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TRADE, TECHNOLOGY, AND THE GREAT DIVERGENCE

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ABSTRACT

Why did per capita income divergence occur so dramatically during the 19th century, rather than at the outset of the Industrial Revolution? How were some countries able to reverse this trend during the globalization of the late 20th century? To answer these questions, this paper develops a trade-and-growth model that captures the key features of the Industrial Revolution and Great Divergence between a core industrializing region and a peripheral and potentially lagging region. The model includes both endogenous biased technological change and intercontinental trade. An Industrial Revolution begins as a sequence of more unskilled-labor-intensive innovations in both regions. We show that the subsequent co-evolution of trade and directed technologies can create a delayed but inevitable divergence in demographics and living standards—the peripheral region increasingly specializes in production that worsens its terms of trade and spurs even greater fertility increases and educational declines. Allowing for eventual technological diffusion between regions can mitigate and even reverse divergence, spurring a reversal of fortune for peripheral regions.

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The huge asymmetries between advanced and developing countries have not disappeared, but they are declining, and the pattern for the first time in 250 years is convergence rather than divergence.

— Michael Spence, *The Next Convergence* (2011)

1. Introduction

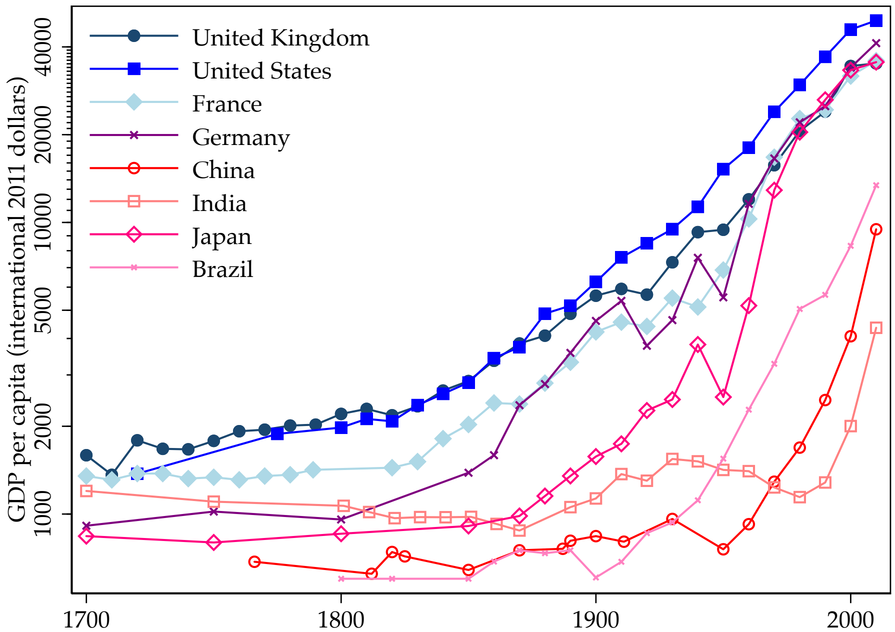
The last two centuries have witnessed dramatic changes in the global distribution of income and one of the great tasks of economics is to explain why. Within that broad debate there lingers the unresolved question as to whether globalization is a force for convergence or divergence.

As Figure 1 shows, at the dawn of the Industrial Revolution, circa 1750–1800, gaps in living standards between the richest and poorest economies of the world were roughly in the range 2 to 1. With industrialization came both income and population growth in a few core countries. But massive divergence in living standards across the globe did not emerge right away. It only got decisively underway a century later, in the latter half of the 19th century, at the time when the first great era of globalization started to take shape. Today the gap in material living standards between the richest and poorest economies of the world is of the order of 30 or 40 to 1, in large part due to the Great Divergence of the 1850–1950 era and its aftermath. And yet today, as the world experiences a second era of globalization, a few formerly developing countries in the "South" are now on an outward-oriented path towards convergence with the "North" and global inequality is starting to abate.

It seems to us an interesting coincidence that the unprecedented growth in 19th century inter-continental commerce (conceivably creating a powerful force for convergence by inducing countries to exploit their comparative advantages) coincided so precisely with an unprecedented divergence in living standards across the world. Why did incomes diverge just as the world became flatter? And yet, in another interesting coincidence, why are some poor countries today able to replace divergence with convergence, even in the midst of a second era of globalization? We want to confront these questions.

Globalization is a multidimensional phenomenon. In this paper, we focus on two dimensions that seem particularly relevant to the international distribution of income: rising levels of inter-continental trade and the faster diffusion of knowledge between countries. Economic theory is ambiguous about whether the former, in particular,

Figure 1: *Real GDP per capita in eight economies since 1700*



Source: Maddison Project (2018).

promotes convergence or divergence between rich and poor countries (Grossman and Helpman 1991). Can a unified model be found which helps explain the very different experiences of the first and second eras of globalization?

The main goal of this paper is to present a unified growth model where both pro- and anti-convergence forces are potentially present, but where their relative strengths are generally state- and history-dependent. We argue that historical trade and technological growth patterns *jointly* sowed the seeds of divergence, contributing enormously to today's great wealth disparities, while they are now operating so as to mitigate these disparities.

Some stylized facts from economic history motivate our search for a new theory. One concerns the nature of industrialization itself—technological change in the Western world was unskilled-labor-intensive during the early Industrial Revolution but became relatively skill-intensive in the late 19th century. For example, the cotton textile industry, which along with metallurgy was at the heart of the early Industrial Revolution, could employ large numbers of unskilled and uneducated workers, thus diminishing the relative demand for skilled labor and education (Galor 2005; Clark 2007; de Pleijt and Weisdorf 2017). By the 1850s, however, two major changes had occurred—technological growth became much more widespread, and it became far more skill-using (Mokyr 2002).

Another factor of great importance was the role of international trade in the world economy. Precisely when inter-continental trade of goods became a major factor influencing wages and incomes continues to be a source of much debate; while both the volume of trade, and the extent of market integration, advanced spectacularly in the 19th century, ocean-going commerce was much older (O'Rourke and Williamson 1994; O'Rourke, Taylor, and Williamson 1996; O'Rourke and Williamson 1999, Chapter 4; de Vries 2010; de Zwart and van Zanden 2018). We thus model the impact of continuously declining trade costs on incomes across the world.

Modeling Trade and Divergence We develop a two-region "North-South" model with several key features mimicking these historical realities. The first key feature of the model is that we endogenize the extent and direction of bias of technological change in both regions. Technologies are sector specific, and sectors have different degrees of skill intensity. Following the endogenous growth literature, we will allow potential innovators in each region to observe factor use in different sectors and tailor their research efforts towards particular sectors, via directed technical change (Acemoglu 2002). Thus, the scope and direction of innovation will depend on each region's factor endowments and hence on its demography.

We also formulate the model in a way that allows for technological diffusion, where technologies can be employed by producers from regions other than those where the technologies were originally developed. From radio to television, fiber-optics, cellular and internet technologies, the 20th century increasingly produced a world where knowledge could no longer be confined to a single locale. In our framework innovators from one region cannot prevent or profit from the use of their inventions in other regions, an assumption perhaps suitable for core-peripheral economies (see Eaton and Kortum 1999 for alternative diffusion processes more aligned with relationships among advanced economies).

The third key feature is that we endogenize demography itself. More specifically, we allow households to make education and fertility decisions based on market wages for skilled and unskilled labor, as in other endogenous demography and unified growth theories in which households face a quality-quantity tradeoff with respect to their children (Galor and Mountford 2006, 2008; Klemp and Weisdorf 2019). When the premium for skilled labor rises, families will tend to have fewer but better educated children.

The final feature is that we allow for trade between the two regions. Trade can occur due to differences both in sector-specific technologies (Ricardian) and in factor endowments (Hecksher-Ohlin).[1] Indeed we assume that initially each region has only

[1] We know that Heckscher-Ohlin trade was important during the 19th century since commodity price

one exogenous difference—when the model starts, the peripheral region is endowed with more unskilled workers relative to skilled workers, compared with the core region. This will have implications for both the pattern of trade flows and the direction of technical change.

In this manner, given our model, we can ask if such an initial endowment difference between two regions, driven by a single parameter difference, can result in dramatic per capita income divergence over time.[2]

The answer? As is so often the case in economics, we find that "it depends." Why, and on what? We simulate the model in two basic ways:

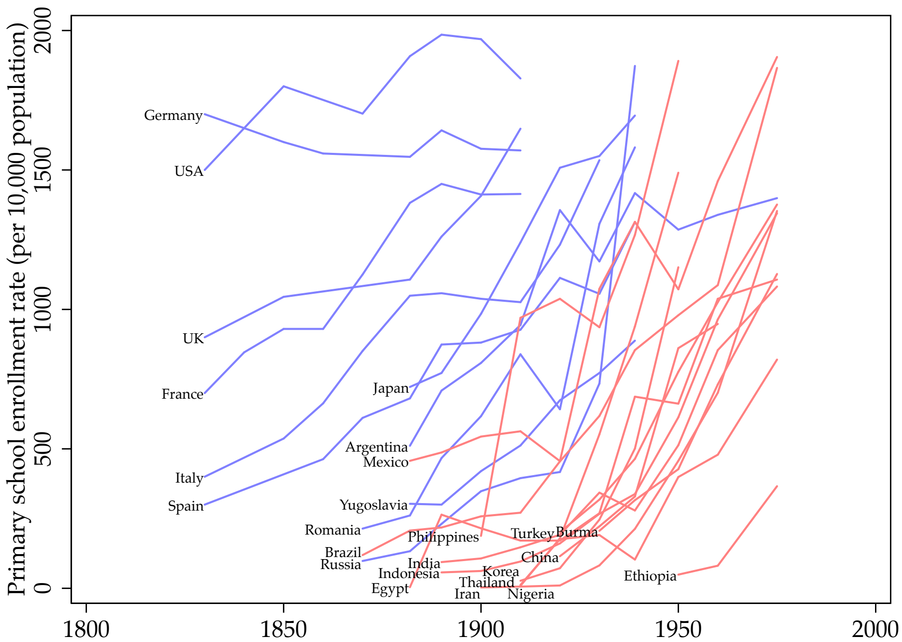
The first assumes that technologies are strictly locally developed and employed, and trade is *initially* not feasible due to high transportation costs. We present results for a case which we suggest roughly captures the dynamics for the period from the 1700s to the mid-1900s. Because of the great abundance of unskilled labor in the world, innovators everywhere first develop unskilled-labor intensive technologies. Early industrialization is thus characterized by a fair amount of unskilled-labor-intensive technological growth and population growth *both* in the North and the South. At first, living standards even *slightly* converge during this period. Once trade develops and becomes more specialized, however, the North becomes more focused on skill-intensive innovation and production. This induces a demographic transition of falling fertility and rising education rates in the North, while the South specializes in unskilled-labor-intensive production, inducing both unskilled-labor-intensive technological growth and further population growth (Figures 2 and 3). This feedback-driven population divergence fosters a deterioration in the South's terms of trade (Figure 4), forcing the South to produce more and more unskilled-labor-intensive goods and generating even more fertility increases. Thus, although North and South both enjoy static gains from trade, over time these become a dynamic impediment to prosperity in the South, and living standards between the two regions eventually diverge dramatically.

We also simulate an alternative scenario more reminiscent of the mid- and later- 20th century, and perhaps the 21st also. The set-up is the same as before, except in this case we allow for the possibility of eventual technological diffusion from one region to the

convergence induced factor price convergence during this period (O'Rourke and Williamson 1999). And Mitchener and Yan (2014) suggest that unskilled-labor abundant China exported more unskilled-labor-intensive goods and imported more skill-intensive goods from 1903 to 1928, consistent with such a trade model.

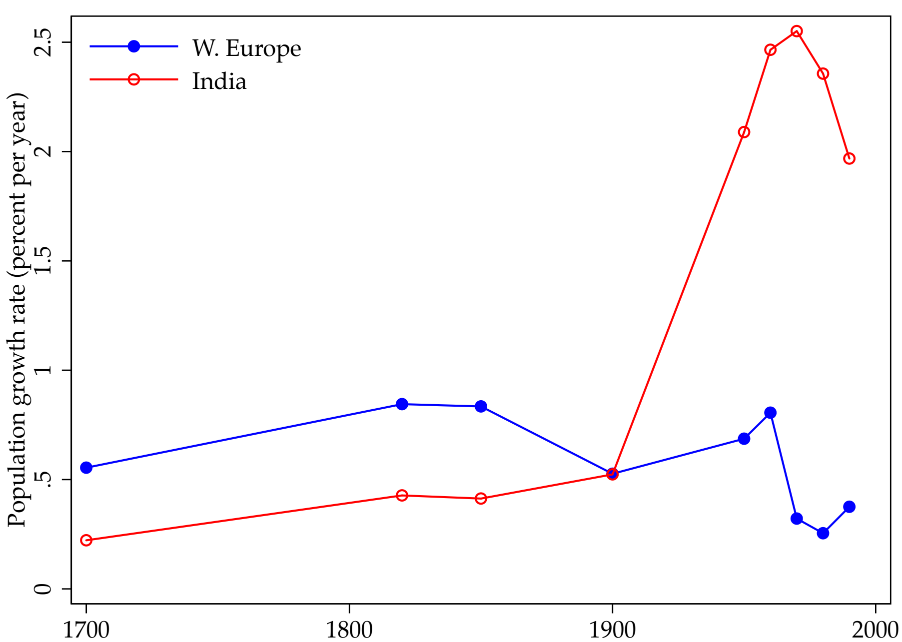
[2]While we fully acknowledge the potential importance of many deeper factors shaping historic divergence between core and periphery (such as those highlighted in Acemoglu and Robinson 2012), here we abstract from all these to highlight the extent to which one simple initial difference can shape long run divergences in growth paths.

Figure 2: *Primary school enrollment rates in many economies since 1800*



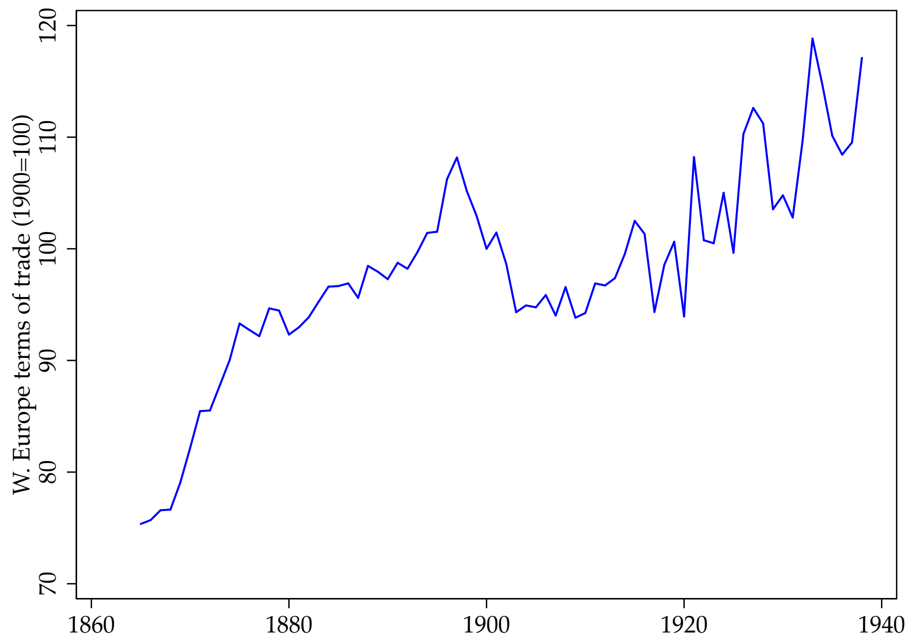
Source: Easterlin (1981).

Figure 3: *Population growth rates in Western Europe and India since 1700*



Source: Maddison (2010).

Figure 4: *Western European terms of trade 1870–1938*



Source: Author's calculations based on Hadass and Williamson (2003).

other. Each region can either develop their own technologies for local use, or adopt from the pool of available world technologies, where the degree of availability is subject to "technology iceberg costs."

We show that in this case trade and technological change can still interact so as to generate some divergence early on. This occurs because skill-oriented technologies developed in the North are somewhat "inappropriate" in the South, given endowment differences. But we also show that this divergence must eventually give way to convergence. This is because trade-induced skilled specialization in the North generates a deep pool of skill-intensive technologies from which even the South, with its relatively low endowment of skilled workers, can benefit in the end. That is, what is in the short run "inappropriate" (for a low-skill, high-fertility South) may in the long run benefit living standards by eventually leading the South down a high-skill, low-fertility path (see the rapid convergence in education for many 20th century economies in Figure 2).

Finally, we explore hybrid cases where iceberg costs for the trade of goods and/or the flow of technologies evolve over different periods of time. Specifically, we highlight the case, perhaps most aligned with historical global trends, where first trade technologies improve followed by improvements in technological transfers. This produces an interesting case where initial trade patterns produce divergence, but this can give way to sudden and dramatic convergence as the South can increasingly adopt Northern technologies. We demonstrate that Northern specialization generates a skill-intensive pool of knowledge that the South can *eventually* exploit. Indeed we show that this can even cause a reversal of technological leadership, with the South becoming the global innovator.

Relation to Galor and Mountford's "Trade and the Great Divergence" The paper presented here relates most closely and obviously to Oded Galor and Andrew Mountford's theoretical works on the Great Divergence (Galor and Mountford 2006, 2008) (henceforward 'GM'). These papers similarly suggest that the developing region's specialization in unskilled-intensive production stimulated fertility increases which lowered per capita living standards. But this narrative remains incomplete — a number of puzzles regarding the evolution of the income gap between core and peripheral regions remain, some raised by GM themselves. Four puzzles in particular stand out, each of which we tackle in this new theory.

1) **Intercontinental trade existed before the 19th century.** As de Zwart and van Zanden (2018) argue in their new book, global flows of ships and commodities between 1500 and 1800 were substantial, yet no great divergence in living standards between the continents emerged. A model is needed that has relative economic parity during early industrialization, considerable divergence during the second Industrial Revolution, and the potential for rapid convergence during the later 20th century, all in a non-autarkic context.

2) **Peripheral economies were not consigned to stagnant sectors.** In GM the South ends up specialized in the inherently stagnant sector once trade becomes possible. This assumption generates divergence, but fits rather awkwardly with both growth theory and history. Early industrialization may have been confined to a few sectors, but by 1900 no economic sector in the North was untouched by technological progress. So called low-technology sectors such as agriculture enjoyed large productivity advances during the early stages of the Industrial Revolution (Lipsey and Bekar 1995; Clark 2007). And in the twentieth century developing countries specialized in textile production which had experienced massive technological improvements more than a century earlier. Rather than consigning the periphery to the inherently slower-growing industry, we endogenize the direction and speed of technologies in both regions.

A related puzzle has to do with the size of the developing world. If fully one third of the world had become either Indian or Chinese by the twentieth century (Galor and Mountford 2002), why were Indians and Chinese not wealthier? After all, most semi-endogenous and endogenous growth theories have some form of scale effect, whereby large populations can spur innovation (Acemoglu 2010; Jones 2003).[3] Any divergence story that focuses on the explosive population expansion in peripheral economies faces this awkward implication from the canonical growth literature.

3) **The pattern of divergence switches to convergence for many during the 20th century due to technological transfer.** Absent from GM is the possibility of technological transfer. This would seem to be of great relevance in the 20th and 21st centuries, as peripheral economies have become increasingly capable of adopting ideas from the world technological frontier as a result of better education, better communications, multinational enterprise, value-chain participation, and so on (Baldwin 2016). Using data for both OECD and non-OECD countries for the later 20th century, Klenow and Rodriguez-Clare (2005) suggest that during this period most gains in income levels above subsistence have been due to the international diffusion of knowledge. For more recent times technologies can be transferred in ways scarcely possible during the 19th century. For example, to facilitate knowledge transfers, multinationals often use local inventors working in affiliate inventor teams in developing countries, helping poor countries escape the knowledge trap (Branstetter et al. 2018). And the presence of foreign multinational enterprises during the 1990s and 2000s typically promoted the technological catch-up of local firms (Peri and Urban 2006, Bilir and Morales 2016).

Our model demonstrates that under the assumption of perfect technological diffusion the trade-technology interactions we emphasize can now work in the opposite direction: they may hasten divergence initially, but they will promote *convergence* in the longer term. Thus we provide the novel insight that the kind of technological diffusion regime in place may play a crucial role in determining whether or not trade generates per capita income convergence or divergence.

4) **By long-run growth standards, the East-Asian growth miracle was remarkably rapid.** Finally, certain East Asian economies were able to converge to Western living standards with unprecedented rapidity in the 1960s and 70s. In particular Korea and Taiwan began rapid industrialization by exploiting "a backlog of technology" that had been globally accumulating for decades (Perkins and Tang 2017). Unified growth theory has yet to uncover a cogent explanation for this within a model that can simultaneously account for other growth episodes and earlier divergence. Once again, we offer a model with a partial explanation — through the confluence of trade patterns and directed technical change, these economies were suddenly able to adopt from the world technological

[3] More specifically, in such seminal endogenous growth models as Romer (1986, 1990), Segerstrom, Anant, and Dinopolous (1990), Aghion and Howitt (1992), and Grossman and Helpman (1991), a larger labor force implies faster technological progress. In "semi-endogenous" growth models such as Jones (1995), Young (1998), and Howitt (1999), a larger labor force implies a higher level of technology.

frontier, and then were able to contribute to it, leading to a reversal of technological leadership and very rapid income convergence.

These key differences allow our model to address two fundamental issues on which the GM approach is silent. The first has to do with the terms of trade between core and periphery. The South's specialization in unskilled-intensive goods allows for plenty of technological advance, but this does not promote per capita growth in our model for two reasons. One is that it fosters fertility increases similar to the process outlined in GM. The other is that the South's terms of trade deteriorate over time. As the South's share of the world population grows, it floods world markets with its products. The North's skill-intensive products become relatively scarcer, and thus fetch higher prices. The South has to provide more and more low-end exports to buy the same amount of high-end imports from North; through the impact of the terms of trade on factor prices, this raises fertility rates even more. This mechanism, absent in GM's work, suggests that productivity growth (and the scale of the Southern economy that generated this growth) could not save the South—in fact, it contributed to its relative decline.

The other issue relates to the potential of technological catch-up and even technological leapfrogging. Without the possibility of knowledge transfer, GM's periphery is consigned to relative stagnation due to its specialization in the inherently slower-growth sector. In our model we demonstrate that trade, while generating divergence for a time, also generates a pool of skill-intensive technologies by the North that can eventually be adopted by the South, resurrecting erstwhile dead sectors and facilitating an educational renaissance.

2. Production with Given Technologies and Factors

We now present our model which describes a world consisting of a core Northern economy and a peripheral Southern economy.

Total production for a region is given by

$$Y^n = \left(\frac{\alpha}{2}\left(Q_1^n + aZ_1\right)^{\frac{\sigma-1}{\sigma}} + (1-\alpha)\left(Q_2^n\right)^{\frac{\sigma-1}{\sigma}} + \frac{\alpha}{2}\left(Q_3^n - Z_3\right)^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}, \quad (1)$$

$$Y^s = \left(\frac{\alpha}{2}\left(Q_1^s - Z_1\right)^{\frac{\sigma-1}{\sigma}} + (1-\alpha)\left(Q_2^s\right)^{\frac{\sigma-1}{\sigma}} + \frac{\alpha}{2}\left(Q_3^s + aZ_3\right)^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}, \quad (2)$$

where $\alpha \in [0,1]$ and $\sigma \geq 0$ is the elasticity of substitution among the three intermediate goods Q_1, Q_2, and Q_3. Z_1 is s's export of good 1 to country n, while Z_3 is n's export of good 3 to country s. Trade may be subject to iceberg costs $0 \leq a \leq 1$ — while amount Z

may be exported from a region, only aZ of the good reaches the other region. If a is too low trade may not be feasible, in which case each region remains in autarky. Given initial factor endowments (which we explain below) and a large enough a, n exports sector 3 goods in exchange for sector 1 goods.[4]

We will suppress country superscripts for now, re-introducing them in section 5. The production of intermediate goods is given by:

$$Q_1 = A_1 L_1\,, \tag{3}$$

$$Q_2 = A_2 L_2^{\gamma} H_2^{1-\gamma}\,, \tag{4}$$

$$Q_3 = A_3 H_3\,, \tag{5}$$

where A_1, A_2 and A_3 are the technological levels of sectors 1, 2, and 3, respectively.[5]

In turn, the technological levels of each sector are represented by an aggregation of *sector-specific* machines per worker. Specifically,

$$A_1 = \int_0^{N_1} \left(\frac{x_1(j)}{L_1} \right)^{\alpha} dj\,, \tag{6}$$

$$A_2 = \int_0^{N_2} \left(\frac{x_2(j)}{L_2^{\gamma} H_2^{1-\gamma}} \right)^{\alpha} dj\,, \tag{7}$$

$$A_3 = \int_0^{N_3} \left(\frac{x_3(j)}{H_3} \right)^{\alpha} dj\,, \tag{8}$$

where $x_i(j)$ is the number of machines of type j that can be employed only in sector i. Intermediate producers choose the amounts of these machines to employ, but the number of *types* of machines in each sector is exogenous to producers. Technological progress in sector i can then be represented by growth in this number of machine-types for the sector, which we denote by N_i (we endogenize the growth of these in the next sections by introducing researchers).

Treating technological coefficients as exogenous for the time being, we assume that markets for both the final good and the intermediate goods are perfectly competitive. Thus, prices are equal to unit costs. Solving the cost minimization problems for producers,

[4]Negative values of Z_1 would imply imports of good 1 by country s; negative values of Z_3 would imply imports of good 3 by country n. We do not consider such cases in this paper.

[5]Thus sectors vary by *skill*-intensity. While our interest is mainly in the "extreme" sectors (1 and 3), we require an intermediate sector so that production of intermediate goods are determined both by relative prices and endowments, and not pre-determined solely by endowments of L and H. This will be important when we introduce trade to the model.

and normalizing the price of final output to one, yields the unit cost functions

$$
\begin{aligned}
1 &= \left[\left(\frac{\alpha}{2}\right)^{\sigma}(p_1)^{1-\sigma} + (1-\alpha)^{\sigma}(p_2)^{1-\sigma} + \left(\frac{\alpha}{2}\right)^{\sigma}(p_3)^{1-\sigma}\right]^{\frac{1}{1-\sigma}}, && (9)\\
p_1 &= \frac{w_l}{A_1}, && (10)\\
p_2 &= \left(\frac{1}{A_2}\right) w_l^{\gamma} w_h^{1-\gamma}(1-\gamma)^{\gamma-1}\gamma^{-\gamma}, && (11)\\
p_3 &= \frac{w_h}{A_3}, && (12)
\end{aligned}
$$

where p_i denotes the price for intermediate good Q_i, w_l is the wage paid to L and w_h is the wage paid to H.

Full employment of unskilled and skilled labor implies factor-market clearing, with

$$
\begin{aligned}
L &= \frac{Q_1}{A_1} + \frac{w_l^{\gamma-1} w_h^{1-\gamma}(1-\gamma)^{\gamma-1}\gamma^{1-\gamma} Q_2}{A_2}, && (13)\\
H &= \frac{w_l^{\gamma} w_h^{-\gamma}(1-\gamma)^{\gamma}\gamma^{-\gamma} Q_2}{A_2} + \frac{Q_3}{A_3}. && (14)
\end{aligned}
$$

The demands for intermediate goods from final producers can be derived from a standard CES objective function.[6] Specifically, as shown in the appendix, intermediate goods market clearing requires

$$
Q_i = \left(\frac{\xi_i^{\sigma} p_i^{-\sigma}}{\left(\frac{\alpha}{2}\right)^{\sigma}(p_1)^{1-\sigma} + (1-\alpha)^{\sigma}(p_2)^{1-\sigma} + \left(\frac{\alpha}{2}\right)^{\sigma}(p_3)^{1-\sigma}}\right) Y, \qquad (15)
$$

for $i = 1, 2, 3$, and for convenience we define constants $\xi_1 = \xi_3 = \frac{1}{2}\alpha$, and $\xi_2 = 1 - \alpha$.

Finally, if trade is feasible it remains balanced, so that balance of payments can be described as

$$
\frac{p_1^n}{p_3^n} = \frac{Z_3}{aZ_1}, \qquad (16)
$$

$$
\frac{p_1^s}{p_3^s} = \frac{aZ_3}{Z_1}. \qquad (17)
$$

Provided that we have values for L, H, A_1, A_2, and A_3, along with parameter values, we have fifteen equations [(1)–(5), (9)–(14), three instances of (15) and balance of payments (16)–(17)] with fifteen unknowns [Y, p_1, p_2, p_3, Q_1, Q_2, Q_3, w_l, w_h, L_1, L_2, H_2, H_3, Z_1, Z_3].

[6] Here demands will be negatively related to own price, will be a function of a price index, and will be proportional to total product.

The solution for all of these variables constitutes the solution for the *static* model in the case of exogenously determined technological and demographic variables.

3. Endogenizing Technologies in Both Regions

In this section we describe how innovators endogenously develop new technologies. In general, modeling purposive research and development effort is challenging when prices and factors change over time. This is because it is typically assumed that the gains from innovation will flow to the innovator over time, and this flow will depend on the price of the product being produced and the factors required for production at each moment in time.[7] If prices and factors are constantly changing (as they will in any economy where trade barriers fall gradually or factors evolve endogenously), a calculation of the true discounted profits from an invention may be impossibly complicated.

To avoid such needless complication but still gain from the insights of endogenous growth theory, we will assume that the gains from innovation last *one time period only.* More specifically, technological progress is sector-specific, and comes about through increases in the numbers of varieties of machines employed in each sector. The new varieties of machines are developed by profit-maximizing inventors, who for one period can *monopolistically* produce and sell the machines to competitive producers of the intermediate goods Q_1, Q_2, or Q_3. However, we assume that the blueprints to these machines become public knowledge in the period after the machine is invented, at which point these machines become old and are *competitively* produced and sold.[8] Thus while we need to distinguish between old and new sector-specific machines, we avoid complicated dynamic programming problems inherent in multiple-period profit streams.[9]

With these assumptions, we can re-define sector-specific technological levels in equations (6)–(8) as a sum over old and new machines at time t (once again suppressing region

[7] For example, the seminal Romer (1990) model describes the discounted present value of a new invention as a positive function of $L - L_R$, where L is total workforce and L_R is the number of researchers. Calculating this value is fairly straightforward if supplies of production workers and researchers are constant. If they are not, however, calculating the true benefits to the inventor may be difficult.

[8] Here one can assume either that patent protection for intellectual property lasts one time period, or that it takes one time period for potential competitors to reverse-engineer the blueprints for new machines.

[9] See Rahman (2013) for more discussion of this simplifying (but arguably realistic) assumption.

superscripts) with

$$A_{1,t} = \left(\int_0^{N_{1,t-1}} x_{1,old}(j)^\alpha dj + \int_{N_{1,t-1}}^{N_{1,t}} x_{1,new}(j)^\alpha dj \right) \left(\frac{1}{L_1} \right)^\alpha , \tag{18}$$

$$A_{2,t} = \left(\int_0^{N_{2,t-1}} x_{2,old}(j)^\alpha dj + \int_{N_{2,t-1}}^{N_{2,t}} x_{2,new}(j)^\alpha dj \right) \left(\frac{1}{L_2^\gamma H_2^{1-\gamma}} \right)^\alpha , \tag{19}$$

$$A_{3,t} = \left(\int_0^{N_{3,t-1}} x_{3,old}(j)^\alpha dj + \int_{N_{3,t-1}}^{N_{3,t}} x_{3,new}(j)^\alpha dj \right) \left(\frac{1}{H_3} \right)^\alpha , \tag{20}$$

where $x_{i,old}$ are machines invented before t, and $x_{i,new}$ are machines invented at t. Thus in each sector i there are $N_{i,t-1}$ varieties of old machines that are competitively produced, and there are $N_{i,t} - N_{i,t-1}$ varieties of new machines that are monopolistically produced (again, suppressing country subscripts).

Next, we must describe the producers of the intermediate goods. In each region, these three different groups of producers each separately solve the profit maximization problems

$$\text{Sector 1 producers:} \quad \max_{[L_1, x_1(j)]} \left\{ p_1 Q_1 - w_l L_1 - \int_0^{N_1} \chi_1(j) x_1(j) dj \right\} ,$$

$$\text{Sector 2 producers:} \quad \max_{[L_2, H_2, x_2(j)]} \left\{ p_2 Q_2 - w_l L_2 - w_h H_2 - \int_0^{N_2} \chi_2(j) x_2(j) dj \right\} ,$$

$$\text{Sector 3 producers:} \quad \max_{[H_3, x_3(j)]} \left\{ p_3 Q_3 - w_h H_3 - \int_0^{N_3} \chi_3(j) x_3(j) dj \right\} ,$$

where $\chi_i(j)$ is the price of machine j employed in sector i. For each type of producer, their maximization problem with respect to machine j yields machine demands

$$x_1(j) = \chi_1(j)^{\frac{1}{\alpha-1}} (\alpha p_1)^{\frac{1}{1-\alpha}} L_1 , \tag{21}$$

$$x_2(j) = \chi_2(j)^{\frac{1}{\alpha-1}} (\alpha p_2)^{\frac{1}{1-\alpha}} L_2^\gamma H_2^{1-\gamma} , \tag{22}$$

$$x_3(j) = \chi_3(j)^{\frac{1}{\alpha-1}} (\alpha p_3)^{\frac{1}{1-\alpha}} H_3 . \tag{23}$$

New machine producers, having the sole right to produce the machine, will set the price of their machines to maximize the instantaneous one-period profit. This price will be a constant markup over the marginal cost of producing a machine. Assuming that the cost of making a machine is unitary implies that their prices will be set at $\chi_1(j) = \chi_2(j) = \chi_3(j) = \chi = 1/\alpha$ for new machines. Thus, substituting in this mark-up price, and realizing that instantaneous profits are $(1/\alpha) - 1$ multiplied by the number of new machines sold, instantaneous revenues for new machine producers are given by

$$r_1 = \left(\frac{1-\alpha}{\alpha}\right)\alpha^{\frac{2}{1-\alpha}}(p_1)^{\frac{1}{1-\alpha}} L_1 \,, \tag{24}$$

$$r_2 = \left(\frac{1-\alpha}{\alpha}\right)\alpha^{\frac{2}{1-\alpha}}(p_2)^{\frac{1}{1-\alpha}} L_2^{\gamma} H_2^{1-\gamma} \,, \tag{25}$$

$$r_3 = \left(\frac{1-\alpha}{\alpha}\right)\alpha^{\frac{2}{1-\alpha}}(p_3)^{\frac{1}{1-\alpha}} H_3 \,. \tag{26}$$

Old machines, on the other hand, are competitively produced, and this drives the price down to marginal cost, so prices will be set at $\chi_1(j) = \chi_2(j) = \chi_3(j) = \chi = 1$ for all old machines. Sectoral productivities can then be expressed simply as a combination of old and new machines demanded by producers. Plugging in the appropriate machine prices into our machine demand expressions (21)–(23), and plugging these machine demands into our sectoral productivities (18)–(20), we can solve for the productivities

$$A_1 = \left(N_{1,t-1} + \alpha^{\frac{\alpha}{1-\alpha}}\left(N_{1,t} - N_{1,t-1}\right)\right)(\alpha p_1)^{\frac{\alpha}{1-\alpha}} \,, \tag{27}$$

$$A_2 = \left(N_{2,t-1} + \alpha^{\frac{\alpha}{1-\alpha}}\left(N_{2,t} - N_{2,t-1}\right)\right)(\alpha p_2)^{\frac{\alpha}{1-\alpha}} \,, \tag{28}$$

$$A_3 = \left(N_{3,t-1} + \alpha^{\frac{\alpha}{1-\alpha}}\left(N_{3,t} - N_{3,t-1}\right)\right)(\alpha p_3)^{\frac{\alpha}{1-\alpha}} \,. \tag{29}$$

Thus, given the number of types of old and new machines that can be used in each sector (where the evolution of these will be described below in section 5.1), we can then simultaneously solve equations (9)–(15) and (27)–(29) to solve for prices, wages, intermediate goods, and technological levels for a hypothetical economy.

4. Endogenizing Population and Labor-Types in Both Regions

Our next goal is to endogenize the levels of skilled and unskilled labor in this hypothetical economy. We utilize an overlapping generations framework where individuals in each region live for two periods. In the first period, representing youth, individuals work as unskilled workers to earn income for their parents; this income is consumed by their parents. In the second period, representing adulthood, individuals decide whether or not to expend a fixed resource cost to become a skilled worker. Adults also decide how many children to have, and these children earn unskilled income for the adults. Adults, however, forgo some income for child-rearing.

Specifically, we assume that each adult (later indexed by k) has the objective to maximize current-period income. If an adult chooses to remain an unskilled worker (L), she aims to maximize income I_l with respect to her number of children, where

$$I_l = w_l + n_l\, w_l - w_l\, \lambda\, (n_l - 1)^{\phi}\,, \tag{30}$$

where w_l is the unskilled labor wage, n_l is the number of children that the unskilled adult has, and $\lambda > 0$ and $\phi > 1$ are constant parameters that affect the opportunity costs to child-rearing. Note that the costs here include a term in the form $(n_l - 1)$ to ensure that at least replacement fertility is maintained.

If an adult chooses to spend resources to become a skilled worker, she instead maximizes income I_h with respect to her number of children, where

$$I_h = w_h + n_h\, w_l - w_h\, \lambda\, (n_h - 1)^{\phi} - \tau_k\,, \tag{31}$$

where w_h is the skilled labor wage, n_h is the number of children that the skilled adult has, and τ_k is the resources she must spend to become skilled.

We solve the resulting first order conditions to obtain optimal fertility. For convenience we solve for fertility in excess of replacement, denoted n_l^* and n_h^*, to obtain

$$n_l^* \equiv n_l - 1 = (\phi\lambda)^{\frac{1}{1-\phi}}\,, \tag{32}$$

$$n_h^* \equiv n_h - 1 = (\phi\lambda w_h / w_l)^{\frac{1}{1-\phi}}\,. \tag{33}$$

Note that with $w_h > w_l$, and given $\phi > 1$, optimal fertility for a skilled worker is always smaller than that for an unskilled worker (simply because the opportunity costs of child-rearing are larger for skilled workers). Also note that the fertility for unskilled workers is constant, while the fertility for skilled workers is decreasing in the skill premium w_h/w_l.

Finally, we assume that τ varies across each adult k. The resource costs necessary to acquire an education can vary across individuals for many reasons, including differing incomes, access to schooling, or innate abilities. For tractability we assume that over all adults k, the level of τ_k is uniformly distributed across $[0, b]$, where $b > 0$.

An individual adult k who draws a particular τ_k will choose to become a skilled worker only if her optimized income as a skilled worker will be larger than her optimized income as an unskilled worker. Let us call τ^* the *threshold* cost to education; this is the education cost where the adult is indifferent between becoming a skilled worker or remaining an unskilled worker. Solving for this, we get

$$\tau^* = w_h + n_h^*\, w_l - w_h\, \lambda\, {n_h^*}^{\phi} - w_l - w_l\, n_l^* + w_l\, \lambda\, {n_l^*}^{\phi}\,. \tag{34}$$

Only individuals whose τ_i falls below this level will opt to become skilled.

Figure 5 shows the optimal fertility rates for two hypothetical individuals. In each case the figure plots the earnings and child rearing costs which they would face, as a function of the number of children, one where τ is relatively high and one where it is relatively low. As for earnings, the straight lines show how income increases as adults have more children; their slope is the unskilled wage (w_l) received by children; the own-wage intercept for a skilled worker (w_h) is higher than for an unskilled adult (w_l). As for costs, the cost curves get steeper with more children since $\phi > 1$. For skilled individuals, the cost curve is both higher (to illustrate the resource costs τ necessary to become skilled) and steeper (to illustrate the higher opportunity cost of having children). Notice then that the only difference between the high-τ individual and the low-τ individual is that the latter has a lower cost curve. Given these differences in the fixed costs of education, we can see that the high-τ individual will opt to remain an unskilled worker (and so have a fertility rate of n_l^*), while the low-τ individual will choose to become skilled (and have a fertility rate of n_h^*).

With all the above household machinery in place, we can now describe aggregate supplies of skilled and unskilled labor (the demands for labor are described by full employment conditions (13) and (14)), fertility, and education. Given a total adult population equal to pop, we obtain

$$H = \left(\frac{\tau^*}{b}\right) pop\,, \tag{35}$$

$$L = \left(1 - \frac{\tau^*}{b}\right) pop + n \cdot pop\,, \tag{36}$$

$$n = \left(1 - \frac{\tau^*}{b}\right) n_l^* + \left(\frac{\tau^*}{b}\right) n_h^* + 1\,, \tag{37}$$

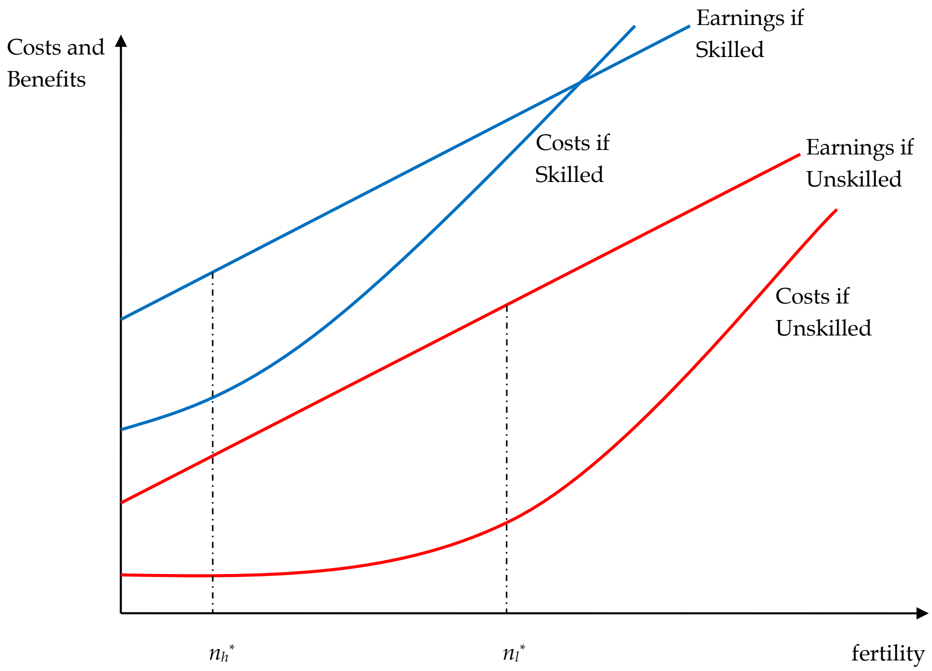
$$e = \frac{\tau^*}{b}\,, \tag{38}$$

where H is the number of skilled workers (comprised strictly of old workers), L is the number of unskilled workers (comprised of both old workers and all the young), n is aggregate fertility including replacement (the term 1 is added in), e is the fraction of the workforce that gets an education, and n_l^*, n_h^*, and τ^* are the optimized fertility rates and threshold education cost given respectively by (32), (33), and (34).

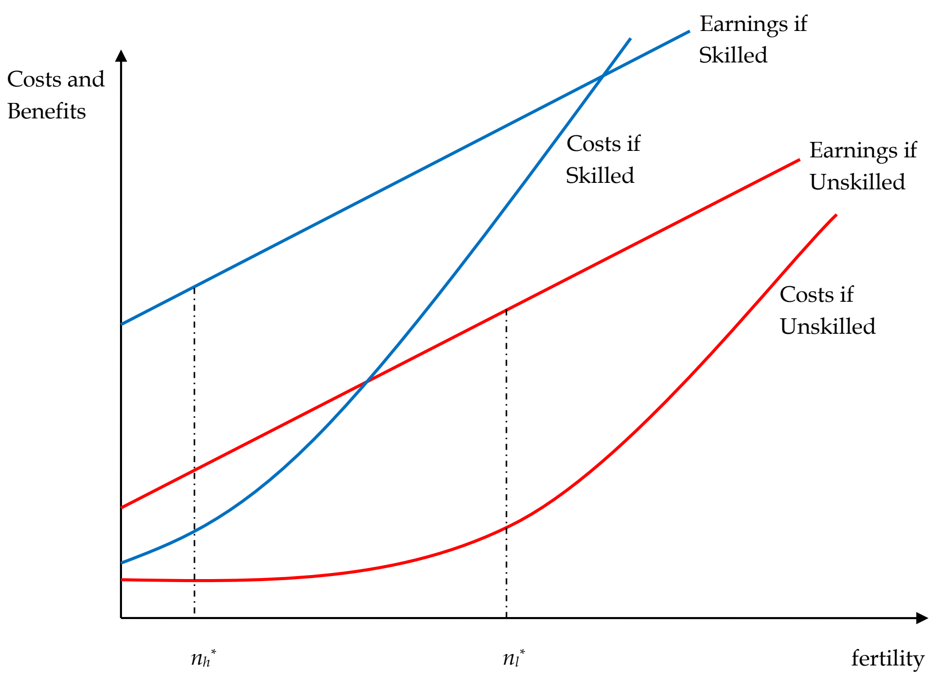
This completes the description of the static one-country model. The next section uses this model to describe *two* economies that endogenously develop technologies and trade with each other to motivate a story of world economic history.

Figure 5: *Optimal Fertility Rates for High and Low τ Individuals (for given w_l and w_h)*

(a) Optimal Fertility Rates for High-τ Individual



(b) Optimal Fertility Rates for Low-τ Individual



5. The Roles Played by the Evolution of Trade and Technologies in Historical Divergence/Convergence

In this section we show how interactions between the growth of trade and evolving factor-biased technologies could have contributed to the Great Divergence of the late 19th and early 20th centuries. We go on to show how such interactions could also have induced per capita income convergence in the later 20th century. The above model describes one hypothetical country — now we use it to describe both a Northern and a Southern economy in a setup where applied technologies are strictly locally used, as well as a setup in which technologies developed in one region may be diffused and utilized in the other region.

A key issue here is the nature of technological progress and diffusion. We argue that early industrialization was characterized by locally-grown technologies, whereby regions developed their own production processes appropriate for local conditions, and where global technological diffusion was of minimal importance. On the other hand, we later conjecture that 20th century growth saw developing economies move to adopting technologies from the world knowledge frontier (Pack and Westphal 1986; Romer 1992).

Our simulations reveal how trade and technological change feed off each other to generate growth paths that broadly mirror historic trends. Distinct from Galor and Mountford (2008), we find that the technological environment determines the qualitative impact of trade on convergence-versus-divergence dynamics in the global economy.

5.1. A Dynamic Model—The Evolution of Technology and Trade

How do technologies evolve in each region? We will assume that a region will either develop its own blueprints N, or else adopt blueprints from the world frontier. The following discussion relates to the former case. We turn to the latter case in a moment.

Recall that equations (24)–(26) describe one-period revenues r for research and innovation. Offsetting these are some resource costs $C(.)$ to research and innovation, which we now specify. We assume that these costs are rising in N ("applied" knowledge, the already-known blueprints or machine-types specific to each sector and to each country), and falling in some measure of "general" knowledge, given by B (basic knowledge, which is global, and thus common across all sectors and countries). The former means that it gets harder to make innovations when more innovations have already been made, but the latter means that it gets easier the more basic knowledge you have.

Specifically, we assume that the no-arbitrage (free entry) condition for potential researchers in each region can be written

$$r_i^c \leq C(N_i^c, B)\,, \tag{39}$$

for country $c = n, s$ and sector $i = 1, 3$.[10] Specifically, we assume the following functional form for these research costs,

$$C(N_i^c, B) = \left(\frac{N_{i,t+1}^c}{B_t}\right)^{\nu}\,, \tag{40}$$

for some $\nu > 0$. Now, given a level of basic knowledge B_t, which we now assume grows at an exogenous rate, and the number of existing machines $N_{i,t+1}^c$, we can determine the resource costs of research and innovation. When basic knowledge is low relative to the number of available machine-types in sector i, the cost of inventing a new machine in sector i is high (see O'Rourke, Rahman, and Taylor 2013 for a fuller discussion). Thus from (39) and (24)–(26) we see that innovation in sector i becomes more attractive when basic knowledge is large, when the number of machine-types in sector i is low, when the price of good i is high, and when employment in sector i is high.

Note that if $r_i^c > C(N_i^c/B)$ there are profits from research in sector i in region c. However, this will induce local research activity, increasing the number of new machines, and hence the costs of research. In equilibrium, we assume that free entry ensures that N_i adjusts up or down such that costs of research and innovation equal the revenues of new machine production. Thus, increases in global B are matched by increases in local levels of N_i^c such that the no-arbitrage condition holds with equality whenever technological growth in the sector occurs.

Note that there is a nontraded good: we assume that there is no trade in Q_2. Because this good is produced using both L and H, differences in p_2 are very small between the North and the South, and thus the assumption is not very restrictive or important.[11,12]

[10] For analytical convenience we assume no research occurs in sector 2, so that technological growth is unambiguously factor-biased. Cases where all three sectors grow technologically complicates the model but do not change the evolutions of either economy.

[11] Indeed, trade in all three goods would produce an analytical problem. It is well known among trade economists that when there are more traded goods than factors of production, country-specific production levels, and hence trade volumes, are indeterminate. See Melvin (1968) for a thorough discussion.

[12] One can conceive of Q_2 as the technologically-stagnant and non-tradeable "service" sector. Thus each labor-type can work either in manufacturing or in services.

5.2. Evolution of the World Economy

World general equilibrium in any period is a 36-equation system that, given changes in the number of machine blueprints, solves for prices, wages, fertility, education, labor-types, intermediate goods, employment, trade, and sectoral productivity levels for both the North and the South.

We impose only one parameter difference between the two regions that is motivated by the following lemma:

Lemma 1. *$\partial n^*/\partial b > 0$ and $\partial e^*/\partial b < 0$.*

Proof. Clearly an increase in b lowers e^* as τ^* is unaffected by b. Further, $\partial n^*/\partial b = (n_l^* - n_h^*)\frac{\tau}{b^2} > 0$. □

Recall that b is the range of individuals arranged by education costs. Regions with a larger b have a higher share of workers facing high education costs. Thus a higher b parameter for an economy raises its fertility further beyond replacement fertility, and lowers its equilibrium share of educated workers. We will motivate the initial difference between the North and the South with this one and only imposed difference: $b^n < b^s$. This is a way to create an initial asymmetry between the regions to match the historical record.

Proposition 1. *With all else equal, $b^n < b^s$ implies that $y^n/y^s > 0$.*

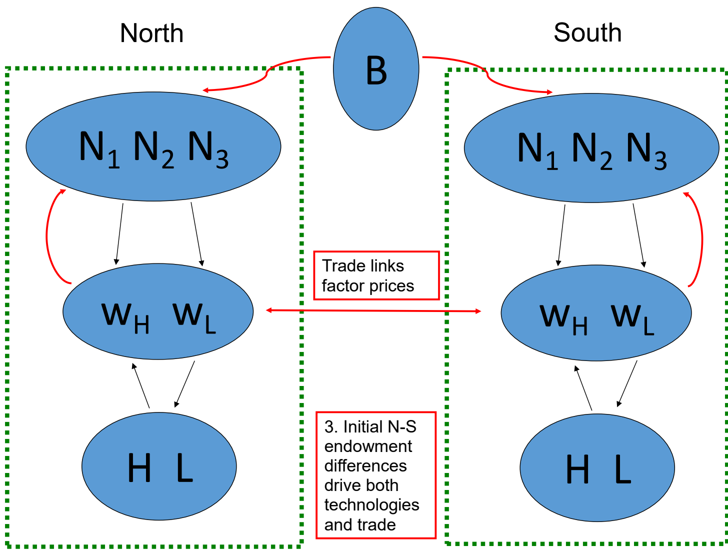
Remark. This follows from Lemma 1. The North will always have greater initial per capita income due to its lower n and hence its lower population. With technology levels N_1, N_2 and N_3 the same for both, the South will tend to have slightly higher sectoral productivity levels due to its greater scale, but the diminishing returns from more machines (in the numerator) will not offset the larger population (in the denominator). □

Our chosen parameterization of $b^n = 2$ and $b^s = 6$ roughly produces an initial 20% per capita income advantage to the North.

Due to considerable model complexity, we solve for general equilibrium numerically. Specifically, we assume that basic technology (B in equation 40) starts low enough so that technological progress is not possible in any region. Our world is initially in stasis. Historical stagnation is thus produced not only via Malthusian forces, but also pre-Baconian technological inertia (Mokyr 2002; O'Rourke et al. 2013). We allow, however, for exogenous growth in basic knowledge, and then solve for the endogenous variables in each period.

Figure 6: *Elements of an Open Economy North-South Model without and with Technological Diffusion*

(a) Without Technological Diffusion



(b) With Technological Diffusion

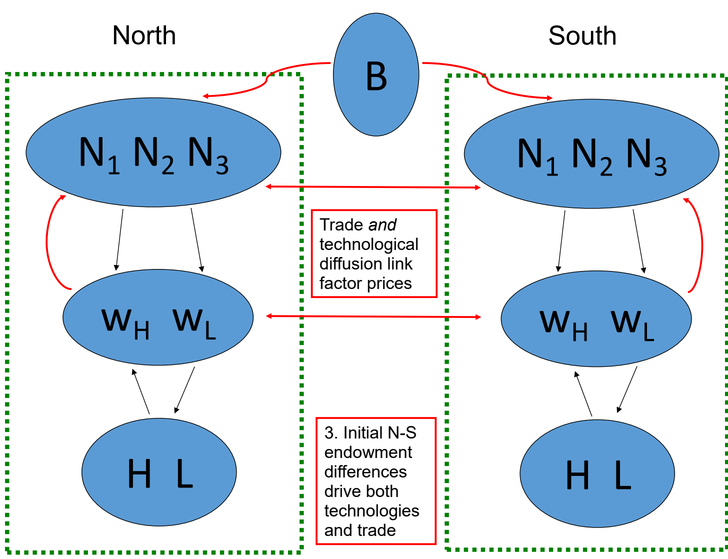


Figure 6 provides a diagram summarizing the simulations with and without technological diffusion. The one exogenous growth variable, B, is accessible to both regions. This will affect sector-level productivities in different ways however, as these interact with wages and factors unique to each region. Demography evolves endogenously as well, influencing sectoral technological developments.

Before demonstrating simulation results we can further summarize the evolution of our two economies with a few more lemmas, starting with the nature of early industrialization in the world.

Lemma 2. *If $N_1 = N_3$, $L > H$, and $\sigma > 1$, then initial technological growth will be unskilled-labor biased.*

Remark. From (24)–(26) we can see that revenues from innovation rise both in the price of the intermediate good (the "price effect") and in the scale of sectoral employment (the "market-size effect"). If intermediate goods are grossly substitutable, market-size effects will outweigh price effects (see Acemoglu 2002 for more discussion of this).

Recall that GM had to exogenously order the sequence of modernization events by sector. However, in our model, the sequencing now materializes endogenously due to directed technological change. Here we see that, as basic knowledge exogenously grows, sector 1 will be the first to modernize if unskilled labor is relatively abundant. The logical implication of this is that early industrialization around the world (provided there are intellectual property rights in these countries) will be relatively unskilled-labor-intensive, as was indeed the case (O'Rourke et al. 2013). □

Lemma 3. *For certain ranges of factors and technologies, the trade equilibrium implies that $Q_3^s = 0$. For other ranges of technologies and factors, the trade equilibrium implies that $Q_1^n = 0$.*

Remark. As trade technologies improve, trade costs fall, and economies specialize more and more. And divergent technological growth paths can help reinforce this specialization. There is indeed a point where region n no longer needs to produce any Q_1 (they just import it from region s), and region s no longer needs to produce any Q_3 (they just import it from region n). These cases will be called "specialized trade equilibria" (either partial or full). These cases are described in detail in the appendix. □

Of course, both trade and technological changes will change factor payments. The final proposition states how these changes can affect the supplies of the factors of production themselves.

Lemma 4. *If $\phi > 1$, any increase in w_l (keeping w_h constant) will induce a decrease in e and an increase in n; furthermore, so long as ϕ is "big enough," any increase in w_h (keeping w_l constant) will induce an increase in e and a decrease in n.*

Proof. Substituting our expressions for n_l^* and n_h^*, given by (32) and (33), into our expression for τ^*, given by (34), and rearranging terms a bit, we obtain

$$\tau^* = (w_h - w_l) \, - \, w_l \lambda^{\frac{1}{1-\phi}} \left(\phi^{\frac{1}{1-\phi}} - \phi^{\frac{\phi}{1-\phi}} \right) \, + \, w_l^{\frac{\phi}{\phi-1}} w_h^{\frac{1}{1-\phi}} \lambda^{\frac{1}{1-\phi}} \left(\phi^{\frac{1}{1-\phi}} - \phi^{\frac{\phi}{1-\phi}} \right) .$$

What must be true to have the condition $\frac{\partial \tau^*}{\partial w_l} < 0$ hold? Solving for this and rearranging yields

$$\left(\frac{w_l}{w_h} \right)^{\frac{1}{\phi-1}} \;<\; 1 \,+\, \left[\frac{1}{\lambda^{\frac{1}{1-\phi}} \left(\phi^{\frac{1}{1-\phi}} - \phi^{\frac{\phi}{1-\phi}} \right)} \right] .$$

Since the inverse of the skill-premium is always less than one, this expression always holds for any $\phi > 1$.

What must be true to have the condition $\partial \tau^* / \partial w_h > 0$ hold? Solving and rearranging yields

$$\lambda^{\frac{1}{\phi}} \phi > \frac{w_l}{w_h} .$$

Thus, for a given value of λ, ϕ needs to be large enough for this condition to hold. Finally, our expression for total fertility, (37), can be slightly rearranged as

$$n = n_l^* \,+\, (n_h^* - n_l^*) \left(\frac{\tau^*}{b} \right) \,+\, 1 .$$

From (32) and (33) we know that the second term is always negative, and that n_l^* is constant. So any increase in education from wage changes will lower aggregate fertility, and any decrease in education from wage changes will increase aggregate fertility. □

5.3. Divergence/Convergence Implications

Before presenting our main sets of simulation results in full detail, we begin by previewing our main findings on long-run divergence, since matching these stylized facts was our core empirical goal in constructing this model. Recall that we can solve the model using two different basic sets of assumptions, localized technological development and perfect diffusion of technologies.

There are essentially one of three possible trade equilibria in each period. These differences have to do with different "cones of diversification" (Feenstra 2004). *Diversified trade* is the case where all three sectors are active in both regions. *Partially specialized trade* is where one region has abandoned the production of one sector. In this case the region imports all of that product from the other region. Finally, *fully diversified trade* is where both regions have abandoned production of one sector. As we will see, these differing diversification cones will play a major role in divergence patterns.

Motivated by the "stylized facts" of unified growth theory and comparative development (Galor 2005, 2010. See also Andorka 1978; Flora et al. 1983; Chesnais 1992; Barro and Lee 2001), we attempt the match the following moments through the simulations. We shall refer to these as we present specific results.

With no diffusion of technologies (18th–early 20th Centuries):

1) Fertility growth was always higher in the South than in the North;

2) Fertility in the North fell faster in the later decades of the period (during its Demographic Transition);

3) Education growth was always faster in the North than in the South;

4) Education growth in the North was faster in the later decades of the period;

5) Income divergence between the North and the South did not occur early in the period;

6) Income divergence between the North and the South occurred during later in the period;

With diffusion of technologies (early 20th-early 21st Centuries):

7) Fertility growth was higher in the South than in the North early in the period;

8) Fertility growth was higher in the North than in the South later in the period;

9) Education growth was higher in the North than the South early in the period;

10) Education growth was higher in the South than the North later in the period;

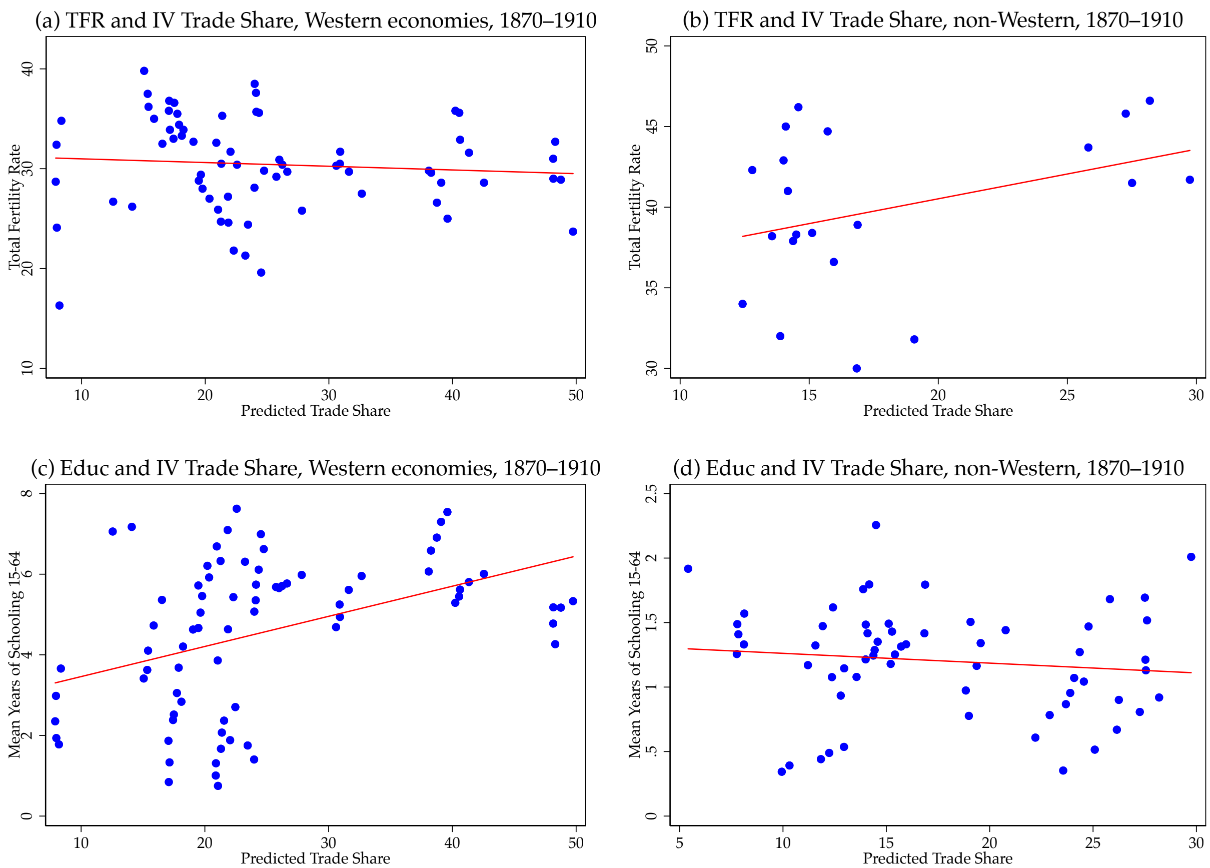
11) Income divergence between the North and the South occurred early in the period;

12) Income convergence between North and South occurred later in the period.

In summary these moments capture the overall trends of demographic and income growth over the last three centuries of global economic history.

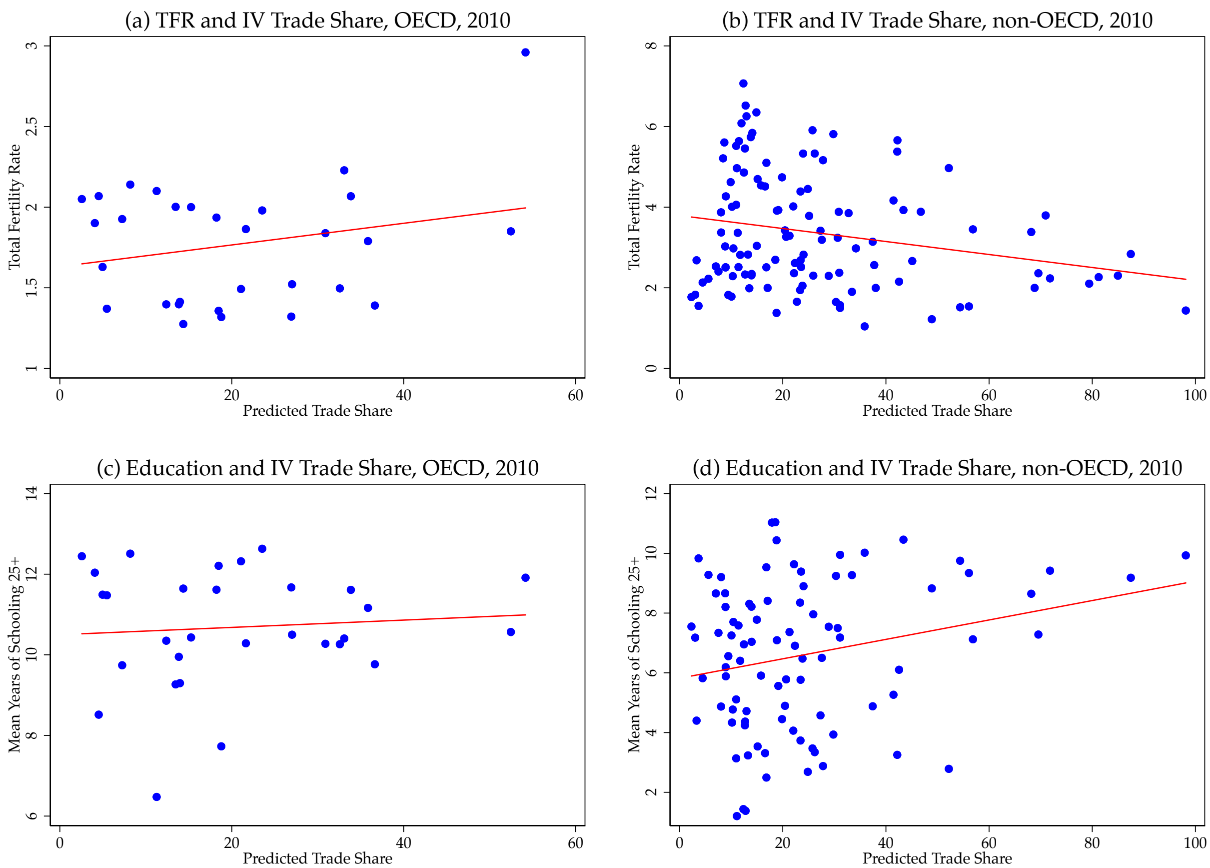
To motivate these moments a bit more we provide some suggestive correlations between globalization and demographics for both the late 19th century and the more recent past.

Figure 7: *Demographics and Trade during the Late 19th century*



Sources: López-Córdova and Meissner (2004); Murtin (2013).
Note: The scatter-plots show that greater trade during the late 19th century is associated with lower fertility and higher education in the developed world (left side diagrams), but *higher* fertility and *lower* education in the developing world (right side diagrams).

Figure 8: *Demographics and Trade Today*



Sources: Frankel and Romer (1999); Weil (2013).
Note: The scatter-plots show that greater trade during the early 21st century is very weakly associated with higher fertility and education in OECD countries (left side diagrams), but *lower* fertility and *higher* education in non-OECD countries (right side diagrams).

First, in Figure 7 we show scatterplots for a decadal panel dataset spanning the years 1870–1910 for both developed regions and developing regions.[13] Here we use López-Córdova and Meissner (2008)'s first-stage estimates for predicted trade shares, and correlate these with fertility and schooling data from Murtin (2013). Here we find that trade is associated with falling fertility and rising education in the "North." In the "South" on the other hand th correlation is the opposite, at least in the cross-section.

Next, in Figure 8 we show the same relationships for a cross-section of countries during more recent times. Now we consider the "North" to be OECD countries and the "South" to be non-OECD countries. We use predicted trade shares estimated by Frankel and Romer (1999), and correlate these with fertility and education rates taken from Weil (2013). Now we observe the opposite tendency—greater trade is associated with lower fertility and higher education in the developing world as well. Indeed, in the developed world it now appears that the historic relation between trade and demographics has broken down, which would be consistent with regions having undergone, and essentially completed, their demographic transitions.

The basic point we make here is that the demographic effects of globalization in the late 19th century may well been quite different from those in the late 20th and 21st centuries. Given eight parameter choices that allow us to satisfy lemmas 2–4, and two distinct technological regimes, can we match these stylized facts?

5.4. Simulation Results

Here we lay out the simulated results of our basic model with various trade and technological-diffusion assumptions. All simulation diagrams for each separate case are presented in the appendix.

Initial basic knowledge and iceberg trade costs are set such that neither technological growth nor trade is possible at first. However, exogenously over time basic knowledge rises and iceberg trade costs fall. We run the simulation for 75 time periods to roughly capture major economic trends during two distinct economic epochs.

The parameter values in the simulations are as follows: $\sigma = 3$, $\alpha = 0.5$, $\gamma = 0.5$, $\lambda = 0.5$, $\phi = 10$, $\nu = 2$. These values ensure that lemmas 2 and 4 hold; beyond that, our qualitative findings are not sensitive to specific parameter values. We set $b^n = 2$, $b^s = 6$,

[13] Developed regions are considered to be Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Italy, Japan, the Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, and Switzerland. Developing regions are considered to be Algeria, Argentina, Brazil, Chile, Costa Rica, Cuba, Egypt, El Salvador, Ghana, Guatemala, Honduras, India, Indonesia, Malyasia, Mexico, Nicagagua, Nigeria, Peru, Philippines, South Africa, Turkey, and Venezuela. Categorization from Murtin (2013). Not all data available for all regions and years.

and $pop = 2$; this gives us initial factor endowments of $L^n = 3.14$, $L^s = 3.48$, $H^n = 0.86$, $H^s = 0.52$. Initial machine blueprints for both countries are set to be $N_1 = 10$, $N_2 = 15$, $N_3 = 10$. Initial B is set high enough in all scenarios so that growth in at least one sector is possible early in the simulation; B grows 2 percent each time period.

We begin by simulating a case where there is no trade or technological diffusion of any kind — each economy evolves independently. The evolution this economy is depicted in figures A.1 and A.2.

Proposition 2. *Under the no trade or technological diffusion model,* $\partial(y_n/y_s)/\partial t < 0$.

Remark. Without any interactions between regions, both regions experience industrialization at roughly the same time, with unskilled technologies taking off first, followed later by skill-intensive technologies. The initial higher fertility in the South produces greater scale, spurring faster technological growth in the South. Neither region experiences a demographic transition. □

This case shows that without some interaction between regions, the model predicts inevitable convergence.

The next case we demonstrate is where there is *free* trade of unskill- and skill-intensive goods, but no technological diffusion. This case may reasonably represent 19th century global growth, and so potentially can address moments 1–6. The evolution of this economy is depicted in figures A.3 and A.4.

Proposition 3. *Under the free trade no diffusion model, for some positive value of* $t = \tilde{t}$, $\partial(y_n/y_s)/\partial t < 0 \;\; \forall \;\; t < \tilde{t}$.

Remark. Trade is initially more beneficial to the South than the North. With initial trade the South immediately abandons production of y_3, but the North continues to produce y_1 even as it imports some from the South. The South's specialization in its technologically-vibrant sector gives it an outsized advantage — convergence is more dramatic in this case than in the no trade or technological diffusion case (Proposition 2). This essentially captures moment 5 — income divergence between regions does not occur during the early onset of industrialization. □

Proposition 4. *Under the free trade no diffusion model, for some positive value of* $t = \tilde{t}$, $\partial(y_n/y_s)/\partial t > 0 \;\; \forall \;\; t > \tilde{t}$.

Remark. Under this model, divergence in per capita incomes will inevitably take place. This occurs once the North abandons production of y_1, at which point it devotes more resources to skill-intensive innovation and production, hastening its education growth and lowering its fertility. □

Thus a purely specialized world develops, and the South specializes in a good which generates population growth and deteriorating terms of trade with the North. Technological growth will not save it! This is the way we match moment 6 — income divergence occurs much after the onset of industrialization.

Figure A.4 also highlights how this scenario can match moments 1–4. Fertility and education between the regions diverge gradually at first, then more rapidly later on.

Though the mechanisms are quite different, this framework generates qualitatively similar results to Galor and Mountford (2008). However, it does not address the possibility of technological transfer across regions, and so it cannot comment on more recent eras where such transfers are commonplace. For this we turn to other scenarios.

For the next case we include the possibility of free technological diffusion as well. This free diffusion regime may reasonably represent 20th century global growth, and so potentially can address moments 7–12. The evolution this economy is depicted in figures A.5 and A.6.

Proposition 5. *Under the free trade free diffusion model, for some positive value of* $t = \hat{t}$, $\partial(y_n/y_s)/\partial t < 0 \;\; \forall \;\; t > \hat{t}$.

Remark. Technological diffusion may cause divergence for some $t < \hat{t}$ due to technological "inappropriateness" — the South for some period of time may not be able to employ skill-intensive technologies from the North if it is not producing skilled goods. But eventually diffusion makes all sectors feasible, and production becomes fully diversified in each region. □

This framework captures moments 7–12 — divergent demographics and incomes initially, followed by convergence. The model thus suggests that in a fully integrated world divergence can occur for a time, but convergence in living standards will inevitably follow.

Of course, we also must acknowledge that at the start of the Industrial Revolution the world was far less integrated than it is today. The *nature* of increased globalization, and how this affected the growth patterns of different regions, leads us to our final simulations.

Specifically we look to two cases where the two iceberg costs exogenously improve at different times. This is depicted in figure A.7. The first case is where technological iceberg costs (ρ) improve early on, and trade iceberg costs (a) improve much later. The second case is the reverse, where trade iceberg costs improve early on, and technological iceberg costs improve much later. Below we focus on the latter (call this the "early trade late diffusion model"), which is the more historically relevant case.

Proposition 6. *Under the early trade late diffusion model, for some positive value of $\rho < 1$ there exists some $\bar{t}$ such that $\partial(y_n/y_s)/\partial t < 0$ for some values of $t > \bar{t}$.*

Remark. Recall from Propositions 3 and 4 that the free trade no diffusion case produces convergence early on but divergence later on. Here we suggest that for $0 < \rho < 1$ and $\bar{t} > \tilde{t}$ this divergence is inevitably reversed.

This case is depicted in figures A.8 and A.9. Note that the convergence occurs before $\rho = 1$. At some critical juncture, adoption of skill-biased technologies originating from the North become feasible in the South even with imperfect diffusion. This generates a dramatic education boom in the South and a rapid demographic transition. □

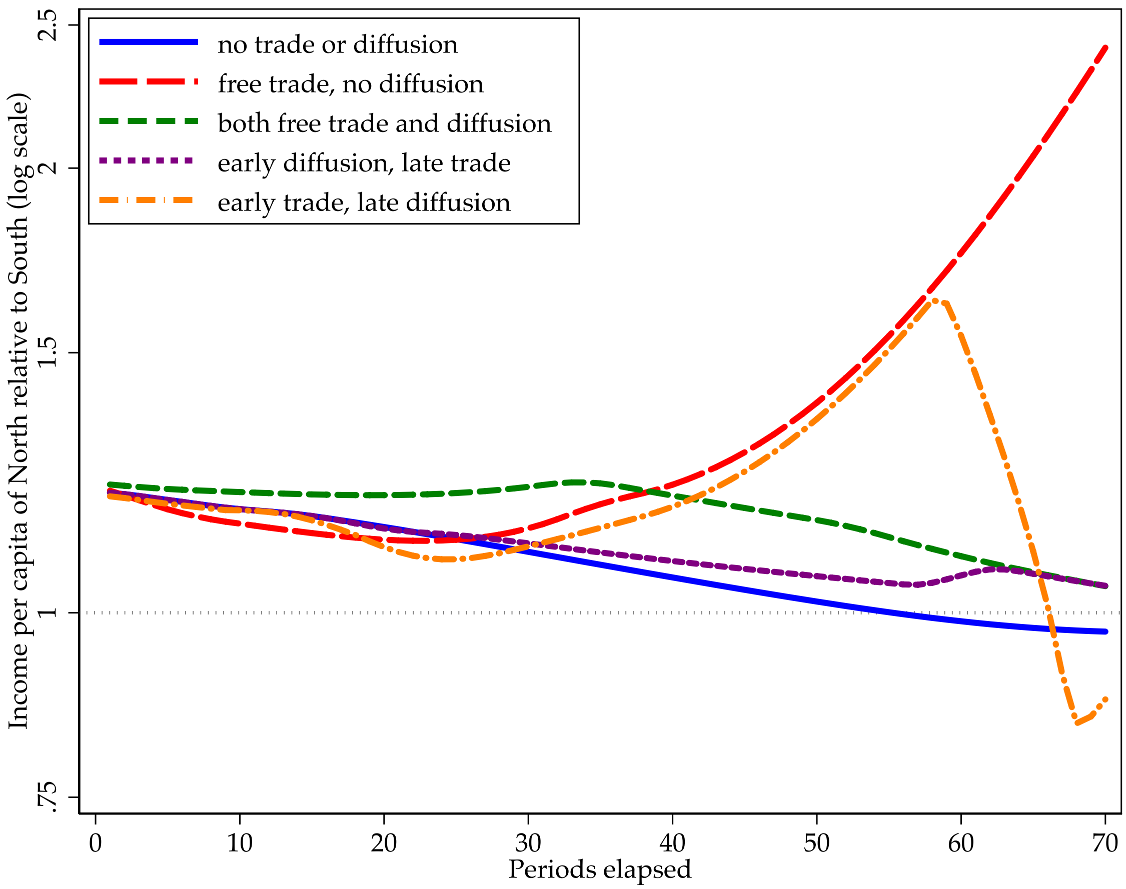
Proposition 7. *Under the early trade late diffusion model, there exists some ρ^* and t^*, where $\rho_{min} < \rho^*$, such that the southern economy becomes the technological leader in all sectors for $t > t^*$.*

Remark. We can see this case in the bottom-right panel of fig A.8. The economy becomes entirely specialized. But the eventual ability to adopt a pool of skill-intensive knowledge from the North resurrects the South's skilled sector. The education boom this creates dramatically raises the Southern value to innovate in this sector; soon thereafter the South develops skill-intensive technologies on its own and the North adopts these. The South becomes the innovator; the North becomes the adopter.

This suggest the timing of technological adoption by the South matters for its potential to leapfrog and become a global innovator. If adoption happens early, convergence occurs more gradually and the North retains its technological leadership. If adoption happens later, the North is able to build a large reservoir of skilled technologies that the South can eventually exploit.

The prolonged divergence that comes from the free trade no diffusion environment is necessary for the South to leapfrog. The greater and more extensive the divergence, the more sudden and dramatic is the eventual convergence. □

Figure 9: *Relative Income per Capital Under Various Scenarios*



Finally, Figure 9 shows all simulated cases together in one diagram. With our final simulation (early trade late diffusion) we essentially capture all our moments described earlier.

The divergence of the late 19th and early 20th century fueled the subsequent growth miracles of East Asian economies. Without the trade-induced specialization by the North in skilled innovations peripheral economies would not have been able to adopt these technologies that helped spark technological leapfrogging among some erstwhile laggards.

6. Conclusion

We have shown how different dimensions of globalization can have different implications for convergence. We provide two important innovations from the Galor and Mountford framework. One is that we endogenize the terms of trade. This can generate an entirely different source for divergence than in GM. We demonstrate that even when the South can innovate on its own, specialization patterns can still drive dramatic divergence in incomes. Through this terms of trade effect, we see that larger and in particular growing populations can be economically costly, even in the context where innovation is endogenous.

The other big difference is that we analyze the case, arguably more relevant for contemporary economies, of technology transfer. Our paper suggests that technological adoption fosters convergence, and that continued divergence among economies in the 20th century must be due to other barriers—i.e., outside our model—preventing such adoption. Barriers may be due to blocking efforts by special interests (Parente and Prescott 1999), or financial constraints (Aghion et al. 2005), or institutions (Acemoglu et al. 2001). On the other hand barriers due to the "inappropriateness" of technologies developed by frontier countries (Basu and Weil 1998; Acemoglu and Zilibotti 2001) should not last in the longer term, as we emphasize in our second simulation. It is striking that here, in contrast to GM, globalization will eventually yield income convergence, even as it fosters a more volatile path towards that convergence.

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Online Appendices

Appendix

A. Simulation Diagrams for Specific Trade–Technological Regimes

B. Diversified Trade Equilibrium

With trade of goods Q_1 and Q_3 between the North and the South, productions in each region are given by (1) and (2).

For each region $c \in n, s$, the following conditions characterize the diversified trade equilibrium:

$$p_1^s = \frac{w_l^s}{A_1^s}, \tag{41}$$

$$p_2^c = \left(\frac{1}{A_2^c}\right) (w_l^c)^{\gamma} (w_h^c)^{1-\gamma} (1-\gamma)^{\gamma-1} \gamma^{-\gamma}, \tag{42}$$

$$p_3^n = \frac{w_h^{ni}}{A_3^n}, \tag{43}$$

$$\left(\frac{1}{A_1^c}\right) Q_1^c + \left(\frac{1}{A_2^c}\right) (w_l^c)^{\gamma-1} (w_h^c)^{1-\gamma} (1-\gamma)^{\gamma-1} \gamma^{1-\gamma} Q_2^c = L^c, \tag{44}$$

$$\left(\frac{1}{A_2^c}\right) (w_l^c)^{\gamma} (w_h^c)^{-\gamma} (1-\gamma)^{\gamma} \gamma^{-\gamma} Q_2^c + \left(\frac{1}{A_3^c}\right) Q_3^c = H^c, \tag{45}$$

$$Q_1^n + aZ_1 = \left(\frac{\left(\frac{\alpha}{2}\right)^{\sigma} (p_1^n)^{-\sigma}}{\left(\frac{\alpha}{2}\right)^{\sigma} (p_1^n)^{1-\sigma} + (1-\alpha)^{\sigma} (p_2^n)^{1-\sigma} + \left(\frac{\alpha}{2}\right)^{\sigma} (p_3^n)^{1-\sigma}}\right) \cdot Y^n, \tag{46}$$

$$Q_1^s - Z_1 = \left(\frac{\left(\frac{\alpha}{2}\right)^{\sigma} (p_1^s)^{-\sigma}}{\left(\frac{\alpha}{2}\right)^{\sigma} (p_1^s)^{1-\sigma} + (1-\alpha)^{\sigma} (p_2^s)^{1-\sigma} + \left(\frac{\alpha}{2}\right)^{\sigma} (p_3^s)^{1-\sigma}}\right) \cdot Y^s, \tag{47}$$

$$Q_2^c = \left(\frac{(1-\alpha)^{\sigma} (p_2^c)^{-\sigma}}{\left(\frac{\alpha}{2}\right)^{\sigma} (p_1^c)^{1-\sigma} + (1-\alpha)^{\sigma} (p_2^c)^{1-\sigma} + \left(\frac{\alpha}{2}\right)^{\sigma} (p_3^c)^{1-\sigma}}\right) \cdot Y^c, \tag{48}$$

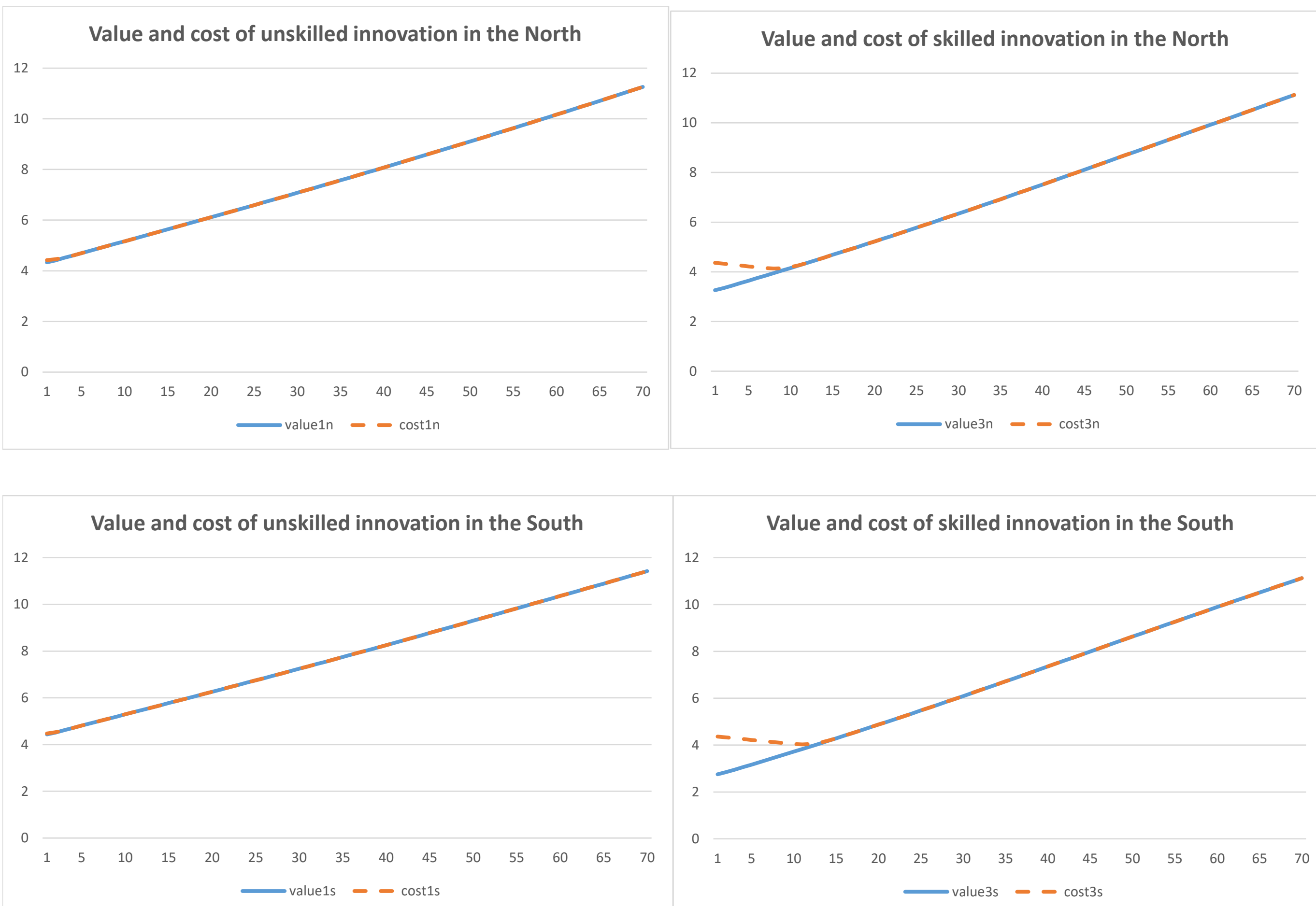
$$Q_3^n - Z_3 = \left(\frac{\left(\frac{\alpha}{2}\right)^{\sigma} (p_3^n)^{-\sigma}}{\left(\frac{\alpha}{2}\right)^{\sigma} (p_1^n)^{1-\sigma} + (1-\alpha)^{\sigma} (p_2^n)^{1-\sigma} + \left(\frac{\alpha}{2}\right)^{\sigma} (p_3^n)^{1-\sigma}}\right) \cdot Y^n, \tag{49}$$

$$Q_3^s + aZ_3 = \left(\frac{\left(\frac{\alpha}{2}\right)^{\sigma} (p_3^s)^{-\sigma}}{\left(\frac{\alpha}{2}\right)^{\sigma} (p_1^s)^{1-\sigma} + (1-\alpha)^{\sigma} (p_2^s)^{1-\sigma} + \left(\frac{\alpha}{2}\right)^{\sigma} (p_3^s)^{1-\sigma}}\right) \cdot Y^s, \tag{50}$$

$$A_1^n (A_1^n L_1^n + aZ_1)^{-\frac{1}{\sigma}} = \left(\frac{2(1-\alpha)\gamma}{\alpha}\right) A_2^{n\,\frac{\sigma-1}{\sigma}} (L^n - L_1^n)^{-\gamma-\sigma+\sigma\gamma} (H^n - H_3^n)^{\gamma+\sigma-\sigma\gamma-1}, \tag{51}$$

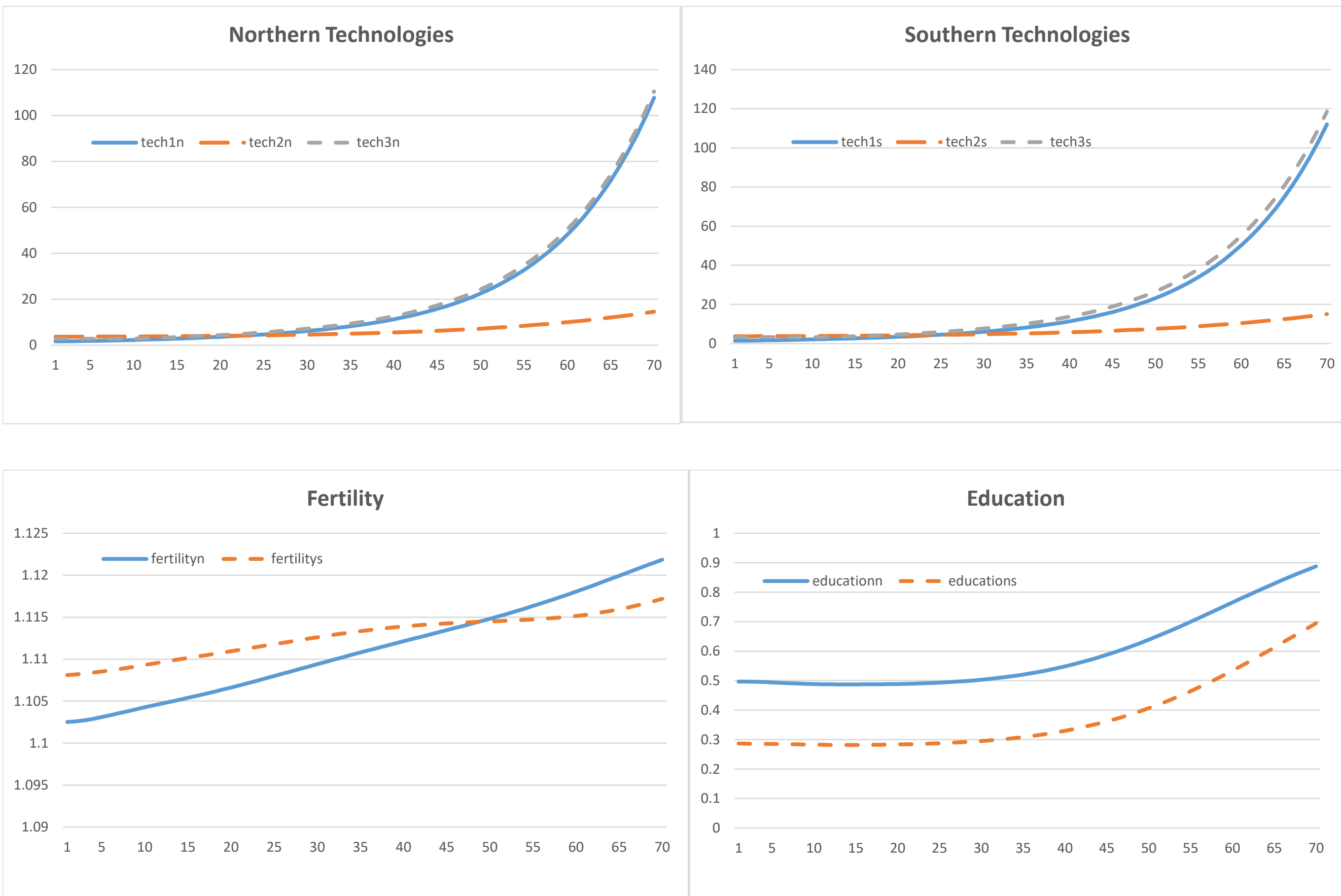
$$A_3^n (A_3^n H_3^n - Z_3)^{-\frac{1}{\sigma}} = \left(\frac{2(1-\alpha)(1-\gamma)}{\alpha}\right) A_2^{n\,\frac{\sigma-1}{\sigma}} (L^n - L_1^n)^{-\gamma+\sigma\gamma} (H^n - H_3^n)^{\gamma-\sigma\gamma-1}, \tag{52}$$

Figure A.1: *Market for Technologies — No Trade or Diffusion*



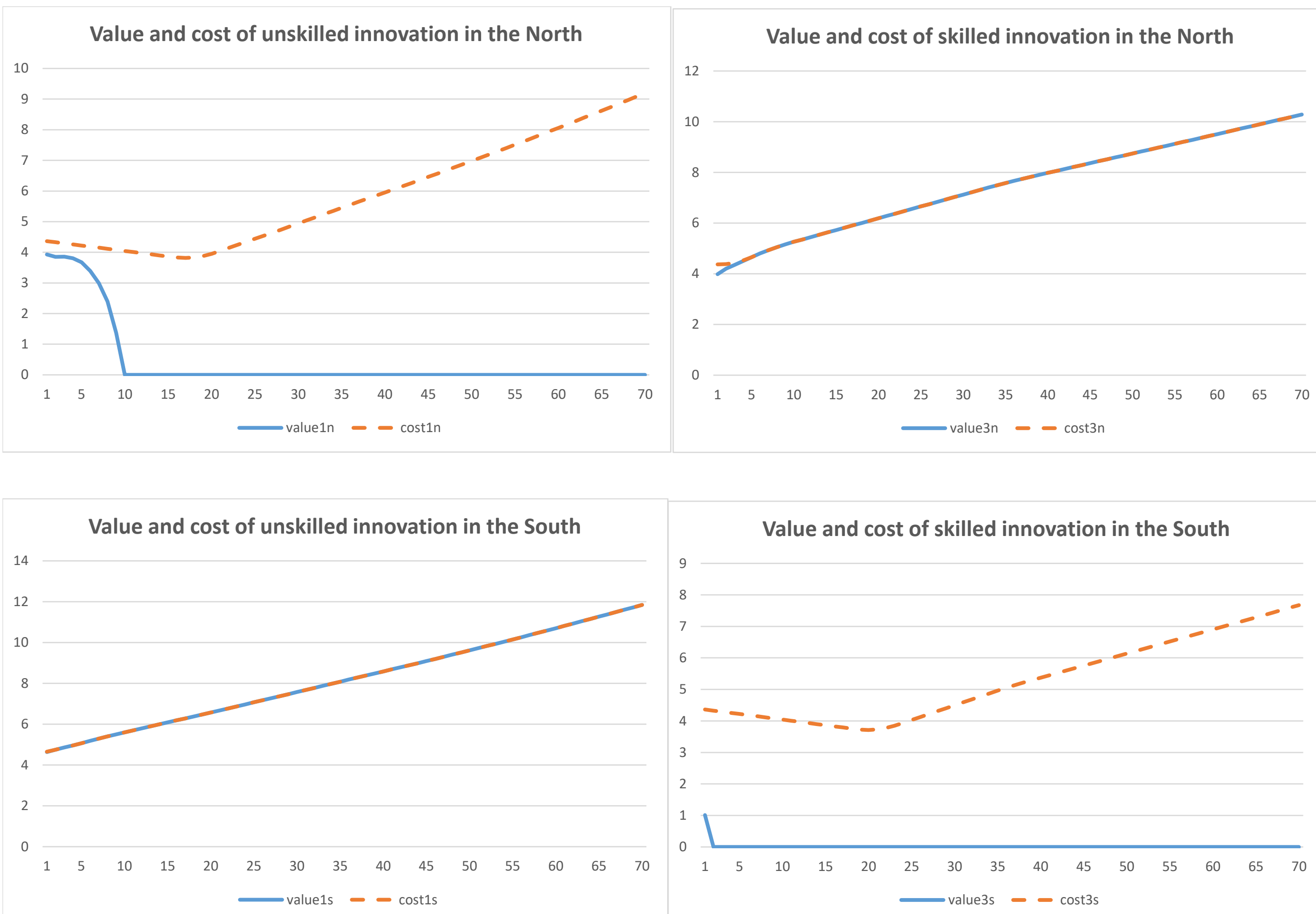
Note: In this case unskilled technologies are the first to develop in both regions (the value and cost for potential innovators in unskilled technologies equal each other right away). Later the costs of skilled innovation catch up with the value of skilled innovation, first in the North and then in the South. After this point there is technological innovation in both sectors in both regions.

Figure A.2: *Technologies and Demographics — No Trade or Diffusion*



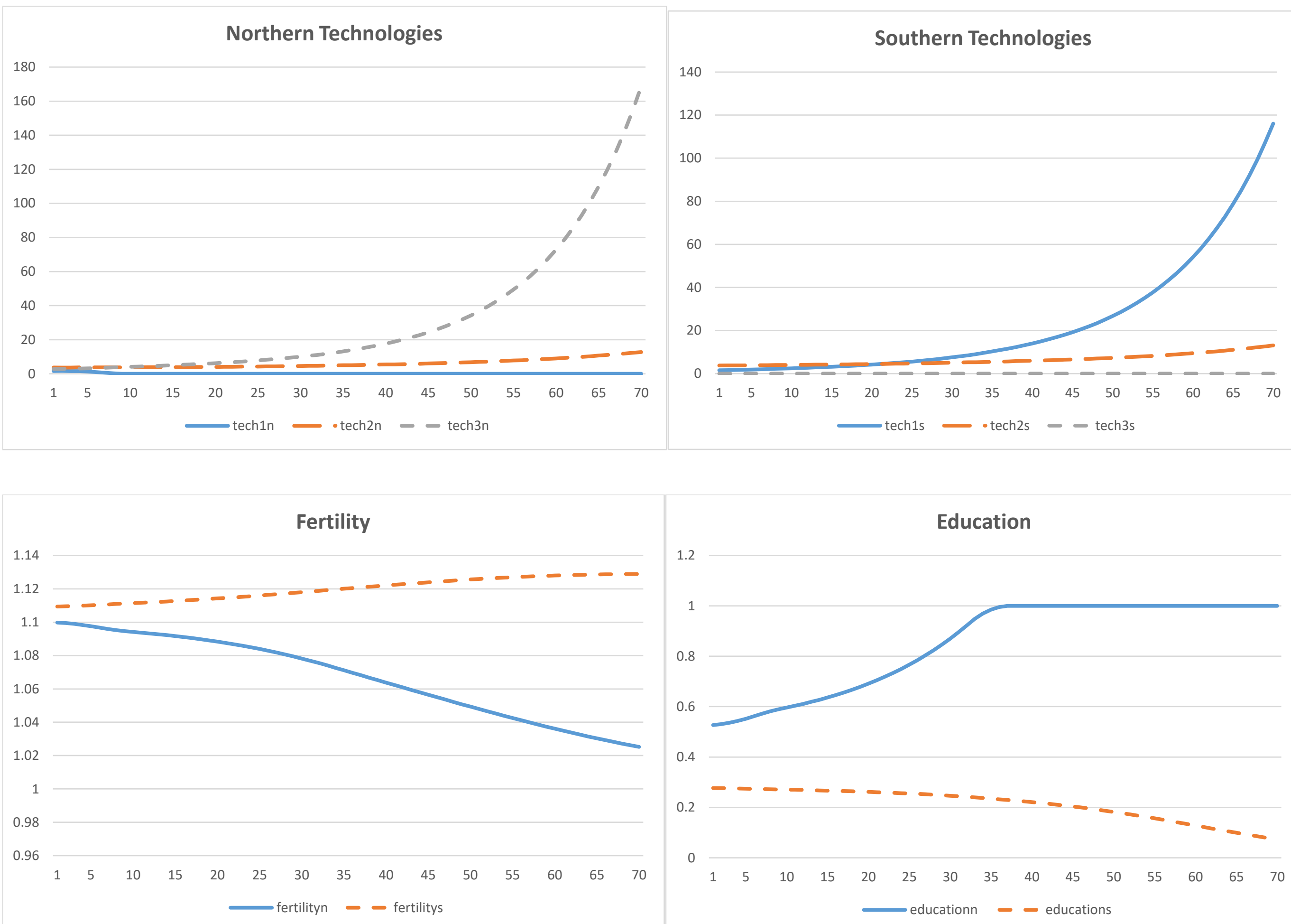
Note: Here we see balanced economic growth in both regions, which generates increases in both fertility and education in both regions.

Figure A.3: *Market for Technologies — Free Trade No Diffusion*



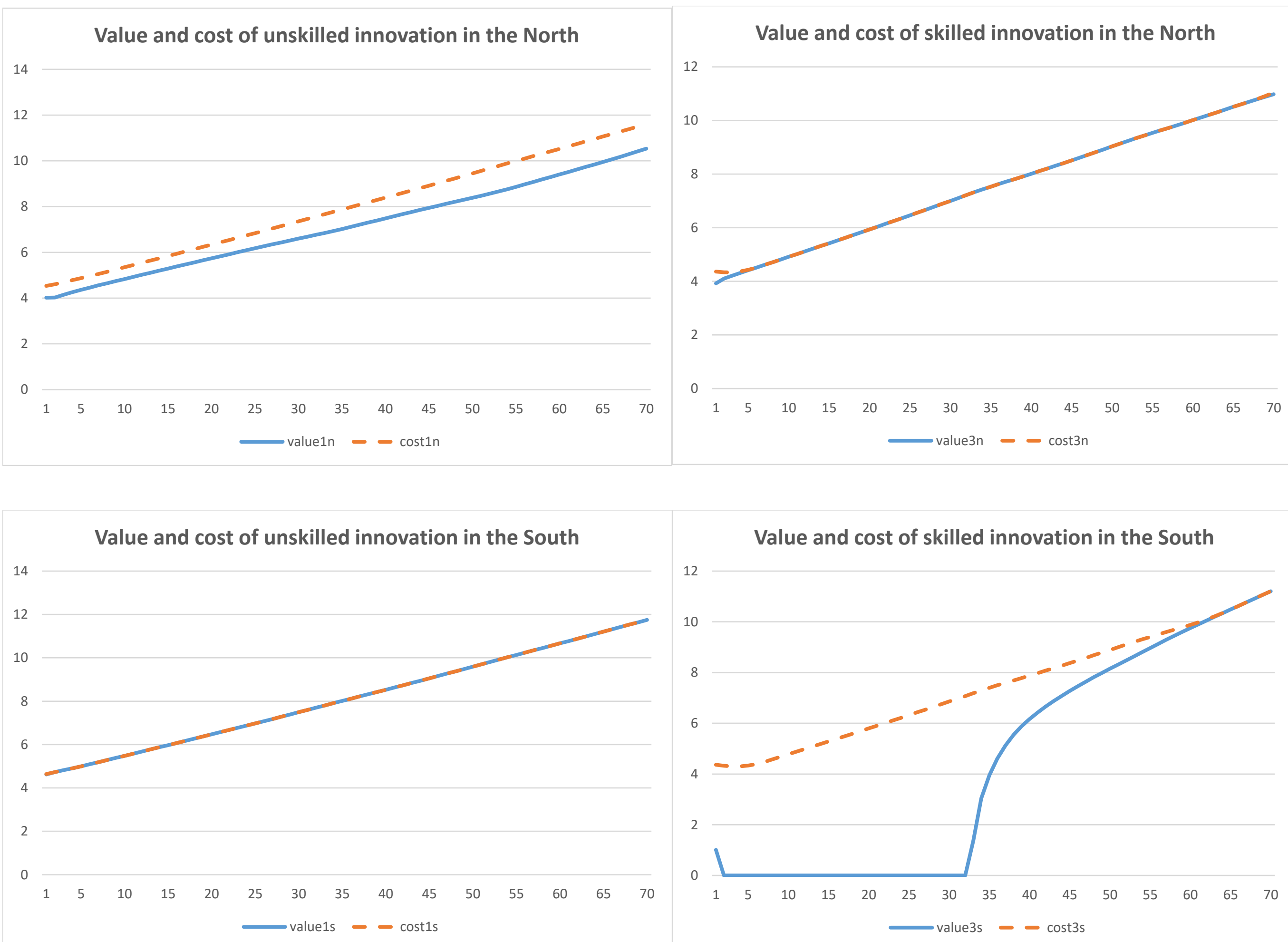
Note: With free trade we have specialization which causes skilled-intensive innovation only in the North and unskilled-intensive innovation only in the South. We also see that the South abandons production of y_3 right away, while the North abandons production of y_1 around $t = 10$.

Figure A.4: *Technologies and Demographics — Free Trade No Diffusion*



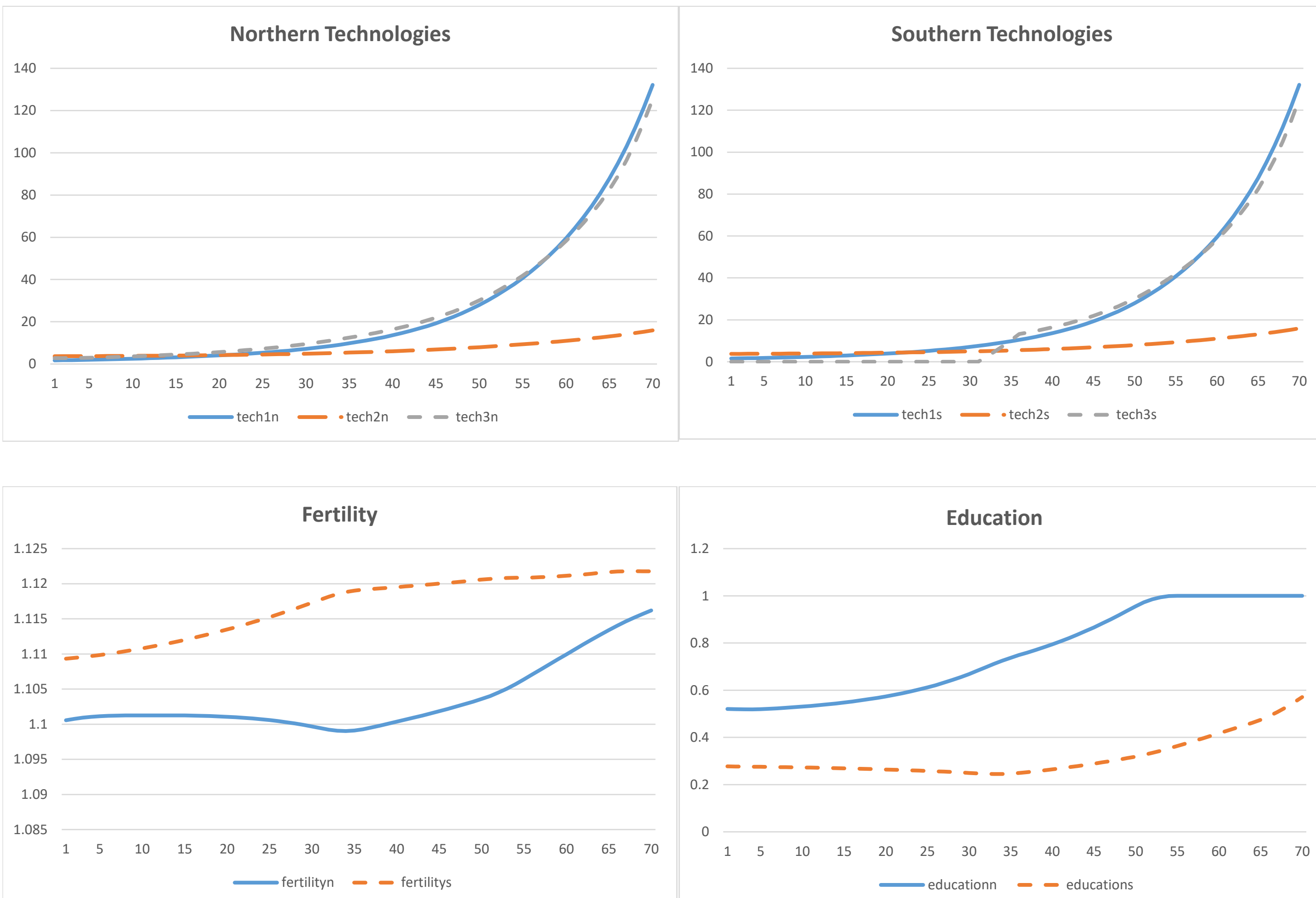
Note: With specialization we observe a demographic divergence — fertility in the North declines slowly in the North and then more rapidly, while fertility rises in the South. Universal education in the North is reached, while most in the South are unskilled.

Figure A.5: *Market for Technologies — Free Trade Free Diffusion*



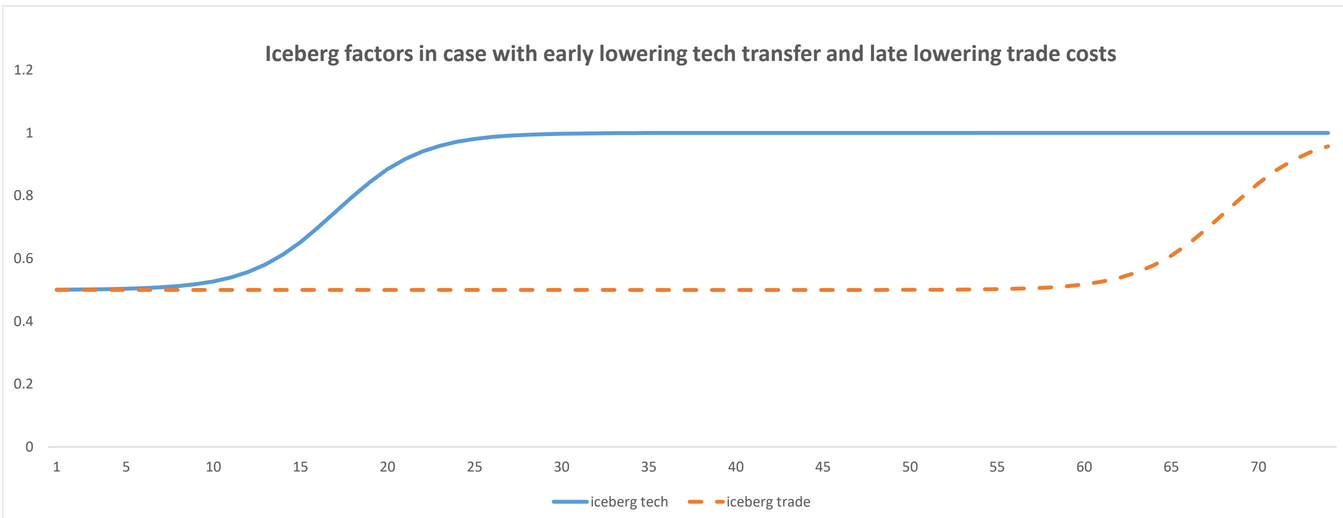
Note: In this case the North never develops unskilled technologies, while the South develops skilled technologies only at the very end. We also see that trade is partially-specialized at first (where the North produces unskilled goods but the South does not produce skilled goods), then trade is fully diversified (The South starts producing skilled goods by adopting Northern technologies).

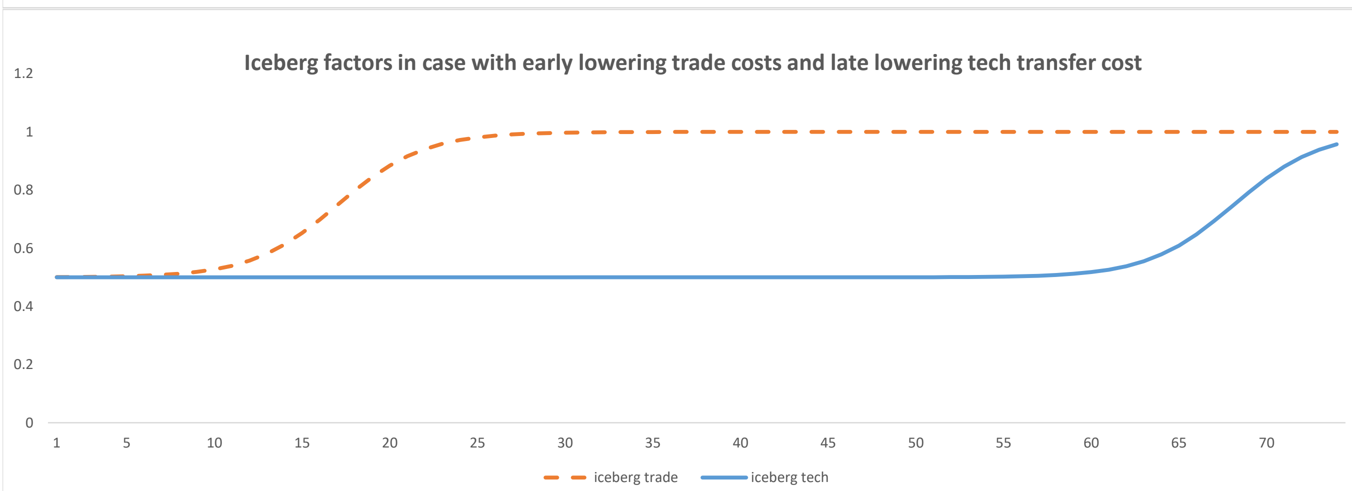
Figure A.6: *Technologies and Demographics — Free Trade Free Diffusion*



Note: Here we see initial divergence in demographic variables. Once the South is able to resurrect its skill-intensive sector, demographic convergence occurs.

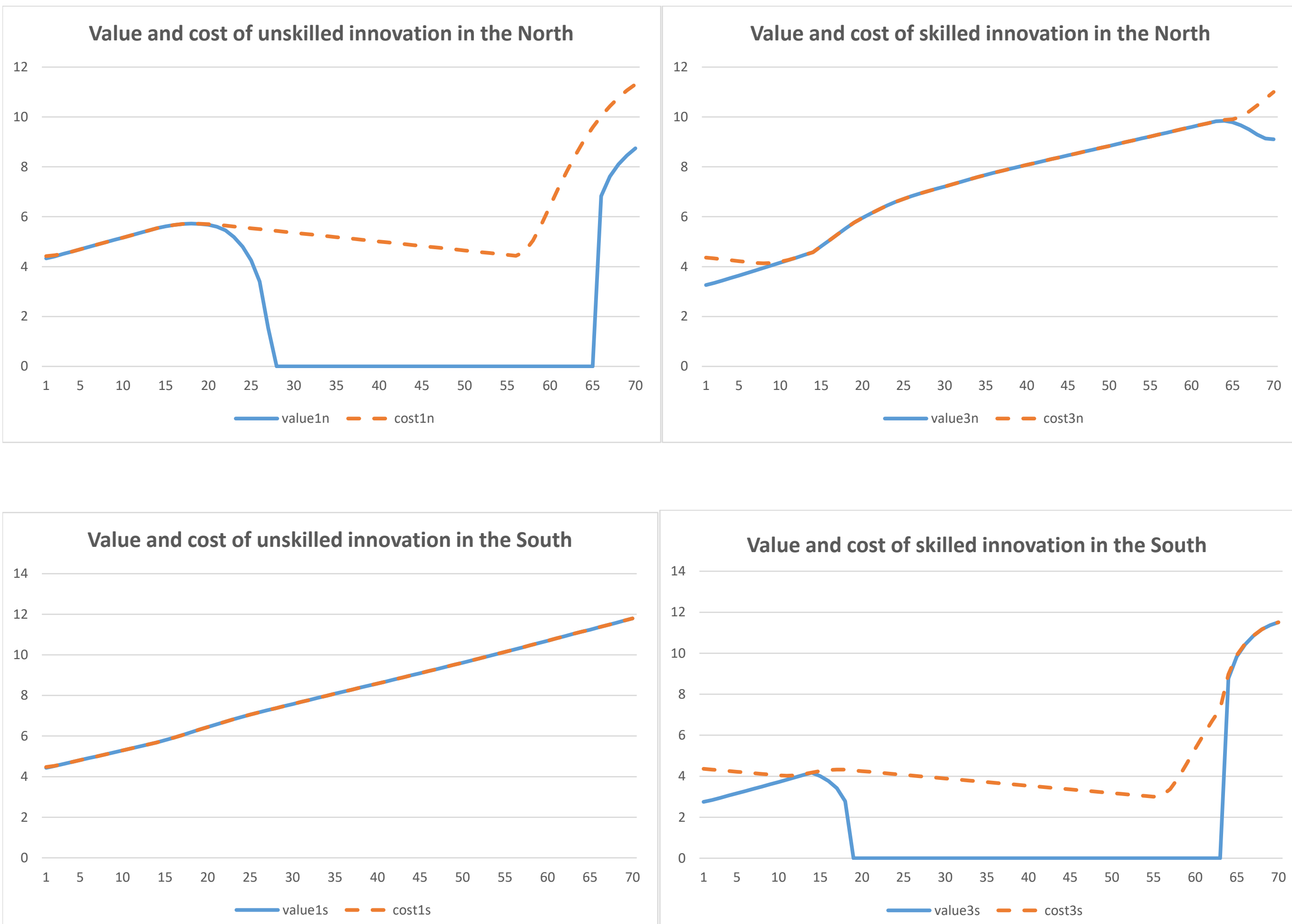
Figure A.7: *Assuming Different Patterns of Trade and Technological Diffusion Potential*





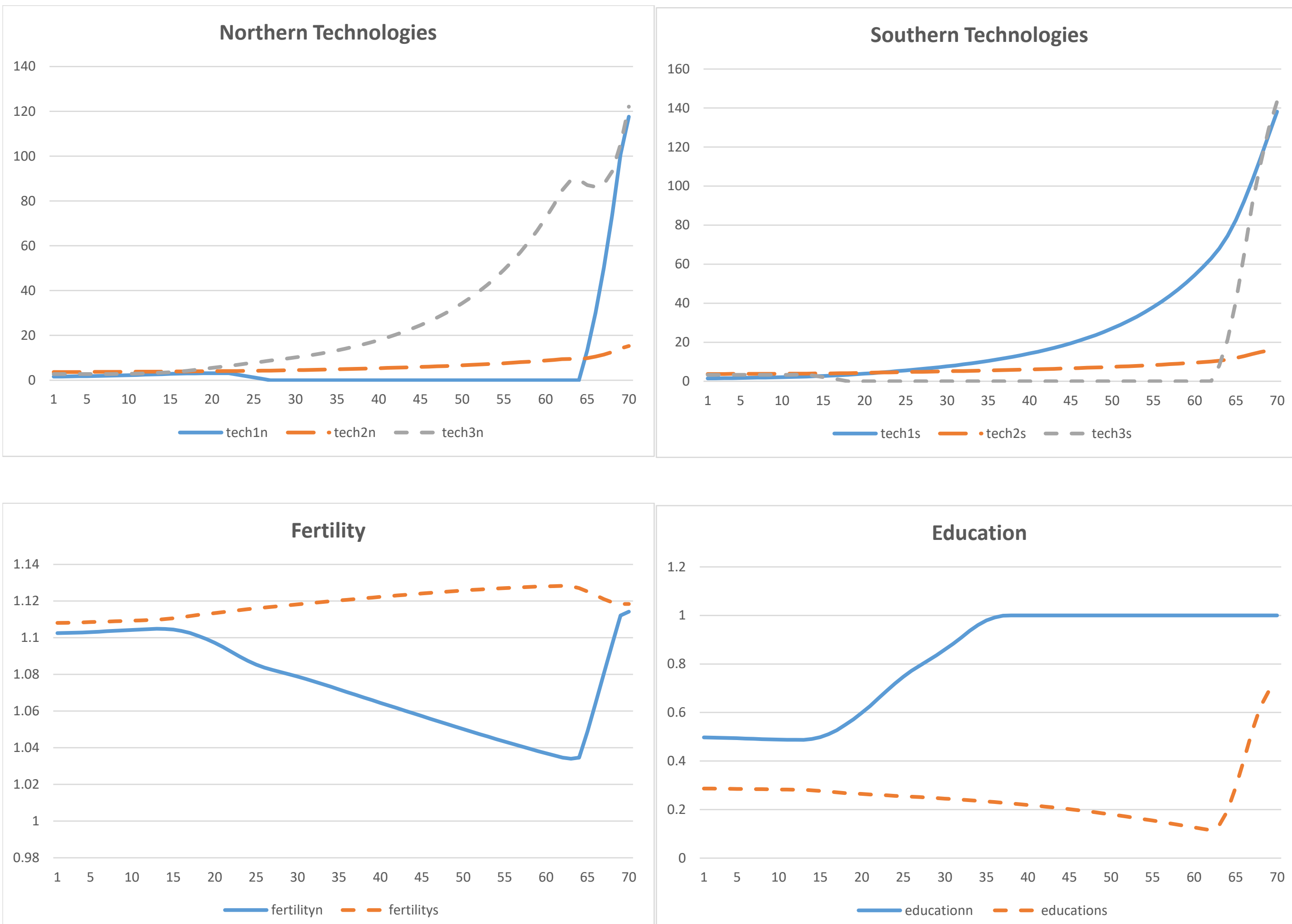
Note: Here we demonstrate two cases. The first is where technological transfer costs are the first to improve, followed by trade costs (via logistic functions). The second case reverses this pattern, where trade costs are the first to improve. The final simulated results are for the latter case.

Figure A.8: *Market for Technologies — Early Trade Late Diffusion*



Note: The upper left diagram shows that the North develops unskilled technologies intially, but then abandons such innovations as it stops producing unskilled goods. The lower left diagram shows the South developing unskilled technologies throughout. The right side shows a remarkable story of technological leapfrogging — the South, having abandoned skilled production, resurrects this industry by adopting Northern technologies, then starts developing these technologies itself! The North then abandons skill-intensive technologies as it adopts from the South.

Figure A.9: *Technologies and Demographics — Early Trade Late Diffusion*



Note: Here we see divergent demographics until the very end. When the pool of skilled technologies from the North is big enough, the South undergoes a dramatic human capital boom as the South resuurects its skilled industry. This also generates a fertility convergence.

$$A_1^s \left(A_1^s L_1^s - Z_1\right)^{-\frac{1}{\sigma}} = \left(\frac{2(1-\alpha)\gamma}{\alpha}\right) A_2^{s\,\frac{\sigma-1}{\sigma}} \left(L^s - L_1^s\right)^{-\gamma-\sigma+\sigma\gamma} \left(H^s - H_3^s\right)^{\gamma+\sigma-\sigma\gamma-1}, \tag{53}$$

$$A_3^s \left(A_3^s H_3^s + aZ_3\right)^{-\frac{1}{\sigma}} = \left(\frac{2(1-\alpha)(1-\gamma)}{\alpha}\right) A_2^{s\,\frac{\sigma-1}{\sigma}} \left(L^s - L_1^s\right)^{-\gamma+\sigma\gamma} \left(H^s - H_3^s\right)^{\gamma-\sigma\gamma-1}, \tag{54}$$

$$A_1^c = \left(N_{1,t-1}^c + \alpha^{\frac{\alpha}{1-\alpha}} \left(N_{1,t}^c - N_{1,t-1}^c\right)\right) \left(\alpha p_1^c\right)^{\frac{\alpha}{1-\alpha}}, \tag{55}$$

$$A_2^c = \left(N_{2,t-1}^c + \alpha^{\frac{\alpha}{1-\alpha}} \left(N_{2,t}^c - N_{2,t-1}^c\right)\right) \left(\alpha p_2^c\right)^{\frac{\alpha}{1-\alpha}}, \tag{56}$$

$$A_3^c = \left(N_{3,t-1}^c + \alpha^{\frac{\alpha}{1-\alpha}} \left(N_{3,t}^c - N_{3,t-1}^c\right)\right) \left(\alpha p_3^c\right)^{\frac{\alpha}{1-\alpha}}, \tag{57}$$

$$H^c = \left(\frac{\tau^{*^c}}{b^c}\right) pop^c, \tag{58}$$

$$L^c = \left(1 - \frac{\tau^{*^c}}{b^c}\right) pop^c + n^c\, pop^c, \tag{59}$$

$$n^c = \left(1 - \frac{\tau^{*^c}}{b^c}\right) n_l^{*^c} + \left(\frac{\tau^{*^c}}{b^c}\right) n_h^{*^c}, \tag{60}$$

$$e^c = \frac{\tau^{*^c}}{b^c}, \tag{61}$$

$$\frac{p_1^n}{p_3^n} = \frac{Z_3}{aZ_1}, \tag{62}$$

$$\frac{p_1^s}{p_3^s} = \frac{aZ_3}{Z_1}. \tag{63}$$

Equations (41)–(43) are unit cost functions, (44) and (45) are full employment conditions, (46)–(50) denote regional goods clearance conditions, (51)–(54) equate the marginal products of raw factors, (55)–(57) describe sector-specific technologies, , (58)–(67) describe fertility, education and labor-types for each region, and (68) and (69) describe the balance of payments for each region. Solving this system for the unknowns p_1^n, p_1^s, p_2^n, p_2^s, p_3^n, p_3^s, Q_1^n, Q_1^s, Q_2^n, Q_2^s, Q_3^n, Q_3^s, w_l^n, w_l^s, w_h^n, w_h^s, L_1^n, L_1^s, H_3^n, H_3^s, A_1^n, A_2^n, A_3^n, A_1^s, A_2^s, A_3^s, L^n, L^s, H^n, H^s, n^n, n^s, e^n, e^s, Z_1 and Z_3 constitutes the static partial trade equilibrium. Population growth for each region is given simply by $pop_t^c = n_{t-1}^c\, pop_{t-1}^c$. Each region will produce all three goods so long as factors and technologies are "similar enough." If factors of production or technological levels sufficiently differ, n produces only goods 2 and 3, while s produces only goods 1 and 2. No other specialization scenario is possible for the following reasons: first, given that both regions have positive levels of L and H, full employment of resources implies that they cannot specialize completely in good 1 or good 3. Second, specialization solely in good 2 is not possible either, since a region with a comparative advantage in this good would also have a comparative advantage in either of the other goods. This implies that each country must produce at least two goods. Further, in such a scenario we cannot have one region producing goods 1 and 3: with different factor prices across regions, a region cannot have a comparative advantage in the production of both of these goods, regardless of the technological differences between the two regions. See Cuñat and Maffezzoli (2004) for a fuller discussion.

C. Specialized Trade Equilibrium

The specialized equilibrium is one where country n does not produce any good 1 and country s does not produce any good 3. Productions in each region are then given by

$$Y^n = \left(\frac{\alpha}{2}\left(aZ_1\right)^{\frac{\sigma-1}{\sigma}} + (1-\alpha)\left(Q_2^n\right)^{\frac{\sigma-1}{\sigma}} + \frac{\alpha}{2}\left(Q_3^n - Z_3\right)^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}, \tag{64}$$

$$Y^s = \left(\frac{\alpha}{2}\left(Q_1^s - Z_1\right)^{\frac{\sigma-1}{\sigma}} + (1-\alpha)\left(Q_2^s\right)^{\frac{\sigma-1}{\sigma}} + \frac{\alpha}{2}\left(aZ_3\right)^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}, \tag{65}$$

Once again, we do not permit any trade of good 2. For each region $c \in n, s$, the following conditions characterize this equilibrium.

$$p_1^s = \frac{w_l^s}{A_1^s}, \tag{66}$$

$$p_2^c = \left(\frac{1}{A_2^c}\right)\left(w_l^c\right)^{\gamma}\left(w_h^c\right)^{1-\gamma}(1-\gamma)^{\gamma-1}\gamma^{-\gamma}, \tag{67}$$

$$p_3^n = \frac{w_h^n}{A_3^n}, \tag{68}$$

$$\left(\frac{1}{A_2^n}\right)\left(w_l^n\right)^{\gamma-1}\left(w_h^n\right)^{1-\gamma}(1-\gamma)^{\gamma-1}\gamma^{1-\gamma}Q_2^n = L^n, \tag{69}$$

$$\left(\frac{1}{A_2^n}\right)\left(w_l^n\right)^{\gamma}\left(w_h^n\right)^{-\gamma}(1-\gamma)^{\gamma}\gamma^{-\gamma}Q_2^n + \left(\frac{1}{A_3^n}\right)Q_3^n = H^n, \tag{70}$$

$$\left(\frac{1}{A_1^s}\right)Q_1^s + \left(\frac{1}{A_2^s}\right)\left(w_l^s\right)^{\gamma-1}\left(w_h^s\right)^{1-\gamma}(1-\gamma)^{\gamma-1}\gamma^{1-\gamma}Q_2^s = L^s, \tag{71}$$

$$\left(\frac{1}{A_2^s}\right)\left(w_l^s\right)^{\gamma}\left(w_h^s\right)^{-\gamma}(1-\gamma)^{\gamma}\gamma^{-\gamma}Q_2^s = H^s, \tag{72}$$

$$aZ_1 = \left(\frac{\left(\frac{\alpha}{2}\right)^{\sigma}\left(p_1^n\right)^{-\sigma}}{\left(\frac{\alpha}{2}\right)^{\sigma}\left(p_1^n\right)^{1-\sigma} + (1-\alpha)^{\sigma}\left(p_2^n\right)^{1-\sigma} + \left(\frac{\alpha}{2}\right)^{\sigma}\left(p_3^n\right)^{1-\sigma}}\right)\cdot Y^n, \tag{73}$$

$$Q_1^s - Z_1 = \left(\frac{\left(\frac{\alpha}{2}\right)^{\sigma}\left(p_1^s\right)^{-\sigma}}{\left(\frac{\alpha}{2}\right)^{\sigma}\left(p_1^s\right)^{1-\sigma} + (1-\alpha)^{\sigma}\left(p_2^s\right)^{1-\sigma} + \left(\frac{\alpha}{2}\right)^{\sigma}\left(p_3^s\right)^{1-\sigma}}\right)\cdot Y^s, \tag{74}$$

$$Q_2^c = \left(\frac{(1-\alpha)^{\sigma}\left(p_2^c\right)^{-\sigma}}{\left(\frac{\alpha}{2}\right)^{\sigma}\left(p_1^c\right)^{1-\sigma} + (1-\alpha)^{\sigma}\left(p_2^c\right)^{1-\sigma} + \left(\frac{\alpha}{2}\right)^{\sigma}\left(p_3^c\right)^{1-\sigma}}\right)\cdot Y^c, \tag{75}$$

$$Q_3^n - Z_3 = \left(\frac{\left(\frac{\alpha}{2}\right)^{\sigma}\left(p_3^n\right)^{-\sigma}}{\left(\frac{\alpha}{2}\right)^{\sigma}\left(p_1^n\right)^{1-\sigma} + (1-\alpha)^{\sigma}\left(p_2^n\right)^{1-\sigma} + \left(\frac{\alpha}{2}\right)^{\sigma}\left(p_3^n\right)^{1-\sigma}}\right)\cdot Y^n, \tag{76}$$

$$aZ_3 = \left(\frac{\left(\frac{\alpha}{2}\right)^{\sigma} \left(p_3^s\right)^{-\sigma}}{\left(\frac{\alpha}{2}\right)^{\sigma} \left(p_1^s\right)^{1-\sigma} + (1-\alpha)^{\sigma} \left(p_2^s\right)^{1-\sigma} + \left(\frac{\alpha}{2}\right)^{\sigma} \left(p_3^s\right)^{1-\sigma}} \right) \cdot Y^s, \tag{77}$$

$$A_3^n \left(A_3^n H_3^n - Z_3\right)^{-\frac{1}{\sigma}} = \left(\frac{2(1-\alpha)(1-\gamma)}{\alpha} \right) A_2^{n\,\frac{\sigma-1}{\sigma}} \left(L^n\right)^{-\gamma+\sigma\gamma} \left(H^n - H_3^n\right)^{\gamma-\sigma\gamma-1}, \tag{78}$$

$$A_1^s \left(A_1^s L_1^s - Z_1\right)^{-\frac{1}{\sigma}} = \left(\frac{2(1-\alpha)\gamma}{\alpha} \right) A_2^{s\,\frac{\sigma-1}{\sigma}} \left(L^s - L_1^s\right)^{-\gamma-\sigma+\sigma\gamma} \left(H^s\right)^{\gamma+\sigma-\sigma\gamma-1}, \tag{79}$$

$$A_1^s = \left(N_{1,t-1}^s + \alpha^{\frac{\alpha}{1-\alpha}} \left(N_{1,t}^s - N_{1,t-1}^s \right) \right) \left(\alpha p_1^s\right)^{\frac{\alpha}{1-\alpha}}, \tag{80}$$

$$A_2^c = \left(N_{2,t-1}^c + \alpha^{\frac{\alpha}{1-\alpha}} \left(N_{2,t}^c - N_{2,t-1}^c \right) \right) \left(\alpha p_2^c\right)^{\frac{\alpha}{1-\alpha}}, \tag{81}$$

$$A_3^n = \left(N_{3,t-1}^n + \alpha^{\frac{\alpha}{1-\alpha}} \left(N_{3,t}^n - N_{3,t-1}^n \right) \right) \left(\alpha p_c^n\right)^{\frac{\alpha}{1-\alpha}}, \tag{82}$$

$$H^c = \left(\frac{\tau^{*^c}}{b^c} \right) pop^c, \tag{83}$$

$$L^c = \left(1 - \frac{\tau^{*^c}}{b^c} \right) pop^c + n^c \, pop^c, \tag{84}$$

$$n^c = \left(1 - \frac{\tau^{*^c}}{b^c} \right) n_l^{*^c} + \left(\frac{\tau^{*^c}}{b^c} \right) n_h^{*^c}, \tag{85}$$

$$e^c = \frac{\tau^{*^c}}{b^c}, \tag{86}$$

$$\frac{p_1^n}{p_3^n} = \frac{Z_3}{aZ_1}, \tag{87}$$

$$\frac{p_1^s}{p_3^s} = \frac{aZ_3}{Z_1}. \tag{88}$$