085
Germany	.300	.238
Italy	.038	.036
Japan	.331	.508
Spain	.006	.004
UK	.146	.082

As Figures 3 and 4 have shown, there is a significant break in the R&D policy before and after 1985. Therefore we calibrate the model to a set of moments which we obtain from the data that spans over 1975-1985 and derive the counterfactual for the laissez-faire economy.

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[11] These are the most innovation intensive countries that compete with the US.

[12] In the figures that compare the two countries in section ??, the former is presented by a blue line whereas the latter by a red one. The legend uses FN for the competitors, if applicable.

Then we will impose the changes in R&D policy observed in the data and test the model's explanatory power using the data from post-1985 period (1985-1995).

In what follows, we will consider two symmetric large open economies that differ only in terms of their initial conditions in their qualities and the imposed R&D policies. In other words, parameters that characterize the household and firm problems share the same values. We follow this strategy to focus solely on the effect of policy differences abstracting from additional heterogeneity.

Our model has 21 structural parameters

$$\theta \equiv \left\{\alpha, \rho, \beta, \lambda, \zeta, \phi, \eta_{-1}, \eta_0, \eta_1, \psi, \gamma, \bar{q}_{-1A}, \bar{q}_{0A}, \bar{q}_{1A}, \bar{q}_{-1B}, \bar{q}_{0B}, \bar{q}_{1B}, \tau_{75}^{A}, \tau_{75}^{B}, \tau_{86}^{A}, \tau_{86}^{B}\right\}.$$

Some of these parameters are calibrated externally and the remaining are calibrated internally. We describe them next. We start with parameters calibrated externally. Table (**??**) summarizes these estimates.

For the CES parameter of the utility function, we take the standard macro value $\psi = 2$. Likewise we assume the incumbent R&D cost function to have a quadratic shape such that $\gamma = 2$, which is the common estimate in the empirical R&D literature (see Acemoglu et al 2013 for more details). We normalize the initial quality levels in the US to 1, i.e., $\bar{q}_{mA} = 1$ for $m \in \{-1, 0, 1\}$.

Table 3. Externally Calibrated Parameters

ψ	γ	$\bar{q}_{-1A}$	$\bar{q}_{0A}$	$\bar{q}_{1A}$	$\bar{q}_{-1B}$	$\bar{q}_{0B}$	$\bar{q}_{1B}$	τ_{75}^{A}	τ_{75}^{B}	τ_{86}^{A}	τ_{86}^{B}
2	2	1	1	1	$\bar{q}_{1A}/\lambda$	$\bar{q}_{0A}$	$\lambda\bar{q}_{-1A}$	17.6%	14.0%	26.3%	14.7%

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 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 1975-1985 averages which is again weighted for the foreign countries. When we simulate the model for the next ten years, we will recalculate the subsidy rates to match the averages across 1986-1995. Doing these, we also recalculate the weights of foreign countries the same way but using 1986 patent counts and the weights are shown in Table **??**.

5.1 Internal Calibration

We have 9 parameters remaining and we use 9 moments to calibrate them. We now describe the moments that we target.

Moments. The first two moments are coming from the patent data and reflect the pattern observed in Figure (5). They represent values in 1985 of the share of sectors dominated by the US and the share of the sectors where the two countries are in a neck-and-neck position. The relative positions are computed in terms of patent counts just in line with the procedure explained in Section 3. These moments provide the targets which the differential equations that govern the share of sectors with US firms in various positions should reach in 10 periods after 1975.[13]

The next two moments are the average growth rates of the real GDP per capita in both countries. In our model, these correspond to the income growth rates of the countries. We obtain the data for real GDP per capita from World Bank database. The get the numbers for the other two moments, R&D intensities, we utilized 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 averages across 1981-1985.[14]

The next target, profit share of US GDP comes from NIPA tables and is an average over 1975-1985. This moment pins down the fixed factor share in the model. In order to discipline the entry margin we use the share of productivity growth that pertains to entrant firms. We obtain this estimate from Foster, Krizan & Haltiwanger (2001). The model counterpart of this moment we calculate setting the innovation intensities of the US entrants to zero. Then we compute the average loss in growth with respect to the benchmark economy. At last, the average volume of trade over 1975-1985 help us calibrate the iceberg cost.

Algorithm and model fit. We assume that our economy start in 1975. The moments that we match are summarized in Table 4. Starting from the steady we obtain the transition values over this period as follows:

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}.

    (a) Using the entrants' optimality conditions, obtain incumbent firm values and innovation intensities using only the parameters.

    (b) Solve for the steady state where the interest rates and thus the entrant innovation intensities do not move over time. We suppose that the economy reaches this state in $T = 100$ years after 1975.

    (c) Guess a time path of interest rates $\left\{r_t^A, r_t^B\right\}_{t=1975}^{1975+T}$. Calculate the entrant innovation intensities. Check if they all have positive values in line with the assumed equality in entrant optimality conditions.

    (d) Compute the aggregate variables and the growth rates $\left\{g_t^A, g_t^B\right\}_{t=1975}^{1975+T}$.

    (e) Check if the equality of Euler equation is supported by the $\left\{r_t^A, r_t^B\right\}_{t=1975}^{1975+T}$ and $\left\{g_t^A, g_t^B\right\}_{t=1975}^{1975+T}$. Update and iterate on $\left\{r_t^A, r_t^B\right\}_{t=1975}^{1975+T}$ until the equality holds at every point in time. Denote the converged path by $\left\{\bar{r}_t^A, \bar{r}_t^B\right\}_{t=1975}^{1975+T}$.

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[13] The corresponding values in 1975 of the these moments we use as the initial conditions to pin down the constant terms of the same differential equations. We do not present them because the constant terms of the differential equations are not fundamental parameters of interest.

[14] Another very minor point is that the data is missing for UK in 1982 and 1984. These are generated by linear interpolation using the numbers of the previous and next years.

3. Using $\{\bar{r}_t^A, \bar{r}_t^B\}_{t=1975}^{1975+T}$ compute the aggregate variables and the model counterparts of the data moments.
4. Minimize $\mathbf{R}\left(\mathbb{M} - \mathbb{M}^m\left(\theta_{guess}\right)\right)$ using an optimization routine.

The results are summarized in Table 4 and Figure 8.

Table 4. Model Fit

Target	Data	Moment	% of Match
Share of sectors w/ US Leadership '85	55%	50.9%	92%
Share of neck-and-neck sectors '85	21%	17.5%	84%
Growth of the US GDP	2.16%	2.06%	95%
Growth of the foreign GDP	2.35%	2.58%	110%
R&D/GDP in the US	1.86%	1.61%	86%
R&D/GDP in foreign countries	2.06%	2.09%	101%
Profit/GDP in US	10%	12.27%	123%
Growth coming from new entry in the US	25%	27.5%	110%
(Exports+Imports)/GDP in the US	17.35%	9.30%	54%

The model captures the evolution of share of sectors in which US has the leadership or is in a neck-and-neck situation in terms of the relative patent counts pretty well. Figure (8) shows the data patterns in bars and the simulated transitional dynamics of the leadership shares for ten years starting in 1985, represented by the line. The performance in output growth rate and R&D intensities is also striking. The share of growth rate due to entrant firms is another successful part whereas there is some overshooting in profit share of income. Lastly, the understatement of trade volume is the weaker aspect when compared to other results.

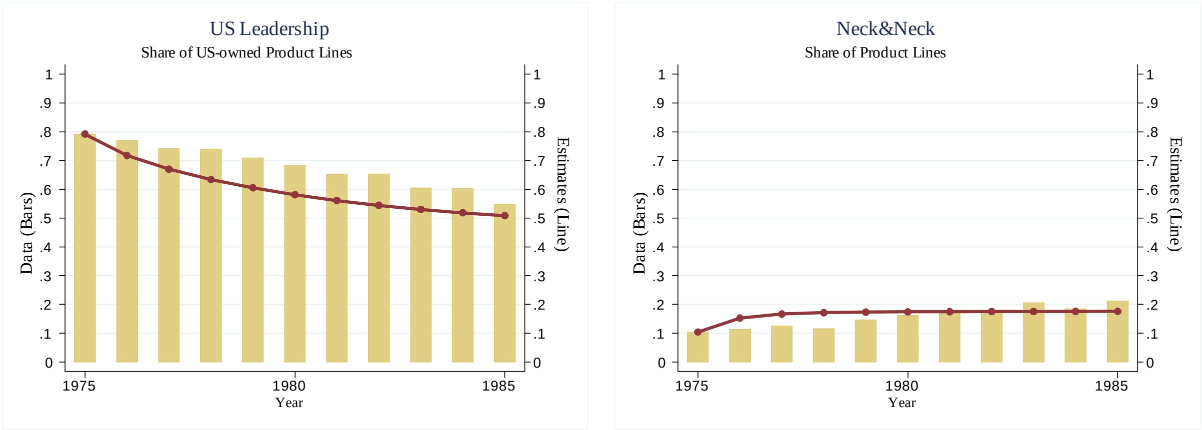

Figure 8: Calibration Results, Shares of US-owned and Neck&Neck Product Lines

The internally calibrated parameters resulting from this procedure are listed in Table (5)

Table 5. Internally Calibrated Parameters

α	ρ	β	λ	ζ	ϕ	η_{-1}	η_0	η_1
9.80	0.02	0.897	1.039	0.046	0.65	3.41	5.78	6.76

6 Counterfactual Constant-policy Economy

Figure (9) left panel shows the resulting behavior of profits and the right panel shows the consumption levels of each country. For the 1975-1985 period, the relevant parts of the graphs are to the left of the dotted black line. Consistent with the evolution of the shares, profits generated by each countries' leading firms show a clear converge trend. This is due to the *profit shifting* effect, whereby foreign firms capture leadership in more markets and formerly collected profits by the US firms are now collected by the foreign firms.

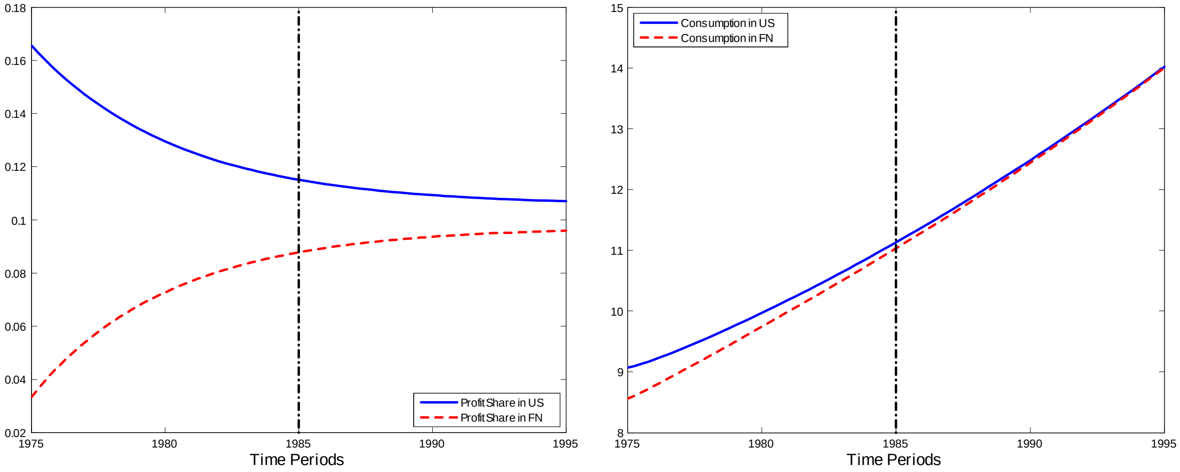

Figure 9: Profits and Consumption

Indeed, in the absence of any policy change, the model predicts full convergence in 30 years. Figure (10), which depicts the evolution of sectors where the US maintains its leadership, describes this shift.

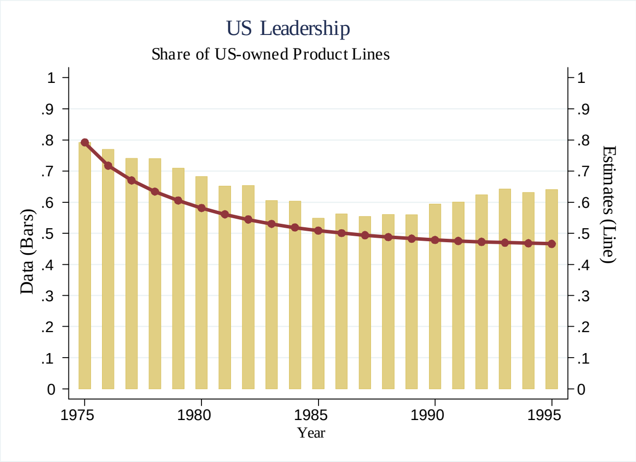

Figure 10: Fraction of Sectors with US leadership

Note, however, that the consumption levels in both countries are increasing over time. The reason for the increasing consumption pattern is due to three reasons: First, there is domestic innovation in both countries, which implies that even in a closed economy, domestic firms would have improved technology and hence consumption would have increased. Second, trade and openness allows consumers access higher quality product at any point in time. Therefore the amount of quality improvements that a consumer faces is the amount of innovation at the global level, not only the domestic innovation. Finally, international technology spillovers make the follower firm in the foreign country keep up with the world frontier and not fall too much behind (even though they don't produce). This avoids wasteful R&D duplication because without the technology spillovers, the firms in the follower country would have had to recover all the technology gaps, whereas in the current setup, the firms in the follower country can catch up with the leader after one innovation.

In short, the consumption per capita in the foreign country catches up with the one in the US while they both continue to increase, as can be seen in Figure (9). Both graphs extend 10 more years to the right of the black line as if there was no changes in R&D tax credit policies in any of the relevant countries.

6.1 R&D Policy

Now we introduce the observed post-85 R&D policies. Before checking the predictions of the model in terms of consumption for the period following the changes in the R&D tax credit policies we want to assess how well this model captures the changing patterns in the international technology leadership. Figure (11) illustrates the success of the model. In this figure, the dotted-green line is the evolution of the market leadership under the unchanged pre-85 policies whereas the solid red line indicates the behavior of the economy with the actual policy changes after 1985. The model is able to reproduce the slowdown in the catching-up process and part of the U.S. comeback in the international technology race.

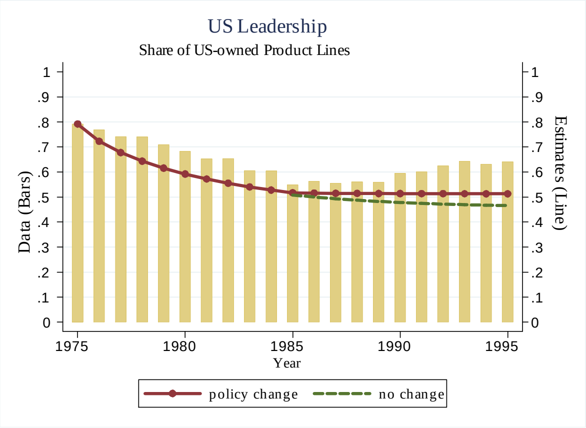

Figure 11: Leadership and Neck&Neck Positions for US, 1975-95

We can compute the exact portion of the US come back explained by the model as follows. In the data the share of US leadership goes from about 53% in 1985 to 64% in 1995. Hence we compute the 1995 share predicted by the model in the absence of policy μ_{1995}^{o}, and the one with policy μ^b_{1995}. Comparing these two different results with the data, we obtain

$$\left(\mu^b_{1995} - \mu^o_{1995}\right) / \left(0.64 - \mu^o_{1995}\right) = 0.24$$

suggesting that the observed innovation policy explains about 24% of the reversal in leadership shares.

The US comeback in international technology competition can be also seen in the dynamics of profit and national consumption. The drop in the share of profits stops, as shown as Figure (12). A comparison of the path after period 10 to the counterpart in Figure (9) shows that a possible further loss of profits has been avoided after the policy was implemented.[15]

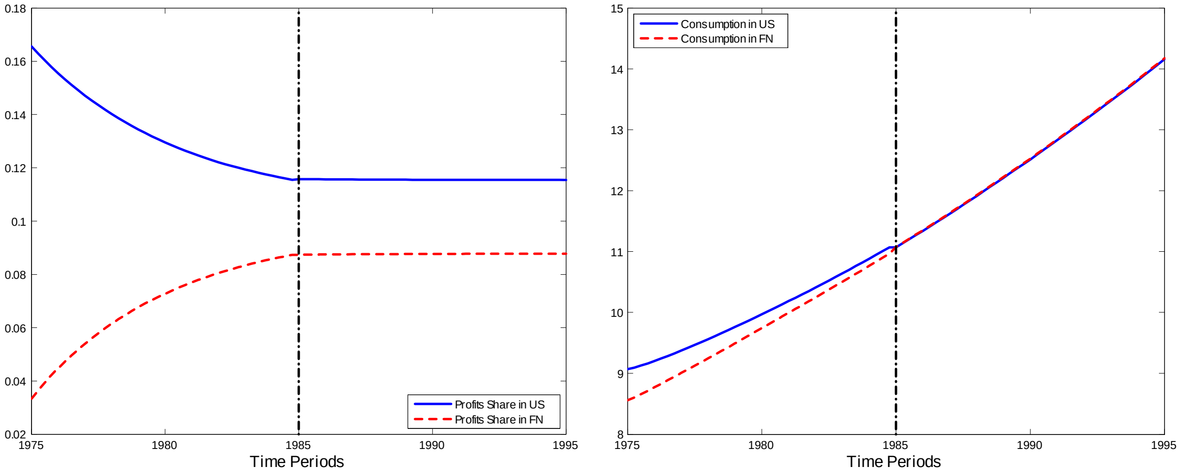

Figure 12: Profits and Consumption, 1975-1995

The shift in profits is reflected on the dynamics of consumption which shows a halt of convergence. Of course, at the time of an increase in the subsidy rates, consumption drops due to the rise in taxes collected from households to subsidize R&D. However, US consumption policy recovers fast as depicted in Figure (12).

Next, we compare the welfare values for the US under with and without the policy intervention to the baseline calibration in N years after 1985, the year when the subsidy levels move. The consumption equivalent terms (ς) used in this comparison are computed as follows:

$$\int_{1985}^{1985+N} \exp(-\rho\,(t-1985))\frac{\left((1+\varsigma)\,C_t^{base}\right)^{1-\psi}-1}{1-\psi} = \int_{1985}^{1985+N} \exp(-\rho\,(t-1985))\frac{\left(C_t^{policy}\right)^{1-\psi}-1}{1-\psi}.$$

Policy changes take place in the year 1985, therefore the consumption equivalent terms are calculated looking forward from that year on. In this expression ς denotes the percentage difference in yearly consumption that is required to make the household in the benchmark economy have the same welfare as in the counterfactual setting. Moreover, N denotes the horizon over which the comparison is drawn. The welfare effects of the change in R&D subsidies are shown in Table 6. "Both" refers to the case when effective subsidy levels change in both

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[15] The parts of the figures to the left of the black line show the initial 10 years and is thus the same as in the previous counterpart of these figures.

countries (US: .176% → .263%; Foreign: .140% → .147%) whereas "Foreign" indicates the shift only in foreign countries (there is a slight change in those, too). The top panels refer to welfare levels, while the bottom shows the welfare gains or losses in consumption equivalent terms, compared to a world where there is no policy change in mid-80s.

Table 6. Welfare Effect of R&D Subsidies

Welfare in Levels

	years						
	5	10	15	20	25	50	100
Base	−1.694	−3.188	−4.505	−5.664	−6.985	−10.223	−13.083
Both	−1.697	−3.182	−4.482	−5.620	−6.615	−10.017	−12.648
Foreign	−1.693	−3.187	−4.501	−5.659	−6.677	−10.204	−13.047

Consumption Equivalent

	years						
	5	10	15	20	25	50	100
Both	−0.17%	0.19%	0.50%	0.79%	1.05%	2.12%	3.44%
Foreign	0.04%	0.06%	0.07%	0.09%	0.11%	0.18%	0.28%

These results suggest that US consumption has to be increased 2.12% on a yearly basis in the baseline model to generate the same level of welfare in 50 years as in the scenario where both countries adjust their subsidy levels. Within a 5-year horizon though, the negative effect of higher taxes needed to fund the subsidies prevails over the benefits from more innovation resulting in a negative effect on welfare. As time goes by, the benefits from international business stealing kick in and turn the losses into gains. The second row implies that, even if the US does not respond in subsidy levels, an increase in foreign subsidy would still benefit the US consumers. This is a consequence of the spillovers generated by the innovations in the foreign country.

Finally, this table tells us that the welfare gains of the R&D subsidies over the past 30 years in the US has been around 0.94% in consumption equivalent terms.

6.2 Gains and Losses from Openness

Next, we explore the welfare effects of our two globalization scenarios. First, we will compute the present value of utility in the factual economy as foreign catching up takes place. In order to single out the pure effects of foreign convergence on home welfare we abstract from the policy intervention. Second we want to analyze the welfare gains from trade liberalization, represented by a reduction in trade costs.

Foreign technological catch-up. In order to understand the effects of foreign technological catching up we need two focus on two key forces at work in our economy. First, as foreign firms conquer market leadership in more sectors, the home country can free ride on foreign innovation, hence benefiting from the higher quality of imports. Second, successful foreign innovation in a larger share of product line trigger business stealing which shift domestic profits abroad, thus yielding welfare losses. We can analyze a counterfactual scenario which allows us to asses the losses from business stealing.

At any time t, consider the average quality in our domestic country

$$Q_{mAt} = \int_{j \in \Gamma_{mAt}} q_{jAt} dj$$

where Γ_{mAt} denotes again the set of product lines in which firms of country A are at position $m \in \{-1, 0, 1\}$. The evolution of Q_{1At} depends on two forces: first, the improvements in q_{jA} for each j, and second, the changes in the leadership structure Γ_{mAt} due to business stealing. Let us also define another variable that measures the "neutralized" quality:

$$\bar{q}_{mAt} = \frac{Q_{mAt}}{\Gamma_{mAt}}.$$

This variable reflects the average quality that abstracts from the changes in the measure of firms, i.e. it is loosely the quality per product line at position m in country A. The idea behind creating this variable is to remove the effect of variations in sector shares on the evolution of Q_{mAt}. Next, we use these "neutralized" values as the basis for creating average qualities in the counterfactual case.

Now consider an economy with constant shares over product lines. That is, let Γ_{mA1975} be the measure of product lines in 1975 that are at position m and belong to country A. Then, in the counterfactual economy we have

$$Q_{mAt}^{1975} = \int_{j \in \Gamma_{mA1975}} q_{jAt} dj.$$

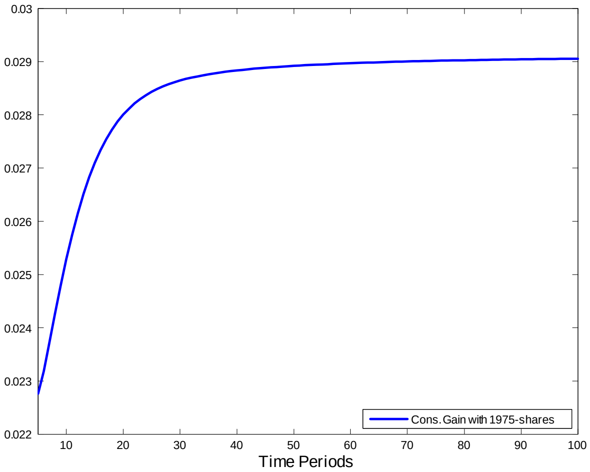
Notice that the measure of j does not move while Q_{mAt} varies. Using Q_{mAt} and Q_{mAt}^{1975}, we calculate consumption, $C\left(Q_{mAt}\right)$ and $C\left(Q_{mAt}^{1975}\right)$, and welfare, $\mathbb{W}\left(Q_{mAt}\right)$ and $\mathbb{W}\left(Q_{mAt}^{1975}\right)$, in the original and the counterfactual economy respectively. Table 7 compares welfare in both settings over certain horizons.

TABLE 7. BUSINESS STEALING

	Welfare	
Years	Benchmark	No Bus. Steal.
5	−2.153	−2.105
10	−4.083	−3.982
25	−8.636	−8.397
50	−13.244	−12.872
75	−15.680	−15.238
100	−16.968	−16.489

Notice that a less negative value implies higher welfare which is the case for the counterfactual economy at any point in the future, as expected. Lastly, Figure (13) shows the welfare difference in consumption equivalent terms over every horizon of $T = 5, 6, ..., 100$ years.

This figure illustrates that households in the original setting would need to consume about 2.9% more every year to receive the same utility as in the constant share economy over longer horizons - from about 50 years from when the policy was implemented. This is a quite sizable magnitude. Intuitively, over time the loss from business stealing stabilizes as the product line shares approach steady state. Moreover, the increasing pattern implies that the loss is larger over longer horizons.



Consumption Equivalent Terms

Figure 13: Welfare Losses from Foreign Catching up

Trade liberalization. Finally we analyze the welfare gains from trade openness. In order to do this we perform the following experiments: a) We compute welfare gains (consumption equivalent) of a 10% reduction in trade costs letting leadership share change, as in the benchmark simulation. b) We compute the welfare gains of a 10% reduction in trade costs with constant shares, hence we do not allow for business stealing along the transition. TO BE COMPLETED.

7 Conclusion

In this paper we analyzed the welfare effect of different dimensions of openness in a dynamic trade model with endogenous technical change. Our analysis is inspired by an interesting historical episode in which the United States was initially being caught up and losing its leadership position in many technology fields. Between 1965 and 1985, its technological leadership, measured as the share of patents, decreased substantially. However, starting in the 1980s we observe a shift toward more aggressive R&D policies in the US which then helped the country rebuild its leadership. Our quantitative analysis suggests that the U.S. experiences sizable short and long-run losses from foreign catching up amounting to about 3% of consumption equivalent from a 50-years horizon onwards. The gains from foreign innovation embedded in imported goods is offset by the business-stealing effect of foreign competition. We also provide a quantitative assessment of the welfare consequences of the R&D policy intervention in the 1980s. These policies not only increased the speed of quality improvements for consumers, but also generated business stealing which then additionally contributed to US welfare. Our analysis suggested that this gain could be up to 2% in 50 years following the policy shift in terms of the consumption equivalence relative to the case without the policy change.

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APPENDIX

A Additional Empirical Material

This section presents the counterpart of regression analysis in subsection 3 which also includes federal analysis. The results are shown in Table 2. 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 2: 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

B Derivations

B.1 Lemma

Proof of Lemma 1. Guessing that incumbent values are linear in qualities, the optimality conditions derived from entrants' problem uniquely determine $v_{cm}'s$, given that entry is positive. Moreover, the conditions suggest that $\dot{v}_{cm} = 0$, thus $\dot{V}_{cm} = 0$, i.e. these values are constant over time. Using these one can show that incumbent intensities are also independent of any time varying variable. Then solving the incumbent maximization, it follows that the time variation in interest rates is fully internalized by the entrant intensities. Notice that if there was no entry margin pinning down the incumbent values, then they would respomd to interest rates such that the $\dot{v}_{cm} \neq 0$. ■

B.2 Law of Motions

Derivations for Equations (26) – (28)**.** Let us also denote

$$\bar{q}_{1c} \equiv \frac{Q_{1c}}{\mu_{1c}},\ \bar{q}_{0c} \equiv \frac{Q_{0c}}{\mu_{0c}} \text{ and } \bar{q}_{-1c} \equiv \frac{Q_{-1c}(t)}{\mu_{-1c}}.$$

Consider the product lines where leader are from country c:

$$\begin{aligned}
Q_{1c}\left(t+\Delta t\right) &= \int_0^1 \left[\begin{array}{c} \mathbf{1}_{[j=1c]}\left[\begin{array}{c} \lambda q_j\left(x_{1c}+\phi\tilde{x}_{1c}\right)\Delta t+ \\ \left(1-\left(x_{-1c'}+x_{1c}+\tilde{x}_{-1c'}+\tilde{x}_{1c}\right)\Delta t\right)q_j \end{array}\right] \\ +\mathbf{1}_{[j=0c]}\left(x_{0c}+\phi\tilde{x}_{0c}\right)\Delta t\lambda\bar{q}_{0c} \end{array}\right] dj \\
&= \left[\begin{array}{c} \lambda\left(x_{1c}+\phi\tilde{x}_{1c}\right)\Delta t\int_0^1 \mathbf{1}_{[j=1c]}q_j dj+ \\ \left(1-\left(x_{-1c'}+x_{1c}+\tilde{x}_{-1c'}+\tilde{x}_{1c}\right)\Delta t\right)\int_0^1 \mathbf{1}_{[j=1c]}q_j dj \\ +\left(x_{0c}+\phi\tilde{x}_{0c}\right)\Delta t\lambda\bar{q}_{0c}\left(t\right)\int_0^1 \mathbf{1}_{[j=0c]}dj \end{array}\right] \\
&= \left[\begin{array}{c} \lambda\left(x_{1c}+\phi\tilde{x}_{1c}\right)\Delta t Q_{1c}\left(t\right)+ \\ \left(1-\left(x_{-1c'}+x_{1c}+\tilde{x}_{-1c'}+\tilde{x}_{1c}\right)\Delta t\right)Q_{1c} \\ +\left(x_{0c}+\phi\tilde{x}_{0c}\right)\Delta t\lambda\bar{q}_{0c}\left(t\right)\mu_{0c} \end{array}\right] \\
\frac{Q_{1c}\left(t+\Delta t\right)-Q_{1c}}{\Delta t} &= \lambda Q_{1c}x_{1c}+Q_{1c}\tilde{x}_{1c}(1-\phi)+\lambda Q_{1c}\tilde{x}_{1c}\phi+Q_{1c}\tilde{x}_{-1c'}(1-\phi) \\
&\quad +\lambda Q_{0c}x_{0c}+\lambda Q_{0c}\tilde{x}_{0c}\phi-Q_{1c}\left(x_{-1c'}+x_{1c}+\tilde{x}_{-1c'}+\tilde{x}_{1c}\right) \\
\dot{Q}_{1c} &= \left[x_{1c}\left(\lambda-1\right)+\tilde{x}_{1c}\phi\left(\lambda-1\right)-\tilde{x}_{-1c'}\phi-x_{-1c'}\right]Q_{1c}+\left(x_{0c}+\tilde{x}_{0c}\phi\right)\lambda Q_{0c}
\end{aligned}$$

$\dot{Q}_{0c}$ and $\dot{Q}_{-1c}$ are derived in similar fashion:

$$\begin{aligned}
\frac{Q_{0c}(t+\Delta t)-Q_{0c}}{\Delta t} &= Q_{1c}x_{-1c'}+Q_{1c}\tilde{x}_{-1c'}\phi+\lambda Q_{-1c}x_{-1c}+\lambda Q_{-1c}\tilde{x}_{-1c}\phi+Q_{0c}\tilde{x}_{0c}(1-\phi) \\
&\quad +Q_{0c}\tilde{x}_{0c'}(1-\phi)-Q_{0c}\left(x_{0c}+x_{0c'}+\tilde{x}_{0c}+\tilde{x}_{0c'}\right) \\
\Rightarrow \dot{Q}_{0c} &= \left(x_{-1c'}+\tilde{x}_{-1c'}\phi\right)Q_{1c}+\left(x_{-1c}+\tilde{x}_{-1c}\phi\right)\lambda Q_{-1c}-\left[x_{0c}+x_{0c'}+\tilde{x}_{0c}\phi+\tilde{x}_{0c'}\phi\right]Q_{0c}
\end{aligned}$$

$$\begin{aligned}
\frac{Q_{-1c}(t+\Delta t)-Q_{-1c}}{\Delta t} &= \lambda Q_{-1c}x_{1c'}+Q_{-1c}\tilde{x}_{1c'}(1-\phi)+\lambda Q_{-1c}\tilde{x}_{1c'}\phi+Q_{-1c}\tilde{x}_{-1c}(1-\phi) \\
&\quad +Q_{0c}x_{0c'}+Q_{0c}\tilde{x}_{0c'}\phi-Q_{-1c}\left(x_{1c'}+x_{-1}c+\tilde{x}_{1c'}+\tilde{x}_{-1c}\right) \\
\Rightarrow \dot{Q}_{-1c} &= \left[x_{1c'}\left(\lambda-1\right)+\tilde{x}_{1c'}\phi\left(\lambda-1\right)-\tilde{x}_{-1c}\phi-x_{-1c}\right]Q_{-1c}+\left(x_{0c'}+\tilde{x}_{0c'}\phi\right)Q_{0c}.
\end{aligned}$$

The evolution of average qualities can be summarized as follows:

$$\dot{Q}_A = \mathbf{Tr}_Q Q_A \Rightarrow \tag{30}$$

$$\left[\begin{array}{c} \dot{Q}_{-1A} \\ \dot{Q}_{0A} \\ \dot{Q}_{1A} \end{array}\right] = \mathbf{Tr}_Q \left[\begin{array}{c} Q_{-1A} \\ Q_{0A} \\ Q_{1A} \end{array}\right] \text{ where}$$

$$\mathbf{Tr}_Q \equiv \left[\begin{array}{ccc} \left\{\begin{array}{c} x_{1B}\left(\lambda-1\right)+\tilde{x}_{1B}\phi\left(\lambda-1\right) \\ -\tilde{x}_{-1A}\phi-x_{-1A} \end{array}\right\} & \left(x_{0B}+\tilde{x}_{0B}\phi\right) & 0 \\ \lambda\left(x_{-1A}+\tilde{x}_{-1A}\phi\right) & \left\{\begin{array}{c} -x_{0A}-x_{0B} \\ -\tilde{x}_{0A}\phi-\tilde{x}_{0B}\phi \end{array}\right\} & \left(x_{-1B}+\tilde{x}_{-1B}\phi\right) \\ 0 & \lambda\left(x_{0A}+\tilde{x}_{0A}\phi\right) & \left\{\begin{array}{c} x_{1A}\left(\lambda-1\right)+\tilde{x}_{1A}\phi\left(\lambda-1\right) \\ -\tilde{x}_{-1B}\phi-x_{-1B} \end{array}\right\} \end{array}\right]. \tag{31}$$

■

Derivation of sector shares Equations (18) and (19) allow us to express the above system of differential equations in the following form

$$\dot{y} = \mathbf{Tr}_y y + \mathbf{b}_y$$

where

$$y \equiv \left[\begin{array}{c} \mu_{1A} \\ \mu_{0A} \end{array} \right], \ \mathbf{Tr}_y \equiv \left[\begin{array}{cc} -\left(x_{-1B} + \phi\tilde{x}_{-1B}\right) & x_{0A} + \phi\tilde{x}_{0A} \\ & \\ \left(x_{-1B} + \tilde{x}_{-1B}\phi\right) - & -\left(x_{0A} + x_{0B} + \tilde{x}_{0A}\phi + \tilde{x}_{0B}\phi\right) \\ \left(x_{-1A} + \tilde{x}_{-1A}\phi\right) & -\left(x_{-1A} + \tilde{x}_{-1A}\phi\right) \end{array} \right],$$

$$\text{and } \mathbf{b}_y \ \equiv \ \left[\begin{array}{c} 0 \\ x_{-1A} + \tilde{x}_{-1A}\phi \end{array} \right].$$

Let $\mathbf{T}$ be the matrix whose columns are the eigenvectors of $\mathbf{Tr}_y$. Define a new variable z such that $y = \mathbf{T}z$. Then,

$$\dot{z} = \mathbf{T}^{-1}\mathbf{Tr}_y\mathbf{T}z + \mathbf{T}^{-1}\mathbf{b} = \mathbf{D}z + \mathbf{h}$$

where $\mathbf{D}$ is the **diagonal** matrix with eigenvalues on the main diagonal. This means that the system of equations became one that is comprised of independent first order ODEs which we can solve separately.

Derivation of consumption expression First we rewrite the consumption of country c in terms of Q_c which was defined earlier:

$$\begin{aligned} C_c &= \left\{ \begin{array}{c} -T_A + w_c \\ r_t^c \left[v_{1c}Q_{1c} + v_{0c}Q_{0c} + v_{-1c}Q_{-1c}\right] \\ -\left[v_{1c}\dot{Q}_{1c} + v_{0c}\dot{Q}_{0c} + v_{-1c}\dot{Q}_{-1c}\right] \end{array} \right\} \\ &= \left\{ \begin{array}{c} -\tau_A\alpha_A\left[x_{-1A}^{\gamma_A}Q_{-1A} + x_{0A}^{\gamma_A}Q_{0A} + x_{1A}^{\gamma_A}Q_{1A}\left(t\right)\right] \\ r_t^c\left[v_{-1c}Q_{-1c} + v_{0c}Q_{0c} + v_{1c}Q_{1c}\right] \\ +\beta\left[\frac{1-\beta}{\eta}\right]^{\frac{1-\beta}{\beta}}\frac{Q_{1c}+Q_{0c}}{1-\beta} + \beta\left[\frac{1-\beta}{(1+\zeta)\eta}\right]^{\frac{1-\beta}{\beta}}\frac{Q_{1c'}}{1-\beta} \\ -\left[v_{-1c}\dot{Q}_{-1c} + v_{0c}\dot{Q}_{0c}\left(t\right) + v_{1c}\dot{Q}_{1c}\right] \end{array} \right\} \\ &= \left\{ \begin{array}{c} -\tau_A\alpha_A\left[\begin{array}{ccc} x_{-1A}^{\gamma_A} & x_{0A}^{\gamma_A} & x_{1A}^{\gamma_A} \end{array}\right] + r_t^c\left[\begin{array}{ccc} v_{-1c} & v_{0c} & v_{1c} \end{array}\right] \\ +\frac{\beta}{(1-\beta)}\left[\begin{array}{ccc} \lambda\left[\frac{1-\beta}{(1+\zeta)\eta}\right]^{\frac{1-\beta}{\beta}} & \left[\frac{1-\beta}{\eta}\right]^{\frac{1-\beta}{\beta}} & \left[\frac{1-\beta}{\eta}\right]^{\frac{1-\beta}{\beta}} \end{array}\right] \\ -\left[\begin{array}{ccc} v_{-1c} & v_{0c} & v_{1c} \end{array}\right]\mathbf{Tr}_Q \end{array} \right\} Q_c \\ &= \Lambda Q_c \end{aligned}$$

where $\mathbf{Tr}$ is the transition matrix used to compute $\dot{Q}$ and Λ is a constant raw vector.