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Technology-gaps, innovation-diffusion and transformation: an evolutionary interpretation

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Abstract

This paper discusses and outlines a perspective on economic growth based on evolutionary theorizing. Consistent with this perspective, capitalist development is shown to be a process of alternating periods of convergence and divergence, with some signs of a shift towards divergence recently. We also show that the importance of innovation for economic growth has increased lately, while at the same time imitation, (or diffusion) has become more demanding. The manufacturing sector which used to be very important for growth has lost much of its dynamism. We relate these findings to the big technological shifts that have occurred during the last decades.

Keywords: Technology gaps; Innovation; Diffusion; Evolutionary models

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 work, to 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 rigorous". (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 one hand, there is an important body of formal 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

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in biology and other natural sciences. However, the term evolutionary economics is also often associated with a less formal (or more 'appreciative') approach in economics that focus on evolution as a process of qualitative change 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 behavior and perfect information). The economists Joseph Schumpeter and, more recently, Christopher Freeman are certainly central contributors to this literature as are many economic historians such as for example, Alexander Gerschenkron, Moses Abramovitz and Nathan Rosenberg. The relationship between the writings of these authors and biological approaches is at best an indirect one. Schumpeter, for instance, explicitly denounced the applications of biological approaches in social science (Schumpeter, 1954, p. 778).

What we in earlier work have called "the technology gap theory of economic growth" (Fagerberg, 1987, 1988b) 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 (Fagerberg, 1994). 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 the 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, as pointed out by several prominent students of long-run growth (Svennilson, 1954; Cornwall, 1977; Freeman and Louçã, 2001), 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.

In the next section, we discuss (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 main conclusions from Section 2, namely that capitalist development is not necessarily a convergence process, as some theories in this area predict. Rather, it is likely to be a process of alternating periods of convergence and divergence as the evidence presented in Section 3 indeed suggests. For instance, there are now signs of a diverging trend emerging in the global economy (after a relatively long period of essentially converging trends). Section 4 relates to the other main conclusion from Section 2, namely that different historical periods (and growth patterns) are characterized by different technological dynamics and hence that the factors that matter for growth (including adequate institutional settings and policies) are likely to differ as well. We show that the importance of innovation for economic growth has increased lately, while at the same time imitation (or diffusion) has become more demanding. The manufacturing sector, which used to be very important for growth, has lost much of its dynamism. We relate these findings to the big technological shifts that have occurred during the last decades. The final section summarizes the lessons from the study.

2. Evolutionary economics and technology dynamics

We have already argued that the term 'evolutionary economics' should not be reserved to applications of strict biological metaphors to the study of economics. The term evolutionary economics is also associated with a less formal (or more 'appreciative') strand in economics that focus on evolution as a process of qualitative change and the roles of technology and institutions in this process. 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, 1988a), Freeman and Soete (1987, 1990) Dosi et al. (1990) or Verspagen (1991).

A central approach in this literature has been to 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 science, technology, economy, politics and culture (Freeman and Louçã, 2001). Each of these domains has its own dynamics and explanatory processes, but what is important is that the domains exert strong mutual influences.[1] Following this approach, 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 writers is one of the world economy as a process of constant transformation. Technologies and institutions change through 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 economics) 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, however, not discuss all these factors in detail here.

The notion of the world economy as a constant process of transformation is perhaps most clearly reflected in the literature on 'long-waves' and 'technological revolutions'. This literature, which dates back to Schumpeter (1939), has later been refined and extended by contributions such as Freeman et al. (1982), Kleinknecht (1987), Van Duijn (1983) and Freeman and Louçã (2001). Although, the dating of a such waves figures as an important issue in some of these contributions, we are more concerned with the overall perspective on growth offered by this literature.[2] The basic hypothesis (as we see it) is that the introduction times of important 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. However, after the new technological paradigm (the term is Dosi's, 1982) has diffused throughout the economy, Wolff's law (Freeman, 1982) of decreasing marginal technological opportunities ultimately brings a slowdown of economic growth. Although, this is clearly a theory of technology driven growth, the role for other factors is vast. Perez (1983) and Von Tunzelmann (1995) are particularly strong examples of contributions in which the notion of technological paradigms is linked to broad institutional change, firm strategy or industry dynamics.

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.

[1] 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 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).

[2] Hence, we do not share the view of some long-wave theorists that this perspective necessarily leads to a postulate of strong regularity in growth and/or the underlying technological dynamics.

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 growth rates 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 depend crucially on the specific historical and institutional context. It is the analysis of this diffusion process that is most interesting from an economic point of view. Second, the (stylized) distinction between innovation and imitation receives central importance. Technology cannot be fully appropriated by the firm that develops an innovation. With 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.[3]

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 the role played by qualitative factors such as institutions and culture. Measurement of these is difficult, 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 (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 relationship gives the trend growth rate. Varying this slope for different periods, and testing for the statistical significance of the differences, gives an indication of changes in economic growth trends. 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. From an evolutionary point of view, one would like to investigate the possibility of more smooth changes.

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 log-linear 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.[4]

Fig. 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.[5] The figures give the growth rate of GDP per capita (left axis, dark line) and the growth rate of GDP

[3] Since 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. See Silverberg and Verspagen (1995) for a quantitative model that illustrates this point.

[4] The specific results 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.

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

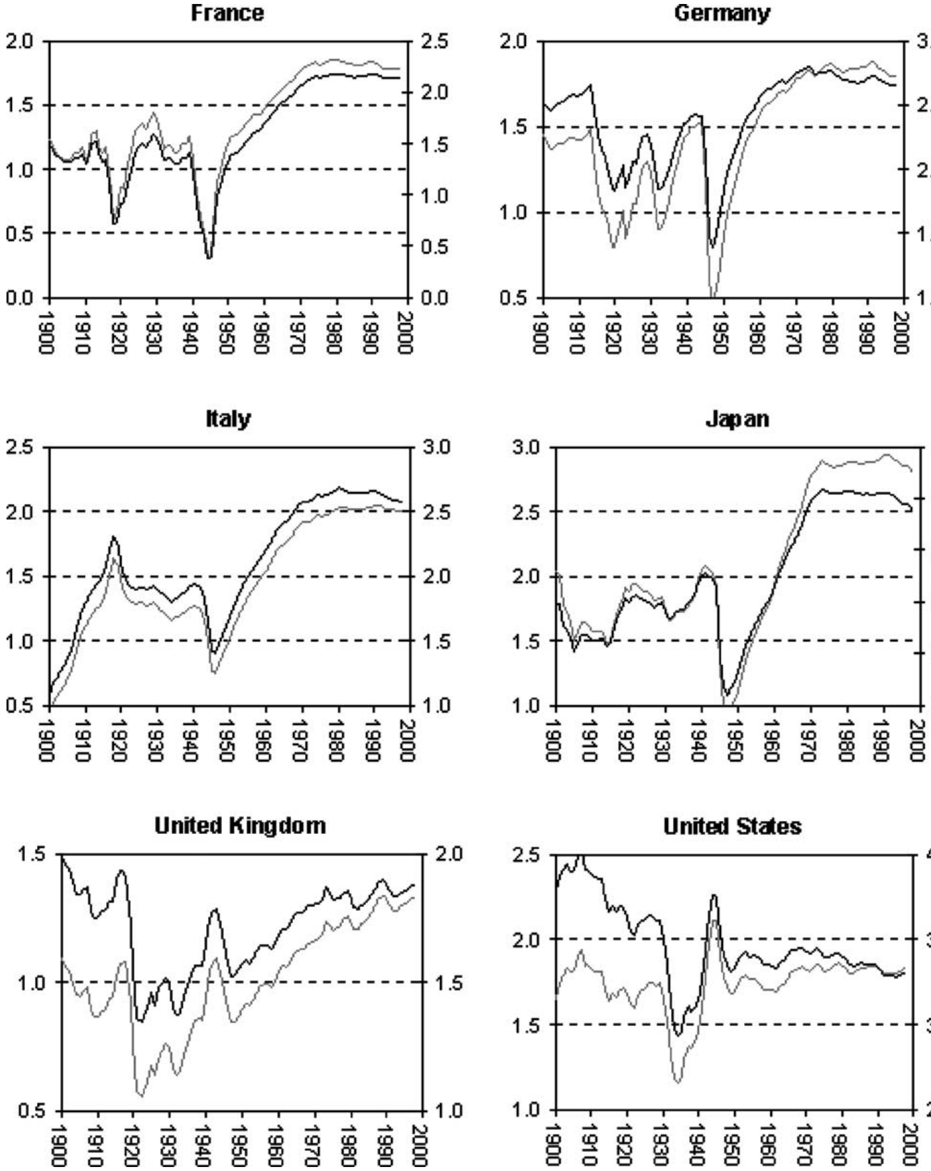

Fig. 1. Trend growth rates of GDP per capita (light line, left axis) and GDP (dark line, right axis), estimated with a Kalman filter.

(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 20th 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 20th century. US is an interesting exception to the

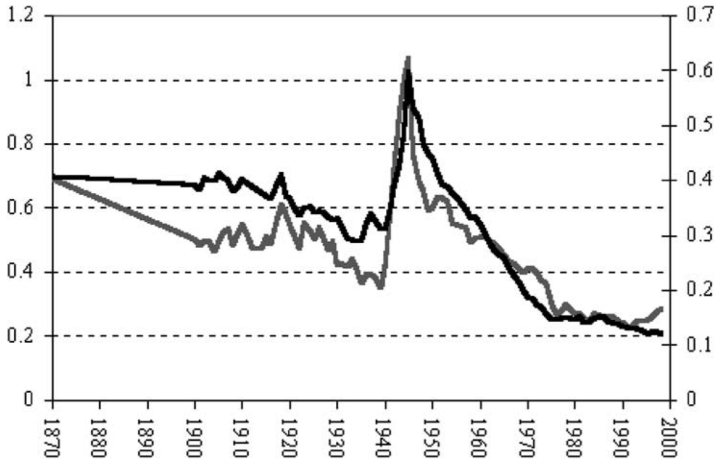

Fig. 2. Long-run trends of convergence and divergence.

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 judgment about possible reversions of the trend. What is interesting, however, is the fact that the estimated trends vary greatly between countries. On one hand, Germany, Italy, and Japan seem to experience a decrease in the trend. UK and the US, on the other hand, seem to show signs of an increase in 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 World War II, 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.

However, our main interest in this paper is on comparative growth performance, or the issue of convergence or divergence of GDP per capita levels. Fig. 2 gives, for a set of 18 countries including those in Fig. 1 as well as a number of other OECD countries,[6] the long-run trends of convergence. Two different indicators of differences between countries are used. The first has been used many times 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 Fig. 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.

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

The figure shows that there was no or little convergence over the period 1870–1913. After this, a weak trend towards convergence sets in until the outbreak of World War II. The latter 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 Fig. 1, convergence also comes to a halt. For about a decade, per capita income differences remain stable. But from the mid-1980s onwards a weak trend towards convergence may again be observed.

The light line in Fig. 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, UK, Switzerland, Germany and the US appear as countries with the highest value of per capita GDP in one or more years. During the post-World War II period, the US 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 post-war 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 20th 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 US), shows relatively strong divergence. In other words, while the US seems to move ahead of the other countries on average, this does not imply that these other countries are not converging to each other.

What is the interpretation of this pattern of development? Note, first, that the immediate post-war period seems to provide a clear break with the immediate past. Another break seems to be encountered some time during the 1970s. Following our evolutionary interpretation of growth patterns in Section 2, one might suggest that growth during the period 1950–1975 (roughly) may be driven by different mechanisms than in the period before or after this. Drawing on the literature discussed in Section 2, we will tentatively suggest the following interpretation. 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 (Freeman and Soete, 1997). These technologies had been pioneered in the US 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 US) to a limited set of other (mostly already developed) countries. In line with some of the literature that will be discussed later, 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 circumstances 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 et al., 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 recent 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 already outlined in the narrative history.

4. 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, 1988b).[7] This model, building on Pavitt and Soete (1982) and others, takes the distinction between the development of new knowledge (in a country) and the diffusion of knowledge (between countries) that was mentioned 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 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'.
(5) 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 test the first of these four relationships, Fagerberg (1987, 1988b) 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 should be expected to be log–linear rather than linear, because countries close to the technological frontier depend more on the development of new knowledge (or innovation) than technologically lagging countries (which were assumed to rely more on imitating knowledge developed elsewhere, that is diffusion). Fagerberg's original regressions, which were undertaken for selected periods prior to the early 1980s, confirmed the hypotheses under test.

Tables 1 and 2 of this paper repeat these tests for the periods 1966–1972 and 1973–1983 and extend the time coverage to more recent data (1984–1995 as a whole and 1990–1995 separately). We use a sample of 29 countries, including, in addition to the countries included in Fig. 2, Ireland, Greece, Portugal, Hong Kong, Malaysia, Philippines, Singapore, South Korea, Taiwan, Thailand and Turkey.

Some slight differences in the data set compared to Fagerberg's original regressions are present. In particular, while the original data on patents refer to total external patents (patents by the country's residents in all foreign countries), this paper uses data on patenting in the US since this source gives easier access to

[7] See also Kortum (1997) for a somewhat similar model.

Table 1
The relation between GDP per capita and patenting activity

	Period	Constant	EPA	Adjusted R^2	F	n
1	1966–1972	0.608 (9.47)	0.392 (8.81)	0.75	77.6	28
2	1973–1983	0.650 (12.8)	0.350 (10.3)	0.80	106.8	28
3	1984–1995	0.802 (15.4)	0.198 (6.70)	0.61	44.9	29
4	1990–1995	0.836 (16.3)	0.164 (5.98)	0.55	35.8	29

Note: *t*-values within brackets.

Table 2
The relation between GDP per capita and R&D intensity (total R&D)

	Period	Constant	RDI	Adjusted R^2	F	n
1	1966–1972	3.199 (10.5)	2.199 (7.33)	0.68	53.8	26
2	1973–1983	2.611 (8.79)	1.611 (5.49)	0.55	30.1	25
3	1984–1995	2.609 (11.8)	1.609 (7.40)	0.67	54.8	27
4	1990–1995	2.527 (12.4)	1.527 (7.60)	0.69	57.8	27

Note: *t*-values within brackets.

data for non-OECD countries.[8] Also, while Fagerberg used civil R&D (total R&D less military R&D), this paper uses total R&D since the latter is available for a larger span of countries. We also test a slightly modified version of Fagerberg's original log–linear equation, in order to be better able to compare regression coefficients over time, and interpret the differences. The equation we test is the following one:

$$\frac{T_i}{\bar{T}} = c + a\frac{\ln(X_i)}{|\ln X|} + e_i,$$

where T is GDP per capita, X either a patenting variable or an R&D variable (defined precisely later), e the usual error term, c and a the coefficients to be estimated, the subscript i indicates a country, and a bar above a variable indicates an average over the sample of countries. Note that the variables are standardized such that the sample means are equal to one (for a variable X with mean ln(X) positive) or minus one (for a variable X with mean ln(X) negative) for each period. This implies that the regression coefficients in different periods in time are not affected by shifts in the means of the variables.[9]

Table 1 gives the relation between GDP per capita and patenting per billion dollar exports (EPA), Table 2 for R&D intensity, which is defined as total R&D as a fraction of GDP. The correlations between the economic and technological levels of development are in both cases positive and significant for all time periods.

It is clear from Tables 1 and 2 that the estimated coefficient a decreases over time, and more so in the case of patents than in the case of R&D. What does this imply? The lower slope means that a given increase in relative GDP per capita requires a larger increase in relative innovative activity (patenting) in the 1990s than it did one or two decades earlier. Hence, one way to put it would be to say that it has become technologically more demanding to catch-up economically. A possible interpretation might be that this reflects increasing technological divergence in the global economy between, on one hand, a group of technological leaders who compete neck to neck with each other, and

[8] 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 outliners in the total sample for the complete period under consideration. These are the US (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, UK and France is replicated in the US patenting data. Details available on request.

[9] Note that because every regression line has to go through the point corresponding to the means of the dependent and independent variable, the standardization procedure also implies that the coefficients a and c will add to one when the mean of ln(X) is positive, while $c - a = -1$ in case of a negative mean for ln(X).

on the other a group of laggards for which technological competition in the form of patenting becomes less and less relevant.[10] The fact that this tendency is somewhat more manifest for patents than for R&D might be explained by the fact that R&D is a broader measure of, say, technological capability than patents and that R&D continue to be of high relevance also for poorer economies that wish to catch-up through imitation.

A really thorough analysis of such changes in dynamics between technology and economic growth, however, requires a more dynamic framework than the static correlations studied so far. Hence, what is done in the following is to re-estimate the dynamic specification of the technology gap growth model, based on points 2–4 earlier (see Fagerberg, 1988b for the formal model). The dependent variable is the average annual compound growth rate of GDP. The model explains economic growth as the joint outcome of three sets of factors:

- innovation (a possible source of divergence, measured through patent growth),
- 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).

Among the complementary factors influencing the realization of catch-up potential, we include—as in the original model (Fagerberg, 1987, 1988b)—investment as a fraction of GDP (average over the period indicated). In addition, we include two variables reflecting the industrial structure of the country, the share of manufacturing and services, respectively, in GDP. While investment is generally viewed as a growth-inducing factor (although, it is sometimes held to be endogenous), the inclusion of the structural variables may be more controversial. Manufacturing was included to take into account the argument brought forward by Cornwall (1977) and others of 'manufacturing as an engine of growth', i.e. that manufacturing is technologically much more dynamic than other sectors of the economy and therefore should be regarded as a growth-inducing factor in its own right. However, it is commonly argued that this positive role for manufacturing is now (and has long been) history, and that the role of 'engine of growth'—or 'carrier branch' for the most progressive technologies of the day has been taken over by the services sector. To take into account this possibility, we include the share of services in GDP as a possible complementary factor.

The model is estimated for the pooled sample of observations of 29 countries and the three time periods as used (1966–1972, 1973–1983, 1984–1995). To check for changes in the working of the variables over time we introduce time-slope dummies (TSDs) for the first two periods. In the case of variables for which there is no significant TSD effect,[11] the reported coefficient holds for all three periods. However, in cases for which the TSD effect was found to be significant, the TSD effect must be added to the estimate of the variable to obtain the coefficient for the relevant period. To check for the possible impact of spatial correlation (especially an 'Asia effect') we also report estimates for a versions of the model that includes continent dummies. Finally, to allow for the possibility that changes over time are influenced by other non-included factors, we include a version with time dummies. The results from the estimations are reported in Table 3.[12]

The main lessons to be drawn from the estimations 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) The scope for diffusion, as measured by GDP per capita (log form), appears to be lower after 1983 than it previously was (especially when compared to the 1973–1983 period).

[10] This issue is explored in somewhat more detail in the working paper version of this paper which is available on request from the Centre for Technology, Innovation and Culture, University of Oslo, P.O. Box 1108, Blindern, 0317 Oslo, Norway.

[11] This means that the inclusion of the dummy could not be defended on statistical grounds, i.e. that it failed to reduce the residual variance, using a backward search.

[12] Sources for the data: Maddison (1995), Groningen Growth and Development Centre website, OECD Economic Outlook Historical Statistics (various issues), World Development Report CD-ROM (version 2000), World Development Report (various issues), US Patent and Trademark Office, OECD Basic Science and Technology Indicators Database (various issues), UNESCO Statistical Yearbook (various issues).

Table 3
Estimation results for the technology gap growth model, 1966–1995

	(1)	(2)	(3)
Constant	−0.007 (0.34)	−0.007 (0.25)	0.029 (1.26)
ln of initial GDP	−0.023 (3.96)	−0.020 (3.07)	−0.012 (1.74)
TSD second period	−0.021 (2.27)	−0.025 (2.45)	−0.017 (2.00)
TSD first period	−0.011 (2.09)	−0.015 (2.12)	−0.017 (2.35)
Investment	0.0014 (4.07)	0.0014 (3.99)	0.00073 (1.86)
TSD first period	–	–	0.0018 (2.38)
Patents	0.160 (4.35)	0.161 (4.34)	0.103 (3.04)
TSD second period	−0.094 (1.98)	−0.098 (2.03)	−0.031 (0.85)
TSD first period	−0.117 (2.30)	−0.133 (2.47)	−0.134 (2.44)
Manufacturing	−0.0003 (0.56)	−0.00023 (0.35)	−0.00016 (0.34)
TSD second period	0.00087 (1.47)	0.0011 (1.17)	–
TSD first period	0.0018 (3.20)	0.0016 (2.08)	0.00083 (1.76)
Services	0.0010 (2.76)	0.00085 (2.05)	0.00043 (1.15)
TSD second period	0.00058 (1.46)	0.0099 (1.42)	0.00077 (2.08)
Europe dummy	–	–	−0.0183 (3.21)
America dummy	–	–	−0.0122 (1.43)
Australia dummy	–	–	−0.0182 (2.29)
First period dummy	–	0.015 (0.68)	–
Second period dummy	–	−0.020 (0.46)	–
Adjusted R^2	0.715	0.710	0.756
N	76	76	76

Note: *t*-statistics within brackets. For definition of variables, see the text.

(3) The importance of innovation (as measured by patent growth) for economic growth appears to increase over time. The impact is especially significant in the most recent period.
(4) The opposite holds for the role of manufacturing which had a much more positive and significant impact before 1973, than it is shown to have later. Services, on the other hand, were found to have a positive impact in all three periods, with the most pronounced effect between 1973 and 1983.
(5) The introduction of time and continent dummies did not have a large impact on the results, but the latter increased the explanatory power of the model significantly, suggesting that there may be something to the idea of an 'Asia effect'.

To chart out how this adds to the explanation of growth rate differentials between countries, we report in Table 4 a decomposition of the differences in economic growth between the leader country, US and other country groupings. There are several interesting features. The first is that although the model is shown to explain most differences in growth rather well, it clearly fails to reproduce the time profile of the growth performance of Japan, with spectacularly high growth before 1973 and much lower growth recently. The model would have suggested a smoother picture. Second, it clearly points to the scope for diffusion as the most important factor behind catch-up and growth (even in the most recent period). Investment plays a more subordinate role except for Japan. Differences in innovation (patent growth) also explains relatively little initially, but emerges as a very powerful factor in the most recent period, in which it turns up as the single most important factor behind the continuing high growth of the Asian NICs. Before 1983, the high growth of the Asian NICs was mainly explained by the large scope for diffusion, now this matters much less for these countries, and has had to give way to innovation as the major growth-inducing factor. Finally, it should be noted that structural factors were indeed important in explaining the difference in growth between the US and other country groupings. In particular, it seems to be the case that the relatively important role played by services in the US economy has been a major growth-inducing factor there, explaining to some extent the failure of most other economies to catch-up. Initially, the US was also

Table 4
Explaining differences in growth in relation to US

	Explanatory variables						
	Actual differences in growth	Estimated differences in growth	Diffusion	Investments	Patents	Manufacturing share in GDP	Services share in GDP
1966–1972							
Japan	6.3	3.48	1.90	1.53	0.11	1.29	−1.36
EU NICs	3.5	1.86	3.04	0.35	0.05	−0.64	−0.93
Other EU	1.2	1.27	1.25	0.64	0.04	0.13	−0.80
Western offshoots	0.9	0.30	0.91	0.27	0.04	−0.34	−0.58
Asian NICs	6.8	4.35	5.21	−0.16	0.044	−0.33	−0.40
Developing	3.1	2.83	6.92	−0.82	0.05	−1.57	−1.73
1973–1983							
Japan	1.2	2.77	1.53	1.63	0.67	0.44	−1.51
EU niches	0.3	2.53	3.20	0.50	0.16	0.04	−1.38
Other EU	0	1.28	1.22	0.42	0.21	0.12	−0.70
Western offshoots	0.1	0.86	1.05	0.33	0.35	−0.10	−0.77
Asian NICs	5.2	6.00	4.68	0.76	1.19	0.15	−0.78
Developing	3.5	4.44	7.93	−0.12	−0.33	−0.15	−2.86
1984–1995							
Japan	0.6	1.12	0.44	1.72	0.43	−0.25	−1.22
EU niches	0.6	0.60	1.61	−0.35	0.24	−0.04	−0.847
Other EU	−0.2	−0.07	0.59	0.02	−0.12	−0.07	−0.49
Western offshoots	0.2	0.41	0.61	0.33	−0.11	0.042	−0.46
Asian NICs	4.6	4.41	1.39	0.73	3.20	−0.16	−0.73
Developing	3.0	2.78	3.96	−0.005	1.17	−0.13	−2.21

Note on country groupings: European NICs: Portugal, Greece, Ireland, Spain; other European countries: Austria, Belgium, Germany, Denmark, Finland, France, UK, Italy, Netherlands, Norway, Sweden; Western offshoots: Canada, Australia, New Zealand; Asian NICs: Korea, Taiwan, Singapore, Hongkong; developing: Thailand, Malaysia, Philippines, Turkey; for definition of explanatory variables, see the text.

helped by its relatively high specialization compared to most other economies (except Japan) but this effect soon faded away and has since the early 1980s been of negligible importance.

5. 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. The most recent period (the last year included in the analysis is 1998) is an interesting example of these issues. The 1990s show both 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.

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 leader country. 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 US). In other words, the US 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 US, 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 earlier, one is tempted to conclude that ICTs are a recent example of such radical innovations. We have in this paper not been able to take this element sufficiently into account, 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 (Dalum et al., 1999; OECD, 1999).

There are also other omens of future divergence in the world economy. The re-estimation of an applied 'evolutionary' growth model, 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 diffusion in some sense seems to have become more 'difficult' and demanding over time. Again, we think that this may be a reflection of the radical technological change in the last decades, with ICT-based solutions substituting earlier mechanical and electromechanical ones, and the derived change in the demand for skills and infrastructure. The second is that innovation, as measured by patenting activity, becomes more important over time. Particularly, 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. Both tendencies arguably increase the probability of divergence in the world economy.[13] We may very well be there already.

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[13] More specifically, a scenario in which the developed world is split up into several 'convergence clubs' (Baumol, 1986; Durlauf and Johnson, 1992), with the leading one formed by those countries or areas that engage most actively into creation and diffusion of radical innovation. In fact, one possible interpretation of recent European regional growth is that a similar process has been going on in that part of the world for some time already (Fagerberg and Verspagen, 1996; Fagerberg et al., 1997).

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