The Role of Knowledge and Capital in Economic Growth

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1. Introduction

During the last fifteen years the study of the forces that shape the rate of economic growth became one of the most active areas of research in economics.[1] On the theoretical front researchers produced a variety of models in which sustained growth can take place in the absence of exogenous growth in productivity. On the empirical front there was an intense search for variables that correlate with growth performance in variants of the Summers and Heston (1991) data set.[2] Why did so many macroeconomists suddenly divert their efforts from the study of business cycles to the quest for a better understanding of the growth process? Lucas (1987) provided a rationale for this reallocation of research effort. He confronted an agent with preferences that are standard in macro models with the question of how much consumption he would be willing to give up to eliminate the fluctuations in his consumption associated with business cycles. The answer was–very little, suggesting that the welfare cost of business fluctuations is very

[1] Four recent textbooks provide an excellent comprehensive view of this large literature. Barro and Sala-i-Martin (1995) survey the literature taking the neoclassical growth model as their point of departure. Aghion and Howitt (1998) emphasize models in the Schumpeterian tradition where creative destruction plays an important role. Grossman and Helpman (1991b) explore the implications of models with endogenous technical progress for trade issues. Jones (1998) is a good non-technical introduction to the literature.

[2] See Barro (1997) for a summary of these empirical findings.

small.[3] In contrast this hypothetical agent would be willing to forego a significant fraction of his consumption to live in an economy which expands at a faster rate. Lucas's welfare calculation suggested that there is much more to be gained from understanding the determinants of the growth process than from fine tuning our understanding of what drives economic fluctuations. But it also reminds us that increasing the growth rate of the economy does not necessarily increase welfare– higher growth rates can often be achieved only at the cost of lower consumption in the present and so a trade-off has to be made.

This paper provides an informal discussion of growth models and their evolution. Section 2 reviews the neoclassical growth model. Section 3 discusses models that broadened the notion of capital to include human capital and the state of technology. Section 4 discusses models of endogenous technological progress. Section 5 concludes.

[3] Lucas's (1987) calculation has been criticized for being appropriate only in a world of complete markets. The costs of business cycles could potentially be higher if there are idiosyncratic shocks that the agents cannot insure against. Recent work suggests that Lucas's calculation is likely to hold up as well in incomplete markets environments. In fact Gomes, Greenwood and Rebelo (1998) find that the costs of business cycles in a version of the neoclassical model with incomplete markets and unemployment associated with search is actually negative.

2. The Neoclassical Growth Model

To set the stage for discussing recent theoretical developments it is useful to start with Solow's (1956) celebrated neoclassical growth model. Later we will discuss new ideas in growth theory in a context that keeps as many attributes of the Solow model as possible. In this model there is a single good whose production (Y_t) involves the use of labor (N) and capital (K_t) according to a production function that exhibits constant returns to scale and some additional regularity conditions. For exposition purposes we will use the familiar Cobb-Douglas production function and assume that the supply of labor is constant:

$$Y_t = AK_t^{1-\alpha}(NX_t)^{\alpha}. \tag{2.1}$$

The variable X_t denotes technical progress which is assumed to expand at a constant, exogenous rate:

$$X_{t+1} = \gamma X_t.$$

Output can be consumed (C_t) or invested (I_t):

$$Y_t = C_t + I_t.$$

Capital evolves according to:

$$K_{t+1} = I_t + (1 - \delta)K_t$$

To complete the model we must specify how agents choose between investment and consumption. It is natural to model this choice as involving the maximization of a utility function defined over the path for consumption. However, since we will focus throughout this paper on how to make sustained growth feasible, it will be sufficient to assume, as in Solow (1957), that a constant fraction of output is devoted to investment:[4]

$$I_t = sY_t.$$

These equations can be combined to describe how the stock of capital evolves

[4] Sato (1963) and Sato (1966) showed that the transition dynamics of the Solow model are very sensitive to the form of this investment function. This exposed the weakness associated with the choice of investment rules not grounded on optimization.

over time:

$$K_{t+1} = sAK_t^{1-\alpha}(NX_t)^\alpha + (1-\delta)K_t.$$

If we define $k_t = K_t/X_t$ we can re-write this expression as:

$$\gamma k_{t+1} = sAk_t^{1-\alpha}N^\alpha + (1-\delta)k_t. \tag{2.2}$$

This equation readily implies that the model has a steady state in which k is constant. In this steady state the level of capital K grows at a constant rate γ. This trend in the capital stock is inherited by output, consumption and investment. All these variables grow at rate γ in the steady state.[5]

Suppose we want to use the steady state of the neoclassical growth model to understand why the post-war average growth rate of GDP has been much higher in Japan than in the U.S. In the steady state output grows at rate γ so the only way to explain Japan's higher growth rate is to assume that γ is higher in Japan than in the U.S. This is not a satisfactory explanation since γ is exogenous to the

[5] This steady state provides a good description of the evolution of the aggregate U.S. economy during the last one hundred years. While this period features smooth growth at the aggregate level it also display considerable structural change, which includes a large reallocation of employment from agriculture to services. Kongsamut, Rebelo and Xie (1997) discuss how the neoclassical growth model can be extended to encompass these reallocation dynamics.

model.

An alternative rationalization for the faster Japanese growth rate comes from the model's transition dynamics. Equation (2.2) implies that the capital stock grows faster when k is below the steady state. And more rapid growth in k readily translates into faster output growth. This means that in the eyes of the model growth could be higher in Japan than in the U.S. because Japan's capital stock is below its steady state path, while the U.S. is already in the steady state. This explanation seems sensible and is acceptable if we disregard its implications for the behavior of the real interest rate. The real interest rate (r) is the return to an additional unit of capital net of depreciation:

$$r_t = (1-\alpha)Ak_t^{-\alpha}N^{\alpha} - \delta. \tag{2.3}$$

As an economy converges to the steady state the interest rate falls. If we assume that the production function is the same in Japan and in the U.S. so that the only difference between the two countries is the lower level of capital in Japan we can quickly compare the real interest rate in both countries. The level of GDP in Japan in 1950 was 5 times smaller that the U.S. Using the production function (2.1) and assuming, to simplify, that N is the same in both countries we can compute the relation between the value of the capital stock in the two countries:

$$\begin{aligned} \frac{Y_{US}}{Y_{Japan}} &= 5 = \frac{K_{US}^{1-\alpha}}{K_{Japan}^{1-\alpha}}, \\ K_{US} &= K_{Japan} 5^{1/(1-\alpha)}. \end{aligned} \tag{2.4}$$

Using (2.3) and (2.4) it is easy to derive the following relation between the real interest rates in the two countries:

$$r_{Japan} = (r_{US} + \delta) 5^{\alpha/(1-\alpha)} - \delta \tag{2.5}$$

Suppose that we measure the real interest rate in the U.S. by the average real rate of return in the stock market, which is roughly 6.5% (Siegel (1992)) and use conventional values for the labor share ($\alpha = 2/3$) and the depreciation rate ($\delta = .10$). Equation (2.5) then implies that the real interest rate in Japan in the 1950's should have been 400%, which is a totally implausible number. This problem with the behavior of the real interest rate along the transition to the steady state extends to the most commonly used versions of the neoclassical growth model (see Christiano (1989) and King and Rebelo (1993)). In order for transition dynamics to be important the capital stock has to be far away from the steady state but, when this is the case, the real interest rate becomes much higher than the steady state real interest rate.

One may argue that the real interest rate comparison we just described makes no sense because it assumes that Japan in 1950 had the same production technology as the U.S. However, this suggests that to understand growth it is important to think about how technology is developed and adopted by different countries.

There are two routes that have been followed to improve upon the neoclassical growth model. The first is to think of K as representing more than physical capital. If K represents a broader notion of capital, the value of α can be much lower than 2/3. This allows transition dynamics to play a role without generating counterfactual implications for the behavior of the real interest rate. The second route that has been adopted is to make technical progress, the mysterious X variable, endogenous. We now discuss in turn these two approaches.

3. Redefining Capital

3.1. Externalities

The first paper in the recent wave of work on economic growth was Romer (1986). In this paper Romer argued that one could reinterpret K as representing a combination of physical capital and of the outcome of investment in R&D. Thus K would include not only buildings and machines but also blueprints and ideas for how to produce new goods. Some of these forms of capital generate externalities– a firm can learn how to build a new product or improve its production process by observing the activities of other firms. These externalities must be one of the forces underlying certain industry agglomerates such as Silicon Valley, so not surprisingly they play an important role in recent research on economic geography (Krugman (1991)). Romer (1986) proposed the following description of the production process for an individual firm:

$$Y_t = AK_t^{1-\alpha} N^{\alpha} \mathbf{K}_t^{\beta}. \tag{3.1}$$

Here $\mathbf{K}$ represents the aggregate stock of capital. Since firms are small in this economy they take the aggregate capital stock as given. Even though in the aggregate there are increasing returns to capital, each individual firm faces constant returns and hence this formulation is compatible with a competitive equilibrium. Note that the production function does not feature exogenous technical progress, so why is growth feasible? Sustained growth is feasible when $1 - \alpha + \beta \geq 1$, that is, when the externality is strong enough to compensate the presence of decreasing returns to capital at the firm level. To see this assume that there are n identical firms. The aggregate capital stock is given by: $\mathbf{K}_t = nK_t$. If the economy saves a constant fraction of the output s, as in the original Solow model, the growth rate of the capita stock is:

$$\frac{K_{t+1}}{K_t} - 1 = sAK_t^{-\alpha+\beta} N^{\alpha} n^{\beta} - \delta.$$

When $1 - \alpha + \beta > 1$ a constant savings rate would yield an accelerating rate of growth. This tendency for the rate of growth to increase has to be very small, and hence hard to detect, to be consistent with the historical data that we have available. For this reason many researchers have focused in the knife-edge case in which $1 - \alpha + \beta = 1$. This parameter configuration is compatible with a steady state because when the savings rate is constant the growth rate of capital and output are also constant.

Early empirical evidence for U.S. manufacturing (Caballero and Lyons (1992)) seemed to support the type of external effect embodied in (3.1), but more recent work which uses better measures of capital services in estimating production functions (Burnside (1996)) finds no evidence of these externalities. Perhaps this is not surprising since the capital stock used in these empirical studies measures physical capital and thus excludes the R&D components with which Romer associated external effects.

This first attempt at dispensing with exogenous technical progress is very reduced form in nature–the capital stock is a mongrel variable which comprises many types of activities, and externalities have to be large to make sustained growth feasible.

3.2. Human Capital

Lucas (1988) proposed a different redefinition of capital that also allows growth to proceed without exogenous technical progress. A simplified, one-sector version of Lucas's (1988) model, discussed in Easterly (1993), can be written as follows:[6]

$$Y_t = BK_t^{1-\alpha}(NH_t)^{\alpha}$$

Here H_t represents the level of human capital of the representative agent in the economy. Suppose that human capital can be accumulated in the same manner as physical capital by foregoing one unit of output:

[6] Lucas's (1988) model has a two sector structure with the first sector producing physical capital and the second human capital. See Mulligan and Sala-i-Martin (1993), Caballe and Santos (1993) and Bond, Wang, and Yip (1996) for a discussion of the transition dynamics of this model.

$$\begin{aligned} Y_t &= C_t + I_t \\ I_t &= I_t^k + I_t^h \end{aligned}$$

$$\begin{aligned} K_{t+1} &= I_t^k + (1-\delta)K_t \\ H_{t+1} &= I_t^h + (1-\delta)H_t \end{aligned}$$

Since the cost of accumulating one unit of human capital is the same as that of accumulating one unit of physical capital, an efficient accumulation plan dictates that in the steady state the marginal products of K and H must be identical:

$$(1-\alpha)BK_t^{-\alpha}(NH_t)^{\alpha} = \alpha BK_t^{1-\alpha}(NH_t)^{\alpha-1}N$$

This implies that the ratio of physical to human capital is: $K_t/H_t = (1-\alpha)/\alpha$. Using this fact the production function can be re-written as:

$$Y_t = AK_t$$

where the new constant $A = B(\frac{\alpha}{1-\alpha})^{\alpha} N^{\alpha}$. This "AK" model became widely used, partly because it is a simple device to transform what are level effects in the neoclassical growth model into growth effects. To see this suppose, as in the Solow model, that a constant fraction of output, s, is devoted to total investment, I_t. To keep the K/H ratio constant the economy needs to devote a fraction $(1-\alpha)$ of total investment to the accumulation of physical capital. This means that the steady state growth rate of output, which coincides with the growth rate of physical capital is given by:

$$\frac{Y_{t+1}}{Y_t} = \frac{K_{t+1}}{K_t} = (1-\alpha)sA + (1-\delta). \tag{3.2}$$

While in the Solow model a change in s produces level effects in the steady state, here it generates growth effects. Economic policies can affect the rate of growth either by affecting the savings rate, s or by affecting the value of A that is relevant for the accumulation of capital by private agents, say by introducing income taxes. Jones and Manuelli (1990) and Rebelo (1991) worked on uncovering the set of assumptions that generate models of this AK variety, where unceasing growth can take place without exogenous increases in productivity or Romer (1986) type externalities. Jones and Manuelli (1990) stressed that sustained growth is compatible with a role for non-reproducible factors provided the importance of these factors shrink as the economy grows. Rebelo (1991) studied multi-sector models and stressed that the assumption that there is a set of capital goods that can be produced without non-reproducible factors (such as land), together with some regularity conditions, leads to models of the AK form. This emphasis on factors that can be accumulated contrasts with a traditional view of the growth process that assigns an important role to natural resources. But recent empirical evidence by Sachs and Werner (1995) suggests that, if anything, high stocks of natural resources seem to correlate with lower rates of economic expansion.

There are two problems with this class of models that redefines the concept of capital. The first problem is a descriptive one: in the model growth takes place because workers become more and more productive over time in a way that does not interact with the invention of new technologies. The second problem is empirical. Models of the AK variety imply that certain policies should have large effects on the rate of economic growth. In particular, income taxes should be important growth determinants: these taxes reduce the A that is relevant for capital accumulation and, in an optimizing model, generally imply a permanent growth slow down. These growth effects are however difficult to detect in cross section data (Easterly and Rebelo (1993)). The U.S. experience also casts some doubts on the presence of growth effects of taxation: income taxes suffered a significant, permanent increase in the end of the Second World War, but it is hard to detect any corresponding slowdown of the growth process (Stokey and Rebelo (1995)). Jones (1995) searches more broadly for growth effects of different policies and fails to find them. Easterly et al (1993) stress a similar result–policies are fairly persistent across decades but growth is not. Despite problems associated with measurement error and short samples this evidence as a whole casts serious doubts on the growth effects that a simple AK model tends to generate.[7]

Partly in reaction to these problems, some of the growth literature adopted models that are in between the original Solow model and the AK model. Barro and Sala-i-Martin (1992), Mankiw, Romer and Weil (1992) and, more recently, Chari, McGratten and Kehoe (1995) have proposed production functions of the form:

$$Y_t = BK_t^{1-\alpha} N^{\alpha},$$

where K represents a broader notion of capital that encompasses human capital,

[7] Measures of financial intermediation seem to be one of the few policy-related variables that are correlated in a robust manner with the growth process (Levine and Renelt (1992) and King and Levine (1993)).

and N stands for raw labor. Under this interpretation it may be reasonable to choose a low value for α, perhaps in the 0.1 to 0.2 range. This means that the capital share is high enough to avoid the implausible implications for real interest rate behavior discussed in Section 2. If returns to capital are close to one we will not observe substantial movements in real interest rates along a transition path. Also the model now allows for protracted transitional growth effects. At the same time, the presence of decreasing returns to capital means that there are no permanent growth effects.

An influential empirical study that revived the use of the neoclassical model to understand the growth process was Alwyn Young's (1992,1995) measurement of productivity growth in the fastest growing countries in the world, the so-called Asian tigers–Singapore, Taiwan, Hong Kong and South Korea. Young went back to a production function such as (2.1) and asked the question–how important is productivity growth X_t in accounting for the growth of the Asian tigers? He found that productivity growth was not very important and that most output growth in these countries represented massive increases in factors of production, labor and capital.[8] From a policy standpoint Young's findings greatly reduced confidence in the idea that the Asian tigers had grown fast because they had followed shrewd

[8] See Hsieh (1997) for a recent reassessment of Young's (1992,1995) findings.

industrial policies that had targeted industries where productivity growth was high.

4. A Theory of X

We just reviewed different ways of redefining the role of capital in the conventional neoclassical model. But none of these re-definitions provided us with a theory of technological progress. These models do not allow us to think of firms as undertaking investments aimed at producing new products and production methods. At first sight it seems trivial to make technological progress, X_t in equation endogenous. Why don't we simply add a production function for X_t, that is, assume that productivity can be increased by devoting resources to this endeavour? The problem with this approach, tried for instance in Uzawa (1965), is that when the production function takes a constant returns to scale form as in (2.1) it is not possible to reward the factor X in a competitive equilibrium. To see this consider a firm that produces output by hiring labor and capital in competitive spot markets. Optimal hiring decisions for this firm are dictated by the familiar equations:

$$(1-\alpha)AK^{-\alpha}(NX)^{\alpha} = R$$

$$\alpha A K^{1-\alpha}(NX)^{\alpha-1}X_t \quad = \quad w$$

where R denote the real rental price of capital and w the real wage rate. Note that because the production function is homogeneous of degree one,

$$wN + RK = Y$$

which means that after paying for labor and capital there is nothing leftover to reward factor X. We have already seen one solution to this problem proposed by Lucas (1988) which is to re-interpret X as human capital.

4.1. Expanding Variety

Many types of innovation involve substantial effort in the development of blueprints that, once produced, can be costlessly used to guide the manufacturing process for new goods. Firms will not be willing to pay for these fixed costs associated with product development if the production of the new good will take place in a competitive environment where economic profits will be zero. To deal with this problem Romer (1990) proposed a theory of endogenous technical progress that uses the Dixit and Stiglitz (1977) model of monopolistic competition. Firms pay a fixed cost to produce a new good but then receive a permanent monopoly in the good that they create. To simplify the exposition we will continue to study an economy that devotes a fixed fraction of resources to investment, which takes the form of the discovery and introduction of new goods. Output is produced by combining labor with n_t differentiated intermediate goods, which we represent by $x_t(i)$:

$$Y_t = A\left[\int_0^{n_t} x_t(i)^{1-\alpha}di\right]N^{\alpha}. \tag{4.1}$$

Note that this production function exhibits constant returns to scale in labor and in the intermediate goods $x(i)$. Output producers maximize:

$$A\left[\int_0^{n_t} x_t(i)^{1-\alpha}di\right]N^{\alpha} - \int_0^{n_t} p_t(i)x_t(i)di - wN.$$

where $p_t(i)$ represents the price of intermediate good i and w is the real wage, all measured in units of output. The optimal solution to this problem is given by:

$$\begin{aligned}(1-\alpha)Ax_t(i)^{-\alpha}N^{\alpha} &= p_t(i), &(4.2)\\ \alpha A\left[\int_0^{n_t} x(i)_t^{1-\alpha}di\right]N^{\alpha-1} &= w. &(4.3)\end{aligned}$$

The first of these equations describes the demand for intermediate good i. Suppose that you have been granted monopoly rights over the production of this good. What is the level of supply that maximizes your profits? Assuming that each unit of $x(i)$ costs ϕ units of output to produce, the monopolist's problem is:

$$\max \; p_t(i)x_t(i) - \phi x_t(i) = (1-\alpha)Ax(i)^{1-\alpha}N^{\alpha} - \phi x(i).$$

This problem has a familiar solution: it is optimal to charge a mark-up over marginal cost, ϕ:

$$p_t(i) = p = \phi/(1-\alpha).$$

Note that since we assume that the marginal cost is the same for all producers, their prices will all be identical. Thus in equilibrium all producers supply the same quantity which can be derived by substituting p into the demand function (4.2):

$$x(i) = x = N\left[\frac{(1-\alpha)^2 A}{\phi}\right]^{1/\alpha}.$$

With this result in hand we can now go back to our production function (4.1) and compute the output that results from using x units of each intermediate good. This reduced form production function is linear in the number of products available in the economy:

$$
\begin{aligned}
Y_t &= B n_t N, \\
B &= A^{1/\alpha} \left[\frac{(1-\alpha)^2}{\phi} \right]^{(1-\alpha)/\alpha}.
\end{aligned}
$$

We will also assume, as in Rivera-Batiz and Romer (1991) that to invent new goods the economy must invest ψ units of output into the R&D process. A potential entrant must weight the cost of producing the blueprint for a new good against the monopoly profits that result from the ability to charge a price above marginal cost throughout the (infinite) life of the product. If we assume that there is free entry into the production of new intermediate goods, it follows that the monopoly profits must be exactly outweighed by the cost of inventing a new good. Since in this survey we are mostly interested in the question of how to generate sustainable growth, let us sidestep the problem of R&D investment faced by new entrants into the intermediate goods industry. Instead, let us focus on the simpler question of what is the growth rate of the economy if a fraction s of output is devoted to the invention and production of intermediate goods.

$$
\begin{aligned}
I_t &= sY_t \\
I_t &= (n_{t+1} - n_t)\psi + \phi x n_t
\end{aligned}
$$

The second equation above has two terms. The first ($(n_{t+1} - n_t)\psi$) represents the cost of inventing new goods, while the second ($\phi x n_t$) is the cost of producing the goods that already exist. It is now easy to compute the growth rate of output in this economy, which coincides with the rate of growth of n_t:

$$
\frac{Y_{t+1}}{Y_t} = \frac{n_{t+1}}{n_t} = 1 + \frac{BN}{\psi}\left[s - (1-\alpha)^2\right]. \tag{4.4}
$$

As in previous models an increase in the savings rate, s, increases the rate of growth. But there is now a new effect–the rate of growth of the economy increases with N, the number of workers in the economy. This results stems from the assumption that there is a fixed cost ψ associated with inventing a new good that is unrelated the number of units of the good that will be manufactured. This reasonable assumption implies that the number of goods invented will depend of the size of the market–in a small economy it will not compensate to pay the fixed cost to develop many goods. The size of the market in this economy is related to the number of workers, and hence the implication that, for a given savings rate, a larger economy will grow faster. This implication is empirically counterfactual–there is no relation between population size and rates of growth in cross-country data. But, as we discuss further below, this model of innovation is only relevant for a handful of advanced economies that undertake significant investments in R&D. And since these economies export their products it is unclear that their population is the correct measure of the size of the market. The world population may be the relevant N in the growth rate formula. Not surprisingly, this model has important consequences for thinking about trade issues that have been thoroughly explored by Grossman and Helpman (1991b).

At a descriptive level this theory is much more satisfying than models in which innovation efforts are agglomerated with physical or human capital accumulation. But at a more abstract level this model uses the same technical tricks for generating sustained growth and has similar implications for issues such as the effects of taxation on growth as do theories that reinterpret the role of the capital stock. Here sustained growth arises because producing new products does not involve factors of production that cannot be accumulated, so innovation never reaches a bottleneck that would slow down the rate of expansion. In Romer's (1990) original formulation of the model new goods were invented by using skilled labor whose stock was assumed to be constant. To allow unceasing growth to still take place Romer introduced an externality–he assumed that the cost of inventing new products declines with the stock of existing products, n_t.[9] To see this in our simple formulation suppose that there are H units of skilled labor that can be devoted to inventing new goods:

$$n_{t+1} - n_t = DH.$$

With this R&D production function it is impossible for n_t to expand at a constant rate–growth will eventually come to a halt. Suppose now we modify this innovation function to take the form:

$$n_{t+1} - n_t = DHn_t$$

Here there is an externality–the larger the stock of existing products n_t the easier it is to produce new products. This externality re-introduces the possibility for unceasing growth.

[9] Weitzman (1995) has produced an interesting analysis of the role of ideas in the sustainability of the growth process. He assumes that new ideas are produced by combining old ideas and uses combinatory calculus to study the limits on the creation of new ideas and on the growth process.

4.2. Quality Ladders

In the model that we just sketched the economy becomes more productive as new goods are introduced. In actual economies old goods stop being produced and are replaced by new ones. Candles have been replaced by electric lamps and vacuum tubes by transistors. Aghion and Howitt (1992) and Grossman and Helpman (1991a) developed a model which embodies this life cycle aspect of innovation.[10] In these models potential entrants must weight the cost of improving an existing good against the benefits of monopoly power associated with successful innovation. Only this monopoly power is now temporary. Each new producer gets its fifteen minutes of fame before seeing its product replaced by a better one. These interactions between producers of different vintages of the same good substantially complicate the model. But the essential features that drive sustained growth can be studied, as before, by focusing on an economy in which investment is a constant fraction of output, and in which old goods stop being produced as new ones are introduced.

Consider now the following production function:

[10] The quality ladders and the expanding variety models are not incompatible–one can write models in which the number of goods expands, at the same time that existing goods are improve. See, for instance Caballero and Jaffe (1993).

$$Y_t = A\left[\int_0^1 \lambda_t^\alpha(i)x(i)^{1-\alpha}di\right]N^\alpha$$

here the number of intermediate goods is constant, but resources can be devoted to improving the quality of existing goods. Quality is denoted by $\lambda_t(i)$. The demand for good i is given by:

$$p_t(i) = (1-\alpha)A\lambda_t^\alpha(i)x(i)^{-\alpha}N^\alpha$$

Assuming that the cost of production of intermediate goods remains constant at ϕ, the optimal monopoly pricing policy continues to be the same:

$$p_t(i) = p = \phi/(1-\alpha).$$

If we assume that the quality of all the goods moves in tandem $\lambda_t(i) = \lambda_t$, we can write the reduced form production function as:

$$Y_t = B\lambda_t N,$$

$$B = A^{1/\alpha}\left[\frac{(1-\alpha)^2}{\phi}\right]^{(1-\alpha)/\alpha}.$$

Suppose now that the quality of new goods can be improved according to:

$$\lambda_{t+1} = \lambda_t + I_t^r/\psi,$$

where I_t^r denotes the resources devoted to R&D. Notice that there is an external effect embedded in this equation–it is easier to achieve a given level of product quality, λ, in an economy where quality is already high. If the economy saves a constant fraction of output, with these resources being used to invent and produce new goods, we have:

$$I_t = sY_t,$$

$$I_t = I_t^r + \phi x.$$

This allows us to compute the growth rate of the economy, which turns out to coincide with that of the expanding variety model:

$$\frac{Y_{t+1}}{Y_t} = \frac{\lambda_{t+1}}{\lambda_t} = 1 + \frac{BN}{\psi}\left[s - (1-\alpha)^2\right].$$

This formula features the same scale effect of population on the rate of growth that we encountered in the variety extension models. Acemoglou (1997) has argued that this scale effect can help us understand the evolution of the skill premium in the U.S. He uses a version of the quality ladders model to study how technological progress can respond to changes in factors of production. In his model there are both skilled and unskilled workers, and investment in R&D can be directed to producing goods that are used by either group. The fixed cost nature of investment in R&D, represented by our parameter ψ means that an increase in the size of one of the groups can lead to an increase of R&D effort aimed at developing intermediate goods that are complementary to this type of labor. Acemoglou (1997) uses the model to explain why the wage rate of skilled workers did not fall despite the large increase in ratio of skilled to unskilled workers in the U.S. during the last three decades. His model implies that increases in the number of skilled workers lead to the invention of goods that are complementary to their production activities. This counteracts the natural tendency for the wage of skilled workers to fall as a result of the increase in their supply.

4.3. Technology Adoption

The two models of endogenous technical progress just reviewed are relevant for economies on the frontier of technological development. But for most economies around the world the issue is not whether to devote resources to innovation but whether to adopt technologies that have been developed by others. To construct a simple model of technology adoption along the lines of Easterly et al (1994) consider a country with a production function of the same form used in the expanding variety model. Assume that all the intermediate inputs are imported and that, to simplify, they share a common price p. The optimal use of intermediate inputs is characterized by the following problem:

$$\max A\left[\int_0^{n_t} x_t(i)^{1-\alpha} di\right] N^{\alpha} - p\int_0^{n_t} x_t(i)di.$$

Since all intermediate goods have the same price it is optimal to use them in exactly the same quantity, x, which can be derived following the same steps used before:

$$x = \left[\frac{A(1-\alpha)}{p}\right]^{1/\alpha} N.$$

We can now write output net of the cost of purchasing intermediate inputs as:

$$\begin{aligned} Y_t &= BNn_t p^{-(1-\alpha)/\alpha}, \\ B &= A^{1/\alpha}\alpha(1-\alpha)^{(1-\alpha)/\alpha}. \end{aligned}$$

Suppose that the spectrum of intermediate goods that have already been invented is $i \in [0\ \infty]$. What prevents the country to use all these goods? Assume that to introduce a new good into the production process it is necessary to teach the workers how to use it. It costs ψ units of output to teach each worker how to use a new good:

$$n_{t+1} = n_t + I_t/\psi N.$$

where I_t is the investment devoted to the adoption of new technologies. If the economy saves a constant fraction of output net of the cost of intermediate inputs the growth rate is given by:

$$\frac{Y_{t+1}}{Y_t} = 1 + \frac{sBp^{-(1-\alpha)/\alpha}}{\psi}. \tag{4.5}$$

Note that the scale effects that we obtained before are no longer present as a result of the assumption that technology adoption costs are proportional to the number of workers. Also note that the price of these goods, which is exogenous to the economy, is a determinant of the rate of growth. For a given level of s an increase in p slows down the rate of growth. This accords with the findings of DeLong and Summers (1991) and Jones (1994) that suggest a strong negative correlation between the price of capital and the rate of growth.

To derive equation (4.5) we assumed that workers learn instantaneously how to use the technology. But in practice there are important learning-by-doing dynamics in adopting new technologies. This learning-by-doing process has been emphasized by Lucas (1988), Stokey (1991) and Young (1991) in human-capital based models. These same dynamics play an important role in Parente (1994). In his model it takes time to learn how to operate a new technology. If firms never upgraded their capital they would eventually learn how to perfectly operate their technology. When they decided to adopt a new production process they loose this technology-specific expertise and have to start once again at the bottom of the learning curve.

Greenwood and Yorukoglu (1997) construct a model in which a major technological revolution can lead to a prolonged decline in productivity for the reasons emphasized by Parente (1994). In their model it takes time and resources to adopt new technologies and learn how to use them. Thus productivity often falls in the initial stages of adoption. This means that the adoption of new information technologies in the 1970's could be responsible for the productivity slowdown. There is some historical evidence that backs up this idea: there were productivity slowdowns in 18th century England with the introduction of the steam engine and in 19th century America with the introduction of electricity. Also, after 1974 we witnessed two effects usually associated with technological revolutions: a drop in the price of new capital equipment and an increase in the wage of skilled workers, which are the ones involved in implementing the new technologies.

5. Conclusion

The last decade produced impressive advances in growth theory that have deepened our understanding of the forces that shape technological progress. It is likely that newer work on growth will move from the study of the frontier countries to those that are behind the technological curve and can advance simply by adopting the technologies created by others. At an empirical level this suggests that there will be gains from de-emphasizing the study of aggregate macro data to focus on studying the impact of technology at the industry level. This opens up the prospect of a fruitful interchange between research on growth and work on industrial organization which will, hopefully, prevent a growth theory slowdown.

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