

# Population Growth, Technological Adoption, and Economic Outcomes in the Information Era<sup>1</sup>

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In this paper we argue that population growth, through its interaction with recent technological and organizational developments, may account for many cross-country differences in economic outcomes observed among industrialized countries over the past 20 years. In particular, our model illustrates how a large decrease in the price of information technology can create a comparative advantage for high population growth economies to jump ahead in the adoption of computer- and skill-intensive modes of production. They do this as a means of countering their relative scarcity of physical capital. The predictions of the model are that, over the span of the information revolution, industrial countries with higher population growth rates will experience a more pronounced adoption of new technology, a better performance in terms of increased employment rates, a poorer performance in terms of wage growth for less skilled workers, a larger increase in the service sector, and a larger increase in the returns to education. We provide preliminary evidence in support of the theory based on an examination of broad wage movements, employment changes, and computer adoption patterns for a set of OECD countries. *Journal of Economic Literature* Classification Numbers: O33, J31, J11. © 2002 Elsevier Science (USA)

*Key Words:* population growth; information revolution; wage structure; human and physical capital accumulation.

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## 1. INTRODUCTION

Over the past 20 years, economic performance and labor market outcomes have differed substantially across industrialized countries (see, for example, Gottschalk and Smeeding (1997)). In particular, the labor market in the U.S. has been characterized by a large increase in the employment rate, poor wage performance for lowly skilled workers, an increase in the returns to education, and a rapid expansion of the service sector. In contrast, continental Europe has witnessed low employment growth, no substantial change in the returns to education, a decent performance in terms of wages for less educated workers, and a slower expansion of the service sector. Our goal in this paper is to present an explanation for these observed cross-country differentials built on the interaction between two driving forces: population growth and the dramatic declines in the costs of using information technologies.

Our approach in this paper builds on our earlier work in Beaudry and Green (2000). In that paper, we showed how differences in wage changes between Germany and the U.S. can be traced back to differential growth in factor usage and especially differences in the ratio of human to physical capital use. Perhaps most importantly, we showed that the evolution of wages and factor usage in these countries fit the tight restrictions implied by a model in which technological adoption is an endogenous phenomenon. In particular, our estimates indicated that firms in both these countries have been choosing between two broad classes of methods of production, with one of these methods of production being skill biased and capital efficient relative to the other. However, our previous analysis was partial equilibrium in nature. In this paper, we build on insights from our previous work in order to propose a general equilibrium answer to the question of why changes in labor market outcomes have differed so substantially across industrial countries over the past 20–25 years. The main elements of our answer reside in changes in the effect of rates of population growth on the process of technological adoption before and after a massive decline in the cost of computer-based capital.

The model we develop shares many features with those presented in the recent literature. For example, we adopt the consensus view that new methods of production are biased in favor of both capital and skilled labor (which is a version of the capital–skill complementarity assumption), and we focus on the adjustment induced by a fall in the relative price of information technology. The main new element we bring to the discussion is our emphasis on the importance of the ratio of human capital versus physical capital in understanding technological adoption and its relationship with population growth. There are two main components to the mechanism at work in our model. The first component involves the effects of population

growth on a country's relative abundance (or scarcity) of human versus physical capital. In the spirit of Solow (1956), our model illustrates why countries with high rates of population growth are likely to exhibit a relatively low capital–labor ratio and a relatively high ratio of human capital to physical capital. The second important element of our model relates to the effects of the computer revolution on the relative costs of adopting the two competing technologies and, hence, on the way a country's relative abundance (or scarcity) of capital translates into the adoption of computer-based means of production. In particular, if high population growth economies are economies with a higher ratio of human to physical capital, then they have a comparative advantage in the adoption of methods of production with similar factor intensities. As we shall show, a fall in the cost of computer-based capital causes high population growth economies to move from being laggards in adoption of computer-based methods of production to being aggressive leaders.

The theoretical approach we adopt in the paper is to consider a set of economies at the dawn of the information revolution, that is, at a point in time after the introduction of computers but before the massive decrease in their price and their associated huge diffusion. We then examine how countries with different rates of population growth will adjust to a fall in the price of computer-based capital. Our main result is that, if the reduction in the cost of information or computer capital is sufficiently large, the effects of population growth on economic outcomes will change radically over the period. In particular, assuming human capital and new information technologies are complementary, we show why countries with higher population growth will experience—over the span of such an information revolution—a poorer performance in terms of wages for lowly skilled workers, a better performance in terms of increased employment rates, a larger increase in the service sector, and a larger increase in the returns to education. Moreover, the countries with higher population growth will appear more dynamic over this period as they adopt new modes of production to a greater extent and tend to invest more in computer-based capital. Based on these results, we argue that differential speeds of technological adoption, driven by underlying differences in population growth, can account for many of the differences in economic performance observed across countries over the past quarter of a century.

The remaining sections of the paper are structured as follows. In Section 2, we present a tractable dynamic general equilibrium model aimed at highlighting how population growth affects economic outcomes over a period in which there is a massive decrease in the cost of computer-based capital. In Section 3, we derive and explain the main theoretical results. In Section 4, we present some empirical evidence in support of our hypothesis, and in Section 5, we offer concluding comments.

## 2. A TRACTABLE GENERAL EQUILIBRIUM MODEL WITH POPULATION GROWTH AND ENDOGENOUS TECHNOLOGICAL CHOICE

### 2.1. *The Model*

As is now well known, the reduction in the cost of computer-based capital has been enormous over the past quarter of a century and can reasonably be thought of as a major force impacting all industrialized economies. The issue that arises in this context is how best to model the opportunities created by such a change. Our choice is to follow the approach of Bresnahan *et al.* (1999) and view computer capital as an essential input into a new mode of production which is organized in order to exploit the joint use of human capital and information technology. To this end, we assume that firms have access to two constant returns to scale (CRS) production techniques (which produce the same final good): an older, traditional form of production, denoted  $F^O(\cdot)$ , which depends on traditional capital ( $K$ ), human capital ( $H$ ), and unskilled labor ( $L$ ); and a modern production technique ( $F^M(\cdot)$ ), which depends only on computer-based capital ( $IT$ ) and on human capital. Hence, as in many recent papers (e.g., Acemoglu (1999), Basu and Weil (1998), Beaudry and Green (1998, 2000), Caselli (1999), Zeira (1998)), we are considering an environment where there is a choice of techniques of production.

To make the analysis as tractable as possible, we will assume that the two production techniques are as in Eqs. (1) and (2). However, it is worth noting that our results are not restricted to these particular functional forms. Equations (1) and (2) are chosen to embody two important properties. First, consistent with much of the literature, the more modern form of production is skill biased relative to the old technology; that is, the modern technology uses more skill per unit of output (since  $\lambda < 1$ ) and does not use unskilled labor. Secondly,  $IT$  capital is an input that complements human capital.

$$F^O(K, H, L) = \min[L^{.5}K^{.5}, H] \quad (1)$$

$$F^M(T, H) = \min[IT, \lambda H] \quad \lambda < 1. \quad (2)$$

A firm's problem is to choose inputs and production techniques in order to maximize profits. Let us denote by  $r_k, r_{IT}, r_h$ , and  $w$ , respectively, the rental price of traditional capital, computer-based capital, human capital, and unskilled labor. With this notation, the firm's problem can be stated as

$$\max_{Y^O, Y^M, K, IT, H^O, H^M, L} Y^O + Y^M - (r_k K + r_{IT} IT + r_H(H_1 + H_2) + wL)$$

s.t.

$$Y^O = F^O(K, H_1, L) \text{ and } Y^M = F^M(IT, H_2), \quad Y^O, Y^M \geq 0.$$

Thus, we allow firms to use both techniques of production simultaneously. This formulation allows for firms to switch smoothly between technologies. We now turn to the formulation of the household's problem.

In modeling the household, our objective is to choose a specification which results in simple but plausible supply decisions. To this end, we assume that the household acts as a dynasty where the decision maker lives for one period and has a bequest motive which leads to savings. This set-up has the attractive feature (compared to the standard OLG formulation) that it allows the aggregate savings rate to be independent of the functional distribution of income, which greatly simplifies the analysis.

In each period, the household must decide on the amount of education to obtain, the amount to save, and the amount of time to supply to the market. However, for the sake of clarity, we begin by omitting the labor supply decision. The household's utility function is given by Eq. (3), where  $C_t$  denotes consumption and  $B_{t+1}$  denotes the bequest to one's descendent.

$$\frac{C_t^{1-\sigma}}{1-\sigma} + \beta \frac{(B_{t+1})^{1-\sigma}}{1-\sigma}, \quad 0 < \sigma \leq 1. \quad (3)$$

Given this formulation, the consumption decision leads to individuals consuming a fraction of their net incomes, with the fraction saved depending positively on the interest rate. Each household is assumed to have one unit of labor time which they supply to the market. Population growth in this economy comes from the entry of new households (or dynasties), with the new households entering at a rate  $\eta$  (i.e.,  $\eta$  is the rate of population growth). We normalize the size of the initial population to 1.

If a household invests in education, their labor time is augmented to include units of human capital, which we denote by  $h$ . In this case, the labor earnings it will receive from the market will be equal to  $w_t + r_{h,t}h$ , that is, the value of unskilled labor plus the value of the human capital. We assume that the cost of education associated with obtaining  $h$  units of human capital (in terms of goods) is given for household  $i$  by  $Q_i(h)$ , where  $Q(0) = Q'(0) = 0$ ,  $Q'_i(h) \geq 0$ ,  $Q''_i(h) > 0$ . We index the cost of education by  $i$  since we will eventually want to allow for heterogeneity across households. With these additional elements, we can now state the household budget constraint as follows.

$$C_t + \frac{B_{t+1}}{(1+r_{t+1})} = w_t + r_{H,t}h_t - Q_i(h_t) + B_t. \quad (4)$$

In the above budget constraint, the household receives net labor earnings (net of education costs) equal to  $w_t + r_{h,t}h - Q(h)$  and potentially inherits

from the past a bequest,  $B_t$ . If the household is a new entrant, then it inherits nothing. The household uses its revenue to spend on consumption and saves output at a return  $(1 + r_{t+1})$  in order to leave a bequest  $B_{t+1}$ . Here, we have specified the cost of education in terms of output instead of as a time cost. This again is adopted to simplify the analysis.

The household's optimal acquisition of human capital must satisfy Eq. (5A), where it can be seen that human capital investment will simply be a nonnegative function of the price of human capital  $r_{H,t}$ . The optimal consumption decision is given by Eq. (5B), where the savings rate is given by  $\frac{1}{\beta^{\frac{1}{\sigma}}(1+r_{t+1})^{\frac{1-\sigma}{\sigma}} + 1}$ . Note that when  $\sigma = 1$ , the savings rate is a constant.

$$Q'_i(h) = r_{H,t} \quad (5A)$$

$$C_t = \frac{1}{\beta^{\frac{1}{\sigma}}(1+r_{t+1})^{\frac{1-\sigma}{\sigma}} + 1} (w_t + r_{H,t}h_t - Q_i(h) + B_t). \quad (5B)$$

To complete the model, we need to specify how saved output is transformed into physical capital. Recall that the two different technologies have different types of physical capital associated with them. We therefore assume that there is a competitive intermediary which transforms a unit of saved output today into either one unit of traditional capital or  $\theta_t$  units of computer-based capital for the next period. Hence,  $\theta_t$  represents the efficiency level by which a unit of output can be transformed into computer-based capital. It is a nonmarginal increase in this variable that we will refer to as the information revolution, a revolution in which creation of computer capital becomes dramatically cheaper. The constant return to scale nature of this transformation technology implies that the rate of return on savings must be equal to rates of return on both traditional and computer-based capital. Assuming full depreciation of capital stocks across periods (again for simplicity), we therefore have the arbitrage conditions

$$1 + r_t = r_{K,t} = \theta_t r_{IT,t}. \quad (6)$$

In the absence of heterogeneity across households (i.e., with  $Q_i(h)$  independent of  $i$ ) a Walrasian equilibrium for this economy is a sequence of prices  $\{w_t, r_{H,t}, r_{K,t}, r_{IT,t}, r_t\}$  and allocations  $\{h_{i,t}, B_{i,t+1}, L_t, H_t, K_t, IT_t\}$  such that (i) given prices,  $h_{i,t}$  and  $B_{i,t+1}$  solve the consumer's problem (i.e., maximizes (3) subject to (4)), (ii) given prices,  $L_t, K_t, H_t$ , and  $IT_t$  solve the firm's problem, (iii) the arbitrage conditions given by (6) are satisfied, and (iv) markets clear. We will focus only on steady-state equilibria,

that is, time-invariant vectors of prices and constantly growing allocations (at growth rate  $\eta$ ) which form a Walrasian equilibrium for a given level,  $\theta$ , of the computer efficiency index.

### 3. EQUILIBRIUM ANALYSIS

In this section, we will examine how a decrease in the price of computer-based capital, that is, an increase in  $\theta$ , affects steady-state outcomes. In particular, we show how this price change affects countries differently depending on their rates of population growth. Our main result is that, if the reduction in the cost of computer-based capital is sufficiently large, countries with high rates of population growth will adopt the new technology more aggressively over the period and this will give rise to different patterns of labor market outcomes.

Before we perform this exercise, it is necessary to be precise with respect to the initial state of technology. The modern technology  $F^M(IT, H)$ , as specified in Eq. (1), depends on the parameter  $\lambda$ , and its adoption depends on the cost of computer-based capital, which is  $\frac{1}{\theta}$ . As we have previously indicated, we assume throughout that this new technology is skill biased in the sense that  $\lambda < 1$ . This is consistent with much of the recent literature which emphasizes the skill biased aspect of recent technologies, and it is consistent with Goldin and Katz's (1998) longer term view suggesting that most techniques of production introduced in the 20th century were skilled biased. Further, we assume that the technology is relevant in the sense that, at the prices that would prevail in the absence of this technology, it would be profitable to adopt the technology. This corresponds to the requirement that  $\frac{r_K^*}{\theta_0} + \frac{r_H^*}{\lambda} \leq 1$ , where  $r_K^*$  and  $r_H^*$  are the prices that prevail in the absence of the modern technology, and where  $\theta_0$  denotes the value of  $\theta$  in this initial period. Finally, we also want to be consistent with Goldin and Katz's evidence that new technologies, at least when they are first introduced, have predominantly been capital intensive as well as skill intensive. In effect, we assume that the computer-based technology was heavily capital intensive (in terms of units of produced output) when it was first introduced (e.g., think of robotics); that is, we assume that its relative capital intensity was initially more important than its skill intensity. To state the requirement formally, let  $k^*$  denote the capital-output ratio in the traditional production method. Our main assumption about the pre-information-revolution era is that the physical capital to human capital ratio in the new technology, which is  $\frac{\lambda}{\theta_0}$ , is greater than the corresponding ratio in the traditional technology, which is given by  $\frac{1}{k^*}$ .

We are now in a position to examine how a fall in the price of computer-based capital will interact with population growth, as stated in Proposition 1.

**PROPOSITION 1.** *In an economy with endogenous accumulation of both physical and human capital, if there is a sufficiently large reduction in the cost of IT capital (starting from  $\theta = \theta_0$ ), then the higher an economy's rate of population growth:*

- *The poorer the performance in terms of the price of unskilled labor.*
- *The greater the increase in the returns to education.*
- *The greater the change toward using the modern mode of organization.*

*Proof.* See the Appendix.

The first key mechanism behind Proposition 1 is that, regardless of the value of  $\theta$ , high population growth economies are characterized by a relatively high ratio of human to physical capital. The reason for this is similar to that emphasized in the neoclassical growth model as developed by Solow (1956); that is, in a high population growth economy physical capital tends to be relatively scarce due to the constant need to use savings to equip new labor market entrants. However, population growth does not induce relative scarcity of human capital to the same extent as physical capital because new households can accumulate human capital but (because they have no wealth) cannot help accumulate physical capital. Given this, values of  $\theta$  are crucial in determining which technology better matches the requirements of the relatively physical-capital-scarce high-population-growth economy. In the initial state, with  $\theta$  low, the capital cost associated with adopting the new technology is high relative to its cost in terms of human capital. Hence, in the economy with a higher population growth rate, where physical capital is the relatively expensive factor compared to human capital, the incentives are for firms to refrain from adopting the new technology aggressively since they do not have a comparative advantage in doing so.

The effect of a large enough reduction in the cost of computer-based capital is to change the relative cost structure of the modern versus the more traditional mode of production. A sufficient increase in  $\theta$  is therefore like inventing a new mode of production, that is, a technology that uses human capital intensively and is efficient in its use of physical capital. This particular pattern of factor intensities conforms well to that desired by high population growth economies and hence they naturally move to adopt the new form of production. Since low growth economies do not exhibit the same factor ratios, they adopt it less aggressively. Greater adoption of the modern technology means less human and physical capital allocated to the traditional technology and, hence, a lower unskilled wage. Moreover, the greater adoption of new technology means that highly skilled workers are in high demand relative to lowly skilled workers, which causes a greater rise in the returns to education in high population growth economies. This makes high population growth countries appear as if they experienced

a more skill biased technical change than their low population growth counterparts even though the actual technological opportunities are identical across countries.<sup>2</sup>

Hence, Proposition 1 indicates that, in response to a fall in the price of computer-based capital, high population growth economies will tend to leapfrog over low population growth economies in terms of their adoption of the new technology as a means of taking advantage of their comparative advantage in using modes of production with a high ratio of human versus physical capital. This, in turn, leads to more substantial changes in labor market outcomes in the high population growth countries. In this sense, our model suggests that the information revolution creates a structural change which is especially evident in high population growth countries.

### 3.1. *Extending the Model to Include Variable Labor Supply Decisions*

In this section, we extend the model to consider movements in the level and sectoral composition of employment. This model extends the household's problem to incorporate two new decision variables, which are time supplied to the market, denoted  $l_t$ , and the amount of household-related services (a second good) purchased from the market,  $s_t$ . The tradeoff we envision involves the household fulfilling its needs in terms of a domestic good by either withdrawing time from market activity or by buying related services on the market. To this end, let us denote by  $D(1 - l_t, s_t)$  the household's production of domestic goods achieved when  $1 - l_t$  of time is devoted to household production and  $s_t$  services are bought on the market (at price  $p_t^s$ ). Furthermore, let us assume that the household's requirement in terms of domestic services is a fixed amount  $\bar{d}$  and that, for simplicity, the function  $D(\cdot)$  takes the following form  $D(l_t, s_t) = D_0(1 - l_t)^\alpha + s_t$ ,  $0 < \alpha < 1$ . The household's problem can therefore be stated as

$$\max_{c_t, B_{t+1}, h_t, l_t, s_t} \frac{c_t^{1-\sigma}}{1-\sigma} + \beta \frac{(B_{t+1})^{1-\sigma}}{1-\sigma}$$

s.t.

$$D(1 - l_t, s_t) = \bar{d}$$

$$c_t + \frac{B_{t+1}}{(1 + r_{t+1})} = (w_t + r_H h_t)l_t - Q_i(h_t) - p_t^s s_t + B_t.$$

<sup>2</sup>Given the work by Blanchard (1997), it would also be of interest to know the predictions of our model with respect to the income share of capital. Although this effect is not unambiguous in our model, we are able to show that, if the endogenous response of human capital is not too large, a low population growth economy will exhibit a higher income share of capital in the post-information-revolution era.

The first-order condition associated with the household's labor supply decision, which is  $\alpha D_o(1 - l_t)^{\alpha-1} = \frac{w_t + r_{H,t}h_t}{p_t^s}$ , implies that the time spent in the market will be positively related to the ratio of the household's effective wage ( $w + r_H h$ ) and the price of household-related services ( $p^s$ ). Hence, changes in relative prices affect labor supply decisions. To see this mechanism most clearly, let us introduce heterogeneity between households and eliminate the education decision by assuming that there is a measure  $\pi$  of households which obtain no education and a measure  $1 - \pi$  which obtain education level  $h_2$  (without loss, we can therefore disregard the cost of education in this case). Furthermore, let us assume that household services,  $s$ , are produced in the market using a CRS production function which produces one unit of services with one unit of unskilled labor. This implies that the price of services is equal to the price of unskilled labor,  $w_t$ . In this case, which will be our case of reference when we refer to the case with endogenous labor supply,<sup>3</sup> the labor supply decision of a no-education household is not affected by changes in either  $w_t$  or  $r_{H,t}$  (since only the ratio of  $w_t$  to  $p_t^s$  enter the FOC, and this ratio is 1). However, the labor supply decision of the more educated household will be affected by changes in the wage structure. In particular, the educated household's labor supply is positively affected by an increase in the price of skilled labor  $r_{H,t}$  relative to the price of unskilled labor  $w_t$ . This ratio is generally referred to in the literature as the return to education, and we will adopt this convention, even though in terms of goods (which is the usual benchmark for most returns), the return to education is  $r_{H,t}$ .<sup>4</sup>

A Walrasian equilibrium for the economy with endogenous labor supply and two types of households, denoted by  $i = 1$  or  $i = 2$ , is a sequence of prices  $\{w_t, r_{H,t}, r_{K,t}, r_{IT,t}, r_t, p_t^s\}$  and allocations such that (i) given prices, allocations of consumption, labor, and household services solve the consumer's problems, (ii) given prices, the allocations  $L_t, K_t, H_t$ , and  $IT_t$  solve the firm's problem, (iii) the arbitrage condition given by (6) is satisfied and  $p_t^s = w_t$ , and (iv) markets clear. We will again only focus on the steady-state equilibrium, that is, the time-invariant vector of prices and constantly growing allocations (growth rate  $\eta$ ) which form a Walrasian equilibrium for a given level of  $\theta$ . Furthermore, for reasons we discuss later, we focus on the case where  $\alpha$ , which governs the elasticity of labor supply, is not too large. Note that if we were to assume that  $\alpha = 1$  (infinite elasticity), this

<sup>3</sup>Note that the more general cases with heterogeneity and simultaneous education and labor supply decisions can be handled, but without any gain in terms of results or insight.

<sup>4</sup>We note this difference in vocabulary since it often leads to confusion. In particular, if a production function is convex, an increase in the use of human capital will always imply a reduction in the return to education in terms of goods, but it does not necessarily imply a reduction in the return to education in terms of the price of unskilled labor.

would by assumption pin down the returns to education and hence defeat the purpose of the analysis.

**PROPOSITION 2.** *In the economy with endogenous labor supply, if there is a sufficiently large reduction in the cost of IT capital (starting from  $\theta = \theta_0$ ) and if  $\alpha$  is not too large, then a higher rate of population growth implies the same effects as those stated in Proposition 1 plus it implies*

- *a larger growth in per capita employment.*
- *a larger growth in per capita employment in the service sector.*

The intuition for Proposition 2 is as follows. Since the economy with the high rate of population growth does not tend to adopt the new technology aggressively in the pre-information-revolution era, it tends to have a more equal wage structure, since a higher adoption of the new technology implies that skilled workers are more demanded. In turn, the more equal wage structure is a deterrent to market transactions in services between more and less educated households. Hence, when  $\theta$  is low, the employment rate tends to be lower in the high population growth rate economies relative to the low growth rate economies, as does the size of the service sector.

In the post-information-revolution era, that is, after an increase in  $\theta$ , the high population growth economy adopts the modern technology aggressively thereby leading to a greater disparity in wages between lowly and highly skilled individuals. This disparity in wages in turn favors greater market transactions in services between highly and lowly skilled households. In effect, households with high levels of human capital increase their labor supply and purchase a greater amount of services in the market. This leads to a higher rate of employment and a larger service sector. The endogenous response of labor supply means that this process is self-reinforcing. Thus, as the more educated household offers more labor in the market this further favors the adoption of the modern form of technology since it is skill biased. Capital will be shifted toward the modern technology, further increasing the capital scarcity in the traditional mode of production. With less capital applied to the traditional technology, wages for the lowly skilled drop and the role of lowly skilled workers as providers of services to the more educated households is expanded.

The general picture that emerges from Propositions 1 and 2 is one suggesting that the information revolution can affect economic outcomes across countries very differently simply because countries differ in their rates of population growth. In effect, these propositions indicate that high population growth economies may experience a transformation induced by the information revolution which, both in terms of the structure of wages and in terms of the structure of production and employment, is much greater in scope than that induced in low population growth economies.

The intuition behind these propositions is that the information revolution transforms modern production processes (or modern forms of work organization), which rely on computer-based capital, from initially being processes which are relatively costly in terms of capital expenditures to processes which are inexpensive in terms of capital expenditures.<sup>5</sup> Due to this change, countries with high population growth rates find it to their advantage to aggressively adopt the more modern form of production as a means of taking advantage of their relatively high ratio of human capital to physical capital. Thus, these countries move from being slow in implementing new computer-based technologies (such as robotics in the 1970s), to being the leaders. The shift toward the modern technology implies a shift away from the traditional technology which, in turn, harms the lowly skilled workers employed there. The lowly skilled workers then respond by exploiting new opportunities in the service sector. The more skilled workers in the high population growth economies recognize the gains associated with reducing their time devoted to household services and instead supply more time to the market and buy more services. Both these latter effects play an amplifying role in the entire process, potentially causing small differences in population growth to generate significant differences in wage profiles and employment patterns.

#### 4. SOME EMPIRICAL EVIDENCE

Propositions 1 and 2 summarize the implications of our model in terms of how cross-country differences in population growth may translate into differences in wage and employment growth arising from the fall in the price of computer-based capital. The means with which we choose to examine these implications is to look at the effects of population growth on a set of outcomes across industrialized countries. We focus exclusively on industrial countries since we interpret the theory as applying to a set of countries sharing the same technological options and at similar stages of development. It is worth immediately noting that, even among rich countries, rates of population growth differ quite markedly. For example, among OECD countries, the lowest rates of population growth are close to zero and the highest rates are around 1.5% per year. Over a 20-year period this implies differences in population growth of about 30% within this set of countries.

<sup>5</sup>In effect, these processes become ones where the major cost disadvantage is in terms of human capital as opposed to physical capital.

#### 4.1. *Changes in Employment, Wages, and Population Across Industrialized Countries*

In this section, we present evidence of the relationship between employment, wages, and population growth before and after 1975 for a sample of rich OECD countries<sup>6</sup> as a means of examining the relevance of the theory. Obviously, it would be desirable to have very detailed data on wages and employment for the entire set of countries over a long period of time. However, these data are not available.<sup>7</sup> Our choice, therefore, is to focus on two summary measures of economic performance for which data are readily available for most of these countries since 1960. The two measures are the employment rate<sup>8</sup> and real wages (measured as real compensation per employee).<sup>9</sup> We begin by examining the relationship between (annualized) changes in the employment rate and population growth since this relationship is easily related to the theory. In particular, Proposition 2 points to the emergence of a positive association between changes in the employment rate and population growth over the course of the information revolution. In contrast, our model does not have an unambiguous prediction with respect to the behavior of the average wage. Recall that there are three elements that enter the average wage: the price of unskilled labor  $w$ ; the price of skill  $r_H$ ; and the average level of education  $h$ . Our theory predicts that, over the course of the information revolution, high population growth will be associated with less growth in  $w$  (possibly negative growth) and high growth in  $\frac{r_H}{w}$ . However, it does not yield clear predictions for cross-country patterns in changes in either  $r_H$ <sup>10</sup> or  $h$ . Nonetheless, we will assume that average wage growth is dominated by changes in the price of unskilled labor and examine—as if an implication of the theory—whether

<sup>6</sup>The countries are Australia, Austria, Belgium, Canada, Denmark, Finland, France, West Germany, Iceland, Italy, Japan, the Netherlands, New Zealand, Norway, Sweden, Switzerland, the United Kingdom, and the United States. These countries all had per capita GDP above 10,000\$U.S. in 1985.

<sup>7</sup>See Beaudry and Green (2001) for a detailed comparative analysis of changes in wages and employment structures for Germany, the U.S., and the UK.

<sup>8</sup>We measure the employment rate as the fraction of employed individuals among the population aged 15–65. The data are from the 1999 OECD Statistical Compendium, Annual Labor Force statistics.

<sup>9</sup>The data are from the 1999 OECD Economic Outlook. The OECD Economic Outlook directly reports real compensation per employee. When available, this is the measure we used. If it is not available, which is the case only in part of the pre-1975 sample, we constructed real compensation per employee by dividing total compensation by the number of employees and deflating by the GDP deflator. We checked the robustness of our results by considering alternative wage measures, such as hourly wages in manufacturing, and found that the results are robust to such changes. Note, though, that we had less scope to verify the robustness of our results for the period of 1960–1974.

<sup>10</sup>Note that the theory has an unambiguous prediction for  $\frac{r_H}{w}$ , but not for  $r_H$  alone.

TABLE I  
Cross-Country Estimate of Effect of Population Growth on Employment Rate

	Const. (s.e.)	Pop. growth (s.e.)	R <sup>2</sup>	No. obs.
1960–1974				
(1)	–0.001 (0.001)	0.074 (0.072)	0.062	18
1975–1997				
(2)	–0.001 (0.001)	0.286 (0.117)	0.272	18
(3), IV	–0.002 (0.001)	0.306 (0.130)	0.257	18
(4), IV	–0.002 (0.001)	0.280 (0.135)	0.229	17

*Note.* The dependent variable is the change in the employment rate over the period 1975–1997 (annualized), that is, the long difference in the ratios of the employed population to the total population 15 growth over the period 1975–1997. Population growth is the annualized percentage change in population 15–64.

In row 4, the U.S. observation is omitted from the sample.

high population growth economies have been particularly associated with low real wage growth since the mid-1970s. Clearly, it would be preferable to have a measure of the price of unskilled labor instead of average wages, but such a measure is not readily available for this set of 18 countries over a long period of time.<sup>11</sup>

Table I reports cross-sectional estimates of the effect of population growth on changes in the employment rate, where changes are calculated over the entire period of interest (a long difference) and then annualized. In row 1, we report an estimate for the period prior to the information revolution, that is, over the period from 1960 to 1974. The results in the table reveal no systematic relationship between population growth<sup>12</sup> and changes in the employment rate over this period. In row 2, we report the estimate of the same effect for the period 1975–1997; that is, we report the regression coefficient associated with regressing the (annualized) long difference in the employment rate between 1975 and 1997 on the (annualized) population growth rate over the same period. In contrast to row 1,

<sup>11</sup>For example, wage data for production workers in manufacturing, which could be argued to be a better proxy for the unskilled wage, are not available for all these countries over this period (they are only available for about half these countries and for shorter periods of time). Nonetheless, for the available subset of countries, we examined whether average wage growth was an unbiased predictor of wage growth for production workers in manufacturing. We found this to be the case and hence it supported our view that cross-country differences in average wage growth are likely dominated by changes in the price of unskilled labor.

<sup>12</sup>We use the growth of the population aged 15–64 as our measure of population growth.

in row 2 we now find a positive and significant relationship between population growth and the employment rate. Since positive employment rate changes may generate immigration and hence population growth, in row 3 we reestimate the relationship over the post-1974 period using the population growth over the 1960–1974 period as an instrument.<sup>13</sup> The estimate in row 3 is almost identical to that in row 2 and hence does not suggest that the observation is driven by reverse causality. Finally, in row 4 we omit the United States from the sample in order to show that the result is not driven by this observation alone. Together, we take the results of Table I as indicating that, over the period of the information revolution, there appears to have emerged a systematic and positive relationship between population growth and employment rate changes as predicted by our theory, and that such a relationship was not present in the earlier sample.

In Table II, we report estimates of the relationship between the percentage changes in real wages (measured as the real compensation per employee) and population growth. We again begin by examining the relationship over the 1960–1974 period. However, before we discuss these estimates, it is relevant to first recall what standard neoclassical growth theory suggests regarding this relation. There are two cases in our theory. In the simplest case, countries are on their balanced growth path. In that situation, the Solow growth model does not predict any systematic relationship between wage growth and population growth. In contrast, on the transitional path, the theory is consistent with a negative relationship between wage growth and population growth, but this coefficient should go to zero over time as convergence is achieved. Finally, in the case where transitional dynamics are thought to be important, the standard approach is to include initial GDP per capita as an additional regressor to capture the forces of convergence.

In row 1 of Table II, we report our cross-sectional estimates of the relationship between wage growth and population growth over the period 1960–1974, in the absence of any additional regressors.<sup>14</sup> In row 2 we add the 1960 level of per capita GDP (in log form) as an additional regressor.<sup>15</sup> The results reported in rows 1 and 2 are interesting in that they are very much in line with neoclassical growth theory. First, in row 1, we find a point estimate of the effect of population growth on wage growth of

<sup>13</sup>The  $R^2$  for the first-stage regression is 0.5.

<sup>14</sup>The OECD Statistical Compendium does not report sufficient employee compensation data for Iceland and hence it is omitted from our sample. Moreover, in the 1960–1974 period, the data for Finland, the Netherlands, and New Zealand were too incomplete to be included in the sample. Hence, over the early period, we only have 14 observations, while we have 17 observations over the 1975–1997 period.

<sup>15</sup>This variable is taken from Barro and Sala-i-Martin (1995).

TABLE II  
Cross-Country Estimate of the Effect of Population Growth on Wage Growth

	Const. (s.e.)	Pop. growth (s.e.)	GDP-60 (s.e.)	$\Delta$ Emp.rate (s.e.)	$R^2$	No. obs.
1960–1974						
(1)	0.035 (0.004)	-0.327 (0.290)	—	—	0.096	14
(2)	0.245 (0.050)	-0.149 (0.192)	-0.024 (0.006)	— —	0.653	14
1975–1997						
(3)	0.020 0.002	-1.01 (0.260)	—	—	0.520	17
(4)	0.071 (0.041)	-0.926 (0.273)	-0.006 (0.005)	—	0.569	17
(5), IV	0.021 0.002	-1.18 (0.266)	—	—	0.568	17
(6), IV	0.082 (0.036)	-1.06 (0.261)	-0.007 (0.005)	—	0.641	17
(7), IV	0.021 0.004	-1.17 (0.497)	—	—	0.317	14
(8), IV	0.023 (0.041)	-1.11 (0.273)	—	—	0.707	17
(9), IV	0.020 0.002	-0.990 (0.291)	—	-0.670 (0.494)	0.622	17

*Note.* The dependent variable is the growth in real compensation per worker over the entire period 1975–1997 (annualized). Row 7 is an exception, where the dependent variable is the percentage change in the hourly wage in manufacturing. Iceland was dropped from our earlier sample because of missing data.

Population growth is the annualized percentage change in population 15–64. When estimating by IV, population growth over the period 1960–1974 is used to instrument population growth over 1975–1997.

In rows 1 and 2, Finland, the Netherlands, and New Zealand are missing from the sample because of missing data.

In row 7, Denmark, Norway, and Switzerland were dropped from the sample because of missing data.

In row 8, a dummy variable for Anglo-Saxon countries and a dummy variable for Scandinavian countries were included in the regressions.

approximately 0.3. Although this coefficient is not statistically significant, it is of a size easily consistent with neoclassical growth theory. In row 2, we find a very significant effect of initial GDP on wage growth, but again find an insignificant effect of population growth. Our point estimate of catch-up is 2% per year which is remarkably similar to that found in the growth literature. Hence, we conclude that prior to the information revolution, the relationship between wage growth and population growth is

rather weak among industrialized countries even though there is evidence of transitional dynamics forces (convergence). Moreover, in the absence of structural change, neoclassical growth theory would suggest that in a subsequent period, the effect of population growth on wage growth should diminish (when not controlling for convergence) since the effects of convergence should be less important.

Rows 3 and 4 of Table II are the analogues to rows 1 and 2 for the period of the information revolution. As with the case of the employment rates, there appears to be a drastic change in the effects of population growth in the post-1974 period as compared to the pre-1975 period. In rows 3 and 4, our estimates of the effect of population growth on wage growth are now much greater in size, very significant, and independent of whether or not we include GDP per capita as additional regressors.<sup>16</sup> Moreover, we find that population growth actually explains an important fraction of the cross-sectional variance, and there is no longer strong evidence of catch-up.<sup>17</sup> In rows 5 and 6, we instrument population growth over the period 1975–1997 with population growth over 1960–1974. Again, we do not find evidence of simultaneity bias and, as is often the case with IV estimation, our point estimates are slightly increased (in absolute value) by this procedure. In row 7, we repeat the exercise using hourly wages in manufacturing as our wage measure instead of real compensation per employee. We only report the case where we estimate the univariate relationship by instrumental variables, since the other cases give very similar results. In all further cases, we focus only on the IV estimates.

Our finding of a strong negative association between population growth and wage growth over the 1975–1997 period is robust to several extensions. For example, we found this observation to always be robust to the exclusion of the United States from the sample. Furthermore, we found the relationship to be robust to the inclusion of a dummy variable for Anglo-Saxon countries (Australia, Canada, New Zealand, the United Kingdom, and the United States) and a dummy variable for Scandinavian countries (Denmark, Norway, and Sweden). In fact, as can be seen in row 8, where these two dummy variables are included, the addition of these dummies barely affects our point estimates. Finally, in row 9 we include the change in the employment rate as an additional regressor in order to see whether we are really only capturing an indirect effect of population growth, operating through employment rate effects. Interestingly we see that, consistent

<sup>16</sup>If we use the growth in hourly wages in manufacturing as our dependent variable, we again find an estimate of  $-1.08$  (s.e. 0.4) for the effect of population growth.

<sup>17</sup>If we exclude population growth, we find a significant effect of 1960 GDP per capital on wage growth (1% catch-up rate) but we do not find a significant effect if we use a more recent measure of GDP per capita.

with our theory, population growth has an effect on wage growth beyond that induced by a change in the employment rate. In summary, over the 1975–1997 period there appears to have emerged a sizable and systematic relationship between population growth and changes in wage and employment patterns. In particular, the 1975–1997 patterns are surprising given the observations over the 1960–1974 period and are therefore difficult to reconcile with a Solow-type growth model. However, such a change in pattern after 1975 is consistent with the type of structural transformation suggested by our model.

#### 4.2. *Patterns of Computer Adoption and Population Growth*

Until now, we have examined the implication of our model in terms of its predictions regarding co-movements between labor market outcomes and population growth. However, this is not the only means of evaluating the theory. An alternative is to look directly at patterns of capital accumulation and especially computer adoption. In particular, the theory suggests that, over the course of the information revolution, higher population growth countries should adopt computers more rapidly to move to a situation with a higher ratio of computer-based capital versus more traditional forms of capital. To explore this issue, we use the data on computer investment gathered by Caselli and Coleman (2001). We again focus our analysis on OECD countries, since we believe the theory applies to the group of countries which have access to the technological frontier.

The data on computer investment we use correspond to a constructed variable built as the sum of production plus imports minus exports of office computing and accounting machinery. This variable, which is in per-worker terms, is available for 15 OECD countries in 1990 and 13 OECD countries in 1985. We will refer to this variable simply as the rate of computer adoption per worker.<sup>18</sup> As a first pass at the data, we pool the 1985 and 1990 observations on computer adoption and regress it on the average rate of population growth between 1980 and 1990. The data on population are drawn from the World Penn Tables 6.0 and correspond to individuals aged between 15 and 64. The result of this exercise is reported in row 1 of Table III.<sup>19</sup> In row 2 of the table, we include additional regressors to control for the country's industrial mix. These regressors correspond to the share of total output in agriculture (*A*-share), manufacturing (*M*-share), and government (*G*-share). Finally, in row 3, we also include Caselli and Coleman's measure of human capital which corresponds to the fraction

<sup>18</sup>Caselli and Coleman refer to this variable as OCAM.

<sup>19</sup>Throughout the table, standard errors are corrected to allow for an arbitrary form of heteroscedasticity and a dummy year for 1990 is included.

TABLE III  
Cross-Country Estimate of the Effect of Population Growth on Computer Adoption

	Pop. gr. (s.e.)	A-share (s.e.)	M-share (s.e.)	G-share (s.e.)	Hum. cap. (s.e.)	R <sup>2</sup>	N
(1)	0.704 (0.318)					0.28	28
(2)	0.919 (0.179)	-0.126 (0.022)	0.099 (0.015)	0.054 (0.020)		0.79	28
(3)	0.619 (0.261)	-0.109 (0.028)	0.081 (0.019)	0.052 (0.026)	0.014 (0.007)	0.83	28
(4)	0.432 (0.208)					0.28	28
(5)	0.611 (0.146)	-0.105 (0.021)	0.060 (0.012)	0.043 (0.011)		0.73	28
(6)	0.442 (0.223)	-0.096 (0.024)	0.050 (0.019)	0.041 (0.024)	0.008 (0.007)	0.75	28

*Note.* The dependent variable in rows 1–3 is the log of computer-adoption-per-worker. The dependent variable in rows 4–6 is the ratio of computer capital to traditional capital as inferred by investment flows. All regressions were estimated with a constant and a time dummy for 1990. Standard errors are corrected for an arbitrary form of heteroscedasticity.

Population growth is the annualized percentage change in population 15–64 over the period 1980–1990.

The variables *A*-share, *M*-share, and *G*-share correspond to the fraction of output in agriculture, manufacturing, and government. The variable Hum. cap. corresponds to the fraction of the population with at least primary education.

of the population with at least a completed primary education.<sup>20</sup> As can be seen from these three sets of estimates, there is a positive relationship between rates of computer adoption and population growth among this sample of OECD countries. The relationship is especially apparent when we control for industrial mix and we also confirm Caselli and Coleman's finding of a positive relationship between human capital and computer adoption.

While the estimates presented in rows 1–3 of Table III provide interesting evidence in favor of the mechanism developed in the paper, it should be noted that the dependent variable is not tied in very closely with the theory. To evaluate the theory more directly, we require a measure of each country's likely steady-state ratio between computer capital and other types of capital, since it is this ratio that the theory predicts will be higher in countries with higher population growth. To construct a proxy for this ratio, we can use investment flow data for both computer capital and other types of capital and exploit the familiar relationship for a steady-state capital–output

<sup>20</sup>These results are also robust to including a dummy variable for Scandinavian countries and a dummy variable for Anglo-Saxon countries.

ratio given by  $\frac{K^j}{Y} = \frac{I^j}{\delta^j + \eta + g}$ , where  $I^j$  is the investment rate in either computer or noncomputer capital,  $\delta^j$  is the (annual) depreciation rate of each asset type,  $g$  is the growth in labor augmenting technological progress, and  $\eta$  is the rate of population growth.<sup>21</sup> The ratio of the computer and noncomputer capital–output ratios then provides an estimate of a country’s steady-state ratio of computer capital to traditional capital. To calculate this ratio, we need to choose values for  $\delta$  and  $g$ . Our approach was to follow much of the growth literature and set  $g$  to 2%, the depreciation rate for traditional capital at 3%, and, based on the work by Jorgenson and Stiroh (1999), the depreciation of computer capital at 20%.

In rows 4–6 of Table III, we regress our (constructed) measure of the ratio of computer capital to physical capital on population growth and a set of control variables. The results in these rows mimic quite closely those observed in rows 1–3. In particular, in the absence of controls, the effect of population growth on computer capital is positive and it remains so even after we control for industrial mix and human capital. Although these results provide interesting support for the theory, a note of caution about the data is in order. In conducting this exercise, we used noisy investment data to infer a steady-state value for a capital ratio. Obviously, such an endeavor is pushing the data to its limits and we recognize this. Nonetheless, the fact that a positive relationship between population growth and this very imperfect proxy for the ratio of computer capital to traditional capital is in itself surprising enough to be worth reporting.

## 5. CONCLUSION

In this paper, we have illustrated how differences in population growth may offer a rather simple unified explanation for certain cross-country differences in recent economic performance. In particular, we have shown theoretically how population growth can accelerate the process of adoption of a new technology and thereby lead high population growth countries to exhibit a more profound change in economic outcomes during the information revolution. Our model offers an explanation for why high population growth economies, such as that of the U.S., appear particularly technologically dynamic in the recent era—especially in comparison to their relative performance in the 1970s—both in terms of the adoption of computers and the adoption of new forms of work organization. Furthermore, since we view this process of technological adoption as endogenous

<sup>21</sup>For this exercise, we use the data on computer adoption and general investment rate from Caselli and Coleman (2001).

and hence of variable speed across countries, it offers an explanation for cross-country differences in wage outcomes as well as the growth of the service sector. We have also provided some empirical evidence in support of the theory. Obviously, there are important aspects of cross-country differences in economic performance that our model has not addressed and there are good reasons to believe that other forces, such as institutions and globalization, may play a role in determining these economic outcomes. Nonetheless, we believe that the theory presented here, and the associated empirical evidence, suggests that differences in population growth may be a—generally neglected—ingredient for understanding cross-country differences in recent economic performance among advanced industrial countries.

## APPENDIX A

In this appendix, we focus on the proof of Proposition 1. The proof of Proposition 2 is almost identical and therefore is omitted here but available in Beaudry and Green (2001). To prove Proposition 1 we proceed as follows. We first begin by presenting the set of equations which characterize the Walrasian equilibrium when the two technologies  $F^O(\cdot)$  and  $F^M(\cdot)$  are in use. Recall that we are assuming the modern technology is sufficiently efficient for it to be adopted in both the pre- and post-information-revolution eras. Moreover, since we are assuming that the modern technology is skill intensive ( $\lambda > 1$ ) and that it does not use unskilled labor, it will necessarily be the case that the old technology always remains in use. Hence, it is appropriate to focus only on cases where both technologies are in use. After presenting this set of equations, we will state an intermediary lemma (Lemma X1). Lemma X1 will highlight certain general features of the Walrasian equilibrium in our setting, that is, features that do not rely on the particular parameterization of technology given in (1) and (2). Once we have proven Lemma X1, the proof of Proposition 1 is rather straightforward.

### *The Walrasian Equilibrium Conditions*

To present the equilibrium conditions explicitly, it is useful to work with unit cost functions instead of production functions. To this end, let  $C^O(w, r_H, r_K)$  and  $C^M(r_H, r_{IT})$  represent the unit cost functions associated with respectively the old and modern processes of production. Moreover, let  $Y^O$  and  $Y^M$  represent the amount of the final good produced using the old and modern forms of production. At this point, we do not impose particular function forms on the cost functions (they need only

be cost functions associated with CRS-convex technologies). Consider the following set of 13 equations in the 13 variables  $\{w_t, r_{H,t}, r_{K,t}, r_{IT,t}, r_t\}$  and  $\{L_t, H_t, K_t, IT_t, Y_t^O, Y_t^M, h_t, B_t\}$ .

$$L_t = (1 + \eta)^t \quad (\text{A1})$$

$$H_t = h_t(1 + \eta)^t \quad (\text{A2})$$

$$Q'(h_t) = r_{H,t} \quad (\text{A3})$$

$$B_{t+1} = (1 + r_{t+1}) \left( \frac{1}{\beta^{\frac{-1}{\sigma}} \left( \frac{1+r_{t+1}}{\sigma} \right)^{\frac{1-\sigma}{\sigma}} + 1} \right) \times \left( w_t + hr_{H,t} - Q(h) + \frac{B_t}{(1 + \eta)} \right) \quad (\text{A4})$$

$$K_t + \frac{IT_t}{\theta} = \frac{B_t(1 + \eta)^{t-1}}{(1 + r_t)} \quad (\text{A5})$$

$$r_{k,t} = \theta_t r_{IT,t} = 1 + r_t \quad (\text{A6}), (\text{A7})$$

$$L_t = C_1^O(w_t, r_{H,t}, r_{K,t}) Y_t^O \quad (\text{A8})$$

$$H_t = C_2^O(w_t, r_{H,t}, r_{K,t}) Y_t^O + C_1^M(r_{H,t}, r_{IT,t}) Y_t^M \quad (\text{A9})$$

$$K_t = C_3^O(w_t, r_{H,t}, r_{K,t}) Y_t^O \quad (\text{A10})$$

$$IT_t = C_2^M(r_{H,t}, r_{IT,t}) Y_t^M \quad (\text{A11})$$

$$C^O(w_t, r_{H,t}, r_{K,t}) = 1 \quad (\text{A12})$$

$$C^M(r_{H,t}, r_{IT,t}) = 1. \quad (\text{A13})$$

Equations (A1)–(A5) give the supply of factors by households, Eqs. (A8)–(A13) give the demand of factors by firms, and Eqs. (A6) and (A7) are the no-arbitrage conditions on the capital markets. Note that in the above equations, a subscript on the cost function represents the derivative with respect to the  $n$ th argument.

Since we will focus only the steady state, it is possible to simplify the above system into the following set of seven equations in seven variables  $\{w, r_H, \tilde{r}\}$  and  $\{\tilde{k}, \tilde{Y}^O, \tilde{Y}^M, h\}$ .

$$Q'(h) = r_H \quad (\text{A1}')$$

$$\tilde{k} = \frac{s}{(1 + \eta)} (w + hr_H - Q(h) + \tilde{k}\tilde{r}) \quad s = \frac{1}{\beta^{\frac{-1}{\sigma}} \left( \tilde{r} \right)^{\frac{1-\sigma}{\sigma}} + 1} \quad (\text{A2}')$$

$$1 = C_1^O(w, r_H, \tilde{r}) \tilde{Y}^O \quad (\text{A3}')$$

$$h = C_2^O(w, r_H, \tilde{r})\tilde{Y}^O + C_1^M\left(r_H, \frac{\tilde{r}}{\theta}\right)\tilde{Y}^M \tag{A4'}$$

$$\tilde{k} = C_3^O(w, r_H, \tilde{r})\tilde{Y}^O + \frac{C_2^M(r_H, \frac{\tilde{r}}{\theta})}{\theta}\tilde{Y}_t^M \tag{A5'}$$

$$C^O(w, r_H, \tilde{r}) = 1 \tag{A6'}$$

$$C^M\left(r_H, \frac{\tilde{r}}{\theta}\right) = 1, \tag{A7'}$$

where  $\tilde{r} = r_K = r_{IT}\theta$ ,  $\tilde{k} = \frac{K + \frac{IT}{\theta}}{(1+\eta)^t}$  is the per capita total capital stock,  $\tilde{Y}^O = \frac{Y^O}{(1+\eta)^t}$  is the per capita production of output using the old technology, and  $\tilde{Y}^M = \frac{Y^M}{(1+\eta)^t}$  is the per capita production of output using the modern technology.

This modified system of equations, where quantities are all expressed in per capita terms, represents the two accumulation equations for human and physical capital and the factor market clearing conditions. Note that traditional and computer-based capital can be aggregated into one variable  $\tilde{k}$  using the relative price  $\frac{1}{\theta}$ .

We are now in a position to ask how population growth affects the steady-state wage and output structure in this economy. A partial answer to this question is given by Lemma X1.

LEMMA X1.

$$(1) \quad \frac{\partial w}{\partial \eta} > 0 \text{ iff } \frac{C_2^M(r_H, \frac{\tilde{r}}{\theta})}{C_3^O(w, r_H, \tilde{r})} > \frac{C_1^M(r_H, \frac{\tilde{r}}{\theta})}{C_2^O(w, r_H, \tilde{r})} \text{ and } \frac{\partial r_H}{\partial \eta} < 0 \text{ if and only if } \frac{C_2^M(r_H, \frac{\tilde{r}}{\theta})}{C_3^O(w, r_H, \tilde{r})} > 1.$$

$$(2) \quad \frac{\partial \tilde{Y}^M}{\partial \eta} < 0 \text{ if } \frac{C_2^M(r_H, \frac{\tilde{r}}{\theta})}{C_3^O(w, r_H, \tilde{r})} > \frac{C_1^M(r_H, \frac{\tilde{r}}{\theta})}{C_2^O(w, r_H, \tilde{r})} \text{ and } \frac{\partial \tilde{Y}^O}{\partial \eta} < 0 \text{ if } \frac{C_2^M(r_H, \frac{\tilde{r}}{\theta})}{C_3^O(w, r_H, \tilde{r})} < \frac{C_1^M(r_H, \frac{\tilde{r}}{\theta})}{C_2^O(w, r_H, \tilde{r})}.$$

*Proof of Lemma X1.* The characterization given in Lemma X1 can be found by totally differentiating the system of Eqs. (A1') to (A7').

The interesting aspect of Lemma X1 is that it shows that the effects of population growth depend on the relative factor intensities of the two underlying production technologies. Hence, from Lemma X1 and our assumption that initially (before the information revolution) the relative capital intensity of the modern technology versus the old technology is greater than the skill intensity, which stated formally is equivalent to

assuming that  $\theta$  is low enough for

$$\frac{C_2^M(r_H, \bar{r})}{C_2^O(w, r_H, \bar{r})} > \frac{C_1^M(r_H, \bar{r})}{C_2^O(w, r_H, \bar{r})},$$

all we need to show to prove Proposition 1 is whether, for a sufficiently large increase in  $\theta$  (starting from  $\theta_0$ ), there will necessarily be a reversal in factor intensities in the sense that for sufficiently high values of  $\theta$ ,

$$\frac{C_2^M(r_H, \bar{r})}{C_2^O(w, r_H, \bar{r})} < \frac{C_1^M(r_H, \bar{r})}{C_2^O(w, r_H, \bar{r})} \quad \text{and} \quad \frac{C_1^M(r_H, \bar{r})}{C_2^O(w, r_H, \bar{r})} < 1.$$

This is shown below using the parameterization of technology given by Eqs. (1) and (2). In effect, given that  $\lambda < 1$  and that  $\frac{C_1^M}{C_2^O} = \frac{1}{\lambda}$ , we need only focus on showing

$$\frac{C_1^M(r_H, \bar{r})}{C_2^O(w, r_H, \bar{r})} < 1.$$

To show the existence of this  $\theta^*$ , it is useful to begin by stating Eqs. (A3') to (A7') explicitly for the case at hand (Eqs. (A1') and (A2') remain unchanged).

$$1 = \left(\frac{\bar{r}}{w}\right)^{0.5} \tilde{Y}^O \quad (\text{A3}'')$$

$$h = \tilde{Y}^O + \frac{\tilde{Y}^M}{\lambda} \quad (\text{A4}'')$$

$$\tilde{K} = \left(\frac{w}{\bar{r}}\right)^{0.5} \tilde{Y}^O + \frac{\tilde{Y}_t^M}{\theta} \quad (\text{A5}'')$$

$$2u^{0.5}\bar{r}^{0.5} + r_H = 1 \quad (\text{A6}'')$$

$$\frac{\bar{r}}{\theta} + \frac{r_H}{\lambda} = 1. \quad (\text{A7}'')$$

Although the entire solution to this system of equations cannot be stated explicitly, the nonexplicit component can be reduced to a system of two equations in the two unknowns  $h, \tilde{k}$ <sup>22</sup>

$$Q'(h) = \lambda \left( 1 - \frac{1 - \lambda}{2\theta \left( \frac{\lambda^2}{4\theta^2} + \tilde{k} - \frac{\lambda h}{\theta} \right)^{0.5}} \right)$$

$$\tilde{k} = \left( \frac{1}{\beta^{\frac{1}{\sigma}} \left( \frac{\bar{r}}{\theta} \right)^{\frac{1-\sigma}{\sigma}} + 1} \right) \left( \lambda h + \frac{(1-\lambda)\lambda}{2\theta} + (1-\lambda) \left( \frac{\lambda^2}{4\theta^2} + \tilde{k} - \frac{\lambda h}{\theta} \right)^{0.5} - Q(h) \right),$$

<sup>22</sup>In the case where  $\sigma = 1$  and therefore the savings rate is constant, we can solve explicitly for  $k$  since it is the solution to a quadratic equation. In this case, solving our initial system of 13 equations is reduced to solving one nonlinear equation in the one unknown  $h$ .

where  $\tilde{r}$  and  $w$  are explicitly given by

$$\tilde{r} = \frac{1 - \lambda}{2\left(\frac{\lambda^2}{4\theta^2} + \tilde{k} - \frac{\lambda h}{\theta}\right)^{0.5}}$$

$$w = \left(\frac{1 - \lambda}{2\tilde{r}} + \frac{\lambda}{2\theta}\right)^2 \tilde{r}.$$

Let us now focus on showing that, for  $\theta$ 's sufficiently large,

$$\frac{C_2^M(r_H, \frac{\tilde{r}}{\theta})}{C_3^O(w, r_H, \tilde{r})} < 1.$$

Note that this condition corresponds (for our parameterization of the cost functions) to showing that for  $\theta$ 's sufficiently large,

$$\frac{1}{\theta\left(\frac{w}{\tilde{r}}\right)^{0.5}} < 1.$$

To see that the above condition will be satisfied when  $\theta$  is sufficiently large, consider the limit of the LHS of this expression as  $\theta$  goes to infinity. Using the solutions for  $w$  and  $\tilde{r}$ , it is easy to verify that this limit take the following simple form,  $\frac{1}{\theta\tilde{k}}$ . Therefore, unless  $\tilde{k}$  goes to zero as  $\theta$  goes to infinity, the above limit will go to zero as  $\theta$  goes to infinity and hence for  $\theta$  sufficiently large it will necessarily be the case that

$$\frac{1}{\theta\left(\frac{w}{\tilde{r}}\right)^{0.5}} < 1.$$

To see that  $\tilde{k}$  does not go to zero as  $\theta$  goes to infinity, note that  $h$  will converge to  $\bar{h}$  defined by  $Q'(\bar{h}) = \lambda$ , and that the accumulation equation for  $\tilde{k}$  will become

$$\tilde{k} = \frac{s(\tilde{k})}{1 + \eta} ((Q'(\bar{h})\bar{h} - Q(\bar{h}) + (1 - \lambda)\tilde{k}^{0.5}),$$

where

$$s(\tilde{k}) = 1 - \frac{1}{\beta^{\frac{1}{\sigma}} \left(\frac{1-\lambda}{2\tilde{k}^{0.5}}\right)^{\frac{1-\sigma}{\sigma}} + 1}.$$

Since  $h$  is optimality chosen, it is necessarily the case that  $Q'(\bar{h})\bar{h} - Q(\bar{h}) > 0$ . Therefore, given that the above limit accumulation equation for  $\tilde{k}$  is a rather standard and well-behaved accumulation equation, it is straightforward to verify that  $\tilde{k}$  will remain strictly above zero as  $\theta$  goes to infinity. Hence, this proves that there exists a  $\theta^*$  such that if  $\theta > \theta^*$ , by Lemma X1 we have,  $\frac{\partial w}{\partial \eta} < 0$ ,  $\frac{\partial \frac{r_H}{w}}{\partial \eta} > 0$ ,  $\frac{\partial \tilde{Y}^O}{\partial \eta} < 0$ ,  $\frac{\partial \tilde{r}}{\partial \eta} < 0$ ,  $\frac{\partial r_H}{\partial \eta} > 0$  as stated in Lemma 2A. ■

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