Trade, Knowledge and the Industrial Revolution*

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Abstract

This paper addresses a basic empirical problem facing previous unified growth models, exemplified by Galor and Weil (2000). In such models, the onset of industrialization leads to an increase in skill premia, which is required in order to induce families to limit fertility and increase the education of their children. However, the onset of the Industrial Revolution saw a marked decline in skill premia, and this cannot be explained by supply-side educational reforms, since these only came much later. We thus construct a model, in the tradition of Galor and Weil and Galor and Mountford (2004), but which endogenizes the direction of technical change. We show that technological change during the early phases of the Industrial Revolution was inevitably unskilled-labor-biassed. We also show that a growth in "Baconian knowledge" and international trade can explain a shift in the direction of technical change away from unskilled-labor-intensive innovations and towards skill-labor-intensive innovations. Simulations show that the model does a good job in tracking reality, at least until the late 19th century with its mass education reforms.

- *Keywords*: endogenous growth, demography, trade
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1 Introduction

The aim of this paper is to contribute to an emerging conversation between economic theorists and economic historians. For decades, the Industrial Revolution was the preserve of the latter group, who measured it and sought to explain it; but the greatest economic breakthrough in human history was largely neglected by economic theorists, and when historians used theory to interpret the event, they used the off-the-shelf models then current in the profession, be these Keynesian, Marxist or Solovian. More recently, however, theorists have begun modeling the transition from Malthusian stagnation to modern economic growth in search of a so-called "unified growth theory"; that is, they have developed models that can generate such a transition without any exogenous shocks being imposed on the system. Since the modeling challenges involved are considerable, the theoretical mechanisms required to reproduce the take-off are the primary focus of the classic papers produced in this phase of the literature (e.g., Galor and Weil 2000; Jones 2001; Hansen and Prescott 2002; Lucas 2002).

Since then, economic historians have started compiling evidence on the behavior of key variables in these models (e.g., Voth 2003; Clark 2004, 2005), while theorists have constructed second-generation models that seek to address empirical shortcomings of the first-generation models (e.g. Doepke 2004). Economic historians have paid special attention to two phenomena that have been stressed in the recent theoretical literature. The first is the fertility transition, which saw the number of births per woman decline dramatically beginning (in Britain) some time around the 1890s (Clark 2007). The second is the increase in education, as measured by literacy. As Clark (2005) emphasizes, English literacy rates were slowly increasing from the late 16th or early 17th centuries; after a temporary 18th century plateau, men's literacy resumed its slow rise in the early 19th century, but it accelerated only after 1860 or so. (Women's literacy improved more or less continuously from the mid-17th century to the early 20th century; but here again there was a noticeable acceleration after 1850 or so).

This paper will tackle head-on a basic timing problem identified by Greg Clark in his recent work. In order to understand this problem, we may consider the benchmark model provided by Galor and Weil (2000)—although the same problem afflicts other models in the literature. In the Galor-Weil account, the economy is initially in a Malthusian equilibrium in which the existence of a fixed factor of production implies diminishing returns, and in which any increase in incomes provokes an increase in population, which then drives down income levels. Eventually, however, by dint of scale effects—à la Romer (1990)—population growth pushes up the rate of technological progress to the point where sustained improvement in living standards becomes possible. Initially, a large proportion of this increased technological progress is "eaten up" by higher population growth, as richer parents find themselves able to spend more time rearing costly children. However, a higher rate of technological progress also (by assumption) raises the demand for human capital, and raises skill premia. This relative price effect eventually dominates, and induces parents to switch to smaller, better educated families: fertility rates fall, and literacy rates rise. From this stage onwards, technological progress coincides with falling fertility rates, and per capita incomes rise rapidly.

The problem with this account is that it does not match the facts. In particular, it implies

rising skill premia after the initial onset of the Industrial Revolution, whereas, as we discuss below, they declined after the onset of the Industrial Revolution in the middle of the 18th century, rather than rising. It was only in the 19th century that they started rising, but they did so only very slightly, and they never rose above their original level. This poses a problem for would-be unified growth modelers. As long as fertility and education decisions are modeled within a Beckerian quantity-quality framework, rising skill premia are going to be the crucial relative price signal required to trigger a demographic transformation. If technological progress is the primary force driving skill premia, by influencing the demand for labor, then it would seem that technological progress is going to have to be skill-biased, by assumption, if a demographic transition is to be generated. Thus the modeler is faced with a dilemma. She can assume that technological change is skill-biased, at the expense of predicting that skill premia started rising with the onset of the Industrial Revolution, when in fact they fell. Or, she can assume that technological change is unskilled-labor-biased, thus correctly predicting that skill premia fell in the late 18th century, but at the expense of concluding that they continued to fall, thus making it extremely difficult to generate a demographic transition.

One solution to this dilemma would be to simply *assume* that technological change was initially unskilled-labor-biased and subsequently skill-biased, but such an approach would seem to us to be *ad hoc* and intellectually satisfactory. Presumably we would like to know why different sorts of technological choices were being made at different points in time. In this paper, we thus propose a different approach, which involves delving into the microeconomics of technological change to a greater extent than previous papers, which have tended to model technological change in a reduced form manner as a function of scale effects and/or human capital endowments. By contrast, we propose a fully-specified research and development model driving technological change, which is appropriate for this period since Allen (2006) has recently shown that British firms were investing significant resources in the search for technical breakthroughs during the Industrial Revolution. Building on the foundations of the benchmark Galor-Weil (2000) and Galor-Mountford (2004) models, we thus make several key changes to previous specifications.

The first key feature of our approach is that we disentangle two distinct elements of technological progress: *basic knowledge* (B) and *applied knowledge* (A). In our model, the former grows according to the level of human capital in the economy and is a public good; the latter describes firms' techniques, which are subject (for a time) to private property rights, generate private profits, and hence create incentives for research. In our model, A is driven by research which generates benefits (increases in A) but also has costs (that are decreasing in B); thus basic knowledge drives the development of applied knowledge.

This distinction between basic and applied knowledge is inspired by Mokyr (2002), who distinguishes between two knowledge types: the "propositional" *episteme* ("what") and the "prescriptive" *techne* ("how"). He terms these Ω-knowledge and λ-knowledge. An addition to the Ω set is for Mokyr a *discovery* and an addition to the λ set is an *invention*. Mokyr's categories can be thought of as close parallels to our B-knowlege (what we might term "Baconian" knowledge) and A-knowledge (the usual notion of total factor productivity, or TFP). We propose the term Baconian knowledge to honor Francis Bacon, whose principles guided the rise of a pragmatic, post-Enlightenment approach to applied "basic" science that would ultimately generate

"applied" material benefit. If Mokyr's (2002, 41) characterization is accurate, then this honor is rightfully bestowed on Bacon since "the amazing fact remains that by and large the economic history of the Western world was dominated by materializing his ideals."[1] Our model can provide a rationale for one of Mokyr's key claims, namely that "the true key to the timing of the Industrial Revolution has to be sought in the scientific revolution of the seventeenth century and the Enlightenment movement of the eighteenth century" (p. 29). As will be seen, basic knowledge in our R & D model has to advance for some time before applied knowledge starts to improve. This helps our model match reality: we find that Baconian knowledge B can increase continuously but applied knowledge or productivity A only starts to rise in a discontinuous manner once B passes some threshold.[2]

The second key feature of our model, and the paper's main contribution, is that it endogenizes the *direction* of technological change. There are two ways to produce output, using either a low-skill technique (based on raw labor L) or a high-skill technique (based on educated labor, or human capital H). For simplicity, these techniques are each linear in their sole input, and have their own applied knowledge, summarized in endogenous productivity coefficients, or technology levels.

Research by firms, which is patentable or otherwise excludable in the short run, can raise these technology levels and generate short-run monopoly profits. In the spirit of Acemoglu (1998), we allow potential innovators to look at the supply of skilled and unskilled labor in the workforce, and tailor their research efforts accordingly. The direction as well as the pace of technological change thus depends on demography. At the same time, demography is explicitly modeled as depending on technology, as is common in the literature (e.g. Galor and Weil 2000). Households decide the quality and quantity of their children (that is, the future supply of L and H) based directly on the anticipated future skill-premium, and thus (indirectly) on recent technological developments. As such the model allows for the co-evolution of both factors and technologies.

The third key feature is that our model can be configured either as a closed-economy model or as an open-economy model. In our benchmark simulations, where we try to calibrate the model to match the British economy from circa 1750 to the present, the choice of configuration cannot be treated as constant over time. It is our maintained assumption that, to a first approximation, the closed economy assumption might be most appropriate from 1750 to 1850, but that after that time, an open economy assumption might be more appropriate, once the first era of globalization started to take shape (O'Rourke and Williamson 2002a, 2005). On the other hand, the British economy presumably did not undergo a discontinuous switch from a closed to an open state, and thus we will impose continuously declining transport costs to achieve such a transition.

In this framework, we argue that the Industrial Revolution initially consisted of a rapid succession of unskilled-labor biased technological innovations. This is what explains the initial decline in the return to skills. Because these innovations simply induced population expansion and limited human capital accumulation, income per capita in these regions remained relatively

[1] In a rather similar manner, Galor and Mountford (2004) distinguish between the 'technological level in the economy as a whole' and 'productivity levels in each sector' (p. 22). We prefer our terminology since it is closer to Mokyr's in spirit.

[2] By contrast,in the reduced form formulation of Galor and Mountford (2004) sectoral productivity levels increase continuously as the 'technological level in the economy as a whole' increases.

low. Indeed, our model suggests that north-western Europe (the "North") required both a highly-developed knowledge base (in order to begin to innovate in high-skill sectors) and highly-developed global transport technologies (in order to specialize in high-skill products) to reverse demographic trends. Both of these took time to appear in the later 19th century. They eventually placed the North on the road to riches, forcing a demographic reversal in the North, with rising education levels and population growth held in check. Thus the robust growth in income per capita enjoyed by Northern economies is really a two-part story, two centuries in the making.

Elsewhere, in the developing world (the "South"), these shocks would play the opposite role: encouraging specialization in low-skill goods, discouraging skill accumulation, and boosting fertility. Hence, we join Galor and Mountford (2004) in arguing that the nature of trade may have played a large role in the Great Divergence. As we will see within the framework of co-evolving factors and techniques, a country that has a *static* comparative advantage in skill-intensive production may ultimately have a *dynamic* advantage as well. Hence by looking more closely at the factor-composition of traded products, we may be able to better reconcile theory and reality. For example, Clark (2007) asserts that by 1900, cities such as Alexandria in Egypt, Bombay in India, and Shanghai in China were all, in terms of transport costs, capital markets, and institutional structures fully integrated into the British and other Western economies. Yet perhaps due to the nature of trade, these societies were unable keep up with the West, leading to an ever-widening income gap in the world economy.

Pointing to such a theoretical link between trade and the Great Divergence is not in itself novel, but we argue that there are several key features which distinguish this exercise from that of Galor and Mountford. While they construct a semi-Ricardian trade model (in which countries are initially distinguished by *technological* differences alone), we construct a Heckscher-Ohlin trade model in which countries initially differ due to factor endowment differences alone, and argue that a Great Divergence was possible even in the context of perfect technology diffusion. Moreover, we allow for the *gradual* opening of goods trade, whereas Galor and Mountford investigate the implications of moving from autarky to free trade; thus we can better track the continually strengthening forces of globalization of the late 19th century which reached their apotheosis in 1913. We incorporate an explicit research and development model into our account of growth, which they do not, and also explore the endogenous evolution of the factor bias of technological change, an issue which they do not address. Finally, in this paper we will 'test' our theory by seeing to what extent the model can track the evolution of key variables such as fertility rates, education rates, wages and skill premia.

To make the nature of the empirical challenge clearer, and to explain why the extant unified growth theories fall short in some important respects, we now turn to the empirical evidence and the specific patterns in the long-run data that we seek to match.

2 The Evidence

2.1 Income and Population Growth

The first stylized fact which any unified growth theory, including our own, must be able to match is the striking coincidence between the development of sustained per capita income growth on the one hand, and population growth on the other. This association, which is stressed by Galor (2005) in his review of which stylized facts must be addressed by unified growth theories, comes across clearly in Figure 1, which is taken from Galor (2005) and based on data taken from Maddison (2001). As can be seen from the figure, there were dramatic accelerations in both per capita income growth and population growth after 1820 in both Western Europe and the 'Western offshoots' (the United States, Canada, Australia and New Zealand). Figure 1 shows similar patterns in Latin America and Africa as well, with the difference being that the transitions to per capita income and population growth took place later in these continents. Everywhere, however, income and population growth went hand in hand, at least initially. As we will see, the leading regions eventually experienced a demographic transition to lower fertility rates, which raises the question of why growth and fertility were initially positively correlated with each other, but negatively correlated thereafter.

2.2 Human Capital Formation and the Fertility Transition

Figure 2 plots the crude birth rates and primary school enrollment rates for four relatively developed countries through the nineteenth and early part of the twentieth centuries. In general, while birth rates either rose or remained high during the first half of the nineteenth century, they began to fall significantly some time after 1870 (while the decline began earlier in the United States, note that it started the early 1800s with a significantly higher fertility rate than other comparable regions). During the same period, education levels began to rise. Thus it would appear that in relatively developed regions, a dramatic substitution from quantity to quality of children was beginning a hundred years after the start of the Industrial Revolution. By the late twentieth century, this transition was underway in the less developed world as well. A model proffering itself as a unified growth theory would have to account for the timing and nature of this shift in some fashion.

These facts beg the questions: why did the demand for education not rise with the initial wave of industrialization? Why did the demand for education significantly rise only by the second half of the 1800s? Further, why did educational attainment not rise in the developing world until well into the latter half of the twentieth century? A theory of growth linking the eighteenth, nineteenth and twentieth centuries should offer some response to these questions.

2.3 The Explosion of International Trade

Although inter-continental trade had been growing for centuries, the rate of growth accelerated dramatically during the 19th century. Both O'Rourke and Wiliamson (2002b) and de Vries (2003) estimate that inter-continental trade grew at around 1% per annum between 1500 and 1800, but

it has grown at around 3.5% per annum since the end of the Napoleonic Wars. In 1820, the ratio of merchandise trade to world GDP was just 1%, but it was eight times this in 1913 (Maddison 1995). Just as important, all regions of the world participated in this unprecedented trade boom. The data in Lewis (1981) imply that tropical country exports grew at an annual real rate of 2.9% between 1850 and 1913. This implied that economies with radically different endowments of unskilled labor, skilled labor and physical capital were becoming increasingly inter-linked through trade, especially after the middle of the 19th century, when transport costs really started to plummet (Harley 1988; Shah Mohammed and Williamson 2004), and our modeling will have to take account of this fact as well.

2.4 Skill Premia During the Industrial and Demographic Revolutions

Figure 3 plots the skill premium between 1700 and 1910, based on decadal averages of wages for craftsmen and laborers in the English building trades (based on the data in Clark 2005). As can be seen, skill premia were slightly above 60% during the first half of the 18th century, but then fell through the 1810s, to below 50%. There was a recovery in the 1820s, and premia remained above 50% until the 1870s, when they declined again, to below 45%. Thus, skill premia fell during the second half of the 18th century, rather than rising with the onset of the Industrial Revolution, as many unified growth theory models predict. The rise in skill premia only came later, after the end of the Napoleonic Wars, and it was not sufficient to restore premia to their pre-1750 levels.

3 The Model

In this section we build a theoretical version of a closed 'English' economy in successive steps, keeping the points enumerated in Section 2 firmly in mind. Section 3.1 illustrates the method used to solve the static general equilibrium model. Section 3.2 allows the economy to evolve over time, and develops a method for endogenizing the scope and direction of technical change, keeping endowments fixed. Finally section 3.3 merges the model with an overlapping generations framework in order to endogenize demographic variables. These three parts form an integrated dynamic model which we use to analyze the industrialization of England during the 18th and 19th centuries.

3.1 Production

We begin by illustrating the static general equilibrium of a hypothetical economy. The economy produces a final good Y out of three intermediate inputs using a CES production function

$$Y = \left(\frac{\alpha}{2} {x_1}^{\frac{\sigma-1}{\sigma}} + (1-\alpha) {x_2}^{\frac{\sigma-1}{\sigma}} + \frac{\alpha}{2} {x_3}^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} \tag{1}$$

where $\alpha \in [0,1]$ and $\sigma \geq 0$. σ is the elasticity of substitution among intermediate goods. Heuristically, one might think of the final good Y as being "GDP" which is aggregated up from three sectoral outputs x_i.

The intermediate goods are produced with the following technologies.

$$x_1 = A_1 L_1 \tag{2}$$

$$x_2 = A_2 L_2^{\gamma} H_2^{1-\gamma} \tag{3}$$

$$x_3 = A_3 H_3 \tag{4}$$

The coefficients A_1, A_2, and A_3 represent sector-specific technologies that respectively augment sectors 1, 2 and 3. Total endowments in this static case are given by the total amount of unskilled labor, $L = L_1 + L_2$, and the total amount of skilled labor, $H = H_2 + H_3$. Thus sector one strictly utilizes raw labor, sector three strictly utilizes skilled labor, and sector two requires both. Throughout the paper, we will call A_1 *unskilled-labor biased* technology, and A_3 *skill-biased* technology.

Production here is a variant of Cuñat and Maffezzoli (2002). We use these technologies instead of the standard ones used in typical Heckscher-Ohlin models because this allows us to focus on factor-biased technological developments, and abstract away from sector-biased technological shifts. Dividing the economy into three sectors greatly abstracts from reality but produces a useful tool of analysis. Economic outcomes heavily depend on which sectors enjoy superior productivity performance. Some authors use loaded terms such as 'modern' and 'traditional' to label the fast and slow growing sectors, at least in models where sectors are associated with types of goods (e.g., manufacturing and agriculture). We employ neutral language, since we contend that growth can emanate from different sectors at different times, where 'sectors' in our model are set up to reflect factor biases in technology. We argue that sector 1 was the leading sector during the early stages of the Industrial Revolution, while sector 3 significantly modernized only from the mid-1800s onwards.

Treating the technological coefficients as exogenous for the time being, we can assume that markets for both the final good and intermediate goods are perfectly competitive. Thus, prices are equal to unit costs. Solving the cost minimization problems for productions, and normalizing the price of final output to one, yields the unit cost functions

$$1 = \left[\left(\frac{\alpha}{2}\right)^{\sigma} (p_1)^{1-\sigma} + (1-\alpha)^{\sigma} (p_2)^{1-\sigma} + \left(\frac{\alpha}{2}\right)^{\sigma} (p_3)^{1-\sigma}\right]^{\frac{1}{1-\sigma}} \tag{5}$$

$$p_1 = \frac{w_l}{A_1} \tag{6}$$

$$p_2 = \left(\frac{1}{A_2}\right) w_l^{\gamma} w_h^{1-\gamma} (1-\gamma)^{\gamma-1} \gamma^{-\gamma} \tag{7}$$

$$p_3 = \frac{w_h}{A_3} \tag{8}$$

where naturally p_z denotes the price for intermediate good x_z.

Full employment of total unskilled labor and total skilled labor implies the following factor-market clearing conditions:

$$L = \frac{x_1}{A_1} + \frac{w_l^{\gamma-1} w_h^{1-\gamma} (1-\gamma)^{\gamma-1} \gamma^{1-\gamma} x_2}{A_2} \tag{9}$$

$$H = \frac{w_l^{\gamma} w_h^{-\gamma} (1-\gamma)^{\gamma} \gamma^{-\gamma} x_2}{A_2} + \frac{x_3}{A_3} \tag{10}$$

Finally, the demands for intermediate goods from final producers can be derived from a standard C.E.S. objective function (so demands will be negatively related to own price, will be a function of a price index, and will be proportional to total product). Specifically, intermediate goods market clearing requires

$$x_i = \left(\frac{\Upsilon_i^{\sigma} p_i^{-\sigma}}{\left(\frac{\alpha}{2}\right)^{\sigma} (p_1)^{1-\sigma} + (1-\alpha)^{\sigma} (p_2)^{1-\sigma} + \left(\frac{\alpha}{2}\right)^{\sigma} (p_3)^{1-\sigma}} \right) Y \tag{11}$$

for $i = 1, 2, 3$, $\Upsilon_1 = \Upsilon_3 = \alpha/2$, and $\Upsilon_2 = 1 - \alpha$.

Substituting (5) into the expressions for intermediate-goods demands simplifies these equations somewhat. Provided that we have values for L, H, A_1, A_2 and A_3, along with parameter values, this yields eight equations with eight unknowns: p_1, p_2, p_3, x_1, x_2, x_3, w_l and w_h. The solution for these variables constitutes the solution for the static model in the case of exogenously determined technological and demographic variables.

The predictions of our model will depend heavily on the parameters σ and α. The elasticity of substitution between goods, σ, plays a critical role in determining how changes in technologies or factors affect prices and wages. For example, suppose that there is an exogenous increase in A_1, the technological coefficient for sector one. Because this sector employs only raw labor, we can expect some unskilled labor to migrate from sector two to sector one. This will lower p_1 and raise p_2 regardless of the elasticity of substitution. But the skill premium, w_h/w_l, will fall *if and only if* $\sigma > 1$. In other words, in order for technological advances in a single-factor sector to be biased towards that factor, intermediates must be grossly substitutable. Furthermore, an increase in A_1 can actually induce a drop in the absolute value of skilled wages if goods are *sufficiently* substitutable.

Similarly, an exogenous increase in one factor of production will lower the price of the good that uses that factor intensively, and raise the price of the good that uses the other factor intensively. The extent of these price shifts however will depend on σ; the lower the substitutability, the more violently will prices react to an endowment shock.

Finally, α proxies for the importance of each sector. The smaller α is, the closer production is to a Cobb-Douglas technology. The larger α is, the larger are the roles of sectors one and three, and so the more specialized are the roles of the factors of production. The role of technological biases, something that we turn to next, will exert itself quite forcefully as long as these sectors play heavy roles in the economy.

3.2 Endogenous Technological Biases

We now endogenize the evolution of the sectoral technology levels. Inspired by the work of Acemoglu (1998), we model technological development as improvements in the quality of a fixed number of products. Specifically, we assume that researchers expend resources to improve the quality of a machine, and receive the revenues for the sale of these new machines *for only one*

time period. For simplicity, we apply this idea to sectors 1 and 3 only. In the context of this paper, we can think of A_1 and A_3 as amalgamations of quality-adjusted machines that augment either unskilled labor employed in sector 1, or skilled labor employed in sector 3, but not both. In this way we can think of quality improvements to machines that will favor the inputs of one sector relative to another. We further assume that these technological advances "spill-over" into sector 2 after a delay, so that eventually both types of labor are augmented no matter which of the three sectors they work in. (We could also explicitly model innovation in sector 2, but the insights would not be so different.)

In our model, costly innovation will be undertaken to improve some machine j (designed to be employed either in sector 1 or 3), get the blueprints for this newly improved machine, use these blueprints to produce the machine, and sell these machines to the producers of the intermediate good, all in the same time period. After this time, the blueprints to this machine j becomes publicly known, in which case either machine j is competitively produced, or some other innovator improves machine j again.[3] In this fashion we simplify the process of "creative destruction" as described by Schumpeter (1934) and refined by Aghion and Howitt (1992), where successful researchers along the quality dimension tend to eliminate the monopoly rentals of their predecessors. Here monopoly rights to new machine j last just one time period whether or not there is a new innovation to machine j.

Intermediate Goods Production

Production remains as before, but now technology levels A_1 and A_3 at time t are defined as the following:

$$A_1 \equiv \frac{1}{1-\beta}\int_0^1 q_l(j)\left(\frac{M_l(j)}{L_1}\right)^{1-\beta} dj, \qquad A_3 \equiv \frac{1}{1-\beta}\int_0^1 q_h(j)\left(\frac{M_h(j)}{H_3}\right)^{1-\beta} dj \tag{12}$$

where $0 < \beta < 1$. M_l are machines that are strictly employed by unskilled workers in sector one, while M_h are machines that are strictly employed by skilled workers in sector three. $q_z(j)$ is the highest quality of machine j of type z. Note that these technological coefficients may thus be interpreted simply as functions of different types of capital per different types of workers; the capital however in this case is specialized and quality-adjusted. The specifications here imply constant returns to scale in the productions of x_1 and x_3, and so the number of firms that produce these intermediate goods is conveniently indeterminate.

We assume machines last one period, and then depreciate completely (but see below—a single period in our simulations will be approximately five years of real time). Once machines can be competitively produced, they can be used anywhere by the appropriate factor, including in sector 2. For analytic convenience we assume that intellectual property is not protected in sector 2; thus innovators do not improve machines for use in this sector. Instead L_2 and H_2 are augmented

[3]Conceptually one may assume that either patent rights to innovation last one time period, or equivalently it takes one time period to reverse engineer the development of a new machine. Either one fits better the historical evidence than the assumption that profits from innovation last so long as a new invention is not made.

by *older* versions of M_l and M_h, respectively.[4] So technological growth in sectors 1 and 3 will also promote growth in sector 2, but with a delay of one time period. Specifically, we assume that if A_1 and A_3 describe unskilled and skilled biased technologies at time t, A_2 at time $t+1$ is given by

$$A_2 \equiv A_1^{\gamma} \cdot A_3^{1-\gamma} \tag{13}$$

so that the technological coefficient in sector 2 is simply a geometric weighting of past biased technologies.

Our modeling approach reflects the idea that different production techniques can be implemented only by particular factors. For example, by way of initial conditions, preindustrial textile production needed highly skilled labor such as spinners and weavers. Similarly, other preindustrial manufactures relied on their own skilled artisans of various sorts. But changes followed: implementing the technologies of the Industrial Revolution (in textile production, iron smelting and refining, mining and agriculture) required large labor forces with little to no specialized training, and happy, highly-valued skilled craftsmen became angry, machine-breaking Luddites. Much later, fortunes changed again: the techniques developed in the 19th century (for example in chemicals, electrical industries and services) raised the demand for a new labor force with highly specialized skills. Finally, developments in both areas spilled over into other sectors (for example, agriculture benefitted from the metal drainage pipes developed for manufacturers, and gas-lighting adapted for miners allowed skilled artisans to work longer hours (Falkus 1982)). These changes are proxied here as increases in A_1, A_3, and A_2 respectively.

Further, these patterns of directed technical change have been observed within particular industries. Goldin and Katz (1998) for example note how the automobile industry began as a highly skill-intensive industry. As production grew more automatized, skilled labor was increasingly replaced by unskilled labor, culminating in Henry Ford's assembly line processes. Only after WWII (with the expansion of trade and competition from Germany and Japan) did car production in the U.S. become skill-intensive again, with the development of continuation and batch processes.

Returning to the model, let us consider a representative firm that competitively produces x_1 (Much of what follows will deal with only sector 1. Parallel inferences can be made for sector 3). Its maximization problem is stated as

$$\max_{\{L_1, M_l(j)\}} p_1 \cdot A_1 L_1 - \int_0^1 p_l(j) M_l(j) dj - w_l L_1 \tag{14}$$

where $p_l(j)$ is the price of machine $M_l(j)$ faced by all producers of x_1. Hence the firm chooses an amount of unskilled labor to hire and amounts of complementary machines to employ, taking the price of its output, the price of machines, and the price of raw labor as given.

From the first order condition on L_1 we have

$$p_1 \beta A_1 = w_l \tag{15}$$

[4]This also allows us to focus strictly on innovation directed at particular factors rather than sectors.

Solving for the price of x_1 we have $p_1 = \frac{w_l}{\beta A_1}$. From the first order condition on machine j we can get the total demand for machine $M_l(j)$

$$M_l(j) = \left(\frac{q_l(j)w_l}{\beta A_1 p_l(j)}\right)^{\frac{1}{\beta}} L_1 \tag{16}$$

The Gains from Innovation

Innovation in a sector takes the form of an improvement in the quality of a machine by a certain multiple. Potential innovators expend resources up front to develop a better machine; let us denote the amount of the final good used in R&D to develop an improved blueprint of machine j used in sector 1 as $c_l(j)$. Assume that innovation is deterministic; that is, individuals who decide to research will improve the quality of a machine with a probability of one. We assume that there is a 'quality ladder' with widely spaced rungs. Quality levels are discrete and increments in quality are not infinitesimal. We further assume these increments are sufficiently large that new, high quality machines supplied monopolistically by innovators are always strictly preferred to old, low quality machines produced competitively from public-domain blueprints. Thus, once a new quality level is reached, all older versions of that machine type are made obsolete.

Once the researcher spends the resources necessary to improve the quality of machine j, she becomes the sole producer of this machine, and charges whatever price she sees fit. Thus she receives total revenue of $p_l(j)M_l(j)$. Solving for the price of machine j in (16) and substituting this, we can rewrite total revenue of machine production as

$$TR = \frac{M_l(j)^{1-\beta} L_1^{\beta} q_l(j) w_l}{\beta A_1} \tag{17}$$

Hence the marginal revenue is given by

$$MR = (1-\beta)p_l(j) \tag{18}$$

Here we must make the distinction between the cost of *producing* a machine, and the cost of *inventing* a better machine. We discuss the costs of innovation in the next sub-section. Here, we assume the cost of producing a machine is proportional to its quality, so that better machines are more expensive to make—a form of diminishing returns. Indeed, we can simply normalize this cost, so that

$$MC = q_l(j) \tag{19}$$

In order to maximize profits, new machine producers will equate marginal revenue with marginal cost. Equating (18) with (19) reveals that machine producers will charge a constant markup over marginal cost, specifically, $p_l(j) = q_l(j)/(1-\beta)$. Substituting this mark-up into (16) gives us a demand equation for machines that is common for all machine types.

$$M_l(j) = M_l = \left(\frac{(1-\beta)w_l}{\beta A_1}\right)^{\frac{1}{\beta}} L_1 \tag{20}$$

Current profit for the producer of machine j is given by total revenue minus total cost, or $\pi_l(j) = p_l(j)M_l(j) - q_l(j)M_l(j)$. Plugging in the mark-up equation for machine price, and machine demand equation (20), profits can be written as

$$\pi_l(j) = \left(\frac{\beta}{1-\beta}\right) q_l(j) \left[\frac{(1-\beta)w_l}{\beta A_1}\right]^{\frac{1}{\beta}} L_1 \tag{21}$$

The Costs of Innovation

We now make assumptions about the costs of innovation. Assume that the resource costs of research to improve machine j in sector 1 is given by

$$c_l(j) = \delta \cdot q_l(j) \left(w_l\right)^{\frac{1}{\beta}} \left(\frac{1}{B}\right)^{\phi_l} \tag{22}$$

and the resource costs of research to improve machine j in sector 3 is given by

$$c_h(j) = \delta \cdot q_h(j) \left(w_h\right)^{\frac{1}{\beta}} \left(\frac{1}{B}\right)^{\phi_h} \tag{23}$$

with the assumption that $\phi_h > \phi_l > 1$. The variable B is our measure of current general knowledge that we label *Baconian knowledge*. The general assumptions in each sector are that research is more costly the higher is the quality of machine one aspires to invent (another sort of diminishing returns), the higher is the labor cost in that sector, and the lower is the stock of general knowledge. All this may seem plausible. But how crucial are the particular choices we have made?

Concerning wages and quality, it is convenient to assume that the research cost in each sector is proportional to the cost of labor in that sector, but the model can also be solved under more general forms (e.g. one might argue that it is only skilled labor that is needed to innovate in any sector, so only skilled wages should appear above).

Concerning Baconian knowledge, however, whilst the above assumptions may seem uncontroversial, it is not just convenient, but also crucial for our argument, that $\phi_h > \phi_l > 1$. Why? We assume that broadening the Baconian knowledge base will lower the costs of developing skill-intensive techniques more than those of developing unskilled-intensive techniques. This implies that as B expands, it becomes *relatively* cheaper to develop skill-intensive techniques. This assumption drives some of the key results in this paper. Is it justified?

Related assumptions have been used before.[5] We draw attention to Mokyr's (2005a) notion of *competence*, a concept hitherto largely neglected in theoretical models of the Industrial Revolution. As Mokyr notes:

> One of the most interesting variables to observe is the ratio between the knowledge that goes into the first formulation of the technique in question (invention) and the competence needed to actually carry out the technique. As we shall see, it is this ratio around which the importance of human capital in economic growth will pivot...

[5]The assumption is in some ways similar to assumption (A2) of Galor and Mountford (2004, p. 23).

> Technological change in the era of the Industrial Revolution, based on invention, innovation, and implementation, did not necessarily require that the entire labor force, or even most of it (much less the population at large), be highly educated; the effects of education depended on whether the relation between innovation and the growth of competence was strong and positive. (pp. 1123, 1157)

To adopt Mokyr's terminology, our approach to this pivotal issue is to specify a dynamic complementarity between the "invention knowledge" (represented here by the level of B), and "competence" (given by the fact that increasing B tends to favor the production of "complex" machines favoring those with more competence, which is represented here by an increase in H).[6] Consistent with Mokyr's view we conjecture that during the early phases of the Industrial Revolution (the "First Industrial Revolution") "technological progress and competence had a complex relation with one another because ingenuity and detailed propositional knowledge could be frontloaded in the instructions or artefacts, thus reducing the competence needed to carry out the actual production." (Mokyr 2005a, p. 1158). That is, we start off with unskilled bias. But we further conjecture that the same was not true for the later Industrial Revolution and the subsequent epoch of modern economic growth stretching to the present. "Idiot proofing" could not last forever—or else why are we all in school these days? As knowledge has advanced, higher levels of competence have been favored by the later, newly invented techniques. To say this is simply to admit that some kind of reversal must have occurred to yield the twentieth century "stylized fact" of skill-biased technological cahnge.

Growth of Baconian Knowledge

We highlight the importance of Baconian knowledge B in influencing the level of technology A. We have now specified dynamics of A. But what are the plausible dynamics of B?

We allow general knowledge to grow throughout human history, irrespective of living standards and independent of the applied knowledge embedded in actual technology levels. According to Mokyr (2005b, pp. 291–2), Bacon regarded "knowledge as subject to constant growth, as an entity that continuously expands and adds to itself." Accordingly, we assume that the growth in basic knowledge depends on the existing stock. Furthermore, we assume that Baconian knowledge grows according to how much skilled labor exists in the economy;[7] specifically, we assume the simple form:

$$\triangle B_{t+1} = \lambda \cdot H_t \cdot B_t \tag{24}$$

Thus we assume that increases in general knowledge (unlike increases in applied knowledge) do not arise from any profit motive, but are rather the fortuitous by-product of the existence of a stock of skilled workers, as well as of accumulated stocks of Baconian knowledge. But in our

[6] This is an analogy and does not imply that human capital and competence are really the same thing. As Mokyr (2005a) notes, there is a far from exact correspondence between the two. Competence may be gained through education; but in part is may also be innate or gained by experience.

[7] Again, Galor and Mountford (2004) make a rather similar assumption.

model, as we shall see, a skilled worker is just an educated worker, so it is here that the link between productivity growth and human capital is made explicit.

Our functional forms (22) and (23) assume that low Baconian knowledge produces relatively large costs to machine improvement, while high Baconian knowledge generates low costs to machine improvement. In our model, of course, B will never fall since (24) ensures that changes in B are nonnegative. Hence, the general knowledge set always expands.[8] Thus we have a mechanism by which the growth in *general* knowledge (B) can influence the subsequent development of *applied knowledge* (A_1 and A_3).

No Arbitrage Conditions

Turning to the decision to innovate in the first place, we assume that all individuals are free to do so. With free entry, the no arbitrage conditions which are guaranteed to hold at each and every time period can be written as

$$\pi_l(j) \leq c_l(j) \quad \Rightarrow \quad \pi_l \leq c_l \quad \Rightarrow \quad \left(\frac{\beta}{1-\beta}\right)^{\frac{\beta-1}{\beta}} \left(\frac{1}{A_1}\right)^{\frac{1}{\beta}} \cdot L_1 \leq \delta \left(\frac{1}{B}\right)^{\phi_l} \tag{25}$$

$$\pi_h(j) \leq c_h(j) \quad \Rightarrow \quad \pi_h \leq c_h \quad \Rightarrow \quad \left(\frac{\beta}{1-\beta}\right)^{\frac{\beta-1}{\beta}} \left(\frac{1}{A_3}\right)^{\frac{1}{\beta}} \cdot H_3 \leq \delta \left(\frac{1}{B}\right)^{\phi_h} \tag{26}$$

$\forall j$. If resource costs of research were actually *less* than the profits to innovation, entry into research would occur. From (21) we can see that the rising applied technology will lower the profit levels. On the other hand, if (25) and/or (26) were not to hold with equality, A_1 and/or A_3 remain stagnant (a society can not collectively forget blueprints once they are created). Thus we assume that applied technologies A_1 and A_3 adjust so that (25) and (26) hold for all time periods as a result of free entry.

It is here that our particular functional form assumptions prove convenient. Because $q(j)$ cancels from both sides of the no-arbitrage relationships, we have equations which govern the dynamics of aggregate technologies. This suits us because we are concerned more with (observable) macroeconomic variables than variations in (unobservable) microeconomic outcomes.

Technology in the Long Run

Finally, dividing (26) by (25) and setting both to equality, we can solve for the long-run values of relative biased technologies:

$$\frac{A_3}{A_1} = \left(\frac{H_3}{L_1}\right)^{\beta} B^{\beta(\phi_h - \phi_l)} \tag{27}$$

[8]This is not a historically trivial assumption, although it is accurate for the episode under scrutiny: Mokyr (2005b, pp. 338-9) comments on the fact that knowledge had been lost after previous 'efflorescences' in China and Classical Antiquity, and states that "The central fact of modern economic growth is the ultimate irreversibility of the accumulation of useful knowledge paired with ever-falling access costs".

Equation (27) encapsulates the long-run endogenous determination of technological bias. Technological bias will depend on the relative quantity of factors, and on the relative importance of general knowledge. In general profits will rise for innovation in sector 3 (1) if the factor used intensively in sector 3 (1) rises, or if Baconian knowledge rises (falls). The first effect corresponds to the market-size effect emphasized in Acemoglu (1998), while the second effect reflects our assumption that general knowledge spurs the growth of applied knowledge, but rather more so in the case of the skilled sector.

Hopefully by now the motivation for these modeling choices are apparent. We argue that basic scientific knowledge has always grown throughout the history of mankind. This growth was not driven by profits, but rather by the incidental interactions of smart people, institutional changes, and a host of other effects that we treat as exogenous. But in order for *economic* growth to occur, applied knowledge must grow as well. As (25) and (26) make clear, applied innovations are motivated by profits, and will not be profitable until Baconian knowledge reaches a certain critical threshold where benefits exceed costs. The natural world needs to be sufficiently intelligible before society can begin to master it (Mokyr 2002). Thus our model embodies the idea that growth in general Baconian knowledge is a necessary but not sufficient condition for output growth—an attribute surely essential in any unified model aiming to explain more than two centuries of economic history.

Wages in the Long Run

Finally, we ask what the the long term economic consequences are for wages, as a result of endowment changes. Since our ultimate goal is to endogenize factor endowments, we need to understand the feedback from relative factor endowments (demography) to relative factor rewards (the skill premium) and vice versa.

We will see in the next sub-section how the current skill-premium will incite demographic shifts. Here we note how demographic shifts affect wages. We can assert the following:

Proposition 1 *If the level of H exogenously rises, and technologies respond endogenously, the long-run skill premium will rise iff $\sigma > \frac{1+\beta}{\beta}$. We label the latter the sufficient substitutability condition.*

Proof: First we note that an exogenous increase in H results in an increase in H_3 since the skilled equate the marginal products of their labor in each sector. Calculating the marginal productivity of raw labor in sector one and the marginal productivity of skilled labor in sector three, we can write the skill premium as $\frac{w_h}{w_l} = \left(\frac{A_1}{A_3}\right)^{\frac{1-\sigma}{\sigma}} \left(\frac{L_1}{H_3}\right)^{\frac{1}{\sigma}}$. Solving this for $\frac{A_3}{A_1}$ and substituting, we solve for the long-run skill premium:

$$\left(\frac{w_h}{w_l}\right) = \left(\frac{H_3}{L_1}\right)^{\frac{\sigma\beta-\beta-1}{\sigma}} B^{\frac{\beta(\sigma-1)(\phi_h-\phi_l)}{\sigma}} \tag{28}$$

Hence we can see that an increase in the ratio of employment in sector 3 to employment in sector 1 will raise the long-run skill premium only if $\sigma\beta - \beta - 1 > 0 \Rightarrow \sigma > \frac{1+\beta}{\beta}$. Q.E.D.

Henceforth, we shall assume that the sufficient substitutability condition holds. With sufficient substitutability between intermediate goods in final production, a relative increase in the supply of one factor will promote technological growth biased towards that factor and actually raise the relative wage earned by that factor. The demographic micro-foundations of how the factors of production endogenously react to changes in the relative wages is the subject of the next subsection.

3.3 Endogenous Demography

We now think about how to allow the factors of production to react to changing prices and wages. In a very simplified model, we assume that 'adult' agents maximize their utility, which depends both on their current household consumption and on their children's expected future income. In an abstraction of family life, we assume that individuals begin life naturally as unskilled workers, accumulate human capital, and then decide as adults whether or not to become skilled workers. Because skilled labor is always paid some premium over unskilled labor, adults always decide to work as skilled labor. Consequently the skilled and unskilled are divided into two distinct age groups. That is, an agent evolves naturally from a 'young' unskilled worker into an 'adult' skilled worker; thus his welfare will be affected by both types of wages.

With this in mind, we now adopt an overlapping generations framework where individuals have two stages of life: young and adult. Only 'adults' are allowed to make any decisions regarding demography. Specifically, the representative household is run by an adult who decides two things: how many children to have (denoted n_t) and the level of education each child is to receive (denoted e_t). The number of children must be nonnegative and to keep things clean all households are single-parent, with $n = 1$ being the replacement level of fertility. The education level is constrained to the unit interval and is the fraction of time the adult devotes to educating the young. We also impose an education constraint on the adult, so that adults must give at least a bare minimum of education $\overline{e} > 0$ to each child.

Our modeling of demography is as follows. An individual born at time t spends fraction e_t of her time in school (something chosen by her parent), while devoting the rest of her time as an unskilled laborer in either sectors one or two. At $t + 1$, the individual (who is by this time a mature adult) works strictly as a skilled laborer, using whatever human capital she had accumulated as a child in sectors two or three.

The Adult Household Planner

Allowing for the time cost of child-rearing, we assume the household consumes all the income that the family members have generated. The adults, who are the household planners, therefore wish to maximize a weighted sum of current household consumption and the future skilled income generated by their children. That is, the individual born at time $t-1$, and now an adult at time t, faces the problem

$$\max_{n_t, e_t} \ \theta \left(I_{h,t} + I_{l,t} - C_t \right) + (1 - \theta) n_t I_{h,t+1} \tag{29}$$

subject to: 1) $n_t \geq 0$ 2) $e_t \geq \overline{e}$

Here $I_{h,t}$ is income generated by a skilled individual (the adult), $I_{l,t}$ is income generated by unskilled individuals (the children), and C_t is the opportunity cost of child rearing. θ lies between zero and one. We assume the following functional forms:

$$I_{h,t} = \widehat{w}_{h,t} \Omega e_{t-1}^k$$

$$I_{l,t} = \widehat{w}_{l,t}(1 - e_t) n_t$$

$$C_t = \widehat{w}_{h,t} n_t^\nu (1 + e_t)$$

When children are not being educated for a fraction of time $1 - e$, they increase the family's unskilled income $I_{l,t}$, but this will reduce their own future skilled income $I_{h,t+1}$. That is because they will receive a lower endowment of H, where $H = \Omega e^k$ can be considered the production of human capital, since it specifies the amount of H produced from a given education input e. Finally, $w_h n^\nu (1+e)$ is a cost function for the adult arising from giving n children an educational level e, and forsaking skilled work. This cost function can be nonlinear in n, and it also includes a fixed cost per child (normalized to 1 time unit).

In our model, wages $\widehat{w}_l$ and $\widehat{w}_h$ are determined by equations (6), (7) and (8). Hat notation is used to imply that households forecast these wages, given the technological coefficients that they perceive. Thus the individual born at $t-1$ will choose a pair of $\{n_t, e_t\}$ that maximizes (29), taking perceived wages as given.

Note that the individual makes decisions as an adult at time t, but bases the decision in part on $w_{h,t+1}$, something that is unknown to the individual. For our simulations below, we shall simply assume that in maximizing (29) individuals treat the current skilled wage as the forecast of the future skilled wage. This assumption of myopic wage forecasts dramatically simplifies the algebra without changing any key results. (We can produce qualitatively identical results with a strict perfect foresight assumption.)

¿From (29), the first-order condition for the number of children is:

$$\theta \widehat{w}_{l,t}[1 - e_t] + (1 - \theta)\widehat{w}_{h,t} \Omega e_t^k = \theta \widehat{w}_{h,t} \nu n_t^{\nu - 1}(1 + e_t) \tag{30}$$

The left-hand side illustrates the marginal benefit of an additional child, while the right-hand side denotes the marginal cost. At the optimum, the gains in income from an extra unskilled worker in the family *and* in future skilled income precisely offsets the foregone current skilled-income that results from child-rearing.

Provided that $e_t > \overline{e}$, the first order condition for education is:

$$\theta \widehat{w}_{l,t} n_t + \theta \widehat{w}_{h,t} n_t^\nu = (1 - \theta)\widehat{w}_{h,t} k n_t \Omega e_t^{k-1} \tag{31}$$

Here the left-hand side is the marginal cost and the right-hand side the marginal benefit. At the optimum, the gains received from more skilled income at $t+1$ offsets the foregone unskilled- and skilled-income required for an additional unit of education for all children at t.

Endowments in the Short Run

Given these functional forms, we want to know how changes in wages affect fertility and education decisions. The following proposition sheds some light on this.

Proposition 2 *The arguments which solve equation (29),* $\{n_t^*, e_t^*\}$*, will be such that:*

$$\frac{\partial n_t^*}{\partial \left(\frac{w_{h,t+1}}{w_{l,t}}\right)} < 0, \qquad \frac{\partial e_t^*}{\partial \left(\frac{w_{h,t+1}}{w_{l,t}}\right)} > 0$$

if $\mu > 1$*,* $0 < k < 1$*, and* $e_t > \overline{e}$*.*

To illustrate this we simply plug our functional forms into (29) and solve for n_t^* and e_t^*:

$$n_t^* = \left(\frac{\left(\frac{w_l}{w_h}\right)(1 - e_t^*) + \frac{(1-\theta)}{\theta}\Omega {e_t^*}^k}{\nu(1 + e_t^*)} \right)^{\frac{1}{\mu - 1}} \tag{32}$$

$$e_t^* = \left(\frac{\left(\frac{w_l}{w_h}\right)\theta n_t^* + \theta n_t^{\nu}}{(1-\theta)k\Omega n_t} \right)^{\frac{1}{k-1}} \qquad if\ e_t > \overline{e} \tag{33}$$

Thus we see that households who observe a rising skill premium will simultaneously lower fertility and raise education rates so long as there are diminishing returns to education and convex costs in the number of children. Note that if $e_t = \overline{e}$ a rising skill premium will still induce families to reduce fertility. Also note that demographic decisions made by households are solely based on skilled and unskilled wages that are observed in the current time period. Of course, as we will see in the next section, after fertility and education rates are determined, the wage structure will inevitably change due either to technological or international shifts. Households thus behave myopically, since they are not permitted to "anticipate" the wages of subsequent time periods. More sophisticated agents might very well make better informed decisions concerning the quality and quantity of their children, and make themselves better off in the process, but such (ahistorical) sophistication would not alter any of the qualitative conclusions of the paper, as we have said.

Endowments in the Long Run

Finally let us note that education and fertility rates translate directly into levels of unskilled labor in the current time period and skilled labor in the next time period. That is,

$$L_t = L(n_t) \tag{34}$$

$$H_t = \Omega e_{t-1}^k \tag{35}$$

As long as we ensure that $\partial L/\partial n > 0$ and $\partial H/\partial e > 0$, increases in fertility rates will *immediately* translate into increased levels of unskilled labor, while increases in education will *eventually* translate into increased levels of skilled labor next period. Thus given Proposition 2, an exogenous raising of the skill premium will immediately decrease the growth of the overall population, and will increase the subsequent level of human capital in the economy.

The combination of Propositions 1 and 2 summarize the long-run co-evolution of factors and technologies in the model. Here, given the necessary parameter restrictions, an increase in the share of skilled labor will induce both an increase in the long-run skill premium (by skewing the technological frontier towards skill-biased technologies by Proposition 1), while further increasing the future share of skilled in the workforce (by Proposition 2). Thus effects on the demand and supply of labor types tend to be self-reinforcing. With this demand-supply backdrop in mind, we turn to the historical puzzles of the Industrial and Demographic Revolutions.

4 A Tale of Three "Revolutions"

We are now ready to see how well our model can account for what happened in England (and other northwestern European economies) and the rest of the world during the 18th and 19th centuries.

We begin by considering two economies, a "northern" economy and a "southern" economy, each which is described by the modeling choices of section 3. We assume that applied technologies are developed in the North according to section 3.2, and diffuse gradually to the South. Thus northern technological developments are mirrored in the South, albeit with some lag. This would appear to match the reality that almost all R&D has occurred—and still does—in the "north" (Sachs 2000).

If only the north innovates, then either TFP doesn't spillover to the south (and divergence is inevitable) or else we must specify a technological diffusion process. Since the Great Divergence is something we seek to explain, rather than trivialize, we take the latter route, and assume a technological catch-up process in the south.

Specifically, we will assume that southern technological coefficients evolve according to the following relationships:

$$\Delta A^S_{k,t+1} = \rho(A^N_{k,t+1} - A^S_{k,t}), \quad 0 < \rho < 1, \quad k \in \{1, 2, 3\} \tag{36}$$

We simulate this process by choosing a value of $\rho = 0.1$ calibrated using recent empirical research on the speed of technological diffusion (Dowrick and Rogers 2002; Comin et al. 2006). In this setting, where a period is five years, the implied speed of technological convergence is roughly 2% per annum.

In our simulations, we initially assume that the North and South are closed to trade due to prohibitively high transport costs. The North goes through both an industrial revolution and a subsequent demographic transition into modern economic growth that is inevitably mirrored in the South. We highlight the initial Industrial Revolution in section 4.1, and the Demographic Transition and modern economic growth in section 4.2. Section 4.3 considers a similar scenario

where trade in goods between the North and the South occurs as transport costs fall. Trade eventually grows and this generates income gains in both regions even as it exacerbates income *divergence*. The simulation results for both cases are described in section 4.4.

4.1 The Industrial Revolution

A critical part of the argument offered here is that the Industrial Revolution was really a sequence of unskilled-labor intensive technological developments. These developments first appeared in England and Wales in the latter half of the eighteen century, and then spread to other parts of continental Europe and European "offshoots" in the early part of the nineteenth century.

Our theory here suggests a number of things concerning this revolution. First, implicit in our model is that the institutional framework protecting intellectual property rights had been in place far before the onset of the Industrial Revolution (at least in 'Northern' economies). Hence we do not rely on an exogenous institutional story to launch the Industrial Revolution. Rather, we rely on basic scientific (Baconian) knowledge to rise above a certain threshold level in order for applied innovation to become feasible. Once this happened in certain Northern economies, the growth of technologies and output became possible. Secondly, technological developments tended to heavily employ unskilled labor, for this factor of production was in relatively great supply in these areas. Finally, by increasing the relative earnings of unskilled labor, these technological developments spurred population growth and at the same time limited the growth of human capital.

We can see these propositions within the context of the model. An economy before its launch into the Industrial Revolution may be described by the one in section 3.1, with technological coefficients A_1, A_2, and A_3 constant. Here wages are fixed, and thus the levels of raw labor and human capital remain fixed as well. Both output and output per capita remain stagnant.

If we assume that the evolution of technological coefficients A_1 and A_3 are described by the relationships in section 3.2, then the economy must wait until Baconian knowledge grows to a sufficient level before applied innovation becomes possible. Further, technological growth will initially be unskilled-labor biased (that is, there is growth in A_1) so long as it becomes profitable to improve machines used in sector 1 *before* it becomes profitable to improve machines used in sector 3. The profitability of innovation is governed by equations (25) and (26). Thus if the economy begins such that $A_1 = A_3$ (as we maintain in the simulations), initial technological growth will be unskilled labor biased so long as there is relatively more unskilled labor than skilled labor in the economy, which was surely the case in the 18th century.

Furthermore, these technological developments change the wage structure, and by implication the evolution of factors. The growth of A_1 lowers the skill premium, and by Proposition 2, increases the future ratio of unskilled labor to skilled labor. This further increases the incentives for innovators to develop better quality machines for sector 1, further increasing subsequent levels of A_1, and so on. This is a major emphasis of our model and this paper. Unlike all extant "unified" models of the Industrial Revolution and Modern Economic Growth, we try to take the Luddites seriously: skilled labor was initially hurt by the Industrial Revolution, and population boomed, a historical fact that current theories explain poorly, if at all.

Note that even if both types of machines are being developed, so that both (25) and (26) hold with equality, technological growth can still be unskilled labor biased. Equation (27) describes the mix of skilled- and unskilled-biased technologies when both are being developed. So long as growth in the employment of sector 1 exceeds that of sector 3, and Baconian knowledge remains relatively small, A_1 will grow faster than A_3. Of course this will tend to narrow the skill-premium (by Proposition 1); so long as intermediate goods used in final production are substitutable enough, this initial wave of industrialization will be self-perpetuating, fostering continual increases in unskilled labor and improvements in A_1.

This seems consistent with history. Well-known studies such as Atack (1987) and Sokoloff (1984) describe the transition of the American economy from the reliance of highly-skilled artisans to the widespread mechanization of factories. And Goldin and Katz (1998) assert that technological advances which led to standardization and assembly-line production processes inevitably replaced skilled workers with raw labor. This paper further argues that the boom in fertility that the industrializing areas experienced was both the cause and consequence of these technological revolutions transpiring in the late 1700s and early 1800s. According to Folbre (1994), the development of industry in the late eighteenth and early nineteenth centuries led to changes in family and household strategies. The early pattern of rural and urban industrialization in this period meant that children could be employed in factories at quite a young age. The implication is that children became an asset, whose labor could be used by parents to contribute income to the household. In English textile factories in 1835, for example, 63% of the work force consisted of children aged 8-12 and women (Nardinelli 1990). This is not to say that attitudes toward children were vastly different in England then compared with now; rather economic incentives were vastly different then compared with now. As a result of these conditions, fertility rates increased during the period of early industrialization.

While our approach may help explain the population growth that coincided with the initial stages of the Industrial Revolution,[9] we are still faced with the challenge of explaining the demographic transition that followed it. Here we have two options. The first is to assume that skill-biased innovations become *inherently* easier to implement as general scientific knowledge grows larger. Indeed there is some intuitive appeal to this idea, and we invoke it by assuming that $\phi_l < \phi_h$. The second option is to impose some other exogenous change that shifts the focus of the economy to skill-intensive production, such as growing inter-continental trade. We now broach each of these topics in turn.

4.2 The Demographic Transition

Human capital presents a challenge for would-be unified growth theories: it appears to hardly play any role at all in the Industrial Revolution, yet clearly is central to the story of growth both in the late-19th and throughout the 20th centuries. We argue that industrialization took on a new form around the mid-1800s, and that this development shifted the world economy in ways

[9]Of course there are a host of other explanations, including falling death rates related to health improvements, and the passage of various Poor Laws. Naturally we are abstracting from these possibilities without dismissing them as inconsequential.

that continue to manifest themselves today.

The educational stagnation in England of the late 18th and early 19th centuries starkly contrasts with the large school enrollment rates of the late 19th century. Schofield (1968) reveals very modest rises in signature rates at marriage (a mark of society-wide illiteracy) from 1780 to 1830, and Mitch (1982) highlights the 1818 and 1833 parochial surveys of elementary schooling which indicate that the proportion of all students enrolled in schools remained constant at 42%. Contrastingly by the turn of the twentieth century in England there was virtually universal literacy and primary school enrollment.

At the same time there was a marked decrease in fertility rates in England and other regions of western Europe. Crude birth rates in England declined by 44% from 1875-1920, while those for Germany, Sweden and Finland between 1875 and 1920, and France between 1865 and 1910, declined by 37%, 32%, 32% and 26% respectively (Andorka (1978) and Kuzynski (1969)). These trends suggest a reversal in the relationship between income and fertility, corresponding to an increase in the level of resources invested in each child.

Part of our argument is that biases inherent in technological growth fostered this reversal. As Baconian knowledge rose further and skill-biased production grew in importance (since by assumption $\phi_l < \phi_h$), the labor of children became less important as a source of family income, and this was reflected in English legislation. The Family Acts passed in Britain limited the employment possibilities for children (Folbre 1994). The costs of raising children and socializing children also rose as urbanization proceeded, child labor became restricted, and compulsory education developed. Further, children achieved independence at a fairly early age, so they did not contribute to the household when the parents were in middle age. The old pact between parents and children that allowed parents to gain benefits from the labor of children through early adulthood began to be broken. On all economic counts then, children turned from a financial asset into an economic liability.

Recent studies raise these points as well. Hazan and Berdugo (2002) suggest that technological change at this stage of development increased the wage differential between parental labor and child labor, inducing parents to reduce the number of their children and to further invest in their quality, stimulating human capital formation, a demographic transition, and a shift to a state of sustained economic growth. Alternatively, the rise in the importance of human capital in the production process may have induced industrialists to support laws that abolished child labor, inducing a reduction in child labor and stimulating human capital formation and a demographic transition (Doepke and Zilibotti 2003; Galor and Moav 2006).

4.3 The Trade Revolution

The second cause of the demographic transition in our account is the opening of the European economy to inter-continental trade in the latter part of the 19th century. In our model, we assume that there is some technological diffusion from the North to the South, and so we abstract away from any exogenous technological differences in explaining the Great Divergence. This is consistent with studies suggesting that English innovations diffused rapidly to other economies: Mokyr (1999) discusses many examples of English exports of micro-inventions (intended or oth-

erwise), and Clark (1987) shows how late-19th century India used the same textile machines as those employed in Lancashire.

We now consider the case of trade in intermediate goods 1 and 3, but these face 'iceberg' costs which evolve over time. Early on these iceberg costs are quite high, so trade is limited; as transport technologies grow, these costs fall and eventually trade volumes rise. This trade is motivated by differences in factor endowments, as in the traditional Heckscher-Ohlin model, and differences in technologies, as in the Ricardian trade model. We assume that the North is relatively skill-abundant, and that the South is relatively unskilled-labor-abundant; thus the North will export good 3, while the South will export good 1.

In this scenario, production for each region is given by

$$Y^n = \left(\frac{\alpha}{2}\left(x_1^n + a_1 Z_1\right)^{\frac{\sigma-1}{\sigma}} + (1-\alpha)\left(x_2^n\right)^{\frac{\sigma-1}{\sigma}} + \frac{\alpha}{2}\left(x_3^n - Z_3\right)^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}} \tag{37}$$

$$Y^s = \left(\frac{\alpha}{2}\left(x_1^s - Z_1\right)^{\frac{\sigma-1}{\sigma}} + (1-\alpha)\left(x_2^s\right)^{\frac{\sigma-1}{\sigma}} + \frac{\alpha}{2}\left(x_3^s + a_3 Z_3\right)^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}} \tag{38}$$

where Z_1 is the amount of good 1 that is exported by the South, Z_3 is the amount of good 3 that is exported by the North, and $0 < a_1 < 1$ and $0 < a_3 < 1$ are iceberg factors for goods 1 and 3 (i.e. the proportion of exports not lost in transit). Thus the North imports only a fraction a_1 of Southern exports, and the South imports only a fraction a_3 of Northern exports. Intermediate goods production is still described by (2) - (4). Given this, it is straightforward to show

Proposition 3 *If* $\left(\frac{p_3^n}{p_1^n}\right) / \left(\frac{p_3^s}{p_1^s}\right) > a_1 \cdot a_3$, $Z_1 = Z_3 = 0$.

If transport costs are large relative to cross-country price differences, no trade occurs. Over time, rising levels of a_1 and a_3 will induce positive and rising levels of Z_1 and Z_3. Note that we assume that there is no trade in x_2 - because this is produced using both L and H, differences in p_2 are very small, and thus the assumption is not particularly restrictive.[10] Further, the limiting case of $a_1 = a_3 = 1$ produces goods and factor price convergence, and thus replicates the integrated equilibrium, even in the absence of trade in good 2. The equilibrium is described in more detail in Appendix A.

In such a set-up, trade between the North and South will raise skill premia in the North, and lower them in the South, as in Galor and Mountford (2004). Thus, trade will promote rising education and falling fertility in the North, and this in turn will promote skill-biased technological change. However, the opposite will be true for the South: there, trade leads to falling skill premia, rising Southern fertility rates, and no human capital growth.

[10] 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, become indeterminate. See Melvin (1968) for a thorough discussion.

4.4 Simulations

Both the closed and open economy models described above are numerically simulated. Each generation is roughly 25-30 years in length, so each period is to be thought of as around 5 years long, and around one fifth of families are thought to adjust their fertility and education rates in each period.

For each time period, we solve the model as follows:

1) Baconian knowledge grows according to (24).

2) Solve the equilibrium described in section 3.1 or Appendix A, depending on whether we are simulating the closed or the open economy model.

3) Using wages produced in 2), solve for demographic variables L_t and H_{t+1} as described in section 3.3.

4) Using new Baconian knowledge from 1) and employment levels from 2), solve for new levels of A_1, A_2 and A_3 as described in section 3.2.

Case 1: The Closed Economy

In this case we simulate an English economy and a "southern" economy through 30 time periods, roughly accounting for the time period 1750-1910. Here we may consider a_1 and a_3 low enough so that trade between the North and South never occurs. The results are given in Figures 4–9, with the parameterizations used being summarized at the bottom of Figure 4. Here we simply note that the gross elasticity of substitution is set high enough ($\sigma = 3$) so that Proposition 1 holds. Initial technologies are set as $A_1 = 1$, $A_2 = 1$, $A_3 = 1$ for both regions, and $B = 1$. Initial levels of labor are $L^n = 2$, $H^n = 1$, $L^s = 2$ and $H^s = 0.6$, so that both economies begin with more unskilled labor. This produces an initial skill premium of 1.42 in the North and 1.83 in the South. This is consistent with the evidence in van Zanden (2004) that skill premia were lower in Europe than in India, Japan or Korea during the 18th and 19th centuries.

Figure 4 illustrates the market for innovation in the North. Initial Baconian knowledge B is set low enough so that the costs of innovation are larger than the benefits early on. As a result technology levels remain stagnant at first. Valuations catch up with costs first for technologies designed for sector 1; hence, at $t = 3$ A_1 begins to grow in both regions. By contrast, $\pi_h < c_h$ early on, so that A_3 remains fixed. Note that this results solely because L_1^n, the employment of northern unskilled labor in sector 1, is larger than H_3^n, the employment of northern skilled labor in sector 3. In other words, endowments dictate that the Industrial Revolution will initially be unskilled-biased. Hence, resources flow out of sector 3 and into sector 1. Rising levels of L_1^n and falling levels of H_3^n make π_l rise and π_h fall, reinforcing the Industrial Revolution while at the same time delaying the transition to modern growth.

However, at $t = 11$ costs of developing skill-intensive techniques fall enough so that A_3 begins to grow as well. This induces something of an endogenous demographic transition; fertility rates reverse directions, while human capital levels remain fixed.

Figures 5 through 8 depict historical and simulated time series for fertility rates, education rates, wages and skill-premia. As can be seen, our model reproduces the early rise in fertility, followed by falling fertility and rising education. Education rates remain at $\overline{e}$ for much

of the Industrial Revolution, and rise only after significant increases in A_3. Wages rise very modestly during the Industrial Revolution, and rise significantly only with the development of skill-intensive techniques. The skill premium in both regions narrows initially, and then rises, provoking the demographic transition.

Finally, despite technological diffusion, a divergence occurs between the North and the South, primarily because only a fraction of Northern technologies diffuse to the South each time period, as dictated by equation 36. This is illustrated in Figure 14 (lower panel, 'closed case').

However, note that for this closed case, divergence between the North and South *slows down* precisely when we believe it should rise (that is, from the 1870s onward). This is because the slowdown of unskilled-intensive technologies in the North allows the South to "catch-up" in this sector. The convergence this implies is offset by the divergence in skill-intensive growth in the North, so that the gap between the two economies ultimately stabilizes. Furthermore, the model implies that demographic trends in the South closely mirror those in the North, for the simple reason that Southern technology is mimicking Northern technology, but with a lag.

Thus we see that a story of historical divergence based solely on lags in biased knowledge diffusion produces some counter-factual results. To deal with this, we introduce specialization patterns arising from gradually increasing inter-continental trade between both regions. We turn to this case next.

Case 2: The Gradual Opening of Two Economies

Again we have two economies: the North and the South. Here however, iceberg costs evolve. The fraction of traded goods that are not lost in transit, a_1 and a_3, are initially set high enough so that trade becomes possible halfway into the simulation (specifically, $a_1 = a_3 = 0.9$). After this point, the North specializes in and exports x_3, while the South specializes in and exports x_1. However, all three goods are produced by both regions at all times. We attempt to "calibrate" these iceberg costs using historical freight rates. The top of Figure 9 illustrates trends in measured freight rates where the mid-eighteenth century is normalized to 100, based on the data in Harley (1988) and Shah Mohammed and Williamson (2004). These rise slightly until 1800, and then continually fall until the Great War. Thus, if $freight_t$ is the freight rate at time t, iceberg coefficients are calculated as:

$$a_{k,t} = (a_{k,0} - 1) * freight_t + 1$$

for $k \in \{1, 3\}$ and initial levels $a_{k,0}$. The bottom of Figure 9 illustrate this time series, which is simply the mirror image of the freight rates. Technological and demographic relations evolve precisely as before, while equilibrium is now described by Appendix A.

Figures 10–14 illustrate this case. Figure 10 illustrates technological developments in the North; these essentially echo those for the closed-economy case. Note however that subsequent growth in skilled-intensive innovation is far more robust in this case. This result occurs because trade becomes possible halfway through the simulation, allowing the North to specialize in skill-intensive production and raising the rewards to skill accumulation. Furthermore, labor flows from sector 1 to 2 in order to complement rising levels of H_2. The combination of falling L_1 and

rising A_3 reinforces the transition, so that growth in unskilled-intensive techniques slows down and growth in skill-intensive techniques rises even faster. The South on other hand specializes in unskilled-intensive production, which then lowers the rewards to skill accumulation in the South.

Figures 11 and 12 compare fertility and education rates between the two regions. Due to the diffusion of applied technologies, both regions experience rising fertility rates and stagnant education rates early on. However, because the South begins to specialize in unskilled-intensive production, its fertility continues to rise until period 21, while education remains stagnant throughout. As is apparent from Figure 13, this happens because the Southern skill premium falls until period 21, reflecting the Stolper-Samuelson Theorem and our assumptions about relative endowments. The skill premium in the North however rises past two, something that is not supported historically.

Differences between the North and South are further illustrated in Figure 14. The transition to modern economic growth dramatically widens the gap in incomes per worker, unlike in the closed economy case. This is due to two factors. First, skilled-intensive technologies which diffuse to the South augment a relatively smaller skilled labor force. Second, the South's specialization in unskilled-labor-intensive production limits the decline in fertility and thus keeps per worker output relatively small. Thus, while both regions experience static gains from trade, the North enjoys a dynamic advantage not available to the South.

5 Conclusion

We believe that by explicitly modeling research and development, thus endogenizing the direction of technical change, we have been able to shed some valuable light on the transition to modern economic growth. Like most unified growth models, our model is subject to the criticism that it makes a take-off 'inevitable', a proposition to which many historians, more comfortable with notions of chance and contingency, might object. Our model makes another claim, however, which seems much more robust: if a take-off took place, it should, inevitably, have first involved unskilled-labor-using technologies, for the simple reason that unskilled labor was the abundant factor of production at this time.

¿From this simple prediction, as we have seen, flow a whole series of consequences. The Industrial Revolution should have seen skill premia fall, which they did. It should therefore have seen an initial increase in fertility rates, which again it did. Out model predicts that these two phenomena would have continued to reinforce each other indefinitely, barring some countervailing force. One such force was the continuing growth in Baconian knowledge, which would eventually lead to the growth of the science-based and skill-intensive sectors of the Second Industrial Revolution. A second such force was international trade, which by familiar Heckscher-Ohlin logic should have seen Europe exporting relatively skill-intensive goods to the periphery. Both forces should have forced skill premia to stop falling, and start rising, and this in turn should have prompted a demographic transition.

Our simulations indicate that our model does a pretty good job of explaining the facts until the late 19th century, when European skill premia started falling again, at a time when according to our model they should have been rising sharply. We explain this fact in the same way

that Galor and Mountford (2004) do: at precisely this time European and North American governments embarked on a massive programme of public education, thus exogenously raising skill endowments and lowering skill premia. Furthermore, public primary education programmes were later followed by two world wars, rising union strength, and public secondary and tertiary education programmes, all of which served to further reduce skill premia, in the U.S. case at least through the 'Great Compression' of the 1940s (Goldin and Katz 1999). In the context of this paper, it seems that these exogenous factors leading to greater equality were all the time having to contend with powerful endogenous technological factors leading to greater inequality. Indeed, as Acemoglu (1998) points out, in the context of a model like this one long run exogenous increases in skill endowments lead to more rapid skill-biased technical change, thus increasing the upward pressure on skill premia in the long run. What is remarkable, therefore, is that western labor markets remained on an egalitarian path until well into the 20th century. In this context, current inegalitarian trends in the U.S. and elsewhere can be seen as late 19th century chickens finally coming home to roost.

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A Partial Trade Equilibrium

Productions in each region are given by (37) and (38).

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

$$p_1^c = \frac{w_l^c}{A_1^c} \tag{39}$$

$$p_2^c = \left(\frac{1}{A_2^c}\right)(w_l^c)^{\gamma}(w_h^c)^{1-\gamma}(1-\gamma)^{\gamma-1}\gamma^{-\gamma} \tag{40}$$

$$p_3^c = \frac{w_h^c}{A_3^c} \tag{41}$$

$$\left(\frac{1}{A_1^c}\right)x_1^c + \left(\frac{1}{A_2^c}\right)(w_l^c)^{\gamma-1}(w_h^c)^{1-\gamma}(1-\gamma)^{\gamma-1}\gamma^{1-\gamma}x_2^c = L^c \tag{42}$$

$$\left(\frac{1}{A_2^c}\right)(w_l^c)^{\gamma}(w_h^c)^{-\gamma}(1-\gamma)^{\gamma}\gamma^{-\gamma}x_2^c + \left(\frac{1}{A_3^c}\right)x_3^c = H^c \tag{43}$$

$$x_1^n + a_1 Z_1 = \left(\frac{\left(\frac{\alpha}{2}\right)^{\sigma}(p_1^n)^{-\sigma}}{\left(\frac{\alpha}{2}\right)^{\sigma}(p_1^n)^{1-\sigma} + (1-\alpha)^{\sigma}(p_2^n)^{1-\sigma} + \left(\frac{\alpha}{2}\right)^{\sigma}(p_3^n)^{1-\sigma}}\right)\cdot Y^n \tag{44}$$

$$x_1^s - Z_1 = \left(\frac{\left(\frac{\alpha}{2}\right)^{\sigma}(p_1^s)^{-\sigma}}{\left(\frac{\alpha}{2}\right)^{\sigma}(p_1^s)^{1-\sigma} + (1-\alpha)^{\sigma}(p_2^s)^{1-\sigma} + \left(\frac{\alpha}{2}\right)^{\sigma}(p_3^s)^{1-\sigma}}\right)\cdot Y^s \tag{45}$$

$$x_2^c = \left(\frac{(1-\alpha)^{\sigma}(p_2^c)^{-\sigma}}{\left(\frac{\alpha}{2}\right)^{\sigma}(p_1^c)^{1-\sigma} + (1-\alpha)^{\sigma}(p_2^c)^{1-\sigma} + \left(\frac{\alpha}{2}\right)^{\sigma}(p_3^c)^{1-\sigma}}\right)\cdot Y^c \tag{46}$$

$$x_3^n - Z_3 = \left(\frac{\left(\frac{\alpha}{2}\right)^{\sigma}(p_3^n)^{-\sigma}}{\left(\frac{\alpha}{2}\right)^{\sigma}(p_1^n)^{1-\sigma} + (1-\alpha)^{\sigma}(p_2^n)^{1-\sigma} + \left(\frac{\alpha}{2}\right)^{\sigma}(p_3^n)^{1-\sigma}}\right)\cdot Y^n \tag{47}$$

$$x_3^s + a_3 Z_3 = \left(\frac{\left(\frac{\alpha}{2}\right)^{\sigma}(p_3^s)^{-\sigma}}{\left(\frac{\alpha}{2}\right)^{\sigma}(p_1^s)^{1-\sigma} + (1-\alpha)^{\sigma}(p_2^s)^{1-\sigma} + \left(\frac{\alpha}{2}\right)^{\sigma}(p_3^s)^{1-\sigma}}\right)\cdot Y^s \tag{48}$$

$$A_1^n\left(A_1^n L_1^n + a_1 Z_1\right)^{-\frac{1}{\sigma}} = \left(\frac{2(1-\alpha)\gamma}{\alpha}\right)A_2^{n\,\frac{\sigma-1}{\sigma}}(L^n - L_1^n)^{-\gamma-\sigma+\sigma\gamma}(H^n - H_3^n)^{\gamma+\sigma-\sigma\gamma-1} \tag{49}$$

$$A_3^n\left(A_3^n H_3^n - Z_3\right)^{-\frac{1}{\sigma}} = \left(\frac{2(1-\alpha)(1-\gamma)}{\alpha}\right)A_2^{n\,\frac{\sigma-1}{\sigma}}(L^n - L_1^n)^{-\gamma+\sigma\gamma}(H^n - H_3^n)^{\gamma-\sigma\gamma-1} \tag{50}$$

$$A_1^s\left(A_1^s L_1^s - Z_1\right)^{-\frac{1}{\sigma}} = \left(\frac{2(1-\alpha)\gamma}{\alpha}\right)A_2^{s\,\frac{\sigma-1}{\sigma}}(L^s - L_1^s)^{-\gamma-\sigma+\sigma\gamma}(H^s - H_3^s)^{\gamma+\sigma-\sigma\gamma-1} \tag{51}$$

$$A_3^s \left(A_3^s H_3^s + a_3 Z_3\right)^{-\frac{1}{\sigma}} = \left(\frac{2(1-\alpha)(1-\gamma)}{\alpha}\right) A_2^{s\,\frac{\sigma-1}{\sigma}} \left(L^s - L_1^s\right)^{-\gamma+\sigma\gamma} \left(H^s - H_3^s\right)^{\gamma-\sigma\gamma-1} \tag{52}$$

$$\frac{p_1^n}{p_3^n} = \frac{Z_3}{a_1 Z_1} \tag{53}$$

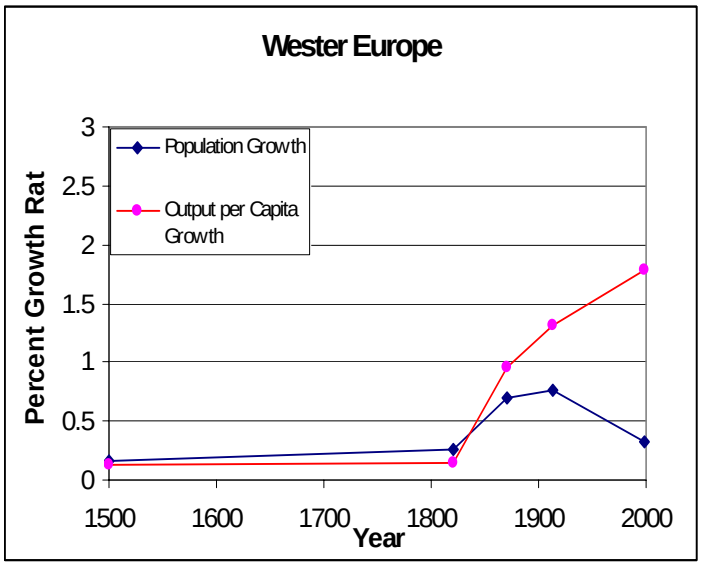
$$\frac{p_1^s}{p_3^s} = \frac{a_3 Z_3}{Z_1} \tag{54}$$

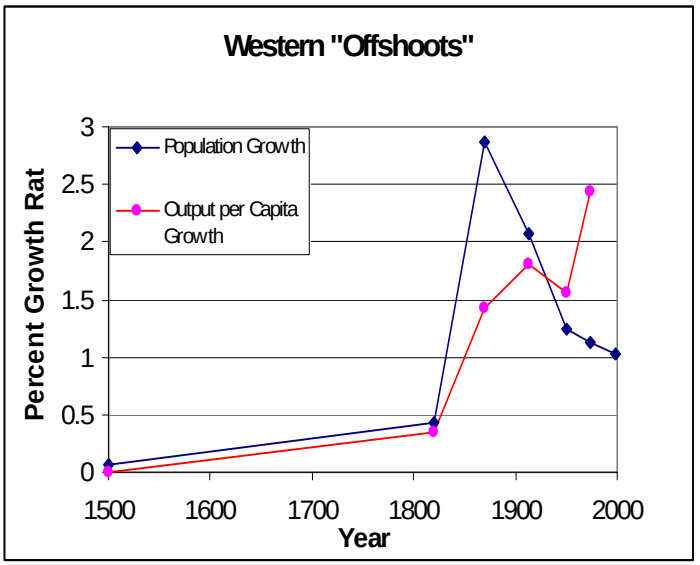
Equations (39) - (41) are unit cost functions, (42) and (43) are full employment conditions, (44) - (48) denote regional goods clearance conditions, (49) - (52) equate the marginal products of raw factors, and (53) and (54) describe the balance of payments for each region. Solving this system for the unknowns $p_1^n,\ p_1^s,\ p_2^n,\ p_2^s,\ p_3^n,\ p_3^s,\ x_1^n,\ x_1^s,\ x_2^n,\ x_2^s,\ x_3^n,\ x_3^s,\ w_l^n,\ w_l^s,\ w_h^n,\ w_h^s,\ L_1^n,\ L_1^s,\ H_3^n,\ H_3^s,\ Z_1$ and Z_3 constitutes the static partial trade equilibrium. Furthermore, equilibrium levels of L_1^n and H_3^n will determine subsequent developments of A_1^n and A_3^n from (25) and (26); this in turn will determine southern technologies via (36).

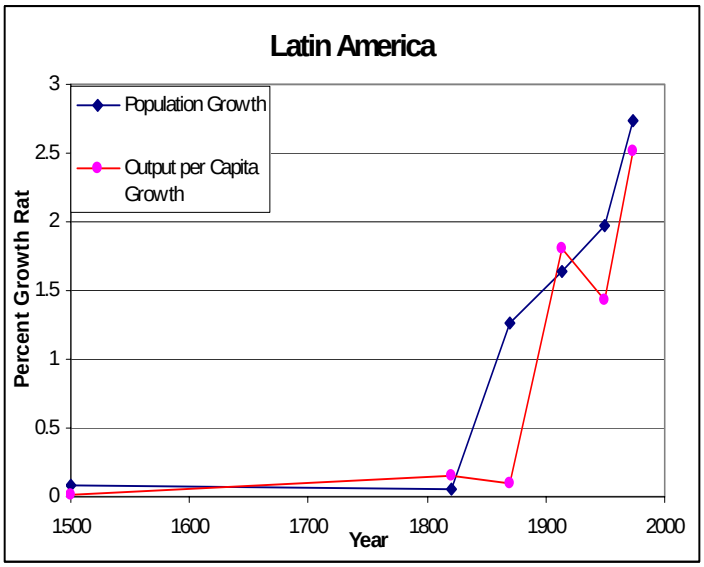
Each region will produce all three goods so long as factors are "similar enough." If factors of production sufficiently differ, the North produces only goods 2 and 3, while the South produces only goods 1 and 2. No other specialization scenario is possible for the following reasons: first, given that both the North and South 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. The simulation only considers the case where all three intermediate goods are produced by both regions. See Cunat and Maffezzoli (2002) for a fuller discussion.

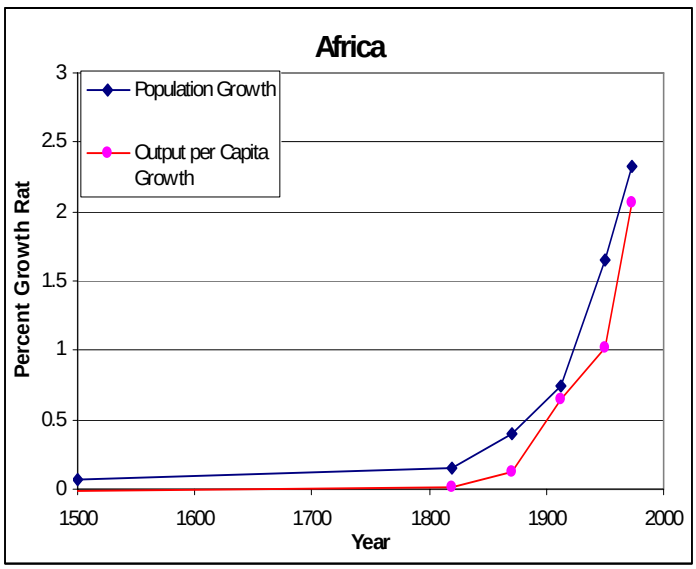
Figure 1

Annual Regional Growth Rates of GDP per Capita and Population: 1500-2000





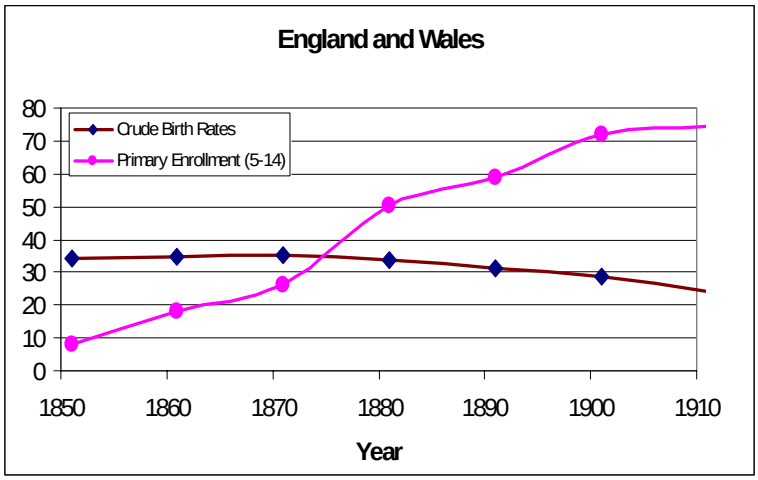


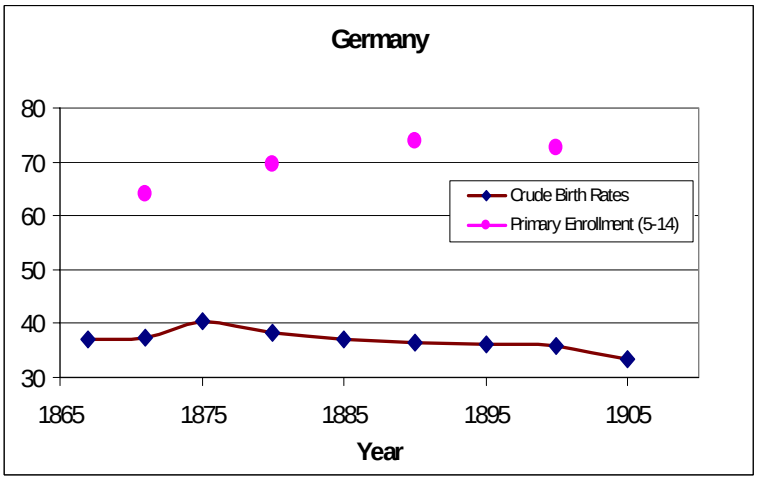


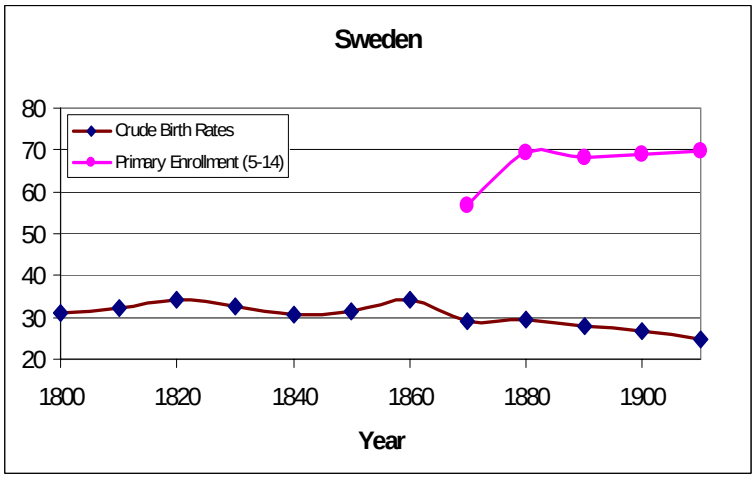
Source: Galor (2005, p. 189), based on Maddison (2001).

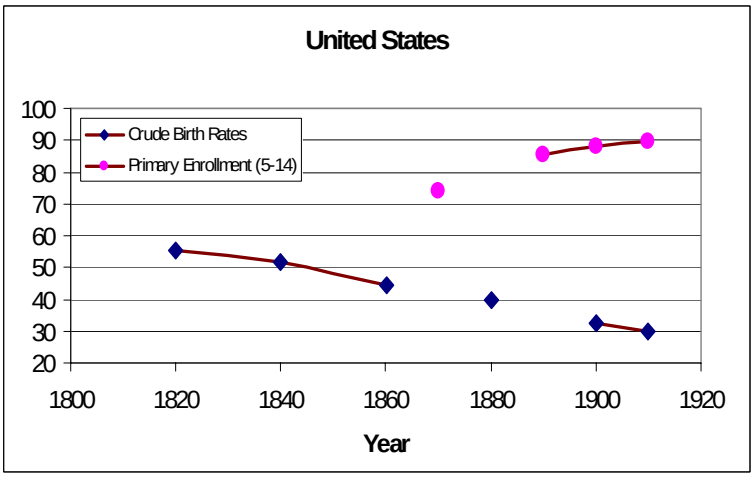
Figure 2

Fertility and School Enrollment Relationships for Four "Developed" Countries



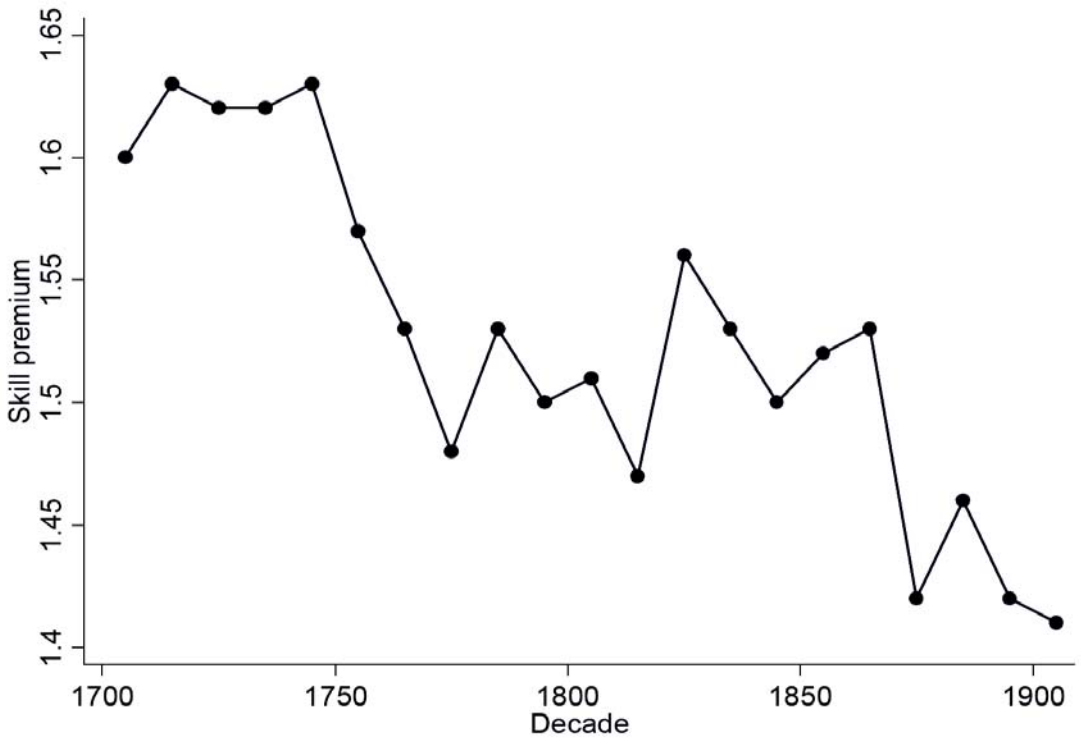






Source: Tan and Haines (1984).

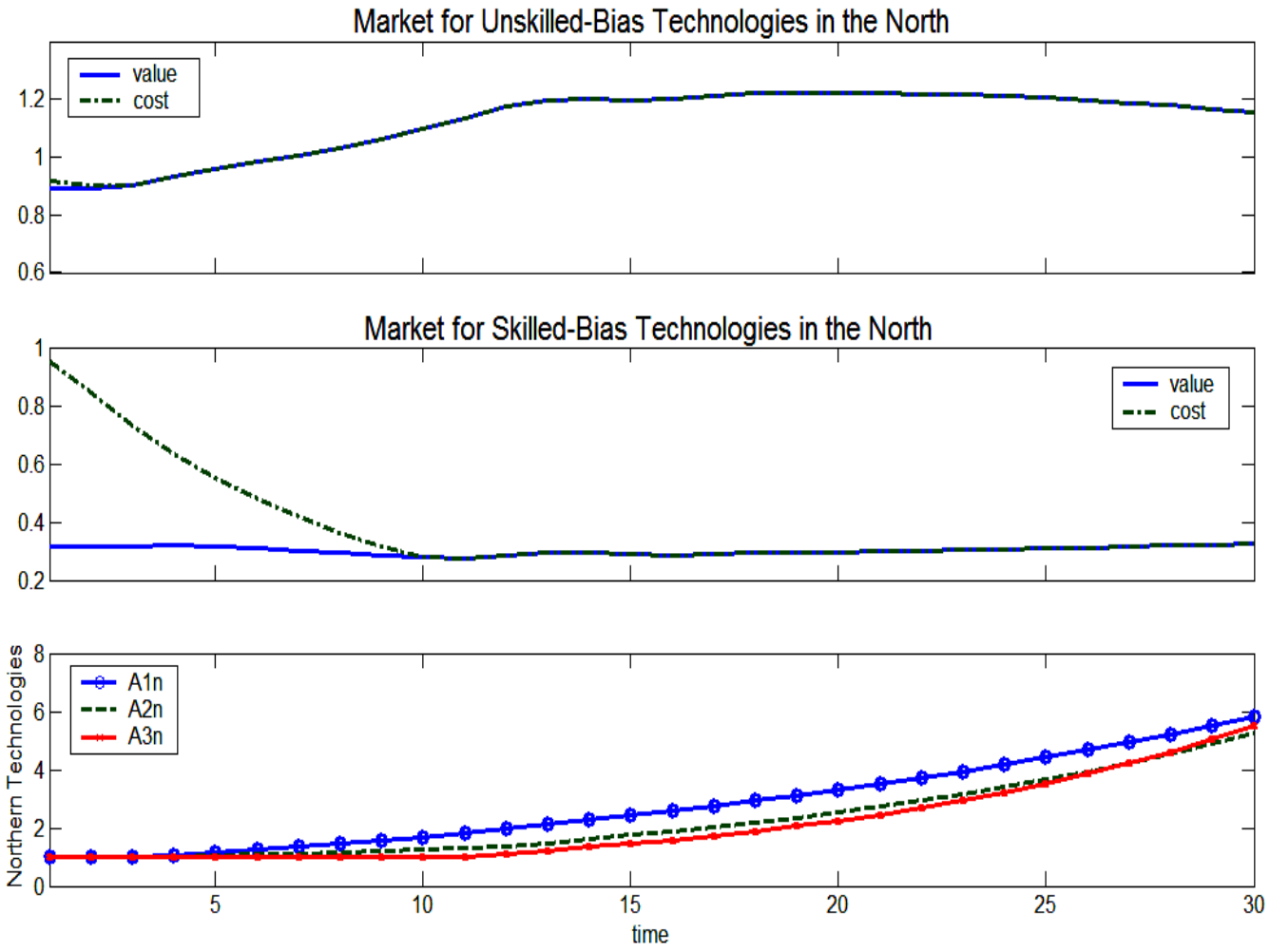
Figure 3. Skill Premia, 1700-1910



Source: Clark (forthcoming).

Figure 4

The Market for Technologies
The Closed Economy



Parameterizations are as follows: $\sigma = 3$, $\gamma = 0.5$, $\alpha = 0.5$, $\beta = 0.6$, $\delta = 0.95$, $\varphi_l = 2.5$, $\varphi_h = 3.6$, $\lambda = 0.695$, $\rho = 0.1$, $\Gamma = 2$, $k = 0.3$, $\nu = 1.8$, $\theta = 0.5$, $e_{min} = 0.3$. These values ensure that Propositions 1 and 2 hold for all t.

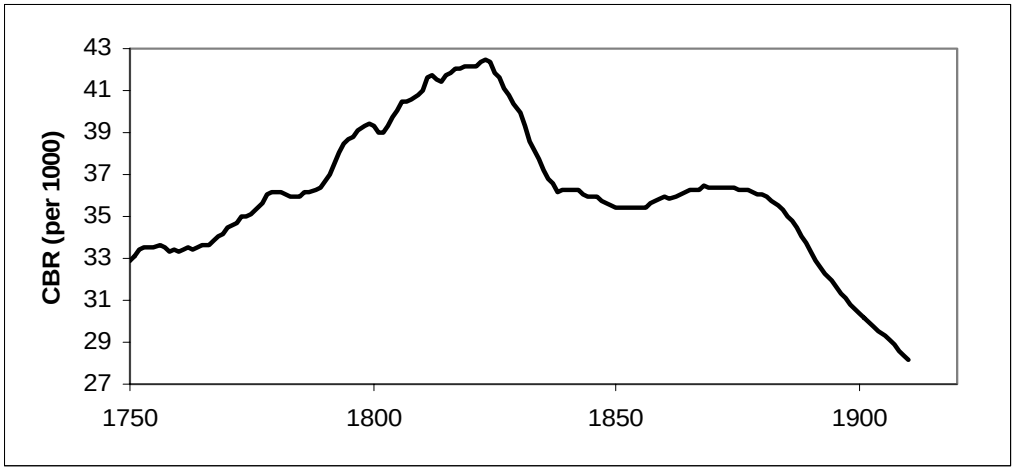
Initial conditions are as follows: $A_1 = A_2 = A_3 = B = 1$ for both regions; $L^N = 2$, $H^N = 1$, $L^S = 2$, $H^S = 0.6$.

Because the North is endowed with more unskilled than skilled labor, unskilled-intensive technologies are the first to develop. This induces rising levels of L^N and so speeds up unskilled intensive tech even more. Now sector 2 also grows somewhat – this pulls human capital from sector 3 (which is technologically stagnant) into sector 2, further delaying the development of skilled intensive technologies. However, because $\varphi_l < \varphi_h$, skill-intensive techniques grow around t=12. Economic growth after this is relatively balanced, with all three sectors growing more or less at the same rate.

Figure 5

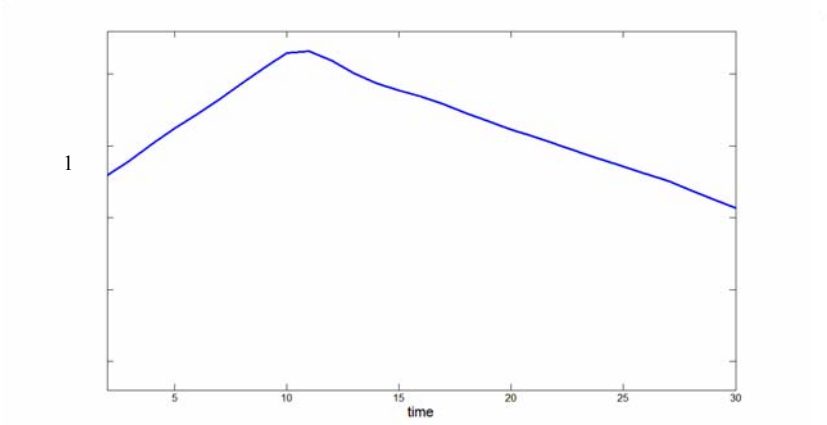
Fertility Rates

Fertility Rates (England)

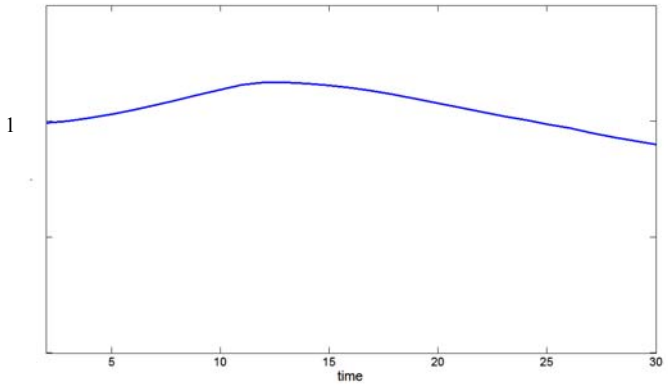


Wrigley & Schofield (1981) and Andorka (1978). 10-year moving average.

Fertility Rates (North)



Fertility Rates (South)



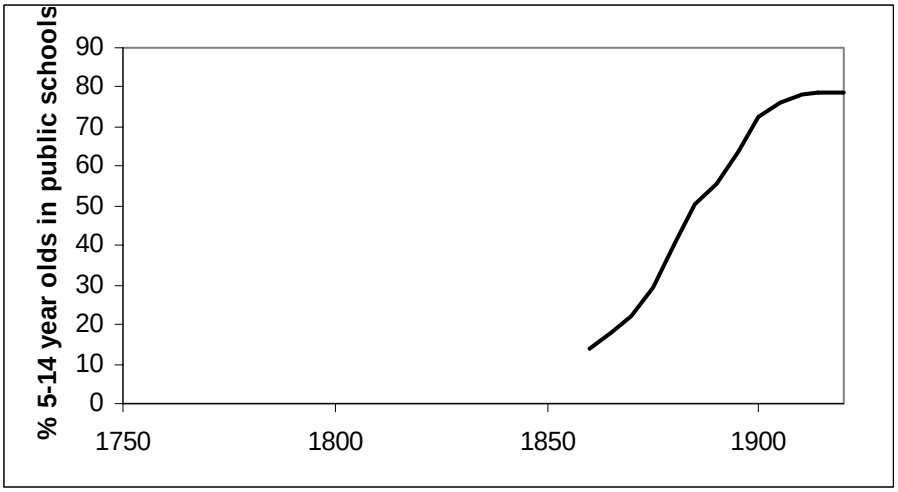
Initial fertility is normalized to 1, which is replacement fertility. Fertility above 1 is associated with population growth, while fertility below 1 is associated with population shrinkage.

Fertility rises initially for both countries and then falls. Delays in technological diffusion limit these movements in the South.

Figure 6

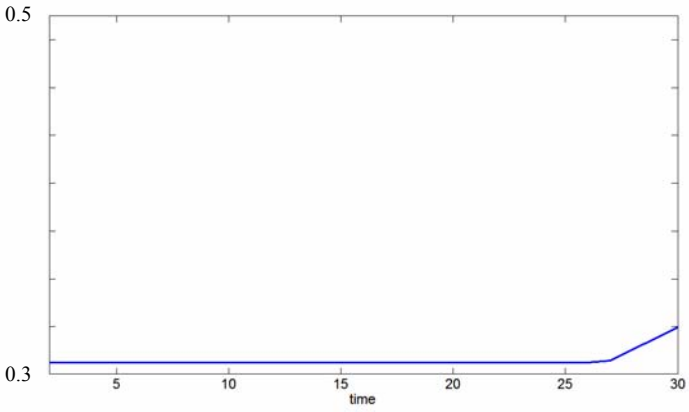
Education Rates

Education Rate (England)

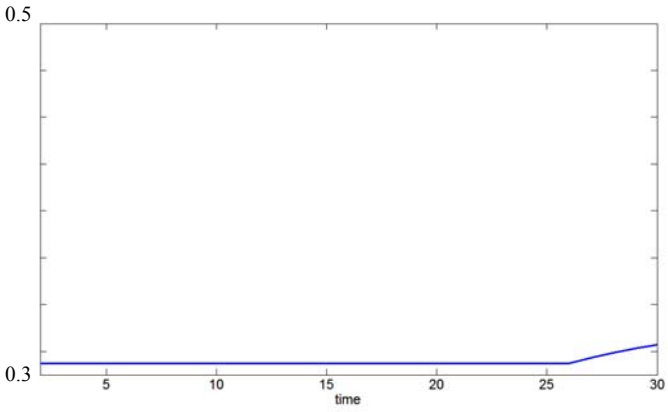


Flora et al (1983). 10-year moving average.

Education Rate (North)



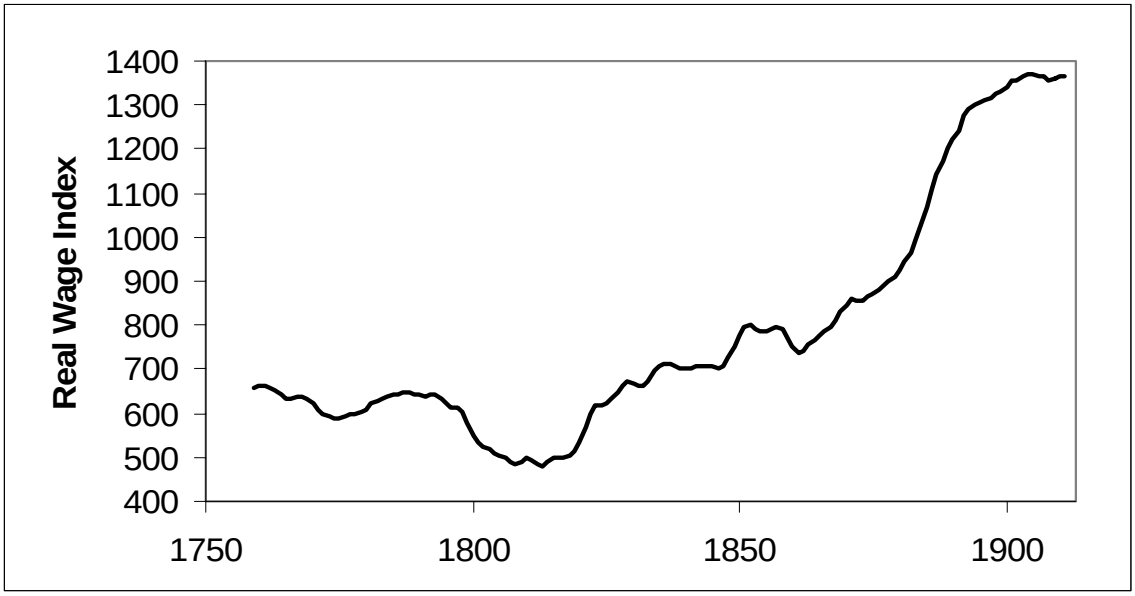
Education Rate (South)



In the closed case, skill-intensive technologies do not grow very fast. As a result, the demographic transition is limited; fertility falls only moderately, while education remains at the constrained minimum in both regions for most of the simulation, rising only at the tail end. Thus in the closed case, education fails to play a key role.

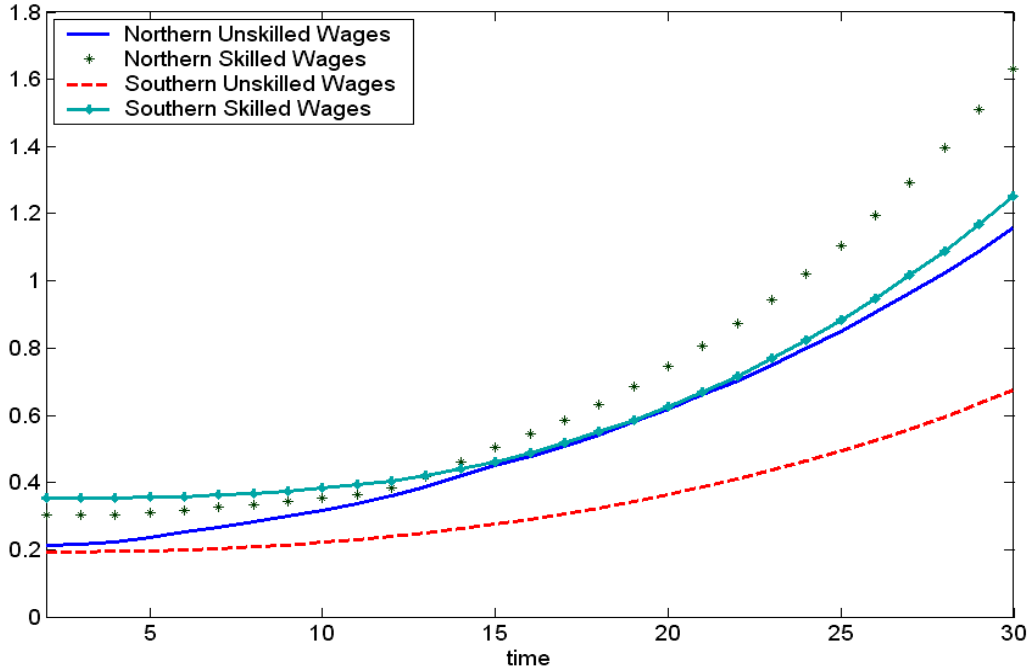
Figure 7

Wage Series (England)



Wrigley and Schofield (1981). 10-year moving average.

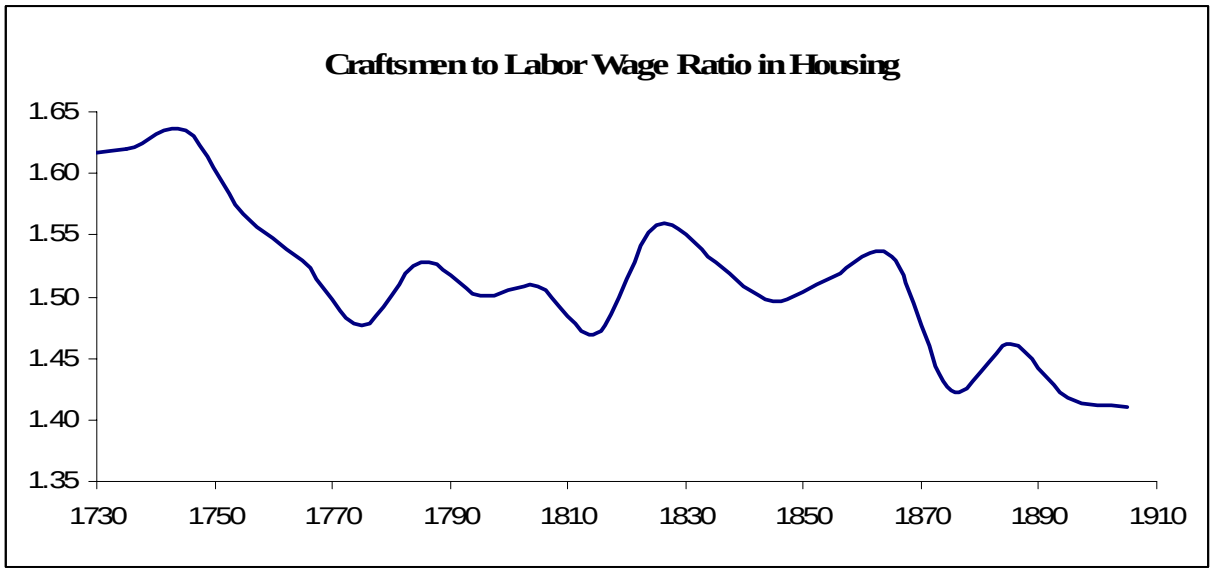
Wage Series (North and South)



Although in the simulation wages do rise slowly in the initial stages, we cannot replicate the *fall* in real wages implied by Wrigley and Schofield's series.

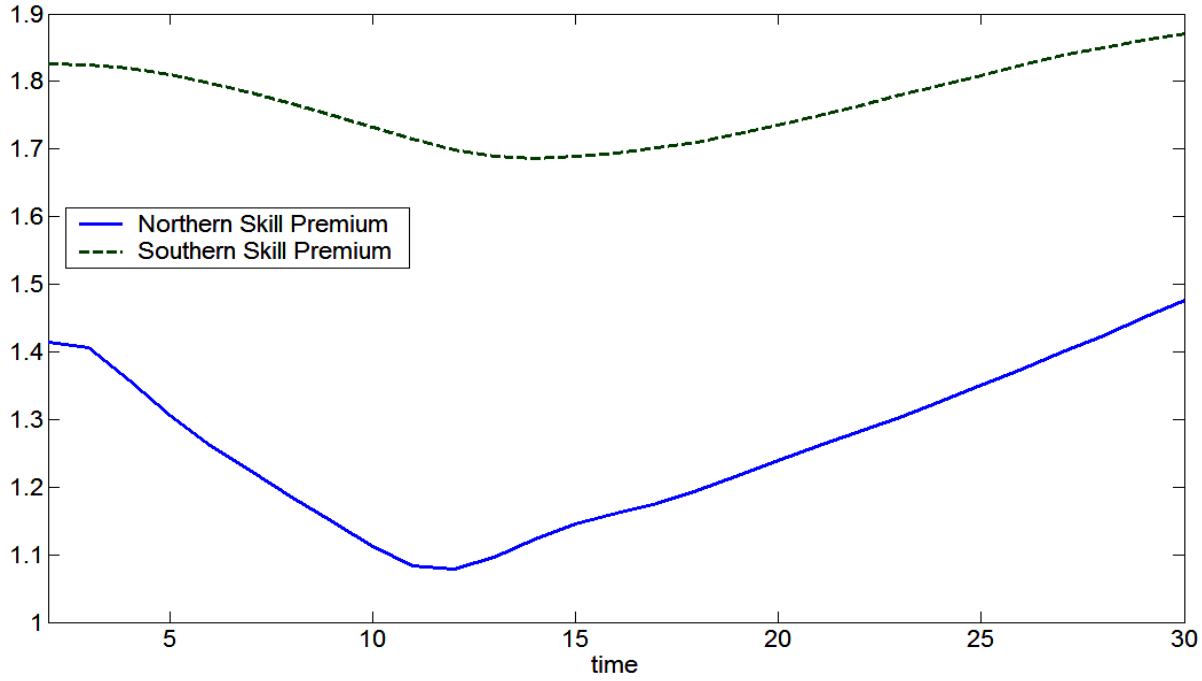
Figure 8

Skill-Premium (England)



Clark (Forthcoming).

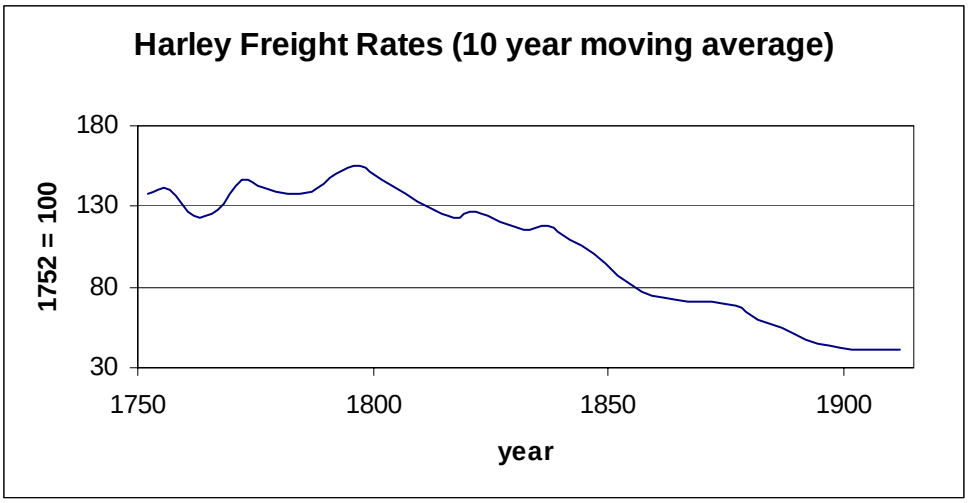
Skill-Premia (North and South)



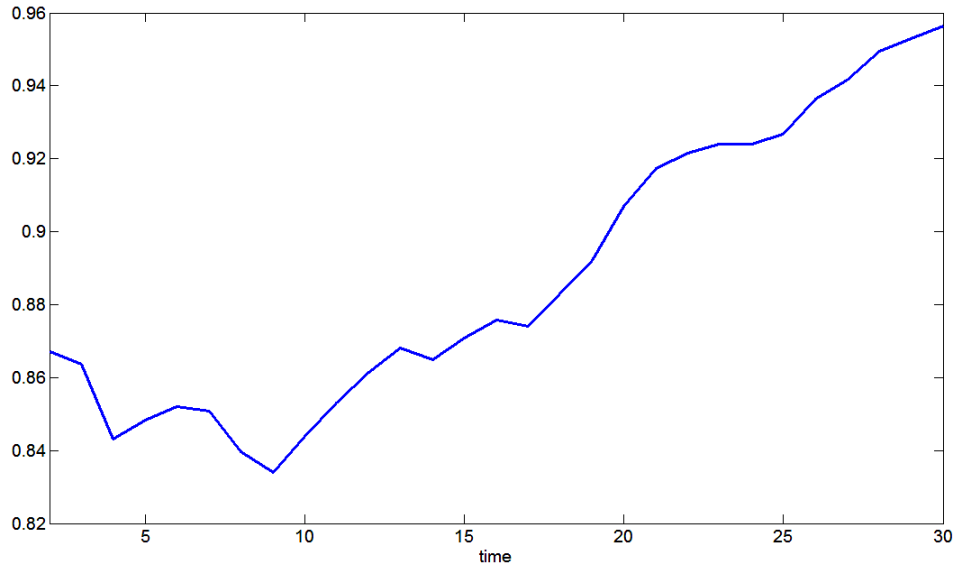
While the fall in the skill-premium followed by its rise around the turn of the 19th century is roughly echoed by historical time series, we cannot duplicate the apparent fall in the premium after 1870.

Figure 9

The Gradual Opening of Two Economies



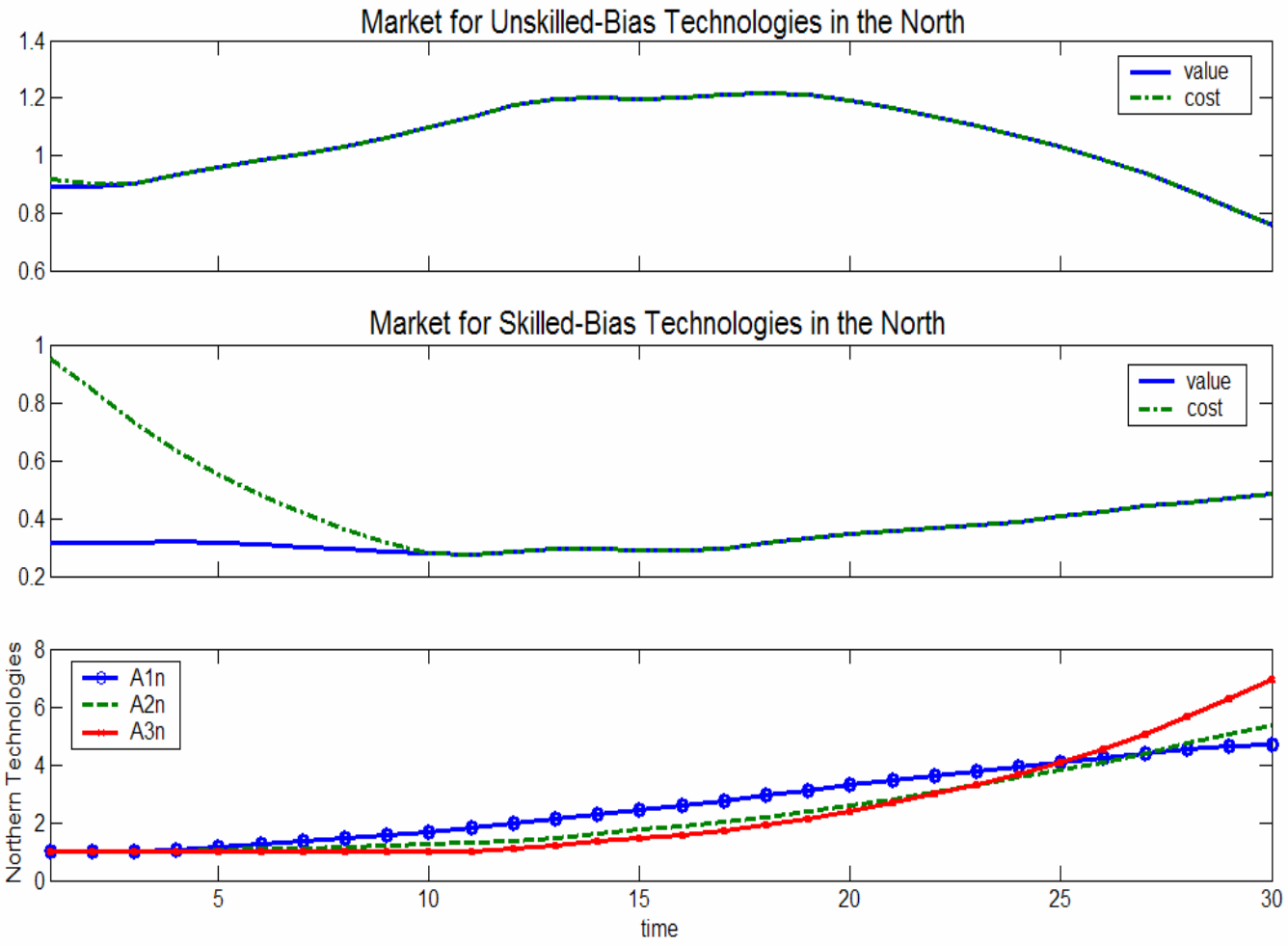
The Fraction of Export that Arrives as Import



Trade costs fall throughout the 19th century. In the open case, we illustrate this by having falling iceberg costs. The graphs above are essentially mirror images of each other.

Figure 10

The Market for Technologies
The Opening Economy



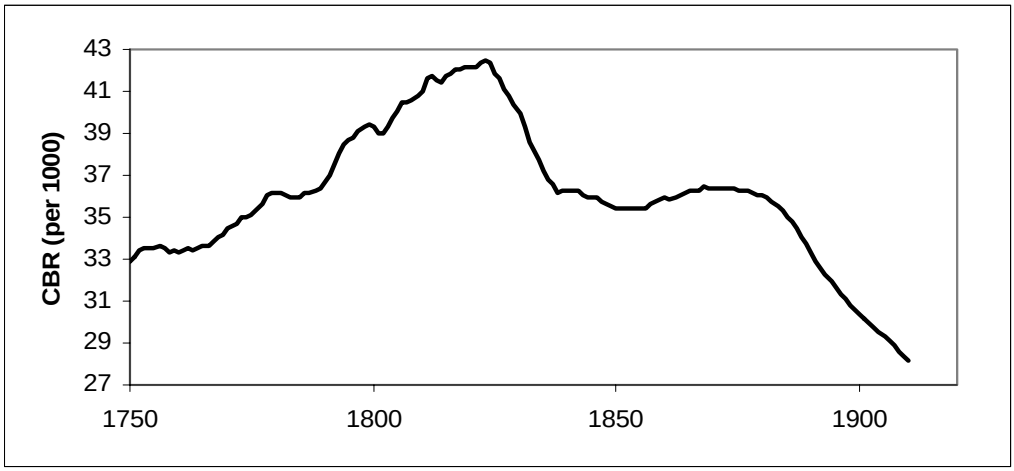
Parameter values are the same as the ones used in Case I, except now a_1 and a_3 are initially set so that trade becomes possible.

Again, technology grows first in sector 1; the first part of the simulation replicates the closed case. But because of increasing levels of trade, the demographic reversal is more dramatic in this case, lowering L^N and raising H^N, and thus slowing down growth in A_1 and speeding up growth in A_3.

Figure 11

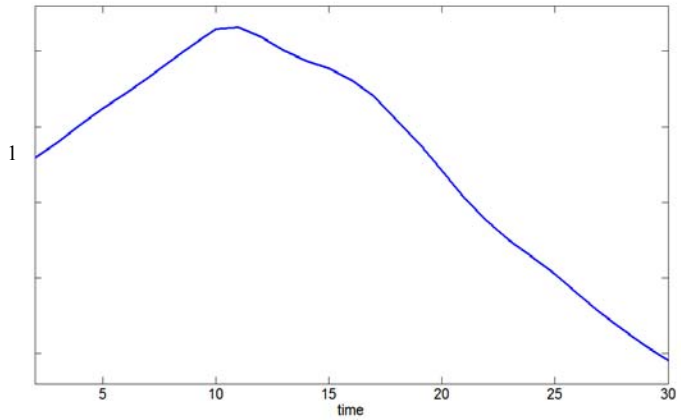
Fertility Rates

Fertility Rates (England)

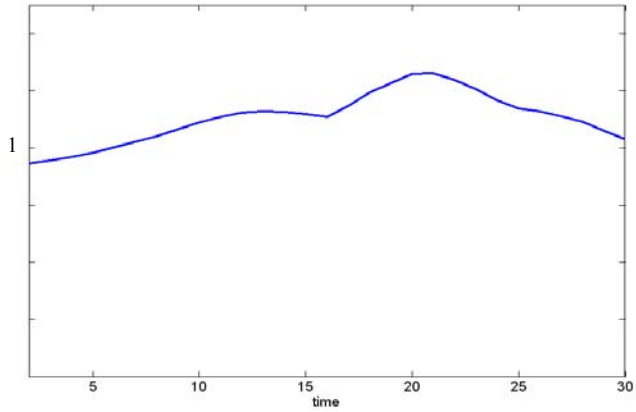


Wrigley & Schofield (1981) and Andorka (1978). 10-year moving average.

Fertility Rates (North)



Fertility Rates (South)

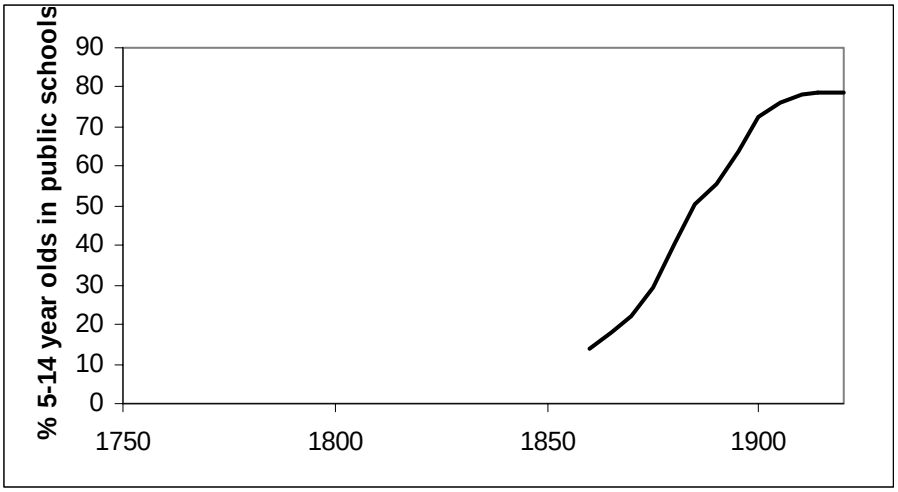


Again, fertility rises initially for both regions. The North however experiences a more dramatic demographic reversal, with falling fertility rates. The South on the other hand consistently has fertility that is above replication.

Figure 12

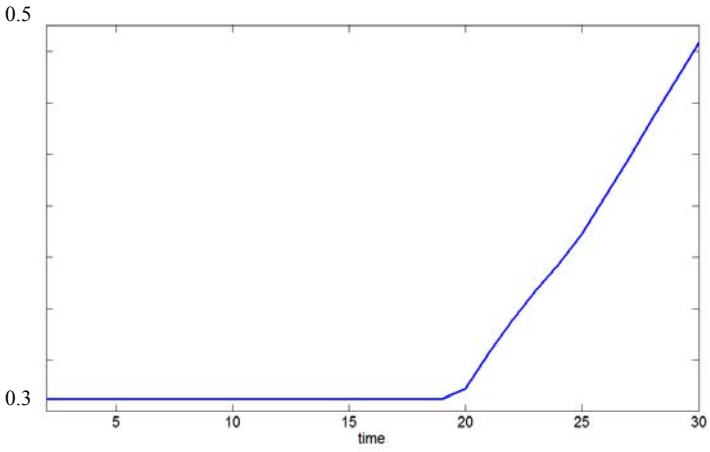
Education Rates

Education Rate (England)

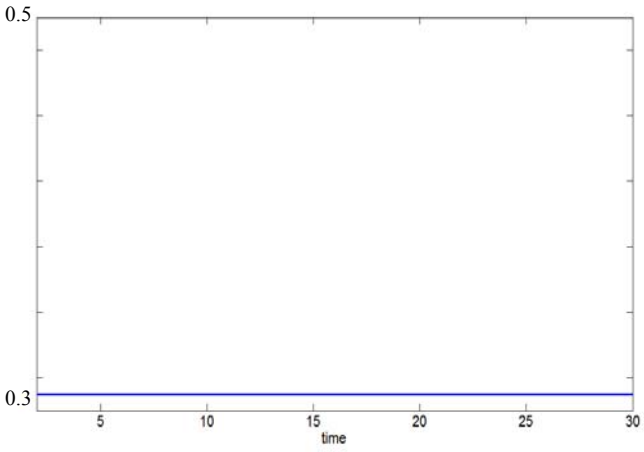


Flora et al (1983). 10-year moving average.

Education Rate (North)



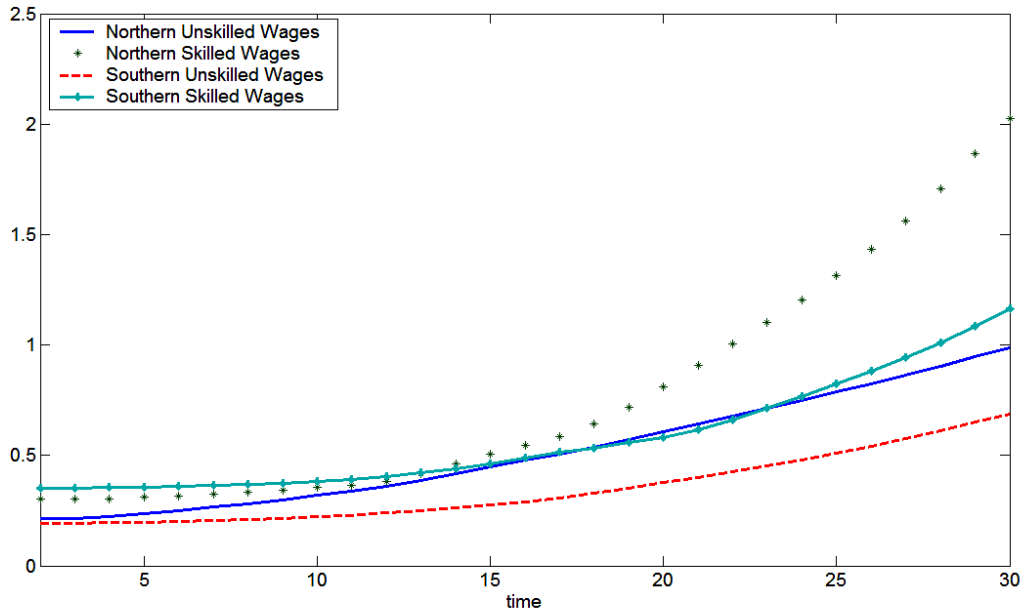
Education Rate (South)



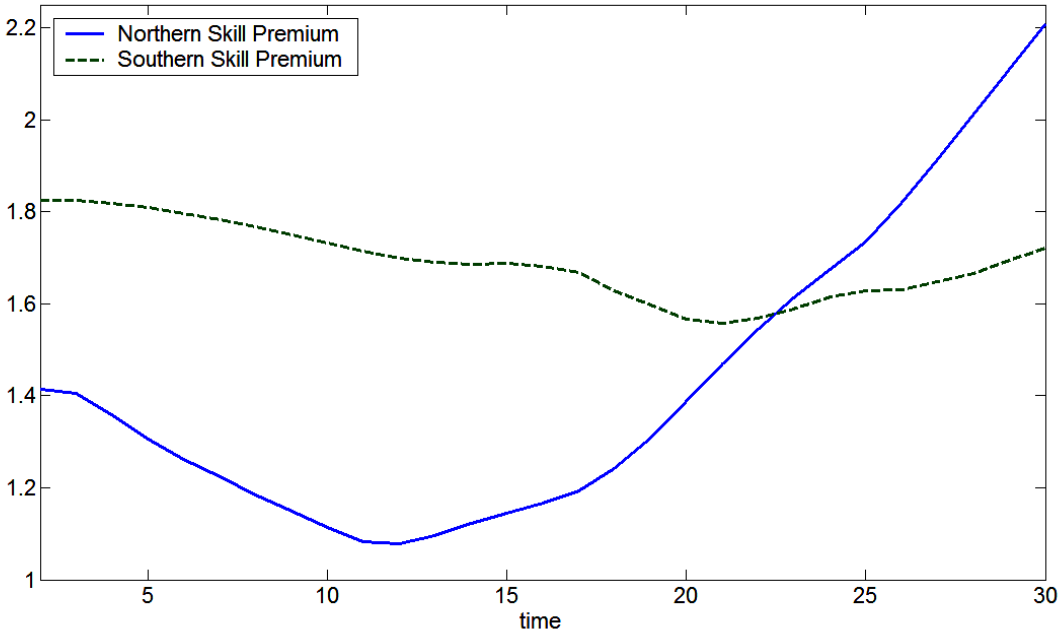
While Southern education rates remain stagnant, Northern education rates rise above the minimum constraint. Thus here both technologies and education are able to grow in the North.

Figure 13

Wage Series (North and South)



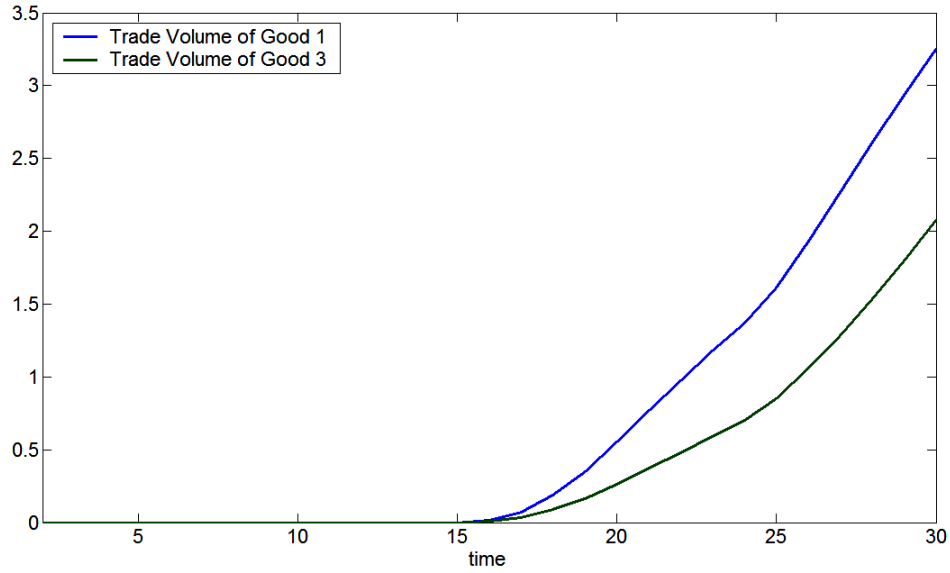
Skill Premia (North and South)



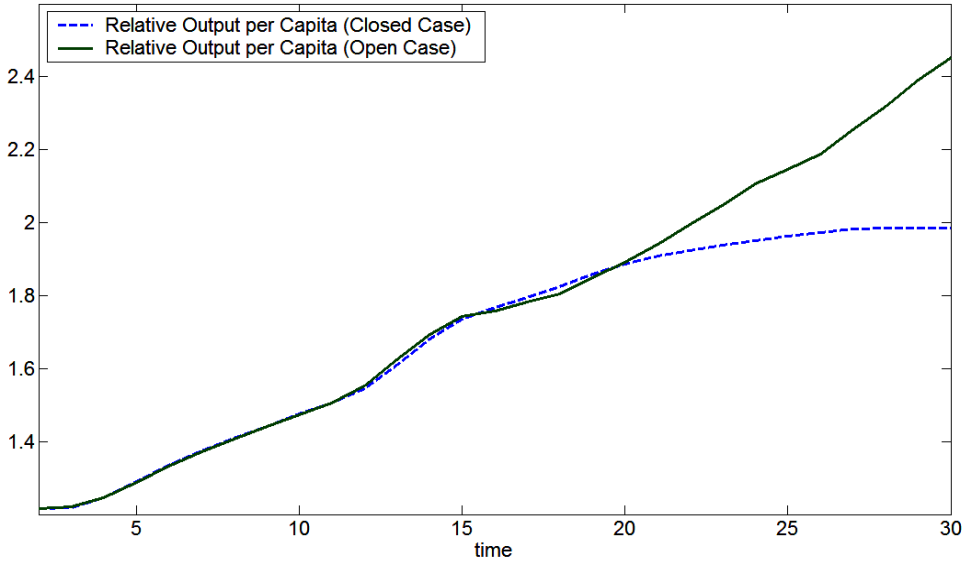
The rise in the Northern skill premium through Heckscher-Ohlin effects produces a more dramatic demographic transition in the North. These same effects limit the transition for the South by anchoring down its skill premium.

Figure 14

Volume of Traded Goods



North-South Income Gap in Closed and Open Cases



The income per capita gap between the North and South (measured as y^N / y^S) essentially stem from two sources – differences in technologies and differences in trade patterns. The initial static gains from trade actually help slightly reduce the income gap at first. But the dynamic incentives of such trade hasten the Demographic Transition for the North and suppress it in the South, thereby exacerbating the gap.