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Endogenous Innovation in the Theory of Growth

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Can economic growth be sustained in the long run? If so, what determines the long-run rate of growth? Which economies will grow the fastest? And what kinds of policies can governments use to accelerate advances in living standards? These questions were central for those who studied growth in the 1950s and 1960s, and remain so in the recent revival of interest in long-run economic performance.

Two observations have motivated many of the recent contributors to growth theory. First, output expansion has outpaced population growth in the 200 years since the industrial revolution. Second, different countries have remained on seemingly disparate growth paths for relatively long periods of time. Related to this second observation is another: in cross-section and time-series data, we find national and regional growth rates correlated with a variety of economic, social, and political variables, including many that are affected by government policies. These observations have led the current generation of growth theorists to formulate models in which per capita income grows indefinitely and long-run performance reflects structural and policy parameters of the local and global economy.

With this apparent similarity of intentions, recent research efforts have headed in several different directions. One strand of theory continues to see capital accumulation—though conceivably with a broad interpretation of "capital" that includes human capital—as the driving force behind economic

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growth. In the work of Jones and Manuelli (1990), King and Rebelo (1990), and Rebelo (1991), firms continually add to their stocks of capital in a perfectly competitive environment with constant returns to scale. Perfect competition requires that this capital be paid its marginal product, which must stay above the (subjective) discount rate for investment to remain profitable. The authors simply posit a lower bound on the private return to capital as a property of the aggregate production function, thus assuring that investment continues to be profitable. A second approach casts external economies in a leading role in the growth process. According to this view, when individuals or firms accumulate new capital, they inadvertently contribute to the productivity of capital held by others. Such spillovers may occur in the course of investment in physical capital (Arrow, 1962) or human capital (Lucas, 1988). As Romer (1986) has pointed out, if the spillovers are strong enough, the private marginal product of (physical or human) capital can remain permanently above the discount rate, even if individual investments would face diminishing returns in the absence of the external boosts to productivity.[1] Growth can be sustained by continuing accumulation of the inputs that generate the positive externalities.

These two approaches offer logically coherent explanations of sustained, policy-sensitive growth. Moreover, they lend many insights into the theoretical properties of dynamic models. But, in our view, they do not identify the mechanism by which real-world growth truly is sustained. It seems to us—as indeed it did to Schumpeter (1934), Solow (1970, p. 33), and countless others—that improvements in technology have been the real force behind perpetually rising standards of living. Also, we believe that most technological progress requires, at least at some stage, an intentional investment of resources by profit-seeking firms or entrepreneurs. This perspective has led us to join Romer (1990), Aghion and Howitt (1992), and others in developing formal models that cast industrial innovation as the engine of growth. With the aid of these models, one can now investigate whether a decentralized market economy provides adequate incentives for rapid accumulation of commercial technology, and one can examine how variations in economic structures, institutions, and policies translate into different rates of productivity gain.

This paper will not attempt to review the burgeoning theoretical literature on "endogenous growth." Rather we have two more modest objectives in mind. First, we hope to convince the reader that purposive, profit-seeking investments in knowledge play a critical role in the long-run growth process. Second,

[1]Many attribute the idea that growth can be sustained by spillovers from investments in physical capital to Romer (1986). But a careful reader will note that the "K" in Romer's model, at least according to the author's interpretation, refers to "knowledge," not "kapital." Romer argued that the special properties of knowledge make spillovers likely and growth sustainable. In his later papers (for example, Romer, 1990) he refined his views about the treatment of knowledge, arguing that private investments in knowledge could only take place in a market environment with imperfect competition.

we hope to convey a sense of the models of endogenous technological progress that have been developed so far and of the lessons they can teach us.

Technology as the Engine of Growth

Neoclassical growth theory, as developed by Solow (1956) and his followers, has dominated economists' thinking about long-term or "trend" movements in per capita income for more than three decades. Solow focused attention on the process of capital formation. Aggregate savings, he argued, finance additions to the national capital stock. An economy with an initially low capital-labor ratio will have a high marginal product of capital. Then, if a constant fraction of the income generated by a new piece of equipment is saved, the gross investment in new capital goods may exceed the amount needed to offset depreciation and to equip new members of the workforce. Over time, capital per worker will rise, which (with constant returns to scale and a fixed technology) will generate a decline in the marginal product of capital. But if the marginal product continues to fall, the savings generated by the income accruing to new capital also will fall, and will eventually be only just sufficient to replace worn-out machines and equip new workers. At this point the economy enters a stationary state with an unchanging standard of living.

Cass (1965) and others showed that this same gloomy prediction survives in a version of the model with a more fully articulated theory of savings. If households save to spread their consumption optimally, then—be they long-lived altruistic families or short-lived selfish individuals—their savings will respond to available rates of return. Additions to the aggregate capital stock will occur only if the marginal machine yields a return at least as great as a household's marginal willingness to delay consumption. But a rising capital-labor ratio means a falling return on investment when technology is characterized by constant returns, so the incentive to accumulate capital might easily vanish over time.

The early authors recognized that stagnating per capita incomes were not an inevitable implication of the neoclassical model. Provided that the marginal product of capital remained above a certain level, the economy with a fixed technology could continue to grow indefinitely. The marginal product of capital could remain high even as the capital-labor ratio grew large if raw labor and other nonaccumulable factors were inessential inputs into production.[2] For example, an aggregate production function with a constant elasticity of substitution between capital and labor greater than one would do the trick (Solow,

[2]Solow (1970, p. 34) also discussed the possibility that increasing returns to scale could preserve a high marginal productivity of capital. However, he regarded it as "difficult to believe that the United States is enabled to increase output per man at something over 2 per cent a year mainly by virtue of unexploited economies of scale."

1956, pp. 70-1). Still, the growth theorists of the time generally dismissed this possibility by imposing "Inada" conditions—that is, a marginal product of capital that approaches zero as capital per worker grows large—so as to ensure convergence to a steady state.

Despite this, the neoclassical growth theorists were not pessimistic about the long-run prospects for the aggregate economy. They viewed their out-of-steady-state dynamics as a story about the "medium run," when capital-labor ratios would be rising over time. During a transition period, autonomous investment in machinery and equipment would be a primary force behind rising incomes, and policies that altered the savings rate could be used to accelerate growth. But even when the transitional phase would come to an end, economic growth could proceed unabated if technical knowledge were to expand over time. Solow showed that with advances in technology—which he took to augment the productivity of labor at an exogenous and constant rate—the marginal product of capital need not decline as capital per worker increased. Rather, improvements in labor productivity would augment the stock of "effective" workers. Even with a constant population, the capital stock would grow in the long run to keep pace with the effective labor force.

We concur with the decision of the early growth theorists to rely on advances in technology, rather than properties of the aggregate production functions, as a means of squaring the predictions of their models with the facts of persistent growth. In our view, a story of growth that neglects technological progress is both ahistorical and implausible. Surely the earth's (relatively) fixed stocks of land, natural resources, and raw labor would impart diminishing returns to accumulated inputs if those inputs were forever combined to produce a fixed set of goods by unchanging methods. Indeed, econometric estimates of aggregate production functions confirm our suspicion that returns to physical capital, human capital, and other accumulable factors are far from constant.

The growth theorist need not choose between models that emphasize technology and those that emphasize capital accumulation. Even in a world in which technological progress provides the engine of long-run growth, accumulation will play an independent role during a (perhaps prolonged) transitional phase. No one would deny the importance of investment in physical capital in explaining, for example, Japanese and western European growth after the war, or the experiences of Korea and Singapore more recently. And when the incentive for capital deepening abates, capital accumulation may still act as the "transmission of growth," as when new ideas must be embodied in machinery and equipment before they give rise to tangible products.

And what of the endogeneity of technological progress? Some might argue that technology is driven by science, which may proceed at a pace and in a direction that is largely independent of economic incentives. But few scholars of industrial innovation accept this view. The commercial exploitation of scientific ideas almost always requires a substantial investment of resources. This is the conclusion of countless studies of particular industries and innovations, including those on machine tools (Rosenberg, 1963), aircraft (Constant, 1980), synthetic chemicals (Freeman, 1982), metallurgy (Mowery and Rosenberg, 1989), and semiconductors (Dosi, 1984), to name but a few. According to these studies, firms have invested in new technologies when they have seen an opportunity to earn profits. In fact, a large proportion of the scientific research conducted in the OECD countries is financed by private industry.[3] In such a setting, the institutional, legal, and economic environments that determine the profitability of these investments must surely affect the pace and direction of technological change. And even in the less developed countries, where technical knowledge would seem to be available "off the shelf," learning to use that technology is far from costless (Pack and Westphal, 1986), and the rate of dissemination reflects the institutions, property-rights regime, and pricing structure that together determine the private profitability of acquiring knowledge.

Interpreting the Evidence

Can the neoclassical growth model—with decreasing returns to capital, perfect competition, and exogenous technology—fully explain the cross-country variation in per capita incomes and national growth rates? Paul Romer (1986, 1989a) has claimed not, pointing to two seeming tensions between the model's predictions and the historical evidence. First, the growth rate of the world's technological leader has been rising over time, not falling, which can happen in the neoclassical model only if the pace of exogenous technological progress steadily accelerates. Second, countries appear not to be converging to a common level of per capita income, as they must be in the neoclassical model if the countries share similar savings behavior and technologies.

An influential paper by Mankiw, David Romer, and Weil (1992) challenges this view. These authors argue that the evidence on the international disparity in levels of per capita income and rates of growth is quite consistent with a standard Solow model, once it has been augmented to include human capital as an accumulable factor and to allow for cross-country differences in savings rates that may reflect differences in tastes or culture. To make their case, they begin by assuming that every country has its own Cobb-Douglas aggregate production function and its own *exogenous* rates of savings and population growth. In the Solow growth model, this would imply convergence to different steady-state

[3]In the United States alone, more than 12,000 industrial research labs are actively searching for profitable innovations. And in Japan, more than 80 percent of all R&D, including much research, as well as development, is financed by private industry. See Rosenberg and Nelson (1993).

paths for per capita income, as represented in the following equation:

$$\ln y_i(t) = \ln A_i + g_i t + \frac{\alpha_i}{1-\alpha_i} \ln s_i - \frac{\alpha_i}{1-\alpha_i} \ln (n_i + g_i + \delta_i).$$

Here, $y_i(t)$ is per capita income in country i at time t (when the country has already entered a steady state with constant growth rate g_i); A_i represents a multiplicative factor in the aggregate production function that augments the productivity of labor at time 0; α_i denotes the exponent on capital in this same production function (and also capital's share of income); s_i is the country's savings rate; and n_i, g_i, and δ_i are the rates of population growth, labor-augmenting technological progress, and capital depreciation, respectively. This equation states that a country will have higher per capita income at a point in time (in the steady state) the more productive are its workers initially, the faster is its technological progress, the higher is its savings rate, and the lower are its rates of depreciation and population growth. A high savings rate means that much of current output is devoted to installing new capital, while low depreciation and population growth rates mean that little of the new capital must be used to replace old machines or to equip new workers. Together these imply a high long-run capital-labor ratio, which translates into abundant income per worker, especially when the elasticity of output with respect to capital (that is, the coefficient α) is large.

Mankiw, Romer and Weil estimate this equation by ordinary least squares, using the Real National Accounts data from Summers and Heston (1988) for 98 non-oil-producing countries. But before they do so, they introduce some additional restrictions. First, they assume that countries are closed to international capital flows, so that the ratio of investment to GDP can be used to represent the national savings rate. Next, they assume that depreciation rates and capital shares are the same in all countries. Third, they suppose that the multiplicative factor on the production function has a country-specific component; $A_i = a + \varepsilon_i$, where a is a constant and ε_i an independently and identically distributed random variable. According to the authors, this variable reflects idiosyncratic national characteristics such as natural resource endowments, climate, institutions, and so on. Finally, and most critically, they imagine that all countries have experienced the same rate of technological progress, so that the country-specific parameter g_i can be replaced by a common parameter g.

Imposing these assumptions, they find in their regressions the predicted signs on the savings and population growth variables (positive and negative, respectively), but the estimated size of α does not conform to independent observations of capital's income share. So they augment the Solow model to allow for a fixed rate of accumulation of human capital—using the percentage of the working age population in secondary school as a proxy for this rate of investment—and re-estimate. Now they find coefficients of plausible magnitude and a model fit much to their liking (an adjusted R^2 of 0.78). They conclude that the augmented Solow model provides a satisfactory explanation of cross-country variations in (long-run) income.

Does this evidence negate our claim that one must understand the determinants of a country's technological advancement to understand its long-run performance? We believe not. First, it should be noted that the adjusted R^2 falls to 0.28 when the sample is restricted to the 22 OECD countries. In the estimation of the basic Solow model without the schooling variable, the fraction of the variation in OECD country incomes "explained" by population growth and the investment ratio is only 1 percent! Mankiw, Romer, and Weil get most of their mileage from the large differences in investment ratios and population growth rates between the rich and poor countries. But, more to the point, we believe that the assumption of a common rate of technological progress in all 98 countries over a 25-year period is simply indefensible. The rate at which producers in Japan have acquired new technologies, be they technologies that were new to the global economy or those that were new only to the local economy or the individual firm, has been markedly different from the rate of technology acquisition in Chad, for example. Indeed, Wolff (1992) provides evidence of strikingly different rates of total factor productivity growth in just the OECD countries alone over the last 20 years.

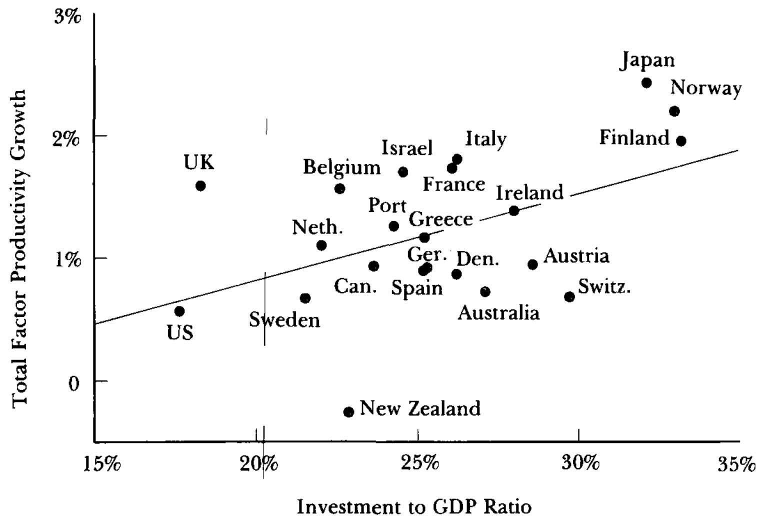
How does this matter for the interpretation of the Mankiw et al. regressions? From an econometric perspective, if technological progress varies by country, and g_i is treated as part of the unobserved error term, then ordinary least squares estimates of the Solow equation will be biased when investment-GDP ratios are correlated with country-specific productivity growth.[4] In particular, if investment rates are high where productivity grows fast, the coefficient on the investment variable will pick up not only the variation in per capita incomes due to differences in countries' tastes for savings, but also part of the variation due to their different experiences with technological progress.[5]

An economist would certainly expect investment to be the highest where capital productivity is growing the fastest. Indeed, Baumol et al. (1989) report

[4]Another point, a bit outside the main line of our argument, may be even more telling. Not only investment ratios, but also population growth rates should be viewed as endogenously determined. It is well known from discussions of "the demographic transition" that population growth rates tend to decline as incomes rise. This may be because children act as a substitute for retirement savings in countries with imperfect capital markets. In any event, the large negative coefficient on n_i in the full sample estimates may reflect the fact that low income causes fast population growth, rather than the other way around. Becker, Murphy, and Tamura (1990), among others, have made a promising start at modeling the joint determinants of population and output growth.

[5]The same problem of interpretation arises for the myriad of regressions that have been computed to explain variation in growth rates across countries. These regressions invariably include the beginning-of-period income level and the investment-GDP ratio, along with a number of the researchers' own favorite variables. A positive coefficient on the investment ratio is a robust finding (Levine and Renelt, 1992), but since the regressions omit any direct measures of a country's state of technical knowledge, this variable may be picking up the effects of disparate technological progress on the growth rate.

Figure 1
Productivity Growth vs. Investment Ratio, 1970–1988



very high correlations between total factor productivity growth and annual growth rates of capital labor ratios for seven OECD countries in the period from 1880 to 1979. Figure 1, which shows the relationship between productivity growth and investment ratios for a sample of 22 countries for the period 1970 to 1988, suggests the same. So we are still left to explain why technology has progressed at different rates in different countries in order to understand why their investment rates have varied and thus so too have their growth experiences.

If the neoclassical model, with its focus on capital accumulation, provides an incomplete story of growth, what role can we attribute to technological progress? And what evidence do we have that such progress is endogenous? Growth accounting is believed by some to provide a method for answering these questions. The standard procedure decomposes changes in output into parts associated with the growth of various inputs, and a residual. The residual, which, depending on the particular study, may be large or small, is often taken to measure the contribution of advancing technology to growth. Unfortunately, there are problems with this interpretation. For suppose that $Y = AK^{\alpha}L^{\beta}$, where Y is output, K is capital, L is labor and A represents the state of technology. As a matter of arithmetic, it is of course true that the percentage growth in Y will be equal to the sum of the percentage growth in A, α times the percentage growth in K, and β times the percentage growth in L. But can we conclude from this that the growth in A measures the full contribution of technological change to the expansion in output? Evidently not. After all, technological improvements typically raise the productivity of capital and thereby induce additional investments. In such cases, the resulting capital formation ought not to be considered as an independent spur to output, but rather as a facilitator of the growth that is due ultimately to the innovation.[6]

Some might argue that the resources spent on commercial research and development are too small for business-generated technological improvements to be the driving force behind growth. It is true that, despite rapid growth in recent decades, business enterprise R&D still comprises only about 2 percent of the domestic product of industry in the OECD countries. However, what generally gets recorded as R&D represents only a portion of the resources that firms spend on learning to produce new goods or with new methods. Learning on the shop floor—consisting of many small improvements in design and technique—is also important in the overall picture of technological advance. Moreover, knowledge is cumulative, with each idea building on the last, whereas machines deteriorate and must be replaced. In that sense, every knowledge-oriented dollar makes a productivity contribution on the margin, while perhaps three-quarters of private investment in machinery and equipment is simply to replace depreciation. Finally, social rates of return on R&D may substantially exceed private rates of return. Detailed studies of particular innovations support this view (Mansfield et al., 1977; Bresnahan, 1986; Trajtenberg, 1990), which suggests that resources spent on commercial research may be especially productive in generating new output.[7]

A few recent papers suggest the central role that endogenous technological progress has played in recent growth experience. For example, Coe and Helpman (1993) show that domestic and foreign "knowledge capital stocks"—that is, accumulated spending on R&D by a country and by its trade partners—both help to explain the growth in total factor productivity in the OECD countries. Eaton and Kortum (1993) and Lichtenberg (1992) find, respectively, that the number of national scientists and engineers and the level of spending on R&D enter significantly in the determination of a country's income level, in an empirical framework similar to that used by Mankiw, Romer, and Weil. Most significantly, Caballero and Jaffe (1993) have begun the arduous task of estimating and calibrating a full general equilibrium model of innovation-based growth, to see how well the model can account for the trends in aggregate productivity and consumption growth in the United States. Their findings are encouraging, though not definitive.

[6]The incorporation of "R&D stocks" (the accumulated value of R&D spending after allowing for some depreciation) as a separate input into aggregate production does not get around the problem, either. As Nelson (1973, 1981) and others have noted, there is an "adding up" problem here: if there are increasing returns to all inputs, including the technology input, then not all factors can be paid their marginal product. Factor shares cannot be used to infer output elasticities. Leaving this aside, it is still true that the profitability of investment depends on the state of technology, and attributing growth to proximate sources reveals nothing about the underlying mechanisms.

[7]It should be noted, however, that De Long and Summers (1991) also find very high social rates of return for investment in fixed equipment.

Perhaps the most convincing direct evidence in favor of viewing industrial innovation as the engine of growth comes from the work of economic historians. For example, Landes (1969) describes the role that new technologies played in spurring the industrial revolution, while Rosenberg (1972) provides a comprehensive survey of the relationship between technological advances and American economic growth since the early 1800s. The latter account, especially, leaves little room for doubting that the bulk of technological progress has been purposive and profit-driven. And Fogel (1964), though trying to argue that the railroads were not indispensable to American growth in the nineteenth century, nonetheless estimated that this single innovation added 5 percent to U.S. GNP by 1890.

As yet, no empirical study proves that technology has been the engine of modern-day growth. Still, we ask the reader to ponder the following: What would the last century's growth performance have been like without the invention and refinement of methods for generating electricity and using radio waves to transmit sound, without Bessemer's discovery of a new technique for refining iron, and without the design and development of products like the automobile, the airplane, the transistor, the integrated circuit, and the computer?

Modelling Innovation-Based Growth

We could go on at length about the potential usefulness of a theory of growth with endogenous technology. But the proof of the pudding is in the eating! The remainder of this article will sketch how recent research has attempted to incorporate industrial innovation into growth theory and describe some of the issues that the new models are able to address.

We begin with the would-be innovators. Presumably, they invest resources in the hope of discovering something of commercial value. This could be a better method for producing some good, a new good that serves an existing function, or an entirely new type of product that has no close substitutes among goods already on the market. In any case, the innovators expect to be able to turn a profit on the fruits of their research efforts.

Evidently, we must depart from the common practice in neoclassical growth theory of assuming that all firms act as price takers in an environment of perfect competition. Firms must be able to sell their products at prices in excess of unit production costs if they are to recover their up-front outlays on research and development. In other words, some imperfect competition in product markets is necessary to support private investments in new technologies. The new growth models draw on advances in the theory of industrial organization for their microeconomic details.

Let us take an example based on Grossman and Helpman (1991a, ch. 4). We begin with the case of a closed economy, but later discuss the implications of international trade. Suppose that a competitive consumer goods industry uses several different intermediate inputs in the production of a single, homogeneous product. Say that the production function is Cobb-Douglas, with uniform input shares (although the latter assumption could be relaxed). For the moment, also suppose that these intermediates are the only inputs into the production of the final good. Let each input have its own "quality ladder;" that is, a boundless sequence of potential quality improvements, where each new generation of input performs proportionately better than the last. Prospective innovators invest in R&D in an attempt to step up the ladder for one or more of these intermediate products.[8]

A successful innovator devises an input that is more productive than the similar input of earlier generations. If the country's patent system effectively protects the innovator's property rights over this new invention, the innovator will have the exclusive right to produce the new product. The firm that markets the superior input may well be able to earn monopoly profits in competition with the extant producers of previous generations of the product. We assume that this is the case, and that producers engage in price competition. Then the market leader earns a stream of monopoly rents that serve as the reward for its prior research investment. These rents continue until a rival firm discovers and perfects still a better version of the same product.[9]

Next consider the R&D process. Some of the recent growth theory treats R&D like other production activities, which automatically convert primary inputs into output—in this case, knowledge (Romer, 1990; Grossman and Helpman, 1991a, ch. 3). However, many observers have stressed the inherent uncertainties associated with industrial research and the fact that producers using new technologies rarely achieve commercial viability until after they experience a prolonged period of learning-by-doing (Rosenberg, 1982). The work of Young (1993) captures this second aspect of the research technology, whereas our own work has incorporated only the first. Here, let us suppose that firms devoting resources to R&D buy themselves a *chance* at developing the next generation of some targeted product. In particular, let us make a firm's probability of research success proportional to the labor employed in its research lab. Newcomers may enter freely into the research activity, and firms invest in knowledge up to the point where the marginal cost of additional

[8]In some other examples of endogenous growth theory, such as Romer (1990), Grossman and Helpman (1991a, ch. 3), and Young (1993), innovation serves to expand the variety of available goods. Aghion and Howitt (1992) treat the case of cost-reducing innovations. Their paper, which predates our own work on quality improvements, develops a model that is similar in many respects to the one described here.

[9]We could also incorporate the (realistic) possibility of imitation of the state-of-the-art product; see Grossman and Helpman (1991a, ch. 12) and Segerstrom (1991).

inputs into R&D equals the expected gain (increased probability of success times the market value of a new product) that those inputs provide.

Most of the contributors to the new literature on innovation-based growth have adopted a general equilibrium perspective. In the example described here, such an equilibrium has the following features. First, oligopolistic competition determines sales and profits for firms offering the various generations of each intermediate input. Second, the supply of savings from households and businesses matches the demand for funds by would-be investors. Third, the value of extant producers on national asset markets reflects the expected present discounted value of the profits those firms will earn, in view of the anticipated (but uncertain) subsequent evolution of technology in the industry. Fourth, supply equals demand in the competitive market for the homogeneous consumer good. And finally, the labor market clears at a wage that equates demands by manufacturers and researchers to the total available supply.

This sort of model predicts sustained growth in per capita output. Output expands in the steady state despite the fact that population size is constant and the economy has no physical capital. Here the economy grows because intermediate goods are forever being improved, thereby raising productivity in the assembly of final output.[10] The innovation process has a distinct Schumpeterian flavor, inasmuch as successful innovators displace previous industry leaders and snatch from them a share (here 100 percent) of industry profits. At the micro level the growth process is uneven and stochastic. Firms continually race to bring out the next generation of product, but there may be long periods without a success in some industries. Meanwhile, other industries may experience rapid successions of research breakthroughs. Aggregation masks this micro-level turbulence and the macroeconomy grows at a steady pace when the number of intermediate inputs is large.

In this model, the costs and benefits of industrial research determine the pace of long-term growth. The model predicts, for example, that a boost in the profitability of R&D, as might result from an increase in the magnitude of the typical quality improvement, attracts additional resources into R&D. Then the growth rate accelerates, not only because the quality steps are larger, but also because advances come more rapidly. As another example, if households become more patient in their savings behavior, the cost of R&D financing falls and again the rate of innovation rises. Finally, if a scientific breakthrough raises the productivity of researchers in the commercial laboratory, the profitability of R&D rises and some resources are released from their former activities and become available to engage in new projects. Innovation is spurred on both accounts.

[10] Confusion has crept into the literature concerning the role of intermediate goods in the growth process. It makes no difference whether innovation takes place in sectors producing intermediate goods or final goods.

Capital Accumulation

It is straightfoward to introduce capital accumulation into this story of innovation-based growth. Capital might be used in the industries producing intermediate goods, the sector producing final goods, or both. For simplicity, suppose it is only used in final goods production and let us rewrite the aggregate production function as $Y = K^{\alpha}L_Y^{\beta}Z^{1-\alpha-\beta}$, where Y now denotes final output, K and L_Y are capital and labor used in producing this output, and Z is an aggregate measure of intermediate inputs (adjusted for their quality). We assume also that the single final good Y can be used either for consumption or for investment purposes. That is, output of Y that is not consumed adds to the aggregate capital stock. We ignore depreciation.

In this specification, the forces that drive long-run growth remain the same as before. The profitability and cost of industrial research determine the rate at which the intermediate inputs climb their respective quality ladders. Improvements in the quality of intermediates boost the productivity of physical capital. So the endogenous learning here—like the exogenous technological progress of the neoclassical model—prevents the marginal product of capital from falling to the point where investment ceases to be profitable. Innovation sustains both capital accumulation and growth.

It is interesting to note that with plausible and realistic parameter values, the predictions of the model roughly match the recent U.S. experience. Suppose we assign capital a share of 30 percent ($\alpha = 0.3$), labor a direct share of 35 percent ($1 - \alpha - \beta = 0.35$), and intermediates (also embodying labor) the remaining share of 35 percent in the production of final goods. Suppose further that we take the subjective discount rate of households to be 5 percent, and assume that each research success generates a 5 percent improvement in the quality of some intermediate product. Then, if we choose the parameter reflecting the productivity of labor in the research lab to be consistent with an annual growth rate of 2.5 percent, the formulas in Grossman and Helpman (1991a, ch. 5) imply that R&D spending will comprise 1.6 percent of sales, while investment will take up 10 percent of output. We see that business R&D need not absorb vast resources for innovation to be the engine of reasonably rapid growth.

Human Capital

Cross-country regressions point to the special role that human capital plays in the growth process (Barro, 1991; Romer, 1989b; Mankiw, Romer, and Weil, 1992; and others). However, different authors have interpreted the positive partial correlation between growth rates and various proxies for the stock of human capital in different lights. We, like Romer (1989b), see human capital as the accumulation of effort devoted to schooling and training. In a finite lifetime, an individual's human capital cannot grow without bound. However, the skills that an individual acquires may be applied to an ever improving set of production technologies, in which case the value of human capital will continually rise through time.

A simple, albeit misleading, way to think about human capital in our model is as a measure of the size of the (effective) labor force. With more labor, the economy could undertake either more R&D , more manufacturing, or more of both activities. In fact, our model predicts that more labor will be employed in both of these uses in the new equilibrium, with the expansion of employment in R&D generating an increased rate of product innovation. This prediction of the model, while consistent with the positive correlation between human capital and growth, has the counterfactual implication that larger economies always grow faster.

A realistic extension of our framework can reconcile the observation that countries with more human capital grow faster with the fact that sheer size does not always promote growth. Suppose there are two different sectors producing final output. Let the sectors be distinguished both by their relative use of skilled versus unskilled labor and by their potential for technological improvements. For example, the sectors might represent industries such as apparel and footwear, on the one hand, and consumer electronics, on the other. Suppose, further, that each young person decides whether to acquire any human capital beyond primary education, and if so, how much. In this setting (described further in Grossman and Helpman, 1991a, ch. 5) larger economies do not always grow faster. A large economy with an abundance of skilled labor will conduct a great deal of industrial research, because R&D uses this factor intensively. Such an economy will grow faster than another with less human capital. But a large economy populated mostly by unskilled individuals might grow more slowly than another with a smaller population. The large labor-abundant country, which specializes relatively in labor-intensive production, might well conduct absolutely less industrial research than a smaller country with a *comparative* advantage in R&D .

Growth and Welfare

Since the times of Adam Smith, economists have wondered whether the invisible hand of the market generates the socially desired pace of economic expansion. With its assumptions of exogenous technology and full appropriability of investment, the neoclassical growth model delivers an unequivocal answer. The government need do nothing to promote accumulation and growth, it tells us, provided that individuals are far-sighted in their savings behavior and take into account the well-being of their offspring. Under these conditions, the equilibrium growth path will be socially efficient.

The recent contributions to growth theory cast doubt on this conclusion. When growth is driven by endogenous innovation, two obstacles stand in the way of market efficiency. First, efficiency dictates marginal cost pricing, but innovation requires the existence of monopoly profits. Second, efficiency demands that investment returns be fully appropriable, but the characteristics of knowledge suggest that spillovers will be prevalent. Romer (1990) describes one kind of spillover from industrial research: as firms develop new technologies they sometimes make scientific discoveries with more general applicability. Such discoveries may be difficult to patent and difficult to keep from the public domain. Aghion and Howitt (1992) and Grossman and Helpman (1991a, ch. 4) highlight another type of externality: when innovators bring out successive generations of similar products, each begins where its predecessors left off. For example, a new entrant into the personal computer industry seeking to improve upon the state of the art need not make its own progression from the abacus to the analog computer to the digital computer to the personal computer. Instead, it can inspect the latest generation of products available on the market and extract much of the cumulative investment in knowledge that is embodied in them.

The fact that endogenous innovation will not necessarily occur at an optimal rate does not immediately tell us whether it will be too fast or too slow. The spillovers emanating from the industrial research lab suggest that markets provide insufficient incentive for investments in knowledge. The inability of innovators to capture all of the consumer surplus from their new products points to the same conclusion. But the setting of imperfect competition precludes any simple policy prescriptions. Overinvestment in R&D can occur because innovators respond to private profit signals, which may diverge from measures of social profitability. Consider, for example, a firm that invests in a new technology merely to displace an existing one. Evidently, this firm has calculated that the profits it can capture by taking over the market exceed the cost of the investment. But much of the profit may come at the expense of the extant industry leaders, so that the invention's contribution to total industry profits may fall short of the research costs. If such occurrences are frequent, the economy will devote too many resources to R&D and too few resources to manufacturing with currently available technologies (Stokey, 1992).

The new models allow for rigorous welfare analysis on issues such as these. They also permit an examination of the efficacy of alternative corrective policies. In situations where the market equilibrium entails too slow a pace of technological progress, the models predict (unsurprisingly) that an R&D subsidy, by raising the private profitability of R&D, can be used to spur innovation and growth. These simple models can also highlight pitfalls in the use of some policies that might seem to be good substitutes for an R&D subsidy. For example, Grossman and Helpman (1991a, ch. 3) show that policies that subsidize *sales* of innovative products may slow the rate of technological advance. Although such policies typically enlarge the reward available to a successful innovator, they may also raise the cost of innovation by bidding up the salaries of scientists and engineers.[11]

The endogenous innovation paradigm could readily be extended to handle a host of other important policy questions that bear on growth performance. Future research will undoubtedly ask: To what extent can policies that promote accumulation of human capital substitute for policies that directly encourage investments in technology? Should collaborative research projects be encouraged or discouraged by the antitrust authorities? What factors determine the optimal length and breadth of patent protection? And so on.

Global Interdependence

Growth theory traditionally has treated each country as if it were an island unto itself. Extensions of the theory to a world with international trade and capital flows have been left as esoteric exercises for algebra lovers. If ever this practice was defensible, surely it is no longer. Countries trade with one another, communicate with one another and learn from one another more than ever before. The increased exchange of goods and ideas has fostered a growing interdependence among countries' technological fortunes and long-term performances. When the new models of endogenous innovation are extended to include international movements of goods, capital, and ideas, they yield a theoretical framework that is rich in predictions and consistent with a host of observed phenomena.

Dynamic Comparative Advantage

We suppose now that there are two countries and two sectors producing consumer goods. One of these sectors comprises a range of different products, each one of which can be improved in the research lab. Since all innovation in the economy will be confined to these products, we will refer to this as the "knowledge-intensive" or "high-technology" sector. The other consumer-good sector is a traditional one, producing a homogeneous product under

[11]This seems a good place to note the mileage one gets from treating questions about the optimal pace of innovation and growth using general equilibrium methods. Of course, one does not need a general equilibrium model to capture technological spillovers, and the inevitable link between market power and innovation has long been recognized in industrial organization. However, partial equilibrium analysis cannot capture the competition of manufacturing and R&D activities for a common set of resources in a setting where one activity cannot expand except at the expense of the other. In our view, such competition accurately reflects the situation in what is often called the "high technology" sector.

competitive conditions, with no prospects for technological progress. All production and research activities make use of two primary factors, human capital and unskilled labor.

It may be that the high technology products manufactured in one country can be improved as readily by research labs in a foreign country as they can by labs located nearby. This would describe a situation where technological spillovers—implicit in firms' abilities to base their research efforts on the existing state of the art—are fully international in scope.

When researchers worldwide draw on a common knowledge base, the history of technological advance in any one country has no bearing on the long-run pattern of international trade. The country that has the greater relative abundance of skilled labor will specialize relatively in the most human capital-intensive activity—namely industrial research. Even if this country initially produces few knowledge-intensive products, it will, over time, win more than its share of the technology races. In the long run, the human capital-rich country will come to acquire leading positions in relatively many of the high-technology industries and will export these goods in exchange for the labor-intensive product of the traditional manufacturing sector. In short, relative factor endowments will determine the long-run pattern of trade.

While this finding is reminiscent of the familiar Heckscher-Ohlin theory of international trade, the model also captures the insights of several other strands of recent literature. For example, the model predicts an ever-evolving web of intraindustry trade. Each country exports the high-technology products of industries in which its firms enjoy a technological lead and imports the products of industries where its firms lag behind. Moreover, if countries' relative endowments differ significantly (or if transport costs are large), direct foreign investment and international patent licensing may take place. Companies with headquarters and research facilities located in the high-wage country may open their own plants in the foreign country or "rent" their technologies to foreign producers. The choice between these alternative modes of technology transfer depends on (among other things) the advantage that indigenous producers enjoy relative to foreigners in operating a plant in the low-wage country and on the cost that firms must incur to write and enforce contracts regulating the use of their patent rights.

While it may appear to the casual observer that knowledge always flows rapidly and costlessly around the globe, the reality is sometimes different. The concentration of high-technology industries in particular locations such as the Silicon Valley and Route 128 suggests that some benefit exists from physical proximity to other researchers. Perhaps this is because new ideas are spread by skilled personnel whose geographic mobility is somewhat restricted, or because firms that are geographically close are exposed more often to the products of their nearby rivals.

The existence of local or national technological externalities introduces an important role for history in the determination of dynamic comparative advantage (Grossman and Helpman, 1991a, ch. 8). Such spillovers can generate a self-perpetuating process whereby an initial lead, however generated, is sustained indefinitely into the future, regardless of a country's relative factor endowments. A model with these features predicts long-lasting effects of temporary industrial policies and may lend theoretical support for some popular arguments in favor of an aggressive response to perceived foreign targeting of high-technology industries (for example, Tyson, 1992).

Integration and Growth

Research on endogenous innovation has helped to elucidate several reasons why participation in a larger world economy may speed a nation's growth (Rivera-Batiz and Romer, 1991). First, residents of a country that is integrated into world markets are likely to enjoy access to a larger technical knowledge base than those living in relative isolation. Trade itself may help the process of technological dissemination, if foreign exporters suggest ways that their wares can be used more productively or foreign importers indicate how local products can be made more attractive to consumers in their country (Grossman and Helpman, 1991b). Second, exposure to international competition may mitigate redundancy in industrial research. Whereas a firm that develops a product for a protected domestic market need only make use of technologies that are new to the local economy, one that hopes to compete in the international marketplace will be forced to generate ideas that are truly innovative on a global scale.

Rivera-Batiz and Romer (1991) suggest a third reason: by expanding the size of the potential customer base, international integration may bolster incentives for industrial research. But as Grossman and Helpman (1991a, ch. 9) and Feenstra (1990) have noted, a countervailing force may be at work here. More open trade will increase the profitability of R&D in a country or region only if its firms can hold their own in the rivalry with foreign firms. For potential innovators in a small and isolated country, or those operating where skilled labor is relatively scarce, this need not always be the case.

While many economists firmly believe that more open trade must always promote more rapid expansion, Grossman and Helpman (1991a, ch. 9) have constructed several examples of cases in which closing off trade might actually increase a country's long-run growth rate. First, a country with a relative abundance of natural resources and unskilled labor and a relative paucity of skilled workers may be induced by trade to specialize in activities that make use of those resources, somewhat at the expense of human-capital intensive activities like R&D.[12] It may be that industrial output will grow more slowly in the long run than it otherwise would if these countries were forced to devote more of their resources to developing new technologies or producing innovative goods. Second, if technological spillovers are national in scope, then re-

[12]For example, resource-rich countries like Canada and Australia devote far smaller shares of their national outputs to R&D than do resource poor countries at a similar stage of economic development.

searchers living in a country with a small knowledge base may find it difficult to compete with rivals in a country with more experience in conducting research. Long-run growth might be faster in such a country if it were to allow itself to "catch up" before fully exposing itself to the world competition.

These arguments should not be taken to imply that illiberal trade policies would generally be beneficial to a country that sees slower growth as a result of openness to trade. A country that lacks the size and technological experience to support a world class R&D effort, or one that has the endowments appropriate to activities like agriculture and mining, typically will gain from specializing in the production of goods that do not require the latest technologies. A country like Saudi Arabia—to take an extreme example—must surely be better off trading its oil for manufactured goods than it would if it tried to develop and produce the latest high-technology goods itself. Although its GDP may grow more slowly in the long run when it specializes in drilling oil, the present discounted value of its consumption stream will almost certainly be higher. The point worth emphasizing here is that output growth rates do not measure economic welfare.[13]

Southern Imitation and the Product Cycle

Another type of technological interdependence arises in trade between the North and the South. Whereas many firms in the industrialized North race to bring out the latest innovative products, most firms in the developing South confine their technological efforts to imitating products developed abroad. This pattern of invention in the North and imitation in the South gives rise to a product cycle in international trade: Northern firms produce and export many goods early on in their technological lives, then manufacturing shifts to the South as production methods become more widely known.

It may seem, as many Northern companies who have lost market share and profits to Southern imitators insist, that such product-cycle trade must be detrimental to the incentives to invest in new technologies. But this is not necessarily so. The new endogenous growth models identify two opposing effects of product cycle trade on the incentives to innovate. The first is the one to which the unlucky Northern firms point: imitators cut into the rewards that accrue to the originators of new ideas. But whereas no Northern innovator wants to see its own technology copied, every such firm is happy to see foreign companies master the technologies of its domestic rivals. When this happens,

[13]In Grossman and Helpman (1991a, ch. 8) we discuss at greater length why a country may gain from trade even when that trade has an adverse impact on its long-run growth rate. We present an interesting example where a country that would innovate if it remained isolated instead specializes in the production of traditional goods when it trades with a country that has a technological head start. Yet trade equalizes wages across the two regions, whereas the lagging country would always have the lower real wage in the absence of trade.

production migrates abroad, and resources are released by the targeted producers. Some of these resources may find their way into the factories of the surviving Northern manufactures of innovative products. Then sales for these firms will expand and profits rise. In short, while a faster rate of Southern imitation means a shorter duration of monopoly profits for the typical Northern innovator, it may also mean a higher level of profits while that monopoly position lasts.

Grossman and Helpman (1991a, chs. 11 and 12) offer models which illustrate that product-cycle trade—by easing Northern manufacturers' demands for scarce resources—actually can accelerate innovation and growth in the global economy. Indeed, Helpman (1993) takes the argument one step further, by demonstrating that the North actually benefits in welfare terms from a relaxation of Southern enforcement of intellectual property rights, provided that the initial rate of imitation is not too high.

Concluding Remarks

Economic policy-makers face the difficult question of how best to promote rapid, sustainable economic growth in the face of depletable stocks of irreproducible natural resources. Improvements in technology are the best chance we have to overcome the apparent "limits to growth." If greater output requires greater tangible inputs, then it seems more than likely that the fixity in the supplies of various of the earth's resources eventually will mean an end to rising per capita incomes. But if mankind continues to discover ways to produce more output (or better output) while conserving on those inputs that cannot be accumulated or regenerated, then there seems no reason why living standards cannot continue to rise for many centuries to come.

We do not profess to understand fully the determinants of technological progress. But we do believe that stylized formal models such as the ones we have described can help us to attain this goal. Growth theory has taken a step in the right direction by including aspects of reality—imperfect competition, incomplete appropriability, international interdependence, and increasing returns to scale—that surely are important to understanding how much an economy will invest in knowledge of various kinds. We hope that knowledge in this particular area of economics, like other knowledge in the economy at large, will continue to accumulate at a rapid rate.

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