Technology and Growth: The Complex Dynamics of Catching Up, Falling Behind and Taking Over

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1. Introduction

Over the post-war period research on economic growth has come to be dominated by theoretical approaches which are strongly model-oriented, and whose empirical content is generally limited to broad tests of the consistency of the real world with established or, in more recent times, new growth models. In such approaches empirical tests which do not fit the theoretical model, can only be expressed in terms of paradoxes or the more down to earth question of the economic theorist who wonders "what's wrong with reality". In many ways this is a logical and natural trend. Opposed to the costs, efforts and time involved in carrying out new, original empirical research, theoretical modelling often appears to be the easy road to academic progress and fame in economics.

It is from this perspective that Angus Maddison's research, with that of a very select group of other empirical researchers, some of whom have contributed to this volume, stands out by its overriding immediate empirical concern and historical content. From this perspective, the title of this volume Explaining Economic Growth describes well the underlying motivation and spirit of much of Maddison's research, even though it gives insufficient credit to what has already been explained about economic growth, mainly thanks to Maddison's numerous investigations into the broad long-term macro-economic empirical regularities in growth and development.

Of course, the choice of the subject of economic growth has itself much been influenced by growth theory, and in particular the old growth models of the 1950s and their "residual" evidence. However, particularly in the field of growth and development and the accompanying patterns of structural change, much old and even some of the new theoretical work, has been dominated by an overriding concern to reduce the complexities of the real world to easily quantifiable relationships, which can be fitted into some straightforward

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modelling framework. In doing so, many of the pioneering investigations on
the complex dynamics linking growth, structural change and technical change
associated with the names of Schumpeter, Kuznets and Gerschenkron, to
name but a few, have often become totally neglected.

In this article, we address in particular the issue of technical change and
economic development. We will do so not from a long term historical
perspective - to do so would require Maddison's detailed historical knowledge
on data and empirical evidence which we lack - but from a relatively short
term empirical perspective (the last 25 years) in a spirit which nevertheless
could still be called Maddisonian.

Technical change itself has often been the major factor behind structural
change and the emergence of new phases of development in different
countries. In a first section we centre therefore on a number of issues related
to technical change. These highlight features which have often been neglected
in traditional neo-classical growth analyses and, as illustrated by some of the
empirical evidence gathered by Maddison, they warrant a different approach
focusing more on the disequilibrium yet endogenous nature of technical
change. In a second section we briefly review some of the recent new growth
and development contributions, allowing, contrary to the standard neo-
classical growth model, for a more endogenous treatment of technical change.
Our review brings to the forefront the fact that these models, while stressing
some of the dynamic 'increasing return' features of knowledge and technical
change, remain nevertheless dominated by notions of equilibria and uniformity
between countries, which do not fit some of the disruptive characteristics of
technical change and its diffusion. In the third section we then present some
of our own empirical evidence. The latter is two-fold. First we bring together
evidence on the variety of converging and diverging growth patterns both over
time and between large geographical areas; second we present evidence on
variety in innovative and imitative behaviour of various (groups of) countries.
Our empirical analysis is purely descriptive. Its aim is to illustrate the wide
variety of growth performance, rather than to try explain it.

2. Technical Change: From Innovation to Diffusion and Imitation

2.1. Technical Change: Some Crucial Features

When discussing the contribution of technical change to growth and
development, it is essential to recognise that the economic impact of technical
innovations and their diffusion can be dramatically different. In this context, it
is useful to make a couple of distinctions.

First, at the level of innovation, it is essential to recognise that there is a
widespread difference in the impact of such technological advances. Thus,
there are many innovations which have very widespread societal effects and might even change the whole quality of life, but whose measurable economic effects are small or at best indirect in terms of macro-economic growth and efficiency. Examples abound. The innovation of an oral contraception device had a major impact on sexual behaviour in the 1960s and 1970s in most countries, giving rise to some fundamental debates about medical and social ethics. Its economic impact was at best indirect through greater participation of women in the labour market.

On the other hand, there are many innovations with significant, but widely divergent economic impact. Thus there are innovations which find applications in only one sector: a so-called "localised" impact (e.g., the float glass process introduced by Pilkington’s in the 1960s), and those which effect many or all sectors of the economy: a so-called "pervasive" impact (e.g., the microprocessor or the electronic computer). In any discussion of the impact of technical change on growth, including productivity growth, it is essential to be aware of this wide variation in the economic impact of technological advances.

Second, with respect to technology diffusion, there is of course a striking degree of methodological similarity between the typical epidemic diffusion model, and the models of industrial growth and economic development, developed in the thirties by among others Kuznets (1930) and Schumpeter (1934). In many ways this is not surprising. The concepts of "imitation" and "bandwagon effects" so crucial to the diffusion literature, are also central to many of the more structural accounts of economic growth, where the S-shaped diffusion pattern is similar to the emergence and long term rise and fall of industries. An attempt at linking the two theories was made in Freeman, Clark and Soete (1982).

The critique of the standard diffusion model led to the application of "Probit analysis" in developing alternative models of inter-firm diffusion. The central assumption underlying the probit model is that an individual consumer (or firm) will adopt an innovation at a time his income (size) exceeds some critical level. This critical or tolerance income level (or size) represents the actual tastes of the consumer (the receptiveness of the firm) which, in turn, can be related to any number of personal or economic characteristics. Over time, though, with the increase in income level and assuming an unchanged income distribution, the critical income level will fall with an across-the-board change in tastes in favour of the new product, due both to imitation, more and better information, band-wagon effects, etc.

The relevance of the probit model for industrial growth theory is self-evident. A "critical" income per capita level is a concept which can be introduced in a straightforward manner in development theories of the stages of economic growth. Replacing the concept of individuals by countries,
differences in growth performance between countries can be explained and expected. Considering both the extreme variation in a country's ability to take risks and assess new innovations (the variation in consumer tastes in the probit model), and the extreme levels of income inequality at the world level, it should come as no surprise that growth at the world wide level (diffusion) has been a widely diverging pattern, and that many countries, even with the fall over time in the "critical" income level for industrialisation, might have fallen behind rather than caught up.

From an economic perspective the static, demand-focused nature of the standard diffusion model is questionable. Once the importance of supply factors is recognised, it becomes more apparent how past investment in old, established technologies can slow down the diffusion of new innovations, past investment not only in physical capital but also in human capital, even "intellectual" capital. The importance of past investment in, and existing commitment to, a technology which is being displaced, in slowing down the diffusion of a new technology, points also towards the phenomenon of inter-technology competition. New technology will compete on disadvantageous terms against existing technology. As Rosenberg (1976) and others have observed, the diffusion of steam power in the last century was significantly retarded by a series of improvements in the existing water power technology which further prolonged the economic life of the old technology.

2.2. International Technology Diffusion: Catching Up, Falling Behind and Taking Over

The voluminous literature on the subject of international technology diffusion and technological "catching up" can be seen as a straightforward application of the epidemic diffusion model discussed in the previous section.1 Again, we do not intend to review this literature here. The basic conclusion that arises from it is that technologically backward countries are in an advantageous situation, because they can assimilate technology spillovers into higher growth rates, and converge rapidly to the per capita income level corresponding to the technological frontier.

The automatic way in which international diffusion of knowledge is assumed to take place in most of these contributions has been criticised in studies based on more in depth historical research on the emergence of technological and economic leadership and the process of taking over, or the

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use or adoption of particular technologies.\footnote{See for example Landes (1969), Hobsbawn (1970), Rosenberg (1970), Amea and Rosenberg (1963), Habakkuk (1962) and von Tunzelmann, (1978).} To a large extent, the arguments found in this latter part of the literature link up with the critique of the basic (epidemic) diffusion model discussed above. However, some convergence between these two strands of literature seems to be taking place (Abramovitz, 1986; Perez and Soete, 1988). As highlighted by Maddison (1989), this convergence puts the emphasis clearly back on the historical institutional framework within which the process of imitation/technological catching up takes place, including the role of historical accidents, developmental constraints, be they primarily economic (such as the lack of natural resources) or more political in nature, the role of immigration (Scoville, 1951) and other "germ carriers", and the crucial role of governments (see Yakushiji, 1986).

A model taking these considerations into account, was developed and tested in Verspagen (1991). The model stresses the importance of the concepts of technological distance and the capability to assimilate knowledge spill-overs in the development process. Its nonlinear specification leads to a bifurcation scheme, in which countries lagging too far behind the frontier, and lacking enough assimilation capabilities, will fall behind rather than catch up. Despite the simple nature of the model, the specification is rich enough to encompass both automatic catching up (as a special case), and a probit-like development pattern. Empirical tests of the model showed that among the factors contributing to the assimilation capability education of the labour force is a most prominent one (see also Baumol et al., 1989, on this matter).

Besides being important for the distinction between catching up or falling behind, the implications of such a development view based on historical and institutional factors are also far-reaching at the other end of the growth spectrum. The possibilities for taking over and forging ahead are also highly dependent on factors influencing the successful adaptation and diffusion of new technologies. The vast majority of new technologies will originate primarily from within the technologically most advanced countries. However, there are good reasons to expect that the intra-national diffusion of such a major new technology might well be hampered by the various factors mentioned earlier, the new technology competing (in its diffusion) on disadvantageous terms. Thus, previous investment outlays in the existing technology and the commitment to the latter on the part of management, the skilled labour force and even the "development"-part of R&D activities geared towards improvements upon existing technology, might all hamper the diffusion of a new technology. These brakes to diffusion might even be so strong that the new technology will diffuse more quickly elsewhere, i.e., to a country less committed, both in terms of actual production and investment, to
the older technology. At the same time, as diffusion proceeds, some of the crucial dynamic returns to scale (incremental innovations), resulting for example from user-feedback information will further shift the technological advantage to the country in which the new technology is diffusing more rapidly.

The industrialisation process of Germany, France, the US and a number of smaller European countries in the 19th century, provides ample support for this view, as Maddison (1991) has illustrated. The dramatic decline in the UK’s position from an absolute technological leadership, producing more steam engines than the whole of the rest of the world put together in the mid-19th century, is a powerful illustration of this phenomenon. It points amongst others to some of the advantages of late industrialisers, both in terms of catching up with present technological leaders, as well as in terms of acquiring foreign technology at a more competitive price. In recent times, as we shall see in section 3, this has been most obvious in the case of Japan in the 1960s and 1970s, and South Korea in the 1980s. In their rapid industrialisation the world’s best-practice productivity levels were achieved over a very short time in steel, cars, electronics, numerically controlled machine tools, and most recently in computers, largely on the basis of initially imported technology. Nevertheless the scarcity of such successful examples of taking over illustrates how non-automatic and exceptional processes of effective technological catching up and leapfrogging are.

Most of these phenomena are hard to catch in the narrow formalism that has become customary in economics. However, the recent so-called new growth theories have tried to capture some of the ideas on increasing returns to scale on which we have elaborated above. Still, the question remains whether the ideas on technical change that have been effectively integrated into this plethora of new theoretical models are rich enough to be able to cope with the more qualitatively inspired ideas on catching up, falling behind and overtaking exposed above. It is this question which we will address in a preliminary way in the next section.

3. Growth Theory: From Old to New Interpretations

Whereas the basic neo-classical growth model (Solow, 1970) treats the rate of technological change as an exogenous parameter, the new neo-classical growth theories follow earlier work in the Schumpeterian tradition by assuming that

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3 This section is largely based on Verspagen (1992). More exact references can be found there.
innovation is an endogenous phenomenon. The crucial argument about innovation in these models follows Arrow's (1962) idea, which was further developed in the industrial economics literature (see Kamien and Schwartz, 1982; Scherer and Ross, 1990), in assuming that part of an innovation consists of externalities flowing to competitors. In this view, only part of the pay-offs of an innovation introduced by an individual firm can be appropriated by this firm.

The start of the new growth models is the assumption that technological advances flow from (private) investment in research and development (R&D) activities. Using intertemporal profit (or utility) maximisation, an optimal investment path for R&D activities is computed by the entrepreneur. However, since part of the knowledge that flows from these investments can also be used by competitors (externalities), the amount of R&D undertaken is sub-optimal from an (aggregate) welfare perspective. The growth rate of production (income, welfare) for society as a whole can be increased by governmental policies taking the form of R&D subsidies. Besides the normative welfare effect, the externalities associated with innovation lead to increasing returns to scale. In simple terms, if one firm doubles its inputs (including R&D), output will more than double, due to knowledge spill-overs.

Broadening the application of the new growth theories to the open economy case leads also to important conclusions with regard to trade and technology policy. In line with strategic trade theory (see Soete, 1991), the basic conclusion is that the arguments in favour of free trade no longer have unlimited validity with respect to time and place. In some specific cases trade policies, in the form of tariffs, or technology policies, in the form of research subsidies, may influence aggregate economic growth or welfare by changing the factor proportions devoted to research and/or manufacturing. The exact outcomes of the policy measures are not, however, very clear-cut from the international perspective. A lot depends on the comparative advantages with regard to technology and manufacturing activities.

The basic mechanism that leads to these conclusions is the general equilibrium framework that is applied in the new growth models. As shown most clearly in Lucas (1988), the single most important difference between the basic Solow model with exogenous technological change and a model based solely on the above principles of endogenous innovation, is exactly the

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5 In the model in Aghion and Howitt (1990), it is possible that too much is invested in R&D. This is caused by the negative externality corresponding to the so-called business stealing effect.
difference between first-best and second- or third-best growth paths. The basic ideas about the nature of the growth process in the Solow model (i.e., balanced growth) are neatly reproduced in the new growth theory.6

This view of the growth process seems to be challenged by the ideas of disruptive structural changes connected with technological change and its (international) diffusion, which were exposed in the previous section, and which are also present in Maddison's (1982, 1991) ideas on phases of economic growth. There seem to be two distinct sources for those different views on the development process.

First, at the level of the basic assumptions underlying the distinct theoretical approaches, it is the equilibrium tendency stemming from (intertemporal) profit or utility maximising agents that makes the difference. Implicitly combined with rational technological expectations, this leads to a theoretical bias against possibilities for lock-in sub-optimal growth paths, path dependency etc., which seem so important when looking at longer term international growth patterns.

Second, it is the characterisation of the nature of technological change itself that is different in the two approaches. The representation of innovation in the new growth models is one of a gradual nature, corresponding to the Solow-model idea of a fixed rate of technological progress. Although this rate is endogenised in the new growth theory, it is still more or less fixed (over time). The development view exposed in the previous section, however, is rooted in the Schumpeterian idea of major fluctuations in the rate of technological change over time (see also Dosi, 1982; Freeman, Clark and Soete, 1982).

Resolving this controversy on the nature of growth (theories) requires above all empirical research. However, both of the theories outline their own specific problems related to empirical implication of the ideas. The rather stylised nature of the new growth models leads to clearly unrealistic conclusions, such as the often obtained hypothesis that the size of the resource base (i.e., population) is a factor leading to faster growth. Also, the math-

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6 Space considerations force us to generalise more on this subject than may be appropriate. Aghion and Howitt (1990) provide a spectrum of growth possibilities ranging from a "no growth" trap, via a "growth cycle" to "balanced growth". In general, however, the nature of growth paths predicted by the new growth theory can be characterised as balanced growth, as indicated by the following quotation from Romer (1989, p. 4): "Even though [the model] departs from the competitive, price taking assumption that has become standard in equilibrium models, it starts from an explicit specification of preferences, an aggregate technology, and an equilibrium concept. (...) the rationale for this modeling strategy is that it offers the most power for generalizing across different types of evidence to reach conclusions about causality". 
emathetical ingenuity applied in the new growth model comes at the expense of some very limiting assumptions. Capital in the usual sense, for example, as a stock variable is absent in most of the models. Applying these models to empirical data in the usual econometric sense would require much less stylised formulations, or would lead to indirect tests of the theories (as in Romer, 1989). Problems involved in testing the implications of Schumpeterian theory mainly come down to problems with regard to clear formalisation of the arguments (see Gomulka, 1991).

The scope for further integration of some of the ideas of new growth theory with a more detailed analysis of the differentiated role of science and technology in specific sectors is undoubtedly a promising avenue for further research in this area. However, this will not be done in the rest of this article. Instead, we concentrate on presenting some empirical evidence which highlights some of the aspects of the relation between technological change and economic growth in an international setting, thus connecting the various theoretical issues to empirical facts.

4. International Growth and Technological Change: An Empirical Interpretation

4.1. Catching Up or Falling Behind?

As a first way of getting some feeling for the relation between growth rates and technology in the world, this section will summarise the available evidence by trying to detect some regularities in growth performance across countries. The ideas discussed in section 2.2 raise the question whether a (negative) relation between initial income and growth (flowing from a mechanistic view on international diffusion) is valid for a large set of countries, including the Least Developed Countries (LDCs).

Figure 1 plots the change in the per capita income gap vis-à-vis the USA against the initial income gap in 1960, for 114 countries. The income gap is defined as the natural logarithm of the ratio of per capita income in the USA to per capita income of the other country. Each point corresponds to a particular country, classified into "Oil exporters", "Newly Industrialising Countries", "Developed Market Economies" and "Other" following traditional

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7 Space prevents us from reviewing here some of the more recent econometric literature on so-called real business cycles. Many of those econometric growth tests, while staying within a multiple equilibria framework, come up with conclusions very similar to ours. See in particular Durlauf and Johnson (1992).
8 See Verspagen (1991) for data and for more details on the construction of the growth rates.
World Bank or UN definitions. The lines drawn in the figure are (linear) regression lines for the different sub-samples of countries. Note that a negative change of the income gap implies convergence, or catching up, while a positive change implies falling behind. Hence, negatively sloped regression lines are consistent with convergence.

**FIGURE 1**
Catching Up and Falling Behind in the World Economy, 1960-1985

If there is any systematic pattern in the total scatter of points in the graph, it is the variance, which grows bigger the larger the per capita income gap becomes. Thus, the countries close to the world economic and technological frontier (as measured by the performance of the USA) show smaller (absolute) growth rate differentials relative to this frontier than those further away from it.

Obviously, the results in figure 1 indicate that there is a dichotomy between catching up and falling behind at the world level (or at least the part of the world included in our sample). Some of the countries facing the largest initial gaps (the developing countries) have also experienced the largest increases in the gap, which is exactly opposite to what the catching up hypothesis predicts.

However, within one or more groups of countries, the catching-up
hypothesis seems to make some sense. Obviously, catching up makes sense for the group of DMEs, and to a lesser extent also for NICs and oil-exporters. Thus, in terms of the results here, there seems to be some indication that catching up is only a relevant phenomenon for the group of DMEs, NICs and oil exporters.

The impression from the graph is confirmed by a more formal analysis. While the lines drawn are regression lines for sub-samples of the total of 114 countries, running a regression for the total sample, and applying a Chow F-test for the hypothesis that this regression fits the data as well as the four separate regressions, yields an F-statistic of 7.59, which rejects the null-hypothesis at the 1 per cent level.

In order to get a first general impression about the possible causes of the dichotomy between catching up and falling behind, the last part of this section presents some additional data and methods. The technique used is cluster analysis. For two periods 1960-1973 and 1973-1988, the average annual growth rate of GDP per capita and population, the average level of R&D intensity, the average share of investment in national income, and the initial level of catching up potential are calculated for each country for which data are available. In order to rule out the influence of scale, each of the variables is scaled on the interval 0-1, with the smallest value in the sample equal to 0 and the largest equal to 1. Then a distance matrix for the countries in 5-dimensional space (each variable represents one dimension) is calculated. This distance matrix is used in a cluster analysis.

Thus, the 1960-1973 world can neatly be divided into three major groups: falling behind, catching up and leading countries. With regard to the question of catching up or falling behind, it seems that investment intensity is a crucial factor. Countries that have (not) been able to catch up are characterised by high (low) rates of investment. R&D intensity seems to be less important for catching up, as both the catching up groups are not characterised by high R&D intensities. Only the technologically leading countries are characterised by high R&D intensities. The role of population growth is unclear.

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9 The periodisation is chosen arbitrarily, although the break in 1973 is of course not coincidental.

10 Data sources and -definitions are as follows: GDP (per capita) and investment shares are taken from Summers and Heston (1991). R&D is defined as total (including higher education and governmental) R&D and is taken from UNESCO and OECD. The catching up potential is defined as the logarithm of the ratio of GDP per capita in the USA to the GDP per capita in the other country in the initial year. See figure 1.

11 Euclidean distances were used.
FIGURE 2
Economic Performance in Different Clusters, 1960-1973

The clusters and their members are the following:\(^\text{12}\)
A. "The Falling Behind Countries" (n=24)
   Argentina, Central African Republic, Colombia, Ecuador, Guatemala,
   India, Iran, Jordan, Madagascar, Mauritius, Mexico, New Zealand
   Nigeria, Pakistan, Peru, Philippines, Senegal, Sri Lanka, Sudan,
   Thailand, Trinidad & Tobago, Turkey, Uruguay, Venezuela.
B. "The Worst Falling Behind Countries" (n=2)
   Egypt, Malawi.
C. "The Catching Up Countries" (n=15)
   Austria, Bulgaria, Cyprus, Denmark, Finland, Greece, Iceland, Ireland,
   Italy, Jamaica, Malta, Norway, Portugal, Spain, Yugoslavia.
D. "The Strongly Catching Up Countries" (n=3)
   Israel, Korea, Singapore.

\(^{12}\) Note that due to the clustering methodology, which does not weight the variables involved in any way, countries may occasionally be grouped under intuitively wrong headings.
Technology and Growth

E. "The Leading Elite" (n=14)\textsuperscript{13}

Australia, Belgium, Canada, Czechoslovakia, France, Hungary, Japan, Netherlands, Sweden, Switzerland, UK, USA, USSR, West Germany.

The results of the cluster analysis for the period 1960-1973 allow us to identify five clusters. Figure 2 presents the characteristics of these clusters. One (small) group has realised high growth rates with high population growth, while elsewhere (especially outside the catching up group) there is a negative relation between population growth and economic growth. There also seems to be a negative relation between the size of the catching up potential and the capability to catch up, suggesting a "critical" value of the catching up potential along the lines outlined above. With regard to the European countries, it can be noted that additional evidence (see for example the results in the next subsections) indicates that even for those present in the leading group, catching up potential relative to the USA was a phenomenon that strongly favoured growth performance during this period, although on a smaller scale than the countries in the catching up groups.

The same clustering exercise can be repeated for the 1973-1988 period, now with a marginally different set of countries (for reasons of data availability). The results of this exercise is that it is again suitable to divide the sample in five different clusters. However, this time the growth performance of the separate clusters is different from the 1960-1973 period. The characteristics of the clusters are represented in Figure 3. The clusters and their members are as follows:

A. "The Established Falling Behind Countries" (n=9)
   Central African Republic, Guatemala, India, Madagascar, Malawi, Nigeria, Rwanda, Senegal, Sudan.

B. "The Missed Opportunities Falling Behind Countries" (n=6)
   Argentina, Chili, El Salvador, Guyana, Jamaica, Trinidad & Tobago.

C. "The Newly Catching Up Countries" (n=19)
   Brazil, Colombia, Congo, Costa Rica, Ecuador, Egypt, Indonesia, Iran, Jordan, Mauritius, Mexico, Pakistan, Panama, Peru, Philippines, Sri Lanka, Thailand, Turkey, Venezuela.

D. "The Established Catching Up Countries" (n=23)
   Australia, Austria, Belgium, Canada, Cyprus, Czechoslovakia, Denmark, Finland, Greece, Iceland, Ireland, Italy, Korea, Malta, New Zealand, Norway, Poland, Portugal, Rumania, Seychelles, Singapore, Spain.

\textsuperscript{13} While interpreting the presence of the centrally planned economies in this group, one should keep in mind that due to differences in statistical concepts used in communist and market economies, the data may be less comparable in this respect than was implicitly assumed.
Yugoslavia.

E. "The Leading Elite" (n=12)

France, Hungary, Israel, Japan, Netherlands, St. Lucia, Sweden, Switzerland, UK, USA, USSR, West Germany.

FIGURE 3
Economic Performance in Different Clusters, 1973-1988

One sees a number of interesting differences with regard to the previous period. First, there are a number of switches of countries from one group to another. Most obvious is the switch of several "falling behind"- countries in the first period to one of the catching up groups in the second. This includes many NICs (Egypt, Thailand and most South American countries). They have realised an active industrialisation process, which resulted among other things in high investment levels and high growth rates. On the other hand, there are a number of countries (mostly incidental) whose position deteriorated: from catching up to falling behind (Jamaica, Trinidad and Tobago), from leading to catching up (Australia, Belgium, Canada, Czechoslovakia).

Considerations of space force us to leave these switches largely undisussed. As the results in Baumol et al. (1989), the contribution by Wolff and Gittleman to this volume and Verspagen (1991) indicate, education might
be a relevant variable in explaining these switches. It can also be noted that they illustrate the general point about the dynamic structural adjustments caused by the process of technological change and its international diffusion discussed in section 2. Moreover, an important lesson that can be drawn from these switches is that there seems to be scope for influencing growth performance, either by governmental policies, or by changes in cultural or entrepreneurial variables. The dichotomy between successfully switching from falling behind to catching up and remaining in a falling behind situation is illustrative in this respect.

A second difference between the two periods is the distinction between catching up groups. In the first period, there were two catching up groups, which were quite similar with regard to all variables in the analysis, except population growth. In the second period, there is one group (the established catching up countries), which is characterised by high investment, the classic (previous period) characteristic of catching up. The other (newly catching up) countries seem to have much lower investment levels, but rapid population growth. Note also that the scope for catching up has decreased considerably, since the growth rate differences between leaders and catching up countries have diminished.

4.2. Technology and Growth in the Catching Up Part of the World

The last two sections focus on a subset of countries which belong to the catching up groups in the cluster analysis above. In order to describe the trends in convergence or divergence in international growth and technological capabilities, we will use statistics on GDP (denoted by $Q$), population ($N$), business enterprise R&D expenditures ($R$), and patents granted ($P$). Using these variables, we define R&D intensity as $R/Q$, and GDP per capita as $Q/N$.

Two indicators will be used. First, a convergence coefficient $C$ which is defined as follows:

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14 Data sources are as follows. R&D statistics as well as GDP used to calculate R&D intensities: OECD; Patents: US Patent and Trademark Office; GDP and population used in secular analysis: Maddison (1991); GDP and population used in postwar-only analysis: Summers and Heston (1991). Country samples are as follows: OECD: jpn, usa, can, bel, dk, fra, deu, grc, ita, nld, por, esp, gbr, aus, nzl, aut, fin, nor, swe, tur, yug, che; Asia: jpn, tha, mys, sgp, phil, kor, hkg; South America: mex, col, bra, arg, ury; technological leaders: deu, fra, jpn, gbr, usa, nld, swe, che.
whereby $Y$ stands for R&D intensity and/or GDP per capita. Subscripts $t$ and $i$ (1..$n$) denote time and countries, respectively. The superscript $f$ denotes the frontier value, which is defined as the maximum of $(Y_f, Y_i)$ in each period $t$.

The convergence coefficient gives the mean value across countries of the percentual deviation from the frontier. If countries with low per capita GDP levels are growing faster (catching up), $C$ will fall. Thus, a decreasing value of $C$ indicates convergence (catching up), while an increasing value points to divergence.

Second, we will define an entropy coefficient $E$ (also known as the Theil coefficient) as follows:\footnote{Slightly different variants of the Theil entropy coefficient exist. The one used here is often found in the literature on market structure, as for example in Kleinknecht and Verspagen (1989).}

$$E = \sum_{i=1}^{n} X_i \ln(1/X_i)$$  \hspace{1cm} (2)

In this equation, $X$ stands for a country’s share in total GDP, or patents. The Theil entropy coefficient is an indicator of concentration. Large values of the indicator go with low concentration, low values with high concentration. Thus, at a given point in time, $E$ only gives an indication of the (spatial) distribution of some variable across the country sample. However, it is the time path of $E$ that is of interest for the analysis here. An increasing trend in $E$ over time indicates that the variable under consideration becomes less concentrated over time, which is interpreted as convergence, a decreasing trend in $E$ denotes divergence. For variables which have a clear (short term) relation to the growth rate of population, like GDP (per capita), $C$ is the better indicator because it is able to distinguish between population growth and other factors (technology) as sources for growth.\footnote{Because the definition of entropy uses shares, the entropy of per capita GDP is not a very useful concept.} However, for variables which bear a less clear relationship to population growth (like patents), and consequently, for which it does not make much sense to express them in per capita terms, $E$ is a better indicator.

First, we consider Maddison’s (1991) long-run data for a subsample of OECD countries, which gives an overview of the trends in convergence/divergence over the 20th century. In figure 4, time trends for $C$ for per capita...
GDP\textsuperscript{17} and $E$ for GDP are given. An impressionistic view of the time series seems to suggest that there are four main periods which differ with regard to convergence/divergence patterns. In the first period (1900-1920), there is no real trend in either of the series. As argued in Maddison (1991), this is the period in which the USA slowly begins to take over technological (i.e., productivity) and economic leadership from Great Britain. The second period corresponds to the 1920s, in which some (very) weak signs of convergence are visible. Then follows the Great Depression of the 1930s and the second world war, which have a dramatic impact on both our indicators $C$ and $E$. The period 1930-1950 is therefore not very useful from an analytical point of view.

\textbf{FIGURE 4}

\textit{Convergence and Divergence in GDP and GDP per Capita, Sub-Sample of OECD Countries, 1900-1990}

Around 1950, the dispersion in (per capita) GDP seems to have settled back again at levels comparable with the pre-1930 period. From that point

\textsuperscript{17} Population figures used are the ones in Maddison (1991), corrected for territorial changes.
onwards a very strong trend of convergence sets in. The figure shows that this period has indeed been an exceptional one from an historical point of view, and that a large part of the growth in the lagging countries must be explained by a catching up effect.

The last part of the time series in the graph seems to suggest that from the mid-1970s onwards the catching up effect is becoming less important. The convergence trend weakens, and the scope for catching up seems to be diminishing considerably. The combination of this and the previously mentioned strong convergence trend makes the postwar period in general, and the most recent decade in particular a rather interesting setting to study the dynamics of imitation, innovation and catching up.

4.3. The Post-war Period and Recent Decades: From Convergence to Divergence?

Figure 5 gives the trends in C for per capita GDP in a larger sample of countries, including the OECD and Asian and South American NICs over the postwar period. For the line describing regional growth trends in Asia, Japan is used as the frontier country. Following Soete and Verspagen (1991), the technologically leading countries are defined as those with R&D intensity in 1967 of 1 per cent or more.

The lines show that the strong postwar convergence trend that had been observed in the previous figure also holds, with the exception of South America and Asia, for the different samples of countries considered in figure 5. However, at the end of the period, the trends flatten, and the latest years even show signs of divergence in some cases. Convergence is strongest in the total group of countries and the sample of OECD-countries, indicating the large catching up potential that has arisen from the huge difference in per capita GDP. The specific stabilisation problems in South America cause the fluctuations around the weak trend in that group. Asia seems to be a special case, with divergence until the early 1970s (mainly caused by the strong growth of Japan) and convergence afterwards (caused by the catching up of the NICs). Even within the group of technological leaders, there has been enough scope for convergence until the mid-1970s, indicating the supremacy of the USA in the earlier period.

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18 In South America, there is not a clear leading country in terms of GDP per capita, so that the USA has been used as the leader. Note that the samples exclude Southern American and Asian Less Developed Countries (LDCs), including countries such as Peru and India. Thus, the described trends only hold for parts of these continents.
TABLE 1
Structural Breaks in Per Capita GDP Convergence Patterns

<table>
<thead>
<tr>
<th>Country group</th>
<th>3 breaks assumed</th>
<th>2 breaks assumed</th>
<th>1 break assumed</th>
</tr>
</thead>
</table>

*Within each column, the break pattern suggested is the one that maximises the Chow F-statistic for the given number of breaks. In the calculation of the statistic, the minimum period length is restricted to 3 years. All breaks observed are statistically highly significant. Breaks are denoted by the first year of the “new” period.

In order to test for the presence of structural breaks in the convergence patterns in figure 5, linear trends were estimated for different periods in time,
and Chow F-statistics were calculated to test for the significance of these breaks. Table 1 gives the optimal break configuration for each of the series. Obviously, the breaks that occur in the beginning of the 1970s or 1960s are related to different values of the intercept of the curves, leaving the sign of the slope more or less unaffected (Asia is the exception) and making them less interesting for the analysis here. The breaks occurring in the mid-1970s (technological leaders) and beginning of the 1980s (others except Asia), however, correspond to trend-reversals.

The structural breaks in some of the series for the convergence coefficients suggest that the relation between innovation, imitation and catching up has changed over the last three decades. In order to investigate this phenomenon further, we will now turn to innovation indicators. Our basic hypothesis is that both R&D and patent statistics show different aspects of the same process of industrial innovation and its diffusion through the economic system. As such, patents involve novelty (by definition), so that they measure the earlier stages of a process leading from novelty/invention, through development, testing and engineering, to full-scale innovation. R&D is an input into the technological process. As such, it is not only related to innovation (invention), but also to imitation (Cohen and Levinthal, 1989). Thus, R&D is not only related to innovation, but also to its diffusion. The strong positive trend in Korean R&D intensity seems to be illustrative for the latter phenomenon.\footnote{The increase in Korean R&D intensity is impressive. It has risen from 0.5 per cent in 1980 to almost 2 per cent in 1988. Despite this drastic increase, the influence on aggregate convergence/divergence patterns is small, as indicated by the similarity of the lines in the figure for the OECD and OECD plus Korea.}

However, one would ideally like to have another indicator measuring the impact of innovation diffusion more adequately. Since such an indicator is not available, however, we will concentrate on R&D and patents, keeping in mind some of the disadvantages mentioned.

Figure 6 shows the trends in $C$ for R&D intensity. The frontier R&D intensity used is an envelope of Swiss, German and USA values for different years. Since no time series for R&D were available for Asian and South American NICs (except Korea\footnote{Korea refers to South Korea throughout.}), the figure is restricted to the OECD countries and Korea.

In general, R&D intensity has risen over the 1970s and 1980s (for more details see Soete and Verspagen, 1991), although at different rates in different countries. Total R&D intensity, especially in the USA has been strongly influenced by military research, which is itself highly dependent on government support. The decline of military spending was one of the main factors behind the exceptional (i.e., downward) trend in R&D intensity of the
US over the late 1960s and 1970s, which caused Switzerland (and shortly Germany) to be the R&D intensity leaders.

FIGURE 6
Convergence and Divergence in R&D Intensity, OECD and Korea, 1967-1989

The lines all show that convergence is an adequate description of the movement of R&D intensities until around 1980. After that, the trend flattens, although the most recent data again indicate a weak convergence trend. This pattern seems to fit closely the convergence pattern of growth of the OECD and the technologically leading countries identified in figure 5. Whether it was the R&D convergence that caused the income convergence, or the convergence of per capita income levels that led to the convergence in R&D spending is an issue which we do not attempt to answer here.²¹

Finally, we turn to patents as a second innovation indicator. Patent data are available for all countries used in the sample of Figure 5, so that they give a more complete overview than R&D data. Moreover, patents measure a

²¹ There exists a voluminous econometric literature which has attempted to shed some light on this causality. For one such attempt see Patel and Soete (1987, 1988).
different aspect of innovation, as they are clearly related to invention, and are a barrier against imitation. Therefore, they are assumed to measure a different aspect of the relation between innovation, imitation and catching up.\textsuperscript{23}

Since national patents cannot be used in an international context due to differences in novelty requirements, we use aggregate USA patents, dated by year of granting. However, the use of patents issued by one national patent office has the drawback that trends in patenting might reflect trends in internationalisation rather than innovative capabilities, and that domestic inventors have a home market advantage.\textsuperscript{23}

Trends in $E$ over time are given in Figure 7. Concentrating first on the country groups for which R&D data are available, it seems like the halt of

\textbf{FIGURE 7}

Convergence and Divergence in International Patenting, Catching Up Countries, 1963-1989

\textsuperscript{23} In the empirical application of the model in Verspagen (1991), which was discussed briefly above, patents are used as an indicator of the increase of a knowledge gap, as opposed to technological spill-overs (imitation) which reduce the gap.

\textsuperscript{23} For a more detailed discussion on the usefulness of patents as indicators of innovation, see Dosi, Pavitt and Soete (1990).
convergence of R&D intensity around 1980 has not left any significant traces in the series for patents. Patenting activity seems to be converging until the late 1980s, when a weak trend towards concentration of patenting seems to set in. The decline of the slope that seems to occur in the OECD and technologically leading group of countries in the mid-1970s cannot be attributed to the R&D trends, especially in light of the average lag of around 2 years between patent applications and grants. With regard to the countries that were not present in the previous figure, the trends observed are quite different from each other. In South America convergence seems to obtain until the mid-1970s, and after that the trend is flat. The heavy fluctuations in the line for this continent are caused by the small numbers, which means that small absolute deviations cause large percentual deviations. For Asian countries, the rise of Japan as a technological leader (and indeed later the largest patenting country after the USA), caused a diverging trend in the 1960s. Entropy reached an absolute minimum (close to zero) around 1970, and remained on that level until the late 1980s. After that, increased patenting in the Asian NICs led to convergence.

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>A. R&amp;D intensity</td>
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<td>B. Patenting</td>
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* Within each column, the break pattern suggested is the one that maximises the Chow F-statistic for the given amount of breaks. In the calculation of the statistic, the minimum period length is restricted to 3 years. All breaks observed are statistically highly significant. Breaks are denoted by the first year of the “new” period.

Table 2 suggests that, contrary to the suggested relation between the breaks
in per capita income growth and R&D intensity, patenting seems to be more loosely connected to income convergence. The case of Asian NICs (and Japan) is perhaps the best one to illustrate the dynamics of imitation, innovation and growth. The Asian NICs have been able to switch from a situation of falling behind to one of catching up during the 1970s (see figure 5). The evidence with regard to patenting indicates that the exploitation of the catching up potential in this case was mainly related to imitation, rather than to expansion of original research and inventions. However, as the dramatic upsurge since 1986 in figure 7 in the patent entropy measure (E) for the Asian NICs illustrates, the Asian NICs have started a rapid and increasing effort in technological investments aimed at moving the technological frontier itself, rather than just imitation.

5. Conclusions

In this paper, we hope to have illustrated that, using a number of different conceptual tools on available macro-economic and technological data, the general patterns of economic growth and technological development, which a large number of countries (114) have displayed over the postwar period, point to a wide variety of development and growth paths. This variety holds between the major different categories of countries we considered (technologically leading countries, OECD countries, Asian and South American NICs, LDCs) as well as over time.

With respect to the latter, it is worth emphasising, that while our analysis was not long-term in focus as in the Maddison tradition, and was limited primarily to the postwar period, this shorter time period, nevertheless contained many interesting features from a longer term growth and technology perspective. First of all, the period covering the 1950s, 1960s and beginning of the 1970s appears clearly as a historically unique period of convergence in growth and technological catching-up in the present DMEs and Asian NICs. Second, over the last decade since the mid-1970s this convergence pattern has clearly come to an end in the OECD countries. Both measures calculated point to an end of this major feature of postwar growth: the convergence of income levels and R&D-spending.

By contrast, in the regional area of Asia (Japan and the Asian NICs), the convergence pattern in growth is of a more recent origin (beginning of the 1970s) and seems to continue. From a technological perspective using patent data, a technological innovation catching-up process seems only to have started over the last decade in those countries. This clearly is not the case with respect to the South American NICs, where both convergence in terms of GDP per capita or technological innovation did not really take off.

In our view the variety in paths of growth and development, convergence
and divergence, also illustrates the limited usefulness of theoretical analyses in this area which focus on concepts such as balanced or equilibrium growth. Such notions seem so far removed from the complexity of the real world that one may well wonder whether progress in the theoretical equilibrium modelling of growth could ever mean progress in economists' capacity to explain growth.

References


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