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Global Innovation Races, Offshoring and Wage Inequality

Giammario Impullitti*

Abstract

In the 1970s and 1980s the US position as the global technological leader was increasingly challenged by Japan and Europe. In those years the US skill premium and residual wage inequality increased substantially. This paper presents a two-region, quality-ladder growth model where the lagging economy progressively catches up with the leader. As the innovation gap closes, the advanced country experiences fiercer foreign technological competition that forces its firms to innovate more. Faster technical change increases the skill premium and residual inequality. Offshoring production and innovation plays a key role in shaping the link between international competition and inequality.

1. Introduction

Wage inequality has increased rapidly in the USA in recent decades. The skill premium, measured as the college/high school wage ratio, increased by approximately 20% from the late 1970s to the early 1990s, while residual wage inequality—the wage dispersion across workers with similar observable characteristics—increased by about 15% over this period (Acemoglu and Autor 2010; Heathcote et al., 2010). At the same time, American firms experienced fiercer international competition as Japanese and European firms were progressively closing the gap with the US technology frontier. Focusing on R&D investment as a proxy for innovation, there is evidence of a substantial change in the geographical distribution of innovation during this period: the US share of global R&D investment in manufacturing sectors declined from about 50% in 1979 to 39% in 1995, while Japan's share increased from 17% to 28% in the same period (Organisation for Economic Co-operation and Development Structural Analysis database—OECD STAN). Although, the across-sector average for Europe is fairly constant, in some innovation-intensive industries Europe's share of global R&D grows substantially in this period. Similar trends are observable for the distribution of patent counts and citations (Cozzi and Impullitti, 2015; Akcigit et al., 2014). This suggests that US global technological leadership was increasingly challenged by foreign firms during the years of increasing wage inequality.

What is the role of foreign technological competition in shaping the dynamics of US wage inequality in the 1980s and 1990s? In this period US firms offshored a non-negligible share of production and innovation activities.[1] How does offshoring affect the link between increasing foreign competition, technical change and wage inequality?

This paper tackles these questions in a version of the quality-ladder growth model (Grossman and Helpman, 1991; Aghion and Howitt, 1992) in which a backward

* Impullitti: School of Economics, University of Nottingham, Nottingham NG7 2QX, UK. E-mail: Giammario.Impullitti@nottingham.ac.uk. The author would like to thank Tiago Cavalcanti, Guido Cozzi, Alexei Onatski, Julien Prat, Gianluca Violante and seminar participants at Bank of Portugal, Durham, Cambridge, IIES Stockholm, IAE–CSIC Barcelona, NYU, Uppsala.

region progressively catches up with the leading region by increasing the number of industries in which it participates in innovation races for global leadership. The increase in international competition for innovation between the two regions affects the incentive to innovate and wage inequality in the leading economy. The two regions, domestic and foreign, share the same size and preferences, and their economies are populated with a continuum of monopolistic competitive sectors with firms investing in innovation to improve the quality of goods. The top-quality firm in each industry becomes the leader and supplier in a global economy without trade barriers. The trade direction of each product may reverse over time as the identity of the quality leader changes. The patterns of trade are determined by the number of sectors in which each countries' firms have technological leadership, which depends on firms' past investment in innovation.

International technological competition is represented by the following feature of the economy. I assume that the domestic region is the world leader in that its firms invest in innovation in all sectors of the economy, while foreign firms innovate only in few sectors. The share of sectors in which firms from both regions compete in innovation is used as a measure of international competition. Each firm undertakes two activities: production of goods using unskilled workers and innovation employing skilled workers. Workers have heterogeneous abilities drawn from a fixed distribution. They can decide to spend time in school in order to become skilled workers and acquire a level of efficiency proportional to their innate ability. The presence of a fixed cost of education determines the ability cutoff above which workers attain education. Hence, the relative supply of skills is endogenous and responds to changes in the skilled/unskilled wage ratio, the skill premium. Moreover, since skilled workers are paid proportionally to the efficiency gained during their schooling period, the dispersion of skilled wages is affected by the cutoff ability level for obtaining education.

As foreign firms enter the global innovation race in a sector, with a probability proportional to their innovation effort, they become the global quality leaders and production shifts abroad. As a consequence, the domestic demand for production workers declines, triggering a reduction in domestic unskilled wages. This *wage-stealing* effect increases the skill premium in the domestic country directly by reducing unskilled wages, and indirectly by increasing firms' profits and therefore their incentive to innovate. Since innovation is the skill-using activity, the increase in profits triggers an increase in the relative demand of skills and in the skill premium. Finally, an increase in the returns to education induces workers with lower ability to acquire education, thereby increasing the ability dispersion of skilled workers and the dispersion of their wages. Hence, stiffer international competition leads to higher residual inequality as well as higher skill premium.

In the benchmark economy labor markets are assumed to be completely local and firms cannot locate either production or innovation abroad. The wage-stealing effect is strictly dependent on the assumption that labor markets are local. Does fiercer international technology competition affect inequality when firms are allowed to produce and innovate abroad? To answer this question I introduce the possibility of offshoring production and innovation at no additional cost. Offshoring allows firms to locate their activities where factor prices are lower, thus leading to factor-price equalization. Since labor markets are global in this economy, the wage-stealing channel cannot operate but changes in international competition affect inequality through a new mechanism: assuming that the innovation technology has decreasing returns at the regional level, foreign entry in innovation in a sector leads to a more efficient international allocation of innovation efforts, thereby increasing the global demand for skills

and the skill premium.[2] This is the "global efficiency" effect. As before, an increase in the skill premium increases the share of skilled workers and reduces their average ability, thus leading to higher residual inequality.[3]

In the quantitative analysis I use OECD STAN data on R&D investment in two and three-digit manufacturing industries to construct an empirical measure of the type of international competition presented in the model. The USA is the domestic region and Japan and Europe represent the foreign region. The sectors where US investment in research dominates global spending in innovation are labeled "gap" sectors, while the sectors where innovation efforts are more evenly distributed across countries are called "neck-and-neck". The share of neck-and-neck sectors in the economy is the empirical measure of international competition I focus on. The data show that about 42% of sectors are neck-and-neck in 1979 rising to 68% in 1995. Feeding the model the observed reduction in competition yields the following results: under local labor markets, there is an increase in inequality accounting for about one-sixth of the increase in the skill premium, and approximately 45% of the growth in residual inequality observed between 1979 and 1995. In the economy with offshoring, the observed increase in competition accounts for 7% of the increase in the skill premium and about one-fifth of the growth in residual inequality. Although the real economy lays in a middle ground between the two theoretical extremes of completely local and completely global labor markets, my stylized economies provide a possible lower and upper bound for the effects of foreign technological competition on inequality.

Related Literature

The large literature on US wage inequality in recent decades focuses on two main sources, globalization and technological change (see Hornstein et al., 2005; Acemoglu and Autor, 2010, for a survey).[4] One strand of the literature studies the effects of trade liberalization on wage inequality when technology is given (e.g. Yeaple, 2005; Burstein and Vogel, 2010), and another analyzes the interaction between trade liberalization, technical change and wage inequality (e.g. Dinopoulos and Segerstrom, 1999; Acemoglu, 2003; Epifani and Gancia, 2008). The present paper follows this second line of research in that technology is endogenous, but analyzes a source of inequality different from trade liberalization: the increase in international technological competition triggered by foreign entry in global innovation races.

The paper is closely related to the research on international technology diffusion and innovation that studies how changes in the cost and speed of diffusion affect the incentives to innovate in trading economies. Keller (2004) provides a comprehensive survey of this large literature. Some examples are Helpman (1993), Eaton and Kortum (1999, 2006), Rodriguez-Claire (2007) and Hsieh and Ossa (2011). Helpman (1993) sets up a quality-ladder growth model with an innovating region (North) and an imitating region (South) trading freely. Faster technology diffusion, represented by a reduction in the imitation cost, spurs innovation by reducing wages—the cost of innovation. Eaton and Kortum (1999) build a multi-country quality-ladder model in which all countries innovate and contribute to the world technology frontier, and diffusion depends on each country's capacity to adopt foreign technologies. Following Eaton and Kortum, in this paper both regions innovate but there is a reduced-form representation of technology diffusion: the exogenously given level of international technological competition can be thought of as the equilibrium outcome of different adoption rates (or barriers to diffusion). This simple way of modeling diffusion allows

me to directly exploit the variation in the geographic distribution of R&D investment obtainable from the OECD STAN data. Similarly, Krugman (1979) presents a diffusion model in which the leading country is assumed to be able to produce virtually all the goods in the economy, whereas the follower country can produce only the "old" goods. As in the present article, both countries have the same preferences and technologies, and the difference in production possibilities is exogenous. Krugman suggests that the source of the productive advantage of the leading economy might be related to a more skilled labor force, external economies, or to a difference in "social atmosphere." In the case of the growing technological competition between the USA, Europe and Japan that is analyzed here, one important exogenous source could be innovation policy. US technology policy mainly targeting military innovations was key in shaping US technological leadership in the post-World War II period (Nelson, 1993), while the aggressive industrial policy of the Japanese Ministry of International Trade and Industry (MITI) and some European success stories like Airbus, could be at the root of these countries' entry in global R&D races in the 1980s (see e.g. Tyson, 1992; Nelson, 1993).[5]

Impullitti (2010) uses a similar model of diffusion to explain the effects of foreign competition on innovation and welfare, but assumes away any effect on the labor market.[6] Akcigit et al. (2014), analyze the effects of foreign competition owing to technology diffusion on welfare and on optimal innovation subsidies, in a multi-country growth model with step-by-step innovation. The main contribution of this paper is first, to provide a theory of how faster international technology competition affects wage inequality—a channel that is not explored in the existing literature—and secondly, to quantify the contribution of this specific channel to the path of inequality observed in US data. In a companion paper, Cozzi and Impullitti (2015) endogenize international competition making it dependent on differences in innovation technology/capabilities across countries. Similarly to what I do here, Cozzi and Impullitti (2015) study the effects of increasing foreign technology competition on innovation and wage inequality, but they focus on wage polarization across different tasks (innovation, production and personal services), and do not consider the possibility of offshoring.

There is a growing body of work analyzing the effects of offshoring on wage inequality. Feenstra and Hanson (1999), Grossman and Rossi-Hansberg (2008) among others have highlighted channels through which trade in intermediates and offshoring opportunities affect the skill premium. In this line of research the source of inequality is represented by changes in the opportunity (cost) of offshoring, for a given level and structure of technology. Acemoglu et al. (2015) contribute to the literature by introducing innovation and studying how lower offshoring costs affect the direction of technical change, which in turn determines wage inequality.[7] I follow a similar approach in analyzing the interaction between offshoring and endogenous technology, but I assume that all goods can be offshored and focus on how changes in international competition affect innovation and inequality in the presence of offshoring.

Finally, the literature on globalization and inequality has mainly focused on one measure of inequality—the skill premium—while little attention has been given to the rise in residual inequality. The record increase of US wage dispersion across workers with similar observable characteristics in recent decades[8] has been mostly linked to changes in the speed and structure of technological change (e.g. Acemoglu, 1999; Caselli, 1999; Galor and Moav, 2000; Violante, 2002). I contribute to this literature by analyzing how globalization, in the form of increasing technological competition, affects innovation and the returns to observed and unobserved ability, thus shaping

the dynamics of residual inequality. The model's prediction that growth in residual inequality is driven by increases in the share of educated workers in the population is in line with the empirical results of Lemieux (2006). Using May Current Population Survey (US Census) data, Lemieux shows that a large fraction of the increase in residual inequality is attributable to an increasing dispersion of unobserved workers' abilities in the 1980s, a period in which the workforce grows older and more educated.

2. Stylized Facts

In this section I introduce and discuss the data providing motivation for the paper as well as empirical support for the quantitative analysis. First I discuss the dynamics of the skill premium and residual inequality in the USA. Second, I explore the evolution of countries' shares of R&D investment at the industry level. As my interest is in international competition among technological leaders, I restrict the attention to the USA, Japan and 10 European countries: Germany, France, the UK, Italy, Sweden, Denmark, Finland, Ireland, Spain and the Netherlands.[9] I then build an index of countries' "neck-and-neckness" in R&D; that is, I construct a measure of the share of industries where domestic and foreign countries effectively compete for innovation. This allows me to obtain an empirical measure for the international technological competition defined in the model, which is used to perform quantitative analysis.

Wage Inequality

The returns to college show a drastic increase starting in the late 1970s, as shown Figure 1. In 1978 the college premium is substantially equal to its value in 1963, with college graduates earning about 50% more than high school graduates and dropouts.
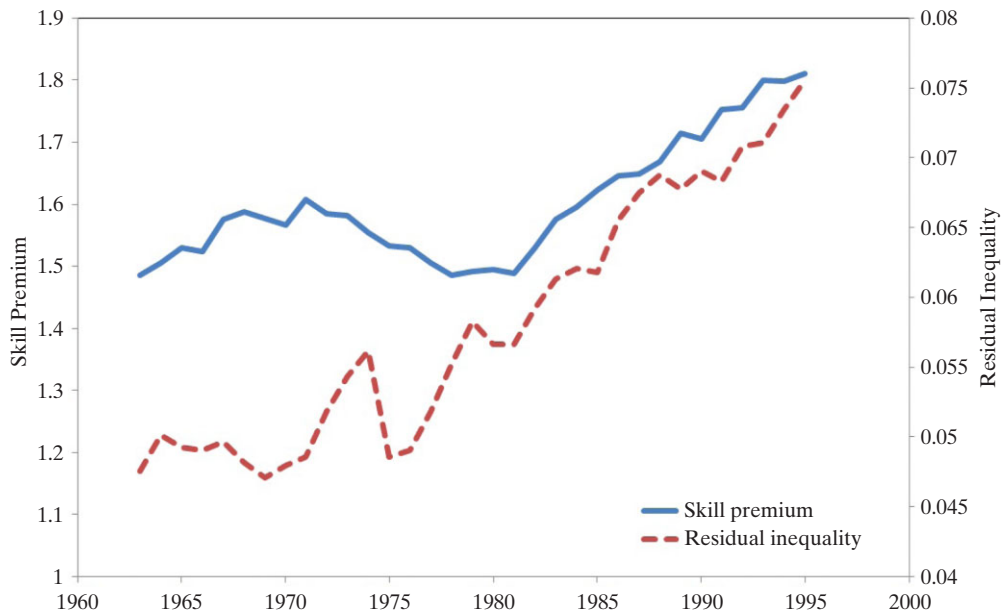

Figure 1. Skill Premium and Residual Inequality in the USA

Sources: Autor et al. (2008), Eckstein and Nagypal (2004) and Lemieux (2006).

From 1979 to 1995 the college premium increases by about 21%, with college graduates earning about 80% more than workers with lower levels of education. Since I interpret the returns to schooling as the true relative price of skills, the college premium will be the definition of the skill premium in the paper.[10]

Figure 1 also shows the trend of residual inequality, measured as the variance of the residuals from a Mincerian regression of log wages on observable characteristics of workers, including education.[11] Residual inequality is therefore a measure of wage dispersion across workers with similarly observable characteristic. The figure shows a small increase before 1979 and, as in the case of the college premium, a steady increase afterwards, scoring a 30% growth between 1979 and 1995.

Global R&D Investment and International Competition

I use OECD STAN Analytical Business Enterprise Research and Develoment (ANBERD) database statistics on R&D investment for two- and three-digit manufacturing industries. Grouping together the 10 European countries, Figure 2 reports sectorial average R&D investment shares for the USA, Japan and Europe. The figure shows that, while European countries as a whole kept a fairly constant share, the US share declined substantially, from 52% to 39% between 1973 and 1995, while Japan's share increased from 17% to 28% in the same period.[12] This suggests that the US position as the global leader in R&D investment was increasingly challenged by Japanese firms, while Europe's share shows only a moderate increase. Figure 2 provides a clear picture of convergence in global R&D efforts. Cozzi and Impullitti (2015) and Akcigit et al. (2014), show that a similar convergence path can be observed for innovation output, patents and its quality, patent citations.
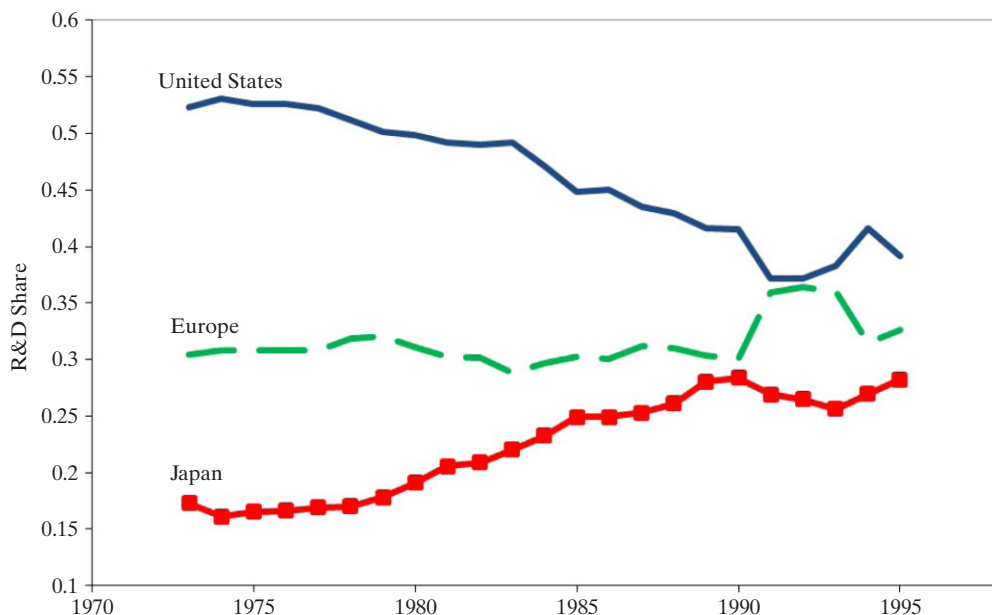

Figure 2. Global R&D Shares

Source: OECD STAN.

Table 1. Global R&D Shares (medium/high-tech secs)

Industry	1973			1995			% change 1973–1995		
	US	JAP	EU	US	JAP	EU	US	JAP	EU
Aircraft**	74.2	0.08	0.241	68.4	1.4	27.3	−7.76	81.6	13.3
Chem. no drugs*	39.7	18.5	39.8	35.9	26.1	36.3	−9.38	40.6	−8.68
Drugs and meds**	41.3	14.5	42.2	45.5	16.8	34.6	10.1	15.7	−18
Electrical machinery*	54.3	16.6	27.8	24.6	43.2	30.8	−54.5	160.3	10.6
Motor vehicles*	56.5	13.6	28.8	45.01	20.1	33.51	−20.4	47.7	16.3
Office & computing mach.**	76.5	6.4	16.1	53.7	30.2	13.98	−29.8	368.5	−13.2
Radio, TV & comm. equip.*	54.2	13.1	29.9	40.3	25.6	28.76	−25.5	95.08	−3.93

Note: * medium high-tech ,** high tech.
Source: OECD STAN.

Table 1 reports countries' shares in medium and high-tech sectors in 1973 and 1995.[13] The US share declines in all sectors except for drugs and medicines, Japan's share scores record increases in the most innovative industries: in electrical machineries the share rises from 16.6% to 43.2% (a 160% increase), in office and computing machineries from about 6% to about 30% (a 368% increase), and in radio, TV and communication equipment from 13% to 25% (a 95% increase). Europe provides a mixed picture with a substantial increase in aircraft (13% increase)—probably related to the entry of AIRBUS in the global market for airplanes—and in motor vehicles (16% increase), as well as decreases in chemicals and office and computing machineries. A similar picture can be obtained in medium and low-tech sectors that I do not show for brevity.

This data can be used to build a measure of countries' "neck-and-neckness" in innovation. For each year, in the period 1973–1995, I consider a sector neck-and-neck if the US share of total R&D investment is smaller than a certain threshold (*NT* henceforth). The measure of the neck-and-neck set of industries, that I call $\bar{\omega}$, is defined as the percentage of sectors with the US R&D share below the threshold *NT*. I compute $\bar{\omega}$ for different threshold values in the grid $NT \in (0.35, 0.68)$, and the final index is chosen taking the average index across thresholds.[14] This empirical index has been built to match the definition of technological competition studied in the model presented in the next section.

Figure 3 shows the values of $\bar{\omega}$ obtained using the bottom threshold $NT = 0.35$ and the top threshold $NT = 0.68$; it also shows the average $\bar{\omega}$, which is computed taking the mean of all the $\bar{\omega}$s obtained at each threshold levels in the set $CT \in (0.35, 0.68)$. All measures show an increasing trend, the average $\bar{\omega}$, which is the index of international competition used in the quantitative analysis, increases from 0.3 (30% of the sectors are neck-and-neck) in 1973 to 0.68 in 1995.[15]

As Figures 2 and 3 show, in the mid-1990s the convergence in R&D investment across countries seems to be completed. Interestingly, the increase in US wage inequality also slows down in that period (see e.g. Acemoglu, 2002; Acemoglu and Autor, 2010). For this reason I focus the analysis on 1979–1995, the period of major increase in inequality and faster innovation convergence.
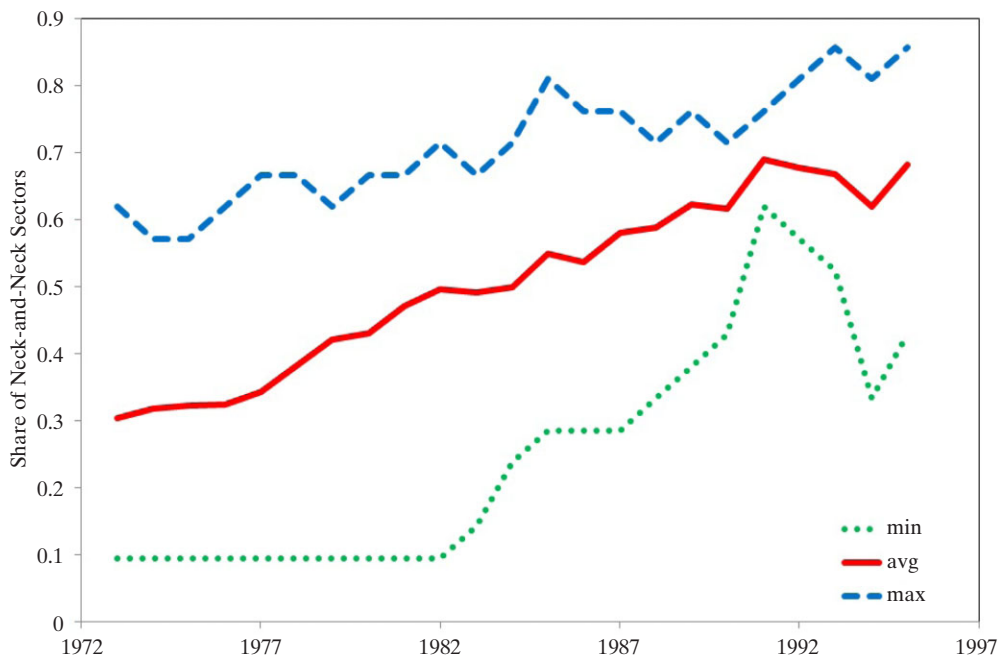
Figure 3. International Technological Competition Index

Sources: OECD STAN and author's calculations.

3. The Model

In this section I set up the model and derive the steady-state equilibrium system of equations. The model combines elements of Dinopoulos and Segerstrom (1999) and Impullitti (2010). It embeds the quality-ladder growth structure with endogenous human capital accumulation of the Dinopoulos and Segerstrom, but considers asymmetric countries, as in Impullitti (2010), and explores global economies with and without the possibility of offshoring production and innovation.

Households

The economy is populated by two regions with the same population and preferences. In both regions there are heterogeneous households, differing in their ability to acquire working skills $\theta \in (0, 1)$. Households have identical unit elastic preferences for a continuum of consumption goods $\omega \in (0, 1)$, and each is endowed with a unit of labor/study time whose supply generates no disutility. The household of type θ is modeled as dynastic family that maximize intertemporal utility

$$U = \int_0^\infty N(0)e^{-(\rho-n)t} \log u_\theta(t)dt, \tag{1}$$

where population is specified according to $N(t) = N(0)e^{nt}$, with initial population $N(0)$ normalized to 1 and a constant population growth rate n. The rate of time preference is ρ, with $\rho > n$. The utility per person is given by

$$\log u_\theta(t) \equiv \int_0^1 \log\left[\sum_{j=0}^{j^{\max}(\omega,t)} \lambda^j q_\theta(j,\omega,t)\right] d\omega \tag{2}$$

where $q_\theta(j,\omega,t)$ is the per-member quantity of good $\omega \in [0, 1]$ of quality $j \in \{0, 1, 2, \ldots\}$ purchased by a household of ability θ at time $t \geq 0$. A new vintage of good ω yields a quality λ times that of the previous vintage, with $\lambda > 1$. Different versions of the same good ω are regarded by consumers as perfect substitutes after adjusting for their quality ratios, and $j^{\max}(\omega, t)$ denotes the maximum quality in which the good ω is available at time t.

At each point in time households choose the quantity purchased of each good $q_\theta(j, \omega, t)$ in order to maximize (2) subject to the per-period expenditure constraint. The utility function has unitary elasticity of substitution between every pair of product lines. Thus, households maximize static utility by spreading their expenditures $c_\theta(t)$ evenly across product lines and by purchasing in each line only the product with the lowest price per unit of quality.[16] Hence, the household's demand for each product is:

$$q_\theta(j,\omega,t) = \frac{c_\theta(t)}{p(j,\omega,t)} \quad \text{for } j = j^{\max}(\omega,t) \text{ and is zero otherwise.} \tag{3}$$

Given the optimal allocation of expenditures across different product lines at a given moment t in (3), the intertemporal optimization problem yields the Euler equation

$$\frac{\dot{c}_\theta(t)}{c_\theta(t)} = r(t) - \rho. \tag{4}$$

Individuals are finitely lived members of infinitely lived households, being continuously born at rate β and dying at rate δ, with $\beta - \delta = n > 0$; $V > 0$ denotes the exogenous duration of their life.[17] They choose to acquire education and become skilled, if at all, at the beginning of their lives, and the duration of their schooling period, during which the individual cannot work, is set at $T_r < V$. In region $K = D$ (domestic), F (foreign) an individual with ability θ decides to acquire education if and only if:

$$\int_t^{t+V} e^{-\int_t^s r(\tau)d\tau} w_L^K(s)\,ds < \int_{t+T_r}^{t+V} e^{-\int_t^s r(\tau)d\tau} \max(\theta - \gamma, 0) w_H^K(s)\,ds, \tag{5}$$

with $0 < \gamma < 1$ defining a threshold ability requirement so that an agent with ability $\theta > \gamma$ is able to accumulate $\theta - \gamma$ units of skills after schooling, while a person with ability below γ gains no skills from education. Parameter γ could be interpreted as an ability-specific fixed cost of education.[18]

I focus on steady-state analysis, in which all variables grow at constant rate and w_L, w_H and c_θ are all constant. From the Euler equation (4) we obtain $r(t) = \rho$ at all dates, and solving (5) with equality implies that agents acquire education if and only if their ability is higher than the following cutoff

$$\theta_0^K = \left[(1 - e^{-\rho V})/(e^{-\rho T_r} - e^{-\rho V})\right]\frac{w_L^K}{w_H^K} + \gamma \equiv \sigma \frac{w_L^K}{w_H^K} + \gamma. \tag{6}$$

with $\sigma \equiv \left[(1 - e^{-\rho V})/(e^{-\rho T_r} - e^{-\rho V})\right]$. I assume that agents draw their innate ability from a cumulative distribution function $\Gamma(\theta)$. This implies that $\Gamma(\theta_0^K)$ is the share of region K

population deciding to not acquire education, and

$$L^K(t) \equiv \Gamma(\theta_0^K)N(t) \tag{7}$$

is the supply of unskilled labor at time t. A fraction $(1-\Gamma(\theta_0^K))$ of the population decides to attain education and the skilled workforce is represented by the subset of these agents that have completed their schooling period, that is individuals born between $t-V$ and $t-T_r$. The supply of skilled labor in efficiency units at time t is then

$$H^K(t) = \tilde{\theta}^K(\theta_0^K)(1-\Gamma(\theta_0^K))\phi N(t), \tag{8}$$

with $0 < \phi \equiv (e^{n(V-T_r)}-1)/(e^{nV}-1) < 1$ and

$$\tilde{\theta}^K(\theta_0^K) = \left[\int_{\theta_0^K}^1 (\theta^K - \gamma)\frac{d\Gamma(\theta)}{1-\Gamma(\theta_0^K)} \right] \tag{9}$$

is the average ability of educated workers. In steady state the growth rate of $L^K(t)$ and $H^K(t)$ is equal to n for $K = D, F$.

Production

In each region, firms can hire unskilled workers to produce any consumption good $\omega \in [0, 1]$ under a constant return to scale technology with one worker producing one unit of product. The unskilled wage rate is w_L^K and I set $w_L^F = 1$, so that the unskilled foreign wage is the numeraire of this economy. As we saw in the previous section, only the top quality of each good is demanded by consumers, therefore in each industry only the product with the highest quality is produced. Quality leaders in each sector are challenged by followers that employ skilled workers to discover the next top-quality product. In this model, as in the baseline quality-ladder growth model, leaders and followers have the same production and innovation technology, thus the Arrow effect implies that in equilibrium only followers innovate.[19] Successful innovation yields global market leadership that is protected by a perfectly enforceable patent law.

I assume that the technologies to produce goods one quality ladder below the top are obsolete and diffuse freely. This assumption allows foreign successful innovators to become global market leaders.[20] The unit elastic demand structure encourages the monopolist to set the highest possible price to maximize profits, while the existence of a competitive fringe sets a ceiling equal to the world's lowest unit cost of the immediately inferior good on the quality ladder. Thus, the profit-maximizing price of the quality leader is a limit price on the cost of the follower (competitive fringe).

In order to determine the optimal pricing I anticipate a fundamental feature of the model that will be discussed more in depth in the next two sections. I assume that domestic firms invest in innovation and compete for market leadership in all sectors of the economy, while foreign firms invest only in a subset of sectors. The share of industries in which domestic and foreign firms invest in innovation is the measure of international technological competition I focus on. I call these industries "neck-and-neck", while the remaining industries in the product space are the "gap" industries. Hence, a larger share of neck-and-neck industries implies a stronger international competition to achieve global market leadership. Since domestic firms can potentially be leaders in all sectors of the economy, they produce more and demand more

unskilled labor, thus paying higher wages. To obtain a non-trivial market structure I focus on the equilibrium in which the gap between the two countries' unskilled wage is constrained by the following condition, $w_L^D/\lambda \leq w_L^F \leq w_L^D$. This narrow gap case (Grossman and Helpman, 1991) allows for equilibrium product-cycle trade with global market leadership shifting from domestic to foreign firms as the latter innovate and vice versa. Although the foreign region has a cost advantage in production, focusing on the narrow gap case guarantees that the wage gap is not so large that a foreign follower can price a domestic leader out of the market without innovating.[21]

Since both domestic and foreign followers operate with the same technology, and foreign unskilled labor is cheaper, domestic followers do not represent an effective competitive threat in sectors where firms from both countries are active in innovation. Thus the price $p^K(j^{\max}(\omega,t),\omega,t)$ of a top-quality good is

$$p^K\left(j^{\max}(\omega,t),\omega,t\right) = \lambda w_L^F(t) = \lambda \tag{10}$$

in neck-and-neck sectors for $K = D, F$. In gap sectors, the competitive fringe cost is the domestic wage and limit pricing leads to

$$p^D\left(j^{\max}(\omega,t),\omega,t\right) = \lambda w_L^D(t). \tag{11}$$

From (3), we can conclude that the demand for each product ω is:

$$\frac{\left(c^D(t)+c^F(t)\right)N(t)}{p^K\left(j^{\max}(\omega,t),\omega,t\right)} = q(\omega,t), \tag{12}$$

where $c^D(t) = \int_0^1 c_\theta^D(t)\,d\Gamma(\theta)$ and $c^F(t) = \int_0^1 c_\theta^F(t)\,d\Gamma(\theta)$ are average per-capita expenditures at time t. Letting $q(\omega,t)$ be the quantity produced of good ω, the above equation implies that supply and demand of goods are equal in equilibrium. It follows that the stream of monopoly profits accruing to domestic quality leaders in neck-and-neck industries is

$$\pi_n^D(\omega,t) = q(\omega,t)\left(\lambda w_L^F - w_L^D(t)\right) = \left(c^D(t)+c^F(t)\right)N(t)\left(1-\frac{w_L^D(t)}{\lambda}\right),$$

where I have used (3) to substitute for $q(\omega,t)$. Profits of domestic leaders in gap industries are

$$\pi_g^D(\omega,t) = q(\omega,t)\left(\lambda w_L^D(t) - w_L^D(t)\right) = \left(c^D(t)+c^F(t)\right)N(t)\left(1-\frac{1}{\lambda}\right),$$

and profits of foreign leaders are $\pi^F(\omega,t) = (c^D(t) + c^F(t))N(t)(1 - 1/\lambda)$.

Innovation Races and the Value of a Firm

In each industry, quality followers employ skilled workers to produce a probability intensity of inventing the next top-quality version of their products. The arrival rate of innovation in industry ω at time t is $I(\omega,t)$, which is the sum of the Poisson arrival rate of innovation produced by all firms targeting product ω. The innovation technology available to a firm i in region K for innovation in sector ω is

$$I_i^K(\omega, t) = \frac{A h_i^K(\omega, t) \left(\dfrac{H^K(\omega, t)}{X(\omega, t)} \right)^{-\alpha}}{X(\omega, t)}, \tag{13}$$

where $X(\omega, t) > 0$ measures the degree of complexity innovation, $\alpha > 0$, $H^K(\omega, t) = \sum_i h_i^K(\omega, t)$ and $I^K(\omega, t) = \sum_i I_i^K(\omega, t)$ are total skilled labor and total innovation rate in sector ω and region K respectively. This technology implies that each firm's instantaneous probability of success is a decreasing function of the total domestic labor resources devoted to innovation in an industry. A possible interpretation of this property is that when firms increase innovation inputs in a sector, the probability of duplicative innovation effort also increases, thereby reducing the probability that any single firm will discover the next vintage of goods. Therefore, the sector-specific negative externality in innovation technology produces decreasing returns to innovation at the industry level. Moreover, (13) implies that this negative externality is also region specific;[22] this feature can be motivated by the presence of fixed costs, such as laboratory equipment, by institutional differences, and by the presence of a workforce with heterogeneous ability in research.[23]

The complexity index $X(\omega, t)$ is introduced to avoid the counterfactual prediction of the first generation innovation-driven growth models that the size of a region affects its steady-state growth (Jones, 1995). Following Dinopoulos and Segerstrom (1999) I eliminate scale effects assuming $X(\omega, t) = 2\kappa N(t)$, with $\kappa > 0$, thereby formalizing the idea that it is harder to innovate in a more crowded global market.[24]

Each innovating firm chooses l_i^K in order to maximize its expected discounted profits. Free entry into innovation races drives profits to zero yielding

$$v^K(\omega, t) A \left(\frac{H^K(\omega, t)}{X(\omega, t)} \right)^{-\alpha} \bigg/ X(\omega, t) = w_H^K(t). \tag{14}$$

where $v^K(\omega, t)$ is the value of a firm in sector ω and region K. This condition states that the cost of one unit of skilled labor employed in innovation w_H^K must be equal to its benefits, represented by the marginal product $A(H^K(\omega, t)/X(\omega, t))^{-\alpha}/X(\omega, t)$ times the prize for a successful innovation $v^K(\omega, t)$.

Efficient financial markets channel savings into innovative firms that issue a security paying the monopoly profits if they win the race and zero otherwise. Since there is a continuum of industries, and simultaneous and independent innovation races, consumers can perfectly diversify away risk: the expected rate of return of a stock issued by a firm is equal to the riskless rate of return $r(t)$. It is easy to show that this leads to the following value of a firm

$$v^K(\omega, t) = \frac{\pi^K(\omega, t)}{r(t) + I(\omega, t) - \dot{v}^K(\omega, t)/v^K(\omega, t)}, \tag{15}$$

where $I(\omega, t)$ denotes the worldwide Poisson arrival rate of an innovation that will destroy the monopolist's profits in industry ω. This is the Schumpeterian rate of creative destruction, the expected value of a patent is inversely proportional to total innovation in the industry. Substituting for the value of the firm from (15) into (14) and using (13) to express the amount of skilled workers in terms of the innovation rate we obtain the following conditions

$$\frac{\pi^K(\omega,t)}{r(t)+I(\omega,t)-\dot{v}^K(\omega,t)/v^K(\omega,t)}\left(\frac{I^K(\omega,t)}{A}\right)^{\frac{-\alpha}{1-\alpha}}\frac{A}{X(\omega,t)}=w_H^K(t),\qquad(16)$$

for $\omega\in(0,1)$ and $K=D,F$. This condition, together with the Euler equation summarizes the utility maximizing household choice of consumption, savings and education, and the profit-maximizing choice of production and innovation. Innovation arrival rates determine the evolution of the average quality of goods in the economy $O(t)=\ln\lambda\int_0^1\left[\int_0^t I(\omega,\tau)d\tau\right]d\omega$, obtained from the preferences in (2).

International Technological Competition

International competition is defined in the model by the share of industries where firms from both regions compete in innovation. I assume that there exists an exogenously given subset of industries $\bar{\omega}\in(0,1)$ where domestic and foreign researchers compete to discover the next vintage of products, while in the complementary $1-\bar{\omega}$ industries only domestic firms compete for innovation. This leads to the following composition of worldwide investment in innovation,

$$I(\omega,t)=I_n^D(\omega,t)+I^F(\omega,t)\quad\text{for }\omega\le\bar{\omega}$$

$$I(\omega,t)=I_g^D(\omega,t)\quad\text{for }\omega>\bar{\omega}\qquad(17)$$

where $I_g^D(\omega,t)$ is innovation in sectors where only domestic firms compete to improve a product's quality, and $I_n^D(\omega,t)$ is domestic innovation in industries in which foreign firms compete in innovation as well; $I^F(\omega,t)$ is foreign innovation.

The set of sectors $\bar{\omega}$ could be obtained as an equilibrium result by, for instance, introducing heterogeneous innovation technologies across industries and countries, as shown in Impullitti (2010) and Cozzi and Impullitti (2015).[25] For tractability I consider $\bar{\omega}$ exogenous but, in order to keep in mind this interpretation of heterogeneous industries, I call goods in the set $\omega\le\bar{\omega}$ neck-and-neck industries and those in the set $1-\bar{\omega}$ gap industries. Besides tractability, there is another reason to consider $\bar{\omega}$ exogenous: the paper is motivated by the evidence discussed in section 2 showing that US leadership in R&D investment is increasingly challenged by Japan and Europe in the period considered. The goal of the paper is to build the simplest model that allows to exploit that evidence. Introducing heterogeneous technologies would require data on innovation technology at the region and sector level, which are not available.[26]

Since goods $\omega\in(0,1)$ are symmetric (same technologies, both in production and innovation, and enter symmetrically in the utility function), the only source of structural asymmetry between the two countries is represented by the partition of sectors in neck-and-neck and gap. Therefore we can write, $I_g^D(\omega,t)=I_g^D(t)$ for all $\omega>\bar{\omega}$, $I_n^D(\omega,t)=I_n^D(t)$ and $I^F(\omega,t)=I^F(t)$ for all $\omega\le\bar{\omega}$.

Labor Markets

To close the model we need to introduce the labor market clearing conditions and trade balance. I analyze two different benchmark economies. In one offshoring is not possible and, consequently, labor markets for both types of workers are local. In the second scenario instead, firms can offshore both innovation and production at no

additional costs, leading to perfectly global labor markets for skilled and unskilled workers, and to equalization of factor prices across regions.

Local labor markets   The production technology specified above implies that the demand for unskilled workers is equal to total production of goods in each national economy. For the domestic region the unskilled labor market clearing condition is

$$\Gamma(\theta_0^D) = \left[\frac{(c^D(t) + c^F(t))}{\lambda} \right] \left[\bar{\omega}\beta(t) + \frac{(1-\bar{\omega})}{w_L^D(t)} \right], \tag{18}$$

where the left-hand side is the population adjusted domestic supply of unskilled workers from (7), and the right-hand side is the domestic demand for unskilled workers. The variable $\beta(t)$ indicates the fraction of neck-and-neck industries with a domestic leader. The structure of global innovation activity specified in (17) implies that $\beta(t)$ evolves according to the law of motion

$$\dot{\beta}(t) = (1-\beta(t)) I_n^D(t) - \beta(t) I^F(t), \tag{19}$$

where the first term on the right-hand side is the flow into β-type industries and the second is the flow out. Hence, the relative strength of domestic innovation determines domestic leadership in neck-and-neck industries. Equation (18) shows that a higher $\bar{\omega}$ leads to a higher global market share of domestic firms and, consequently, to a higher domestic demand for unskilled workers. Similarly for the foreign region we have

$$\Gamma(\theta_0^F) = \left(\frac{c^D(t) + c^F(t)}{\lambda} \right) \bar{\omega}(1 - \beta(t)). \tag{20}$$

The market clearing condition for skilled workers in the domestic region is

$$\tilde{\theta}^D(\theta_0^D)(1 - \Gamma(\theta_0^D))\phi = 2\kappa \left[\bar{\omega} \left(\frac{I_n^D(t)}{A} \right)^{1/(1-\alpha)} + (1-\bar{\omega}) \left(\frac{I_g^D(t)}{A} \right)^{1/(1-\alpha)} \right], \tag{21}$$

where the left-hand side is the domestic supply of skilled labor (per capita) from (8), and the right-hand side is the domestic demand for skilled workers obtained from (13) and $X(\omega, t) = 2\kappa N(t)$. Similarly, the skilled labor market clearing condition for the foreign region is

$$\tilde{\theta}^F(\theta_0^F)(1 - \Gamma(\theta_0^F))\phi = 2\kappa\bar{\omega} \left(\frac{I^F(t)}{A} \right)^{1/(1-\alpha)}. \tag{22}$$

To close the model we need to introduce the conditions for balanced trade: in each region total expenditures plus savings (investment in innovation) must equal national income, wages plus profits (or interest income on assets). The trade balance condition is

$$w_H^D(t)\tilde{\theta}^D(\theta_0^D)(1 - \Gamma(\theta_0^D))\phi + c^D(t)$$
$$= w_L^D(t)\Gamma(\theta_0^D) + \frac{c^D(t) + c^F(t)}{\lambda} [(1-\bar{\omega})(\lambda - 1) + \bar{\omega}(\lambda - w_L^D(t))\beta(t)], \tag{23}$$

for the domestic region and

$$w_H^F(t)\tilde{\theta}^F(\theta_0^F)(1-\Gamma(\theta_0^F))\phi + c^F(t) = \Gamma(\theta_0^F) + \frac{c^D(t)+c^F(t)}{\lambda}\bar{\omega}(\lambda-1)(1-\beta(t)), \qquad (24)$$

for the foreign region. Notice that investment in innovation is simply the wage bill of skilled workers and that each region appropriates the monopoly rent associated to quality leadership in the subset of industries where that region is the world leader.

Offshoring: global labor markets   Next, I consider an economy in which both production and innovation activities can be offshored. In order to keep the model tractable I focus on the simple case in which production and innovation can be offshored at no additional cost. The first implication of full offshoring is that both labor markets will be perfectly global, thus leading to factor-price equalization (FPE henceforth), implying $w_L^D(t) = w_L^F(t) = 1$, $w_H^D(t) = w_H^F(t) \equiv w_H(t)$, and consequently $\theta_0^D = \theta_0^F \equiv \theta_0$. FPE and free entry in innovation imply that innovation in neck-and-neck sectors is equalized, that is $I_n^D(t) = I^F(t) \equiv I_n(t)$. The possibility of locating production and innovation abroad changes the labor market clearing conditions described above as follows: there is only one market clearing condition determining the equilibrium of the global market for unskilled workers,

$$2\Gamma(\theta_0) = \left(\frac{c^D(t)+c^F(t)}{\lambda}\right), \qquad (25)$$

and one equilibrium condition for the global market for skilled labor,

$$2\tilde{\theta}(\theta_0)(1-\Gamma(\theta_0))\phi = 2\kappa\left\{2\bar{\omega}\left(\frac{I_n(t)}{A}\right)^{1/(1-\alpha)} + (1-\bar{\omega})\left(\frac{I_g^D(t)}{A}\right)^{1/(1-\alpha)}\right\}. \qquad (26)$$

4. Steady-State Equilibrium

A balanced growth path for this economy is an equilibrium in which per-capita variables are constant, the share of industries with a domestic leader is constant, the share of population acquiring skills is constant, and the average quality of goods grows at a constant rate. Since wages are constant in steady state, the free entry condition (14) and $X(\omega, t) = 2\kappa N(t)$ imply that $\dot{v}^K(\omega,t)/v^K(\omega,t) = \dot{X}(\omega,t)/X(\omega,t) = n$, for $K = D, F$ and for all $\omega \in (0,1)$. Per-capita expenditure is constant in steady state, then the Euler equation (4) yields $r(t) = \rho$. The global distribution of innovation and the equations for profits specified above imply that conditions (16) become

$$v^D(\omega) = \frac{(c^D+c^F)(1-w_L^D/\lambda)}{\rho+I_n^D+I^F-n}\frac{A}{2\kappa}\left(\frac{I_n^D}{A}\right)^{\frac{-\alpha}{1-\alpha}} = w_H^D, \quad \text{for } \omega \le \bar{\omega}$$

$$v^F(\omega) = \frac{(c^D+c^F)(1-1/\lambda)}{\rho+I_n^D+I^F-n}\frac{A}{2\kappa}\left(\frac{I^F}{A}\right)^{\frac{-\alpha}{1-\alpha}} = w_H^F, \quad \text{for } \omega \le \bar{\omega} \qquad (27)$$

$$v^D(\omega) = \frac{(c^D+c^F)(1-1/\lambda)}{\rho+I_g^D-n}\frac{A}{2\kappa}\left(\frac{I_g^D}{A}\right)^{\frac{-\alpha}{1-\alpha}} = w_H^D, \quad \text{for } \omega > \bar{\omega},$$

where I have used $X(\omega, t) = 2\kappa N(t)$, $r(t) = \rho$, and $\dot{v}^K(\omega,t)/v^K(\omega,t) = n$.

The steady-state version of the labor market clearing conditions (18), (20), (21), and (22) can be obtained by simply dropping the time index and considering that in steady state (19) implies $\beta = I_n^D / (I_n^D + I^F)$. Similarly the trade balance conditions (23), (24) can be obtained by simply dropping the time index and using the steady-state values for β and θ_0^K. Using (6) to express θ_0^K as a function of wages, the equilibrium system is composed of nine equations, (27), the steady-state versions of (18)–(22), (23) and (24), and eight unknowns $(c^D, c^F, I_g^D, I_n^D, I^F, w_H^D, w_L^D, w_H^F)$. This is a general equilibrium model, thus for the Walras law we can solve for eight equations and eight unknowns.

Factor-price equalization in the economy with offshoring leads to a simpler equilibrium system. With global wages, domestic and foreign firms' values in neck-and-neck sectors are equalized, $v^D(\omega) = v^F(\omega)$ for $\omega \leq \bar{\omega}$, leading to equal innovation, $I^F = I_n^D \equiv I_n$. Equations (27) then become

$$\frac{(c^D + c^F)(1 - 1/\lambda)}{\rho + 2I_n - n} \frac{A}{2\kappa} \left(\frac{I_n}{A} \right)^{\frac{-\alpha}{1-\alpha}} = w_H, \quad \text{for } \omega \leq \bar{\omega} \qquad (28)$$

$$\frac{(c^D + c^F)(1 - 1/\lambda)}{\rho + I_g^D - n} \frac{A}{2\kappa} \left(\frac{I_g^D}{A} \right)^{\frac{-\alpha}{1-\alpha}} = w_H, \quad \text{for } \omega > \bar{\omega}.$$

The other equilibrium conditions are the steady-state versions of global market clearing conditions (25)–(26) and trade balance (23)–(24). Using (6) to express θ_0^K as a function of wages, the equilibrium system is composed of six equations, (28), the steady-state versions of (25)–(26) and (23)–(24), and five unknowns $(c^D, c^F, I_g, I_n, w_H)$. The Walras law allows us to solve for five equations and five unknowns.

I complete the description of the model by deriving the two measures of inequality I focus on, the skill premium and residual inequality. The skill premium, defined as the average wage of skilled workers over the unskilled wage is

$$s^K = \frac{w_H^K \tilde{\theta}^K (\theta_0^K)}{w_L^K} \qquad (29)$$

where $\tilde{\theta}^K (\theta_0^K)$ is the average efficiency units of a skilled worker defined in (9). Wage dispersion in the economy is pinned down by the dispersion of skilled wages. Since the wage of a skilled worker with ability θ is $w_H^D(\theta) = (\theta^D - \gamma) w_H^D$, residual inequality is the variance of $w_H^D(\theta)$,

$$\text{res}^K = \text{var}(\theta) = \left[\int_{\theta_0^K}^1 (\theta^K - \gamma)^2 \frac{d\Gamma(\theta)}{1 - \Gamma(\theta_0^K)} \right] - \left[\tilde{\theta}^K (\theta_0^K) \right]^2. \qquad (30)$$

5. Foreign Competition, Innovation and Wages: Analytical Results

In this section I derive a few analytical results providing some key intuitions for the effects of an increase in international competition on innovation and wages in the home country. In the following section I calibrate the model and explore its properties numerically.

Local Labor Markets

To gain some intuition we derive analytical results for a simplified version of the model where technology is constant. The purpose of this exercise is to highlight the

mechanism behind the wage-stealing effect of international competition, which does not hinge on the presence of endogenous technical change. As we will see in the numerical analysis this channel will be present in the full model with innovation as well. Assuming constant technology implies that there is only one activity, production, and both types of workers are used in this activity. Since in this case workers operate the same constant returns technology, there is only one wage in each national economy, the production wage, and no incentive to obtain education. The equilibrium is characterized by the steady-state version of the unskilled labor market clearing conditions (18) and (20), and by trade balance (23)–(24), yielding the equilibrium values of c^D, c^F and w^D. The labor market clearing conditions, modified to take into account that workers do not acquire education and that technology is constant, are

$$L^D = \left(\frac{c^D + c^F}{\lambda} \right) \left[\bar{\omega} \beta + \frac{(1 - \bar{\omega})}{w_L^D} \right] \text{ and } L^F = \left(\frac{c^D + c^F}{\lambda} \right) \bar{\omega}(1 - \beta),$$

where the labor supply is simply proportional to population $L^K = N^K$, and for simplicity we assume $L^D = L^F$. Since there is no innovation, we assume that with exogenous probability β domestic firms are the global leaders in neck-and-neck sectors $\bar{\omega}$, and with probability $1 - \beta$ the leadership is obtained by foreign firms. Combining these two equations we obtain

$$w_L^D = \frac{(1 - \bar{\omega})}{\bar{\omega}} \frac{1}{l(1 - \beta) - \beta}, \tag{31}$$

where $l = N^D / N^F = 1$ is the relative population. It is easy to see that $dw_L^D / d\bar{\omega} < 0$.

PROPOSITION 1. *In an economy with constant technology and no offshoring, a larger number of neck-and-neck sectors $\bar{\omega}$ leads to lower domestic wages.*

An increase in the fraction of sectors in which both domestic and foreign firms obtain a share of the global market reduces domestic wages. This is the wage-stealing effect of increasing foreign competition: as foreign firms enter new sectors in which previously only domestic firms were operating, with some positive probability β production shifts abroad and the domestic labor market clears at a lower wage. This admittedly harsh simplification for the model with local labor markets serves the sole purpose of illustrating the wage-stealing effect. In the next section, we calibrate the full model with local labor markets and show that this result holds also with endogenous technology. With endogenous technology, the share of sectors with domestic leaders is an equilibrium result of global innovation races, and an increase in $\bar{\omega}$ shifts a fraction of production abroad, thereby reducing the domestic demand for unskilled labor.

Offshoring

Factor-price equalization attained in the economy with offshoring simplifies the model substantially and allows us to derive the effects of foreign competition on inequality analytically. The results are summarized below.

PROPOSITION 2. *In an economy with complete offshoring an increase in foreign competition, triggered by a larger number of neck-and-neck sectors $\bar{\omega}$, stimulates innovation, thereby raising the relative skilled wage (w_H) and decreasing the ability cutoff θ_0*

in both regions. If the ability distribution is logconcave, a reduction in θ_0 increases the variance of skilled wages, thus raising residual inequality.

PROOF.　See Appendix.　　　　　　　　　　　　　　　　　　　　　　□

The transmission mechanism from competition to inequality here is due to the endogenous technology feature of the model. Innovation increases with $\bar{\omega}$ because global innovation in neck-and-neck sectors is higher than in gap sectors, $2I_n > I_g^D$, therefore the total labor resources devoted to innovation, the right-hand side of (26), increases with $\bar{\omega}$. This is what I call the global efficiency effect and it operates through the decreasing returns to innovation featured in technology (13): the region-level concavity of the innovation technology implies that in each industry, two skilled workers from two different regions are more productive than two skilled workers from the same region. Thus, a higher $\bar{\omega}$ leads to a larger number of sectors with higher arrival rate of innovation and, consequently, to higher demand for skills worldwide. Notice that the positive impact of a higher $\bar{\omega}$ on global innovation could be offset by a negative effect on sectorial innovation rates I_n and I_g^D. As I show in the Appendix, although $\partial I_g^D / \partial \bar{\omega}$ and $\partial I_n / \partial \bar{\omega}$ are both negative, the composition effect dominates, thus leading to an overall positive effect of foreign competition on global innovation.[27]

Equation (6), shows that an increase in the relative wage of skilled workers w_H/w_L, raises the return to education and reduces the ability cutoff θ_0 to choose education, thus increasing the share of skilled workers in the workforce. As a consequence, workers with lower ability enter the skilled workforce. If the ability distribution is logconcave—a property of many common distributions—a reduction in the cutoff θ_0 increases the variance of skilled wages, our measure of residual inequality.[28] Logoconcavity is only a sufficient condition for the wage variance to be decreasing in θ_0. In the quantitative analysis I choose a distribution among those that can be logconcave under the restrictions of the parameter and I let the calibration pin down the value of the parameters.

Finally, since an increase in skilled wages triggers a reduction in θ_0, thereby leading to a lower average ability of skilled workers, I cannot show analytically that higher $\bar{\omega}$ leads to higher average skill premium $(w_H \tilde{\theta}(\theta_0))$. The quantitative analysis that follows shows that the skill premium, as defined in (29), is increasing in competition for a wide set of plausible parameters.

Note that the complete absence of the wage-stealing effect in the economy with offshoring depends on the assumption that firms can offshore at no costs. This is a simplifying assumption that allows me to show the new channel, the global efficiency effect, as clearly as possible. Introducing costly offshoring would not change the basic result. The labor market would be only partially global, both the wage-stealing and the global-efficiency effects will be operative, and their relative strength will be determined by the offshoring costs. Multi-country quality-ladder growth models with costly offshoring became quickly intractable if one wants to maintain the key feature that both economies innovate.[29]

6.　Quantitative Analysis

In this section I calibrate the parameters of the model to match some basic long-run empirical regularities of the US economy, compute the numerical solution using the calibrated parameters and explore the effects of increasing international competition

on wage inequality. I first analyze the model for the economy with local labor markets and then study the economy with offshoring.

Calibration

I assume that abilities are drawn from the cumulative distribution function $\Gamma(\theta) = \theta^{\varepsilon}$. This is a fairly general distribution function in $(0, 1)$: when $\varepsilon = 1$, the ability is distributed uniformly in the population, when $\varepsilon < 1$ the ability distribution is skewed towards low-ability workers, and for $\varepsilon > 1$ the ability distribution is logconcave.[30] I need to calibrate ten parameters: six of them, ρ, λ, n, T_r, γ and V are calibrated using benchmarks that are standard in the literature, while the other four, A, k, α and ε are calibrated internally so that the model's steady state matches salient facts of the economy. In the quantitative analysis, I explore the effects of the increase in the international competition index shown in Figure 3 on inequality from 1979 to 1995. Instead of comparing two steady states, corresponding to the initial and final value of international competition, we show our key endogenous variables for each intermediate value of international competition to provide a more complete numerical characterization of this comparative statics.

Parameters calibrated "externally"   Some parameters of the model have close counterparts in real economies so that their calibration is straightforward. I set λ to 1.4, to match an average markup over the marginal cost of 40%. Since, estimates of average sectorial mark-up are in the interval $(0.1, 0.4)$ (Basu, 1996), I take a value within this range.[31] I choose n to match a population growth rate of 1.14% (Bureau of Labor Statistics, 1999). I choose the total schooling time $T_r = 4$ to match the average years of college in the USA, and total working life $V = 52$ to match a life expectancy at birth for cohorts turning 18 years old in 1979 of 70 years (National Vital Statistics Reports, 2010).[32] Autor et al. (2008) show that the relative supply of skills (college and above over non-college) rises from 0.138 in 1970 to 0.25 in 1990. I follow this evidence by choosing the threshold $\gamma = 0.75$ to bound the relative supply of skilled workers below 25% of the workforce. I set the discount rate equal to $\rho = 0.07$, which corresponds to an annual discount factor of about 93%.

Parameters calibrated "internally"   I simultaneously choose A, κ, α and ε so that the numerical steady-state solution of the model matches relevant US statistics. The calibrated values of parameters for the economy with local labor markets must be different from those for the economy with offshoring. In this section, I match the data to the theoretical moments from the model with local labor markets, and at the end of section 6 I consider the model with offshoring. A, α and κ are technology parameters relevant for innovation, the demand for skills and the skill premium. The shape parameter of the ability distribution ε affects the skill premium and wage dispersion. Hence I choose to calibrate A, κ, α and ε targeting the following statistics: the overall growth rate of the economy, the innovation investment share of income, the skill premium and residual inequality.[33] The parameters are calibrated in order to minimize a loss function defined by the quadratic distance between the moments in the model and the targeted statistics.

Since the paper focuses on innovation, it seems natural to use data from Corrado et al. (2009), where US national account data have been revised to introduce investment in intangible capital, a new more comprehensive measure of investment in innovation.[34] The model I set up does not have tangible (physical) capital, therefore

Table 2. Model Fit (1979)

Targeted	Data	Source	Benchmark model
Skill premium (logs)	0.4	Autor et al. (2008)	0.5
Growth rate	0.0117	Corrado et al. (2009)	0.011
Innovation/GDP	0.09	Corrado et al. (2009)	0.09
Residual inequality	0.05	Heathcote et al. (2010)	0.017

national accounting statistics used in the calibration must be adapted to the model economy. Hence, the growth rate of productivity is obtained subtracting the share attributable to tangible capital from the overall growth rate, and the income share of intangible investment is obtained subtracting investment in tangible capital from national income. After these adjustments Corrado et al. (2009) data report an average growth of labor productivity of 1.17% a year in the period 1970–1979, and an average income share of intangible investment of 0.09 in the same period. I target a skill premium of 0.4 (in logs), which is the 1979 value in Autor et al. (2008), and a residual inequality of 0.05, the 1979 data point of Figure 1 obtained with data from Heathcote et al. (2010) and Lemieux (2006). Finally, in order to calibrate $\bar{\omega}$ I use the 1979 value for the international competition index obtained in Figure 3 above, hence I set $\bar{\omega} = 0.425$. The resulting calibrated values are $A = 1.5$, $\kappa = 0.95$, $\alpha = 0.1$ and $\varepsilon = 0.9$. Table 2 shows how well the model fits the US data at the initial data, 1979.

The calibrated model fits the targeted statistics fairly closely.

International Competition and Wage Inequality: Local Labor Markets

I now analyze the effects of increasing international competition from its benchmark calibrated value $\bar{\omega} = 0.425$ to full symmetry ($\bar{\omega} = 1$) on the skill premium and on residual inequality in the economy without offshoring. Figure 4 below reports the simulation results using the benchmark parameters, the robustness of the results to change of parameters is analyzed in a separate Appendix, available upon request.

The wage-stealing effect, derived analytically for a simplified version of the model with constant technology in the previous section, is confirmed in the numerical simulation of the full model. Foreign entry in innovation in new sectors shifts market shares abroad and reduces production wages in the home region. This can be easily seen looking at the demand for domestic unskilled labor, the right-hand side of (18): an increase in $\bar{\omega}$ raises the share of industries for which global leadership is shared according to countries' relative innovation intensity $\beta = I_n^D / (I_n^D + I^F)$, therefore reducing the domestic demand for unskilled labor. Notice that this result is not simply produced by competition from a region with lower production wages. The Schumpeterian innovation structure built in the model implies that global leadership can be attained only producing a higher quality good. In existing multi-country models of endogenous technical change, wage-stealing from foreign competition is obtained as the lagging country imitates the leading technology and replaces the leading country's firm because of lower wages (e.g. Helpman, 1993). The novelty of the current model is to allow for technological leapfrogging: in order to become the world leader, the lagging country's firm must innovate and produce a higher quality good.

Endogenous technical change plays an additional role in shaping the effects of foreign competition on inequality. Foreign entry in innovation reduces domestic
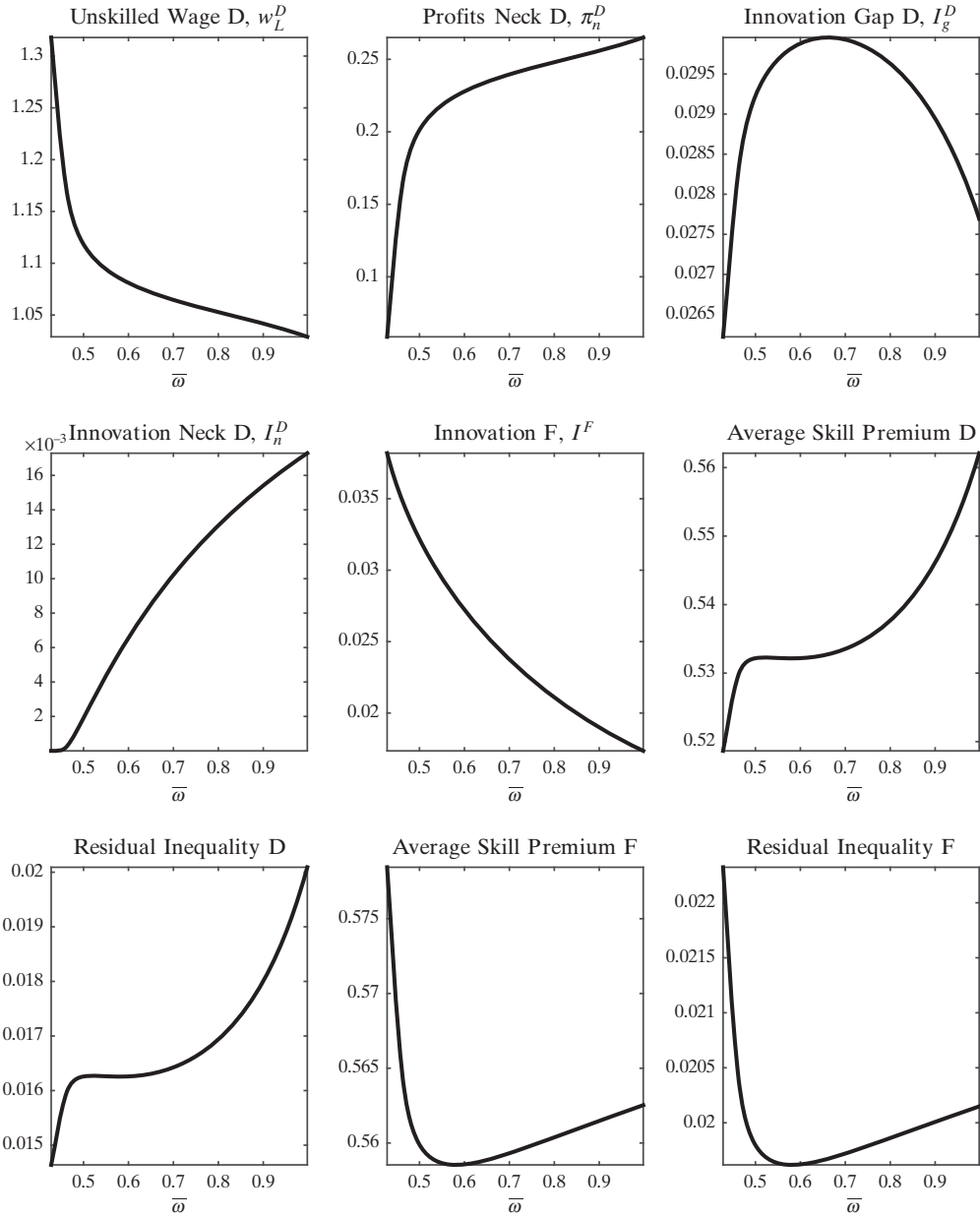
Figure 4. International Competition and Inequality: No-offshoring

unskilled wages in neck-and-neck sectors. Lower unskilled wages imply lower production costs and therefore higher domestic profit rate in those industries ($\lambda - w_L^D$ is the markup), as we can see in the figure. Since innovation is profit-driven, innovation in neck-and-neck sectors I_n^D increases, boosting the domestic demand for skills and the skill premium.[35] Hence international wage stealing increases the skill premium in the domestic region directly, because it reduces unskilled wages and indirectly, because it increases the incentive to innovate.

Besides its effect on firm-level innovation efforts, international competition can affect innovation and the relative demand of skills by changing the sectorial composition of innovation. It is easy to show that domestic firms invest less in innovation in neck-and-neck sectors, $I_n^D < I_g^D$: dividing up the first and the third condition in (27), we obtain

$$\frac{(\lambda - w_L^D)}{(\lambda - 1)} \frac{\rho + I_g^D - n}{\rho + I_n^D + I^F - n} = \left(\frac{I_n^D}{I_g^D}\right)^{\frac{\alpha}{1-\alpha}}.$$

Since domestic unskilled wage is higher than foreign, $(\lambda - w_L^D)/(\lambda - 1) < 1$, domestic innovation must be higher in gap sectors, $I_g^D > I_n^D$. This result depends on the different obsolescence of innovation in the two types of sectors: in neck-and-neck sectors there is less domestic innovation because the equilibrium value of a patent needs to accommodate foreign innovation as well. Domestic demand for skilled workers in (21) is a weighted average of I_n^D and I_g^D with weights $\bar{\omega}$ and $1 - \bar{\omega}$ respectively, hence an increase in $\bar{\omega}$ reduces total domestic demand for skills and consequently the skill premium. Quantitatively, this composition effect seems to be of second order and the wage-stealing channel seems to be the key driver of the link between international competition and inequality.

The mechanism through which increases in foreign competition affect residual inequality is the one described in section 5: a larger skill premium implies higher returns to education, leading to a lower ability cutoff θ_0^D and to a higher dispersion of skilled wages.[36] The empirical evidence in Lemieux (2006) shows that a similar channel has been driving the increase in US residual inequality in the 1980s. He shows that a large fraction of the growth in residual inequality in the 1980s is driven by an increasing dispersion of workers' abilities, which in turn can be attributed to a growing share of educated workforce.

Although the main scope of the paper is to study the response of inequality in the domestic region to increasing international competition, it is worth to briefly discuss the dynamics of foreign inequality. Figure 4 shows a U-shape relationship between $\bar{\omega}$ and both dimensions of foreign inequality, with the declining part dominating the increasing one. The economic intuition can be easily grasped because it follows from the same mechanisms at work for the domestic region. In this case the wage-stealing effect simply operates in the opposite direction: foreign entry in innovation races in a sector leads to a larger foreign production and higher demand for unskilled workers, and hence to a lower skill premium. The increasing part of the U-shaped inequality response to competition is generated by the increase in the number of sectors where foreign firms innovate, which raises foreign demand for skills.

I conclude this section assessing the quantitative relevance of the channels described above in accounting for the observed increase in the US wage inequality. Recall that the skill premium increases in the data by 21.8% and residual inequality increases by 30% in the period between 1979 and 1995. In the same period the index of international competition shown in Figure 3 raises from 0.425 to 0.69, suggesting that the foreign region, Japan and Europe in the data, was progressively catching up with the USA in the race for global innovation leadership. Taking this index as a measure of $\bar{\omega}$, I now quantify the effects of the observed increase in $\bar{\omega}$ on the two measures of inequality. Table 3 summarizes the results.

The increase in international competition observed in the data accounts for about 16% of the 21.8% increase in the US skill premium and about 45% of the observed

Table 3. International Competition and Inequality: No Offshoring

		Model	*Data*	*Explained*
Skill premium	% change (1979–1995)	0.0331	0.218	0.158
Residual inequality	% change (1979–1995)	0.136	0.3	0.453

increase in residual inequality. Notice that the particular form of the skill premium s^D adopted in (29) biases downward the effects of increasing international competition on the skill premium. Since, skilled wages are computed as w_H^D times the average ability level of the skilled workforce $\tilde{\theta}^D(\theta_0^D)$, when w_H^D increases and θ_0^D decreases, agents with lower abilities enter the skilled workforce reducing its average skill level $\tilde{\theta}^D(\theta_0^D)$ and, consequently, the average skill premium. Unskilled wages instead are not proportional to the average ability of the unskilled workforce, hence, the effects of changes in $\bar{\omega}$ on the skill premium shown in Table 3 should be interpreted as a fairly conservative quantitative evaluation.

Finally, Figure 4 shows that as $\bar{\omega}$ increases from 0.425 to 0.69, the skill premium and residual inequality in the foreign region decrease, but quantitatively the size of this effect is fairly small. Although the scope of the paper is not to explain the dynamics of inequality in the foreign region, it is worth highlighting that the model's predictions are not at odds with the evidence on foreign inequality. In fact, there is consensus that wage inequality in these countries is fairly stable and in some cases declining in the period of analysis. Fuchs-Schuendeln et al. (2010) find a declining education premium and a stable residual wage variance in Germany between 1982 and 1995. Similar results can be found in Pijoan-Mas and Sanchez-Marcos (2010) for Spain, but the data are limited to the 1990s. Domeij and Floden (2010) report sharp declines of both measures of inequality for Sweden in the period 1975–1995. Kambayashi et al. (2008) and Kawaguchi and Mori (2008), show that inequality in Japan is stable or slightly declining in our period of analysis. Jappelli and Pistaferri (2010) find a stable education premium in Italy but an increasing residual wage variance.

Although the model's predictions shown in Figure 4 suggest that inequality decreases in Japan and Europe as $\bar{\omega}$ increases from 0.425 to 0.69, in the previous section we have shown analytically that the presence of offshoring introduces a new channel that can potentially lead to an increase in inequality in both regions. This can counterbalance the negative effect shown in Figure 4 and potentially yield stable or even increasing inequality in the set of countries labelled the foreign region.

Offshoring

I now turn to the quantitative analysis of the economy with offshoring, featuring global labor markets for both types of workers. I calibrate this version of the model using the same externally calibrated parameters of the benchmark model without offshoring summarized earlier in section 6, and recalibrate the four "internal" parameters (α, A, κ, ε) targeting the same statistics of the benchmark model (growth rate, innovation/gross domestic product (GDP), the skill premium and residual inequality) but using the relevant moments computed for the model with offshoring. The new calibrated parameters are, $\alpha = 0.2$, $A = 1.12$, $\kappa = 0.1.49$ and $\varepsilon = 0.9$, Table 4 shows the fit of the model.

In Table 5, I repeat the exercise of computing the share of the observed increase in inequality that can be accounted for by an increase in $\bar{\omega}$ from 0.425 to 0.69.

Table 4. Offshoring: Model Fit (1979)

Moments	Data	Source	Benchmark model
Targeted			
Skill premium	0.4	Autor et al. (2008)	0.52
Growth rate	0.011	Corrado et al. (2009)	0.01
R&D/GDP	0.09	Corrado et al. (2009)	0.12
Variance log wages	0.05	Heathcote et al. (2010)	0.17

Table 5. International Competition and Inequality: Offshoring

		Model	Data	Explained
Skill premium	% change (1979–1995)	0.015	0.218	0.069
Residual inequality	% change (1979–1995)	0.061	0.3	0.203

In this economy the observed increase in international competition can explain about 7% of the increase in the skill premium, and about 20% of the growth in residual inequality. Thus this version of the model accounts for a smaller portion of the increase in inequality than the economy with local labor markets. Compared with the latter, here factor-price equalization implies that the increase in international competition does not trigger any wage-stealing effect. The only channel through which changes in international competition affect inequality in the leading region is by increasing the global efficiency of innovation and the results in Table 5 show the quantitative relevance of this channel only. In the economy without offshoring, instead, the efficiency effect does not operate but wage-stealing is active and seems to be quantitatively powerful.

A unified framework accounting for all these channels is the ideal next step needed to obtain a more complete assessment of the link between foreign technological competition and inequality. Available data show that the US economy is closer to the local labor market scenario than to the perfect offshoring model, but the share of offshored production and innovation is far from negligible. The BEA International Investment Statistics show that the employment share of US affiliates of multinational corporations is on average 26% in the period I focus on, and the R&D employment share of US affiliates is on average 12%. Using this data to calibrate an hybrid version of the model featuring partial offshoring is an interesting task for future research. Offshoring could be obtained as an equilibrium result driven by the balance between the costs (offshoring costs) of producing abroad and the benefits (saving trade costs). This would on the other hand enrich the set up with an interesting feature of the real world but would also complicate it severely. There are several models in the literature with equilibrium offshoring, but they mostly feature exogenous technology. Recent attempts of modeling offshoring within an endogenous technical change framework are Naghavi and Ottaviano (2009), Acemoglu et al. (2010) and Gustafsson and Segerstrom (2011). In these papers countries are symmetric, while the framework used here presents the additional difficulty of studying asymmetric countries. In a companion paper, I have undertaken a first step toward modeling costly offshoring in a quality-ladder growth model with asymmetric countries (Borota et al., 2015).

7. Conclusion

In this paper I have built a quality-ladder model of endogenous technical change in which a backward region progressively catches up with the leading region by increasing the number of industries in which its firms participate in innovation races for global leadership. Entry of firms from the lagging country in global innovation races increase innovation and wage inequality in the leading region through two channels: the wage-stealing and the global efficiency channels. The increase in international technological competition produced by foreign entry in innovation leads to global market-share losses for the leading region, and to lower production (unskilled) wages. This wage-stealing effect increases the skill premium directly by reducing unskilled wages, and indirectly by reducing the cost of innovation, the skill-using activity in the economy. Moreover, an increase in the skill premium induces workers with lower ability to acquire education and, since skilled wages are proportional to workers' ability, raises wage dispersion. Offshoring production and innovation leads to equalization of factor prices across regions and neutralizes the wage-stealing effect. With global labor markets, fiercer international competition produces higher inequality by increasing the efficiency of global innovation: if innovation technology is characterized by decreasing returns at the regional level, as empirical evidence suggests, foreign entry in innovation leads to a more efficient international allocation of resources, thereby increasing the global demand for skills and the skill premium worldwide.

The quantitative analysis uses OECD data on R&D investment in manufacturing sectors to build a model-specific measure of the degree of international technological competition between the global leader, the USA, and its followers, Japan and Europe. This measure is then used to assess the relevance of the observed change in international competition for the dynamics of US wage inequality in the 1980s and 1990s. I find that the increase in foreign competition observed in the data accounts for up to one-sixth of the surge in the US skill premium and up to about one-half of the increase in residual inequality between 1979 and 1995.

As discussed in the introduction, there are several channels contributing to the evolution of US wage inequality, each accounting for a portion of the observed increase. For instance, Burstein and Vogel (2010) study the effects of trade on wages in a quantitative trade model showing that the increase in trade and multinational production observed between 1966 and 2006 accounts each for about one-ninth of the increase in the US skill premium in that period. Dinopoulos and Segerstrom (1999) perform a similar quantitative analysis with a model of trade and endogenous technical change showing that trade liberalization accounts for about one-fifth of the increase in the US skill premium between 1970 and 1990. These numbers, together with the results of this paper, suggest that there are several plausible and quantitatively relevant channels linking globalization and wage inequality, each explaining only a fraction of the overall increase shown in the data.

Further research could extend the model by removing the assumptions of costless trade and offshoring, thus allowing for a joint analysis of trade liberalization, lower costs of offshoring, and increasing technological competition. This would provide a unifying framework to asses the role of these key features of globalization in shaping the distribution of wages. Removing the assumption of costless trade by introducing variable trade costs is straightforward, while introducing costly offshoring would be an interesting challenge. Endogenous offshoring decisions would provide a more realistic benchmark economy by making the share of offshorable activities an equilibrium

result (as e.g. Grossman and Rossi-Hansberg, 2008; Gustafsson and Segerstrom, 2011; Burstein and Vogel, 2010). This economy would be a combination of the two extreme economies studied in this paper, featuring both the wage-stealing and the efficiency effect of fiercer international competition.

Appendix

Proofs

Proof for proposition 2   Let $C = (c^D + c^F)/\lambda$ be global consumption, from (26) we know that $2\Gamma(\theta_0) = C$, thus $\theta_0 = \Gamma^{-1}(C/2)$. Using this expression for θ_0 into (6) we obtain $w_H = \sigma/[\Gamma^{-1}(C/2) - \gamma]$. Substituting this into (26) and (28) we obtain a system in three unknowns, C, I_g^D, I_n.

$$\frac{C(\lambda-1)}{\rho+2I_n-n}\frac{A}{2\kappa}\left(\frac{I_n}{A}\right)^{\frac{-\alpha}{1-\alpha}} = \frac{\sigma}{\Gamma^{-1}(C/2)-\gamma} \tag{A1}$$

$$\frac{C(\lambda-1)}{\rho+I_g^D-n}\frac{A}{2\kappa}\left(\frac{I_g^D}{A}\right)^{\frac{-\alpha}{1-\alpha}} = \frac{\sigma}{\Gamma^{-1}(C/2)-\gamma}, \tag{A2}$$

$$2\tilde{\theta}(C)\left(1-\frac{C}{2}\right)\phi = 2\kappa\left\{2\bar{\omega}\left(\frac{I_n}{A}\right)^{1/(1-\alpha)} + (1-\bar{\omega})\left(\frac{I_g^D}{A}\right)^{1/(1-\alpha)}\right\}. \tag{A3}$$

Totally differentiating equations (A1)–(A3) with respect to (w.r.t.) C, I_g^D, I_n and $\bar{\omega}$ we obtain

$$\begin{bmatrix} \Phi_1 & \Phi_2 & \Phi_3 \\ \Phi_4 & \Phi_5 & \Phi_6 \\ \Phi_7 & \Phi_8 & \Phi_9 \end{bmatrix} \begin{bmatrix} \dfrac{dC}{d\bar{\omega}} \\ \dfrac{dI_g^D}{d\bar{\omega}} \\ \dfrac{dI_n}{d\bar{\omega}} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \Phi_{10} \end{bmatrix}.$$

where Φ_1, Φ_2, Φ_3 are the derivative of (A1) w.r.t. C, I_g^D, and I_n respectively, Φ_4, Φ_5, Φ_6 are the derivative of (A2) w.r.t. C, I_g^D and I_n respectively, Φ_7, Φ_8, Φ_9, Φ_{10} are the derivative of (A3) w.r.t. C, I_g^D, I_n and $\bar{\omega}$ respectively. It is easy to show that the following results hold: $\Phi_1 > 0$, $\Phi_2 = 0$, $\Phi_3 < 0$, $\Phi_4 > 0$, $\Phi_5 < 0$, $\Phi_6 = 0$, $\Phi_8 < 0$, $\Phi_9 < 0$ and $\Phi_{10} > 0$. As I show below the sign of, Φ_7 is not relevant for the purpose of this proof. While $\Phi_{10} > 0$ if $2^{1-\alpha}I_n > I_g^D$, which can be proved as follows: combining (A1) and (A2) we obtain

$$(I_g^D)^{\frac{\alpha}{1-\alpha}}(\rho+I_g^D-n) = (I_n)^{\frac{\alpha}{1-\alpha}}(\rho+2I_n^D-n),$$

which if $2^{1-\alpha}I_n = I_g^D$ yields $1 = 2^{1-\alpha}$, which holds only for a linear R&D technology, that is $\alpha = 0$. For any $0 < \alpha < 1$, (A1) and (A2) are satisfied only if $2^{1-\alpha}I_n > I_g^D$, which allows us to proof that Φ_{10} is positive. Once we signed all of the Φs it is easy to show that $\det(\Phi) > 0$, and using Cramer's rule we obtain

$$\frac{dC}{d\bar{\omega}} = -\frac{\Phi_3\Phi_5\Phi_{10}}{\det(\Phi)} < 0, \quad \frac{dI_g^D}{d\bar{\omega}} = \frac{\Phi_3\Phi_4\Phi_{10}}{\det(\Phi)} < 0, \quad \frac{dI_n^D}{d\bar{\omega}} = \frac{\Phi_1\Phi_5\Phi_{10}}{\det(\Phi)} < 0.$$

Since $2\Gamma(\theta_0) = C$ and $w_H = \sigma/(\theta_0 - \gamma)$, we can conclude that increases in $\bar{\omega}$ raise the share of skilled workers in the economy, and increase the skill premium and residual inequality.

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Notes

1. The employment share of US affiliates of multinational corporations is on average 26%, and the R&D employment share of US affiliates is on average 12% in these years (BEA International Investment Statistics).

2. There is strong empirical evidence on decreasing returns to innovation at the country level (see e.g. Hall et al., 1986; Kortum, 1993; Blundell et al., 2002).

3. For simplicity, I abstract from offshoring costs, as they are not necessary to show the emergence of this new channel. Costly offshoring though can have an important role in affecting the quantitative results, as I discuss below.

4. Social and institutional changes have also contributed to the dynamics of wage and income inequality in the US and other countries. A line of research have studied the link between the rapid increase in assortative mating and income inequality across households (e.g. Fernandez and Rogerson, 2001; Fernandez et al., 2005; Greenwood et al., 2005). Another line of research has shown that changes in labor market institutions, such as unionization, minimum wage, firing restrictions and unemployment benefits, has contributed to the increase in several dimensions of inequality (e.g. DiNardo et al., 1996; Acemoglu et al., 2001; Koeniger et al., 2007).

5. The main argument made by the innovation policy literature is that goverments can stimulate entry in innovation by either providing, through procurement, a sufficiently large market size that allows firms to pay the high fixed entry costs and bear the high risk of investing in innovation; or facilitate commercial innovation through tax subsidies and technology transfer (see e.g. Hart, 1998; Hausman and Rodrik, 2003). For an in-depth discussion of innovation and industrial policy theories and evidence, see Fagerberg et al. (2004) and Harrison and Rodriguez-Claire (2010).

6. Rodriguez-Claire (2007) and Hsieh and Ossa (2011) focus on quantifying the welfare effects of international technology diffusion/competition as well, using different data and frameworks.

7. Davis and Naghavi (2011) study the effects of offshoring on innovation and wage inequality in an occupational choice model with heterogenous workers' skills and endogenous growth.

8. Juhn et al. (1993) and Lemieux (2006) provide comprehensive empirical analyses of the evolution of residual wage dispersion in the USA.

9. In the period 1973–1995, R&D expenditures in these countries represent between 95% and 98% of global R&D investment in manufacturing (OECD ANBERD Rev.2, 2005).

10. Since returns to schooling may reflect returns to individual ability, the changes observed in Figure 1 might be driven by composition effects (changes in the distribution of ability across education groups). As shown in Acemoglu (2002) and Acemoglu and Autor (2010) composition effects cannot account for the observed dynamics of the wage structure in the last 30 years. Hence the changes in the returns to schooling shown in the figure can be interpreted as changes in the true price of skills.

11. Since in the model residual inequality will be defined as the dispersion of wages of educated workers, the series for residual inequality in Figure 1 is obtained considering only wage dispersion among workers with a college degree or higher. The share of the total variance of residuals attributable to educated workers is obtained from Lemieux (2006) decomposition. The total variance of residuals is taken from Eckstein and Nagypal (2004).

12. Similar results are obtained with a weighted average, where sectors' shares of total R&D are used as weights. The US weighted share, for instance, decreases from 57% in 1973 to 44% in 1995.

13. The OECD classifies sectors in high-tech, medium high-tech, medium low-tech and low-tech according to their R&D intensity (see Hatzichronoglou, 1997). High-tech and medium-high-tech industries represent 77% of total manufacturing R&D in the period considered.

14. The grid is chosen in order for the bottom threshold to yield a low and the top threshold to yield a high Herfindhal index of market concentration. More precisely, when the US share of global R&D is 0.35 and the rest of the market is equally spread between the Japan and Europe, the Herfindhal index for a sector (adjusted for the number of countries) is 0.01, which indicates

a highly competitive market. While when the US R&D share is 0.68 the Herfindhal index is about 0.18, which is the level above which a market is considered highly concentrated.

15. Using the average index allows me to address the problem of sensitivity to small changes that fixing one specific threshold might produce.

16. I assume that if there are two goods with the same quality-adjusted price, consumers will buy only the good with higher quality.

17. It is easy to show that the above parameters cannot be chosen independently, but they must satisfy $\delta = n/(e^{nV} - 1)$ and $\beta = ne^{nV}/(e^{nV} - 1)$ in order for the number of births at time t to match the number of deaths at $t + V$.

18. This way of modeling the accumulation of skills has been first introduced by Findlay and Kierzkowski (1993), and extended to heterogeneous agents by Dinopoulos and Segerstrom (1999).

19. An incumbent considering investing in innovation needs to subtract its present monopoly profits from the payoff of successful innovation, whereas followers have zero profits before innovating. It follows that the value of innovation for the followers is higher than for the leader. See Aghion and Howitt (1992) for a discussion of the Arrow effect and Cozzi (2007) for a recent interpretation.

20. Without this assumption if a leader experiences successive innovations, followers will be pushed out of the market permanently. The assumption of immediate diffusion of the old production technology is discussed in Glass (1997) and widely used both in North–North models of trade and growth (e.g. Dinopoulos and Segerstrom, 1999), and in North–South models (Glass, 1997; Glass and Saggi, 1998).

21. If the cost for foreign firms is instead always lower than that of domestic firms, we would have a less general and less interesting equilibrium with only foreign firms producing in neck-and-neck sectors.

22. There is strong empirical evidence on the nonlinearity of the relation between innovation activity of a country (measured using patent data) and its R&D investment. Working with a large sample of US firm-level data, Hall et al. (1986) find an elasticity of patents to R&D of 0.5. The evidence surveyed in Kortum (1993) suggests point estimates for the patent/R&D elasticity in the range 0.1–0.6. More recently, Blundell et al. (2002) found a long-run elasticity of 0.5.

23. Eaton and Kortum (1999) adopt a similar technology in their multi-country version of the quality-ladder growth model. They suggest a microfundation for decreasing returns in innovation at the country level based on heterogeneous ability workers. As investment in innovation increases in a country, workers of lower ability will be used and productivity will decline. This microfundation applies to this model as well.

24. This specification of the difficulty index is a reduced-form version of the solution to the scale effects problem based on the assumption that aggregate R&D becomes more difficult over time as it is spread over more varieties (see e.g. Howitt, 1999). In my simplified version of this approach, population growth mimics the expansion in the variety of goods.

25. The goods in $\bar{\omega}$ would be those for which the technology gap between the most advanced country (home) and the laggards (foreign) is sufficiently small to allow the laggards to effectively compete in innovation with the leaders.

26. See Impullitti (2010) for a detailed discussion of this issue.

27. The effect of changes in $\bar{\omega}$ on innovation per sector can be attributed to the higher obsolescence of innovation produced by foreign entry.

28. An (1998) shows that the the left-truncated variance of logconcave distributions decreases in the truncation point. A probability distribution is logconcave if the log of its pdf is concave. Many common distributions are logconcave: the normal, uniform, logistic, extreme value, χ, χ^2 and Laplace. Other common distributions such as the power, Weibul, γ, χ, χ^2 and β are logconcave for values of their parameters larger than one (Bagnoli and Bergstrom, 2005). Logconcavity is only a sufficient condition for the variance of a left-truncated distribution to be decreasing in the truncation point. The Pareto distribution, for instance, is not logconcave but its variance is decreasing in the left-truncation point.

29. Dinopoulos and Segerstrom (2010) introduce costly offshoring in a North–South quality-ladder model in which only the North innovates while the South imitates. A first attempt at introducing costly multinational activity in multi-county quality-ladder growth models where firms from both countries innovate can be found in Borota et al. (2015).

30. This distribution is often used in quantitative models with heterogeneous agents, to match wage, income and earning dispersion. See e.g. Chatterjee et al. (2007) and Antunes et al. (2008).

31. I take the upper value of the range because the numerical solution is more robust with high λs.

32. I consider that agents choose whether to go to college at age 18, so that the 18 years old cohort in 1979 is represented by people born in 1961, and life expectancy at birth in 1961 in the USA is 70 years. I also include retirment years into working life assuming that pensions are proportional (equal for simplicity) to wages during working life.

33. In the present framework with quality-improving goods, growth is interpreted as the increase over time of the consumer's utility level, which is pinned down by the growth rate of quality. It is easy to show that the growth rate is

$$g = \frac{\dot{u}}{u} = \frac{\dot{O}(t)}{O(t)} = [\bar{\omega}(I_n^D + I^F) + (1 - \bar{\omega})I_g^D]\ln \lambda.$$

34. It includes R&D, computer software, and investment in a set of activities aimed at improving existing goods, such as, advertising, design, marketing, etc.

35. Notice that the domestic innovation per firm in gap sectors I_g^D increases for low levels of $\bar{\omega}$ and then it decreases. The increase in I_g^D is a general equilibrium result produced by the optimal allocation of domestic innovation investment between neck-and-neck and gap sectors. This additional innovation effect of competition is, though, quantitatively of second order with respect to the increase in I_n^D: the former increases by about 10% as $\bar{\omega}$ goes from 0.425 to 1, while the latter grows by more than 250%. Thus the relevant source of the increase in the relative demand of skills is innovation in neck-and-neck industries.

36. Notice that, although the calibrated ability distribution is not logconcave ($\varepsilon = 0.9$), the simulation in Figure 4 shows that the variance of skilled wages increases as the cutoff θ_0^D declines. As discussed above, a logconcave ability distribution is only a sufficient condition for the wage dispersion to be decreasing in the ability cutoff.