TECHNOLOGY-GAPS, INNOVATION-DIFFUSION AND TRANSFORMATION: AN EVOLUTIONARY INTERPRETATION

by

Jan Fagerberg
(TIK, University of Oslo)

&

Bart Verspagen
(ECIS, Eindhoven University of Technology)

Second draft, June 2001

Bart Verspagen's contribution to this paper draws on an earlier paper by this author entitled 'Economic Growth and Technological Change: An Evolutionary Interpretation', OECD Directorate for Science, technology and Industry, STI Working Papers, 2001/1. This paper also uses material from Fagerberg, J. and B. Verspagen, 1999, 'Modern Capitalism in the 1970s and 1980s', in: Setterfield, M. (ed.), *Growth, Employment and Inflation. Essays in Honour of John Cornwall*, London: Macmillan Press.

Eindhoven Centre for Innovation Studies

Eindhoven Centre for Innovation Studies (ECIS), Eindhoven University of Technology, PO Box 513, 5600 MB Eindhoven, the Netherlands

1. Introduction

In their path breaking book *An Evolutionary Theory of Economic Change* (1982) Richard Nelson and Sidney Winter suggested that theoretical progress should be understood as interaction between two different levels of theorizing: formal theory and appreciative theory. While the former is described as logical and mathematical, the latter is said to be closer to empirical observation, to the development of which it is assumed to provide both guidance and interpretation. "In a well-working scientific discipline", they argue, "the flow of influence is not only from formal to appreciative theorizing, but in the reverse direction as well. Phenomena identified in applied work that resist analysis with familiar models, and rather causal if perceptive explanations for these, become the grist for the formal theoretical mill. Somewhat informal explanations in the style of appreciative theory are abstracted, sharpened, and made more rigourous." (Nelson and Winter 1982, p. 47). It was Nelson and Winter's view that the orthodoxy's (as they called it) neglect of appreciative theorizing was one important reason behind the failure of the discipline to cope with many important real world phenomena.

Arguably, the distinction between formal and appreciative theorizing may also be important for understanding the field of evolutionary economics itself. On the one hand, there is an important body of work on evolutionary modeling, following the initial contributions by Nelson and Winter and others. This work is often inspired by evolutionary biology and draws on mathematical tools that have become popular in biology and other natural sciences. However, the term evolutionary economics is also often associated with a rather influential approach in economics that stresses the importance of out-of-equilibrium dynamics, without this tradition necessarily being directly influenced by biological approaches. The economist Joseph Schumpeter is certainly a central contributor to this literature as are many economic historians such as, for example, Alexander Gerschenkron, Moses Abramovitz and Nathan Rosenberg. What these authors have in common is that they focus on evolution as a process of qualitative change that take place in historical time, driven by firms, governments and other organizations (rather than individuals) with a diverse set of motivations, decisions rules and capabilities (rather than optimizing behaviour and perfect information).

What we in earlier work have called "the technology gap theory of economic growth" (Fagerberg 1987, 1988) is in our view also an example of appreciative theorizing. It emerged mainly because of the failure of formal growth theories to recognize the role of innovation and diffusion of technology in global economic growth. These formal theories either ignored innovation-diffusion altogether, or assumed that technology is a global public good created outside the economic sphere, and therefore could (should) be ignored by economists. However, it became obvious for many students of long-run growth that the perspective on which this formal theorizing was based had little to offer in understanding actual growth processes. Rather than a global public good, available to everyone for free, it became clear to observers that there were large technological differences (or gaps) between rich and poor countries, and that engaging in technological catch-up (narrowing the technology gap) was perhaps the most promising avenue that poor countries could follow for achieving long-run growth. But the very fact that technology is not a global public good, i.e., that such technological differences are not easily overcome, implies that although the prospect of technological catch up is promising, it is also challenging, not only technologically, but also institutionally (Gerschenkron, 1962). Moreover, since, as emphasized by Schumpeter, economic growth is a process of qualitative change (with leading technologies and perhaps industries changing through time), engaging in technological catch-up is like trying to hit a moving target. Hence, technological catch-up is not a question of replacing an outdated technological set up with a more modern one, but to continually transform technological, economic and institutional structures, as pointed out by several prominent students of long-run growth (see, e.g., Svennilson 1954, Cornwall 1977).

In the next section we discuss the relationship between appreciative and formal evolutionary theorizing in a bit more detail and outline a perspective on economic growth that will be applied later in the paper. Section 3 is concerned with one of the conclusions from section 2, namely that capitalist development is not necessarily a convergence process, as some theories in this area suggests. Rather it is likely to be a process of alternating periods of convergence and divergence. Then, in section 4 and 5, we turn to main empirical parts of the paper, in which we attempt to reassess some of the previous work done by "appreciative evolutionary theorists" on post-war economic growth on new and more recent evidence. The final session summarizes the lessons from the study.

2. Evolutionary Economics and Technology Dynamics

One central division in the many different ways in which the term evolutionary economics has been used is that between approaches that take biological metaphors rather strictly, and those that do not. In the first set of contributions, the biological notions of natural selection and (random) genetic mutation are applied to economic processes such as industrial dynamics (Dosi, Marsili et al., 1995) or economic growth (Silverberg and Verspagen, 1998). An early overview of the methods and issues in this branch of literature is Silverberg (1988). This leads to a central role of heterogeneity between economic agents (and hence the rejection of the standard neoclassical concept of the representative agent), and to the use of economic selection as a counterpart of natural selection. Although this has led to interesting models, we will not concern ourselves too much with this approach in this paper.

A second interpretation of the term 'evolutionary economics' takes the analogy to biology much less strictly. In this case, the term is used to refer to a set of theories, more often informal than formal, which pay particular attention to the role of technology and institutions in the process of economic growth. Usually, these contributions draw inspiration from Schumpeter's (1912) notion of disequilibrium dynamics resulting from the introduction of (basic) innovations. Examples of this approach are Fagerberg (1987), Fagerberg (1988), Freeman and Soete (1987) or Dosi, Pavitt and Soete (1990).

The central theme in this literature is that one cannot make a useful distinction between 'economic' and 'non-economic' factors when trying to explain economic growth. These authors think of the 'social system' as composed of different 'domains', e.g., the techno-economic domain and the socio-institutional domain (Perez, 1983), or the separate domains of technology, economy and institutions (Dosi, 1984). Each of these domains has its own dynamics and explanatory processes, but what is important is that the domains exert strong mutual influences. Examples of such interaction are the impact of European integration (a process that started very much as a way of stabilizing Europe in a political way after the 1940s) on economic growth (Fagerberg, Guerrieri et al., 1999), the impact of culture on regional innovation systems (Saxenian, 1994), or the influence of firm organization on economic growth (Von Tunzelmann, 1995). In this view, any 'model' that limits itself to pure economic factors (such as R&D, capital investment or human capital) provides a much too narrow perspective on economic growth.

The perspective offered by these theories is one of the world economy as a process of constant transformation. Technologies and institutions change in time, and what drives economic growth in one era (e.g., economies of scale in relation to mass production) might become much less important, or substituted by a different factor (e.g., network economies) in a different era. In terms of economic growth rates, such a process is quite different from the neo-classical notion of steady state growth.

OECD (2000), under the heading of ‘The changing role of innovation in growth performance’, discusses a number of transformations that are good examples of the processes we have in mind. Among the factors mentioned there are shortening technology cycles, changes in financial markets enabling easier financing of innovative activities (venture capital), the increasing role of networks and alliances in technology development, and the closer link to science. We will not discuss these factors in any detail here.

The notion of the economy as a constant process of transformation is perhaps most clearly pictured in the literature on long waves and technological revolutions. While we conform to the usage of the term long waves, we do not take this to imply any strong implications of regularity in growth rates, or in the underlying technology dynamics (more comments on this will follow below). The literature on long waves is interesting for our purpose because it brings out very nicely the non-steady state, evolutionary nature economic growth in historical perspective. The tradition originates from Schumpeter (1939), and was later refined by contributions such as Freeman, Clark and Soete (1982), Kleinknecht (1987) and Van Duijn (1983).

In its basic form, the hypothesis states that the introduction times of basic innovations are clustered in time. A ‘bunch’ of innovations may lead an upswing of economic growth once it creates a bandwagon of follow-up, incremental innovations. Wolff’s law (Freeman, 1982) about decreasing marginal technological opportunities ultimately brings a slowdown of economic growth, after the new technological paradigm (the term is Dosi’s, 1982) is diffused throughout the economy. Although this is clearly a technology driven theory of economic growth, the role for other than pure economic or technological factors is large. Perez (1983) and Von Tunzelmann (1995) are particularly strong examples of approaches where the notion of technological paradigms is linked to broad institutional change, firm strategy or industry dynamics.

Many researchers in the evolutionary school would argue against a strict cyclical interpretation of economic growth (e.g., Freeman, Clark and Soete, 1982; Silverberg and Lehnert, 1994). In this weaker interpretation of Schumpeter’s theory of innovation and growth, periods of rapid and slow growth take over from each other, but the exact duration of different phases, as well as the ‘amplitude’ of trend deviations depends on specific historical and institutional factors. In this vein, Freeman, Clark and Soete (1982) have called for a focus on the diffusion of radical technological breakthroughs rather than Schumpeter’s original focus on clustering of innovation times. Silverberg and Lehnert (1994) proposed a model that implements this idea. Their assumption is that (radical) innovations are Poisson distributed with a constant expected arrival rate over time, rather than an assumption of clustering. The model (still) clearly shows long-run fluctuations of economic growth, generated by the long diffusion time of the innovations. Although the growth pattern generated by this model is far from regular, it is certainly also a long way from any steady state as suggested by a more mainstream interpretation. Silverberg and Verspagen (2000) provide supporting evidence for the assumption of Poisson distributed radical innovations.

This short discussion brings us to the following two conclusions that will guide our analysis in the remainder of this paper.

1. Economic growth is first of all a process of transformation, not of convergence to a steady state growth path. The transformation of capitalism involves interaction of the economic sphere with other domains, such as science and technology, and institutions. This has three major implications. First, that differences in economic growth (both over time and between countries) are hard to predict *ex ante*, but often have clear underlying explanatory factors *ex post*. Second, that in the long run, economic growth is not a process of general convergence. One might indeed observe historical periods of convergence during times when institutions and technological developments allow this, but periods

of divergence of economic growth must also be expected. Third, any distinction between trend growth and cyclical variations around the trend is problematic.

2. Technology is a key factor shaping economic growth, and the changes in growth rates. This leads to two issues. First, the distinction between radical and incremental innovation becomes of crucial interest. Radical innovations open up new possibilities for long-run changes in the trend rate of economic growth. When radical (or basic) innovations occur, they disrupt the existing economic structure and dependencies in the economy. This leads to changes in the growth rate that are (again) hard to predict in a detailed way *ex ante*. Incremental innovations are associated with the diffusion of the radical innovations throughout the economy, and they depend crucially on the specific historical and institutional context. It is the analysis of this diffusion process that is interesting, rather than the explanation of the occurrence of basic innovations.

Second, the (stylized) distinction between innovation and imitation receives central importance. Technology cannot be fully appropriated by the firm that develops an innovation. In time, technological knowledge spills over to other firms and other nations. While innovation (the development of new technology) may lead to divergence between firms or nations, imitation tends to erode differences in technological competencies, and hence lead to convergence. When diffusion of innovations takes time, and depends on 'fuzzy' institutional factors such as those mentioned above, the exact mix between innovation and diffusion may lead to turbulent growth paths (Silverberg and Verspagen, 1995) provide a quantitative model that illustrates this point).

3. Economic growth: transformation or steady state?

What evidence is there for the evolutionary hypothesis of economic growth as a non-steady state process of constant transformation? As argued in the previous section, this question is very much related to non-economic variables such as institutions and culture. Measurement of these factors is hard, although not completely impossible. Nevertheless, we will approach the issue here from a purely quantitative perspective, focusing only on growth rates of GDP and GDP per capita, thus providing rather indirect 'evidence'.

The issue of changes in the trend rate of growth has been investigated in a recent set of papers (e.g., Crafts and Mills, 1996, and the references there). In general, the methodology used to investigate this question is to estimate the log of GDP or GDP per capita as a (linear) function of time, where the slope of the estimated relation ship gives the trend growth rate. Varying this slope for different periods, and testing for the statistical significance of the differences, gives an indication of trend changes in economic growth. Although this method has intuitive appeal, it has one major disadvantage in the present context. The method posits trend breaks as discontinuous events: the trend growth rate is assumed to change suddenly from one year to the other, and then to stay constant for a longer period. Form an evolutionary point of view, one would like to investigate the possibility of more smooth changes in the trend.

One way of dealing with this problem is to estimate the trend growth rate as a time varying parameter, as can be done by using the Kalman filter. In this way, one may specify the trend growth rate itself as a (stochastic) function that changes yearly. This is the method used here. As is commonly done, GDP and GDP per capita are modeled as a loglinear function of time. However, both the constant and the slope of this relation are modeled as time varying parameters in a Kalman filter model, i.e., these parameters are assumed to change on a yearly basis by a stochastic process. [1]

Figure 1 gives the Kalman filter estimations for six of the countries for which long time series are available in Maddison (1995). For the most recent years (up to 1998), Maddison's data were updated with the data developed by the Groningen Growth and Development Centre.[2] The figures give the growth rate of GDP per capita (left axis, dark line) and the growth rate of GDP (right axis, light line). The results indicate that there is indeed a great variability in the 'trend' growth rates for these countries over time. Most evidently, the two world wars cause violent interruptions of trends. For all countries except Italy the start of the twentieth century is a period of high growth. The early 1910s signify radical breaks, usually with rapidly falling trend growth rates. With the two wars, the roaring twenties and the Great Depression in the 1930s, the next 35 years are turbulent, with no clear steady state settling in.

After 1950, the European countries and Japan show a common pattern of rapidly increasing trend growth rates. In most cases, this strong increase of the trend brings the countries involved on a path with growth rates that are higher than ever experienced before in the twentieth century. The United States is an interesting exception to the increasing trend growth rate in the post World War II period. The 1970s bring a well-documented break with the golden age of the 1950s and 1960s. In all countries, trend growth settles down at a relatively constant level. It is notable, however, that compared to the end of the golden age, the trend growth rates in most countries are at a similar or just slightly lower level. What is different in the 1970s and 1980s as compared to the previous period is that the trend growth rates no longer increase.

The 1990s show some ripples in time. Obviously, compared to the time span of the graph, this period is rather short for any firm judgement about possible reversions of the trend. What is interesting, however, is the fact that the estimated trends vary greatly between countries. On the one hand, Germany, Italy and Japan seem to experience a decrease in the trend. The United Kingdom and the United States, on the other hand, seem to show signs of an increase of trend growth.

In summary, the Kalman filter estimations seem to show that the concept of steady state growth is not very useful from an empirical point of view. Growth paths of countries show a high degree of variability over time. Periods of rapid and slow(er) growth take turns, without, however, a clear cyclical pattern with fixed periodicity. There are some features of historical growth patterns that seem to be shared by most countries: generally erratic patterns of trend growth before 1940, a long period of increasing trend growth rates after the second world war, and slowdown of growth from the mid-1970s. Despite these common patterns, there are important differences between countries with respect to the timing of changes in the trend, the level of growth rates, and the detailed shape of the patterns. Moreover, there are quite a few exceptions to these common patterns. Interestingly, the 1990s are a clear example of the variability of growth trends between countries. In some countries, one sees a clear pattern of take off of growth rates, while in others the flat trend of the 1970s and 1980s is continued.

[1] The specific result of the Kalman filter estimations depend on a number of parameters, of which the variance factors in the transition and measurement equations are two important ones. We inferred the variance factor in the transition equation from a number of initial estimations, according to the procedure described as "bootstrapping a variance for the transition equation" in the TSP 4.4 Reference Manual under the KALMAN command. We used defaults for all other estimation parameters, among which the identity matrix for the transition factor in the measurement equation. However, the results are not very sensitive for these parameters, especially not for the years in the graphs.

[2] The updates were taken from the GGDC Total Economy Database, University of Groningen, Fourth Quarter 1999, http://www.eco.rug.nl/ggdc.

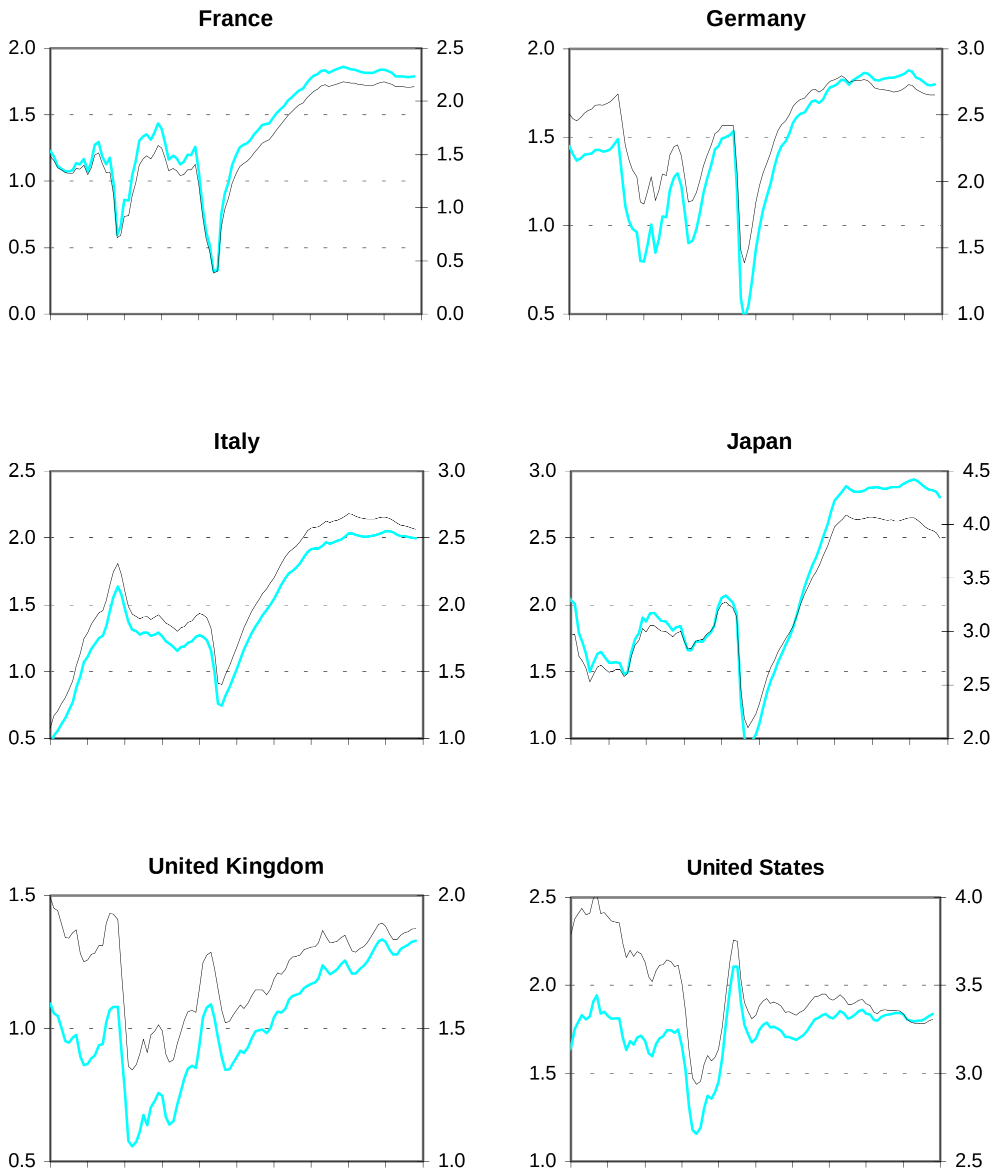

Figure 1. Trend growth rates of GDP per capita (light line, left axis) and GDP (dark line, right axis), estimated with a Kalman filter

Our main interest in this paper is in comparative growth performance, or the issue of convergence or divergence of GDP per capita levels. Part of the empirical facts of this debate is by now well established, such as the strong tendency for convergence that the OECD countries experienced during the period from 1950 to the mid-1970s. However, in order to set the agenda on what must be explained in terms of 'macroeconomic population dynamics', these facts will be summarized here again, with an emphasis on the most recent period.

Figure 2 gives, for a set of 18 countries including those in Figure 1 as well as a number of other OECD countries[3], the long-run trends of convergence. Two different indicators of differences between countries are used. The first one is one that has been used often in the convergence-divergence debate. It is defined as the standard deviation of the log of GDP per capita in the sample of countries. This is the dark line in Figure 2. A falling standard deviation points to convergence (country differences diminish over time). This measure essentially compares a country's GDP per capita to the (unweighted) sample average.

The figure shows that there was no or little convergence over the period 1870 - 1913. After this, a weak convergence trend sets in until the outbreak of World War II. This event increases the heterogeneity in the sample drastically. From the late 1940s onwards, a very strong convergence process sets in. Around 1960, the level of the indicator is back to where it was before the war, but convergence keeps going on. In the mid-1970s, when trend growth starts to slow down in Figure 1, convergence also comes to a halt. For about a decade, per capita income differences remain stable, but from the mid-1980s, a weak convergence trend sets in again.

The light line in Figure 2 gives a different convergence indicator. This indicator is defined as the mean of the log difference of per capita income in a country relative to the most advanced country in the sample. Australia, the United Kingdom, Switzerland, Germany and the United States appear as countries with the highest value of per capita GDP in one or more years. During the post-World War II period, the United States are in the lead for most of the time. This includes the most recent period (from 1983 onwards). Abramovitz and David (1996) suggest that this indicator fits the idea of catching-up as a result of technology diffusion relatively well. The reason for this is that technology diffuses from the relatively advanced countries to the more backward countries, and this suggests comparing a country to the productivity frontier rather than to the sample average.

For the postwar convergence boom and the slowdown of this in the mid-1970s, the two indicators match relatively well. However, for the earliest period, the second indicator points to more convergence than the first one, and the opposite is true for the period from the start of the twentieth century to 1920.

Of most immediate interest, however, is the strong divergence of the two indicators in the most recent period. While the first indicator, which measures convergence relative to the sample mean, shows weak convergence from 1990 onwards, the second indicator, measuring convergence relative to the leader in terms of GDP per capita (i.e., the United States), shows relatively strong divergence. In other words, while the United States seems to move ahead of the other countries on average, this does not imply that these other countries are not converging to each other.

Figure 3 enlarges the most recent period (after World War II), and also adds two more countries for which only postwar data are available (Portugal and Ireland).

---

[3] In addition to the countries in Figure 1, Australia, Austria, Belgium, Canada, Denmark, Finland, Netherlands, New Zealand, Norway, Spain, Sweden and Switzerland are included. Data are again taken from Maddison (1995) in combination with the GGDC database.

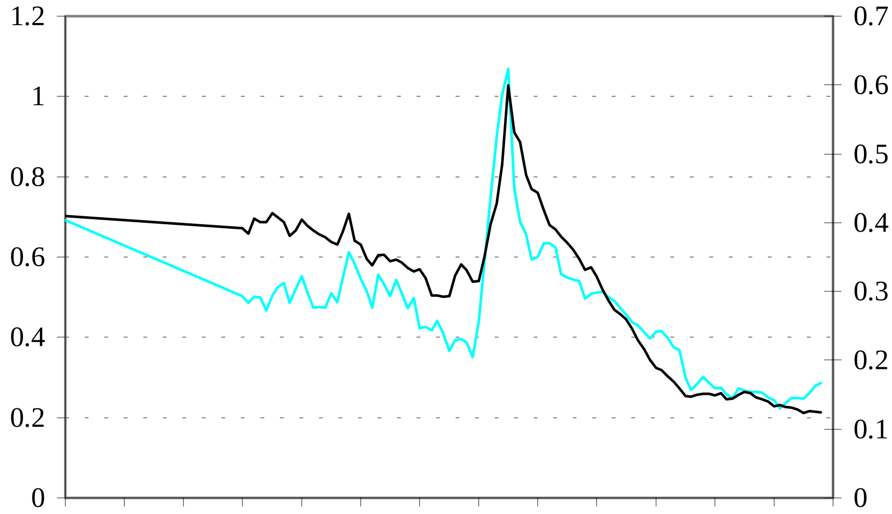

Figure 2. Long-run trends of convergence and divergence

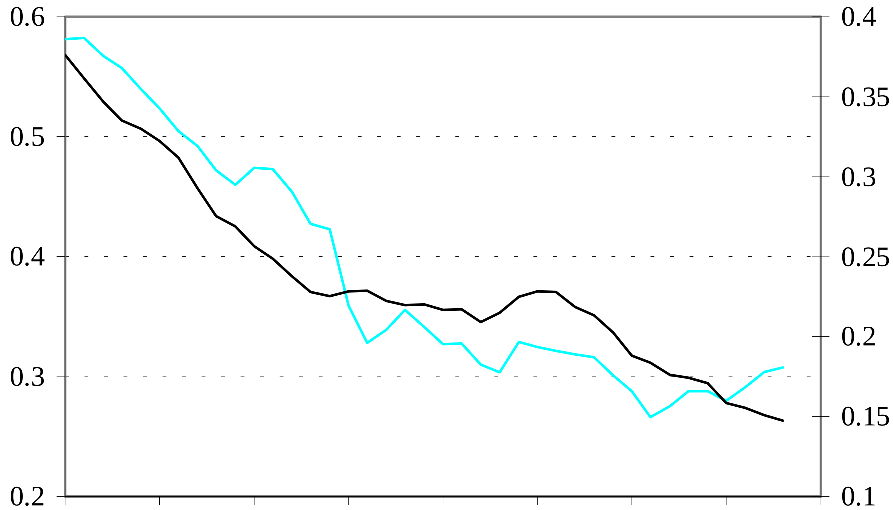

Figure 3. Convergence and divergence after World War II

What is the interpretation of these dynamics? In order to answer this question, we will draw on the discussion of Section 2 and try to sketch a stylized interpretation. The first issue to notice is that the immediate postwar period seems to provide a clear break with the immediate past. Another break seems to be encountered some time during the 1970s. In line with our 'long wave' interpretation of evolutionary growth patterns of Section 2, this suggests that growth during the period 1950 - 1975 (roughly) is driven by different mechanisms than in the period before or after this. While the broad historical characterization of these periods and the differences between them certainly deserves our utmost attention, we choose not to develop this issue in very much detail here. Instead, we mainly draw on and extrapolate from the interpretation offered by Freeman and Soete (1997).

In their perspective, the period immediately following World War II was one in which a set of innovations jointly characterized as 'mass production' diffused through the economies of the developed part of the globe. These technologies had been pioneered in the United States during the first half of the 20th century, for example in the form of Henry Ford's assembly belt and the organizational innovations around this ('Taylorism'), or a whole bunch of new products and processes arising from the use of oil as an energy source and raw material ('cracking'). Growth in this period can thus be characterized as based on the spread of technological knowledge from the technological leader (the United States) to a limited set of other (mostly already developed) countries. In line with some of the literature that will be discussed below, we propose to term this period as one of catching-up based growth.

Abramovitz (1994), Abramovitz and David (1996) and Nelson and Wright (1992) have explained how the spread of this new techno-economic paradigm to other parts of the world became temporarily deferred, and how the circumstance after World War II helped to overcome these barriers. The Bretton Woods system, which spurred world trade and hence enabled even small countries to reap the economies of scale underlying the mass production paradigm, increased possibilities for travel and communication over large distances, and the establishment of the European Community (Fagerberg, Guerrieri and Verspagen, 1999) were some of the more important factors in this.

Continuing in time, the period from the mid-1970s can be seen as one in which the further opportunities of the mass production paradigm had become depleted to such an extent that it started to have a negative impact on growth. This involves both the gradual depletion of technological opportunities, and an emerging 'mismatch' between the techno-economic and socio-economic spheres. The latter issue is developed into much detail in the French literature on 'regulation theory' (e.g., Boyer, 1989). With the depletion of opportunities for further growth also came a depletion of opportunities for convergence and catching-up based growth.

While getting closer to the present, the argument obviously becomes more and more speculative. Freeman and Soete (1997), however, argue that there is evidence for a renewed upswing of economic growth during the 1990s, this time based on a new set of radical technological breakthroughs. These are the set of technologies now jointly referred to as Information and Communication Technologies (ICTs). There is obviously some connection between this hypothesis of an ICT-based upswing of economic growth as the start of a new 'long wave' and the mostly popular debate about the concept of the 'new economy' (on which we will not elaborate here any further). What such an upswing would imply for the possibilities for catching-up based growth and convergence is still rather unclear, and worthy of both theoretical and empirical investigations.

Compressing this already sweeping account of economic history of the 20th century even further, we arrive at a central notion that we will develop further in terms of empirical estimations for the relationship between economic growth and technology. The notion is that if we investigate the relationship between technology-related or catching-up factors and economic growth, we should be able to detect structural changes in this relationship over the breakpoints in the above historical picture. The exact nature and direction of these structural changes in the estimated equations would have to correspond to the broad directions of technology dynamics outlined in the narrative history above.

4. Manufacturing - an 'engine of growth'?

We start our empirical investigation by looking at an hypothesis formulated by John Cornwall in his seminal volume "Modern Capitalism" (1977), and which can be seen as implicit in the above sweeping account of economic history. The hypothesis is that of the manufacturing sector as the engine of economy wide growth. Arguably, attributing such a special role for manufacturing is in accordance with the notion of mass-production as a central force in economic growth. Moreover, Cornwall's arguments for the special role of manufacturing indeed point to technological factors as the driving forces of the process. Specifically, Cornwall points to the following two factors.

First, the manufacturing sector displays dynamic economies of scale through so-called "learning by doing" (Young, 1928, Kaldor, 1966, 1967): When production expands, the scope for learning and productivity increases becomes larger. Hence, the rate of growth of productivity in manufacturing will depend positively on the rate of growth of output in manufacturing (the Kaldor-Verdoorn law[4]).

The second line of argument concerns the special role of the manufacturing sector in enhancing productivity growth through its linkages with the non-manufacturing sectors. Cornwall argues that the manufacturing sector is characterized by strong backward linkages, i.e., increased final demand for manufacturing output will induce increased demand in many sectors 'further down the line'.[5] In other words, increased output in manufacturing, due to increased final demand, does not only lead to increased productivity in the manufacturing sector (the Kaldor-Verdoorn law), but also to increased output and, perhaps, productivity in the sectors further down the line. In addition to these backward linkages, Cornwall emphasizes that the manufacturing sector also has many forward linkages, through its role as a supplier of capital goods (and the new technologies that these goods embody). In fact, he considers capital goods from the manufacturing sector to be the main carriers of new technology (Cornwall 1977, p. 135). Moreover, although "learning by doing" may be an important source of productivity growth in non-manufacturing industries as well, it is argued that the realization of this 'learning potential' will in many cases require capital goods supplied by the manufacturing sector.

Cornwall's model of economic growth can be summarized in two equations as follows (ibid., p. 139):

$$\hat{Q} = c_1 + a_1\hat{Q}_m \qquad \textbf{(1)}$$

$$\hat{Q}_m = c_2 + a_2\hat{Q} + dq_r + e(I/Q)_m \qquad \textbf{(2)}$$

[4] There is an extensive literature on this topic, both theoretical and empirical, which it is beyond the scope of this paper to summarize (see, e.g., McCombie and Thirlwall, 1994).

[5] An empirical approach to the study of such linkages is the so-called triangulation of input-output matrices (Cornwall 1977, pp. 130-135). This procedure takes an input-output table and rearranges the order of the sectors (rows and columns) of the table such that (in the 'ideal' case) a sector only supplies to sectors listed above it, and only purchase from sectors listed below it. Hence, sectors ranked at the top tend to purchase large quantities from other sectors (further below) and supply mostly to final demand, while sectors ranked at the bottom tend to supply mostly to other sectors (instead of final demand), only being dependent on a limited number of other sectors for their inputs. Cornwall argues that work based on this methodology show that manufacturing is a sector with strong backward linkages: it supplies a relatively large part of its output to final demand, and purchases large quantities of inputs from other sectors.

In these equations, Q is output, q_r is GDP per capita relative to the technology leader (the U.S.), I/Q is investment as a fraction of output, c, a, b, d and e are parameters and the subscript m indicates the manufacturing sector. Equation (1) states that manufacturing is the engine of growth, hence the parameter a_1 is expected to be positive, and larger than the share of manufacturing in GDP. Equation (2) introduces a feedback from overall demand growth on manufacturing production, hence a_2 is expected to be positive. In addition it allows for catching up by industrial latecomers (hence d is expected to be negative). The inclusion of the investment share (e positive) reflects Cornwall's emphasis on investment as a necessary supporting factor for successful catch-up.

Cornwall does not estimate equation (1), but refers to OLS estimates by Kaldor (1966), Cripps and Tarling (1973) and the UN (1970). Based on data for developed market economies in the fifties and sixties, these studies estimate a_1 to be about 0.6, more than twice the share of manufacturing in GDP. Hence, the evidence from these studies seems to support the hypothesis of manufacturing as an engine of growth. However, in Cornwall's model, both GDP growth and growth of manufacturing output are endogenous variables, and in that case equation (1) should have been estimated by a method other than OLS. Indeed, the OLS estimate of 0.6 may be seriously biased.

Looking at the model in equations (1) and (2) from a simultaneous equation perspective, one must conclude that the second equation is not identified. It does not satisfy the order condition, which says that the equation must exclude at least N-1 exogenous variables, where N is the number of equations in the model (in this case 2). Hence, it cannot be estimated by any estimation technique.[6] The first equation, however, is over-identified, and may be estimated by a single equation technique that takes the simultaneous equation bias into account, such as for, instance, the instrumental variables/two-stage least squares method (2SLS).

The analysis here will proceed by using such a procedure to estimate equation (1) for a large sample of countries. The sample includes 67 countries: 19 developed countries (including Japan), 6 countries from East Asia and the Pacific (excluding Japan), 18 countries in Latin America and the Caribbean, 17 sub-Saharan African countries, and 7 other countries (among which 2 oil exporters). We thus have a rather heterogeneous set of countries. The dependent variable is the growth rate of GDP in real terms over 1973 - 1989 (taken from the Penn World Tables[7], version 5.5). The independent variable is the growth rate of manufacturing value added (in fixed prices) for the same period, taken from World Development Indicators (World Bank).[8] However, for some of the developed countries, no data on manufacturing growth were available in World Development Indicators. For these countries data were taken from the STAN database (OECD). Both growth rates are average annual compound growth rates over the period specified.

To estimate the equation with the chosen (instrumental variable) technique, we need a number of exogenous variables (or instruments). The chosen variables are in most cases well known from previous econometric work in this area: *Initial GDP per capita* (in log-form, taken from the Penn World Tables), *investments in physical capital* as a share of GDP (mean value over 1973 - 1989, also from the Penn World Tables),[9] *education* (enrollment of the relevant age group in secondary education, from the World Development Indicators) and *inflation* (yearly average increase in the CPI

[6] Cornwall solved the identification problem by estimating only the reduced form of the model, which is adequate for testing the overall explanatory power of the model. However, when one wants to test the role of manufacturing as an engine of growth separately from the other elements of the theory, this approach is not sufficient, because in general one can not calculate a parameter estimate for a_1 from the reduced form.

[7] We use the RGDP variable, i.e., real GDP in international prices using a Laspayeres price index.

[8] Version on CD-ROM, 1997.

[9] Due to data availability we use economy wide investment as a share of GDP instead of investment in manufacturing as a share of manufacturing output.

1973-1989, taken from the World Development Indicators). Finally, and less conventionally, we include a variable for *technology investment*[10] as proxied by patents (taken out in the US over the 1975 - 1985 period per head of the population of the country in question, as recorded by the U.S. Patent and Trademark Office).[11]

A well-known problem in estimations using cross-country data sets is the possible bias from inclusion of outliers, i.e., countries with patterns that deviate from the other countries in the sample. If such countries are included, we may be lead to conclusions that in fact are not valid for the majority of the countries in our sample. We therefore adopt a procedure that identifies and excludes such outliers.[12]

Table 1. Estimation results for Cornwall's 'manufacturing as an engine of growth' equation, OLS and 2SLS, various country samples, 1973 - 1990

Eq. num	Est. method	Sample (n)	Manufacturing growth	constant	adj. R^2
1	OLS	Market economies (17)	0.104 (0.70)	0.024 (11.55***)	0.00
2	2SLS	Market economies (14)	0.083 (0.21)	0.024 (6.01***)	0.00
3	OLS	East Asia, Latin America (22)	0.721 (12.36***)	0.008 (3.20***)	0.88
4	2SLS	East Asia, Latin America (17)	0.829 (8.45***)	0.006 (1.82*)	0.83
5	OLS	Other countries (22)	0.371 (4.47***)	0.014 (3.00***)	0.47
6	2SLS	Other countries (15)	0.827 (2.86***)	-0.005 (0.35)	0.40
7	OLS	all countries, no dummies (61)	0.514 (10.54***)	0.014 (7.49***)	0.65
8	2SLS	all countries, no dummies (49)	0.488 (5.98***)	0.016 (5.62***)	0.49
9	OLS	all countries, dummies (61)	0.473 (8.45***)	continent dummies	0.69
10	2SLS	all countries, dummies (45)	0.719 (4.54***)	continent dummies	0.57

Values between brackets are absolute *t*-statistics. One, two and three stars denote significance at the 10%, 5% and 1% level, respectively, in a 2-tailed *t*-test.

The results of the instrumental variable/2SLS estimations are given in Table 1. The results for OLS are also provided for reference.[13] Estimates are reported for the three country groupings and for the

[10] See Fagerberg (1987,1988) for discussion of different indicators of technology gaps and technology investment, and an analysis of the impact of technology gaps and technology investment on growth.

[11] As with most of the literature in this area we use patents taken out in the U.S., because this provides us with the more consistent and economically relevant data than data drawn from a variety of different national sources.

[12] This method identifies outliers by calculating the so-called hat-matrix, $X(X^TX)^{-1}X^T$, where X is the matrix of independent variables. Observations with entries larger than $2*k/n$, where k is the number of independent variables, and n the number of observations in the regression, were excluded. See Belsley *et al.* (1980).

[13] Note that the 2SLS estimates generally have fewer observations, due to missing values for some of the instrumental variables.

sample as a whole. The three country groupings are the developed *market economies*, comparable to Cornwall's sample (though larger), the industrializing countries of *East Asia and Latin-America* and a group of *other countries* (low income), most of which are from Sub-Saharan Africa.

In general, the results obtained by the instrumental variable/2SLS method are not very different from those obtained by OLS.[14] Hence, simultaneity bias does not seem to be an important problem here. This might indicate that the feedback from overall growth on manufacturing output is not so important after all, i.e., that manufacturing growth is important for overall growth, but not the other way around.

For the sample as a whole there appears to be a significant positive relationship between manufacturing growth and GDP growth, with coefficient estimates close to the 0.6 estimate cited by Cornwall, and significantly larger than the share of manufacturing in GDP at the 5% level. This might be interpreted as supporting the idea of manufacturing as an engine of growth. But from inspecting the estimates for the three sub samples it becomes clear that this result is very much dependent on the inclusion of countries other than the developed market economies. For the East Asia - Latin America group as well as the 'other countries', we find a highly significant and positive relationship between the two variables. However, for the developed countries the evidence is less clear. Initially, a significant and positive relationship was found for the developed market economies, but this result turned out to depend heavily on the inclusion of three outliers (Italy, Japan and Finland). When these countries were excluded, we found no evidence of a relationship between the growth of GDP and manufacturing growth.[15] Thus, although manufacturing may explain some of the difference in growth between the three outlier countries and the remaining developed countries in the sample, it clearly does not explain the differences in growth performance among the latter.

In summary, the results in this section indicate that for most developed market economies, manufacturing no longer plays the important role it was found to play in the 1950s and 1960s. Although Cornwall's argument on the relevance of manufacturing seems to hold good for a number of fast-growing 'newly industrializing countries' (NICs) as well as for some developing ones, this clearly points to the possibility that there may have been important changes taking place in the way the global economy works. In the next section we will in a similar way assess the explanatory power of another "appreciative" theory in this area, the technology-gap theory of economic growth (Fagerberg 1987, 1988) which, although related, puts more emphasis on diffusion of technology as a source of innovation (as opposed to "learning by doing, using etc.").

5. Innovation-diffusion, convergence and divergence

In order to look at technology diffusion and catch-up based growth in more details, we will draw on the technology gap growth model developed by Fagerberg (1987, 1988) (see also Kortum, 1997, for a somewhat similar model). This model, building on Pavitt and Soete (1982) and others, takes the

[14] The 2SLS estimates are higher than the ones obtained by OLS in three cases, and in two cases is it the other way around. However, in no case are the 2SLS estimates significantly different from those obtained by OLS at a 5 % level of significance.

[15] It is possible that the engine of growth equations as estimated here suffer from a bias due to omitted variables. Manufacturing may indeed be an important factor explaining growth in other sectors, but there may be other factors explaining economy wide growth, or growth in non-manufacturing sectors, which should have been taken into account when estimating the relationship. For instance, one might argue (e.g., Cornwall, 1977, p. 133) that some of the factors explaining growth in manufacturing also explain economy wide growth, i.e., one may include some of the instrumental variables in our 2SLS procedure as exogenous variables in equation (1). We

distinction between the development of new knowledge (in a country) and the diffusion of knowledge (between countries) that was mentioned out in Section 2 as its point of departure. Fagerberg (1987, p. 88) summarized the basic hypotheses of this approach in four points as follows:

1) "There is a close relation between a country's economic and technological level of development.
2) The rate of economic growth of a country is positively influenced by the by the rate of growth in the technological level of the country,
3) It is possible for a country facing a technological gap, i.e., a country on a lower technological level than the countries on 'the world innovation frontier', to increase its rate of economic growth through imitation or 'catching up').
4) The rate at which a country exploits the possibilities offered by the technological gap depends on its ability to mobilize resources for transforming social, institutional and economic structures."

In an attempt to quantify the first of these four relationships, Fagerberg (1987, 1988) regressed the level of GDP per capita on two different technology indicators: external patents per dollar of export, and total R&D expenditures as a fraction of GDP. The hypothesis was that this relation is loglinear rather than linear, because countries closer to the technological frontier depend more on the development of new knowledge than on diffusion. Especially patents must be considered as an indicator of the development of new knowledge, while a part of R&D will generally be related to assimilating foreign technology. Thus, countries with high values of GDP per capita are expected to have relatively higher values of patenting per dollar export, while this relationship may be somewhat less steep for R&D.

Fagerberg's original regressions were undertaken for the period 1973-1983. Tables 2 and 3 repeat the regressions for this period, and extend the time coverage to an earlier period (1966-1972) as well as two more recent periods (1984 - 1995 as a whole and 1990-1995 separately). We use a sample of 29 countries, including Hongkong, Malaysia, Philippines, Singapore, South Korea, Taiwan, Thailand and Turkey in addition to the countries used so far.[16] Some slight differences in the data set compared to Fagerberg's original regressions are present. In particular, while the original data on patents refers to total external patents (patents by the country's residents in foreign countries), this paper uses data on patenting in the United States since this source gives easier access to data for non-OECD countries.[17] Also, while Fagerberg used civil R&D, this paper uses total R&D (including non-business financed/performed R&D), because the former data were not available for a number of countries.

Table 2 gives the relation between GDP per capita and patenting per billion dollar exports (EPA). In addition to the adjusted R^2, three additional statistics are given as (indirect) tests of the nonlinearity assumption.[18] The first of these (LM het.) is a Lagrange multiplier test for heteroscedasticity of the residuals. The second (JB test) is a Jarcque-Bera test for normality of the residuals. The final test (RESET test) is a Ramsey RESET test for the specification used.

---

tested various equations from this perspective, but always found that the results reported above are robust to the inclusion of other possible explanatory factors. These results are available from the authors on request.

[16] Compared to Fagerberg, the present sample excludes India, Mexico, Brazil, Argentina, but adds Malaysia, Philippines, Turkey, Singapore and Thailand.

[17] We compared data on total external patenting and data on patenting in the US to each other for the OECD countries in the sample. There are three countries that are clear outliers in the total sample for the complete period under consideration. These are the United States (because of a 'home market effect'), Canada (similar) and Japan. We adjusted the data for these three countries downwardly in such a way that the ratio between their value for total external patenting and the mean value of that variable of Germany, the United Kingdom and France is replicated in the US patenting data. Details available on request.

Table 2. The relation between GDP per capita and patenting activity, variables all standardized

	const.	EPA	ln(EPA)	adj. R^2	LM het.	JB test	RESET test	n
1966 – 1972								
1	0.713	0.306		0.51	0.87	1.54	6.28	28
	(0.00)	(0.00)			(0.35)	(0.46)	(0.02)	
2	1.269		0.257	0.75	0.25	0.45	1.39	27
	(0.00)		(0.00)		(0.62)	(0.80)	(0.25)	
1973 - 1983								
3	0.711	0.300		0.53	3.78	1.14	8.08	28
	(0.00)	(0.00)			(0.05)	(0.57)	(0.01)	
4	1.217		0.258	0.80	0.98	1.96	0.015	28
	(0.00)		(0.00)		(0.32)	(0.38)	(0.90)	
1984 – 1995								
5	0.748	0.252		0.44	4.79	0.83	2.53	29
	(0.00)	(0.00)			(0.03)	(0.66)	(0.12)	
6	1.148		0.179	0.61	2.58	0.27	0.08	29
	(0.00)		(0.00)		(0.11)	(0.88)	(0.79)	
1990 – 1995								
7	0.780	0.220		0.35	4.45	1.41	1.51	29
	(0.00)	(0.00)			(0.04)	(0.49)	(0.23)	
8	1.131		0.158	0.55	1.88	0.63	1.07	29
	(0.00)		(0.00)		(0.17)	(0.73)	(0.31)	

Note: GDP per capita is always in levels, not logs; *p*-values of a two-sided *t*-test between brackets.

Table 3. The relation between GDP per capita and R&D intensity (total R&D), variables all standardized

	const.	RD	ln(RD)	adj. R^2	LM het.	JB test	RESET test	n
1966 – 1972								
1	0.780	0.439		0.58	0.69	0.53	0.00	16
	(0.00)	(0.00)			(0.41)	(0.77)	(0.98)	
2	1.286		0.336	0.55	1.06	0.70	0.84	16
	(0.00)		(0.00)		(0.30)	(0.70)	(0.38)	
1973 – 1983								
3	0.822	0.417		0.58	0.06	0.45	1.42	19
	(0.00)	(0.00)			(0.81)	(0.80)	(0.25)	
4	1.287		0.361	0.64	0.33	0.31	0.00	19
	(0.00)		(0.00)		(0.56)	(0.85)	(0.98)	
1984 – 1995								
5	0.543	0.480		0.58	0.21	1.89	5.53	27
	(0.00)	(0.00)			(0.64)	(0.39)	(0.03)	
6	1.103		0.374	0.67	0.09	9.01	0.00	27
	(0.00)		(0.00)		(0.76)	(0.01)	(0.95)	
6a	1.166		0.356	0.66	0.75	0.59	0.94	19
	(0.00)		(0.00)		(0.39)	(0.74)	(0.35)	
1990 – 1995								
7	0.561	0.459		0.55	0.02	2.82	9.06	27
	(0.00)	(0.00)			(0.89)	(0.24)	(0.01)	
8	1.091		0.360	0.69	0.50	7.88	0.09	27
	(0.00)		(0.00)		(0.48)	(0.02)	(0.77)	
8a	1.147		0.342	0.63	2.33	0.98	1.54	19
	(0.00)		(0.00)		(0.13)	(0.61)	(0.23)	

Note: GDP per capita is always in levels, not logs; *p*-values of a two-sided *t*-test between brackets.

[18] We do not test the double ln relationship that was originally used in addition to the linear and loglinear one.

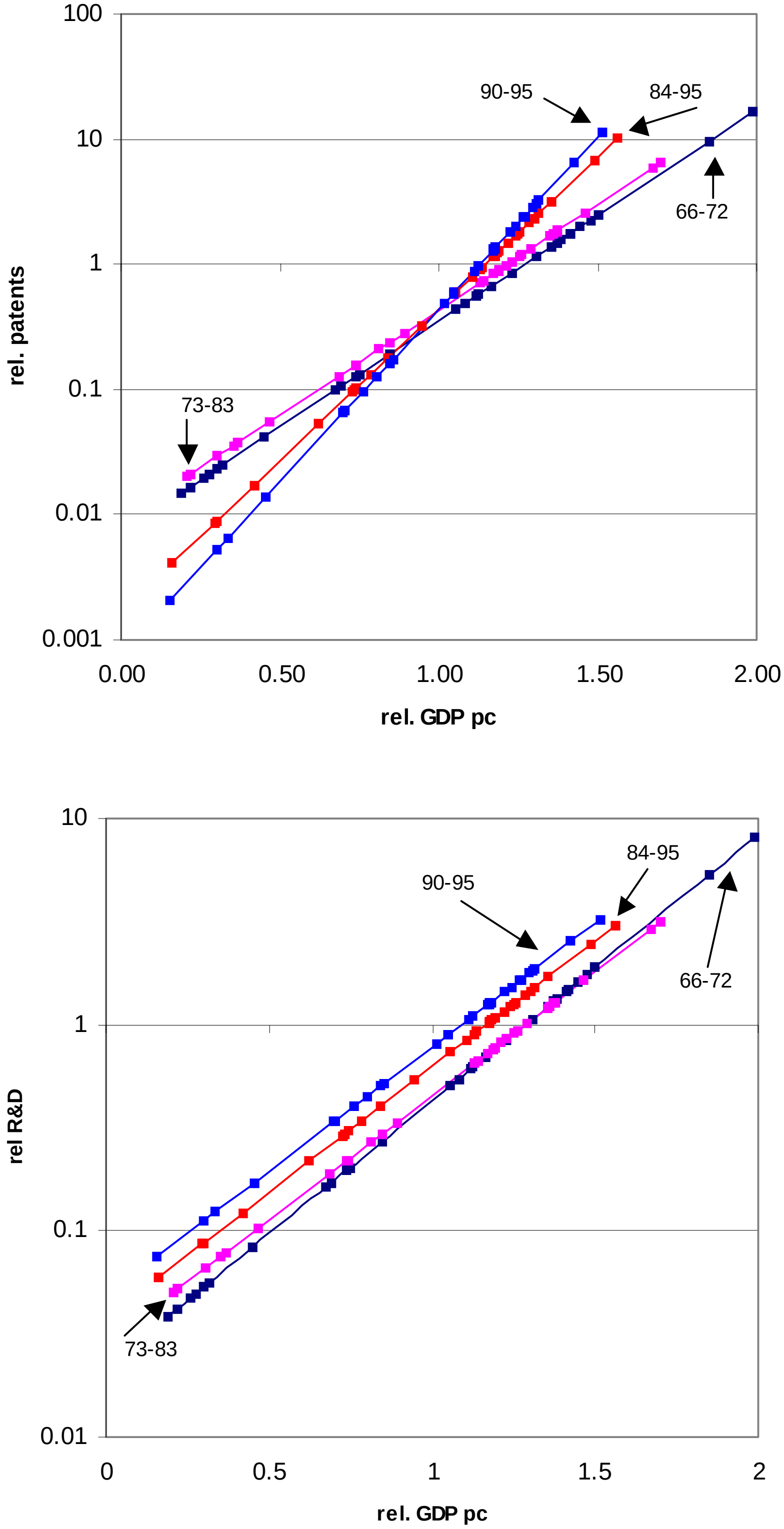

Figure 3. A graphical representation of the equations estimated in Tables 2 and 3

The table generally points to the outcome that the log-linear specification is better than the linear specification, as expected. For example, the RESET test for the two early periods rejects the null hypothesis of correct specification for the linear variant, while it does not reject the same hypothesis for the log-linear form. Also, for the linear equations 3, 5 and 6, homoscedasticity is rejected, while this is not the case for the log-linear counterparts 4, 6 and 8.

The correlation between GDP per capita and patenting (ln(EPA)) changes somewhat over time. For the two periods before 1984, the slope and intercept are roughly equally. Post 1983, however, much lower values are obtained for the slope, and the most recent sub period of this shows an even lower value than the whole 1984-1995 period. The intercept is also a bit lower recently.

Table 3 gives the same regressions for R&D intensity (RD). Here again the specification tests generally point to the log-linear form as a better approximation of the true relationship, especially so for the period since 1984 (RESET test). There is one crucial difference with Table 2, however, and that is the fact that the coefficient on ln(RD) remains rather stable over time. The intercept in the R&D equation falls with time, however. Because the sample size also grows over time (especially the Asian countries do not have R&D observations for the two early periods), equations 6a and 8a repeat, respectively, equations 6 and 8 for the same sample of countries as in equation 4. The results show that the influence of the sample is relatively minor.

Because the intercept and slope do not always change in the same direction, it is hard to assess the exact implications fort the relationship between relative GDP per capita and relative R&D or relative patenting. Figure 3 displays the estimated relationships. An interesting difference between patenting and R&D emerges. For R&D, it is clear that a given level of (relative) GDP per capita in the recent period comes with a higher level of (relative) R&D. The curves in the bottom part of the figure simply shift up over time. This points to a trend where all countries, whether relatively backward or relatively advanced, increase their R&D intensity over time (note, however, the logarithmic vertical axis). In other words, both catching-up based growth and growth at the technology frontier become more R&D intensive over time.

Patenting is a different story. Here the curve is gradually rotated to the left around the point that roughly corresponds to average GDP per capita. Thus, for the advanced economies, patenting becomes more intense, for the relatively backward countries is becomes less so (but note again the logarithmic vertical axis). One possible interpretation of this may be that the differences between R&D as technological activities have become more pronounced over time. Arguably, due to the increasing importance of knowledge in modern production, imitation becomes more demanding, and R&D capabilities more and more critical. Hence, even countries on relatively low levels of development now need to develop their own R&D capabilities, if they wish to exploit the potential for catching-up with the more developed ones. Patenting, on the other hand, remains an indicator of innovation rather than assimilation of diffused knowledge. What this shows is that catching-up by assimilating foreign technology becomes a more active process, at least in terms of R&D, while the ultimate technological frontier remains to be a matter of (a handful of) highly developed countries.

Table 4 re-estimates the dynamic specification of the technology gap growth model, based on points 2-4 above (see Fagerberg, 1988 for a formal model). The dependent variable is the average annual compound growth rate of GDP. The basic point about the model is that it takes into account three factors:

- innovation (a possible source of divergence, reflected in either patents or R&D),
- the potential for diffusion (a possible source of convergence, proxied by the level of productivity or GDP per capita) and
- complementary factors that contribute to the exploitation of this potential (“absorptive capacity”).

Table 4. Estimation results for dynamic technology gap growth model

	1	1a	2	2a
constant				
DME	0.233	0.231	0.095	0.069
	(5.87***)	(5.84***)	(1.94**)	(1.79*)
84-95	-0.129	-0.127	-0.084	-0.076
	(5.04***)	(5.10***)	(1.65*)	(1.46)
73-83	-0.177	-0.178	-0.056	-0.056
	(3.95***)	(4.01***)	(1.79*)	(2.14**)
66-72	-0.044	-0.039	-0.046	-0.036
	(0.78)	(0.76)	(1.62)	(1.16)
R&D				
DME	-0.015			
	(0.28)			
84-95	0.050	0.049		
	(2.82***)	(2.87***)		
73-83	0.094	0.079		
	(0.94)	(1.00)		
66-72	-0.182	-0.196		
	(1.73*)	(2.18**)		
patents				
DME			0.052	
			(0.71)	
84-95			0.126	0.133
			(3.44***)	(3.53***)
73-83			0.061	0.064
			(1.91*)	(2.21**)
66-72			-0.008	0.027
			(0.13)	(0.41)
investment				
DME	-0.109	-0.117	-0.095	
	(2.12**)	(2.21**)	(1.39)	
84-95	0.205	0.206	0.199	0.159
	(5.93***)	(6.17***)	(2.62***)	(2.25**)
73-83	0.227	0.234	0.142	0.102
	(4.13***)	(4.25***)	(2.90***)	(3.81***)
66-72	0.250	0.251	0.267	0.202
	(3.18***)	(3.18***)	(2.50**)	(2.23**)
catch-up potential				
DME	0.049	0.049	0.040	0.036
	(3.67***)	(3.62***)	(2.97***)	(2.32**)
84-95	-0.067	-0.067	-0.037	-0.033
	(11.3***)	(11.4***)	(3.21***)	(2.71***)
73-83	-0.044	-0.044	-0.054	-0.053
	(2.99***)	(2.95***)	(7.38***)	(7.80***)
66-72	-0.132	-0.134	-0.049	-0.040
	(5.13***)	(5.45***)	(4.47***)	(4.10***)
manufacturing share				
DME	-0.0047	-0.0046	-0.0015	-0.0016
	(7.16***)	(7.17***)	(2.13**)	(2.28**)
84-95	0.0041	0.0041	-0.0009	0.0010
	(6.93***)	(6.88***)	(1.19)	(1.22)
73-83	0.0036	0.0036	0.0013	0.0016
	(5.03***)	(5.02***)	(1.45)	(2.18**)
66-72	0.0059	0.0059	0.0015	0.0015
	(5.36***)	(5.35***)	(2.71***)	(2.55**)
services share				
DME	-0.0036	-0.0036	-0.0024	-0.0021
	(5.74***)	(5.69***)	(3.75***)	(3.53***)
84-95	0.0029	0.0029	0.0022	0.0020

	(5.02***)	(5.11***)	(2.71***)	(2.47**)
73-83	0.0026	0.0026	0.0026	0.0026
	(3.96***)	(3.89***)	(5.39***)	(6.35***)
66-72	0.0035	0.0035	0.0019	0.0016
	(5.74***)	(5.16***)	(3.58***)	(3.07***)
adj. R^2	0.82	0.83	0.74	0.74
n	56	56	70	70

t-values of a two-sided *t*-test between brackets; one, two and three starts point to 10, 5 and 1% significance, respectively.

The patent variable is specified as the average annual growth rate of the number of patents in the United States, R&D as the average annual growth rate of real R&D expenditures.[19] In addition, and in line with the 'Cornwall model' that was estimated above, we include investment (as a fraction of GDP, average over the period indicated) and industrial structure (the shares of manufacturing and services in GDP) as two factors influencing the realization of catch-up potential.

The model is estimated for a pooled sample of observations of 29 countries and the three time periods used above (1966-72, 1973-83, 1984-1995). To check for the possibility of different dynamics between already developed countries (developed market economies, DMEs) and countries in the process of catching-up (NICs), we introduce a separate slope dummy for the former (DME). To check for changes in the working of the variables over time we time-slope dummies for each time period and variable. This means that the reported coefficients for the three time periods hold for the NICs, while one must add the value of the DME dummy to obtain the results for the developed countries.

We report estimates for two versions for the model, one with R&D as the innovation variable (model 1/1a) and one with patenting (model 2/2a). The main lessons to be drawn from these are the following:

1) In general, the test confirms the basic hypotheses underlying the model, i.e., that innovation, diffusion potential and other (complementary) factors related to the exploitation of this potential matter for economic growth.
2) There appear to be important differences in the working of the model for the two sets of countries taken into account by the study (as witnessed by the estimates for the DME-dummy). In particular, the catch-up potential seems to be very important for the NICs, while it matters much less for the DMEs, and this to some extent holds for the other conditioning variables, i.e. investment and industrial structure, as well.
3) The importance of innovation for economic growth appears to increase over time. This holds for both R&D- and patents-based measures of innovation, and for NICs as well as DMEs. The impact is especially significant in the most recent period.
4) The opposite holds for the role of manufacturing which had a higher and more significant impact before 1973 than it is shown to have later.
5) The choice of innovation variable has only a few implications for the impact of other variables. When R&D is used, the estimated impact of the catch-up potential decreases through time, while this evidence is less clear in the case of patents.[20] Another difference relates to the impact of manufacturing on growth, which is higher and more significant when R&D is used.

[19] The GDP deflator is used, and R&D expenditures are total expenditures (GERD).
[20] However, it turns out that this particular difference depends more on the difference in sample than the choice of innovation indicator. When patents are used, and the sample reduced to 56 (as for R&D), the catch up potential was clearly higher in the first period than the following ones.

In conclusion, the results in this section suggest that there have been important changes through time in the way innovation-diffusion and economic growth and welfare are linked. Although the link between economic and technological levels of development is in itself not new, the importance of R&D and innovation for the outcome of economic dynamics has increased. This holds not only for the countries at the frontier, but for countries in the process of catching up as well.

6. Conclusions

The empirical analysis of this paper started with a discussion about the character of economic growth at the country level. It was concluded that changes in the trend rate of economic growth over time, or differences in the growth performance of countries are too numerous for the notion of a steady state to be interesting. Economic growth seems to be a process of constant transformation rather than adjustment to a long-run fixed target path. The most recent period (the last year included in the analysis is 1998) is an interesting example of these issues. The 1990s both show large differences in trend growth between countries, and, for some countries, the first signs of what might be a take-off of trend economic growth rates compared to the earlier decades, which were characterized by slow growth.

Associated with this, is an historically unique pattern in the indicators for convergence or divergence of GDP per capita in the OECD area. Convergence can either be relative to the (OECD) average value of GDP per capita, or relative to the country with the highest value of this variable. For most of the 20th century, and certainly for the post-1950 period, the two indicators have shown very similar trends. The 1990s form, however, a break with this pattern. While convergence to the sample mean is still going on at a pace that is more or less comparable to that observed since the mid-1970s, divergence is taking place for the indicator based on differences relative to the leading country (in this case the United States). In other words, the United States seem to be ‘running away’ from the other countries, while the latter are still, by and large, converging to the sample mean. The results on take-off of economic growth at the country level summarized at the start of this section suggest that besides the United States, there may be some other countries that are also ‘running away’. These results are based on relatively few observations, so care must be taken in extrapolating them into the future.

The evolutionary approaches to economic growth that we discussed suggest that radical innovations are important for economic growth, and especially for changes in trend growth. With the empirical evidence and the interpretation of this discussed above, one is tempted to conclude that information and communication technologies (ICT) are a recent example of such radical innovations. We have in this paper not been able to take this element sufficiently into account in our analysis, which we will attempt to do in future work. However, we hold it as likely that the changes in global growth dynamics that have been researched in this paper are related to the increasing role of ICT in the world economy, and that the latter is one potential source for divergence. For instance, evidence based on data on the diffusion of several types of ICT equipment and services (mobile telephones, computers, Internet, etc.) suggest a very uneven rate of diffusion of new ICT both within Europe and at a global scale (Dalum, Freeman *et al*., 1999; OECD, 1999).

However, there are also other omens of future divergence in the world economy. The re-estimation of two applied growth models, based on what we - following Richard Nelson and Sidney Winter – call “appreciative evolutionary theorizing”, suggests two major forms of transformation in the technology-economy domain. The first is that convergence (or catching-up) based on the assimilation of foreign technology is becoming a more and more active process in which R&D plays a more and more crucial role. This implies that undertaking R&D is no longer – if this ever has been the case - an activity that is unequivocally associated with moving the world technological frontier. The second is that at the technology frontier, the differences between countries in terms of 'pure' innovative efforts (as primarily indicated by patents, hence not including catching-up) become more and more important for explaining differences in growth performance. In other words, assimilating foreign technology requires more and more active efforts, which increases the danger for countries without the necessary capabilities to fall behind to the world technological frontier, while at the frontier technological differences between countries translate more easily into growth rate differentials. Both tendencies arguably increase the probability of divergence in the world economy. We may very well be there already.

In conclusion, the evolutionary interpretation of recent OECD growth patterns that we have offered in this paper seems to the possibility of divergence in the OECD area. More specifically, a scenario in which the developed world to split up into several 'convergence clubs' (Baumol, 1986; Durlauf and Johnson, 1992), the leading one of which is formed by those countries or areas that engage most actively into creation and diffusion of radical innovation. Lagging behind the leading 'club' can be several other clubs, which have to rely either on (compared to the first club) slow assimilation of knowledge spillovers from abroad, or on low-costs strategies based on low wages rather than technological competencies. In fact, one possible interpretation of recent European regional growth patterns is that a similar process has been going on in that part of the world since the early 1980s (Fagerberg and Verspagen, 1996; Fagerberg, Verspagen and Caniëls, 1997).

References

Abramovitz, M.A. 1994. The Origins of the Postwar Catch-Up and Convergence Boom. In *The Dynamics of Trade, Technology and Growth*, edited by J. Fagerberg, B. Verspagen and N. Von Tunzelmann. Aldershot: Edward Elgar.

Abramovitz, M. A. and P. A. David (1996). Convergence and deferred catch-up: productivity leadership and the waning of American exceptionalism. *The Mosaic of Economic Growth*. R. Landau, T. Taylor and G. Wright. Stanford, Stanford University Press**:** 21-62.

Aghion, P. and P. Howitt (1992). "A Model of Growth Through Creative Destruction." *Econometrica* **60**: 323-351.

Baumol, W. J. (1986). "Productivity Growth, Convergence, and Welfare: What the Long Run Data Show." *American Economic Review* **76**: 1072-1085.

Benhabib, J. and M. M. Spiegel (1994). "The role of human capital in economic development: Evidence from aggregate cross-country data." *Journal of Monetary Economics* **34**: 143-173.

Boyer, R. 1989. Wage Labour Nexus, technology and Long Run Dynamics: an Interpretation and Preliminary Tests for US. In *Technological and Social Factors in Long Term Fluctuations*, edited by M. Di Matteo, R. M. Goodwin and A. Vercelli. Berlin: Springer Verlag.

Cohen, W. M. and D. A. Levinthal (1989). "Innovation and Learning: The Two Faces of R&D." *Economic Journal* **99**: 569-596.

Cornwall, J. 1977. *Modern Capitalism. Its Growth and Transformation*. London: Martin Robertson.

Crafts, N. and T. C. Mills (1996). Europe's Golden Age: and econometric investigation of changing trend rates of growth. *Quantitative Aspects of Post-war European Economic Growth*. N. Crafts and B. v. Ark. Cambridge, Cambridge University Press**:** 415-431.

Dalum, B., C. Freeman, Simonetti, R., Verspagen, B and N. Von Tunzelmann (1999). Europe and the Information and Communications Technologies Revolution. *The Economic Challenge to Europe. Adapting to Innovation Based Growth*. J. Fagerberg, P. Guerrieri and B. Verspagen. Aldershot, Edward Elgar**:** 106-129.

David, P. (1990). "The Dynamo and the Computer: An Historical Perspective on the Modern Productivity Paradox." *American Economic Review* **80**: 355-361.

Dosi, G. (1982). "Technological Paradigms and Technological Trajectories." *Research Policy* **11**: 147-162.

Dosi, G. (1984). *Technical Change and Industrial Transformation*. London, Macmillan.
Dosi, G., O. Marsili, Orsenigo, L. and R. Salvatore. (1995). “Learning, Market Selection and the Evolution of Industrial Structures.” *Small Business Economics* **7**: 411-436.
Dosi, G., K. Pavitt, and L. Soete. (1990). *The Economics of Technological Change and International Trade*. Brighton, Wheatsheaf.
Durlauf, S. N. and P. A. Johnson (1992). Local versus Global Convergence across National Economies, NBER Working Paper.
Fagerberg, J. (1987). “A Technology Gap Approach to Why Growth Rates Differ.” *Research Policy* **16**: 87-99.
Fagerberg, J. (1988). “International Competitiveness.” *Economic Journal*: 355-374.
Fagerberg, J. (1988). Why Growth Rates Differ. *Technical Change and Economic Theory*. G. Dosi, C. Freeman, R. R. Nelson, G. Silverberg and L. Soete. London, Pinter. **16:** 87-99.
Fagerberg, J. (1994). “Technology and international differences in growth rates.” *Journal of Economic Literature* **32**: 1147-1175.
Fagerberg, J. and B. Verspagen (1996). “Heading for divergence? Regional growth in Europe reconsidered.” *Journal of Common Market Studies* **34**: 431-448.
Fagerberg, J., B. Verspagen, and M. Caniëls. (1997). “Technology, Growth and Unemployment across European Regions.” *Regional Studies* **31**: 457-466.
Fagerberg, J., P. Guerrieri and B. Verspagen (1999). Europe **-** A Long View. in: *The Economic Challenge to Europe. Adapting to Innovation Based Growth*. J. Fagerberg, P. Guerrieri and B. Verspagen. Aldershot, Edward Elgar**:** 1-20.
Fagerberg, J. (2000). “Technological progress, structural change and productivity growth: a comparative study.” *Structural Change and Economic Dynamics* **forthcoming**.
Freeman, C. (1982). *The Economics of Industrial Innovation*. London, Pinter Publishers.
Freeman, C., J. Clark, and L. Soete. (1982). *Unemployment and Technical Innovation*. London, Pinter.
Freeman, C. and L. Soete, Eds. (1987). *Technical Change and Full Employment*. London, Basil Blackwell.
Freeman, C. and L. Soete (1990). “Fast Structural Change and Slow Productivity Change: Some Paradoxes in the Economics of Information Technology.” *Structural Change and Economic Dynamics* **1**: 225-242.
Freeman, C. and L. Soete (1997). *The Economics of Industrial Innovation. 3rd Edition*. London and Washington, Pinter.
Härdle, W. (1990). *Applied nonparametric regression*. Cambridge, Cambridge University Press.
Heertje, A. (1993). Neo-Schumpeterians and Economic Theory. *Evolutionary Approaches to Economic Theory*. Magnusson. Dordrecht, Kluwer**:** 265-276.
Helpman, E. H. and M. Trajtenberg (1994). “A time to sow and a time to reap: Growth based on general purpose technologies.” *NBER Working paper*(4854).
Katsoulacos, Y. (1986). *The Employment Effect of Technical Change. A theoretical study of new technology and the labour market*. Brighton, Wheatsheaf.
Kleinknecht, A. (1987). *Innovation Patterns in Crisis and Prosperity. Schumpeter’s Long Cycle Reconsidered*. London, Macmillan.
Kortum, S. (1997). “Research, Patenting and Technological Change.” *Econometrica* **65**: 1389-1419.
Los, B. (1999). *The Impact of Research and Development on Economic Growth and Structural Change*. Enschede, Ph.D. thesis University of Twente.
Lucas, R. E. B. (1988). “On the Mechanics of Economic Development.” *Journal of Monetary Economics* **22**: 3-42.
Maddison, A. (1995). *Monitoring the World Economy 1820-1992*. Paris, OECD Development Centre.
Nelson, R. R. and S. G. Winter (1982). *An Evolutionary Theory of Economic Change*. Cambridge, MA, Harvard University Press.
Nelson, R.R., and G. Wright. 1992. The rise and fall of American technological leadership: the postwar era in an historical perspective. *Journal of Economic Literature* 30:1931-1964
OECD (1999). *The Knowledge-Based Economy. A Set of Facts and Figures*. Paris, OECD.
OECD (2000). Differences in economic growth across the OECD in the 1990s: the role of innovation and information technologies. DSTI preliminary findings and contribution to the growth project. Paris, OECD.

Oliner, S. D. and D. E. Sichel (1994). “Computers and output growth revisited: How big the puzzle.” *Brookings Papers on Economic Activity*: 273-334.
Pavitt, K. and L. Soete (1982). International Differences in Economic Growth and the International Location of Innovation. *Emerging Technologies: The Consequences for Economic Growth, Structural Change and Employment*. H. Giersch. Tuebingen, Mohr**:** 105-133.
Perez, C. (1983). “Structural change and the assimilation of new technologies in the economic and social systems.” *Futures* **15**: 357-75.
Petit, P. and L. Soete (2000). Technical change and employment growth in services: analytical and policy challenges. *Technology and the future of European employment*. P. Petit and L. Soete. Aldershot, Edward Elgar.
Raa, T. t. and E. N. Wolff (1999). *Engines of growth in the U.S. economy*. ECIS/SCED Conference on Economic Growth, Trade and Technology, 3-4 October, Eindhoven.
Rebelo, S. (1991). “Long-Run Policy Analysis and Long-Run Growth.” *Journal of Political Economy* **99**: 500-521.
Romer, P. M. (1990). “Endogenous Technological Change.” *Journal of Political Economy* **98**: S71-S102.
Saxenian, A. (1994). *Regional Advantage. Culture and Competition in Silicon Valley and Route 128*. Cambridge MA and London, Harvard University Press.
Schumpeter, J. A. (1912). *Theorie der wirtschaftlichen Entwickelung*. Leipzig, Duncker & Humboldt.
Schumpeter, J. A. (1939). *Business Cycles: A theoretical, historical and statistical analysis of the capitalist process*. New York, McGraw-Hill.
Silverberg, G. (1988). Modelling Economic Dynamics and Technical Change: Mathematical Approaches to Self-Organisation and Evolution. *Technical Change and Economic Theory*. G. Dosi, C. Freeman, R. Nelson, G. Silverberg and L. Soete. London, Pinter**:** 531-559.
Silverberg, G. and D. Lehnert (1994). Growth fluctuations in an evolutionary model of creative destruction. *The Economics of Growth and Technical Change. technologies, Nations, Agents*. G. Silverberg and L. Soete. Aldershot, Edward Elgar**:** 74-108.
Silverberg, G. and B. Verspagen (1994). “Learning, Innovation and Economic Growth. A Long Run Model of Industrial Dynamics.” *Industrial and Corporate Change* **3**: 199-223.
Silverberg, G. and B. Verspagen (1995). “Long Term Cyclical Variations of Catching Up and Falling Behind. An Evolutionary Model.” *Journal of Evolutiuonary Economics* **5**: 209-227.
Silverberg, G. and B. Verspagen (1998). Economic Growth and Economic Evolution: A Modeling Perspective. *Selbsorganisation. Jahrbuch für Komplexität in den Natur-, Sozial- und Geisteswissenschaften*. F. Schweitzer and G. Silverberg. Berlin, Duncker & Humblot. **9**.
Silverberg, G. and B. Verspagen (2000). "Breaking the Waves. A Poisson Regression Approach to Schumpeterian Clustering of Basic Innovations", *ECIS Working Paper 00.16*, Eindhoven University of Technology.
Solow, R. M. (1970). *Growth Theory: An Exposition*. Oxford, Oxford University Press.
Triplett, J. E. (1996). High-tech Industry Productivity and Hedonic Price Indices. *Industry Productivity; International Comparisons and Measurement Issues*. Paris, OECD.
Van Duijn, J. J. (1983). *The Long Wave in Economic Life*. London, Allen & Unwin.
Van Meijl, H. (1995). Endogenous Technological Change: The Case of Information Technology. Theoretical Considerations and Empirical Results. *MERIT*. Maastricht, University of Limburg**:** 289.
Von Tunzelmann, N. (1995). *Technology and Industrial Progress. The Foundations of Economic Growth*. Cheltenham, Edward Elgar.