# Endogenous Growth, Productivity and Economic Policy: A Progress Report

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THE NEW "ENDOGENOUS" GROWTH theory that was spawned by the contributions of Romer (1986) and Lucas (1988) has now largely displaced the old neoclassical growth theory of Solow (1956) and Swan (1956) from the frontiers of academic research. But endogenous growth theory vintage 2004 is different in many respects from vintage 1988. These differences are the result of a fruitful interaction that has taken place between theoretical developments and empirical findings, an interaction reminiscent of the manner in which the basic building blocks of Keynesian macroeconomics were refined in the 1950s and 1960s. Attempts to test the theory have in some cases confirmed its predictions and led to new unsuspected applications. In other cases tests have uncovered important weaknesses, which theorists have remedied by introducing elements of reality that were missing from the original theory. My purpose here is to describe how the theory has been changed in the past decade and a half in response to new empirical findings, to point out which of the basic ideas underlying the original models have survived this refining process and which have been cast aside, to survey some of the empirical successes of the theory in its current state and to point out some of its major policy implications.

## R&D, innovation, productivity and endogenous growth

Endogenous growth theory starts by accepting one of the main implications of neoclassical theory, namely that in the long run the main underlying determinant of economic growth is the long-run growth rate of total factor productivity (TFP), which in turn depends mainly on the rate of technological progress. Where it differs from neoclassical theory is in maintaining that the rate of technological progress depends on economic forces, and can be influenced by economic policy. Technological progress comes from innovations – new products, new processes and new markets that allow us to satisfy our material wants in ways that had never been thought of. Some innovations come from the application of fundamental science, and in that sense they depend on the rate of scientific progress. But many are also the result of economic activity and economic decisions. For example, firms learn how to produce more efficiently as a result of experience, and they also learn how to design better products from their customers' experience. A higher level of economic activity in the economy will give firms and customers more experience in producing and using products, which will thus lead to a faster rate of

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process and product innovation. As another example, many innovations are the result of R&D expenditures undertaken by firms seeking to increase their profits. Economic policies with respect to trade, competition, education, taxes and intellectual property will all affect the costs and benefits of doing R&D and hence will affect the rate of technological progress.

The first wave of endogenous growth theory to enter the mainstream was the "AK theory" according to which technological progress can be thought of as just another form of capital accumulation. That is, technological progress consists in the accumulation of knowledge, which is a kind of intellectual capital, much like physical or human capital except that it is not embodied in machines or people. According to AK theory, technological progress is as much an economic phenomenon as is capital accumulation. Both occur as a result of the intertemporal decisions that people make when determining how much of their income to save.

AK theory was followed by a second wave of endogenous growth theory, which Aghion and I have elaborated in our recent (1998a) book, and which we call "Schumpeterian" or "innovation-based" theory, a theory that emphasizes the distinction between technological knowledge and capital, and analyzes the process of technological innovation as a separate activity from saving. This new theory is explicit about who gains from technological progress, who loses, how the gains and losses depend on social arrangements, and how such arrangements affect society's willingness and ability to create and cope with technological change. My discussion in what follows will focus mainly on the Schumpeterian variety of endogenous growth theory. This is partly because I believe that it corresponds more closely to the way innovations take place and the way markets work than does the more general AK theory. But it is also because, being very explicit about the causes and consequences of technological progress, it is easier to confront the theory with evidence – not just cross-country and time-series evidence but also micro evidence at the level of the industry and even the firm. Accordingly the most productive interaction with empirical evidence has taken place in this branch of the theory.

## Cross-country convergence

One of the first empirical challenges to endogenous growth theory came from authors pointing out that over the second half of the 20th century most countries seem to have been converging to the same long-run growth rate of per-capita GDP (e.g. Barro and Sala-i-Martin, 1992; Evans, 1996). This "convergence in growth rates" is not what was predicted by the first generation of endogenous growth models, according to which each country's long-run growth rate should depend on the institutions and policies that affect the incentive to generate and diffuse innovations in that country. Mankiw, Romer and Weil (1992) went on to point out that the observed convergence in growth rates is exactly what the neoclassical Solow-Swan model predicts, under the assumption that all countries are able to tap into the same exogenous technological frontier and hence share the same underlying rate of technological progress.

To account for these observations of convergence in growth rates, endogenous growth theorists have modified their original theories to take into account the important force of technology transfer from one country to another. In Howitt (2000), for example, I point out that technology transfer fits naturally into the Schumpeterian framework because it works just like the cross-industry technology spillover that was already incorporated in closed-economy versions of the theory. In either case, the R&D undertaken in a particular industry in a particular country incorporates knowledge learned from innovations that have taken place elsewhere, either in other industries or in other countries. Moreover this modification of the theory is supported by strong evidence to the effect that TFP growth in any one country depends on R&D expenditures not just there but also in that country's trading partners (Coe and Helpmann, 1995; Eaton and Kortum, 1996).

When technology transfer is incorporated into the theory, it predicts that all countries that perform R&D will end up growing at the same rate in the long run, thus making it consistent with the observation of convergence in growth rates over the past half-century. The force that ensures this in the theory is what Gerschenkron (1952) once labelled the "advantage of backwardness." That is, a country that is growing more slowly than the world's technology leaders will find it increasingly easy to speed up its growth rate simply by implementing new technologies that have been discovered elsewhere. Eventually this advantage will bring its growth rate up to that of the leaders.

In these modified endogenous growth models, the incentives to perform R&D in a small open country will determine not its long-run growth rate but its long-run TFP level relative to the rest of the world. An increase in R&D will give rise to a temporary acceleration of technological progress, and hence of TFP growth, but as this brings the country closer to the world technology frontier it removes some of the country's "advantage of backwardness" and hence brings its growth rate back down again. Although the country's long-run growth rate will be unaffected, the temporary acceleration will have served permanently to reduce the TFP gap separating it from the frontier.

Howitt (2000) shows that such a modified theory is capable of explaining the same features of the cross-country per-capita GDP distribution as the Solow-Swan model, and also some additional features. For example, the theory predicts that countries will have different levels of per-capita GDP not only because of different saving rates and population growth rates but also because of different R&D intensities, a fact that Lichtenberg (1993) has confirmed with cross-country regression analysis. It also predicts that countries will differ in TFP levels as well as in levels of capital per worker, and that these two determinants of per-capita GDP will be positively correlated across countries. This has been verified by the empirical work of Klenow and Rodríguez-Clare (1997) and Hall and Jones (1999). Moreover, the model predicts that countries at the bottom of the distribution, in which the incentive to perform R&D is so weak that firms in those countries make no investments in technological change and hence are not able to benefit from technology transfer, will not converge in growth rates but will instead grow more slowly than the technology leaders, even in the long run. This further prediction accords with the finding of club-convergence by several empirical researchers (e.g. Quah, 1996).[2]

Thus the new versions of Schumpeterian endogenous growth theory emphasize the importance of policies aimed at facilitating technology transfer. This includes not just policies supporting formal R&D but also programs facilitating the importation and licensing of foreign technologies like the Industrial Research Assistance Program of Canada's National Research Council which several earlier writers have lauded as a model of successful technology policy (e.g. Lipsey and Carlaw, 1996; Nicholson, 2003).

Another critical factor in technology transfer is the level of educational attainment of the workforce. Griffith, Redding and Van Reenen (2001) show that education is an important

2 Club-convergence refers to the convergence of countries to the long-run growth rate of the leaders in their particular peer group. Thus convergence only takes place within groups of countries that share common structural characteristics and initial conditions, rather than across all countries in general.

determinant of the rate at which an industry in an OECD country can catch up to the world technology leader in that industry. The theoretical model of Howitt and Mayer-Foulkes (2002) shows that a country's education level can be important enough to spell the difference between convergence in growth rates and divergence. Education affects the speed of technology transfer, and hence the country's long run relative TFP, partly because skilled labour is used intensively in the R&D process that is necessary for technology transfer and partly because the benefits to engaging in technology transfer are greater in a country where there are skilled workers able to adapt to new technologies and work productively with them. These advantages of having a highly educated workforce go beyond the usual ones mentioned in policy discussions, which stress the increased productivity of workers in any given technological environment, for they work through changing the technological environment itself.[3]

Yet another policy implication of these modified models is that a country's openness to international trade can raise its productivity in the long run, not just through the usual channels of comparative advantage, specialization and competition but also through facilitating technology transfer. As Keller (2002) has emphasized, technology transfer can work not just through the "direct" channel that I have described above, in which a country's R&D embodies the ideas generated elsewhere, but also the "indirect" channel of being embodied in high-tech imported capital goods and intermediate products.

## Evidence on long-run covariates of economic growth

The newest versions of endogenous growth theory predict not only that most countries will converge to the same growth rate but also that the world growth rate itself will vary with the same incentives to perform R&D as in the original versions of the theory. The difference is just that in the new versions what matters for a country's growth rate is the configuration of R&D throughout the world, not just in that country. Thus there is nothing that a relatively small country like Canada, that performs only a small fraction of the world's R&D, can do to influence its long-run growth rate. The same is not true however for the United States, which is large enough that changes in its R&D intensity can have a significant effect on the rate of progress of the global technology frontier.

Thus even when modified to take into account technology transfer, endogenous growth theory is potentially vulnerable to the critique by Jones (1995a) to the effect that long-run trends in economic growth in the United States are not correlated with long-run trends in the various determinants of growth suggested by endogenous growth theories – R&D intensities, education levels, government spending and taxation, and so forth. This finding reflects the more basic fact that the trend growth rate of per-capita GDP in the United States has been virtually constant since 1880. Thus the only way that it could be correlated with a combination of exogenous determinants would be if trends in those exogenous determinants just happened to be linearly related to each other, and in such a way that whenever there is a shock to the trend of one determinant, the trends in the others change so as just to offset its effects on economic growth. Jones argues that this could only be through an improbable coincidence.

This empirical critique has not led to any great modification of endogenous growth theory, and the reason is that the critique has been effectively countered with subsequent empirical

3 The theory thus embodies the idea put forth by Nelson and Phelps (1966) to the effect that human capital is not so much a factor of production to be used under a given state of technological knowledge as it is an agent for creating and diffusing technological knowledge – in this case for diffusing it from one country to another.

findings. Kocherlakota and Yi (1997), for example, find that there is indeed such a combination of exogenous determinants whose trends have a significant effect on long-run growth. Those two determinants are tax rates and public capital. Long-run growth in the United States (and the United Kingdom) is negatively related to the former and positively related to the latter. Moreover, they point out that the fact that variations in one have been associated with offsetting variations in the other, instead of being just an unlikely coincidence, is precisely what one would expect from taking into account the government's budget constraint. An increase in public capital by itself tends to raise growth, but this incipient increase in growth is nullified by the increase in tax rates needed to finance the capital expenditure.

Another finding that counteracts Jones's critique is Arora's (2001) demonstration that long-run variations in growth are correlated with long-run variations in a variety of indicators of population health in ten different countries. Technically speaking he finds that growth and health are co-integrated variables in the time-series sense. Moreover, he uses an error-correction analysis to show that when short-run fluctuations disturb the co-integrating relationship, the subsequent adjustments take place almost entirely in growth rather than in health, suggesting that the long-run correlation he has detected is more likely to reflect causation going from health to growth than the reverse.

Two important policy implications follow from these refutations of Jones's critique. One is that the long-run trajectories of technological progress and TFP can be influenced by government fiscal policy. In particular, one of the benefits of long-term deficit reduction is that by reducing the annual expenditure on debt service it allows the government to reduce tax rates without cutting back on other services. Also, governments have other choices when it comes to financing expenditures on infrastructure. Instead of raising taxes they can cut back on other spending programmes. The evidence of Kocherlakota and Yi suggests that both of these policies – long-term deficit reduction and shifting expenditures towards public capital – can have long-term effects on growth in a large country on or near the technology frontier, and on the level of TFP in a relatively small country like Canada.

The other major policy implication is that education is not the only dimension of human capital that matters for long-run technological progress and TFP. Population health also matters. In Howitt (2004) I have argued that a present-generation Schumpeterian model incorporating population health implies that, for a relatively small country like Canada, improvements in population health can raise long-run TFP and per-capita GDP through several channels: (1) healthier workers are more productive when working in any given technological environment; (2) increased life expectancy will encourage people to acquire more education, thus also raising the other main component of human capital in the country; (3) improvements in early childhood and pre-natal health enhance a person's learning capacity and therefore lead to a larger stock of effective human capital for any given number of years of schooling (Heckman and Carneiro, 2003); (4) the same improvements in early childhood and pre-natal health also make a person more creative, and hence more innovative; (5) these same improvements strengthen the coping skills that people need to remain healthy when dealing with the stresses created by the rapid technological change needed to stay close to the world's technology frontier (McCain and Mustard, 1999); and (6) many measures that lead to increased population health have their biggest effect on the least advantaged members of society, thus tending to reduce the overall level of inequality in society, and thus promoting more rapid economic growth through a variety of channels, one of which is reduced pressure on governments to raise tax rates in order to finance transfers to the poor.

## The scale effect of growth theory

Jones (1995b) has also argued that the evidence on TFP growth and R&D inputs in the United States and other OECD countries refutes the "scale effect" of Schumpeterian endogenous growth theory. That is, according to the theory an increase in the size of population should raise long-run growth, through two channels – first by providing a larger market for a successful innovator and second by providing a larger stock of potential innovators. When applied to relatively small countries this theoretical prediction is easily refutable. Canada is a thousand times more populous than Liechtenstein but does not have a correspondingly higher long-run growth rate or level of TFP.

To some extent this problem can be remedied by taking the same global perspective as was used to account for post-war convergence. That is, the relevant scale variable is a global one, which is arguably as large for Liechtenstein as for Canada. More specifically, not only is the source of ideas feeding into the country's R&D more than what is produced by residents in that country but also the relevant market consists of more than residents of that country.

Nevertheless, as Jones points out, even when modified to take this global perspective, the theory is still hard to reconcile with the postwar evidence concerning the United States and other large technology leaders, where R&D spending *should* have a significant effect on long-run growth. Specifically, the number of scientists and engineers engaged in R&D in the United States has risen by a factor of five since the early 1950s, and despite that massive increase in R&D input there has been no visible long-run increase in TFP growth over the period of the sort predicted by Schumpeterian theory. He shows that similar patterns are found in the data for France, West Germany and Japan.

Jones suggests that the appropriate response to this refutation of first-generation Schumpeterian theory is to recognize that there are decreasing returns to the stock of technological knowledge, so that as technology continues to advance it takes an ever-increasing stock of R&D workers to keep the rate of progress from slowing down. His proposed modification would imply that in the long run the only way to sustain technological progress is through population growth, because with a constant stock of R&D workers the productivity of R&D in generating innovations would continue to decline as technology advanced, with the result that the rate of innovations would fall to zero. Indeed in Jones's proposed theory the rate of population growth is the *only* determinant of the rate of technological progress and of long-run TFP growth. Encouraging R&D would have at best a transient effect on TFP growth according to this "semi-endogenous" growth theory, even in a large country on the technology frontier.

Howitt (1999) proposes an alternative resolution to the puzzle which preserves the distinctive long-run implications of earlier Schumpeterian models. This alternative incorporates Young's (1998) insight that as an economy grows, proliferation of product varieties reduces the effectiveness of R&D aimed at quality improvement, by causing it to be spread more thinly over a larger number of different sectors. When modified this way the theory is consistent with the observed coexistence of stationary TFP growth and rising R&D input, because in a steady state the growth-enhancing effect of rising R&D input is just offset by the growth-reducing effect of product proliferation.

In dealing with this problem Schumpeterian growth theorists have also taken into account that the scientists and engineers whose numbers Jones takes as the primary input to R&D are not the only input. Indeed less than half of the cost of industrial R&D in the United States consists of wages and salaries.[4] In particular, R&D also uses a lot of physical capital, in the form of laboratories, equipment, prototypes, office buildings, and so forth.

Taking this simple fact into account turns out to have an unsuspected policy implication that Howitt and Aghion (1998) first derived, namely that long-run growth in a closed economy is affected not just by policies that impinge directly on the incentive to perform R&D but also by policies that are aimed directly at the incentives to accumulate physical capital. The reason is that if people accumulate more capital they will end up with more income per person, because they will be able to produce more output per person. This in turn will enhance the demand for the products that a successful innovator will be marketing and will thereby strengthen the incentive to innovate.[5] (Of course in a small open economy with technology transfer these forces will lead not to a higher long-run growth rate but a higher level of aggregate TFP relative to the world's technology leaders.) Thus policies aimed at promoting physical capital accumulation have an even more powerful effect on long-run living standards in new endogenous growth theories than in the old neoclassical theory, because they work not just by providing people with more income per person in any given technological environment, but also by leading to an improvement in the technological environment itself.

## Competition policy and economic growth

The first generation of Schumpeterian growth models implied the well-known Schumpeterian tradeoff between static efficiency and dynamic innovation, according to which if competition policy is effective in reducing monopoly profits it will reduce the reward to a successful innovator, thereby discouraging innovation and slowing down the rate of TFP growth. However, the available evidence seems to contradict this prediction. In particular, recent empirical work (e.g. Blundell, Griffith and Van Reenen, 1995; Nickell, 1996) points to a positive correlation between product market competition (as measured either by the number of competitors in the same industry or by the inverse of a market share or profitability index) and TFP growth or innovativeness within a firm or industry. Likewise, Porter (1990) presents evidence supporting the view that product market competition is good for growth because it forces firms to innovate in order to survive.

This evidence has led endogenous growth theorists to incorporate a variety of channels through which competition might in fact spur economic growth. The simplest of these involves barriers to entry. To the extent that such barriers raise the cost to outside firms of introducing a new technology, they reduce the incentive to perform R&D and thereby reduce the growth rate. Thus competition in the form of lower barriers to entry ought to be favourable to economic growth.

Consider next the role of agency costs that allow managers to operate businesses in their own interests rather than maximizing the owners' profits. Aghion, Dewatripont and Rey

4 According to the National Science Foundation (1999:Table A-34) wages and salaries of R&D personnel constituted 44.8 percent of the cost of industrial R&D in the United States in 1999.

5 More capital will also raise real wages in the economy, which to some extent offsets the rise in R&D by raising the cost of R&D labour. If labour were the only input to R&D, as imagined by Jones, this increase in the cost of performing R&D would be so large as to nullify the effect of increased profits, leaving the equilibrium R&D intensity unchanged. But when we take into account that labour is less than half the cost of R&D we end up with a significant positive effect of capital accumulation on R&D.

(1999) have shown that when these costs are severe, competition can act as a stimulus to growth through a channel much like the "innovate or die" story told by Porter. Because an increase in competition reduces the firm's flow of profits it reduces the scope for managerial slack, and thus forces managers to innovate more often in order to avoid bankruptcy.

Another channel is provided by the work of Aghion, Harris, Howitt and Vickers (2001), who take into account not just the absolute level of profits obtained by a successful innovator but the incremental profits, that is, the difference between the profits of a firm that innovates and one that does not. These authors show that although an increase in the intensity of competition will tend to reduce the absolute level of profits realized by a successful innovator, it will tend to reduce the profits of an unsuccessful innovator by even more. Therefore competition can have a positive overall effect on the rate of innovation because firms will try to innovate in order to *escape* competition.

Thus we have a variety of theoretical reasons for doubting that the commonly accepted tradeoff between static efficiency and growth exists. Moreover, the detailed predictions of the model of Aghion, Harris, Howitt and Vickers have been confirmed by the empirical results of Aghion, Bloom, Blundell, Griffith and Howitt (2003), who examine the effects of competition across UK manufacturing industries. Specifically they verify the prediction that competition will have an inverse-U effect on innovation and productivity growth. That is, the theory predicts that industries in which there is little competition will not be innovative because firms in such industries can earn lots of profit even without having to innovate. Innovation will also be low in industries where there is so much competition that once one firm establishes a technological lead the followers are discouraged by their inability to earn profits until they have climbed into the lead themselves, and the leader finds that because the followers are discouraged it does not have to innovate very frequently in order to retain the lead. Thus innovation typically takes place most rapidly at some intermediate degree of competition between these two extremes. This specific non-linear relationship is an extremely robust feature of UK manufacturing data.

Thus, while modern endogenous growth theory does not make simple uni-directional predictions it does create a framework in which to determine which industries are on the upward-sloping part of the inverse-U and which are on the downward part. In the UK manufacturing sector it seems that most are on the upward-sloping part, suggesting that a strengthening of competition policy is likely to have a positive overall effect on innovation, in contradiction to the Schumpeterian tradeoff of the earlier models. It would be interesting to redo this study on Canadian data to see if such is the case here as well. Moreover, the theory suggests another channel through which openness to international trade raises prosperity, namely by raising the intensity of competition faced by domestic producers and hence inducing them to be more innovative.[6]

## Patent policy and economic growth

Technological progress clearly requires that intellectual property be protected. If patent and copyright laws were so weak that people could copy innovations with little effort or penalty,

6 The idea that increased foreign competition can stimulate domestic innovation has also been advanced by Grubel (1999) and by Courchene and Harris (1999), as one reason for Canada to enter a North American currency union. They argue that a currency union would remove the disincentive to innovate that is created under a flexible exchange rate system every time a depreciation artificially shields Canadian firms from competition. See Laidler and Shay (2002) for a critical analysis of this argument.

then no one would have an incentive to innovate. This is the rationale for the emphasis placed by the United States on stronger protection of intellectual property in recent international trade negotiations.

Schumpeterian growth theory has shown, however, that the case for stronger protection is not as clear cut as it might seem. For example, the above-mentioned analysis of Aghion, Harris, Howitt and Vickers shows that stronger patent protection can in some cases reduce the overall pace of technological change, through a "composition effect." Innovation takes place at the greatest rate in those industries where the leading firms are neck-and-neck; that is, where they produce using similar technologies. This is because profits are lowest in such industries and hence the incentive to escape competition by innovating is strongest. If patent laws were weakened, the incentive to innovate of a firm with any given technological lead over its rivals would indeed be blunted, but the steady-state distribution of lead sizes would also be changed. Specifically, more firms would be forced to engage in neck-and-neck competition because of a rival's success in imitating its technological capability. As a result, it can be shown theoretically that under a wide variety of circumstances a little bit of imitation always has the overall effect of raising the economy's long-run rate of technological progress and therefore of raising the long-run growth rate.

Grossman and Helpman (1991) used Schumpeterian growth theory to show that strengthening international patent protection in the South can even weaken the incentive to perform R&D in the North. Consider a world in which products go through cycles – they are invented in the North, where they are first produced, but then someone invents a way to copy their production in the South, where wages are lower, and then someone in the North invents a new generation starting the cycle over again. In such a world, innovation and imitation take place at the same frequency in a stationary state, with the flow of goods whose production is being relocated to the South (through imitation) being just offset by the flow of goods whose production is being relocated to the North (through innovation). Making imitation harder in such a world by strengthening intellectual property rights in the South will reduce the flow of imitation but it will also necessarily have the effect of reducing the flow of innovation. This happens through a rise in Northern wages; as few products get imitated, more of them remain in production in the North, and this raises the demand for labour in the North, leading to an increase in wages and hence drawing labour out of R&D and into manufacturing. The overall result is thus a decrease in the rate of growth not just in the South but also in the North.

In addition to these effects, fear of patent litigation can also slow down the diffusion of technology and impede the technology transfer that modern Schumpeterian theory highlights as critical for long-run prosperity. Thus the more broadly we extend patent rights to include such things as software and genetic combination, the more we inhibit the flow of ideas by giving a strategic advantage to patent-holders with deep pockets.

In short, Schumpeterian growth theory suggests that strong protection of intellectual property does not always promote more innovation. A thorough rethinking of patent policy in the light of the new growth theory seems in order, to bring the policy in line with the new economy of the 21st Century.

## General purpose technologies

In the long run, growth is sustained by the occasional arrival of a major innovation that creates a new "General Purpose Technology" (GPT), a technology that is used throughout the economy, has a profound effect on the way economic life is organized, and gives rise to a wave of complementary innovations associated with its increasing use, like the steam engine, electric power or the computer. Endogenous growth theory has shown, however, that the short-run effect of the arrival of a new GPT can often be to reduce growth, by putting the economy through a long and costly adjustment period.

There are many aspects to this adjustment cost. Helpman and Trajtenberg (1998) emphasize the lost output that occurs because the GPT does not arrive ready to use but requires the invention of a set of complementary components. During the period when the components are being developed, the new GPT will not be used extensively. Meanwhile the labour that is drawn into developing new components will be drawn out of producing final output. The result will be a fall in the overall level of output.

Greenwood and Yorukoglu (1997) emphasize the real resources that are used up in learning to use the new GPT. Aghion and Howitt (1998b) point out that the process of reallocating labour from sectors using older technologies to those using the new GPT may involve a rise in unemployment, for the same reason that any large reallocation of labour often entails unemployment in a less than frictionless economic system. Howitt (1998) calibrates to U.S. data a Schumpeterian model with capital-embodied technological change, and shows numerically that the speedup in the rate of innovation induced by a new GPT can reduce the rate of output growth by increasing the rate of induced capital obsolescence, both human and physical. In these calibrations, the introduction of a new GPT that raises the productivity of R&D by 50 per cent until overall TFP has doubled will reduce the level of per-capita GDP below the path it would otherwise have followed, for a period of about two decades, before eventually resulting in a level of per-capita GDP twice as high as it would otherwise have been.

This last point indicates a general phenomenon associated with the macroeconomic dynamics of innovation-based growth. In the short run, as in the neoclassical model of Solow and Swan, the growth rate in output per person can be decomposed into two components, one depending on the rate of capital deepening (the increase in capital per "effective" worker), and the other depending on the rate of technological progress. Technological progress is the only component that matters in the long run, because the amount of capital per effective worker will stop growing as it approaches its long-run equilibrium value. But capital deepening is quantitatively the component that dominates the economy's adjustment dynamics, often for long periods of time, and it very often goes in the opposite direction to technological progress. In the specific example of the above-mentioned simulations, the short-run effect of an increase in the pace of innovation is to increase the rate of capital obsolescence, resulting in an accelerated decline in the stock of capital per effective worker that lasts for much longer than the duration of the typical business cycle.

Thus it seems that Schumpeterian growth theory may have something to say about the TFP slowdown that occurred between the mid-1970s and the mid-1990s. It could be that the famous Solow paradox was based on a misinterpretation of the data, that is, rather than the development and increased use of computers having no effect on growth, computers could indeed be seen in the TFP data, because they were inducing the observed TFP slowdown! (Recall that computers were first introduced into businesses on a large scale in OECD countries sometime in the 1970s). This reinterpretation of the data suggested by Schumpeterian theory is also one that bodes well for the future, for it implies that sooner or later the costs of adjusting to computer technology will be behind us. Indeed the speedup of TFP growth since the mid-1990s suggests that this is already starting to happen, particularly in the United States but also in Canada, which is among the OECD leaders in employment in sectors using information and communication technologies (OECD, 2003).

## Conclusion

One of the few unambiguous lessons we have learned from research into the determinants of long-run prosperity is that there is no single magic bullet, no unicausal explanation that leads to a simple recipe for success. Many factors are involved, and they are largely interdependent. As Nicholson (2003) puts it, the only sensible approach to take is a systems approach. That is, just as there is more than one critical organ in the human body, whose well-functioning is necessary but not sufficient for good health, so there is more than one critical factor necessary for strong economic growth, none of which is enough by itself to solve the growth problem. As the recent OECD report on sources of growth indicates (OECD, 2003), long-run prosperity is promoted by sound fiscal policies, low and steady inflation, openness to international trade, high levels of human capital, strong investment in plant and equipment, innovativeness and R&D, a strong degree of competition and appropriate protection of intellectual property. There is no simple formula for assessing the relative importance of these factors. But detailed empirical investigations can give us clues as to how they relate to each other and how to measure the long-run impact of any one of the factors. To do this requires an organizing theoretical framework capable of representing the various interconnections at work, a framework that has been developed not just on grounds of a priori plausibility but also on grounds of its correspondence with empirical evidence. I have tried in this article to show how recent developments in the Schumpeterian branch of endogenous growth theory are beginning to provide such a framework. Of course much work remains to be done.

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