**Endogenous Growth and International Trade: A Survey***

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## 1. Introduction

Economists have long been interested in searching for the causes and effects of the growth of income and wealth of countries. Some earlier attempts to analyze economic growth with rigorous models appeared in the twenties and thirties, mainly characterized by the work of Ramsey (1928), Harrod (1939) and Domar (1946). While Ramsey was concerned about the maximization of intertemporal utility, Harrod and Domar concentrated on the equilibrium path of an economy. The work of Harrod and Domar was followed by growing interest in the theory of growth and a series of relevant papers, mainly in the fifties. One of the more influential contributions was due to Solow (1956) and Swan (1956). By introducing production substitution possibilities that exist in neoclassical production functions, Solow and Swan showed that the equilibrium paths in the Harrod-Domar model could be more stable than what was suggested.

The work of Solow and Swan has been extended in many directions (for example, an increase in the dimension of the model and the introduction of new factors that may affect growth), and has been applied in different economic fields. In the field of international trade, different versions of the neoclassical model have been used to examine a wide range of issues. (See Findlay, 1984; and Smith, 1984 for two in-depth surveys.)

The interest of economists on economic growth was rekindled recently. First, there was the paper by Romer (1986) who heavily criticizes the neoclassical theory. Romer also suggests a model that endogenizes the growth rate of economies. Lucas (1988) provides some alternative, more appealing, ways of fixing some of the shortcomings of the neoclassical theory. Since then, there has been a flood of papers and books on endogenous growth in the literature. For example, more than 50 papers published in economic journals (not including working papers) and several books can be found, all between 1990 and early 1996, that have contributed, in one way or the other, to the endogenous growth and international trade literature.

The purpose of the present survey is to introduce the major contributions of this literature, focusing on what this literature has emphasized, what new ideas have been suggested, and the main features of some of the models. It is hoped that this survey, using some unified frameworks, can give the reader a brief summary and introduction to this growing literature. However, because the literature has become so voluminous, there are issues and results that have not been covered in this survey, and the reader are encouraged to read some of the original articles.

Section 2 introduces a unified growth model, which reduces to the neoclassical growth model and many of the endogenous growth models in some special cases. The unified model thus brings out the fact that the neoclassical growth model and many endogenous growth models are mathematically similar. Section 3 uses a reduced form of the unified model to examine the basic features of the neoclassical growth theory. This will help the reader understand the recent criticism on this theory. Section 4 explains the basic mechanics of the endogenous growth theory. Different models and how they endogenize the growth rates of economies are explained and compared. It will be pointed out that some of the ideas that have been used and developed in several endogenous growth papers can be traced back to several papers in the sixties and seventies. In particular, we found some "old" papers in the sixties and seventies that have already developed endogenous growth models. In Section 5, we focus on two types of technological progress: horizontal innovation and vertical innovation. Section 6 introduces some of the papers on endogenous growth and international trade, while section 7 focuses on some recent work on growth and international factor mobility. Section 8 provides some concluding remarks.

## 2. A Unified Growth Model

Consider a closed economy, in which many competitive firms produce a homogeneous good using two factors, physical capital and labor. The good can be used for either consumption or production. The aggregate technology at time $t$, $t \in [0, \infty]$, can be represented by the following production function:

$$Y = AF(K, L), \tag{1}$$

where $Y$ is the output, $A$ a technology index, $K$ the physical capital input, and $L$ the labor input. Unless confusion arises, the time subindex is dropped for simplicity. We assume that the production function in (1) satisfies all neoclassical assumptions: increasing, linearly homogeneous, and concave in $(K, L)$.

The labor input depends on two factors: the average human capital level, $h$, and the number of workers, $M$. For simplicity, we assume that the labor force is equal to $L = hM$. This formulation implies that a worker with two units of human capital is as productive as two workers each with one unit of human capital working together. Using this formulation, the production function reduces to

$$Y = AF(K, hM). \tag{1'}$$

Linear homogeneity of the production function (1′) implies that the per capita output, $y \equiv Y/M$, is equal to

$$y = Ahf(k), \tag{2}$$

where $f(k) \equiv F(k, 1)$, and $k \equiv K/L$ is the capital-labor ratio.

Perfect competition and cost minimization mean that factors are paid their marginal products, and perfect price flexibility implies that factors are fully employed.

The accumulation of physical capital in the economy comes from saving, or the gap between output and consumption. Denote the saving rate as a fraction of output by $s \in (0, 1)$. In equilibrium, saving is equal to investment, $I$. Thus $s = I/Y$. There are two common ways of determining the optimal saving: (a) It is chosen optimally by some or all individuals in a decentralized economy; and (b) It is chosen optimally by a social planner to maximize the per capita consumption under the Golden Rule, or to maximize the intertemporal utility of a representative consumer, as in the Ramsey model. In the present context, it suffices to treat $s$ as a parameter.

Saving of the economy is converted into investment, meaning that the change of the capital stock over time is

$$\dot{K} = I - \delta K = sY - \delta K, \tag{3}$$

where a "dot" above a variable denotes the change of the variable with respect to time, and where $\delta > 0$ is the (exogenously given and stationary) depreciation rate. Suppose that the population grows at an exogenously given rate of $n$. Equation (3) then gives the rate of growth of the capital-labor ratio:

$$\widehat{k} = \frac{sy}{hk} - \delta - \widehat{h} - n, \tag{3'}$$

where a "hat" denotes the proportional rate of change of a variable; for example, $\widehat{k} \equiv \dot{k}/k$.

The growth of the economy is usually expressed in terms of the growth rate of its per capita output/income, which is obtained from (2):

$$\widehat{y} = \widehat{A} + \widehat{h} + \varepsilon_f \widehat{k}, \tag{4}$$

where $\varepsilon_f$ is the elasticity of function $f(k)$. Condition (4) states that the growth of the economy depends on how technology, human capital and physical capital grow over time. The growth rate of physical capital is given by (3′).

We now explain how the above model may reduce to the neoclassical model and some endogenous growth model.

## 3. Features of the Neoclassical Theory of Growth

Before turning to the endogenous growth literature, we first explain the features of the neoclassical model due mainly to Solow (1956) and Swan (1956). Suppose that in the economy under consideration the human capital stock is constant over time, meaning that we can write $h = 1$ and $L = M$. Furthermore, the production function is of the Cobb-Douglas type:

$$Y = AK^{\alpha}L^{1-\alpha} \qquad 0 < \alpha < 1, \tag{5}$$

which means that the per capita output is given by

$$y = Ak^{\alpha}. \tag{5′}$$

Therefore the growth rate of per capita output reduce to

$$\widehat{y} = \widehat{A} + \alpha\widehat{k}, \tag{6}$$

where in the present case $\varepsilon_f = \alpha$.

Very often attention is paid to the steady state or long-run equilibrium of the economy. In the present model, the marginal product of capital is equal to $\alpha Ak^{\alpha-1}$ and its average product, $y/k$, is equal to $Ak^{\alpha-1}$. As a result, for a given $A$, the steady-state value of $k$ is bounded from above and below: As $k \to \infty$, $y/k \to 0$, and by (3′), $\widehat{k} < 0$, and as $k \to 0$, $y/k \to \infty$, implying that $\widehat{k} > 0$. From (3′), we can obtain a value of $k$ at which $\widehat{k} = 0$. This is used to define the steady state of the economy, i.e.,

$$sy/k = \delta + n. \tag{7}$$

In the steady state, factor prices are stationary. This equilibrium condition is illustrated in Figure 1. The schedule representing $sy/k$ is strictly downward sloping, and the steady state occurs when this schedule has a value of $n + \delta$, giving a steady-state capital-labor ratio equal to $\widetilde{k}$. It is clear from the above analysis and this diagram that in the present model the steady state exists and is unique. This result can also be obtained using any linearly homogeneous production function with the following Inada conditions: $f'(k) > 0$, $f''(k) < 0$, $f'(0) = \infty$, and $f'(\infty) = 0$.

As a result, the growth of the economy's per capita output is zero in the long run, unless there is growth in technological knowledge. Since the neoclassical model does not have an explicit theory of technology progress, the latter is either assumed as given exogenously or treated as zero. Therefore in a steady state an economy in the neoclassical model either does not grow or grows according to the exogenously given technology progress.

The above model, however, has been under criticism recently. We now present some of the more common criticism, and explain how this criticism has been used to motivate the endogenous growth theory.

*(A) Exogeneity of the Growth Rate* — As explained earlier, because $k$ is constant in a steady state, the per capita output must grow according to the exogenous growth rate of technology. Exogeneity of the growth rate in the present model has several important implications. First, in a steady state, the per capita output of an economy with fixed technology will not grow. Second, by condition (7), the steady-state output-capital ratio is positively related to the saving rate. This means that policies such as a saving subsidy will eventually raise the steady-state capital-labor ratio. However, policies that change the saving rate will not change the steady-state growth rate of the economy. In other words, saving has only *level* effect but no *growth* effect (Pitchford, 1960; Lucas, 1988).[1]

This result is contradictory to the usual notion that an economy can grow faster if it saves more. Similarly, a once-and-for-all change in technology or population will not have any long-run growth effect. Furthermore, government policies that do not affect the growth rate of technology or that of population will not change the steady-state growth rate of the economy. For example, trade liberalization will not have any growth effect, as long as it does not affect the growth rate of technology (Lucas, 1988).

*(B) Disparities in International Growth Rates* — The above model suggests that for any two

countries that have the same steady-state (or long-run) growth rate of technology should have the same steady-state growth rate of their per capita income, irrespective to their prevailing size or technology level. What we see instead is that countries consistently have wide disparities of growth rates. (Azariadis and Drazen, 1990). Furthermore, for some countries this simple model is not supported by data. For example, by using (5′) and (3), (6) reduces to

$$\widehat{y} = \widehat{A} + \alpha\big[sA^{1/\alpha}y^{-(1-\alpha)/\alpha} - \delta - n\big]. \tag{6'}$$

Romer (1994) notes that between 1960 and 1985, the United States and the Philippines had about the same growth rate of per capita income, but in 1960, the Philippines' per capita income was only about ten percent of that of the United States. If the parameter $\alpha$, which is the capital share, is taken to be 0.4 for both countries, equation (6′) suggests that the saving rates for the United States over this period should be 30 times larger than those of the Philippines in order to produce the same growth rate, assuming that both countries had the same technologies, population growth rate, and depreciation rate of capital, but this condition does not seem to be supported by evidence. It is possible, and likely, that these two countries have different technologies, population growth and depreciation rates, but it is not clear whether these differences are large enough to explain why these two countries grow so differently.

*(C) Convergence of Growth Rates* — The neoclassical growth theory has important implications on the movements of growth rates of different countries. In terms of Figure 1, the gap between the $sy/k$ schedule and the horizontal line corresponding to $n+\delta$ gives the speed of adjustment of the capital-labor ratio (or the per capita output) for a closed economy. Since the $sy/k$ schedule is strictly downward sloping for an economy with a Cobb-Douglas production function, the speed of adjustment of $k$ or $y$ decreases monotonically while $k$ moves toward the steady-state point. Suppose that we have two countries, North and South, which are identical except that North has a higher initial capital-labor ratio, $k_0^n > k_0^s$. Assuming that they are below the steady-state level, both $k_0^n$ and $k_0^s$ are increasing over time, but that of the South will grow faster because its capital-labor ratio gives a bigger gap between $sy/k$ and $n+\delta$. So the South is catching up until both countries have the same capital-labor ratio and the same growth rate.

Some casual observations could easily suggest that many countries do not show convergence of the growth rates. In fact, there are many countries that show persistent growth rates higher than others, and for many developing countries, there is no sign of catching up with the growth rates of developed countries. Both Romer (1986) and Lucas (1988) cite the lack of convergence of the growth rates of different countries as a sign of the inadequacy of the neoclassical growth theory in explaining the growth experience of countries.

Recently, the views of Romer and Lucas have been challenged, and alternative interpretations of the convergence hypothesis have been suggested. We will have some more discussion of this issue in the last section.

## 4. The Basic Mechanics of Endogenous Growth[2]

We now present some of the more popular models that endogenize the growth rate of an economy. We will pay particular attention to how these models attempt to address the above criticism on the neoclassical model.

### *4.1. Growth with Non-Essential Labor: The Solow-Pitchford AK Model*

We have seen that in the neoclassical framework with a Cobb-Douglas production function, because the marginal product of capital approaches zero as the capital-labor ratio becomes infinite; in a steady state, the capital-labor ratio of the economy must be bounded from above. This implies that in the absence of technological progress the per capita output must also be bounded from above. Solow was aware of this limitation and did give alternative examples of an economy that is "so productive and saves so much that perpetual full employment will increase the capital-labor ratio (and also output per head) beyond all limits." (Solow, 1956, pp. 72 and 77.) On p. 77, he even suggested an example of a CES production function that can give perpetual growth of an economy. Pitchford (1960) is probably the first one to suggest a rigorous, general theory of endogenous growth using CES production functions, and to show how "in some circumstances a rise in the saving ratio can achieve a permanently higher rate of growth of income" (p. 499).

In the Solow-Pitchford model, human capital is also assumed to be constant so that we can write $h = 1$ and $L = M$. Its main feature is that it gives up the Cobb-Douglas production function used in the neoclassical model, and assumes instead a CES production function:

$$Y^{\alpha} = (aK^{\alpha} + bL^{\alpha}) \tag{8}$$

where $a, b > 0$. For perpetual growth, we assume that $0 < \alpha < 1$, which implies that the elasticity of substitution is greater than unity. The reason is given below. The marginal products of capital and labor are, respectively,

$$r = a\big[a + bk^{-\alpha}\big]^{(1-\alpha)/\alpha} \tag{9a}$$

$$w = b\big[ak^{\alpha} + b\big]^{(1-\alpha)/\alpha}. \tag{9b}$$

By (9a), if the capital-labor ratio is finite, physical capital accumulation still shows decreasing returns. However, because $0 < \alpha < 1$, if $k$ approaches infinity, the rental rate approaches its lower bound, $a^{1/\alpha}$, while the wage rate approaches infinity. If at this point the saving of the economy is high enough, the economy can have a perpetual growth in terms of its per capita output.

To see this point more rigorously, note that because $0 < \alpha < 1$,

$$\lim_{k \to \infty} \frac{Y}{K} = A, \tag{8$'$}$$

where $A = a^{1/\alpha}$. In other words, the production function is asymptotically linear. Equation (8′) represents the famous AK model. Assuming no technological progress, the growth rate of output is

$$\widehat{Y} = \widehat{K}, \tag{10}$$

or that of the per capita output is

$$\widehat{y} = \widehat{K} - n. \tag{10$'$}$$

Making use of the investment equation (3′) and (8′), the growth rate of the economy's per capita income is

$$\widehat{y} = sA - \delta - n. \tag{10$''$}$$

Equation (10″) has two important implications. First, if the saving rate is high enough and if $A$ is big enough, the economy can have a positive sustained growth. Second, the growth rate of the economy depends on variables such as saving rate, technology *level*, and population growth rate. Therefore any government policies that affect these variables will have a growth effect.

The adjustment and steady state of the economy can be illustrated in Figure 2. Assuming a constant saving rate, the schedule $sy/k$ is downward sloping but is bounded from below by the line $sA$. If saving is sufficiently high, the line $sA$ is above the line $n + \delta$. Equation (3′) implies that the gap between the schedule $sy/k$ and the line $n + \delta$ gives the rate of adjustment of $k$. Since the schedule $sy/k$ is downward sloping, the rate of adjustment declines over time. Asymptotically $sy/k$ is equal to $sA$, and the perpetual growth rate of the economy is equal to $sA - \delta - n$.

This model implies (conditional) convergence, as does the neoclassical model. For example, assume that there are two economies, North and South, which are identical except that the initial capital-labor ratio is higher in the North than in the South, $k_0^n > k_0^s$. In both countries, the capital-labor ratios are increasing over time, but the South has a higher growth rate and is catching up.

When the aggregate production function is of the CES type, as in the Solow-Pitchford model, both labor and capital are non-essential. It is obvious from the above analysis that it is the non-essentiality of labor that is necessary for perpetual growth with physical capital accumulation. Non-essentiality of capital is not required, as pointed out by Jensen and Larsen (1987). Jensen and Larsen (1987), Jensen (1994) and Jensen and Wang (1997) provide more elaboration of this point and suggest examples of production functions that can lead to sustained growth.

In the above analysis, saving is assumed to be a fixed proportion of the aggregate output. However, if part of the saving in the economy comes from wage earnings, sustaining the growth of the economy may be difficult in the Solow-Pitchford model because the share of labor income approaches zero when the capital-labor ratio approaches infinity. To avoid this problem, Saint-Paul (1992) suggests the use of taxation to redistribute income within the economy.

Other extensions of the Solow-Pitchford endogenous growth model were provided in some recent papers, including Jones and Manuelli (1990) and Rebelo (1991), where a generalization to a two-sector economy is shown to be possible.[3] Even if labor is essential in the production of the consumption good, as long as the investment good can be produced without labor, it is possible to have per capita consumption growing at a constant positive rate forever. To see this, denote the aggregate capital stock by $K$ and the fraction of $K$ working in the consumption sector by $\phi$, meaning that $(1 - \phi)K$ is the amount of capital working in the investment sector.

Consider the following production functions:

$$Y_c = A(\phi K)^{\alpha} L^{(1-\alpha)} \tag{11a}$$

$$Y_i = \beta(1-\phi)K, \tag{11b}$$

where $Y_c$ and $Y_i$ are the outputs of the consumption sector and investment sector, respectively, and $\beta > 0$ is a parameter. Both sectors are competitive. Using lower-case letters to denote per capita output, $y_c = Y_c/L$ and $y_i = Y_i/L$. Assuming no technological progress, $A$ is a constant. In a steady state, which we are focusing on right now, $\phi$ is a constant. Using (11), we have

$$\widehat{y_c} = \alpha\widehat{k} \tag{12a}$$

$$\widehat{y_i} = \widehat{k}. \tag{12b}$$

Denote the price of the investment good (capital) relative to the consumption good by $p$. Perfect mobility of capital between the sectors equalizes the rental rates of the two sectors:

$$p\beta = \alpha A k_c^{\alpha-1},$$

where $k_c = \phi K/L$, or, in terms of growth rate,

$$\widehat{p} = -(1-\alpha)\widehat{k}. \tag{13}$$

Condition (13) implies that if the capital-labor ratio is rising, the relative price of capital is falling. Combining conditions (12b) and (13), we see that $py_i$ is growing at a rate of $\alpha\widehat{k}$, the same as that of $y_c$.

The per capita national income is equal to $I/L = y_c + py_i$, which grows at a rate of $\alpha\widehat{k}$. The growth rates of capital and the capital-labor ratio depend on saving, which may be chosen by the government in a social planner's problem or by individuals in a decentralized economy. Let $s$ be the ratio of saving to national income. The capital-labor ratio then grows according to

$$\widehat{k} = \frac{sI}{pK} - \delta - n. \tag{14}$$

With enough saving, the economy grows over time, i.e., $\widehat{k} > 0$. Equation (14) thus implies that disparities in growth rates among countries can be explained in terms of the saving rates of the countries. In particular, a country grows faster if it saves more.

*4.2. Growth with Knowledge Spillovers and Increasing Returns: The Romer AK Model*

Another way of endogenizing growth rates was suggested by Romer (1986). His model has three main features. First, knowledge is used by firms as a capital good. Second, knowledge can be augmented so that we can talk about aggregate knowledge in the economy. Third, firms are competitive, taking prices and the aggregate knowledge as given. Knowledge and other factors are chosen optimally by firms, and knowledge accumulates by sacrificing current consumption. Thus with knowledge as a factor, Romer's model is subject to factor-generated Marshallian externality. Because he did not consider human capital, we can write $h = 1$.

Consider a representative firm which chooses a knowledge input of $K_i$. Let the aggregate knowledge be $K \equiv \sum_i K_i$. Since the firm takes the technology and the aggregate knowledge as given, in the production function given by (5), we replace $A$ by $AK^\beta$, $0 < \beta < 1$. After substitution, the production function reduces to

$$Y_i = AK^\beta K_i^\alpha L_i^{1-\alpha}. \tag{15}$$

This means that the firm treats $K$, which it can hardly control, and technology as exogenously given, and then chooses $K_i$ and $L_i$ optimally. All firms have the same production function. Adding up the firms' production gives the aggregate production function

$$Y = AK^{\alpha+\beta} L^{(1-\alpha)}. \tag{15$'$}$$

Supposing that $\beta = 1 - \alpha$, and setting $L$ at unity, the production function in (15′) reduces to the AK model asymptotically. Alternatively, the production function can be expressed in terms of the per capita output:

$$y = AK^\beta k^\alpha,$$

which gives the growth rate of per capita output:

$$\widehat{y} = \widehat{A} + \beta \widehat{K} + \alpha \widehat{k}. \tag{16}$$

Equation (16) shows the sources of perpetual growth. Assuming a Cobb-Douglas production function with no technological progress, the capital-labor ratio, $k$, remains constant in a steady state, and the growth of per capita output is proportional to that of knowledge capital.

Romer (1986) actually assumes that knowledge capital displays strictly increasing marginal product, i.e., $\beta > 1 - \alpha$. A problem of this model is that for any constant saving rate $s > 0$, the stock of knowledge capital will become infinite after some finite time if $\dot{K} = sY$. To avoid this problem, Romer assumed a bounded investment technology, $\dot{K} = g(sY/K)$ where $g(.)$ is strictly less than some upper bound. Xie (1991) provides an explicit example of this type, and suggests an alternative formulation:

$$Y_i = K_i^{\alpha}(KL)^{1-\alpha}B(K) \tag{17}$$

where $B(K)$ is positive, increasing, and bounded above by unity. Clearly, this has the same structure as the $AK$ model discussed earlier. Xie shows that for some appropriate initial condition, the growth rate of $K$ will be monotonic increasing and approach an upper bound. For more discussion of possible explosiveness of this type of models, see Solow (1994).

In Romer (1986), $K$ is the stock of public good that enters each firm's production function. Obviously a flow or a stock of public good produced by the government can also generate perpetual growth. See Barro (1990) and Turnovsky (1997).

### *4.3. Growth with Education: The Uzawa-Lucas Model*

We now turn to endogenous growth models which examine explicitly the accumulation of human capital. There are two main channels through which individuals acquire human capital: education and learning by doing. In this subsection, we focus on education.

Earlier efforts that analyze human capital in a dynamic model generally have a limited success in explaining perpetual growth.[4] To allow for a perpetual growth, Uzawa (1965) proposes to treat the skill level of workers as a variable which can increase over time.[5] Lucas (1988) extends this idea and allows for external effects of human capital. We now present a simple version of their models.

At any time let $h$ be the average human capital level which is a general knowledge available to everyone. Individuals, possessing this general knowledge, can acquire more by receiving education. Each individual is endowed with one unit of nonleisure time. A fraction of this time, denoted by $\tau$, is spent on receiving education, and the rest, $1 - \tau$, on work. The increase in human capital depends positively on the amount of time spent on education and the prevailing human capital level. For simplicity, it is assumed that there is no depreciation of human capital. Human capital is postulated to increase according to the following function:

$$\dot{h} = hg(\tau), \tag{18}$$

where $g'(\tau) > 0$. Note that $h$ is both the average human capital stock and the human capital stock each individual acquires through education in the next period. Individuals, taking the existing human and physical capital as given, choose $\tau$ to maximize their utility subject to the budget constraint and condition (18). After an individual has accumulated human capital, the new level of knowledge is immediately available to all individuals.[6]

In the presence of human capital, the available efficiency units of labor is $L = (1-\tau)hM$. The production function (5′) reduces to

$$y = (1-\tau)hAk^{\alpha},$$

and the growth rate of the per capita output is given by

$$\widehat{y} = \widehat{(1-\tau)} + \widehat{h} + \widehat{A} + \alpha\widehat{k}. \tag{19}$$

Therefore the growth of per capita output depends on that of $\tau$, $h$, $A$, and $k$.

As explained before, because of diminishing returns of capital, if $\widehat{A} = 0$ then in a steady state (balanced growth path) the capital-labor ratio remains constant, i.e., $\widehat{k} = 0$. Furthermore, $\tau$ must remain constant in such a path, i.e., $\widehat{\tau} = 0$. This implies that the growth of human capital in a steady state is equal to

$$\widehat{h} = g(\widetilde{\tau}),$$

where $\widetilde{\tau}$ is the steady-state value of $\tau$. Substitute these growth rates into (19) to give $\widehat{y} = \widehat{h} = g(\widetilde{\tau})$. In other words, the per capita output and human capital grow at the same rate, and this rate depends on the steady-state value $\widetilde{\tau}$ which is chosen endogenously by individuals. See Caballé and Santos (1993) for a rigorous discussion of other properties of the model such as existence of a steady state and dynamics.

In this model, the growth of an economy depends crucially on $\widetilde{\tau}$: Any policy or economic factor that affects $\widetilde{\tau}$ can thus change the economy's long-run growth. This model is much richer than the neoclassical one for explaining the international differences in growth rates. Thus two countries which have the same technology may still grow at different rates in steady states if individuals in different countries choose to spend different amounts of time on education (Azariadis and Drazen, 1990), or if they have different education policies. In particular, two countries may have two different steady states and in general there is no reason to believe that their growth rates should converge.

Stokey (1991) extends the Uzawa-Lucas model and considers a model with a continuum of individuals with different human capital and a continuum of products with different qualities. Firms are competitive and hire individuals with higher levels of human capital to produce higher quality products. She shows explicitly how human capital accumulation depends negatively on the rate of time preference but positively on the elasticity of intertemporal substitution.

Grossman and Helpman (1991a, Section 5.2) extend the model of Findlay and Kierzkowski (1983), endogenizing the determination of education in the presence of innovation. In their model, growth is driven not by education but by innovation, and they show that an increase in the fraction of skilled workers does have positive effect on the rate of innovation. Eicher (1996) takes another approach by considering explicitly an education sector, which, in addition to providing education and human capital accumulation, also generates technological spillovers. He shows that higher rates of technological progress and growth may be accompanied by a higher relative wage but lower relative supply of skilled labor.

The Uzawa-Lucas model and many of its extension assumes that the only cost of education is the opportunity cost of the time spent on education. Some attempts have been made to relax this assumption. For example, Manning (1975, 1976), Shea and Woodfield (1995), Eicher (1996) and Wong (1997) consider an education sector in which students are educated by educators. Ohyama (1991) and Galor and Stark (1994) assume explicitly that investment in human capital requires real resources, while Bond, Wang and Yip (1996) and Bond and Trash (1997) develop models with an education sector, which requires physical capital and labor time in the production process.

### *4.4. Growth with Learning by Doing*

Another channel through which human capital and knowledge accumulates is learning by doing. As Arrow described it, "Learning is the product of experience. Learning can only take place through the attempt to solve a problem and therefore only takes place during activity." (Arrow, 1962, p. 155.) The experience that a worker acquires through learning augments the productivity of the worker, implying that for any given factor endowments the production possibility set of the economy expands. This is similar to human capital accumulation through education, except that learning by doing requires very little, if any, resources: At least a worker does not have to (in fact, should not) stop working in order to learn.

However, an increase in workers' productivity may or may not lead to a perpetual growth of the economy. In formalizing the concept of learning by doing, Arrow (1962) postulates that the productivity of a given firm is an increasing function of cumulative investment in the industry. In his model, however, the growth rate of consumption converges to zero because it is assumed that for the economy as a whole the marginal product of capital eventually falls to zero. See also Levhari (1966a, 1966b), and Sheshinski (1967) for the same result.

In an alternative formulation, Lucas (1988) drops the diminishing returns assumption made by Arrow, and shows how the growth of an economy may depend positively on the rate of accumulation of human capital through learning by doing. Other formulations of endogenous growth with learning by doing have also been suggested by Stokey (1988) and Young (1991, 1993).

To show how learning by doing may sustain growth, let us refer to the Cobb-Douglas production function used earlier. Since workers do not have to spend time on learning, the function in (5′) reduces to

$$y = hAk^{\alpha}, \tag{20}$$

or, in terms of growth rates,

$$\widehat{y} = \widehat{h} + \widehat{A} + \alpha\widehat{k}. \tag{20′}$$

Again, assuming technological progress, in a steady state $\widehat{k} = 0$ and the growth rate of per capita output depends on how human capital grows.

As Arrow (1962) suggests, the experience a worker acquires through learning depends on the amount of activity he/she goes through. However, learning is assumed to occur accidentally and individuals do not take it into account in making consumption and time-allocation decisions.

Let us postulate that the human capital stock is a positive function of a variable $Z$ which is an index of accumulated experience, i.e.,

$$h = g(Z), \tag{21}$$

where $g'(Z) > 0$. In terms of growth rates, (21) gives

$$\widehat{h} = \varepsilon_g \widehat{Z}, \tag{21'}$$

where $\varepsilon_g$ is the elasticity of the function $g(.)$. It is required that $\varepsilon_g \widehat{Z}$ be endogenously determined and remain constant in a balanced growth path.

We now explain two ways of specifying $Z$ that ensure the above balanced growth condition. The first one is due to Lucas (1988, 1993). Suppose that the initial human capital at time 0 is given, $h_0$. Let $Z$ be the cumulative human capital, and

$$g(Z) = a \int_0^t uh \, \mathrm{d}v, \tag{22}$$

where $0 < a, u < 1$. The variable $u$ represents the fraction of time a representative worker spends on working,[7] and is determined endogenously. The parameter "$a$" represents the efficiency unit of labor. By equation (22), the growth rate of human capital is equal to $au$. Therefore equation (22) implies that the growth rate of human capital is proportional to the amount of time individuals spend on producing the good: the more time they spend on producing good, the faster human capital and per capita output will grow.

In a steady state, $u$ is a constant, and therefore the growth rates of human capital and per capita output in the absence of technological progress are both equal to $au$.

Another way of modelling human capital accumulation is to assume that $Z$ is the accumulated output, and

$$g(Z) = a \int_0^t Y \, \mathrm{d}\tau, \tag{23}$$

where $a > 0$ is a parameter and $Y$ is the output level. Equation (23) implies that the current level of human capital depends on cumulative experience, the latter being represented by the cumulative output level. Equations (20) and (23) give

$$\dot{h} = aAhMk^{\alpha}. \tag{24}$$

If we assume no technological progress or population growth, the growth rate of human capital and that of per capita output in a steady state is $aAM\widetilde{k}^{\alpha}$, where $\widetilde{k}$ is the steady-state capital-labor ratio.[8] Clemhout and Wan (1970), Stokey (1988), Young (1991, 1993), and Ishikawa (1992) make similar assumption of human capital accumulation through learning by doing.[9]

Despite their success in endogenizing the growth rate, the above formulations of learning by doing have their weaknesses. It is widely believed that the learning curve of a person in general rises rapidly initially, but then it slows down, and eventually may become flat. Arrow (1962) is aware of this fact, and it is suggested that new goods continually appear while some old goods disappear. The same argument was used by Lucas (1988), but he did not explicitly consider continuing emergence of new goods. Stokey (1988) and Young (1991, 1993) assume that there is diminishing returns in learning by doing with respect to any given product, but because of emerging new products growth can be sustained. Both Stokey and Young adopt the model first proposed by Wan (1975) where there is an infinite continuum of produceable goods, of which a finite number are produced at any given time.

Note that some learning-by-doing growth models imply scale effects: A country or an industry that becomes bigger in size will experience a higher growth rate of the economy (e.g., Backus et al., 1992). For example, consider again the growth of an economy due to learning by doing as implied by equation (24). The steady-state growth rate implied is $aAM\widetilde{k}^{\alpha}$. Suppose that a country becomes twice as big as before so that the number of workers increases from $M$ to $2M$. Then the growth rate is doubled. The existence of scale effects is an uncomfortable feature of these models because it is not supported by evidence, including both time-series data for a particular country and cross-sectional data for different countries. For example, the growth rate of the United States does not seem to increase over time with its population, and a country like India does not have a higher growth rate than that of a much smaller country like Singapore. The scale effect has the further implication that countries do not converge.

However, it should be noted that not all endogenous growth models have scale effects. For example, the education model represented by equation (18) and the learning-by-doing model suggested by (22) do not have scale effects. In models in which growth of an economy depends on R&D, however, scale effects are more common.

*4.5. Growth with Endogenous Technological Progress*

So far we have been assuming that the general technology level of the sectoral production function is either fixed or given exogenously, i.e., variable $A$ has been kept as an exogenous variable. We now relax this assumption.

In economic theory technology still remains a black box which we know not too much about. Technological progress is usually treated exogenously, or is based on some ad hoc process. In the past decade, some new approaches and analyses have been suggested and applied to the growth theory.

Technological progress can take place in one or more of the following forms: (a) It improves the productivity of factors (or lowers the cost of production); (b) It leads to the emergence of new products; and (c) It improves the quality of existing products or productivity of existing intermediate products. Sometimes a product with a higher quality can be regarded as a new product and there is hence very little difference between form (b) and form (c) of technological progress. However, distinguishing between forms (b) and (c) is generally useful, because very often the emergence of new products is analyzed when products are assumed to be characterized by horizontal product differentiation, while by definition quality improvement involves vertical product differentiation.

In this subsection, we focus on technological progress that improves the productivity of factors. In terms of the production function (5) that we have been using, this is represented by an increase in the value of variable $A$.[10]

In a series of papers written in the later fifties and early sixties, Kaldor criticized the neoclassical assumption of exogenous technological progress. Kaldor and Mirrlees (1961–62) suggest a formal model with perpetual growth that is dependent on new investment and saving. They postulate that the rate of growth of productivity per worker operating on new equipment is a positive function of the rate of growth of investment per worker. Therefore policies that affect new investment directly could have growth effects.

Chipman (1970) suggests another model of endogenous technological progress. He recognizes the fact that technological improvement requires the use of resources: engineers, researchers, computer programmers, computers, laboratories, and so on. He postulates that the rate of technological progress is directly related to the amount of resources devoted to research. As a result, government policies that encourage research will have a positive effect on the growth of the economy.

Chipman's model, while explicitly considers the use of resources on improving technology, sidesteps some fundamental questions: Who conducts research? How is the fruit of research appropriated? How is the new technology transferred to the firms?

These questions are related to each other. Specifically, in the absence of technology transfer from abroad, technological improvement can be done through R&D (i) by firms that are currently producing a good, (ii) by firms that are potential producers, (iii) by firms or agents that are specializing on research and development, or (iv) by the government.

In what follows, we provide a simple model that is based on Chipman (1970), assuming explicitly that research is being conducted by the government. Let the aggregate labor force, $M$, be constant over time. Because human capital accumulation is not considered, we let $h = 1$.

Workers are hired either by the firms in the production sector to produce the homogeneous good, or by the government to conduct research. Let the fraction $\phi$ of the labor force be employed in the production sector, while the rest are hired by the government to conduct R&D. Using the notation defined earlier, the labor input in the production sector is $L = \phi M$, and the production function can be written as

$$Y = AK^{\alpha}(\phi M)^{1-\alpha}, \tag{25}$$

which implies that the per capita output, $Y/M$, is equal to

$$y = \phi A k^{\alpha}. \tag{25'}$$

The growth rate of per capita output is

$$\widehat{y} = \widehat{\phi} + \widehat{A} + \alpha \widehat{k}.$$

By employing $(1 - \phi)$ of the total labor force to carry out R&D, the government is able to improve technology according to

$$\dot{A} = \sigma A(1 - \phi)M, \tag{26}$$

where $\sigma > 0$ is an index representing the effectiveness of labor in R&D. The government then distributes the fruit of R&D to all the firms in the economy. Due to its non-rival property, technology is a public good in the sense that the government can provide the technology to an extra firm without hurting the technological level of other firms. The cost of R&D is $w(1-\phi)M$, where $w$ is the wage rate. It is financed by lump-sum taxes on all individuals.

In a steady state, $\phi$ and $k$ are constant. Therefore the growth rate of $A$, and thus that of per capita output, is equal to $\sigma(1-\widetilde{\phi})M$, where $\widetilde{\phi}$ is the steady-state value of $\phi$.

If the government expands its R&D activity, it can increase the rate of technological progress, but it also lowers the amount of labor available to firms. Thus there is a trade-off. It is assumed that the government chooses the size of the R&D activity, or $\phi$, to maximize an objective function such as the steady-state per capita consumption or the sum of the discounted stream of the utility levels of a representative consumer.

This model, though simple, does bring out some important features of R&D. First, the new technology developed by the government is one type of public good: It is provided free to the firms, and is non-rival and excludable. Thus similar public goods can also have growth effects. See, for example, Barro (1990) and Turnovsky (1997).

The present model can be used to explain the divergence in growth rates of different countries. Because the technological progress is controlled by the government, unless different governments choose the same policies, one would not expect that their countries will grow at the same rate. One can further argue that a country like the Philippines which is not growing as fast as Taiwan is because the technology growth rates of the countries are chosen to be different. This argument is in fact supported by some casual observations: the positive correlation between technological progress and growth (countries that grow rapidly are usually those that experience substantial technological progress), and the important roles of government in R&D in many countries. However, further thinking will raise the question: If technological progress is so crucial to growth, why does a government not choose to provide more technological progress?

The most straightforward answer is that different governments have different objective functions. (A government chooses to have a low growth rate because this is what it wants.) For example, they have different preferences. In general, a country with a smaller rate of time preference (with a bigger discount of future consumption), other things being equal, will prefer to have a lower growth rate. This thus brings out an often-neglected fact: a higher growth rate does not necessarily mean a higher welfare level.

Another reason is that different governments may be subject to different budget constraints. If a government finds it too costly to raise revenue to finance R&D activities, the growth rate of the country has to be compromised. This argument is compatible with the observation that countries that grow fast usually have substantial government budget surpluses. (Of course, growth and budget surpluses may be inter-related.)

## 5. Innovation and Growth in a Closed Economy

In the previous subsection, we focus on the type of technological progress that improves the productivity of factors. We now turn to two other types of technological progress: the one that leads to the emergence of new products, and the one that improves the quality of some existing products. The former type of technological progress is called horizontal innovation and the latter called vertical innovation.

The type of models described in the previous section with one homogeneous good is no longer suitable for analyzing horizontal or vertical innovation. Some simple ways of extending the neoclassical model is now explained.

### *5.1. Horizontal Innovation*

The most common way of extending the neoclassical model to allow for the emergence of new products is to consider a sector of differentiated products as originally suggested by Spence (1976) and Dixit and Stigliz (1978). The advantage of the Spence-Dixit-Stigliz approach is that the goods enter the utility function of a representative consumer in an additive way so that the utility is an increasing function of the number of varieties. Moreover, by treating the goods symmetrically and assuming a large number of varieties, the model can be solved in a simple way. Ethier (1982) extends the Spence-Dixit-Stigliz model by treating the differentiated products as intermediate inputs used by other firms to produce a final product. This approach is followed by Romer (1987, 1990), Grossman and Helpman (1990b, 1991a), and Rivera-Batiz and Romer (1991a).

Following Romer (1990), Grossman and Helpman (1990b), and Rivera-Batiz (1991a), let us divide the economy into three sectors: the final-good, the intermediate-good, and the research sectors. The final good, which is a consumption good, is homogeneous and produced under perfect competition, while the intermediate goods are differentiated. There is only one type of primary factor, labor. The labor endowment is constant over time. The final good is produced using labor, $L_f$, and $N$ intermediate inputs:

$$Y = AL_f^{1-\alpha} \sum_{i=1}^{\infty} X_i^{\alpha}, \tag{27}$$

where $X_i$ is the input of the $i$th intermediate good. This production function is a modified Cobb-Douglas function. Note that all immediate goods enter the production function symmetrically.

Because at time $t$ there are $N$ intermediate inputs available, in the production function in (27), $X_i = 0$ for $i = N+1, \ldots, \infty$. Note how the additivity of the inputs in the production function allows the inclusion of some intermediate inputs that currently do not exist.

At least three different formulations of the intermediate-good sector has been suggested. They have different economic interpretation, but they have similar mathematical implications. We briefly describe and compare them. The first one is due to Romer (1990) who assumes that the intermediate inputs are different types of capital. Each type of capital can be produced by sacrificing one unit of the final product. Since the intermediate products are treated symmetrically on both the demand and the supply sides, in equilibrium equal amount of each of the intermediate products is produced and used in producing the final good. We let this amount be $X$. This implies that the production function of the final good reduces to

$$Y = ANL_f^{1-\alpha} X^{\alpha}. \tag{27$'$}$$

The total amount of capital is $K = NX$. Physical capital accumulation comes from saving:

$$\dot{K} = Y - C, \tag{28}$$

where no depreciation of capital is assumed and where $C$ is the consumption of the final good. Equation (28) is the usual investment equation. Firms in the intermediate-good sector compete in an oligopolistic way. Because the number of firms is restricted by the level of technology, firms may earn positive profits.

The R&D sector consists of a large number of firms. Each of them hires workers to conduct R&D activities which lead to new intermediate goods. The rate of increase in the number of intermediate goods, which for convenience is treated as a real number rather than an integer, depends on the knowledge each research firm possesses and the number of workers they hire. All research firms has access to the same pool of knowledge, which is assumed to be proportional to the existing number of intermediate goods. When a firm discovers a new product, it is granted a patent which lasts forever, meaning that any firms that receive a license from the innovating firm can produce the new product. This is an important feature of this type of models: There is perfect knowledge spillover in the research sector but zero spillover in the intermediate product sector. Denoting the total labor force engaged in research by $L_r$, the number of intermediate goods is postulated to change according to

$$\dot{N} = \sigma N L_r, \tag{29}$$

where $\sigma$ is an index representing the productivity of labor in R&D. There is free entry in the research sector. In equilibrium, the cost of developing a new product is equal to the sum of the discounted stream of profits from producing the new product.

In the balanced growth path of the economy, the distribution of labor between the final-good sector and the research sector is constant, and so is the amount of each type of capital. The growth of the number of intermediate goods, as given by (29), provides the sustained growth. Both $N$, $K$, and $Y$ are growing at a rate of $\sigma L_r$.

In the model of Grossman and Helpman (1990b), the production of intermediate products requires labor using a Ricardian-type technology. Firms also compete in an oligopolistic way and earn positive profits. In a balanced growth path, the distribution of labor among the three sectors are constant. This implies that the total quantity of intermediate products, $NX$, is constant. This is contrary to the assumption in the model in Romer (1990) in which under a balanced growth path the quantity of each intermediate product, $X$, is constant.

The production function of the final good can be written as

$$Y = A L_f^{1-\alpha} (NX)^{\alpha} N^{1-\alpha}. \tag{27$''$}$$

As $NX$ is constant under a balanced growth path, the growth rate of $Y$ is equal to $(1-\alpha)$ times that of $N$.

The above two models share one common feature of the research sector: the growth of the number of intermediate products depends on two factors, the amount of labor employed and the existing level of knowledge. Rivera-Batiz and Romer (1991a) call this knowledge-driven (KD) specification of research. They propose an alternative formulation which they call the lab-equipment (LE) model: the technology for research uses the same inputs as the final-good technology, in the same proportions. In other words, research requires both labor and intermediate products, just like the production of the final good, and is independent of the existing knowledge. Thus the change in the number of intermediate goods is given by

$$\dot{N} = BL_f^{1-\alpha} \sum_{i=1}^{\infty} X_i^{\alpha}, \tag{30}$$

where $B$ is an R&D technology index which is given exogenously. If we keep the assumption that intermediate inputs, which are different types of capital, are produced from the final good, the equilibrium condition of the final-good market is

$$C + \dot{K} + \dot{N}/B = Y = AL_f^{1-\alpha} K^{\alpha} N^{1-\alpha}. \tag{31}$$

Recall that $K = NX$ and that $X$ is constant in a balanced growth path. Thus $\widehat{K} = \widehat{N}$. In other words, the source of growth in this model, as that in the KD model, is the continuous emergence of new products. Furthermore, equation (31) shows clearly how saving, which is equal to $Y - C$, affects the growth of the economy. In another version of the LE model, the intermediate goods are *non-durable*. (See Barro and Sala-i-Martin, 1995.) Then $\dot{K}$ in (31) is replaced by $NX$.

The above models of horizontal innovation can be used to explain why countries may have different growth rates and why these rates may not converge over time, even if they have the same technology. Saving, which may be determined by market forces or chosen by the government, is the key factor behind an economy's growth. In these models, saving also contributes directly to the growth of the number of new products.

### *5.2. Vertical Innovation: Schumpeterian Creative Destruction*

A rigorous theory of repeated quality upgrades of existing products was first developed by Segerstrom et al. (1990) and Aghion and Howitt (1992). The former paper assumes that the time of arrival of a new invention that replaces an existing product is a deterministic function of the aggregate R&D expenditure in the industry, but the identity of the successful inventor is a random variable. Another assumption is that the patent races take place sequentially in one industry after another, in a predetermined order. Aghion and Howitt, on the other hand, assume that the time of arrival is stochastic, but there is only one firm producing the intermediate good, which is rendered obsolete by the arrival of a new invention. Thus there is a sequence of monopolists, the new one stealing the business of the old one. The following is a simple version of the Aghion-Howitt model.

There are two types of goods: consumption good and intermediate good, and two types of workers of fixed stocks over time: unskilled workers and skilled workers. Unskilled workers are used to produce the consumption good while skilled workers can be used to produce the intermediate good or to perform R&D. Let $y$, $x$ and $A$ denote the output of the consumption good, the amount of the intermediate input, and the quality of the latter. With a fixed endowment of the unskilled workers, the production function for the final good is written as

$$y = AF(x), \tag{32}$$

where F is strictly concave and increasing. Let $L_r$ and $L_x = L - L_r$ denote the amounts of (skilled) labor employed in R&D and in intermediate good production respectively, with the amount of skilled labor $L$ fixed over time. The consumption good sector is perfectly competitive. The production of the intermediate good requires labor only. Assuming a linear technology, $x = L_x$.

The quality of the intermediate good is measured in terms of its productivity in producing the consumption good. Its quality can be upgraded, and each upgrade represents a constant multiple of the original productivity. Thus we write

$$A = \gamma^m, \tag{33}$$

where $\gamma > 1$ and $m$ (an interger) is the number of times the intermediate good has been upgraded (which is the same as the number of innovations that have occurred).

Because the intermediate good, no matter what its quality level is, is produced with one unit of skilled worker per unit of output, the firm that has the technology of producing the good with the highest quality will capture the whole market, and is therefore a monopolist. Taking the wage rate of skilled workers as given, it chooses the price of the intermediate good it produces to maximize its profit.

Quality improvement of the intermediate good is done by research firms. Note that these outside firms get a bigger return from a successful research than the existing monopolist has, because they do not have to pay the price of losing the profit from the prevailing quality. Thus the monopolist chooses to do no research. While the amount of each upgrade is fixed, the time at which an innovation occurs is random. Let $\pi(m,t)$ denote the probability that there will be $m$ innovations up to time $t$. The expected output of the consumption good at time $t$ is

$$Z(t) = \sum_{m=0}^{\infty} \pi(m,t)\gamma^m F(L - L_r). \tag{34}$$

Assume that the innovation process is Poisson with parameter $\lambda\phi(L_r)$ representing the arrival rate. Then

$$\pi(m,t) = \frac{[\lambda\phi(L_r)t]^m e^{-\lambda\phi(L_r)t}}{m!}. \tag{35}$$

Substitute (35) into (34) to obtain

$$Z(t) = F(L - L_r)e^{\lambda\phi(L_r)(\gamma-1)t}. \tag{36}$$

A research firm that is successful in its innovation gets patent protection from the government, and sells its technology to a (new) intermediate producer. Being the only firm with this new technology, it extracts all the monopolist rent from the new intermediate good producer. Therefore when a research firm chooses to do research, the value of the next innovation is the expected present value of the flow of monopolist profit generated by this new innovation over an interval whose length is exponentially distributed with parameter $\lambda\phi(L_r)$. Note that even though the patent prevents any horizontal spillover between firms, there are intertemporal spillovers, as each successful innovation raises the general knowledge base, helping the next innovation.

The research firms choose the amount of skilled labor to do research, taking the wage rate as given, to maximize its expected profit. The equilibrium of the economy is characterized by the labor market equilibrium.

The steady state of the economy requires that the distribution of skilled labor is constant over time. Denote the steady-state value of $L_r$ in this decentralized economy by $\widetilde{L}_r$. From (36), the instantaneous rate of growth of expected consumption is $\lambda\phi(\widetilde{L}_r)(\gamma - 1)$. Note that $\gamma - 1$ is approximately the same as $\ln\gamma$.

It is immediately clear that any policies that directly increases the employment of labor in the research sector will increase the growth rate of the economy in the sense that future innovations tend to arrive sooner.

The above model has important welfare implications. Suppose there exists a social planner who chooses labor distribution to maximize

$$W = \int_0^\infty e^{-rt} Z(t)\,\mathrm{d}t, \tag{37}$$

where $r$ is great enough to ensure the convergence of the integral. Denote the optimal amount of labor in the research sector by $L_r^*$. Whether the growth rate (of the expected consumption) of the decentralized economy is higher or lower than the optimal growth rate depends on whether $\widetilde{L}_r$ is greater or smaller than $L_r^*$. However, in general the sign of $\widetilde{L}_r - L_r^*$ is ambiguous. For example, consider the special case in which $\phi(L_r) = L_r$ and $F(x) = x^\alpha = L_x^\alpha$. It can be shown that

$$\widetilde{L}_r = \frac{\lambda\gamma(1-\alpha)L - \alpha r}{\lambda[\gamma(1-\alpha)+\alpha]} \tag{38a}$$

$$L_r^* = \frac{\lambda(\gamma-1)L - \alpha r}{(1-\alpha)(\gamma-1)\lambda}. \tag{38b}$$

Which of these two labor employment is bigger is ambiguous. If $\gamma = 2$, $\alpha = 0.5$, $\lambda = 1$, then $\widetilde{L}_r < L_r^*$, but if $\gamma$ is close to unity and $\alpha$ is very small, then $\widetilde{L}_r > L_r^*$.

Aghion and Howitt (1992) offer four reasons for the difference between the two growth rates: the intertemporal-spillover effect (private research firms attaching no weight to the benefits that accrue beyond the succeeding innovation), the appropriability effect, the business-stealing effect (the private research firm not internalizing the loss to the previous monopolist caused by an innovation), and the monopoly-distortion effect. The intertemporal-spillover and appropriability effects tend to make the laissez-faire average growth rate less than optimal, whereas the other two effects affect the laissez-faire average growth rate in an opposite direction.

Building on the work of Segerstrom et al. (1990) and Aghion and Howitt (1992), Grossman and Helpman (1991d) suggest an alternative model of vertical innovation. They postulate a continuum of final goods, each with its own quality ladder. Patent races take place simultaneously and are risky.

The intertemporal utility of a representative consumer is

$$U = \int_0^\infty e^{-\rho t} \ln u(t)\, \mathrm{d}t, \tag{39}$$

where $\rho$ is the rate of utility discount and $\ln u(t)$ represents the flow of utility at time $t$ and is defined as

$$\ln u(t) = \int_0^1 \ln \left[ \sum_{j=0}^{\infty} q_j(s) X_j(s) \right] \mathrm{d}s, \tag{40}$$

where $X_j(s)$ is the consumption of quality $j$ of product $s$. If a quality is not yet available, its price is infinity. The consumer chooses the consumption bundles to maximize her utility as given by (40) subject to the intertemporal budget constraint

$$\int_0^\infty D(t)E(t)\, \mathrm{d}t \leq M(0), \tag{41}$$

where $E(t)$ is the expenditure at $t, D(t)$ is the discount factor, and $M(0)$ is the present value of the consumer's income stream. In equilibrium, the safe interest rate is $r(t) = -\dot{D}/D$. The solution to the utility maximization problem is

$$\frac{\dot{E}}{E} = r(t) - \rho. \tag{42}$$

For convenience, the problem of the consumer can be broken up into two steps. First, she chooses the streams of expenditure, $E(t)$, to maximize her intertemporal utility; then taking the expenditure $E(t)$ as given, she chooses the consumption of each product to maximize her instantaneous utility.

On the production side, several assumptions are made to give a tractable model. First, quality of a product is measured in fixed increments: quality $j$ of product $s$ is given by $q_j(s) = \gamma^j$, where $\gamma > 1$ is the same for every $s$. Second, one unit of labor is needed to manufacture one unit of any product, regardless of quality. Third, firms compete in a Bertrand fashion. Fourth, the leader always stands exactly one step ahead of its nearest rival.

These assumptions have several implications. If there are several firms producing the same product of the same quality, Bertrand competition implies that all of them earn zero profit. If there is one leader in each industry with some potential firms being able to produce the product with inferior quality, the leader can set the price low enough to drive the followers out of the market, leading to only one producer in each market. Also, being only one step ahead of the nearest rival, the leader will set the "limit" price as

$$p = \gamma w, \tag{43}$$

where $w$ is the wage rate. Note that the same price is set for all products of the leading quality. Condition (43) further implies that the demand for the product is equal to $E(\gamma w)^{-1}$ and that the flow of profit of each monopolist producing each product of the highest quality is equal to $(1-\gamma^{-1})E$. This profit disappears when the product of a higher quality is invented and produced.

Research for quality improvement is done by potential competitors of the existing monopolist. By the same argument presented above, the return of a successful innovation is bigger to an outside firm than to an existing firm. A research firm, knowing enough about the state of knowledge, hires $a_r$ units of labor per unit of R&D activity per unit of time, producing a probability of success of $\widetilde{\iota}\mathrm{d}t$, where $\widetilde{\iota}$ is the R&D intensity for a time interval of d$t$. The research success is thus Poisson with the arrival rate dependent on the level of R&D activity.

With symmetry between the industries, we let $\iota$ be the aggregate research intensity, and $L_r$ be the aggregate labor employment. Therefore $\iota = L_r/a_r$. While in each industry there is randomness in R&D success or failure, for the economy as a whole the law of large numbers ensures that in the aggregate there is virtual certainty.

There is free entry into the patent race. In equilibrium, no arbitrage implies that the expected rate of return of investing in a research firm is equal to the safe interest rate. Making use of this "no arbitrage" condition and condition (42), we get the adjustment of a consumer's expenditure:

$$\frac{\dot{E}}{E} = \left(1 - \frac{1}{\gamma}\right)\left(\frac{E}{a_r}\right) - \rho - \left(\frac{L_r}{a_r}\right). \tag{44}$$

It is noted that the manufacturing employment is $L_x = L - L_r = E/\gamma$. Using this condition, (44) reduces to

$$\frac{\dot{E}}{E} = -\rho - \frac{L-E}{a_r}. \tag{44$'$}$$

Since the adjustment of $E$ as given by (44′) is unstable, it is argued that the system jumps to that steady state instantaneously. It follows that $E$ is a constant, and hence, from (42), $r = \rho$ always. From this, we can solve for the steady state $L_r$ which is positive provided $L$ is sufficiently large.

The growth rate of the instantaneous utility can be obtained from (40), and after simplification and by the fact that the research success is Poission distributed, it is equal to

$$G_u = \frac{L_r \ln \gamma}{a_r}. \tag{45}$$

Condition (45) implies that the growth rate of the instantaneous utility is proportional to the employment in the research sector.

The welfare implications of the Grossman-Helpman model are similar to those of the Aghion-Howitt model. In particular, the R&D expenditure in the market economy may be smaller or greater than the socially optimal one. The latter case occurs when $\gamma$ is close to unity, or when it is quite large. This result is consistent with the findings of Aghion and Howitt (1992).

### *5.3. Comparing Different Types of Technological Progress*

We have distinguished between several types of technological progress: factor productivity improvement, horizontal innovation, and vertical innovation. These three types of technological progress enlarge the production and consumption possibilities of an economy in different ways. They therefore have different implications on both the production and the consumption of the economy.

As surveyed above, models describing different types of technological progress vary a lot in terms of the underlying preferences, market structures, production technology, features of the research sector, extent of technology spillover, the role of the government, and so on. The results obtained also vary a lot. Moreover, the growth of an economy is usually measured in different ways. For factor productivity improvement, growth of an economy is represented by the growth rate of the per capita income or output. For horizontal innovation, it is the growth of the number of varieties, and for vertical innovation, the growth rate of the (instantaneous) utility of a representative consumer is a good measure of the growth of the economy.

Despite the differences between their economic interpretations, these models have very similar mathematical expressions, especially the expression for the growth rate of an economy. In particular, the growth rate of an economy in a steady state, as one may note from these models, can always be expressed as an increasing function of the employment engaged in the research activity. (See more discussion below.)

These models also have very different implications on empirical studies. Suppose one wants to determine the growth of factor productivity of an economy. The straightforward way is to compare the growth rate of per capita output and that of capital-labor ratio (assuming a two-factor, one-sector economy). See, for example, Young (1994). However, to measure the other two types of technological progress is much more difficult.

### *5.4. Scale Effects of R&D*

The R&D models introduced above do carry the implication that an increase in the size of the economy or the size of the R&D sector will increase the growth rate of the economy. This effect, which is called the scale effect of R&D, is embedded in equations (26) (for improving factor productivity), (29) and (30) (for increasing the number of varieties), (36) (for the growth rate of expected consumption), and (45) (for growth rate of the instantaneous utility). Since these growth rates are directly related to the growth rate of the economy, these equations imply that an increase in the level of employment in the research sector will increase the growth rate of the economy.

The existence of scale effects of R&D comes from the appealing idea that the bigger the knowledge base and the more resources devoted to research, the easier it is to accumulate more knowledge. This idea reflects three important features of knowledge. First, knowledge has an intertemporal spillover effect, which allows the economy to accumulate knowledge and sustain growth. Second, knowledge is non-rival, meaning that it can be used by more than one agents simultaneously without affecting the benefit each of them gets from using the knowledge. Third, in many cases, knowledge is non-excludable; for example, the general knowledge reported in scientific journals. These three features imply that when an innovator introduces a new knowledge, it not only improves its own competitiveness, but also raises the knowledge base of the economy and thus helps other and future firms in their R&D efforts. These effects thus have the implication that a large country, or a large research sector, will lead to a higher growth rate. They also have policy implications. For example, policies that encourage the employment in the research sector have positive effects on growth.

These R&D models, however, have been under criticism recently because the implications of these scale effects are not supported by observed data. For example, Backus, Kehoe and Kehoe (1992) find little empirical evidence of a relation between the growth rate of GDP per capita and several measures of scale implied by the theory. They do find a significant relation between the growth rate of output per worker and the relevant scale variables. Jones (1995a) points out that the U. S. growth rates exhibit no large persistent changes, even though there have been permanent changes in certain government policies that, according to the endogenous growth theory, should have effects on growth. Similarly, there are little or no persistent changes in growth in other OECD countries. Jones (1995b) further points out that while the number of scientists and engineers employed in R&D in the United States grows by more than five times from 1950 to 1988, the total factor productivity growth for the same period is constant or even negative.

It is noted that the scale effects come from the formulation of the technological progress: growth caused by R&D is directly proportional to the amount of resources (such as the number of engineers) engaged in R&D. The scale effects go away if growth is written as a function of some scale-free variables such as the share of labor working in the research sector. This alternative formulation, however, is not satisfactory because it is contrary to the belief that innovation is tied to the number of people engaged in the research activity, and moreover, it is also rejected by the US evidence because, as Jones (1995b) shows, the share of scientists and engineers in the total labor force has also gone up.

Several efforts have been made to eliminate the scale effects in R&D. Jones (1995b) modifies the R&D equation by allowing declining rate of innovation with the level of knowledge and externalities due to duplication in the R&D process. Segerstrom (1995), following Lucas (1988), introduces human capital which grows through education and knowledge spillover. [See equation (18).] An alternative formulation is introduced by Young (1995) where there are both vertical innovation (quality improvement) and horizontal innovation (increase in the number of varieties). To avoid scale effects, he assumes intertemporal knowledge spillover in the vertical dimension but not in the horizontal dimension. A larger market will lead to an increase in the number of horizontal product varieties, thus affecting the *level* of utility, but not the growth *rate*. Eicher and Turnovsky (1996) extend Jones' approach and develop a more general model that may or may not have scale effect.

Even though these papers suggest models with no scale effects, it seems that this is achieved at a cost of eliminating the endogeneity of growth due to R&D. Because Jones (1995b) assumes declining rate of innovation, the growth of the economy decreases over time until it reaches a level that is directly proportional to the growth rate of population, the proportionality constant being dependent on some exogenous parameters. In other words, Jones' model, though assuming endogenous R&D, implies exogenous growth: government policies such as R&D subsidy have no growth effect. He describes this model as "semi-endogenous." This feature is also shared by the model of Eicher and Turnovsky (1996) when scale effect is absent. Segerstrom's (1995) model has endogenous growth, but endogeneity comes from education and human capital accumulation, not from R&D.[11] Thus education subsidies have growth effects but R&D subsidies do not. In Young's model, the absence of scale effects implies exogenous growth even though vertical innovation and horizontal innovation are determined endogenously. Thus government R&D subsidies or trade policies have no growth effect, even though the number of varieties and welfare may change.

## 6. Trade and Endogenous Growth

So far, we have examined growth of closed economies. We now try to see how the above models can be extended to open economies. In this section, we focus on international trade in goods. In the next section, we will look at international factor mobility.

To analyze trade and growth, note that the neoclassical one-sector, homogeneous-good model is not suitable for considering trade. Either a multi-sectoral model or product differentiation has to be considered. This can be done easily by extending the models introduced above.

### *6.1. Trade and Growth With Physical Capital Accumulation*

We first consider models where growth is driven by capital accumulation alone. Fisher (1995) extends the two-sector AK model of Jones and Manuelli (1990) and Rebelo (1991) to an overlapping-generations model. Individuals live for two periods, inheriting nothing when born except being endowed with one unit of labor, and leaving no bequest when dead. Each individual works, saves, and consumes only when young, and consumes when old. Thus in this model saving of the economy comes entirely from workers when they are young. Population and labor force are constant over time.

The consumption good is produced by labor and capital using a Cobb-Douglas production function, and the investment good is produced with capital only and with constant marginal product of capital. Markets are perfectly competitive. Fisher shows that with sufficient saving, the growth rate of the capital-labor ratio of a closed economy is

$$\widehat{k} = \frac{s(1-\delta+\beta)(1-\alpha)}{\alpha + s(1-\alpha)}, \tag{46}$$

where $s$ is every individual's saving as a fraction of the wage rate, and $\alpha, \beta$ are technology parameters defined by (11a) and (11b). Assuming a Cobb-Douglas utility function for every individual, $s$ is constant.

Now consider two countries with identical technology and preferences, except with different time preferences. In particular, they have different values of $s$. An important feature of the present two-sector AK model is that the investment good is infinitely capital intensive, because it employs no labor. This has two very important implications when free trade is allowed. First, because the more thrifty country (with a bigger value of $s$) has a higher growth rate of capital-labor ratio, it tends to have a comparative advantage in the investment good; for example, if they begin with the same capital-labor ratio, then in the next period, the thrifty country will become capital abundant. Second, if a country is completely specialized under free trade, irrespective to the trade patterns, it must produce the labor-intensive consumption good only. These two points combined together imply that if the two countries have substantially different factor endowment ratios so that complete specialization occurs under free trade, then the less thrifty country will be completely specialized in producing the consumption good while the other country is diversified. In this case, the less thrifty country has a lower wage-rental ratio. All investment will occur in this country and none in the thrifty country. This means that the former has a growing capital-labor ratio while the ratio in the latter country is constant. Sooner or later, the capital-labor ratios of the countries are close enough so that both countries are diversified.

When both countries are diversified, the usual argument shows that factor price equalization (FPE) exists, meaning that the countries reach an integrated equilibrium of the world under free trade. Both countries have the same capital-labor ratio, which grows over time according to equation (46), except that the saving rate is the weighted average of those of the countries. Two implications can be drawn. First, at this integrated equilibrium each country's share of the world wealth remains constant. Second, the growth rate of the world is in between the autarkic growth rates of the countries. As a result, the more thrifty country experiences a drop in its growth rate while the less thrifty country gets a faster growth rate. The possibility is that trade can reverse the autarkic growth path of a country (Fisher, 1995). Third, because both countries have the same capital-labor ratio and grow at the same rate, they will remain diversified with FPE forever.

Fisher and Vousden (1995) extend Fisher's model to analyze the effects of changes in tariffs and of the formation of customs unions and free trade areas. They show that policies that encourage the import of the consumption good by countries with high saving rates will provide a source of increased outward foreign investment and stimulate growth.

Jones and Manuelli (1990) show that in an AK model with infinitely lived agents trade liberalization can have growth effects. In their model there are no externalities, and laissez-faire is therefore optimal for the world as a whole.

### *6.2. Trade and Growth with Human Capital and Learning by Doing*

Lucas (1988) extends his one-sector model of accidental learning by doing to a two-good model, and examines the roles of human capital accumulation in international trade. His model illustrates some of the features of dynamic models that we find in other papers. (See, for example, Ishikawa, 1992.) So we present a brief description of his model and results.

There are two consumption goods. Consumers have homothetic preferences so that the ratio of the demands for the goods is a function of the relative price. The two good sectors are characterized by perfect competition and one input, labor. Workers can accumulate experience, or human capital, by working in a firm. As assumed earlier, learning is accidental in the sense that no one will take the learning process into consideration in choosing employment or production. Following equation (22), the growth rate of human capital accumulation in sector $i$, $i = 1, 2$, is postulated to be $a_i u_i$, where $u_i$ is the fraction of the labor force working in the sector, and $a_i > 0$ is a measure of the efficiency of learning. Without loss of generality, assume that sector 1 is the "high-technology" sector with $a_1 > a_2$. Ricardian technologies are assumed, i.e., the output of a good is equal to the efficiency units of labor input (by a choice of labor unit). This means that the marginal product of labor in a sector is equal to the level of human capital specific to that sector. If both goods are produced, profit maximization implies that the price ratio is equal to the reciprocal of the ratio of skill levels in the two sectors.

The first question we can ask is whether the economy, if closed, will be diversified. This question can also be asked for a static model, but for a dynamic model, this is a more interesting question because the price ratio may change over time. Thus if an economy is diversified in a steady state, the price ratio is stationary. This requires that the two types of human capital grow at the same rate, or that $a_1 u_1 = a_2 u_2$. This will indeed be an equilibrium if at the corresponding price ratio the good markets clear. Note that because the technological coefficients in both sectors are determined endogenously, the autarkic price ratio depends on both the technology and preferences of the economy.

Analyzing the stability of the steady state is less straightforward. It turns out that it depends on the elasticity of substitution between the goods. If the goods are poor substitutes, the steady state tends to be stable with diversification in production because consumers prefer to consume positive quantities of both goods. If the goods are good substitutes, then the steady state with diversification is unstable. For the case of CES preferences, the critical value of the elasticity of substitution is unity.

Lucas (1993) extends the above model to trade, assuming a continuum of small countries facing exogenously given world prices under free trade. The comparative advantage of a country depends on the country's autarkic price ratio and the world's price ratio. As in a static model, countries tend to be completely specialized, but what is different in the present dynamic model is that a country will accumulate only the type of human capital that is specific to the good produced. Therefore when different countries are producing different goods under free trade, they will have different growth rates: Countries do not converge, even if they have the same technologies, as long as they have different preferences and different autarkic price ratios.

For the case of CES preferences and if the elasticity of substitution is greater than unity, then countries that produce the "high-technology" good will grow faster. Over time, the growth of this sector tends to drive down the relative price of this good, and if this terms-of-trade effect dominates the direct effect of productivity improvement, then those countries with faster technological improvement will have slower real income growth, a phenomenon analagous to immeriserizing growth. Furthermore, if the relative price of this "high-technology" good is decreasing over time, there may come a time at which countries that are producing this good may switch to producing the other good.

Lucas' model has some interesting policy implications. Consider a country which has a long-run comparative advantage in the "high-technology" good. Suppose that currently it is under autarky but has not reached its steady state and that it shows a short-run comparative advantage in the "low-technology" good. If the country adopts a free-trade policy, it will export the latter good, become completely specialized in it and never produce the "high-technology" good. In terms of the economy's growth, the "right" policy for this country is to restrict (or even prohibit) trade at first and let the economy adjust closer to its steady state. When the economy has gained a comparative advantage in the fast growing good, trade can then be liberalized. A similar argument has also been presented by Krugman (1984). However, neither Lucas (1988) nor Krugman (1984) has provided a welfare analysis.

Other models of trade with learning by doing have been suggested. For example, Young (1991) also considers accidental learning and allows for spillovers across goods. He shows that less developed countries (LDC) would experience higher growth rates under autarky than under free trade. This loss from trade may be compensated for by the usual static gains from trade. The fall in growth when an LDC is opened to trade is due to the fact that static comparative advantage causes the LDC to specialize mostly in traditional goods, where learning has been exhausted. However, in the special case where the initial gap between an LDC and a DC (developed country) is small, under free trade the LDC can overtake the DC if it has a greater workforce. This result reflects the assumption that learning is an increasing function of the scale of production. An implication of this model is that in a world with two identical economies, temporary subsidies to high-tech industries in one country will give the country a permanent advantage. In a recent hybrid model, Young (1993) combines invention with learning by doing as complementary activities, but the implications for trade have not been explored.

Stokey (1991) distinguishes individual human capital from the social stock of knowledge. The former disappears when the individual dies, but private investment in human capital raises the social stock of knowledge. There is a continuum of goods, already invented, with quality ranging from zero to infinity. High quality goods can only be produced by workers with a higher stock of human capital. (Two workers with human capital level one may not produce the good that one worker with human capital level two can. This is in sharp contrast with the Lucas (1988) formulation.) Along a balanced growth path, human capital and the index of the highest quality good in existence grow at the same rate. What will happen to the growth rate of a backward country that decides to renounce autarky and embrace free trade? Assuming that there are no international knowledge spillovers, it can be shown that the investment in human capital in that country will fall. The reason is simple: free trade reduces the reward to the highly skilled labor in the backward country. This in turn reduces the incentive to accumulate human capital in that country. This does not necessarily mean that trade is harmful, because the usual static gains from trade may outweigh the loss caused by a fall in the growth rate of human capital.

A more recent work that analyzes the relationship between technological transfer through learning by doing and trade is Van and Wan (1997). Drawing upon the contagion theory suggested by Findlay (1978), they argue that technological progress, foreign trade and factor accumulation are complements in the growth of an economy. Thus, foreign trade provides a channel to an economy through which it learns from other economies, and physical capital accumulation, instead of being a source of growth, is the consequence as the economy grows.

Bond and Trash (1997), making use of the Uzawa-Lucas model of education and extending the work of Bond, Wang and Yip (1996), analyze the growth and trade of an economy that is characterized by human capital and physical capital accumulation. They show that under free trade between the economy and another one, both economies may experience balanced or unbalanced growth. In the case with balanced growth, they derive a result related to the patterns of trade similar to the static Heckscher-Ohlin theorem.

Wong and Yip (1997) analyze the effects of industrialization and international trade on economic growth in a two-sector model with learning by doing. The interesting feature of their model is that the two sectors grow at different rates (in fact, zero growth for the agricultural sector) in a balanced growth path, thus making the relative price of manufacturing declining over time. This is in sharp contrast to most multi-sector models in the literature where sectors grow at a uniform rate in a balanced path, with constant relative prices. Whether the economy is diversified under trade in the Wong-Yip model has important implications on the growth of the economy.

### *6.3. Technological Progress, Trade and Growth*

The models on technological progress and endogenous growth described above can be extended to analyze trade and growth. As we explained above, technological progress, either in the form of an improvement in the productivity of factors, emergence of new products or quality improvement is due to the R&D efforts made by either profit-seeking enterpreneurs or the government. Because R&D activities require the explicit use of resources, they must be supported and financed by saving (or taxes). Thus when we bring two economies together and allow flow of goods (or ideas) and analyze the effects of trade and other policies on growth, we focus on two major quantities: how these policies may affect the R&D efforts through a change in the amounts of resources allocated to the research sector and the productivity of these resources in conducting research activities, and whether international knowledge spillover occurs. As will be shown later, there are no unanimous answers to the above questions.

Let us first consider the case of trade with horizontal innovation. Suppose that there are two identical economies that are initially separated and are at their balanced growth paths. Two separate ways of trade between the economies are considered: free trade in goods (at least intraindustry trade in the differentiated intermediate goods) but not ideas (i.e., no international knowledge spillover and complete patent protection in the world), and free trade in ideas (perfect international knowledge spillovers) but not goods. In these cases, how would trade affect the growth rates of the countries?

Consider first the knowledge driven (KD) models. Recall that in this type of models, the growth of the economy comes from the growth of new products, while the increase in the number of new products depends on the existing knowledge base and the amount of labor employed in the research sector. Whether the growth of each economy changes is dependent on how the knowledge base and/or the research employment may change.

If there is no trade in ideas, i.e., no international knowledge spillover, then the current knowledge base of each country will not change. How may the research employment change? The answer to this question depends on whether the production of intermediate goods requires sacrifice of the final good or requires primary inputs, and whether the final goods in the two countries are homogeneous. If there is no trade in the final good because of homogeneity and if production of the intermediate capital goods requires the final good, the employment in the research sector is not affected by trade. As a result, trade has no effect on the growth of each country (Rivera-Batiz and Romer, 1991a).

Suppose we consider an alternative case in which there is free trade in ideas, i.e., perfect international knowledge spillover, but no trade in goods. Suppose further that the ideas in the two countries are nonintersecting. Then the international knowledge spillover will double the knowledge stock in each country. Even if the research employment does not change, the growth rate of each country will be doubled. In fact, because of the increase in profitability in the research sector, firms will employ more labor, meaning that the growth rate of each country will be more than doubled (Rivera-Batiz and Romer, 1991a).

In the lab-equipment (LE) model of Rivera-Batiz and Romer (1991a), the rate of change of the number of new products is independent of the existing knowledge stock, implying that free trade in ideas between the countries will have no economic effect. Free trade in goods (only intraindustry in the differentiated capital goods), however, will have a positive growth effect. The reason is that the intraindustry trade increases the profitability of research, thus drawing more labor into the research sector and creating a higher saving rate.[12]

In the case where there are perfect international knowledge flows, countries converge to a common growth rate and global stability is assured; see Wälde (1996) for a proof. What happens if there are only *partial* international knowledge flows? Feenstra (1996) shows that if the domestic knowledge is the sum of its past innovations and a *positive* fraction of past innovations abroad, then countries will have a common growth rate in the long run; however, if spillovers depend on the volume of foreign inputs used at home, then countries will in general differ in their long run growth rates.

We now turn to some other issues related to horizontal innovation and the above models. The first one is about the stability of a steady state. Many papers have not paid much attention to this issue, but an exception is Devereux and Lapham (1994). They note one important feature of the KD model of Rivera-Batiz and Romer (1991a) without international knowledge spillover. They show that if the home country's initial stock of knowledge is smaller than that of the foreign country, then the opening of trade will cause the home country to devote more human capital to manufacturing, and its share of knowledge in the world stock of knowledge will eventually go to zero. However, with trade, world growth rate will exceed the autarkic growth rate, because the foreign country, which has an initial comparative advantage in R&D, will devote more resources to this sector. The Devereux-Lapham instability result holds only when there are no international knowledge flows. For a somewhat different model with a similar instability result, see Grossman and Helpman (1991a, Chapter 8).

Another issue analyzed in the above models is about policy implications. Rivera-Batiz and Romer (1991b) study the effects of trade restrictions on growth in a world with two identical countries that produce non-overlapping intermediate goods. Both countries impose a tariff on all imported intermediate goods. They show that the growth rate is a non-monotone function of the tariff rate: it declines when the tariff rate rises from zero, but after some positive critical value of the tariff rate, the growth rate rises, though it never reaches the growth rate in the free trade regime. This non-monotonicity is a rather surprising result. Essentially the tariff has two effects, a trade distortion effect and a R&D resource reallocation effect. When two effects work in opposite directions, the size of the tariff rate may determine their relative strength.

Grossman and Helpman (1990b) also study the effects of tariffs. As explained earlier, the growth effect of a policy depends on how it affects the amount of the resource (labor) devoted to the R&D sector. Suppose that country 1 has a comparative advantage in R&D. If country 2 imposes a tariff on country 1's export, more labor will be driven to the R&D sector, thus improving the latter country's growth. In the presence of international knowledge spillover, both countries grow at the same rate in the long run, and the tariff can improve this growth rate. For the same reason, an R&D subsidy imposed by country 2 could hurt the growth of both countries if international knowledge spillover is present. It is because the R&D subsidy draws resources from the country's production sector to the R&D sector. This policy thus encourages country 2's export but discourages that of country 1, hurting the R&D activity in the latter country which has a comparative advantage in R&D. As a result, the world's growth rate tends to be hurt by the subsidy.

However, a faster growth does not necessarily imply a higher welfare, a point made clearly in Grossman and Helpman (1991e). They show that a trade policy that speeds up growth may reduce welfare if, for example, it causes a fall in the outputs of the intermediate goods that are undersupplied due to monopolistic pricing.

So far we have been focusing on trade under technological progress with horizontal innovation. How would the above results be different if instead vertical innovation exists? The several models of vertical integration introduced in the previous section can be extended to open economies. Consider the vertical innovation model of Grossman and Helpman (1991d). Let us modify it so that there are two primary factors, skilled labor ($H$), and unskilled labor ($L$). There is also an outside good that does not benefit from innovation, which is assumed to use unskilled labor intensively. Suppose the foreign country is relatively well endowed with unskilled labor. Under certain assumptions (such as identical technology and diversification), the two countries without international factor mobility achieve a world integrated equilibrium. The production pattern is then identical to that which would obtain under international factor mobility.

Does this equilibrium achieve a higher growth rate than the autarkic growth rate? Grossman and Helpman (1991d) show that the answer is in the affirmative if the elasticity of substitution in the production of the outside good is greater than one. This is because (a) an increase in $H$ will increase the supply of skilled labor for R&D, and (b) an increase in $L$ will increase the $w_H/w_L$ ratio, and the outside good sector will release skilled labor (despite the Rybczynski effect which implies that, at constant factor prices, more labor of both types will be demanded for by the outside good sector). On the other hand, if the elasticity of substitution is less than one, then the Rybczynski effect may dominate, causing a worldwide contraction of the R&D sector, thus slowing growth.

Tariff policies for a small open economy are the subject of study in Grossman and Helpman (1991e). The protection of a final good that uses human capital intensively will raise the reward to human capital and make R&D costly, thus slowing growth. However, faster growth does not necessarily mean higher overall welfare for this economy. A trade policy that speeds up growth may reduce welfare if it causes a fall in the outputs of the intermediate goods that are undersupplied due to monopolistic pricing.

Issues related to trade patterns and specialization with vertical innovation are examined by Taylor (1993). He generalizes the Grossman-Helpman quality-ladder model by allowing asymmetry among the continuum of goods. Under the Ricardian technology, the interaction between the comparative advantage rankings in production and in innovation determine the long-run pattern of trade.

### *6.4. Technology Transfer*

In the previous subsection, two polar cases in terms of the flow of technology between countries are examined: the one with costless and instantaneous knowledge spillover, and the one with absolutely no knowledge spillover. Both cases are not realistic in the world. Production technology, in the form of knowledge that can be described in blueprints or embedded in finished products, have many properties of a public good: It is non-rival and non-excludable. It may be transferable from one firm to another, whether the firms are in the same or different countries, and the use of it by an additional firm does not affect the use of it by the existing firm. However, because the technology, if it is advanced, allows the user to produce a new or better product or to improve the productivity of the employed factors, the firm that has the sole possession of it wants to guard its secrecy or to prevent other firms from using it (through legal protection, for example), while other firms have incentives to try to learn the technology, a process called imitation, and use it in their production. Obviously, guarding a possessed technology from its rivals and trying to copy an advanced technology are costly, but in the literature more attention is paid to the cost of imitation.

In the present context, we are interested in possible technology transfers between countries so that we simply assume that domestic protection of a new technology is perfect, through perfect patent protection, for example. Once technology transfer between countries becomes the focus of analysis, several issues arise. The first one is the process and costs of imitating the technology in the advanced countries by the firms in the backward countries. The second one is about the interactions between innovation and imitation. The third one is the analysis of the product cycle theory, and the fourth one is the analysis of some government policies that directly affect the rate of innovation and/or the rate of imitation. These policies include research (either innovation or imitation) subsidies and intellectual property rights protection. These four issues are interrelated. We present a brief discussion about them.

The product cycle theory as suggested by Vernon (1966) provides a rigorous theory that postulates the invention and initial production of new products in countries such as the United States, and later the shift of production of these products to countries with lower wage rates. This paper provides many new ideas and observations, and despite the lack of a mathematical model, it refers to a dynamic environment in which new products continually emerge and production continually shifts from the United States to less developed countries. In his model, he emphasizes investment of the U. S. firms in less developed countries as the major vehicle of transferring the technology of producing new products from the United States to other countries.

Vernon's product cycle theory has been extended and formalized by many papers. Krugman's North-South model (Krugman, 1979) provides a rigorous model of innovation and imitation. He shows that in the steady state of the world there is a constant gap between the number of products produced in the North and that in the South. In his model, the channel of technology transfer is not foreign direct investment but imitation. His model is later extended by Feenstra and Judd (1982) who examine several welfare and policy issues. These two models, however, consider only exogenous innovation.

Endogenizing innovation and imitation is a natural step in the endogenous growth literature. Segerstrom (1991), by extending the model of Grossman and Helpman (1991c), examines the interactions between endogenous innovation and imitation in a closed, growing economy. However, to examine the product cycle theory with endogenous growth, two countries is the lowest dimension of a suitable model. In a series of papers, Grossman and Helpman (1991b, 1991c, 1991d) investigate innovation, imitation and product cycle using several different models.[13]

A simple version of Grossman and Helpman (1991c) is now presented to illustrate how imitation in the presence of vertical innovation can be introduced. Suppose that there are two countries labeled North and South. North has a comparative advantage in innovation while South has a lower wage rate. If both countries have the same access to technologies, products will be produced in the South only (at least in the short-run before wages adjust). Assuming Bertrand competition, three types of firms may exist in equilibrium: (i) Northern leaders (firms that can produce the state-of-the-art products) that are competing with another Northern firm that can produce the second-to-top quality; (ii) Northern leaders that are competing with a Southern firm that can produce the second-to-top quality; (iii) Southern firms that are able, via imitation, to produce the state-of-the-art products. In the presence of imitation threats, the Northern leaders have incentives to conduct research: to master the next generation technology as a safeguard against future imitation; to deter rival firms from targeting its product for imitation; and to try to gain a two-step advantage over its nearest rival.

Imitation is treated as a process similar to innovation in the sense that it is risky, and it requires resources. Southern firms choose products to imitate. The probability of success of an imitation is represented by a Poisson distribution, with the arrival rate dependent on the amount of a resource (such as labor) that a firm chooses to conduct the research. In a steady state, the difference between the measures of products manufactured in the North and that in the South is zero, and the composition of Northern products remain constant.[14]

Two types of equilibria may arise. In the first type, leaders enjoy a large technological advantage over followers in research, and only the leaders engage in R&D. The equilibrium involves alternating phases of Northern and Southern production of each good. In the second type, followers are relatively efficient in innovation, and both the leaders and the followers engage in R&D. The path followed by any particular good can be complex, because it may pass from the leader to another Northern firm or to a Southern firm.

Note that because no learning by doing or human capital accumulation is assumed in the Grossman and Helpman model, the South conducts only imitation and is always behind the North in the technology race.

Another paper that models product cycles of products is Dinopoulos et al. (1993). They use the Heckscher-Ohlin framework and show how differences in relative factor endowment may explain product cycles in the presence of factor price equalization. This is in contrast to Grossman and Helpman (1991c) where product cycles are due to lower wages in the South.

Grossman and Helpman (1991b) suggest a product-cycle model with horizontal innovation. The results are closer to what Vernon observed: New products are being invented in the North, which are later imitated by the South. With a wage advantage, the South eventually becomes the sole producer in the world.

Another issue related to technology transfer between two countries is trade-related intellectual property rights (TRIPs) protection. As mentioned earlier, every technology leader has incentive to protect the secrecy of its technology knowledge while other firms (especially those in another country with other advantages such as lower wages) have incentives to imitate and produce a similar product. For a closed economy, imitation may be prevented by patent laws, but in a two-country model with a leader in one country and many potential imitators in another country, patent protection is less effective.

Helpman (1993), by extending the Krugman (1979) model of exogenous innovation and the

Grossman and Helpman (1991b) model of endogenous innovation, analyzes the effects of intellectual property rights (IPRs) protection on the welfare of both countries, and the effects on innovation and imitation. IPRs protection is modeled as an increase in the cost of imitation by firms in the South (the backward country). He shows that an IPRs protection hurts the South, but its effects on the welfare of the North and that of the world is ambiguous. Under certain conditions, the North benefits, but in some cases, both the North and the South are hurt by the protection. Helpman also examines the effects of the IPRs protection on the growth rate of innovation, and shows some cases in which the protection hurts, not helps, the Northern firms' innovation.

Taylor (1994) extends his previous paper of quality ladder to examine the implications of TRIPs. He shows that the failure to provide patent protection reduces R&D activities worldwide and slows growth. These results are different from those in Helpman. For an alternative formulation of the same issue, see Rivera-Batiz and Romer (1991b).[15]

*6.5. Poverty Traps, Trade and Growth*

Development economists have argued that a poor country may remain poor forever unless there is a big push to industrialize it. A poverty trap is a stable steady state with low per capita consumption. See Lewis (1954), Barro and Sala-i-Martin (1995, Chapter 1), Murphy, Schleifer and Vishny (1989), and Azariadis and Drazen (1990).

Does trade create an opportunity to escape from the poverty trap? The answer is "yes" and "no," depending on the assumptions. Majumdar and Mitra (1995) assume that capital is the only factor of production that is mobile between two sectors, the consumption good sector and the investment good sector. In the former sector, marginal product of capital is constant. The production function of the latter sector exhibits increasing returns at low levels of capital, and diminishing returns beyond a certain threshold, with zero marginal product of capital in the limit. It follows that it is not possible for the closed economy to have positive growth forever. If the country is open to trade and the rest of the world has a better technology for the investment good sector, then growth becomes possible: the country can import the investment good and specialize increasingly in the production of the consumption good. In fact trade has effectively endowed the country with the AK technology with which it can indirectly produce the investment good.

Long, Nishimura and Shimomura (1997) adopt the Heckscher-Ohlin framework, but allow for variable returns to scale of the S-shaped type. They show that there is a threshold level of non-consumable and non-depreciating capital stock, above which the country will choose to grow perpetually, thanks to a high marginal productivity of capital, like in other AK models. Below that threshold level, the country will run down its capital stock to zero, by selling its capital in exchange for the consumption good. This contrasts sharply with the autarkic case in which the capital stock is a positive constant in the long run. In the free trade case, the country will eventually specialize in one good, but during the transition phase, it may produce both goods. The country switches in and out of diversification by discrete jumps because it is never efficient to produce a good at a small scale.

## 7. Growth and International Factor Mobility

In this section, we examine the roles of international factor movement in the neoclassical and endogenous growth models. We will first consider international capital movement, and then international labor migration.

In the trade literature, international factor mobility occupies an important part. However, previous work on the factor movement among countries usually assumes static frameworks with given factor endowments in countries, even though it is recognized that factor endowments may change over time due to investment and population growth. The assumption of given factor endowments is sometimes justified by the argument that only steady states are considered. In the endogenous growth literature, this argument may no longer be valid because the factor endowment ratios of countries may change under balanced growth paths.

In this section, we examine how the theory of international factor movement may change when growth is endogenous. We will pay more attention to several issues: how factor mobility may affect growth, how it may affect convergence of countries' growth rates, and how growth may affect international factor mobility.

### *7.1. International Capital Movement*

We first begin with the neoclassical framework. As we showed earlier, the steady-state growth rate of an economy analyzed in a neoclassical model is given exogenously. When given technologies, movement of capital therefore does not change the steady-state growth rates. In fact, if two countries are identical, they will have the same steady state with the same factor prices. This means that in a steady state, capital will not move.

However, if two countries have not reached their steady states, capital may move even if they have identical technology, as long as they have different initial capital-labor ratios. Capital may also affect the adjustment of the economies.

To see this point, consider Figure 3. There are two countries, North and South. They have identical and fixed technology, but the North has a higher initial capital-labor ratio, $k_0^n > k_0^s$. These capital-labor ratios are lower than the countries' steady-state ratios.

If the two countries are isolated, then they will grow over time until the steady state is reached, as explained in Section 3. Suppose now that international capital movement is allowed by both countries. For simplicity, we assume no risk and negligible moving costs. However, capital movement takes time so that any rental differential between the countries cannot be eliminated by capital movement instantaneously. The higher capital-labor ratio in the North implies a higher wage-rental ratio. Thus capital flows gradually from the North to the South. Let us denote the amount of capital that comes from the North to the South by $Z$, and its rate of change by $\dot{Z}$.

The presence of capital movement requires modification of the neoclassial model examined in previous sections. First, national income includes not just the domestic output but also the repatriation of national capital working abroad (or less the payment to foreign capital working locally). Second, the change in domestic capital stock comes not only from domestic investment but also from more foreign capital inflow (or less domestic capital outflow).

To analyze the adjustment of an economy, let us focus on the North for the time being. Its capital stock at any time grows over time according to

$$\dot{K}^n = sY^n - \delta K^n - Z,$$

where $s$ is the saving rate, which is assumed to be a constant fraction of the domestic output $Y^n$ (superscript $n$ for the variables of the North and superscript $s$ for those of South).[16] A similar equation holds for the South. The growth rates of the capital-labor ratio in the countries are

$$\widehat{k}^n = sy^n/k^n - n - \delta - \widehat{z}^n \tag{47a}$$

$$\widehat{k}^s = sy^s/k^s - n - \delta + \widehat{z}^s, \tag{47b}$$

where $\widehat{z}^n = \dot{Z}/K^n$ and $\widehat{z}^s = \dot{Z}/K^s$. For simplicity, the two countries are assumed to have the same saving rate.

The effect of international capital movement on the growth rates is illustrated in Figure 3. Points N and S represent the initial points of the North and the South. Without capital movement, they adjust along schedule $sy/k$ until the balanced-path point B is reached. In the absence of capital movement, the gap between schedule $sy/k$ and line $n + \delta$ represents the speed of adjustment.

When capital moves, construct schedule $n + \delta + \widehat{z}^n$ for the North and schedule $n + \delta - \widehat{z}^s$ for the South. If we assume that the growth rate of capital movement is an increasing function of the rental rate differential between the countries, both $\widehat{z}^n$ and $\widehat{z}^s$ decrease over time as more capital flows from the North to the South. In other words, schedules $n + \delta + \widehat{z}^n$ and $n + \delta - \widehat{z}^s$ converge and meet at point B, where capital movement ceases.

The speed of adjustment of the North depends on the gap between schedules $sy/k$ and $n+\delta+\widehat{z}^n$ while that of the South depends on the gap between schedules $sy/k$ and $n+\delta-\widehat{z}^s$. Thus international capital movement slows down the growth of the North and speeds up that of the South. This allows the South to catch up, and the growth rates of the countries converge faster.

How would the above conclusion be different if we have an endogenous growth model? Let us consider the Solow-Pitchford AK model. In this model, even though the growth rate of an economy is endogenously determined, international capital movement between two countries with identical and fixed technology has *no* effect on the steady-state growth rate of each country. The reason is that in a steady state, the rental rate is equal to $A$. In other words, there is no international capital movement in a steady state, and the growth rate of each country is given by (10′′).

International capital movement in this model has the same positive effect on the rate of convergence of the countries' growth rate as it does in the neoclassical framework. It is because the growth rate of the countries' capital-labor ratios are still given by equations (47). Thus the above analysis also applies to the AK model.

International capital mobility could lead to perpetual growth of an economy which when closed has no growth in the long run. This result was first established by Deardorff (1994). To see this point, consider two neoclassical economies with identical technology, North and South, with the North's exogenous and constant population growth rate being lower than that of the South. Suppose that the North is a small economy so that free capital mobility anchors the rental rate in North to that in the South, thus avoiding diminishing marginal product of capital in the North. If the saving in the North is high enough, then the North can grow perpetually. As long as the North's saving rate is not too high, the North can remain a small open economy for ever. If the North's saving is high enough, then it will sooner or later own a significant share of the world capital stock. Because it has a lower population growth rate, asymptotically the share of its labor force in the world drops to zero. In the long run, the capital-labor ratio in the world is contant, with the North owning a constant share of the world's capital, meaning that asymptotically both countries' capital stock grow at the same rate as that of the South's population. Thus the North's capital-labor ratio is rising while that of the South is constant.

### *7.2. International Labor Migration*

Although many papers on international migration consider only static models, there have been efforts to analyze migration in a dynamic context, especially in models in which education and training are explicitly examined. Some of the more important papers include Bhagwati and Hamada (1974), Rodriguez (1975), Miyagiwa (1991), Galor and Stark (1994), and Shea and Woodfield (1996). These papers determine the transformation of unskilled workers to skilled workers through education in the presence of international labor migration. However, because these papers assume that the skill level of the skilled workers is fixed, knowledge does not accumulate. Thus growth of the economy is not sustained.

To see how international labor migration can be introduced into growth theory, let us begin with the neoclassical model we described in Section 3. Consider again a one-sector closed economy with a Cobb-Douglas production function. It has been shown that without technological progress the per capita output remains stationary in a steady state. The steady-state equilibrium is represented by equation (7).

Suppose now that the economy allows an inflow of foreign workers at a rate of $m$. Right after their arrival, foreign workers become permanent residents in the economy. For simplicity, assume that foreign workers do not bring physical capital with them and that they have the same saving rate as the domestic residents.[17] With the inflow of foreign workers, local population and thus labor force grow at a rate of $n + m$. The new steady state equilibrium condition is

$$sy/k = n + m + \delta. \tag{48}$$

Differentiation of equation (48) shows that an increase in $m$ decreases $k$ and thus the local wage rate.[18]

As explained before, in the absence of technological progress, the per capita output of the economy remains stationary in a steady state. Therefore its growth rate is not affected by labor inflow. International migration, however, does have effects on the convergence of the growth rates of two economies when they are currently off their steady states.

Consider two economies labeled North and South. Suppose that they have the same technology that is stationary, the same depreciation rate, the same population growth rate, and the same saving rate. Thus they have the same steady state.

Suppose that currently the capital-labor ratios of both countries are below their steady-state level, $\widetilde{k}$, with the North having a higher capital-labor ratio, i.e., $\widetilde{k} > k_0^n > k_0^s$. If the economies are closed, both capital-labor ratios will move up over time until the steady state is reached.

With $k_0^n > k_0^s$, the North has a higher wage rate, meaning that if migration is allowed, workers will move from the South to the North. Suppose that the rate of migration is $m$.[19] The vertical gap in Figure 3 between the $sy/k$ schedule and line $n + \delta + m$, shown as NN′, represents the speed of increase in the North's capital-labor ratio, while SS′ represents that of the South. The diagram shows that migration has slowed down the growth rate of the North but speeded up that of the South, allowing the latter to catch up faster.[20]

This model, though simple, does not imply a perpetual growth of the economies. A more interesting approach is to include human capital and permit endogenous accumulation of human capital. Galor and Stark (1994), and Shea and Woodfield (1996) are two recent attempts. The former paper, by considering an economy with multiple steady-state equilibria, presents cases in which admitting foreign workers who are slightly less skilled than the average native could move the economy to a steady state with a substantially lower human capital level. The latter paper derives the optimal immigration policy when skilled and unskilled workers come at the same time. The growth of the economies in these two papers, however, is not sustained because in a steady state human capital does not accumulate. Barro and Sala-i-Martin (1995, Chapter 9) assume that a country can maintain a constant growth rate of migration, $m$ (at least for a certain period of time). Then migration can have a growth effect.

Wong (1995, Chapter 14) considers three types of international labor migration: permanent migration, temporary migration and brain drain, and discusses two channels through which human capital accumulates: learning by doing and education. His main concern is the choice between the three types of migration, but he does not examine explicitly the growth rates of the host and source countries.

An attempt to analyze the inter-relationship between international labor migration and growth rate of an emigration economy is given in Wong (1997). By extending the Uzawa-Lucas model of education and human capital accumulation, he analyzes how growth rate affects and is affected by each of the three types of migration. By allowing workers to choose the type of migration, i.e., when and where to work and to get education, he shows some cases in which permanent migration switches to temporary migration as the emigration economy grows. A deeper analysis of the case of brain drain is given by Wong and Yip (1996).

## 8. Concluding Remarks

In this paper, we have surveyed the major models and issues of endogenous growth and international trade. We first described major endogenous growth models, and then turned to the literature of growth and trade.

Endogenizing and explaining growth of economies has become a major focus in the literature recently. The main feature of this literature, as explained in Sections 4 and 5 above, is to link the growth of an economy with some of the features of economies such as preferences, technologies, and government policies. Several factors of growth have been outlined: accumulation of factors, external effects, learning by doing, education, and R&D.[21] This survey uses a unified model to present the main features of some of the endogenous growth models and their mathematical similarities.

It has been realized that even though most papers on endogenous growth were written in the past decade, there had already been papers in the sixties and early seventies that have dynamic models with growth rates endogenously determined by individuals or government policies. Even Solow has mentioned the conditions for perpetual growth of economies.

It is thus interesting to ask why these "old" papers on perpetual growth have not generated the kind of interest on endogenous growth like what was experienced in the past decade.

Several reasons can be suggested. First, one major objective of the papers of Solow, Swan, and others in the fifties and sixties was to introduce production substitution possibilities in order to solve the instability problem in the Harrod-Domar growth models. The growth rate per se was not the main focus of the analysis, and these papers were by and large content with models that suggest a steady state with no perpetual growth for an economy.

In the past decade, however, growth rates of countries were a much bigger issue. On the one hand, countries show wide disparities in their growth rates. It is interesting to explain why many countries have different growth rates and whether these rates tend to converge over time. The neoclassical model of Solow and Swan is not the right tool because it implies that countries with identical and fixed technologies and preferences will converge in terms of their growth rates until they reach the steady state with the same (exogenous) growth. On the other hand, people are interested in knowing the implications of different government policies on growth. Again the neoclassical model is not the appropriate tool, as long as long-run growth is concerned.

If we judge the recent endogenous growth literature by the three points of criticism on the neoclassical model mentioned in Section 3, we can see that its biggest success is its endogenous determination of economies' growth rates. By providing different rigorous mathematical models, these papers highlight several important factors that may affect the growth of economies. The more practical implication of these models is that the government has a role in economic growth.

Empirically, the endogenous growth models can easily be adopted to explain why countries do not have the same growth rates and why their growth rates do not converge. However, how much success these models really have in passing empirical tests is debatable. First, as we explained earlier, there is the uncomfortable implications in many of these models that the size of a country or an industry holds a paramount influence over the country's growth. This implication is not supported by both time-series and cross-country data. Second, it has been suggested that the Solow model with exogenous growth rates, when suitably augmented, can explain the growth rates of countries at least as well as some endogenous growth models do (Mankiw, at el., 1992; Jones, 1995a, 1995b). Third, most of the endogenous models are based on some ad hoc assumptions about how human capital or technology accumulate, how growth is determined, and whether scale effects are present. In many cases, the results depend crucially on the range of a particular parameter: whether it is zero or positive, or whether it is greater than unity. Sometimes the functional form of a function is important. Fourth, most models on endogenous growth consider only an economy with one homogeneous final good. Mathematically, this assumption allows tractability of the algebra and simplifies the non-essential elements of the model in order to highlight different factors of growth. Empirically, this assumption could be misleading because it neglects stuctural changes, interactions between sectors, and different distributions of sectors in different countries. In particular, very little work has been done to examine the empirical relevance of some of the microfoundation equations of the models such as the R&D equation, the education equation, and so on. Fifth, despite the work on how R&D, education, learning by doing, factor accumulation and so on may affect growth, we still have little knowledge about why countries like Taiwan, Hong Kong, Singapore and Korea grew so rapidly in the past several decades, while countries like the Philippines and India did not experience such growth.[22] Sixth, nearly all empirical work in the endogenous growth literature (for example, Young, 1994; Barro and Sala-i-Martin, 1995; Jones, 1995a, 1995b) uses the growth rate of per capita income (or output) of countries as a measure of growth. However, we saw above that growth can be due to horizontal innovation (increase in the number of varieties) and vertical innovation (quality improvement of existing products). How important these factors of growth are in the growth experience of economies such as Hong Kong and Taiwan is unknown, but neglecting them in empirical studies could give misleading results.

Another issue that has become controversial is the convergence hypothesis. As explained earlier, several papers have cited the persistent divergence in countries' growth rates and the lack of convergence of their growth rates as evidence that the neoclassical growth theory is inadequate. This view, however, has been challenged recently. For example, Barro and Sala-i-Martin (1992) observe convergence among the 48 states of the United States in terms of the growth rates of their per capita income and per capita gross state product. Similar convergence among the 47 Japanese prefectures can also be observed (Sala-i-Martin, 1996). However, convergence among different countries is less obvious (Barro and Sala-i-Martin, 1992, 1995). Several concepts of convergence have been introduced. First, it has been argued that the neoclassical growth theory implies only convergence (called conditional convergence) among those countries with the same economic structure (technologies, preferences, saving policies, and so on), not convergence (called absolute convergence) among all countries possibly with different economic structures. Barro and Sala-i-Martin (1992) and Sala-i-Martin (1996) do observe conditional convergence.[23] Second, while many countries have persistent gaps between their growth rates, countries with similar economic structures seem to have their growth rates converging over time.[24] This is confirmed by Sala-i-Martin (1996). Furthermore, Quah (1996) and Galor (1996) argue that under certain conditions countries can show multiple steady states, and different countries with similar economic structures can converge to different steady states and thus different growth rates, a phenomonon called club convergence.[25]

The literature on trade and growth, with its diversity of results, suggests that no simple policy recommendations should be made without a thorough understanding of the structure and the key features of the economies under consideration. The results and the relationship between growth rates and international trade in general are sensitive to the structures of the economic models. The opening of trade can increase growth (Rivera-Batiz and Romer) or retard growth (Young). Moreover, faster growth may imply higher, or lower, welfare. The classical gains from trade theorem relies on the absence of externalities. Growth, on the other hand, is largely associated with dynamic spillovers.

It is no doubt that the recent endogenous growth literature has improved our understanding of some of the factors that may affect countries' growth. Despite the voluminous literature in the past decade, there remain many unanswered questions.

## FOOTNOTES

1. The level effect of an increase in the saving rate can also be shown in Figure 1. An increase in the saving rate shifts up the schedule for $sy/k$, leading to an increase in the steady-state capital-labor ratio. The steady-state growth rate of per capita output remains to be the same as that of technological progress. However, it should be noted that an increase in saving could have positive effects on growth during the transitional period.
2. The term "mechanics" is borrowed from Lucas (1988).
3. For a more general formulation of endogenous growth models with many capital goods, see Dolmas (1996).
4. See, for example, Razin (1972a, 1972b), Manning (1975, 1976), Hu (1976), and Findlay and Kierzkowski (1983).
5. While so much attention has been paid to the growth factors on the production side of economies, Uzawa, in a less known paper (Uzawa, 1969), suggests a growth model that endogenizes the rate of time preferences.
6. Note that the free-rider problem may exist in this type of models.
7. The rest of the time may be spent on leisure. In the Lucas (1988) model, there are two sectors, and $u_i$ is the fraction of the nonleisure time a worker spends on working in sector $i$.
8. If population growth rate is positive, the growth rate of human capital as given by (24) will not be constant. To have a constant growth rate of human capital, one can assume instead that $Z$ is a positive function of the cumulative per capita output.
9. Kemp (1974) suggests an alternative learning function: the human capital level in period $t$ is a positive function of the output level in the previous period. This function may or may not lead to perpetual growth, but he has not provided any analysis of this point.
10. For convenience, three types of technological progress can be distinguished: Hicks-neutral, labor-augmenting (Harrod-neutral), and capital-augmenting (Solow-neutral), but in general only the labor-augmenting technological progress is consistent with a balanced growth. See Barro and Sala-i-Martin (1995, pp. 54–55). With a Cobb-Douglas production function, these three types of technological progress when given exogenously are not distinguishable.
11. Segerstrom's result is not surprising because from equation (18) we know that human capital

accumulation through education could have endogenous growth without scale effects.

12. In the knowledge-driven model, free trade in goods also causes an increase in profitability in the research sector, but does not lead to an increase in the employment in the research sector because the positive effect is exactly offset by the increase in the marginal product of labor in the final-good sector.

13. Grossman and Helpman (1991b) assumes horizontal innovation while the other two papers consider vertical innovation. A survey of some of the results in these papers and some further extensions are given in Grossman and Helpman (1991a, Chapter 11).

14. In an alternative setting, Segerstrom (1991) shows that imitation by Northern firms is possible if firms collude by trigger strategies, rather than compete a la Bertrand.

15. While these papers analyze the effectiveness of IPRs, an important question has not been raised or answered: Since a country (e.g., a less developed country) usually benefit from learning from advanced firms in another country, why would it be willing to protect the intellectual property rights (IPRs) of the technology leader in another country?

16. The assumption that saving is a constant fraction of the domestic output is made for convenience. A probably more realistic assumption is that it is a constant fraction of the national income, or is chosen by either the government or individuals to maximize some objective functions.

17. These two assumptions can be relaxed easily. See Barro and Sala-i-Martin (1995, Chapter 9) for an analysis of cases in which foreign workers bring physical capital with them. Galor and Stark (1990) argue that foreign temporary workers, who are facing the possibility that they may leave soon, may save more.

18. While these effects of labor immigration are similar to those in a static model, a major difference should be noted. If there is a once-and-for-all inflow of foreign workers, as is assumed in a static model, there will be no effect on the steady-state capital-labor ratio and factor prices. The reason is that the steady-state equilibrium is still described by (7). The intuition is that as foreign workers come in, saving of the economy goes up until the steady-state capital-labor ratio climbs up back to its original level.

19. The migration rate can be regulated exogenously by either government or it may depend

endegenously on the wage differential between the countries. This point is not crucial in the present analysis.

20. However, if the migration rate drops as the growth rates of the countries are getting closer to each other, the gap between their adjustment rates will decrease, too.

21. To the extent that government regulations may divert talents away from the R&D sector, the extent of regulations may also affect growth rate. See Goff (1996) and Berger (1996), for example.

22. The literature on indeterminacy [for example, Xie (1994) and several other papers in the same *JET* issue] tells us that, starting from the same initial conditions, different countries can move along different paths with different growth rates, depending on agents' expectations about the future. This literature does not explain why expectations differ, and/or how they can be manipulated.

23. The conditional convergence hypothesis is supported in Barro and Sala-i-Martin (1992) and Sala-i-Martin (1996) only if the technology and preference parameters of the countries are assumed to depart substantially from the usual benchmark cases. For example, the capital share is required to be in the neighborhood of 0.8.

24. Sala-i-Martin (1996) calls this $\beta$-convergence in the sense that the ratio of the per capita income of the North to that of the South declines over time.

25. In the neoclassical framework introduced in Section 3, the steady state of a closed economy must be unique. However, Quah (1996) and Galor (1996) argue that multiple steady states may exist in the presence of overlapping generations, threshold externality, capital market imperfections, heterogeneity, country size, or club formation. See the papers cited in these two papers for more details.

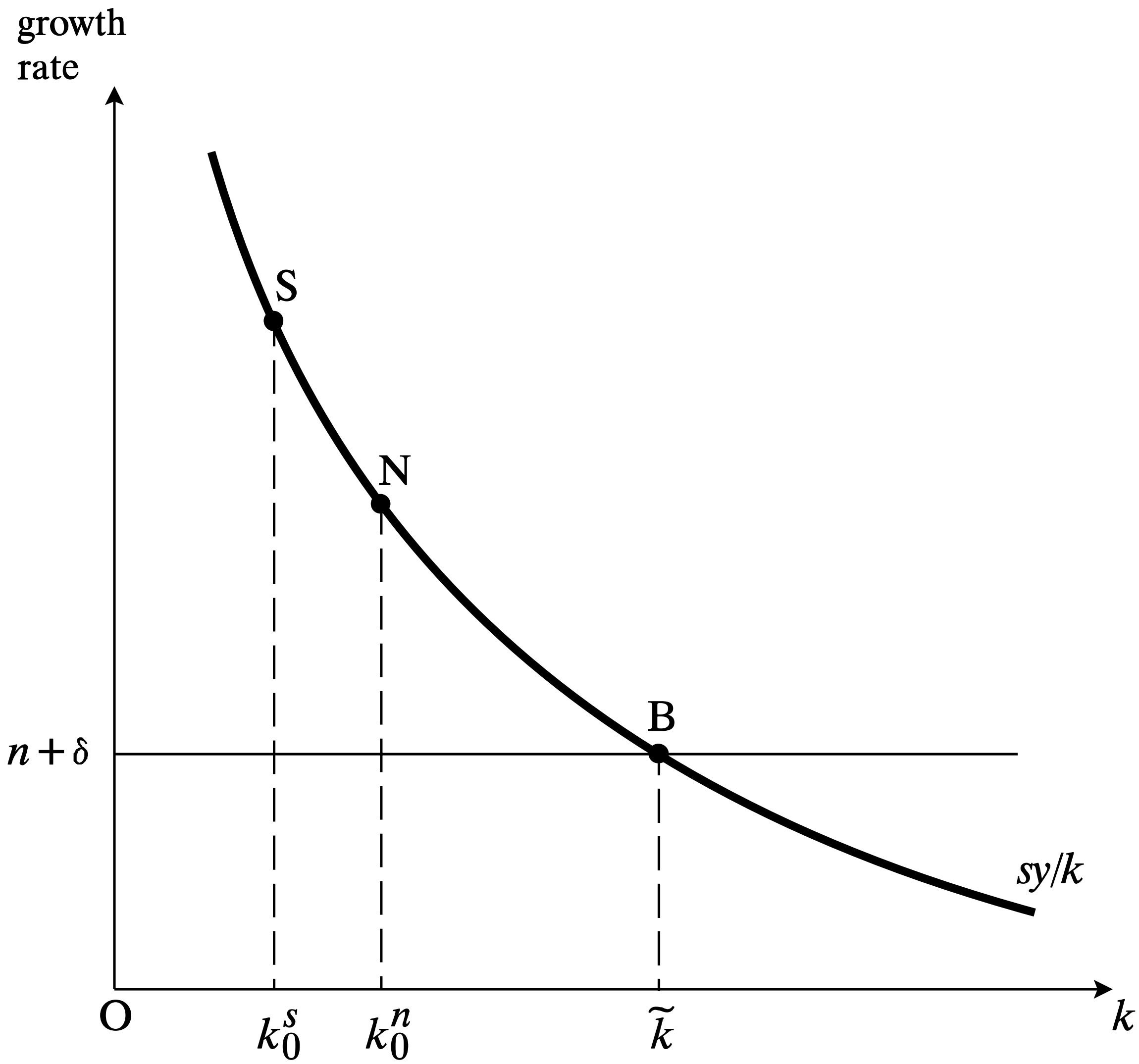


Figure 1

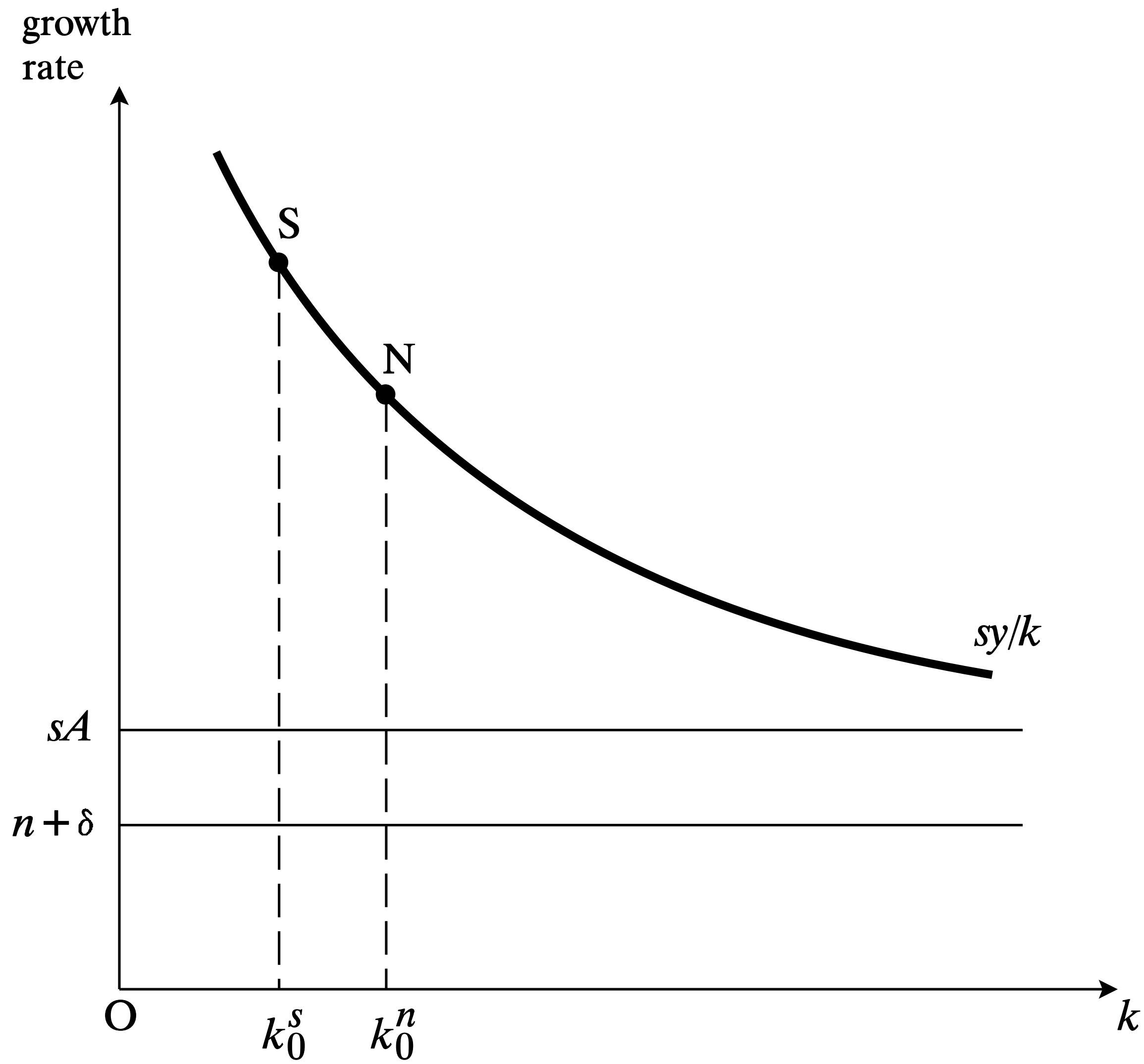


Figure 2

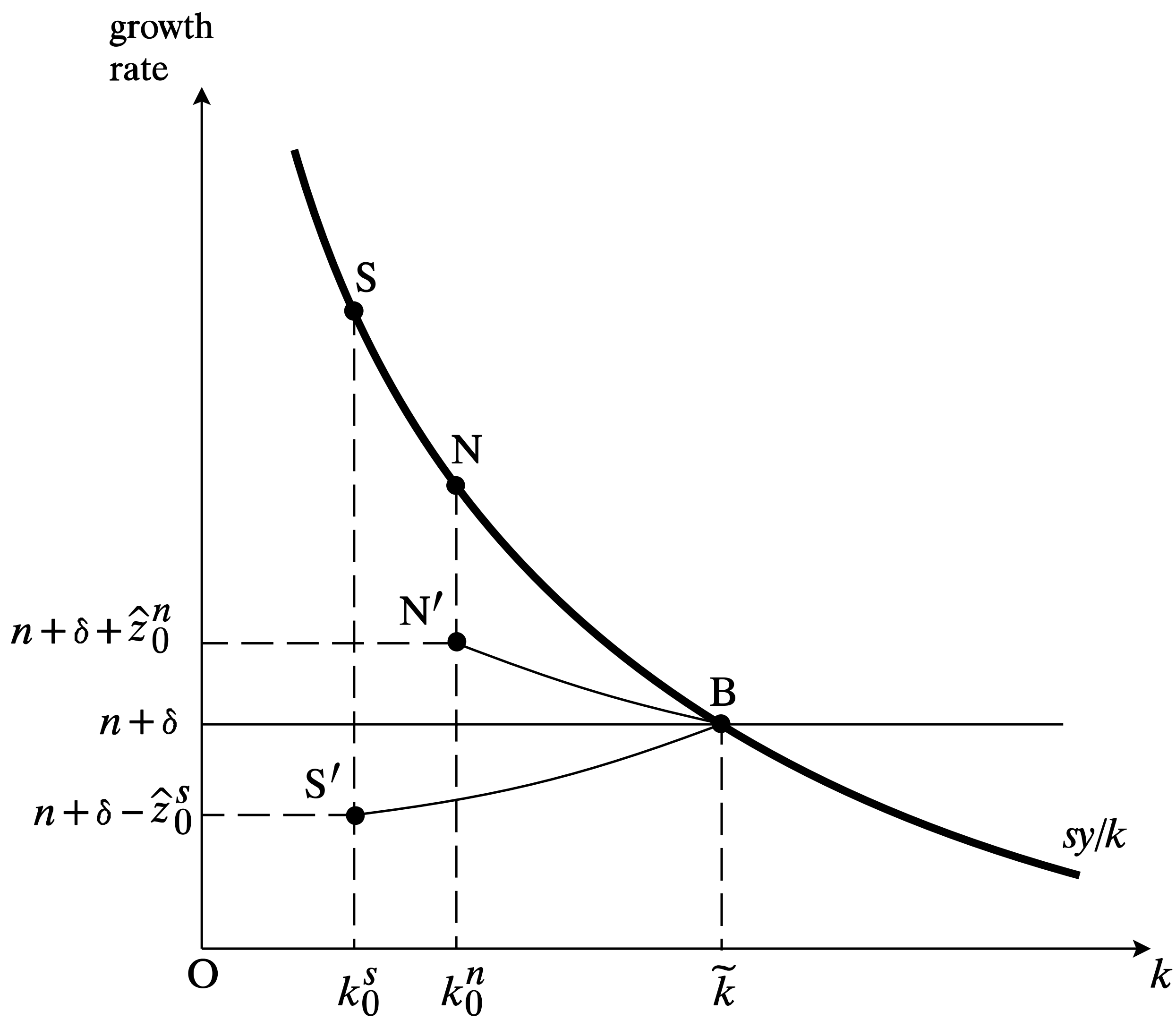
growth
rate
S
N
N′
$n+\delta+\hat{z}_0^n$
B
$n+\delta$
S′
$n+\delta-\hat{z}_0^s$
$sy/k$
O
$k_0^s$
$k_0^n$
$\tilde{k}$
$k$

Figure 3

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