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ENDOGENOUS MACROECONOMIC GROWTH THEORY

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**ABSTRACT**

The paper focuses on the innovation-based approach to endogenous growth. It begins by spelling out conditions for sustained long-run growth in neoclassical economies and uses these conditions as a standard of comparison for the conditions required to sustain long-run growth in economies with product innovation. It presents two models of product innovation that can sustain growth in the long run. The models share the same fundamental mechanism of economic growth. They are used to derive a variety of implications relating structural features to long-run growth rates and they are then applied to a number of policy issues. The usefulness of the approach represented by these models is examined by considering a number of issues, such as unemployment and trade relations.

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## 1. INTRODUCTION

Fortunes of nations change over time. Leading economic powers of the past have become poorly performing economies of the present, and poor economies of the past have become the new leaders. The determinants of the wealth of nations and its evolution over time have mystified economists ever since the beginnings of our discipline. Why do some countries grow faster than others? And how have the underlying forces of growth changed over time? Complete answers to these questions cannot possibly be provided within the narrow limits of a single branch of economics, such as macroeconomics, nor even within the confines of our profession as commonly perceived. Nevertheless, macroeconomic theories of economic growth have much to offer, as exemplified by the seminal contributions of Ramsey (1928), Harrod (1939), Domar (1946) and Solow (1956).

The neoclassical theory of economic growth has been mostly concerned with capital accumulation. When confronted with data, however, its central tenet could explain only a fraction of the variations in growth rates, while the rest was attributed to technical progress (see Solow [1957] and Maddison [1987]). On the other hand, attempts to explain technical progress were, unfortunately, not very successful, with Arrow's (1962a) theory of learning-by-doing being an exception. But that theory suffers from the limitation that it assumes that productivity improvements occur serendipitously as a byproduct of capital accumulation, while deliberate efforts to develop new products and technologies have been very prominent indeed. It suffices to recall the dramatic developments in consumer electronics, computers and pharmaceuticals in order to see the important role of deliberate research and development in raising our standards of living. R&D has grown in importance in all industrial nations. In the OECD countries

in particular real expenditure on R&D has grown at 6% per annum in the decade ending in 1985 (see OECD [1989]). And some of the large Japanese companies now invest more in research and development than in plant and equipment. We have to bear these facts in mind when constructing our theories.

The new wave of research on economic growth was stimulated by Romer (1986) and Lucas (1988). Their work relies on Arrow's mechanism of learning-by-doing. But following Uzawa (1965), they have redirected its application to the accumulation of knowledge and human capital rather than the accumulation of plant and equipment. And at least as important, they have changed the focus towards explanations of sustained long-run growth and cross country variations in growth rates.

Following Arrow (1962a) they have taken the view that aggregate production exhibits increasing returns to scale. But the returns to scale are external to single economic agents and internal to a sector or larger parts of the economy. Consequently competition can prevail. This approach avoids complications of market conduct and structure that arise when economies of scale are internal to firms. Such complications are unavoidable, however, when we wish to deal explicitly with profit seeking investment in innovation, as we should, given the rising importance of commercial R&D in the industrial world.

The integration of imperfect competition with innovation-based growth was first achieved by Judd (1985). His main interest was in issues of industrial organization, however. For this reason he did not explore the implications of his work for growth. Romer (1990a) combined Judd's approach with learning-by-doing *in innovation* and thereby developed a model that sustains long-run growth at an *endogenous rate*. This was an important achievement, because it opened the door to a new research line with attractive realistic features.

Learning-by-doing in research and development is a natural phenomenon.<sup>1</sup> Current researchers use the stock of knowledge that has been accumulated over long periods of time. They draw upon the laws of physics and mathematics, properties of chemical compounds, the structure of a cell, and other fruits of past labor. And they make use of accumulated knowledge about commercial traits, such as methods of refrigeration or the architecture of personal computers. Many commercial R&D efforts generate not only an appropriable product such as a technology for the manufacturing of a new good, but also a nonappropriable product such as a new way of using components, or a new material that can be used in a variety of applications. The nonappropriable product adds to society's general stock of knowledge, which is freely used by many parties. These spillovers from industrial research drive a wedge between the private and social return on R&D (see Arrow [1962b]). Existing estimates indicate that the social rate of return on R&D is more than twice as high as the private rate of return (see Mansfield et al. [1977] and Scherer [1982]). It follows that the uncompensated product of R&D is substantial. Naturally, the incentive of entrepreneurs to innovate derives from the return on the compensated product. These features will be taken into account in what follows.

New innovation-based models of economic growth come closer than ever before to Schumpeter's view of the capitalist system:

"Was not the observed performance [of technological progress] due to that stream of inventions that revolutionized the technique of production rather than to the businessman's hunt for profits? The answer is in the negative. The carrying into effect of those technological novelties was of the essence of that hunt." (p.110)

His emphasis on the entrepreneur and the link between innovation and profits are

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<sup>1</sup>Empirical studies of productivity have used knowledge capital variables that are based on cumulative R&D expenditure long before their use in the theoretical models; see Griliches (1979).

clearly manifested in this literature, as is his belief that the marginal productivity of innovations need not decline, because new inventions can be as productive as old.

## 2. NEOCLASSICAL GROWTH

We are all familiar with the neoclassical theory of economic growth; it has been taught almost unrivaled for about three decades. For this reason there is no need for me to dwell upon it in detail. Nevertheless, my discussion of endogenous growth would be grossly incomplete if I neglected to point out its place in the neoclassical theory. I will therefore lay out conditions needed for sustained endogenous growth in neoclassical models, and relate them to similar conditions in innovation-based models of growth.

The main point I wish to make in this regard appears already in Solow's (1956) classic paper and can be seen most clearly with the help of his model. Consider a stripped down version of a Solow economy in which the labor force does not grow, capital does not depreciate, and the state of technology does not change over time. Under these conditions accumulation of capital equals saving:

$$(2.1) \quad \dot{K} = sF(K,L),$$

where  $K$  represents the capital stock,  $L$  the labor force,  $s$  the savings rate, and  $F(\cdot)$  the constant returns to scale production function. Evidently, in this economy the capital stock grows without bound. It follows that output also grows without bound and so does income per capita. But what happens to the growth rate of per capita income?

The rate of growth of income per capita equals

$$(2.2) \quad g_{Y/L} = sF_k(K,L),$$

where  $F_k(\cdot)$  denotes the marginal product of capital. Therefore the long-run growth rate approaches zero unless the marginal product of capital remains positive as capital accumulates without bound. The assumption that the marginal product of capital approaches zero (an Inada condition) has been common in the literature. When this condition holds growth peters out. Observe, however, that this simple Solow economy sustains long-run growth whenever the marginal product of capital is bounded below by a positive constant.

The condition for sustained growth becomes more demanding in the presence of capital depreciation or population growth. If, for example, the population grows at the rate  $g_L > 0$ , the lower bound on the marginal product of capital that is needed to sustain long-run growth becomes  $F_k(K,L) > g_L/s$  (rather than  $F_k(K,L) > 0$ ). Evidently, this lower bound is higher the higher the rate of population growth and the lower the rate of savings. The main point remains the same, however: *the economy grows in the long run if the marginal product of capital does not decline too much as a result of capital accumulation.*<sup>2</sup>

Our last conclusion depends only partially on the postulated form of saving behavior. As an alternative to the fixed saving rate take, for example, the case of infinitely lived consumers who optimize over their choice of consumption and saving, using a time separable intertemporal utility function with a constant elasticity of the

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<sup>2</sup>This insight has been exploited in a number of recent studies, such as Rebelo (1990) and Jones and Manuelli (1990a).



marginal utility of consumption. The intertemporal utility function is given by

$$(2.3) \quad U_t = \int_t^{\infty} e^{-\rho(\tau-t)} u(\tau) d\tau,$$

where  $u(\tau)$  describes the flow of utility at time  $\tau$  and  $\rho$  represents the subjective rate of time preference, and

$$(2.4) \quad u = \frac{C_Y^{1-\nu} - 1}{1 - \nu}, \quad \nu > 0,$$

where  $C_Y$  stands for the consumption level of the final product  $Y$ . The parameter  $\nu$  represents the elasticity of the marginal utility of consumption while its inverse  $1/\nu$  equals the intertemporal elasticity of substitution. A consumer that maximizes (2.3)–(2.4) subject to an intertemporal budget constraint allocates consumption according to the rule:

$$(2.5) \quad \frac{\dot{C}_Y}{C_Y} = \frac{1}{\nu} \left[ r - \rho - \frac{\dot{p}_Y}{p_Y} \right],$$

where  $r$  stands for the nominal interest rate and  $p_Y$  for the nominal price of output. It follows that consumption grows over time at a rate given by the product of the intertemporal elasticity of substitution and the difference between the real interest rate and the subjective discount rate.

Equation (2.5) shows clearly that this type of an economy sustains long-run growth only if the real interest rate remains above the subjective discount rate in the

long run. As is well known, however, in the absence of capital depreciation the real interest rate equals the marginal product of capital. It follows that income per capita grows in the long run if and only if the marginal product of capital remains higher than the subjective rate of time preference. In this case the long-run rate of growth is higher the lower is the subjective rate of time preference and the higher the intertemporal elasticity of substitution.

We have thus seen that a sufficiently high marginal product of capital leads to long-run growth in per capita income for two forms of saving. It may appear therefore that savings behavior does not constrain growth in neoclassical economies. This conclusion is unwarranted, however. First, even in the above discussed cases parameters of the saving function do matter whenever growth does not peter out. And second, there exist economic structures in which aggregate saving is insufficient to sustain long-run capital accumulation even with high marginal products of capital. Jones and Manuelli (1990b) and Boldrin (1990) provide examples of this phenomenon. They show that in a one-sector overlapping generations model growth peters out in the long run because the young generation does not have enough resources to purchase an ever increasing capital stock. For this reason aggregate saving, that amount to the savings of the young, cannot support continued growth.

Leaving aside the case of overlapping generations, recall the role that technical progress can play in the neoclassical theory. With labor augmenting technical progress the production function takes the form

$$(2.6) \quad Y = F(K, AL),$$

where  $A$  represents the state of technology. Technical progress raises  $A$  and thereby

the marginal product of capital. Higher marginal productivity of capital leads to a higher real interest rate. Now take the case in which the rate of consumption growth is governed by (2.5). In this case capital accumulation depresses the real interest rate and therefore the rate of consumption growth, while technical progress raises the real interest rate thereby increasing the rate of consumption growth. In steady state the rate of capital accumulation equals the rate of technical progress and the real interest rate remains constant. This describes the case of exogenous technical progress that leads to exogenous long–run growth.

Following Arrow's analysis of learning–by–doing, however, some growth theorists have linked the state of technology to cumulative investment experience. With this view the state of technology parameter  $A$  becomes a function of the economy's capital stock  $A(K)$  (see Sheshinski [1967]). The effect of capital on productivity is assumed to be external to an individual investor. For this reason the real interest rate equals the private marginal product of capital  $F_K[K, A(K)L]$ . It follows that with this form of endogenous technical progress an economy can sustain long–run growth as long as the state of technology is sufficiently responsive to capital accumulation.

This discussion points to the fact that sustainability of long–run growth depends critically on the extent to which capital accumulation depresses its marginal productivity as perceived by investors, and on whether there exist offsetting forces that prevent the marginal product of capital from declining too much. In the model of learning–by–doing, learning provides an offsetting device, but this mechanism will not suffice if the pace of learning is not fast enough or learning is bounded.

Now that we have identified the mechanisms of long–run growth in the neoclassical theory, we may turn to the more recent innovation–based theories of

economic growth. I begin with an approach based on horizontal product differentiation. This approach suffers from several shortcomings, some related to the specification of product differentiation and others related to the mechanism of knowledge accumulation. It is important, however, to bear in mind as I proceed that these details are not particularly important, as they can and will be replaced with more appealing ingredients without affecting the results in any fundamental way. On the other hand, the approach I will describe first has the advantage of being simple, and it brings out in a clear way important characteristics of the innovation-based approach to economic growth.

### 3. EXPANDING PRODUCT VARIETY

A particularly simple model of innovation-based growth builds on the Dixit and Stiglitz (1977) formulation of horizontal product differentiation. We define an index  $D$  by means of the following constant elasticity of substitution function:

$$(3.1) \quad D = \left[ \int_0^n x(j)^\alpha dj \right]^{1/\alpha}, \quad 0 < \alpha < 1,$$

where  $x(j)$  represents the quantity of variety  $j$  of a high-tech product,  $n$  stands for the measure (the number) of available brands, and  $\alpha$  is a parameter. The elasticity of substitution between every pair of brands equals  $1/(1-\alpha)$ . The postulated restriction on  $\alpha$  implies an elasticity of substitution larger than one, which means that varieties substitute well for each other. Equation (3.1) yields constant elasticity demand functions with marginal revenue  $MR(j) = \alpha p(j)$ , where  $p(j)$  represents the price of

brand  $j$  (the demand elasticity with respect to the price equals the elasticity of substitution).

Next assume that all brands require the input of one unit of labor per unit output. Then marginal costs equal the wage rate  $w$  for all brands, and  $MR(j) = MC(j)$  implies that all brands are equally priced at

$$(3.2) \quad p = \frac{w}{\alpha}.$$

With this pricing rule operating profits are

$$(3.3) \quad \pi = (1 - \alpha) \frac{pX}{n}$$

per brand, where  $X$  represents aggregate output of high-tech products.

These relationships are well known from the static theory of monopolistic competition. In a static environment one would add fixed costs of, say,  $f$  units of labor per brand in manufacturing, and close this model with Chamberlain's free entry condition for the large group case that requires zero (excess) profits; i.e.,  $\pi = wf$ , and a labor market clearing condition,  $X + nf = L$ , where  $L$  represents available labor.<sup>3</sup>

This simple general-equilibrium model of horizontal product differentiation has been extended by Judd (1985) to a dynamic framework. His formulation, like most of the new literature on innovation-based growth, interprets the fixed costs as a research and development expense, where R&D leads to the development of new varieties of the differentiated product. Other specifications assign R&D the role of product

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<sup>3</sup>From these two conditions together with (3.2) and (3.3) we calculate the equilibrium number of brands  $n = (1-\alpha)L/f$  and the output level  $X = \alpha L$ .

improvement (vertical product differentiation) or cost reduction (see Aghion and Howitt [1990] and Grossman and Helpman [1991a]). A central feature of R&D costs is that they have to be paid up front, before operating profits can be appropriated. Consequently operating profits accrue at different points in time from R&D costs. This realistic time structure introduces natural dynamics.

In the dynamic version of monopolistic competition we replace Chamberlain's static free entry condition with a dynamic free entry condition that takes the following form (this discussion follows Grossman and Helpman [1991b, chap. 3]). Firms are valued according to their expected profit stream. A typical firm owns the technology for manufacturing a single brand of the differentiated product and it possesses indefinite monopoly power in the supply of its brand. It follows that the value of a firm equals the present value of its profits,

$$(3.4) \quad v(t) = \int_t^{\infty} e^{-R(\tau,t)} \pi(\tau) d\tau,$$

where  $v$  represents the value of a firm and  $R(\tau,t) = \int_t^{\tau} r(z) dz$  represents the discount rate from time  $\tau$  to  $t$ . This implies the no arbitrage condition

$$(3.5) \quad \frac{\pi}{v} + \frac{\dot{v}}{v} = r.$$

It states that the rate of return on the ownership of a firm — consisting of the profit rate  $\pi/v$  (the inverse of the price-earning ratio) and the rate of capital gain  $\dot{v}/v$  — has to equal the nominal interest rate  $r$ .

An entrepreneur that contemplates investing resources in the development of a new brand expects a reward of  $v$  on his R&D effort. He therefore engages in product development unless the cost of R&D exceeds this value. Now suppose that the productivity of research labs rises with the stock of available knowledge  $K_n$ . This property plays a central role in bringing about endogenous long-run growth, as we will shortly see. In this case the dynamic free entry condition implies that at each point in time the value of a firm does not exceed product development costs  $wa/K_n$ , where  $a$  represents a parameter (because otherwise labs will have an unbounded demand for labor), and the flow of newly invented products equals zero, unless product development costs just equal the value of a firm:

$$(3.6) \quad v \leq \frac{wa}{K_n}, \quad \text{with equality whenever } \dot{n} > 0.$$

Now labor market clearing requires employment in R&D plus employment in manufacturing to equal the available labor supply:

$$(3.7) \quad \frac{a}{K_n} \dot{n} + X = L,$$

where the first term on the left hand side represents employment in R&D and the second term represents employment in manufacturing.

In this economy investment consists of developing new products (as opposed to building new capital equipment in the neoclassical growth model). This investment has to be financed by savings. For this purpose we may borrow the intertemporal structure of preferences (2.3) from the previous section, where this time

$$(3.8) \quad u = \frac{C_D^{1-\nu} - 1}{1 - \nu}, \quad \nu > 0.$$

As before, the parameter  $\nu$  represents the elasticity of the marginal utility of consumption, while  $C_D$  represents consumption in terms of the index  $D$ . In equilibrium  $C_D = D$ . It follows from our discussion in the previous section that in this case too infinitely lived households allocate spending over time according to (see [2.5])

$$(3.9) \quad \frac{\dot{C}_D}{C_D} = \frac{1}{\nu} \left[ r - \rho - \frac{\dot{p}_D}{p_D} \right],$$

where  $p_D$  is the price index of  $D$ , given by

$$(3.10) \quad p_D = \left[ \int_0^n p(j)^{-\alpha/(1-\alpha)} dj \right]^{-(1-\alpha)/\alpha}$$

This completes the description of the growth model, except for the evolution of knowledge capital.

#### 4. IMPLICATIONS

As we will see shortly, long-run properties of economies of the type I have described depend in important ways on the evolution of knowledge capital. For this reason I deal first with the case in which knowledge capital is constant and only later on with the more interesting case of a positive feedback from R&D experience to the



knowledge stock.

### Constant Knowledge Capital

In the case of a constant stock of knowledge capital *the economy does not grow in the long run*. This result is important for understanding the forces of long-run growth that I will describe later. It is necessary, however, first to spell out what we mean by growth in the present context. What growth rate should we measure? Real gross domestic product is a natural candidate. So is the real consumption index  $C_D$  (= D). For current purposes I use the latter (see, however, Grossman and Helpman [1991b, chap. 3] for the relationship between these two growth rates).

The first thing to observe is that the real consumption index can grow in the long run if either variety expands over time or aggregate output of manufacturing rises over time. For a constant stock of knowledge capital, however, the resource constraint (3.7) implies that the flow of new goods and the output volume are both bounded. Therefore the rate of innovation  $g$ , defined as the rate of increase of the number of products (i.e.,  $g = \dot{n}/n$ ), converges to zero, and the rate of growth of the real consumption index also converges to zero.<sup>4</sup>

### Rising Knowledge Capital

The assumption of a constant stock of knowledge capital is not realistic. An economy that engages in product innovation expands its knowledge base. It is, however, necessary to distinguish between different forms of knowledge. For even in the above

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<sup>4</sup>Since all brands are equally priced they are used in the same quantities. In the event (3.1) implies  $D = n^{(1-\alpha)/\alpha} X$  and the rate of growth of D equals  $\frac{1-\alpha}{\alpha} g + \frac{\dot{X}}{X}$ .

described economy with a constant stock of *knowledge capital* innovation leads to an expansion of knowledge, in the sense that it increases the number of brands that the economy knows how to produce. Knowledge, as measured by the number of blue prints, rises over time in an innovating economy, and this knowledge expansion raises the productivity of resources in *manufacturing*. There exists, however, another measure of knowledge that we have termed *knowledge capital*. This stock of knowledge affects productivity in the *research lab*. Cumulative experience in R&D raises the productivity of labs by raising the stock of knowledge capital available to researches, as I have explained in the introduction. Unlike some forms of learning by doing, however, such as on the job training, important parts of knowledge that accumulates in the process of research and development can be used by other agents.

In order to capture these features I now follow Romer (1990a) in assuming that the stock of knowledge capital equals cumulative experience in R&D as measured by the number of brands that have been developed; namely

$$(4.1) \quad K_n = n.$$

This specification implies that every developer of a new brand contributes equally to the future stock of knowledge, but more flexible forms can be used without altering the main thrust of the argument (see Grossman and Helpman [1991b, chap. 3]) In our case the economy settles down immediately on a steady state that can be characterized by the following two equations:<sup>5</sup>

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<sup>5</sup>The first equation is a direct consequence of the resource constraint (3.7). The second results from the no-arbitrage condition (3.5) in the following way. Take the wage rate to be the numeraire; i.e.,  $w(t) = 1$  for all  $t$ . Then from the pricing equation (3.2)  $p = 1/\alpha$ , a constant, and output per brand equals for all brands (although it may vary

$$(4.2) \quad ag + X = L,$$

$$(4.3) \quad \frac{(1-\alpha)X}{\alpha a} = \rho + \beta_D g, \quad \beta_D = \left[ 1 + \frac{1-\alpha}{\alpha}(\nu-1) \right].$$

The first equation represents the resource constraint, where  $g$  is the rate of innovation, while the second describes the no-arbitrage condition. The left hand side of (4.3) represents the inverse of the price earning ratio while the right hand side represents the effective cost of capital; namely, the real interest rate minus the rate of capital gain on equity holdings. I assume  $\beta_D > 0$ .

Our steady state conditions are depicted in figure 3.1; line LL represents the resource constraint while NN represents the no-arbitrage condition. The latter may be termed the Schumpeter line, because it embodies the notion that innovation is driven by the quest for profit opportunities. LL slopes downwards because an increase in the rate of innovation involves more employment in research labs and therefore less employment in manufacturing. On the other hand NN slopes upwards. An increase in the rate of innovation raises the effective cost of capital to an entrepreneur, because it leads to a higher real interest rate and a faster depreciation of the value of a firm. Consequently the entrepreneur requires a higher profit rate (a lower price earning ratio) in order to

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over time). It follows from (3.1) that  $\dot{D}/D = (1-\alpha)g/\alpha$  (because  $X$  is constant) and from (3.10) that  $\dot{p}_D/p_D = -(1-\alpha)g/\alpha$ . The consumer's intertemporal allocation rule (3.9) implies then an interest rate

$$r = \rho + g \frac{1-\alpha}{\alpha}(\nu-1).$$

Assuming positive product innovation (see the discussion that follows in the text) the free entry condition (3.6) implies  $v = a/n$  and  $\dot{v}/v = -g$ . Substituting these results together with the profit equation (3.3) into the no-arbitrage condition (3.5) yields (4.3).

engage in R&D. To attain a higher profit rate, however, more resources have to be employed in manufacturing. The intersection point A describes a long-run equilibrium.

The figure describes a fundamental tradeoff between resource deployment in innovation and manufacturing. Growth is constrained by resource availability on the one hand and by market incentives on the other. One sees from the figure that a country innovates faster when it has: (a) a larger resource base (an expansion of  $L$  shifts out the LL line);<sup>6</sup> (b) a lower rate of time preference (a reduction of  $\rho$  shifts down the Schumpeter line NN); (c) a higher degree of monopoly power (a reduction of  $\alpha$  shifts down the Schumpeter line); and (d) a higher intertemporal elasticity of substitution (a reduction of  $\nu$  shifts down the Schumpeter line). Evidently, the rate of growth is endogenous. These structural determinants of the rate of innovation can also be seen directly from the explicit solution

$$(4.4) \quad g = \frac{1}{\alpha + (1-\alpha)\nu} \left[ (1-\alpha)\frac{L}{a} - \alpha\rho \right].$$

Note that a positive rate of innovation obtains if and only if  $L/a > \alpha\rho/(1-\alpha)$ . This restriction applies whenever the effective size of the country is large enough (as measured by  $L/a$ ), the degree of monopoly power is large enough (as measured by  $1/\alpha$ ), or the rate of time preference is low enough. Otherwise the country does not innovate.<sup>7</sup>

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<sup>6</sup>This result will be qualified later on.

<sup>7</sup>When the proposed parameter restriction does not hold, line NN in figure 3.1 lies everywhere above LL in the positive orthant. In this case the intersection point of LL with the vertical axis represents the equilibrium. At this point the present value of profits falls short of R&D costs. In the event entrepreneurs have no incentive to innovate. There also exists a restriction on parameters that prevents innovation from proceeding at a pace that is so rapid as to make the utility level in (2.3) unbounded. Since  $D$  grows at the rate  $g(1-\alpha)/\alpha$ , the functional forms in (2.3) and (3.8) imply

### Welfare

My discussion has concentrated on the determinants of innovation and growth. A natural question that arises is whether the market allocates resources efficiently between innovation and manufacturing. There are four sources of potential market failure.

- First, manufacturers price goods above marginal costs. Relative prices of different brands are not distorted, however, because all suppliers of brands exercise the same degree of monopoly power. In addition, brands of the differentiated product are the only goods supplied. For these reasons the departure from marginal cost pricing does not distort resource allocation (see Lerner [1934]).
- Second, an entrepreneur that contemplates the development of a new product does not take into account the contribution of his product to consumer surplus.
- Third, the entrepreneur does not take into account the effect of his R&D effort on profits of competing firms, despite the fact that he depresses the profitability of competing brands. This feature exemplifies Schumpeter's notion of creative destruction.
- Fourth and last, the benefits to future product developers, that will work with a larger stock of knowledge capital, are not considered in the decision to invest in R&D.

It so happens that in this model underinvestment in product development as a result of the disregard for consumer surplus just equals overinvestment in product development as a result of the disregard for destruction of profits. Thus the allocation of resources *is efficient when product development does not affect the stock of knowledge*

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$\rho > g(1-\nu)(1-\alpha)/\alpha$  for that condition to hold. Substituting (4.4) into this inequality yields a restriction on the economy's parameters. Observe, however, that the inequality is satisfied whenever the intertemporal elasticity of substitution is smaller than one; i.e.,  $\nu \geq 1$ .

capital (see Grossman and Helpman [1991a, chap. 3]). When R&D contributes to the stock of knowledge capital, however, the equilibrium pace of innovation is too slow.<sup>8</sup>

## 5. CAPITAL ACCUMULATION

Up to this point my description of innovation-based growth has disregarded investment in plant and equipment. I have purposely chosen to present the theory in this way in order to emphasize its novel elements. In practice, however, investment in plant and equipment constitutes a large share of GDP (20% or more in many countries), and the share of investment relates positively to the growth rate of GDP (see Barro [1991]). For these reasons we need to ensure that the theory can encompass investment in plant and equipment in a suitable way.<sup>9</sup>

The basic story to be formalized below incorporates the type of capital accumulation emphasized in the neoclassical growth model. We have seen that in the neoclassical model technical progress raises the marginal product of capital, thereby raising the profitability of investment in plant and equipment. In the event capital deepening, that ceteris paribus depresses the marginal product of capital, can nevertheless continue indefinitely. The same applies here, except that now *technical*

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<sup>8</sup>The last point can be seen as follows. It can be shown by means of optimal control or variational methods that the optimal rate of innovation remains constant over time. In this case we can compute consumer welfare from (2.3) and (3.8) as

$$U_t = \frac{1}{1-\nu} \left[ \frac{n(t)^{(1-\nu)(1-\alpha)/\alpha} X^{1-\nu}}{\rho - (1-\nu)(1-\alpha)g/\alpha} - \frac{1}{\rho} \right].$$

Maximizing this expression with respect to  $g$  and  $X$  subject to the resource constraint (4.2) yields the optimal rate of innovation. The equilibrium rate of innovation (4.4) is a fraction  $(1-\alpha)\nu/[\alpha + (1-\alpha)\nu]$  of the optimal rate of innovation.

<sup>9</sup>My description follows Grossman and Helpman (1991b, chap. 5). For an alternative view see Romer (1990a).

*progress is driven by profit seeking entrepreneurs.* In other words, the invention of new brands generates the incentive to install more fixed plant and equipment.

In order to demonstrate the role of conventional capital, consider an economy in which the differentiated product is an intermediate input. The economy manufactures a single final homogeneous output  $Y$  that can be used for either consumption or investment in plant and equipment, just like in the neoclassical model. The production function of  $Y$  takes the Cobb–Douglas form:

$$(5.1) \quad Y = A_Y D_Y^\eta K_Y^\beta L_Y^{1-\beta-\eta}, \quad \eta, \beta > 0, \quad 1 > 1-\beta-\eta > 0,$$

where  $A_Y$  is a constant,  $D_Y$  denotes a Dixit–Stiglitz index of differentiated products (see [3.1]),  $K$  represents the stock of plant and equipment, and  $L_Y$  represents direct labor employment in the production of  $Y$ . In this specification the production of final output takes place under constant returns to scale.

In this economy the demand for labor derives from three sources: R&D, manufacturing of differentiated intermediate inputs and production of the final output. Therefore labor market clearing requires  $ag + X + L_Y = L$ .

It is shown in Grossman and Helpman (1991a) that in this type of an economy with non–depreciating capital the steady state growth rate of output  $Y$  equals

$$(5.2) \quad g_Y = \frac{\eta}{1-\beta} \frac{1-\alpha}{\alpha} g,$$

and the rate of investment equals<sup>10</sup>

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<sup>10</sup>These calculations assume that (2.3)–(2.4) describe preferences.

$$(5.3) \quad \frac{\dot{K}}{Y} = \frac{\beta g_Y}{\rho + \nu g_Y}.$$

Moreover, the equilibrium rate of innovation and the volume of manufacturing of high-tech differentiated products can be described by means of a figure similar to 3.1. An analysis of the figure confirms our earlier findings that a country innovates faster in the long run when its resource base is larger, it is more productive in R&D, it has a lower rate of time preference, its intertemporal elasticity of substitution is larger, or its degree of monopoly power is higher (see Grossman and Helpman [1991b, chap. 5]).

Evidently, the rate of investment increases with the rate of output growth while the latter increases with the rate of innovation. Combined with the results concerning the determinants of the rate of innovation, these relationships imply, for example, that countries with low rates of time preference innovate faster, experience faster output growth, and have a higher rate of investment. Importantly, however, investment is *not* a primary source of growth in these economies. Rather, the primary sources of growth are a variety of factors (such as the rate of time preference and the degree of monopoly power) that affect the incentive for industrial research, while the rate of investment adjusts so as to keep the rate of expansion of conventional capital in line with the growth rate of output. In terms of causality, the investment rate and the rate of growth are simultaneously determined by technological progress that affects them in essentially the same direction, while the pace of technological progress is endogenously determined by more primitive factors.



## 6. QUALITY LADDERS

In the theory of innovation-based growth that has been described so far entrepreneurs invest resources in R&D in order to develop new brands of a horizontally differentiated product. Diversity is valuable per se because it raises productivity of manufacturing for a given volume of inputs, or household utility for a given volume of consumption. When coupled with productivity gains in R&D as a result of the accumulation of knowledge capital, they lead to sustained long-run growth. The growth rate depends on an economy's resource base, subjective rate of time preference, degree of monopoly power, and parameters of the production function.

This model has several unattractive features, however. First, new goods are no better than old. As a result, every brand competes on equal footing with all existing products. Second, society uses old brands side by side with new ones, without ever dropping a product. Finally, whereas innovation involves risk taking, the model employs a deterministic R&D technology. All of these shortcomings notwithstanding, we have identified a mechanism of economic growth that does not depend on the model's details: (a) Profit-seeking drives innovation; (b) Innovation contributes to the society's stock of knowledge in addition to providing the innovator with an appropriable asset; and (c) An expansion of knowledge capital reduces future innovation costs. This cost reduction mitigates the decline in the profitability of inventive activity that would have taken place in its absence. As a result, the profitability of innovation can be sustained, and with it a positive growth rate. The rate of growth depends on structural features and on economic policy.

In this section I describe a model of quality ladders in which innovation improves the quality of a fixed set of goods or reduces their manufacturing costs. New products

drive out old products from the market, and R&D is risky. In this model the rate of innovation equals the fraction of goods that are improved per unit time. Despite these marked departures from the model of horizontal product differentiation, I will show that the same mechanism of economic growth also operates in the new model. Moreover, both models have a similar reduced form. For this reason a figure similar to 3.1 can be used to describe its equilibrium. My presentation follows Grossman and Helpman (1991b, chap. 4), where readers can find the missing details of the arguments.

The economy manufactures a continuum of goods indexed by points on the interval  $[0,1]$ . The utility derived from a good depends on its quality. A consumer enjoys a unit of good  $j$  that was improved  $m(j)$  times,  $j \in [0,1]$ , as much as he would enjoy  $\lambda^{m(j)}$  units of the good had it never been improved;  $\lambda > 1$ . In this sense innovation that leads to product improvement raises the quality of a good. One can verify that all the results that follow also apply when innovation leads to cost reduction, whereby a product  $j$  that was improved  $m(j)$  times requires  $\lambda^{-m(j)}$  times the inputs per unit output that would have been required if the product had not been improved at all. I will use the quality improvement interpretation for convenience. Evidently, in this case the consumer chooses to buy a quality of good  $j$  that extracts the lowest price per unit quality; i.e., the lowest ratio  $p(j,m)/\lambda^m$ , where  $p(j,m)$  represents the price of good  $j$  that was improved  $m$  times.

We continue to represent intertemporal preferences by means of (2.3) and the flow of utility by means of (3.8), as in the case of horizontal product differentiation. This time, however, the real consumption index  $C_Q$ , that replaces  $C_D$ , takes on the Cobb–Douglas form

$$(6.1) \quad C_Q = \exp \left[ \int_0^1 \log X(j) dj \right],$$

where  $X(j)$  represents the quality equivalent consumption level of good  $j$ . If, for example, good  $j$  was improved only once, it is available in two qualities:  $\lambda^0 = 1$  and  $\lambda^1 = \lambda$ . Then a consumer who purchases quantity  $x(j,0)$  of the lowest quality and  $x(j,1)$  of the improved brand enjoys the quality equivalent consumption level  $X(j) = x(j,0) + \lambda x(j,1)$ . We have argued above, however, that a consumer will choose the quality that provides the lowest quality adjusted price. In the event  $X(j) = \bar{x}(j)$ , where  $\bar{x}(j)$  represents the consumption level of the brand that provides the lowest quality adjusted price. We denote by  $\bar{p}(j)$  the price of this brand. It follows that the price index of real consumption  $C_Q$  equals

$$(6.2) \quad p_Q = \exp \left\{ \int_0^1 \log \left[ \bar{p}(j) \lambda^{-\bar{m}(j)} \right] dj \right\},$$

where  $\bar{m}(j)$  represents the number of improvements of the brand of good  $j$  that provides the lowest quality adjusted price. This price index can be used to calculate the optimal intertemporal allocation of real consumption, in analogy with (3.9). Namely,

$$(6.3) \quad \frac{\dot{C}_Q}{C_Q} = \frac{1}{\nu} \left[ r - \rho - \frac{\dot{p}_Q}{p_Q} \right].$$

We turn next to manufacturers and innovators.

An innovator that succeeds in improving a good can charge a price  $\lambda$  times higher than the next to the top quality brand and remain competitive in the market.

Let the manufacturing of a brand require one unit of labor per unit output independent of quality. Then in the ensuing price competition between the suppliers of existing qualities the manufacturer of the top quality brand captures the entire market by charging a price that is a shade lower than  $\lambda$  times marginal manufacturing costs. Consequently the top of the line brand provides the lowest quality adjusted price

$$(6.4) \quad p = \lambda w.$$

The same price, which is marked up above marginal costs by the factor  $\lambda$ , applies to the top quality of all goods  $j \in [0,1]$ . It follows that profits derived from owning the technology to manufacture a top quality product equal

$$(6.5) \quad \pi = \left[1 - \frac{1}{\lambda}\right] pX,$$

where  $X = x$  represents the common output level of the top quality brand of every good  $j$  as well as aggregate output (recall that the measure of goods equals one). Lower quality products are neither manufactured nor consumed, and the owners of their technologies derive zero profits. An important thing to note at this stage is the resemblance of the pricing and profit equations (6.4)–(6.5) to the equivalent equations (3.2)–(3.3) for the case of horizontal product differentiation (with  $1/\lambda$  replacing  $\alpha$ ). A significant difference from the point of view of the theory of the firm, however, is that now a firm does not maintain monopoly power forever, but rather loses it and shuts down when a better variety of its good appears on the market. Old products drop out; they are replaced with new brands.

Entrepreneurs have to target particular goods for improvement and they face a risky R&D technology. By employing  $u(l,j)a$  workers per unit time in lab  $l$  that targets good  $j$  the lab attains a flow density of  $u(l,j)$  per unit time of product improvement (as before,  $a$  represents a productivity parameter in R&D). An important feature of our R&D technology is that it is available to everybody and it can improve the top of the line quality. This means that experience in the improvement of a particular good does not provide a lab with future advantages in the improvement of this good. Whatever learning has taken place during the innovation process becomes public. This assumption introduces a spillover from private R&D to the society's stock of knowledge capital. And this contribution is not appropriable by the innovator.

It follows from this specification that the firm that owns the technology to manufacture the top quality brand of good  $j$  faces the hazard rate  $u(j)$  of losing the monopoly profit stream, where  $u(j)$  equals the aggregate across labs of  $u(l,j)$ . This hazard rate is the same for all goods in a symmetric equilibrium, and we denote it simply by  $u$ . The stock market will value a firm according to its *expected* present value of profits, implying a no-arbitrage condition

$$(6.6) \quad \frac{\pi}{v} + \frac{\dot{v}}{v} = r + u.$$

Compared with (3.5) this condition describes the reality that a firm needs to add a risk premium  $u$  to its cost of capital, reflecting the risk of displacement from the market.

An entrepreneur that contemplates investing in product improvement obtains the prize  $v$  if successful. In a time interval of length  $dt$  his probability of success is  $u(l,j)dt$  if he employs  $u(l,j)a$  workers per unit time. The difference between his

expected reward and costs equals  $v u(l,j)dt - u(l,j)wadt$ , and he chooses  $u(l,j)$  so as to maximize this difference. It follows that in equilibrium the value of a firm cannot exceed  $wa$  and it has to equal  $wa$  for innovation to take place (compare with [3.6]):

$$(6.7) \quad v \leq wa, \quad \text{with equality whenever } \iota > 0.$$

It remains to identify the resource constraint. Workers are employed in research labs and in manufacturing plants. Employment in research labs equals  $a\iota$  while employment in manufacturing plants equals  $X$ . Therefore full employment requires (compare with [4.2])

$$(6.8) \quad a\iota + X = L.$$

This completes the description of the model. Our next task is to compare implications of quality–ladder based growth with expanding–variety based growth.

## 7. QUALITY LADDERS vs EXPANDING PRODUCT VARIETY

We can characterize the steady–state of the model with quality ladders by means of two equations, just as we have done for the expanding variety model. One equation consists of the resource constraint that was derived in the previous section, (6.8), whose analogy with the resource constraint (4.2) has already been pointed out. The second equation consists of a no–arbitrage condition, in parallel with (4.3). For the quality

ladders model it takes the form<sup>11</sup>

$$(7.1) \quad \frac{(1-\lambda^{-1})X}{\lambda^{-1}a} = \rho + \beta_Q \iota, \quad \beta_Q = [1 + (\nu-1)\log\lambda].$$

This equation is indeed very similar to (4.3).

We may now use a figure similar to 3.1 to describe the resource constraint (6.8) and the no arbitrage condition (7.1) (where  $\iota$  replaces  $g$  on the horizontal axis). From this figure we can derive the dependence of the long-run rate of innovation on an economy's parameters. In particular, we find again that the rate of innovation is larger the larger the economy's resource base, the higher its productivity in the lab, the lower its subjective rate of time preference, and the higher its degree of monopoly power. Observe, however, that the degree of monopoly power in the quality ladders model

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<sup>11</sup>In steady state  $\iota$  remains constant and so does the volume of output  $X$  (that also equals output per product of the highest quality  $x$  because the measure of goods equals one). Take the wage rate to be the numeraire. Then  $p = \lambda$  and  $\pi = (1-\lambda^{-1})\lambda X$  (see [6.4] and [6.5]). Suppose also that  $\iota > 0$ . Then  $v = a$  (see [6.7]) and  $\dot{v}/v = 0$ . It follows that the no-arbitrage condition (6.6) can be written as

$$(i) \quad \frac{(1-\lambda^{-1})X}{\lambda^{-1}a} = r + \iota.$$

It remains to derive the interest rate by means of (6.1)–(6.3). In (6.1)  $\log X(j) = \log X + \bar{m}(j)\log\lambda$ , where  $\bar{m}(j)$  represents the number of times good  $j$  has been improved (because the top quality product provides the lowest quality adjusted price). Since all goods are equally targeted, the arrival of improvements follows a Poisson process with the arrival probability  $\iota$  per unit time. In the event

$$\int_0^1 \bar{m}(j) dj = \iota \log\lambda$$

in a time interval of length  $t$ . Therefore  $\dot{C}_Q/C_Q = \iota \log\lambda$ . A similar argument establishes that  $\dot{p}_Q/p_Q = -\iota \log\lambda$ . Substituting these results into (6.3) we obtain

$$r = \rho + (\nu-1)\iota \log\lambda.$$

Finally, substituting this interest rate into the no-arbitrage equation (i) above we obtain (7.1).

results from limit pricing rather than from monopoly pricing (the price elasticity of demand equals one). It is measured by  $\lambda$ , which determines the extent to which a manufacturer of the top quality can charge a price above his nearest rival. But the rival's price is driven to their common marginal manufacturing costs. Therefore  $\lambda$  also describes the markup factor above marginal costs.

From (6.8) and (7.1) we can solve the equilibrium rate of innovation

$$(7.2) \quad \iota = \frac{\lambda}{\lambda + (\nu-1)\log\lambda} \left[ (1-\lambda^{-1})\frac{L}{a} - \lambda^{-1}\rho \right].$$

Comparing this equation with (4.4) — that describes the rate of innovation for the expanding variety model — we see that the terms in brackets are the same in both, with  $\lambda^{-1}$  playing the role of  $\alpha$ . If the intertemporal elasticity of substitution in consumption equals one (i.e.,  $\nu = 1$ ), we obtain the remarkable result that there exist no further differences in these equations (see Grossman and Helpman [1991a]). Since both  $\lambda$  and  $1/\alpha$  describe degrees of monopoly power, it follows that these equations represent exactly the same economic content. When the elasticity of intertemporal substitution in consumption differs from one, however, they differ slightly, but do retain the same economic implications concerning the qualitative effects of various parameters on the rate of innovation.

The above similarity is not accidental. Rather, the same economic mechanism sustains long-run growth in both models. Recall that expanding variety based growth leads to declining profits per brand that are compensated by declining R&D costs. The latter results from the accumulation of knowledge capital. In the model of quality ladders innovation adds quality. An innovator that improves a good that was improved  $m$  times in the past derives profits  $(1-\lambda^{-1})pX/\lambda^{m+1}$  per unit quality of his product



(see [6.5]). It follows that profits per unit quality decline as more innovation takes place (given a constant price). At the same time innovation costs per unit quality decline at an equal pace, because innovation costs equal  $w a$  (see [6.7]) and the price is proportional to the wage rate. Here, as in the case of expanding product variety, there exists a spillover of knowledge from current to future innovators. An innovator that adds the  $(m+1)$ th improvement builds on the knowledge that has been accumulated during the past  $m$  improvements. The only difference is that with quality ladders every good has its own stock of knowledge while with horizontal product differentiation the same stock of knowledge serves all brands.

The similarity of the models extends to investment in plant and equipment. Parallel to the analysis of capital accumulation by economies with expanding variety in section 5, we can develop an analysis of capital accumulation by quality–ladders driven economies (see Grossman and Helpman [1991b, chap. 5]).

Now consider the relationship between the rate of innovation and the rate of real output growth. With quality ladders the real consumption index  $C_Q$  provides a good measure of real output. Quality improvements increase this index over time. In a short time interval of length  $dt$  innovators improve a proportion  $\lambda dt$  of the goods. Since consumed quantities are constant in steady state, this implies a real consumption increase  $dC_Q = C_Q \lambda dt$  in this time interval (see [6.1] and footnote 11). Therefore the rate of growth of real consumption equals  $\lambda \log \lambda$ .

With Dixit–Stiglitz type horizontal product differentiation a market economy always innovates too slowly. With quality ladders, on the other hand, it may innovate too slowly or too fast (see Grossman and Helpman [1991a]). This difference affects policy implications, to which I now turn.

## 8. POLICY

Whenever economies feature endogenous long–run growth we expect the growth rate to depend on economic policies. In these circumstances we need to understand how various measures affect the growth rate. This is the more so for economies with innovation–based growth of the type I have described, in which free markets may lead to growth that is either too slow or too fast, and in which growth is only one among several determinants of welfare.

Now let us consider industrial policies in the simple expanding–variety and quality–ladders based growth models. For this purpose I use a common representation by means of figure 8.1, where  $q$  stands for the rate of innovation in both models. The downward slopping line  $LL$  represents the the economy’s resource constraint. The upwards slopping line  $NN$  describes the no–arbitrage condition. Equilibrium obtains at the intersection point  $A$ . The equations behind these lines consist of the steady state conditions (4.2)–(4.3) and (6.8)–(7.1):

$$(8.1) \quad aq + X = L,$$

$$(8.2) \quad \frac{(1-\mu)X}{\mu a} = \rho + q\xi,$$

where in the case of expanding product variety  $q$  represents the rate of innovation  $g$ ,  $\mu = \alpha$  and  $\xi = 1 + (1-\alpha)(\nu-1)/\alpha$ , while in the case of quality ladders  $q$  represents the rate of innovation  $\iota$ ,  $\mu = 1/\lambda$  and  $\xi = 1 + (\nu-1)\log\lambda$ . In either case  $1/\mu$  represents the markup factor of prices over marginal costs.

First consider a subsidy to R&D. This policy has no effect on the resource constraint. It reduces, however, the cost of innovation and thereby the value of a firm. As a result it reduces the price earning ratio for a given volume of manufacturing. Therefore the volume of manufacturing has to decline in order to eliminate arbitrage opportunities. In terms of figure 8.1 the provision of an R&D subsidy shifts down NN to the broken line, and the equilibrium point to B. It follows that an R&D subsidy raises the rates of innovation and growth. At the same time it contracts the manufacturing sector. The contraction of manufacturing represents the cost of faster innovation.

Is this a good policy? The answer depends on whether the initial rate of innovation was too low or too high. I have argued that expanding product variety leads to an outcome with insufficient innovation. Then a small R&D subsidy that brings about a resource reallocation from manufacturing to labs raises welfare.<sup>12</sup>

Contrary to expanding product variety, quality ladders can lead to either insufficient or excessive innovation. In the former case an R&D subsidy can be useful. In the latter case, however, an R&D subsidy speeds up innovation but hurts welfare. In the event a tax on innovation, that removes the overincentives on creative destruction, raises welfare.

An alternative industrial policy provides direct support to high-tech manufacturing in the form of an output subsidy. This policy does not affect the resource constraint. It also has no effect on the no-arbitrage condition. Therefore it does not change the rate of innovation and growth nor the volume of output (see Grossman and Helpman [1991a]).

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<sup>12</sup>The optimal rate of subsidy can be calculated by means of the welfare measure developed in footnote 8 (see also Grossman and Helpman [1991a]). Additional complications arise when the differentiated products are capital goods; see Barro and Sala i Martin (1990).

The ineffectiveness of this policy results from the simple structure of these economies: The existence of a single input and no employment outside the high-tech sector. I now show that if we extend the model to include an additional sector that manufactures traditional goods with constant returns to scale, then an output subsidy to high-tech manufacturing accelerates innovation and increases the output level of high-tech products. The expansion of the high-tech sector comes at the expense of the traditional sector, which contracts.

Suppose that in addition to the high-tech sector the economy manufactures a traditional good  $Z$  with a unit of labor per unit output. Perfect competition prevails in the supply of  $Z$ . Consumers allocate a fraction  $\sigma$  of their spending to high-tech products and a fraction  $1-\sigma$  to traditional goods. We replace the real consumption index  $C_D$  with  $C_D^\sigma C_Z^{1-\sigma}$  in the case of horizontal product differentiation and  $C_Q$  with  $C_Q^\sigma C_Z^{1-\sigma}$  in the case of quality ladders. Under these circumstances the no-arbitrage condition (8.2) remains valid, except for the fact that now  $\xi = 1 + \sigma(1-\alpha)(\nu-1)/\alpha$  for the expanding variety model and  $\xi = 1 + \sigma(\nu-1)\log\lambda$  for the model with quality ladders.

Three activities absorb resources: R&D, manufacturing of high-tech goods, and manufacturing of traditional goods. The resource constraint becomes  $aq + X + Z = L$ , where  $Z$  represents output of traditional goods. Consumer preferences imply that relative spending on high-tech goods equals  $pX/p_Z Z = \sigma/(1-\sigma)$  (because in equilibrium  $pX = p_J C_J$ ,  $J = D, Q$ , and  $C_Z = Z$ ). Commodities are priced according to  $p = w/\mu$  and  $p_Z = w$ . Therefore in equilibrium the output level of traditional goods is proportional to the output level of high-tech goods;  $Z = X\mu\sigma/(1-\sigma)$ . It follows that the resource constraint can be represented by

$$(8.3) \quad aq + \left[1 + \frac{1-\sigma}{\mu\sigma}\right]X = L.$$

Now (8.2) and (8.3) can be used to represent equilibrium of both models with the aid of figure 8.2, which is similar to 8.1 except for the fact that the slopes of lines LL and NN depend on the share of spending on high-tech products. The simpler model represented in figure 8.1 is a special case with  $\sigma = 1$ .

In order to see how the equilibrium rate of innovation depends on the composition of consumer spending, consider the case in which the elasticity of intertemporal substitution in consumption does not exceed one; i.e.,  $\nu \geq 1$ . In this case an increase in the expenditure share on high-tech products rotates the resource constraint line LL in a clockwise direction around its intersection with the horizontal axis, and the Schumpeter line NN in a clockwise direction around its intersection with the vertical axis. The movement of each line raises the rate of innovation. We therefore conclude that economies with larger spending shares on high-tech products innovate faster.

The existence of a traditional good does not alter the long-run impact of an R&D subsidy. As before an R&D subsidy does not affect the resource constraint but shifts down the Schumpeter line. Consequently it speeds up innovation and growth and reduces the volume of high-tech products. Since this policy does not affect relative manufacturing volumes  $X/Z$ , the traditional sector contracts. It follows that an R&D subsidy induces a resource reallocation from both manufacturing sectors towards research labs.

And what about an output subsidy to high-tech producers? As before this policy does not affect the no-arbitrage condition. It changes, however, the resource constraint. Recall that  $aq + X + Z = L$ ,  $pX/p_Z Z = \sigma/(1-\sigma)$ , and  $p_Z = w$ . But with the output

subsidy in place,  $p = w/\mu(1+\phi_x)$ , where  $\phi_x$  is the subsidy rate. Therefore the subsidy inclusive resource constraint becomes

$$(8.4) \quad aq + \left[1 + \frac{1-\sigma}{\mu\sigma(1+\phi_x)}\right]X = L.$$

What this equation shows is that, given the output volume  $X$ , an increase in the subsidy reduces the relative price of high-tech products to consumers and thereby demand for traditional products. Consequently it reduces aggregate manufacturing employment. Evidently, an increase in the subsidy rotates clockwise line  $LL$  around its intersection point with the horizontal axis, as indicated by the broken line in figure 8.2. The equilibrium point shifts from  $A$  to  $B$ . We see that this time an output subsidy to high-tech products speeds up innovation and expands manufacturing of high-tech goods. The expansion of the high-tech sector comes at the expense of the traditional sector, which contracts.

Even this result is not robust, however. There exist reasonable economic structures in which a subsidy to high-tech manufacturing will actually reduce the rates of innovation and growth. To see how, suppose that in addition to labor an economy employs human capital in all three activities — manufacturing of high-tech goods, manufacturing of traditional goods, and R&D — with constant input-output ratios. R&D uses the highest ratio of human capital to labor while traditional manufacturing uses the lowest ratio. Finally, the supply of human capital is constant. Under these circumstances an expansion of high-tech manufacturing leads to a contraction of both, the manufacturing of traditional goods and R&D, because the factor intensity of high-tech manufacturing is intermediate between R&D and traditional manufacturing.

In the event an output subsidy to high-tech products leads to an expansion of high-tech production but to a *slowdown of innovation and a contraction of the traditional sector* (see Grossman and Helpman [1991b, chap. 10]). Thus, this modeling approach allows us to investigate whether policies that would appear to promote growth actually do so.

The two-factor two-sector model that I outlined above can also be used to shed new light on the relationship between an economy's resource base and its rate of innovation and growth (see Grossman and Helpman [1991a]). Recall that in the one-factor one-sector economy the rates of innovation and growth are higher the larger the economy's resource base. The same applies to the two-sector one-factor economy. In the presence of two factors, however, a larger resource base does not guarantee faster innovation. Given that the human capital to labor ratio is highest in R&D and lowest in traditional manufacturing, economies with higher stocks of human capital innovate faster. If in addition the elasticities of substitution in manufacturing exceed one, then economies with more labor also innovate faster. But if instead the elasticities of substitution are low in all three activities, *economies with more labor innovate slower* (see Grossman and Helpman [1991b, chap. 5]).<sup>13</sup> The general point that emerges from this discussion is that inputs that are used intensively in R&D are conducive to innovation and growth while inputs that are used intensively in the manufacturing of traditional goods may discourage innovation and growth.

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<sup>13</sup>Romer (1990b) presents a two-factor one-sector example in which an expansion of labor, in which manufacturing is relatively intensive, reduces the rate of innovation and growth.

## 9. FURTHER CONSIDERATIONS

My description of the macroeconomic theory of endogenous growth has been incomplete; it did not cover all existing approaches nor did it deal with all the issues that have been treated in the literature. Admittedly, my choices exhibit a large dose of subjectivity. This type of bias is, however, unavoidable, and I did not intend to survey the literature. I focused my presentation on one important class of mechanisms that sustain long-run growth, a small number of models that employ them, and a limited number of issues that demonstrate the usefulness of viewing economic growth in this particular way. In these closing comments I do not wish to take a position on the important issue of which model is best. As a rule I believe in pluralism. We gain much insight by dealing with economic problems from a variety of perspectives. This is the more so for a major problem of the type considered in this paper. For this reason I limit the remaining remarks to a number of issues that were not treated so far, but which I feel deserve special mention.

### **Real Interest and Growth Rates**

The models that we discussed have the unfortunate implication that, given taste parameters, the real rate of interest increases with the growth rate, while the evidence does not support this relationship (see Barro and Sala i Martin [1990]). Does this fact destroy the usefulness of these models? I think it does not. The models were designed to study supply-side mechanisms of economic growth that build on the accumulation of physical capital, the accumulation of knowledge capital, and innovation. For this reason they treat consumption in a simple way. Elaborations that allow for different determinants of consumption can break this link without diminishing the role of the



supply–side mechanisms in the growth process. One way to proceed would be to replace the time separable preference structure with a non–separable form of the type studied by Weil (1989) and Epstein and Zin (1990).

An alternative route to the same end would be to use an overlapping generations economy populated by consumers with finite lifetimes. The latter approach has been explored by a number of authors. Using Yaari–Blanchard type consumers and a neoclassical technology that exhibits learning–by–doing in capital accumulation, Alogoskoufis and van der Ploeg (1990) constructed a model in which the rate of long–run growth depends on fiscal variables while the real interest does not. It follows that countries that pursue different fiscal policies may experience different long–run growth rates and nevertheless share the same real interest rate. They show that, other things equal, countries that maintain a higher public debt to output ratio grow slower, because consumers consider government debt to be net wealth and therefore save less in high public debt countries. In the event real interest rates and growth rates are not positively correlated.

### **Fluctuations**

Innovation–based growth can proceed smoothly or in bursts. We have seen two models in which it proceeds smoothly. Of particular interest on this issue is the model of quality ladders. There every good is improved after an irregular interval of time has elapsed. Because there exists a large number of such goods, however, the proportion of goods improved in a given time interval remains constant in the steady state. For this reason the rate of growth of the macro–economy remains constant as well (out of steady state this rate changes smoothly). Naturally, the smooth pace of progress of the macro–economy masks substantial turmoil at the industry level.

One may argue that there exist important innovations that are not limited to a particular product, but rather have broad applications, such as general purpose technologies discussed by Bresnahan and Trajtenberg (1990). In the event a successful innovation leads to a step increase in real output. If such drastic innovations occur infrequently and at irregular intervals of time, the economy exhibits irregular bursts of growth. Then the growth rate exhibits substantial variability even when its mean remains constant.

A model of this nature was analyzed by Aghion and Howitt (1990). In their model output experiences positive shocks at irregular intervals of time and the logarithm of output follows a random walk.

### **Unemployment**

Innovation-based growth entails a constant reallocation of labor. In the presence of horizontal product differentiation manufacturers of new brands employ labor that has been released by contracting old product lines. In the presence of quality ladders manufacturers of new products employ labor that has been released by old product lines that shut down, as superior new goods replace lower quality old products. My presentation assumed full employment, implying that these labor shifts take place instantly and without friction. This assumption is obviously extreme, and one expects some frictional unemployment in a reallocation process of this magnitude. This is the more so when labor is heterogeneous and the skill composition of new hires does not necessarily match the skill composition of displaced workers. In short, innovation-driven growth may not be as painless as assumed in our models. In the event one wonders whether growth that generates new jobs on the one hand and destroys jobs on the other raises or reduces the rate of unemployment.

This question has been addressed by Aghion and Howitt (1991). The answer proves to be involved. In particular, the effect of faster innovation and growth on the rate of unemployment depends on the factors that speed up innovation.

### **International Trade**

Economic growth of countries depends on a variety of structural features and government policies. Since so far my discussion was confined to isolated economies, the structural features and policies that I considered were also confined to isolated economies. Economies are, however, linked with each other by means of international trade, capital flows, imitation of cultural traits, and the transfer of ideas and scientific discoveries. Does this openness affect the growth opportunities of nations? And are the growth processes of open economies interdependent? The answers to both questions are in the affirmative. A recent book-length treatment of innovation and growth in open economies has been provided by Grossman and Helpman (1991b), and I could not possibly deal with this subject in a satisfactory way in the framework of this paper that has been confined to macroeconomic theory. Let me therefore provide only brief comments on some open-economy issues that have been investigated.

The integration of a nation into a world trading system unleashes powerful forces that speed up growth. But it also unleashes forces that are harmful to growth. The former dominate, however, when countries do not differ too much in terms of resource composition, and knowledge flows freely across national borders. The extent to which the accumulation of knowledge capital is country specific or international in scope also plays an important role in the determination of trade patterns and growth differentials across countries. Internationalization of knowledge leads to long-run trade patterns and GDP growth rates that are governed by traditional forces, such as differences in factor

composition. In the event initial differences in comparative advantage that result from historical experiences do not affect long-term outcomes. When knowledge accumulation is localized, however, history can extract powerful effects on the evolution of trade patterns and growth rates. Under these circumstances small initial differences in knowledge capital can translate into large long-run differences in sectoral structures, trade patterns and growth rates.

In open economies trade policies affect innovation and growth. Not only do they influence the policy active country but also its trade partners. Other policy measures, such as R&D or output subsidies, spread their influence across national borders and alter the rates of innovation and growth of trade partners.

Research and development need not be directed to the invention of new goods or production processes. Less developed countries invest substantial resources in learning to operate technologies that were originally developed in advanced economies. This process of imitation by the South affects the incentive to innovate in the North, and vice versa. The rate of innovation is jointly determined with the rate of imitation by more fundamental ingredients, and this interdependence can be quite involved.

I have outlined a new approach to economic growth. The emerging theory complements Solow's contribution in explaining technical progress. It provides a richer structure with realistic new attributes, and it is capable of dealing with a variety of new issues. Although there exists a fair number of new empirical studies, some supporting Solow and others supporting the new theory, it is fair to say that at this stage the data do not distinguish sharply enough between the alternatives. This has partly to do with the fact that the neoclassical theory and the new one are complements rather than substitutes, and partly because the existing tests are not powerful enough. We will undoubtedly see much more work on this subject in the coming years.

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Figure 3.1

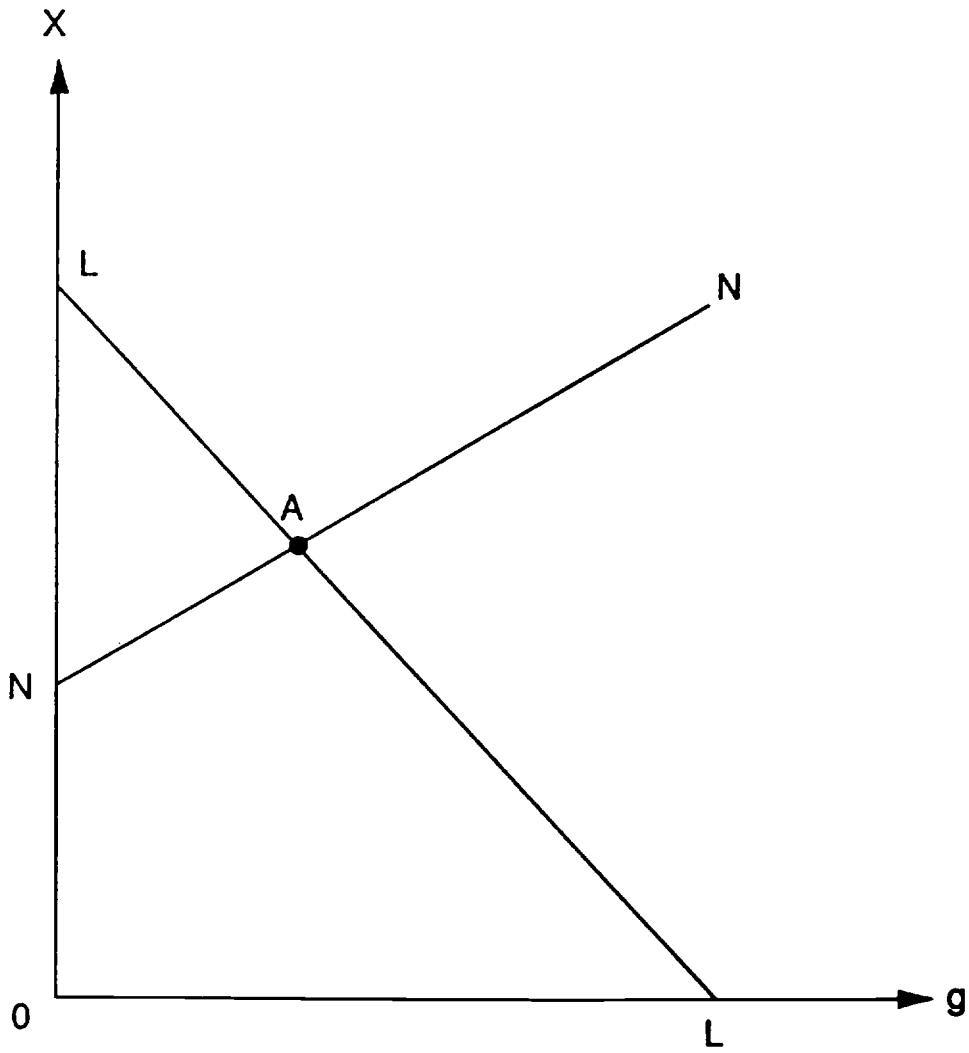


Figure 8.1

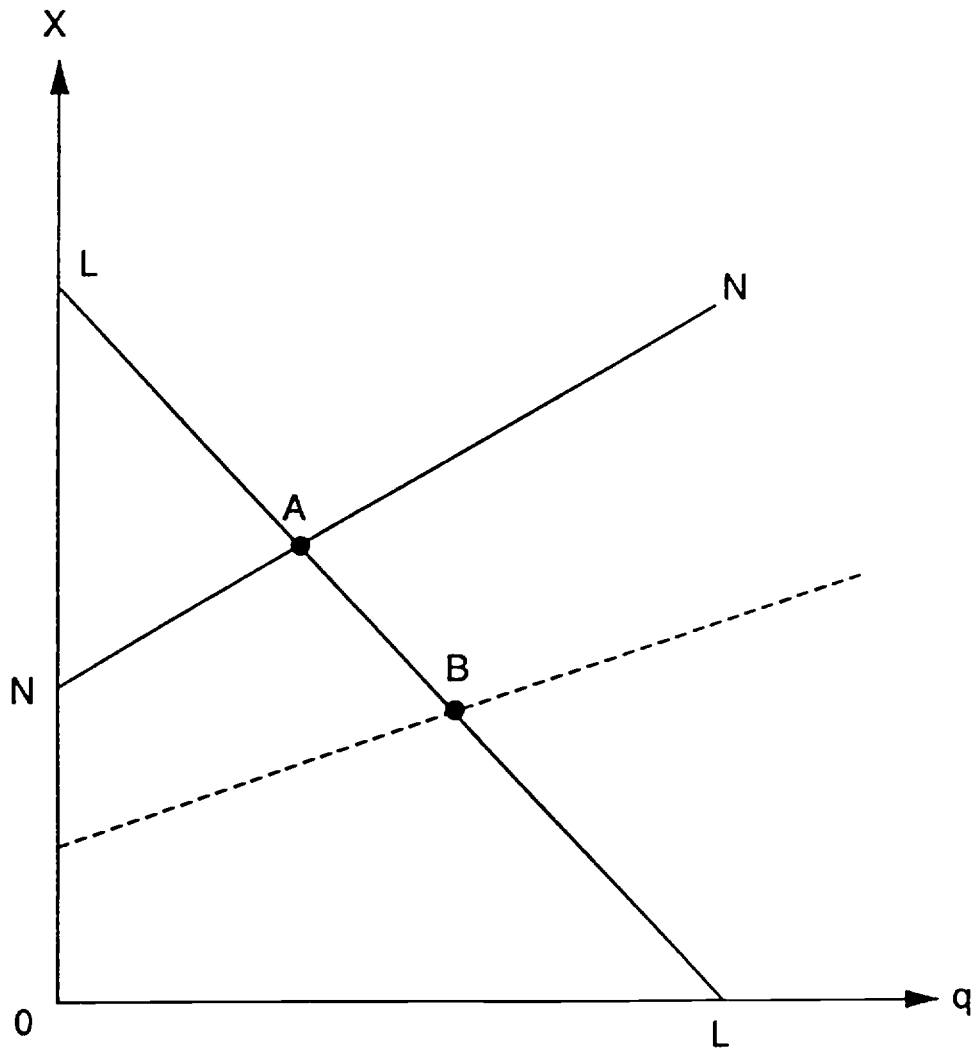


Figure 8.2

