Economic growth and technological change in the long run

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A Survey of Theoretical and Empirical Literature

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Abstract

This paper reviews the literature on technological change in relation to economic growth with the aim to bring different strings of the literature together. On the one hand it reviews the theory on the standard neo-classical growth models as well as modern endogenous growth theories that incorporate learning by doing, education and monopolistic elements. Besides, it deals historical and empirical approaches to technological change and growth. These include empirical studies on growth accounts, growth regressions, sectoral growth performance as well as empirical tests of R&D-models. The historical approach emphasises the importance of path dependency of technological change as a major explanatory factor for persistent differences in growth performance. It is argued that a systematic integration of the various approaches will be necessary to fully understand the dynamics of long term growth. More specifically, it is proposed to integrate the concept of "path dependency" in the growth models.

Contents

Introduction

Since its early days, the economic discipline has been interested in issues concerning economic growth, as these concern the wealth of nations and its people in the long run. Various scholars have explored the area of economic growth since the publication of the book in which Adam Smith (1776) analysed labour specialization in a pin factory, which increased the possibilities of economic growth. Malthus (1815) had a pessimistic view in which population growth would overcome the growth in agricultural production. Ricardo (1817), J. S. Mill (1848) and Marx (1867) also concentrated on capitalistic growth. The early scholars did not pay much attention to business cycles. During the period 1870 to 1920 the marginalistic revolution was set in by Jevons (1871), Walras (1874) and Menger (1871).[1]

Other scholars like Schumpeter (1934) and Allyn Young (1928) remained occupied with the analysis of economic growth. Schumpeter, for example, developed the theory of creative destruction, in which discoveries by entrepreneurs with temporary monopoly power generated new knowledge, which were spilled over the whole economy through imitation and which shifted the economy to another (higher) level of income. The dynamics of the economy was caused by competition. When Schumpeter became older, he observed a different development in the economy. Monopoly positions appeared to be able to exist in the longer run. Schumpeter constructed a theory of trust capitalism in which long-run monopoly positions existed. In both theories technology was the engine which drives economic growth. Neo-classical economists, Post-Keynesians and evolutionary economists have used Schumpeter's ideas and that of other early scholars in different ways.

Schumpeter (1934) was also the first to identify and define technological change more clearly than its predecessors. He defined technological change in a very broad sense as the "carrying out of new combinations", which generate growth along qualitative changes of economic variables. Schumpeter enumerates five types of innovation. The first concerns the introduction of a new good or of a new quality of a good. In the second case a new method of production is introduced. The third type of innovation is the opening of a new market, the fourth concerns the discovery of new resources or intermediates, and the fifth type introduces a new organisational form (Schumpeter, 1983, p. 66). Technological change emerges from technical innovations generated by research and development, patenting and software, and productivity-enhancing developments in the field of education, management and marketing.

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[1] References are given in M. Blaug (1978), Economic Theory in Retrospect.

Another revival in theory of economic growth occurred with the construction of the Swan/Solow neo-classical models of economic growth. As these models still treated technological change as exogenous to the growth process, some early attempts to develop endogenous growth models took place during the 1960s (Arrow, 1962). However, the endogenous growth models were put at the centre stage of growth theory during the 1980s by Romer (1986) and Lucas (1988).

During the first part of the twentieth century, substantial progress was also made in the field of the empirical analysis of economic growth. This was caused by the creation of national accounts, first in advanced countries and since World War II across the world. During the 1950s and 1960s, many empirical growth studies were published by, among others, Kuznets (1965), Abramovitz (1956) and Kendrick (1956). Particularly important from an international perspective were the growth accounts for nine advanced nations by Denison (1967).

Economic historians also became increasingly involved in the discussion on the relation between technological change and economic growth. They continued to emphasise the specific characteristics of different technological regimes, the importance of institutional arrangements concerning property rigths, and the variation in impact on long term growth. The idea was formalised in the concept of "path dependency" of technological change, which has dominated the economic-historical literature on technological change in the past decades (David, 1975).

This literature survey discusses theoretical, empirical and historical approaches to the explanation of the impact of technological progress on economic growth. In chapter 1, some important concepts of productivity growth are given and the economic development of Western countries since 1870 is described. The next two chapters deal with the neo-classical theories of growth. The development of these theories was stimulated by the construction of the Swan/Solow growth model, which assumed technological progress to generate sustained growth (chapter 2). Modern growth theories, developed in particular from the mid-1980s onwards, tried to endogenize technological change (chapter 3). Of course, other factors, such as capital accumulation and population growth, may affect productivity growth, but I will concentrate on the role of technology.

The empirical and historical approaches, described in chapter 4, consider data on technology, productivity growth and its components and try to induce a specific pattern. Some scholars considered technological change from the viewpoint of economic history, emphasizing the path-dependency of growth. Various empirical economists estimated growth equations with technological change as one of the explanatory variables. The underlying assumptions of these regressions came from formal theory, but they were

adjusted if the facts called for it. Others tried to decompose productivity growth and the famous 'residual' in growth accounts. A more microeconomic approach was used by those who searched for measures of technological change itself with data on patents or R&D.

Clearly the theoretical and empirical approaches have been influenced by each other over times, but received major scientific attention at different times. For example, when the development of neo-classical growth theory came more or less to a standstill in the 1960s, substantial progress was made with empirical studies, especially growth accounting, during the late 1960s, the 1970s and early 1980s. In the mid-1980s the growth theory underwent a new revival, but empirical studies remained scarce or very crude. Recently, more empirical tests of hypotheses of economic theory have been carried out, because more data are available nowadays and which are even more accurate than before. However, whereas formal theories have not been put to the test in proper empirical studies, some empirical and historical approaches are not based on sound theoretical models which could give any insight in the nature of growth and its determinants. Therefore, in the conclusion I will emphasize the gains of a synthesis of the different approaches. An integration of the different strings of the literature is needed to construct a long run sectoral model that takes into account path-dependency of technological progress and international technological spillovers.

1 Growth differentials

1.1 Productivity growth, convergence and catch-up

Economic growth refers to the trend of the time paths for macroeconomic variables such as national income (Wan, 1971). The increase in real GDP per capita or labour productivity (GDP per hour worked) of a country is an indicator for increases in the national income per capita or worker. The growth rates of per capita GDP or labour productivity differ significantly among countries and in time. These growth differentials matter because they have a large impact on economic welfare in the long run. In order to understand the large differences in standards of living, it is necessary to explain the deviations in long-run growth rates (Barro and Sala-i-Martin, 1995).

Various scholars agree on which economic forces are the most important determinants of productivity growth, such as technological change, although they have different views on how to estimate the relative impact of these forces. Historians and economists divide the past in different periods or epochs to indicate that in each period specific forces were important, which have relatively less influence in other periods. In Maddison's (1995) view, the transition from one phase of development to another is an historical accident or the consequence of a sort of system shock. The new situation will change policy attitudes and institutions. In section 1.2 the historical development of technology and economic growth is sketched. This story makes clear that productivity levels and growth rates have differed across countries and over time. However, the stylized facts show that real per capita GDP in Western countries had been increasing since the industrialization in the late eighteenth century.

Tables B.1 to B.3 in Appendix B confirm this image. These tables present the development of GDP per capita (B.1), the growth rates of GDP per capita (B.2) and labour productivity (B.3) in six countries. These countries belong to the group which is economically developed well nowadays and the tables show that the average growth rates of these countries have been positive from the nineteenth century onwards. This picture may change if short periods are considered. For example, in the Second World War some countries experienced a negative growth rate. The image also changes if developing countries are presented. However, according to Maddison (1995) the growth rate of world per capita income increased since 1870. In this period, the world population increased by a factor 5 in the period 1820 to 1992, while GDP per capita increased eight-fold (Maddison, 1995, table 1.2).

Tables B.2 and B.3 show that the growth rates differed among countries. The deviations changed through time. For example, in the period

1950-1973, the difference between the growth rates is larger than in the previous period. From 1950 to 1973, after a period of war and depression, the Western economies experienced a Golden Age of economic opportunities, which they did not realize in the same measure. In the period 1973-1992 the deviations among the growth rates decreased. The difference between these six countries and developing countries is, however, still large. From the eighteenth century onwards, the spread between the growth rates of advanced countries and developing countries had been increased.

The changes in spreads among growth rates or per capita income levels of countries are described by the concepts of convergence and catch-up. Various definitions of convergence are in use. Growth theorists and those who do cross country regressions of productivity growth on different possible determinants use the so called β-convergence concept (Barro and Sala-i-Martin, 1995). Absolute β-convergence refers to the hypothesis that economies with low levels of income per capita tend to grow faster in per capita terms than economies with high levels, so that both kinds of economies eventually have the same income levels per capita, thus are converged. Evidence has, however, shown that absolute convergence only takes place within groups of homogeneous countries or regions, which act in similar institutional, legal and economic environments with the same technologies and tastes. An example are the states of the USA or the regions in Japan. In order to show that convergence occurred, growth regressions were corrected for differences in country-specific parameters, so that these show that a form of conditional β-convergence occurred between groups of homogeneous countries (Mankiw et al., 1992).

β-convergence is often confused with another definition of convergence, σ-convergence. The latter concept means that the dispersion or inequality of real per capita income across a group of economies reduces over time. Dispersion is measured by the sample variance of the income per capita of a country in the sample. If β-convergence occurs, this does not imply that σ-convergence takes place (Quah, 1993). Empirical studies showed that the standard deviations of the logarithm of incomes per capita had increased, so no σ-convergence among countries has taken place. Sometimes the concept of relative convergence is used as a counterpart of absolute convergence. In panel studies the real income level of a country or region is divided by the average income level of a group to which the country or region belongs, thereby abstracting from the average growth of the group. So one can look at the development over time and determine whether relative convergence takes place (Ben David, 1995, Kuper, 1995).

Finally, economic historians use a catch-up concept. This concept implies that a country tries to catch up with another country which performs

the highest productivity levels, whereas 'convergence' implies that in the long run countries with different initial growth rates tend to grow at about the same rate. In Fagerberg's (1995) opinion, catch-up emphasizes the differences in scope for imitation, and the standard neo-classical transition dynamics the differences in profitability and capital accumulation (p. 273). In any case, an inverse relationship exists between initial GDP per capita and the growth rate. But in the historians' view, GDP per capita is an indicator for the degree of technological advancement of the country, whereas the neo-classicals consider GDP per capita as a proxy for the capital-labour ratio.

Catch-up should not be interpreted too narrowly. For a following country, there are different possible growth paths to the pursued productivity level with use of different (mixes of) technology systems and institutional arrangements (chapter 4). These technologies and institutions may be developed well, although the highest possible productivity level is not achieved. Patterns of 'convergence and divergence' take place because of the differences in growth paths among countries. So, for example, the catch-up of the USA with the UK in productivity levels in the beginning of the twentieth century cannot be generalized for other countries with different technologies or for other periods.

1.2 Economic growth in the 19th and 20th century

Kuznets (1965) was convinced that the economic growth in Western Europe in the past two hundred years differed fundamentally in nature from that of the protocapitalistic period (1500-1800). In the protocapitalistic period Western European countries underwent many important institutional, social and political changes which prepared them on a period of a large economic potential (in absolute and relative terms) to increase productivity and improve technology   (p. 8). Therefore growth differentials are interesting because the economic potential is realised in different ways and measures. Maddison (1995) enumerates various factors which changed before and after 1800. Rationalisation, the end of feudalism, the emergence of a system of nation state which were tied in international trade, modest population growth, change in policies with respect to democratic institutions and the welfare state, international cooperation: all played a role in the fast Western economic growth in the 19th and 20th century.

The first signs of modern industrialization in Western Europe could already be observed in the eighteenth century, when cotton, iron and steel industries were founded and steam power was introduced. In this phase, the nature of technological systems used in production changed, but the technological developments were diffused gradually and productivity growth was only affected significantly in all Western countries in course of time.

Anno 1820 the world was recovering from an era of wars. European countries and the Western Offshoots (Australia, Canada, New Zealand and US) experienced economic growth from 1820 onwards. In the Western Offshoots the growth rate in this period was higher than it would ever be. They had huge natural resources, fast population growth and were not mixed up in wars like the European countries before 1820.

Of all countries, the early industrializer Great Britain did best in the nineteenth century. The UK acquired an advantageous position in both technology and productivity. The Continental entrepreneurs differed from their British colleagues in attitude and had to cope with different institutions. For instance, the British were more willing to develop inventions for commercial application. This was because the British government, which had reduced the feudal and landownings powers gradually form the seventeenth century on, was able to create a more stable economic situtation than the Continental governments could do. Dutch economic institutions, which were so successful in the eighteenth century, were copied and adjusted by the British entrepreneurs. The parliamental reforms and the commercial orientation of the entrepreneurs contributed to the good economic performance of the UK. British policy focused on a free (international) trade system, removing tariff barriers and other regulations.

An important development which reduced economic uncertainty significantly in the nineteenth century, was the emergence of property rights protected by law. These property rights were important to realize economies of scale (created by companies), to encourage innovations (by patenting), to improve the efficiency of factor markets and to reduce market imperfections. As North and Thomas (1973) stated: "... economic growth will occur if property rights make it worthwile to undertake socially productive activity" (p. 8). If the potential profit is larger than the transaction cost involved in the economic activity, it will be established and enforced by property rights. In the UK property rights were better and earlier protected than on the Continent. The well developed British system of banking also lowered transaction costs and patenting was tied up by law.

In 1870, the world trade system was liberal compared to the previous century. International trade had increased strongly and transport costs were decreased, so that specialization yielded profits for countries involved in international trade. The US began to catch up with the UK in productivity terms. The US succeeded in this respect, because it had a huge domestic market with low economic barriers and because the American entrepreneurs constituted a more economically free state than the British. Moreover, the US could also borrow technology cheaply from Europe, although this was adjusted to American circumstances. The Americans lacked skilled labour and American demand required highly standardized products, so that they

developed labour-saving techniques for mass production (Habakkuk, 1962). This occurred also because of the specific attitudes of American entrepreneurs. The American techniques might have been very resource intensive and relatively inefficient, but the American products could compete well in the international market.

So technological progress, whatever its nature be, had occurred in all countries, but it was slower than after 1870. In the period 1870 to 1913 communication methods improved further and factor mobility increased strongly (Maddison, 1995). Large-scale migration of labour, more foreign direct investments and capital flows took place among European countries and Western Offshoots, particularly from the UK. Because the nature of the technological systems differed widely among the countries, only embodied diffusion of technological knowledge took place, knowledge embodied in physical and human capital. Although little knowledge spilled over, a convergence in relative factor price ratios took place in the subsequent decades, so that it became easier and cheaper to apply foreign technological knowledge for trade purposes.

1870 also marked the start of a period of global acceleration of growth in productivity. International trade grew less strongly than before and after 1870 some new tariff barriers were established. Furthermore, it was a period of political changes, such as the abolition of slavery in the US and the emergence of Italy and Germany as nation states. Property rights were considered important everywhere. The initial position of Germany and Japan, the latecomer industrializers, differed from that of the UK and US. In Japan a purposive state policy played a very important role in the enhancement of productivity growth. Japan, however, needed more time to catch up with the US in productivity terms than Germany did. In Germany, education and management organisation were spearheads of international policy (Vernon, 1989). In this respect Germany played a pioneering role, for human capital became very important for all countries in the twentieth century, a century in which innovations became more and more science driven.

The following epoch, 1913-1950, was characterized by war, depression and protectionism (Maddison, 1995). A common development in Europe was the increasing role of government as a driving force of economic growth and allocation of resources. After the First World War an international golden standard determined international relations and the trade volume increased. But these development ended with the depression of 1929-1933, which origined in the US and Germany. The collapse of the financial system affected international order and policy. The golden standard was rejected and a protectionistic wave went through many countries. Trade decreased and capital flowed from Europe to the US. In the late 1930s most economies recovered, mainly in Europe and Latin America, but governments intervened

8

more than ever. The US did not recover fully (despite the New Deal) until 1941.

The impact of the Second World War was uneven by country. In Europe large losses of lifes and damage to the capital stock determined the course of economic development immediately after war. Not until 1950 the West European countries were fully recovered in income terms from war. In wartime the US economy had experienced a large increase in its labour productivity and technological progressed faster. This could happen because the US investments and R&D expenditures increased, and newly organized giant firms were established, which captured new economies of scale. However, little diffusion of American technological knowledge to other countries occurred, because of the wars in Europe, the limited role of the US in international trade and investment, the collapse of the US economy immediately after the war and its isolationistic policy (Maddison, 1995). The Marshall plan reflected the start of a new international order after the chaos in Europe and the beginning of the Cold War.

After 1950 the world economy grew at a very high rate until the first oil crisis in 1973. This period is sometimes called the Golden Age, because the then prevailing growth rates have never been beaten again after this time within Europe. The US grew slower than the Western European countries, but it determined the international (monetary) order until the collapse of the Bretton Woods system of fixed exchange rates. International trade expanded and became more liberal. Domestic policies were devoted to economic growth and full employment. European investments in physical capital increased in response to larger technological opportunities to catch up with the US. The US technology progressed faster and was diffused to West Europe, which could adopt it with relatively low costs, because West European labour was already highly educated. Moreover, more disembodied diffusion was taking place, which was very important for small open countries like the Netherlands. So technology systems of the Western countries converged in productivity.

After 1973 a global slowdown in income terms occurred. According to Abramovitz (1991), West Europe performed still better than in the prewar epochs. There came only an end to the acceleration of growth, although convergence in productivity terms was still achievable. The oil shocks, inflation and the breakdown of Bretton Woods hampered economic growth. There was limited liberalisation of trade, so that it remained to increase, but unemployment increased and remained high until recently. The US experienced a slowdown in productivity and technological progress.

2 The standard neo-classical model

2.1 Introduction

The neo-classical study of long-run economic growth underwent a revival after the Second World War in a reaction to J. M. Keynes' 1936 static analysis of the economy. The recent developments in mainstream neo-classical growth theory are mainly drafted upon the ideas of Solow (1956, 1957), Swan (1956) and Meade (1961). The Swan model (1956) was combined with that of Solow in later textbooks. Keynes' theory also formed a starting point for Keynesian growth analysis constructed by, for instance, Harrod (1939) and Domar (1946). In the so called Harrod-Domar model sustained positive growth was only achieved by chance, because the parameters which determine equilibrium were given. The natural growth rate, which equaled the sum of the population growth rate and the rate of technological progress, deviated nearly always from the warranted growth rate, the rate at which a growth path is guaranteed (Wan, 1971). The warranted growth rate is not necessarily stable (Hahn and Matthews, 1964), but in the neo-classical model the steady state is stable.

        Post-Keynesians like Kaldor (1961) and Robinson (1965) rejected the neo-classical view that changes in production techniques can be described by a neo-classical production function, which is too simple. Factors of production were not completely substitutable. Furthermore, the price mechanism does not work very well in the Keynesian setting. For instance, in contrast to the neo-classical model, Kaldor assumed a varying propensity to save s_t at time t, which responds to investments. Define W_t as the real wage rate and N_t as the labour force, r_t the profit rate and K_t as the real capital stock at time t. ξ_w is the share of savings out of labour income $W_t N_t$ and ξ_z is the share of savings out of capital income. s_t is a function of the categorial income distribution. If we assume that ξ_w is equal to zero and that savings are a linear function of technological progress, then the capital coefficient $\kappa = K_t/Y_t$ is constant (Y_t being the output). Then just one production technique exists and $s_t = \xi_z \kappa r_t$, with $\xi_z \kappa$ the yield on capital. The constant capital coefficient was an important difference with the neo-classical theory. In neo-classical models the marginal productivity of the factors of production K and L were equal to their factor prices. Therefore, a change in real wage rate, profit rate or prices lead to a change in the capital intensity K/L, which in turn changed the capital coefficient K/Y. In Keynesian theory instead, only price changes lead to a change in the savings rate, which affected the capital coefficient.

The neo-classical scholars answered the Keynesian attacks with extensions of the standard neo-classical models of Solow. Samuelson (1958) provided a microfoundation for the neo-classical macroeconomic model. The two-sector model of Meade (1961) is a straightforward extension of Solow's models. One result of Meade's explorations was that the growth path may be indeterminate because there could exist uniqueness problems. Models with 'vintages' in capital equipment took into account embodied technological changes (Solow, 1962). Theories of the savings behaviour were developed by among others Cass (1965). Tobin (1965) combined real effects with monetary phenomena.

Sections 2.2 to 2.5 question whether the original Solow models of 1956 and 1957 are able to explain growth differences between countries. In the 1956 Solow model technological progress and population growth generate sustained positive growth of labour productivity, because they change the capital-labour ratio. A weak point of the model is that both factors are not explained within the framework. In 1957 Solow wrote an article on technical change and the aggregate production function, in which the famous Solow residual was formalized for the first time. This residual should be labelled the Abramovitz residual, following Moses Abramovitz' earlier work in 1956. The term is, however, called the Solow residual in most recent literature on economic growth. Recent developments in neo-classical growth theory are directed to the explanation of the Solow residual (chapter 3).

2.2 The Solow model

In his 1956 paper, Solow applied assumptions of the Harrod-Domar model to his own model. He assumed a constant savings rate and exponential (exogenous) growth of labour at a constant rate n. Furthermore, he assumed a linearly homogenous production function, and malleability of capital, which are no necessary assumptions in the Harrod-Domar model. Solow rejected the assumption of fixed proportions or complementarity of the Harrod-Domar model. The relaxation of this assumption renders the conclusions of the Harrod-Domar model invalid. A full employment balanced growth path may be possible according to the neo-classicals (Wan, 1971, p. 43), while in Keynesian theory adjustment to such a growth path is practically excluded, at least via the K/Y ratio.

Solow assumed that labour and capital produce a single composite good in one sector under the standard neo-classical conditions, which can be consumed by households or used in production by firms. The market is characterized by perfect competition, with smooth, instantaneous adjustment of the homogeneous inputs, labour L and capital K, to changes in production. Both inputs are fully employed. The propensity to save is exogenous and

constant, because Solow did not want to deal with normative decisions about savings and consumption over time or between individuals. Depreciation is assumed to be zero (so that gross investments equal net investments), but this does not affect the outcomes of the model. Investments are generated by, and equal to, savings.

The production function has the form $Y = F(K, L)$, where Y is output. Production exhibits constant returns to scale in all inputs and diminishing returns to capital and to labour. Capital accumulation occurs over time through investments, net of depreciation (if any). Capital accumulation equals $K° = dK/dt = I$, the increase of the stock of capital. Net investment I is equal to savings $S = sY$. Labour supply grows according to $L_0 e^{nt}$. Here n is the natural growth rate. Because of full employment, labour supply is equal to labour demand L in the production function. In a competitive market the marginal productivity of capital and labour determine the real rental rate and the real wage rate respectively.

The differential equation which determines the time path of capital accumulation runs as follows:

$$K° = dK/dt = I = sY = sF(K,L) = s\, F(K, L_0 e^{nt}).$$
(1)

Properties of possible growth patterns can be deduced from the accumulation equation. Suppose $k = K/L$, the ratio of capital to labour, with $L = L_0 e^{nt}$. Here k is defined now in so called 'efficiency units', capital per natural unit of labour (if technological progress, discussed in section 2.3, is taken into account, k is defined in capital per effective unit of labour). Differentiating $K = kL_0 e^{nt}$ with respect to time and substituting the result in (1) gives $(k° + nk)L_0 e^{nt} = sF(K, L_0 e^{nt})$. Because constant returns to scale apply, the production function can be written in an 'intensive form', thus $Y = F(K, L)$ is divided by L. Then $Y/L = y = F(K/L, 1) = F(k, 1) = f(k)$ (Wan, 1971). Hence, dividing K and L by $L_0 e^{nt}$ and multiplying F by the same factor (and dividing both sides by $L_0 e^{nt}$) gives:

$$k° = sf(k) - nk,$$
(2)

or

$$k°/k = sf(k)/k - n,$$
(3)

stating that the growth rate of k γ_k ($= k°/k$) is equal to the difference between the warranted rate of growth $sf(k)/k$ and the natural rate of growth n. $k°$ provides for capital deepening, while the amount nk is necessary capital widening to hold k constant (Choi, 1983). If $k° = 0$, then the K/L-ratio is constant. Then capital must expand at the same rate as the labour force,

12

namely at rate n. The warranted rate of growth is then equal to the natural rate n. One possible configuration of the savings curve sf(k) is depicted in figure 1. The vertical axis measures the values of effective depreciation nk and gross investment sf(k), whereas the horizontal axis measures the capital-labour ratio k.
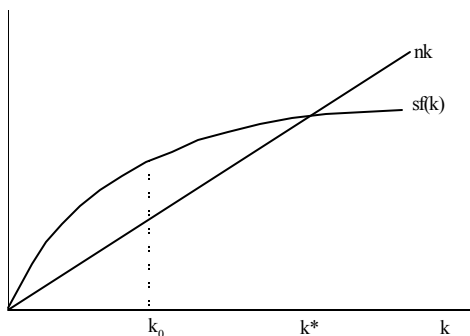
Figure 1. The Solow model (1956) in absence of technological change

In this form f(k) exhibits diminishing marginal productivity of capital and the so called Inada conditions are fulfilled.[2] The intersection between the curves of nk and sf(k) is where $k^o = 0$. The value k* fitted in this intersection is the steady state value, where all economic variables grow at constant rates. The steady state is also stable: If the initial capital stock k_0 is less than the steady state capital stock k*, then the figure shows that nk < sf(k). The accumulation equation (2) tells us that k^o will be positive, so capital will accumulate and k will move towards the equilibrium value k*. If k_0 > k*, k will decrease towards k*. In short, in the steady state K and L grow at rate n. Because output per capita y = f(k) and k* are constant, steady state output per capita must also be constant and output grows at rate n. Hence, the levels of the variables will increase at rate n, but variables per capita remain constant.

Other forms of savings curves than that of figure 1 are possible, in some cases resulting in multiple equilibria, stable or unstable (Solow, 1956). Above all, Solow's conclusion is that in a neo-classical framework with factor substitution and constant returns to scale, the natural rate is tied to the warranted rate of growth by means of completely flexible factor prices. An equilibrium will result, which does not depend on luck, such as in the Harrod-

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[2] The Inada conditions are: f'(k)>0; f''(k)<0; f'(0)=∞; f'(∞)=0; f(0)=0; f(∞)=∞. A production function f(k) satisfying these conditions is called "well-behaved". According to Sala-i-Martin (1990) the condition f'(∞)=0 will be no longer valid in endogenous growth models as discussed in chapter 3.

Domar model, because actual growth is equal by definition to the warranted rate of growth.

The Cobb-Douglas function $Y = K^\alpha L^\beta$ with constant returns to scale ($\alpha+\beta=1$) is an example of the savings curve drawn in figure 1. The Cobb-Douglas function is often used in growth models, because the Inada conditions apply and because the derivation of the steady state values is not difficult. Moreover, in the 1950s it was believed that the Cobb-Douglas function fitted actual growth well. The differential equation (2) turns to $k^\circ = sk^\alpha - nk$ with $y = f(k) = k^\alpha$. The equilibrium rate k^* equals $(s/n)^{1/\beta}$, with $\beta = 1-\alpha$.[3] By constant returns to scale, output asymptotically behaves like K and L and grows at rate n.

Solow concluded that the full employment assumption might be rejected. However, his goal was to "examine what might be called the tight-rope view of economic growth and to see where more flexible assumptions about production would lead a simple model" (Solow, 1956, p. 189). Solow (1994) argued that the model works well without constant returns to scale, the simplifying assumption of the model. The diminishing returns to capital only spell that growth in the long run is completely independent of investment, and thus of savings. The output level can be changed permanently, but not the growth rate per capita (or the slope of the trend path).

2.3 Technological change

In the Solow model the rate of growth of capital per worker γ_k is zero in the long run. How did Solow then explain positive sustained growth? He assumed an exogenous variable was the force behind growth, namely technological change. This force could be represented in the aggregate production function $Y = F(K, L, t)$ by the variable t for time (Solow, 1957). This implies that technological change is fully disembodied, because it depends only on time. With technological progress embodied in new equipment, the capital stock consists of machines of different ages or vintages. Solow developed such a vintage model a few years later (1962).

A simple model of disembodied technological change can be given by multiplying the production function by an increasing scale factor A_t:

$$Y = A_t F(K,L).$$
(4)

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[3] Per capita output in the Cobb-Douglas case with constant returns to scale is $y = Y/L = (K^\alpha L^\beta)/L = (K^\alpha L^{1-\alpha})/L = K^\alpha L^{1-\alpha}L^{-1} = K^\alpha L^{-\alpha} = (K/L)^\alpha = k^\alpha$. The accumulation equation (2) turns to $sk^\alpha - nk$. In the steady state $k^\circ=0$, so $sk^\alpha = nk$, hence $k^* = (s/n)^{1/(1-\alpha)} = (s/n)^{1/(\beta)}$.

This is Hicks neutral technological progress, which implies that the ratio of marginal products remains constant. In figure 1 the savings curve would be 'blown up' (Solow, 1956, p.183). Solow (1956) extends his model with labour-augmenting technological change, or Harrod-neutral technological progress. Harrod neutrality means that the relative input shares remain unchanged for a given K/Y. In the Cobb Douglas case, Harrod neutrality and Hicks neutrality give the same result: $Y = AF(K,L) = F(K,AL)$. Uzawa (1965) proved that by definition, Harrod-neutrality is equivalent to labour-augmenting technological progress. Labour-augmenting technological progress implies that with the same amount of capital one needs less and less labour to produce the same amount of output. Barro and Sala-i-Martin (1995) argue that technological progress must always be labour-augmenting to have a model with a steady state (Barro and Sala-i-Martin, 1995, pp. 54-55).

Technology A_t changes in time exponentially at rate x. In per capita terms, the production function becomes $y = f(k,A_t)$. In steady state the growth rate of y is constant, so the average product of capital $f[(A_t/k, 1)]/k$ must be constant (other parameters are given). Because A_t grows at rate x, $k = K/L$ must grow at the same rate and thus is not constant.

If a ratio $k' = k/A_t = K/(A_t L)$ is defined, this ratio is constant in the steady state. k' is capital per effective unit of labour. Output per effective unit of labour can be written as $y' = f(k')$. The accumulation equation changes to

$$k'° = sf(k') - (n+x)k' \tag{2'}$$

or

$$k'°/k' = sf(k')/k' - (n+x). \tag{2''}$$

Accumulation equation (2)' is in the Cobb Douglas case

$$k'° = sk'^{\alpha} - (n+x)k'. \tag{2'''}$$

The incorporation of technological change implies that in figure 1 the nk line rotates upwards to a $(n+x)k'$ line, whereas $sf(k)$ changes into $sf(k')$. Since the Inada conditions are fulfilled, there are diminishing returns to capital and the steady state capital intensity $k'*$ is constant. Capital and output per effective worker remain constant, but capital and output per capita grow forever at rate x. Capital and output levels grow at rate n+x. Then the income distribution and the capital-output ratio remain the same. In short, in the neoclassical model sustained economic growth was achieved by using technological change A as an exogenous variable.

Solow (1957) described a way of decomposing different sources of growth in order to quantify the influence of technological change on

variations in output per head, together with the influence of capital accumulation per head. He assumed constant returns to scale and competitive markets. In the case of neutral technological change the production function runs as $Y = A_t F(K,L)$, which is differentiated totally with respect to time. After dividing the result by Y, the growth equation is $Y^\circ/Y = A^\circ/A + A(\partial F)/(\partial K)*(K^\circ)/(Y) + A(\partial F)/(\partial L)*(L^\circ)/(Y)$. Given the relative shares of factors of production $w_i = (\partial Y/\partial i)(i/Y)$ with i being K or L, Solow derived the equation which would become a famous one:

$$Y^\circ/Y = A^\circ/A + w_K K^\circ/K + w_L L^\circ/L, \qquad (5)$$

with the growth rate of output, decomposed in the growth rates of technology, capital and labour respectively (the latter two multiplied with their relative shares in output, w_K and w_L). With constant returns to scale, implying $w_L = 1 - w_K$, it runs in intensive form as

$$y^\circ/y = A^\circ/A + w_K k^\circ/k. \qquad (6)$$

The term A°/A is the so called Solow residual. More formally, it expresses Total Factor Productivity (TFP) growth, defined as the growth rate in output minus the relative share of capital in output multiplied by the growth rate of capital per worker. Solow (1957) labels this term 'technical change', but recognized that it could contain other influences such as measurement errors. Furthermore, other inputs than pure technological change could account partially for growth of output, as Solow states that "any kind of shift in the production function" is possible, such as "slowdowns, speed-ups, improvements in the education of the labor force, and all sort of things" (p. 402).

If in equation (6) the capital-labour ratio increases, output can grow without any technological change. But the study of Solow showed that technological change plays a very important role. One of the conclusions Solow derived from the empirical application to American data is that technical change is neutral in that shifts of the production function did not change the marginal rates of substitution. The rate of technological change varies between 1 and 2 per cent per year. The doubling of output during the interval is for 80 per cent attributable to technology and for 20 per cent to the accumulation of capital. Hence, despite of the simplifying assumptions in equation (6), it can be shown that growth of labour or capital can account only for a very small fraction of output growth, leaving a substantial part of output growth unexplained (Choi, 1983).

This residual may contain technological change, but unless this factor is endogenized, one cannot measure its relative impact compared to other

changes. In any case, Schumpeter (1934) and many others seemed to be right in considering improvements in technology as a major force behind sustained economic growth. This conclusion however changed already when economists like Phelps (1963) assumed technological progress to be embodied in capital. Solow (1962) himself developed a vintage model in which all technological progress was embodied in equipment.

2.4 Convergence

So far the steady state properties of the model have been described. But what happens in the transition period to steady state? These transition dynamics are more interesting, because they bring the main differences between the standard neo-classical model and the modern endogenous theory.

If the Inada conditions are satisfied and a balanced growth path exists, then the long-run growth rate is neither dependent on s nor on the form of the production function. This seems to be a paradox, because savings must generate investments, and new investments lead to a higher growth rate. Suppose, however, that the savings rate is exogenously given in accumulation equation (2). Figure 1, now with technological progress, is altered to figure 2 for convenience, following Sala-i-Martin (1990). Depreciation is still assumed to be zero.
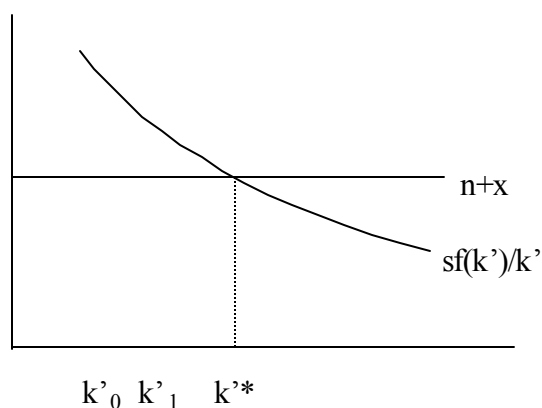

k'_0 k'_1 k'^*

Figure 2. Transitional dynamics of the Solow model with technological change

Suppose k'^* prevails and suddenly the savings rate s increases (by some exogenous cause). The price mechanism provides the smooth adjustment of the variables to a new steady state. If s increases, then the growth rate of the

capital stock is larger than that of labour (in effective units). The $sf(k')/k'$ curve in figure 2 will shift to the right and nothing will happen with the $n+x$ line. If the technological level remains the same, more labour will be demanded and the wage-profit ratio increases. Firms will choose to use more capital and $k'=K/A_tL$ increases. The growth rate of capital in effective units $k'°/k'$ will immediately increase after the increase in s, but will fall over time and eventually return to zero or the prevailing steady state growth rate. The average capital productivity y' decreases, coupled with a reduction of the growth rate of K'. This is a difference with the Keynesian models, where K/Y is constant (section 2.1). The steady state level of capital is permanently higher in the neo-classical model. The speed of convergence to steady state is very fast, although simulation studies in the 1960s already found adjustment periods of more than 45 years (Sato, 1966).

If economies differ only in initial k', then a poor country with a low k' will grow faster than a rich country. In figure 2 the initial capital-labour ratios of a poor and rich country are depicted by k'_0 and k'_1, respectively. The poor country has a larger growth rate than the rich country. But when capital evolves over time, they will both end up with the same steady state value of k'. This argumentation confirms the convergence hypothesis.

If, however, countries also differ in A, s, n or depreciation and other parameters, then the resulting steady state values of a poor and rich country may differ. Their growth rates may differ, too. Then no convergence in the absolute sense occurs. In order to demonstrate a convergence motion, new terminology had been introduced: conditional convergence. In this view each country moves to its own steady state at diminishing growth rates. Figure 3 depicts conditional convergence, where a poor country has initial level of capital k'_0 and a rich country starts at k'_1. Their capital stocks will evolve over time to a steady state, $k'*_{poor}$ for the poor country and $k'*_{rich}$ for the rich country. The steady state values and growth rates will differ depending on the parameters mentioned above. If, for instance, the savings rate of the rich country is higher than that of the poor country, the rich country will grow faster than the poor one. Absolute convergence does not take place. However, if these parameters are held constant, then a lower initial level of k' would lead to a higher growth rate. If conditional convergence is found in empirical studies, then diminishing returns to capital must exist, thereby supporting Solow's theory. The countries differ only in the stage where they are staying.
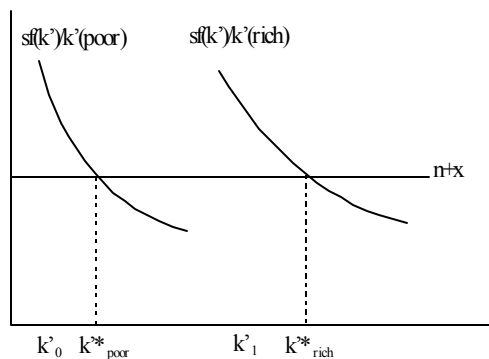
Figure 3. Conditional convergence in the Solow model with technological change

Mankiw et al. (1992) showed that conditional convergence occurred within the neo-classical framework. They extended the model with human capital H, because the Solow model predicts the direction of variables well, but not their values (Mankiw et al., 1992, pp. 407-408). The concept of human capital is developed by among others Schultz (see chapter 4). Human capital includes education, skills and on-the-job training of workers, while crude labour L concerns unskilled handicraft. Total labour force can be divided between crude labour and human capital. In the model of Mankiw et al. (1992) savings and population growth are exogenous. The estimation results imply a large role for human capital. They estimate the following production function with Y being output, K physical capital (such as equipment and machinery), H human capital, A the constant technology parameter and L crude labour:

$$Y = K^{\alpha}H^{\beta}AL^{1-\alpha-\beta} \tag{7}$$

Mankiw et al. concluded that the share in income of each input accounts for at about one third, $\alpha = \beta = 1-\alpha-\beta = 1/3$. Conditional convergence can take place because $\alpha+\beta<1$. Once the differences in s and n are accounted for, convergence can be predicted roughly with this augmented model. In contrast to endogenous growth models, where $\alpha+\beta=1$, the model predicts that countries with similar technologies A, rates of accumulation, and population growth should converge in income per capita. Mankiw et al. (1992) estimate a rate of 2% per year, so that the adjustment period lasts for 25 to 35 years, before the growth differences are reduced.

Grossman and Helpman (1994) did not believe that the model of Mankiw et al. (1992) is a plausible theory for convergence between countries. The results of the estimations are very sensitive to the choice of countries. The large differences in savings and population growth between poor and rich countries explain more of the differentials than the factor human capital, so that the augmenting of H to the Solow model explains little. Furthermore, Romer (1994) argues that the model of Mankiw et al. (1992) inadequately describes the differences in the richness in technology among countries. No analysis can be made of the production and diffusion of technological knowledge and information, because A is the same for all countries.

2.5 Deficiencies of the Solow model

The Solow model predicts that the steady state level of income depends on the propensity to save and on the growth rate of population. The steady state growth rate of income per capita depends only on the rate of technological progress. Furthermore, the marginal product of capital is constant, while the marginal product of labour grows at the rate of technological progress. Another conclusion of the model is the constancy of the capital-output ratio, which is valid if the economy is near its steady state. However, the result that the long run steady state is independent of the initial conditions is not supported by evidence (Mankiw, 1995). This is the convergence problem, which is tackled by Mankiw et al. (1992) and other economists who construct endogenous models.

New inputs, like human capital, had to be introduced in the Solow model if it has to be able to explain the magnitude of growth differentials between countries. In the sources-of-growth analyses by Denison (1967) and others such factors have always been considered as important to understand the developments in economic growth (see chapter 4). They introduce factors like human capital, economies of scale and macroeconomic determinants. Furthermore, conditional convergence as it takes place in reality might be predicted by an augmented Solow model, as the model of Mankiw et al. (1992) did. However, countries converge more slowly than the standard model predicts. Moreover, growth regressions are very sensitive to the choice of countries or the period that is considered (see section 4.4). Finally, the size of the actual differences between the rates of return to capital among countries cannot be predicted correctly. The elasticity of substitution between capital and labour in the production function plays a key role. In fact, this elasticity depends on technology and on the ability to move resources among industries. The elasticity should be very high to explain the differences between the rates of return on capital (Mankiw, 1995).

Solow himself recognized that his model can be criticized with respect to important elements like the assumption of perfect competition, homogeneity of the production function, neutrality of technological change and the labelling of the residual just as 'technical change'. He saw possibilities to incorporate monopolistic competition in his model. Furthermore, imposing Inada conditions were necessary (although not sufficient) to ensure a convergence to the steady state. If these conditions are not valid, then growth rates are not constant. But the major deficiency of the Solow model is that the determinants of technological progress are left unexplained. Therefore, the following wave of economic research was directed mainly at the systematic explanation of technological change within the model. Some economists used technological indicators based on R&D and patent data. Recent growth models developed by among others Romer (1990) and Grossman and Helpman (1991) approach an explanation of technological changes within the framework (chapter 3).

Endogenizing the savings rate in the Ramsey-Cass-Koopmans (RCK) model (1965) or in an OverLapping Generations (OLG) model (Samuelson, 1958, Diamond, 1965), described in Appendix A, is important to analyse transition dynamics, but this of course does not solve the problem of how to endogenize technological change (Grossman and Helpman, 1994, p. 25). By abstracting from household behaviour one can focus on technological progress, capital accumulation and population growth. In his 1994 article Solow argued that endogenizing technological progress within a growth model will be the most promising way to explain output growth. Of course, other parameters like population growth can be endogenized, although technological progress is the theme of this survey. In the next chapter the modern endogenous growth theories, which try to tackle the problems of the standard neo-classical model, are discussed.

3 Endogenous growth theory

3.1 Introduction

After the promising start with the Solow model the interest for neoclassical growth theory declined in the 1970s, among other things as a result of vanishing steady growth that contrasted the Solow model. In the 1960s unemployment and inflation showed a trade-off, depicted in the Phillips-curve. In the subsequent decade, in which the oil crises hampered economic growth, the validity of the Phillips-curve was questioned. The attention of many scholars turned to short-term issues like the explanation of the real business cycle under rational expectations. Moreover, the Cambridge-Cambridge controversy on the existence of the aggregate production function had brought its own doubts on the Solow type production function, which could not be answered in a satisfactory way by the neoclassicals (Blaug, 1978, pp. 487-488). Practically, the lack of data and their inaccurateness made it difficult to find empirical evidence that might confirm the insights of the Solow type model. Finally, the Solow model showed important deficiencies, sketched in section 2.5, of which the exogeneity of the technological factor was the main problem. In the 1960s and 1970s the neoclassical analyses of economic growth became very technical and few empirical studies supported these analyses. The vintage models of Salter (1960) and Solow (1962), which distinguished embodied and disembodied technological progress, did not receive much attention. According to empirical scholars like Maddison (chapter 4), this was a failure of the neo-classical school.

Since the mid-1980s some economists regained interest in studying the problem of long-term growth, recognising that determinants of growth were not fully discovered yet and that convergence, predicted by the Solow type models, had not taken place. Furthermore, to understand the determinants of growth, deficiencies of the old models had to be removed: the apparently inexplicable non-decreasing per capita growth and the exogeneity of technological progress. In addition, more data about growth became available, so empirical testing of the theory became more appealing. These data were compiled by, among others, Denison (1967), Maddison (1972) and Summers and Heston (1984). However, the work of these empirical scholars was considered by various neo-classicals as data assembling instead of a profound analysis of economic growth. Only recently the neo-classicals pay more attention to the insights of growth accountants and other empiricists (chapter 4). The analyses of the empirical economists are founded on observation of the reality, by gathering data and trying to induce specific patterns.

Among others Mankiw et al. (1992) tackled the convergence problem within the Solow framework and tried to prove that the Solow model is applicable, if it is augmented with human capital (chapter 2). In addition, alternatives to the Solow model were already developed after 1985. One of the features of the modern growth models is that a change in the propensity to save influences the long-run growth rate. An example of such a growth model is the AK model constructed by Rebelo (1991), discussed in section 3.2. The assumptions of this model, however, are very restrictive and have a weak link to reality. Other models account for economies of scale: the spillover models and the models which incorporate monopolistic competition (section 3.3). The spillover model is studied by, among others, Romer (1986) and Lucas (1988). However, their models captured only a part of the problem. The rejection of the perfect competition assumption was stimulated by new theories about monopolistic competition, developed by for example Dixit and Stiglitz (1977). Growth models with an R&D sector were constructed by growth theorists like Romer (1990). In these R&D models monopoly power was essential for the firms producing intermediate capital goods and technological change is endogenized.

Meanwhile, alternatives to the modern neoclassical models have been developed in heterodox economics. For instance, the theory of Scott (1989,1990) does not distinguish between investment and technological change or innovation. Scott based his ideas on the technological progress function (TPF) of Kaldor (1961) and Robinson (1965). The TPF exhibits a nonlinear relationship between productivity growth and technological change. In neoclassical theory a shift of the aggregate production function reflects an innovation. Both functions lead to the same conclusion, namely that balanced growth is possible. Scott (1989) extended Kaldor's model. The TPF is also dependent on the propensity to invest i. A change in investments which leads to innovations will generate new investments. A high i indicates a strong tendency to technological change, by which the TPF moves outwards and thus generates a higher growth rate of output.

Solow agreed with Kaldor and Robinson that the neoclassical aggregate production function and the measurement of capital as done by neoclassicals could be rejected on theoretical grounds. However, according to Solow they could not provide a satisfactory alternative.

Another approach, which has close links with some empirical studies discussed in chapter 4, is the evolutionary economic theory. Nelson and Winter (1982), Dosi et al. (1990) and Verspagen (1991) study technological change within this framework. A common feature of all these models with the neo-classical models is the recognition of role of government policy, which can affect the growth rate of productivity within the models.

3.2 Constant returns growth models

The most direct approach to endogenize growth is to develop a model with reproducible capital goods, which produce without the help of nonreproducible factors available in fixed supply (Van de Klundert and Smulders, 1992). In the 1980s models were developed in which the production function exhibits Constant Returns to Inputs that can be Accumulated (CRIA). A simple model is the AK model of Rebelo (1991). In this model, the aggregate production function had the form $Y = AK$, where Y reflected output, A technology and K (physical) capital. A standard Cobb-Douglas production function with constant returns to both factors of production capital K and labour L and with technology A runs as $Y = AK^\alpha L^\beta = AK^\alpha L^{(1-\alpha)}$. The share of capital α in production was equal to one in the AK model and the role of crude labour (and land) was ignored. This followed the view (often implicitly underlying historical accounts), that nonreproducible factors are not a key variable in long run growth (Rebelo, 1991, p. 518). The AK model can be considered as a very rudimentary basis on which other endogenous models can be extended (section 3.3).

In the Solow model diminishing returns to capital lead to a zero long run growth rate. The AK model was characterized by constant returns to capital. According to Solow (1994) the AK model was partly a return to the Harrod-Domar ideas. The marginal productivity of capital was namely also constant in the Harrod-Domar model. But, in contrast to the Harrod-Domar model, labour supply was no bottleneck in the AK model. A CRIA model is called endogenous, because it generates a positive long-run rate of growth thanks to the constant returns.

The solution to the AK problem is placed in an infinite horizon optimizing framework to be able to compare it with that of R&D models (see Appendix A). In the R&D models the allocation of resources between different sectors and the intertemporal choice of consumption interact (see section 3.3). Furthermore, savings have a long run impact in an endogenous growth model, so the decisions of individual households about savings are important for the outcomes. However, within the AK model there is no link between differences in incomes per capita and the returns to capital.

The Cobb Douglas production function in the AK model in per capita terms runs as $y = Ak$. In an infinite horizon optimizing framework (following the approach in Appendix A) a CIES utility function is assumed and a Hamiltonian and first order conditions for steady state growth are derived. In the following conditions for consumption growth (1) and the accumulation equation (2) (without depreciation and with zero population growth), γ_c is the growth rate of consumption and σ the intertemporal elasticity of substitution

of consumption, which is constant by assumption of a CIES utility function. A is the state of technology and ρ the discount rate, reflecting the impatience of generations to consume.

$$\gamma_c = \sigma^{-1}(A - \rho) \tag{1}$$

and

$$k^{\circ} = Ak - c. \tag{2}$$

Consumption, capital and output grow at the same rate $(A - \rho)/\sigma$. No transitional dynamics take place in this model, because the growth rates of k and y are constant and equal to that of c. The growth rate depends on savings and technology. Savings are taken exogenously (the discount rate and substitution elasticity being given).

Solow (1994) argued that the intertemporal optimizing model does not contribute any essential change to growth theory in general. Instead, the assumption of constant returns was important. The AK model was not robust, because no satisfactory evidence existed on the assumption of constant returns. Furthermore, A was still unexplained.

3.3 Increasing returns growth models

If the CRIA model ($\alpha = 1$) is extended with nonreproducible inputs like (raw) labor ($\beta > 0$), then a model evolves with increasing returns to scale (IRS): $\alpha + \beta > 0$ (Sala-i-Martin, 1990). A crucial assumption in those models, n=0, is made to avoid a forever growing growth rate of capital per effective unit of labour $\gamma_{k'}$. The problem with IRS models is that no general equilibrium will result, because the increasing returns imply unlimited profits to production. Various methods were developed to solve this problem, under which the incorporation of spillovers and the rejection of the perfect competition assumption. Externality or spillover models are of the Marshallian type, with increasing returns to scale at the aggregate level but constant returns to scale at the firm level. Spillovers emerge from R&D, education or study, experimentation and learning by doing. The model without perfect competition has Chamberlinian monopolistic elements.

Examples of the spillover model are Arrow (1962) and Romer (1986). In those models learning effects appeared in production. There was a general pool of knowledge in society, which was taken as given by the individual entrepreneur. Mankiw (1995) argued that this was a model of capital with externalities, where the accumulation of capital included the accumulation of knowledge. Lucas (1988) also introduced externalities from human capital accumulation or education. Other models took into account monopoly power

in the intermediate goods sector, so an incentive to research and development was preserved in the long run (Romer, 1990). In those models the accumulation of knowledge was no unintentional by-product, like in the Arrovian models. In the Lucas model a separate sector for education existed, but Lucas neglected the fact that human capital had a non-rival element which generated externalities. In Lucas' model education was tied to physical bodies.

Growth models developed after 1990 began to combine the elements of invention and learning by doing into models with economic uncertainty, variety and creative destruction. Such models contain Schumpeterian ideas and are called Schumpeterian models. They are constructed by among others Aghion and Howitt (1992, 1996), Caballero and Jaffe (1993), Coe and Helpman (1993), Young (1993a, 1993b), Jaffe et al. (1993). The estimation results of some of these models are discussed in section 4.6.

Learning by doing and education

Arrow (1962) constructed one of the first models that ascribed technical change to experience effects. His concept of 'learning by doing' meant that workers learn by experience in production. Learning was not just a repetition of actions in production, but also a steadily evolving pool of experience. Experience could be measured by investment because new equipment changed the environment, "so that learning is taking place with continually new stimuli" (Arrow, 1962, p. 157). Investment influenced production via learning in three ways: via capital accumulation, in embodiment of the latest technological advances, and by stimulating innovations. The incentive to innovate was not compensated by the market, because the knowledge which resulted from innovation was a public good. Therefore innovation generated externalities, which resulted in a divergence between social and private returns, causing inefficiencies. Romer (1986) had worked out that the resulting market equilibrium is not Pareto optimal. This was a normative conclusion, derived within the Ramsey-Cass-Koopmans framework.

One of the simplifying assumptions Arrow made in his model was that of fixed proportions between capital and labor. Furthermore, new capital goods were more productive than old goods. Depreciation did not matter in the full employment case for the outcomes of the model. Instead, obsolescence was the reason that capital goods were retired (p. 159). Firms were acting according to neoclassical rules and subject to diminishing returns to capital.

In the Arrow model experience was thus the result of past investment of all firms. Gross investments, equal to the aggregate capital stock, capture the externalities and generated a scale effect. This scale effect would not occur if the externality was captured by the average capital stock. In the latter case the growth rate of consumption would be independent of total labour supply. Learning is external to the firm in that its stock of knowledge is related to the aggregate stock of capital, which increases at zero cost. The total capital stock κ_t or experience is the sum of individual capital stocks. It was related to the state of knowledge A_t, which depends on time t, as:

$$A_t = \kappa_t^{\eta}$$
(3)

where η is the technical parameter for total capital stock ($0<\eta<1$). κ_t is an input given for the individual firm. This relationship is derived by Arrow based on experience in the airframe industry. The individual production

function, in which the state of knowledge A_t plays a role can be written as (following Sala-i-Martin, 1990, p. 18)

$$Y_i = F(K_i, L_i, \kappa) = K_i^{\alpha} L_i^{1-\alpha} \kappa^{\eta}. \tag{4}$$

This form exhibits constant returns to both K_i and L_i with a given κ^{η} but exhibits increasing returns to all inputs. The aggregate production function is (assuming that the individual firm is representative and aggregating the outputs of all individual firms):

$$Y = F(K, L, \kappa) = K^{\alpha} L^{1-\alpha} \kappa^{\eta}. \tag{5}$$

In per capita terms $y = k^{\alpha} \kappa^{\eta}$. In the accumulation equation (6), consumption per capita is represented by c ($n = 0$ and $\delta = 0$):

$$k^{\circ} = k^{\alpha} \kappa^{\eta} - c. \tag{6}$$

After deriving the first order conditions from the Hamiltonian, the growth rate of consumption is a function of the intertemporal elasticity of substitution σ, the capital-labour ratio k, aggregate labour supply L, the individual discount rate ρ and the technical parameters α en η. The growth rate is proportional to the difference between the marginal product of capital and the individual discount rate.

$$\gamma_c = \sigma^{-1} [\alpha k^{-(1-\eta-\alpha)} L^{\eta} - \rho]. \tag{7}$$

This was a striking result, because countries with a large population would experience fast growth (Van de Klundert and Smulders, 1992). The growth rate γ_c was constant as long as L and k was constant. This result was implausible according to Romer (1986, p. 1034). Growth is determined by an exogenous L. Romer (1986) showed how the growth rate is independent of population growth.

Sala-i-Martin (1990) described the different cases that could result from this model. The case in which $\alpha + \eta < 1$ looks like the Ramsey-Cass-Koopmans model and results in a zero long run growth rate. Hence, increasing returns by themselves are not enough to generate persistent growth. Only 'very increasing returns' could generate such growth. η has to be so large that $\alpha + \eta = 1$. In this case the model is similar to the AK model. However, in contrast with the AK model, a difference existed between private and social

returns. A planner would take into account the externality from the general pool of knowledge, so that

$$\gamma_{planner} = \sigma^{-1}[(\alpha+\eta)k^{-(1-\eta-\alpha)}L^{\eta} - \rho]. \tag{8}$$

This implied that the growth rate of the market economy was too low. Therefore the market outcome was not optimal (Romer, 1986). Romer assumed that the production function exhibited such increasing returns to scale. He justified this assumption by quoting empirical studies of Maddison, Baumol and growth accountants like Kendrick, arguing that the data did not exclude the possibility of increasing returns. This assumption was also the difference with the Arrow model, which assumed that the externalities from knowledge did not compensate for diminishing returns to capital (Romer, 1986, p. 1016).

Sala-i-Martin (1990) concluded that increasing returns to scale were neither necessary nor sufficient to generate endogenous growth. They were not necessary, because endogenous growth was possible with constant returns to scale like in the AK model. In the Romer model there were constant returns to reproducible inputs. Nor were increasing returns sufficient because it was possible to have $\alpha+\eta<1$. According to Rebelo (1991), increasing returns were only required if nonreproducible factors were necessary for the production. Another problem in the Romer model was that the assumption of perfect competition broke down if technological diffusion would spread over only gradually. Then monopolistic profits were possible. Not until Romer's later research (1990) these monopoly elements were taken into account.

In Lucas' model (1988) externalities which lead to increasing returns arised despite the absence of Arrovian learning effects, because labour tends to migrate across countries. The Lucas model is a kind of AK model, with K including both physical and human capital. The concept of human capital was developed by among others Schultz (chapter 4) and Lucas used his ideas. The Lucas model contained two sectors, namely one for goods and one for education. In the Arrow model knowledge was generated within one production sector, whereas in the Lucas model a separate sector for education existed, where knowledge could be accumulated. Human capital was accumulated by education and on-the-job training of workers, so that labour quality increases and the K/Y ratio changes. The K/Y ratio might increase because more workers would use more sophisticated tools, but it might also decrease because productivity is higher. Lucas applied Uzawa's (1965) assumption that the existing human capital is the only input in the education sector. No physical capital was involved in the accumulation of human capital. The allocation of human capital between the sectors was determined by its relative returns in each sector. In the education sector the return on

human capital accumulation was higher, so that in this sector its relative role was larger than that of physical capital.

Although the learning process by individuals was an intentional one in Lucas' opinion, knowledge from human capital was rival and excludable, because it was tied to individual workers. Nonrival knowledge was not taken into account by Lucas, whereas in the Romer model (1990) nonrivalry was very important. Furthermore, in the Lucas model learning did not take place in production as in the Arrow model, but in leisure time. Because leisure time was assumed to be constant, human capital changed in a fixed proportion to education in a reaction to changes in output, so returns to human capital accumulation were nondecreasing.

The production function in this two-sector economy runs as follows:

$$Y = AK^{\beta}H^{1-\beta},\qquad\qquad(9)$$

where H is human capital. H is equal to uhL, where u is the fraction of nonleisure time, h a measure of the average quality of workers and L the number of workers. According to Sala-i-Martin (1990) no externalities were necessary if there were constant returns to all reproducible inputs, but Lucas postulated externalities in H to reflect the fact that people are more productive when they are around clever people. If h_a is the average human capital stock of the labour force, then the production function is

$$Y = AK^{\beta}H^{1-\beta}h_a{}^{\varphi}.\qquad\qquad(10)$$

The human capital accumulation equation is $h^{\circ} = \phi h(1-u)$, reflecting accumulation of knowledge by studying in leisure time. ϕ is the study productivity parameter. The assumption that there were non-diminishing returns to human capital was crucial in the derivation of this accumulation equation. By solving the Hamiltonian one could derive the growth rates of consumption, capital and human capital. If no externalities should emerge, the growth rates would be equal to $\gamma=(\phi-\rho)/\sigma$. In the Rebelo model A accomplished the role of ϕ. So in the Lucas model the education sector was the driving force behind growth. The transitional dynamics of the Lucas model are difficult to derive, but one conclusion was that there was not always convergence to the steady state. Mulligan and Sala-i-Martin (1993) for instance analysed transition dynamics in a two-sector model of the Lucas type. Similar to the Romer (1986) model, the market growth rate in the Lucas (1988) model was less than the growth rate in a command economy.

In contrast to the Arrow (1962) model and the Lucas (1988) model, Romer (1986) argues that new knowledge is produced by investing in

research which exhibits diminshing returns. The production of goods from increased knowledge, however, shows increasing returns. The Romer model had three key elements: externalities, increasing returns in the production of output and decreasing returns of new knowledge. These were consistent with the assumption of perfect competition. In the Romer model, no transitional dynamics occurred.

The aggregate capital stock is affected in two ways. In the Arrow (1962) and Sheshinski type models learning effects emerge from the production function of the individual firm, which has the form $y_i = f(l_i, k_i, K)$ with l_i the labour supply used by the firm, k_i the firm's capital stock and K the general stock of capital. The first derivative of y_i to k_i is larger than zero, the second derivative is smaller than zero. The aggregate production function therefore runs as $Y = F(L,K)$, of which the second derivative to K is larger than zero. In the Romer (1990) (see below), Lucas (1988) and Uzawa (1965) models the economy is divided in two sectors, one sector for products and one for knowledge. In this type of models the capital stock is affected via the accumulation of knowledge.

Monopolistic competition and R&D

The models of Romer (1986), Lucas (1988) and Rebelo (1991) were not really theories of endogenous technological progress, because technology is not determined within the models and still is like 'manna from heaven'. Spillovers from knowledge and externalities from human capital do help to avoid diminishing returns to the accumulation of capital, but they are only a part of the process. According to Barro and Sala-i-Martin (1995), (broad) capital accumulation cannot actually be infinite in the long run. Capital will ultimately exhibit diminishing returns in the long run, because the most productive units will be used up first, so that its possibilities are eventually exhausted. Although international growth differentials can be explained with spillover models, we have to look at another factor which could generate persistent economic growth, namely knowledge or technological progress itself. Population growth can also be endogenised, like other parameters such as the discount rate ρ and the elasticity of intertemporal substitution σ, but we concentrate on technological change. Barro and Sala-i-Martin (1995) defined technological progress as the 'continuing advances in methods of production and types and qualities of products' (p. 212) following Grossman and Helpman (1991). If technological change is endogenous, growth will persist forever because there are non-decreasing returns in broad capital. In the sense that there exist economies of scale, the difference with the previously discussed models is not fundamental. The difference between knowledge and human capital is that "...knowledge is the quality of society's textbooks; human capital is the amount of time that has been spent reading them" (Mankiw, 1995, p. 298).

A problem in modelling technological progress is that it is difficult to model how precisely R&D affects production. Furthermore, there is a large uncertainty surrounding the production of new designs with respect to the height of pay-offs. Moreover, it is unclear whether a model is plausible in the choice of technological indicators and their links with productivity growth. According to Solow (1994) formal growth models had to co-operate with case studies to determine the plausibility of endogenous growth models. This possibility is discussed in the conclusion of this literature survey.

In the Arrow model (1962) spillovers from knowledge were a side product of production and they were not generated intentionally. According to Romer (1990), the accumulation of knowledge in the Lucas model was also unintentional. In recent endogenous growth models knowledge is accumulated intentionally by scientific research and commercial development in a separate Research & Development (R&D) sector. R&D will evolve new ideas and designs that can be employed by workers but are not necessarily tied to them. R&D is used by firms in search for blueprints of new varieties of

32

products or higher quality products. This R&D is not directly productive, but will contribute to the expansion of the frontiers of knowledge. The accumulation of knowledge will generate growth, which in turn will stimulate capital accumulation, and not the other way around (Romer, 1990, p. S72).

R&D enters the model in two ways according to Sala-i-Martin (1990). First, output per capita is a function of all existing varieties or qualities of capital goods. R&D increases the productivity of other inputs in the production of manufacturing goods. If there are constant returns to all varieties of capital goods, the stock of knowledge and output grow at the same rate. This is the way Romer (1990) introduced the R&D sector. Second, the spillovers on aggregate stock will reduce costs of R&D. Then constant returns to R&D are possible, the incentive to innovate remains positive and knowledge grows forever. It does not matter why firms do R&D. R&D seeks improvement of quality or discovery of new varieties. Examples of such models are the studies of Aghion and Howitt (1992) and Grossman and Helpman (1991).

Because of the assumption of perfect competition in the neoclassical framework, it is difficult to incorporate technological progress in the model. Technological advances involve the creation of new ideas, which are nonrival but partially non-excludable and therefore have characteristics of public goods. Then increasing returns exist, conflicting with the assumption of perfect competition. In the Arrow (1962) and Lucas (1988) models the nonrival inputs were completely nonexcludable. The problem in the Romer (1986) model was the perfect competition assumption. In the other Romer (1990) model knowledge was nonexcludable for researchers, but the use of blueprints can be patented. The introduction of new varieties required imperfect substitution, so that it was profitable for firms to introduce new varieties and to continue if other competitors enter the market. In the intermediate goods sector monopoly power was necessary for researchers to recover their initial expenditure on the design. In this analysis a Schumpeterian idea returned, namely that of a profit-seeking entrepreneur generating growth by his purposive activities, which are stimulated by market imperfections (Romer, 1990, p. S78).

Monopoly power will bring some distortions in the market, so governments will have a task to create a Pareto optimal long-run growth rate (Mankiw, 1995).[4] The monopoly profits are earned by the discoverers. Because imitation is in general cheaper than innovation, the other agents will

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[4] Readers interested in the optimality problem are referred to for instance A. Heertje's (1995) article in De Economist, Observations on technical change and Paretian welfare economics (Vol. 143:4, November 1995).

copy the technology and their activities will generate technological diffusion. This diffusion leads to a form of conditional convergence.

Romer (1990) made three premises. First, technological change was the driving force of growth. Second, the intentional R&D was responding to market incentives such as profits. This means that it was at least partially excludable. Third, technology research generated spillovers in knowledge, which were used without additional cost. Thus it was nonrival, what implied that knowledge could be accumulated without bound, whereas human capital could not be accumulated infinitely. In the Romer economy three sectors existed, namely for R&D, intermediate goods and final goods. In the R&D sector the only inputs were human capital and knowledge. In the intermediate goods sector the knowledge generated from the R&D sector was applied. And in the final goods sector raw labour, human capital and durables were used as inputs. Output could be consumed or saved as new capital. For simplicity it was assumed that population growth is zero and that the total stock of both human capital and raw labour is fixed.

The Cobb Douglas production function in the final goods sector of the Romer model is

$$Y(H_Y, L, x) = H_Y^{\alpha} L^{\beta} \int x(i)^{(1-\alpha-\beta)} di \qquad (11)$$

where $x(i)$ is a capital good of variety i. The total human capital employed in the R&D sector is the only input in the accumulation of knowledge:

$$A° = \delta H_A A \qquad (12)$$

with δ a productivity parameter and H_A the human capital used for knowledge accumulation. According to Romer human capital is the correct measure of scale, not population. Because equation (11) is linear and does not have restrictions, unbounded growth is possible. Knowledge enters both the final goods sector and R&D sector, but in the final goods sector knowledge is excludable (patented), whereas in the R&D sector it is nonexcludable (learning effects). This nonexcludability makes it possible to imitate or copy a new variety in the final goods sector. The intermediate goods sector maximizes profits, which depend on the demand for durables by the final goods sector. The initial expenditure on the design are sunk costs. The resulting monopoly price is a mark-up, determined by the elasticity of demand, over the marginal cost. The conditions in the final goods sector determine the monopoly price $p_M = r\eta/(1-\alpha-\beta)$, where η reflects units of forgone consumption and r the rate of return on capital. Price discrimination was not possible for the entrepreneurs in the Romer model. Romer (1990) thus combined a R&D sector with monopolistic elements together with spillovers

34

like those in learning models. This combination was the most promising development in growth theory according to, among others, Solow (1994). A model with only R&D generated the same outcome as previous models with public spending (Barro, 1990), learning-by-doing or human capital models. As Romer (1990) stated: "There is little doubt that much of the value to society of any given innovation or discovery is not captured by the inventor, and any model that missed these spillovers would miss important elements of the growth process. Yet, it is still the case that private, profit-maximizing agents make investments in the creation of new knowledge and that they earn a return on these investments by charging a price for the resulting goods that is greater than the marginal cost of producing the goods" (p. S89). The promise lies in the effort to take into account microeconomic elements like profit-maximizing firms striving for monopoly power by doing knowledge research, patenting their inventions and borrowing ideas from other firms on which they can build their knowledge. An R&D model would force economists to think carefully about technology and knowledge and offer a broader perspective (Romer, 1995). Moreover, knowledge differences do exists in the real world because of interfirm differences.

The Romer (1990) model is one of the Schumpeterian models which are developed recently. These models tried to capture the Schumpeterian elements of dynamic economic growth and disequilibria into a formal model, although this remained difficult. Aghion and Howitt (1992, 1996) and Young (1993a, 1993b) are examples of the new road taken nowadays. Aghion and Howitt (1992) presented a model which captures the creative destruction process of Schumpeter. A separate research sector generates endogenous innovations which intertemporally cause changes in productivity growth. Different equilibria are possible in this model. The growth rate is dependent on inventive activity, education, productivity of research and (negatively) on the rate of time preference. The average growth rate might not be socially optimal because of conflicting distortionary effects. Growth is hampered by appropriability and intertemporal spillover effects as discussed in Romer's (1990) model, but too much growth is also possible because of a business-stealing effect in that "researchers do not internalize the destruction of existing rents created by their innovations" (p. 325), taking the size of innovations as given. If this size is endogenized, innovations may be too small. Aghion and Howitt (1992) concluded that some extensions of the model were desirable, such as bounded technology, so that the size of innovations are required to fall.

The Aghion and Howitt (1996) model explored a structural aspect of growth, namely that of competition. Other aspects are likely to be examined by other scholars, such as the difference between fundamental and secondary research, business cycles, waves of technological change, and unemployment.

Competition and growth were inversely related in the recent elementary Schumpeterian models, while evidence did not support this result. Aghion and Howitt (1996) therefore extended the Aghion and Howitt (1992) model to demonstrate that a more competitive market structure can contribute to growth. In the opinion of Aghion and Howitt (1996), the model provides a new starting point for further empirical research. The model namely suggested that "competition in research, as opposed to market competition, is almost likely to be favourable to growth" (p. 43). Furthermore, in subgroups of the economy the impact of market competition on growth may be positive.

Young (1993a, 1993b) explored some extensions of the Aghion and Howitt (1992) model and Aghion and Howitt (1996) also refer to Young. The Young (1993a) model combined two elements, namely that of invention (like Romer, 1990, and Grossman and Helpman, 1991) and that of learning by doing (like Arrow, 1962, and Lucas, 1988). Young assumed that the ability to learn is 'bounded'. After introduction of a new technology, the inherent physical limit on its productivity slows down learning, unless a new innovation is made (p. 445). Young founded this assumption on historical evidence, which indicates that pre-industrial economies experienced long-run technical stagnation. As Crafts (1995b) argued, the role of learning as opposed to R&D or invention is understated (section 4.6). Historical examples also support the statement of Young (1993b), that the Schumpeterian model of creative destruction 'forgets' the possibility of new technologies complementing older ones, which create rents instead of destroying them. Substitution and complementarity opportunities produce a "stylized life cycle" (p. 804). The model could generate multiple equilibria.

However, modern growth models have a thin empirical basis. Most theory based empirical studies started from the Solow type model and tested it instead of an endogenous model. Growth regressions founded on growth models were estimated by Barro (1991) and others. The measurement of technological variables is very difficult, as Griliches (1994) and others argued. The Solow model had, however, been a good starting point for the extension of neoclassical growth theory. Recent theories consider factors like education and research, of which the benefits are of a long run nature. International technology spillovers and variety of products are also better highlighted nowadays, among others by Grossman and Helpman (1991). Endogenous innovation is incorporated within models of creative destruction. But those 'new' factors have always been considered as important by empirical scholars, who emphasise the path-dependency of technological progress and economic growth. In chapter 4 the empirical studies of Abramovitz (1991), Maddison (1995), Barro (1991), Griliches (1994) and other scholars will be discussed. In section 4.6 some results of Schumpeterian models are discussed together with these empirical studies.

The model of Scott (1989) shows an overlap with Arrow's learning effects. Scott found ideas of Schmookler (1966), Hirschman (1958) and Arrow (1962) interesting. Furthermore, in Scott's opinion "...there is no reason to suppose that undertaking investment depresses the rate of return to it at a later date, and all experience suggests that it does not" (1992, p. 625). Because future is uncertain, investment opportunities are founded on the present situation. This situation changes because of these investments, so that new chances are created by them. R&D is just one of the many forms of investments in Scott's opinion.

4 Empirical analyses of technological progress

4.1 Introduction

Standard neo-classical theory and modern endogenous growth theory are analytical approaches, which try to explain the change in productivity growth deductively. However, long before the formal theories incorporated aspects like economies of scale, endogenous change or spillovers from research and development, economic historians and historically oriented economists already commented on the importance of those factors and their interdependency. These scholars observe the actual developments in productivity growth and technology and induce possible links between economic variables. This line of research has been strongly supported by the development of detailed historical national accounts.

Four groups of empirical scholars can be distinguished, although sharp boundaries cannot be drawn between these groups. The first group carries out quantitative analyses of technological change in the long run. The starting point of these analyses is economic history. For example David (1991), Broadberry (1994a, 1994b) and Crafts (1995a, 1995b) study technology within this framework. Different technological-gap theorists, such as Gerschenkron (1962), Rosenberg (1976) and Abramovitz (1986), have developed ideas about a 'national innovation system', the leaders at the technological frontier, catch-up of the followers, social capabilities and technological congruence (section 4.2).

In contrast to these scholars, a second group sometimes uses a production function from growth theory as a basis for growth accounts. In these accounts, productivity growth is decomposed in components like accumulation of physical and human capital. Factors which cannot be measured and measurement errors are left in a residual, referred to as the Abramovitz or Solow residual. Growth accountants try to reduce the residual by better measurement of some variables or by adding other possible influences of productivity growth. Section 4.3 describes the analyses of among others Denison (1967), Kendrick (1976), Maddison (1991) and Abramovitz (1993).

Estimating growth equations is another possible way to study the impact of technological progress. This approach is used by a third group of scholars like Barro (1991) and Mankiw et al. (1992), who constructed productivity equations with the help of economic theory (section 4.4). Of all empirical studies the studies within this approach bear most heavily on economic theory. The final group of empirical economists estimates technology and technological change by measuring outlays in R&D, patents,

licenses and other indicators. Schmookler (1966), Griliches (1994) and in the Netherlands Soete and Verspagen (1991) are good examples. Their work is discussed in section 4.6, together with other spillover studies. In section 4.5 the gains of a sectoral approach are outlined. This approach is used by various empirical scholars in all the four groups, among others Van Ark (1996).

4.2 Technological change in the long run

In the opinion of historically oriented economists, technological change is path-dependent. Abramovitz (1991), for instance, argued that technological progress is more than just an interaction between the accumulation of physical and human capital and technology. Technological development is also a learning and feedback mechanism, which can generate economies of scale and structural changes. According to various scholars like Gerschenkron (1962), Kuznets (1965) and Abramovitz (1991), technological progress is dependent on the specific (historical and national) characteristics of the environment of firms in which innovations take place. They also make a distinction between the potential of an economy to innovate and diffuse new technologies and the realisation of this potential or adaptation of new technologies.

Countries at the technological frontier try to enhance their technical efficiency. For those countries invention, innovation and diffusion of technological knowledge is very important. The frontier countries invest in the research and development of technological knowledge necessary for the creation of products. The technological regime at the frontier is the feasible limit that allows a certain level of output for a given level of inputs (Choi, 1983). Technological progress increases this level of output or improves its quality with the same level of inputs, or the same output with less inputs. However, most countries exploit technology systems with an average, lower, productivity and might use obsolete techniques. The extent in which those technologies are exploited to increase productivity is more important for these follower countries.

In the early literature on technological change (Schmookler, 1966, Mansfield, 1968) a distinction is made between technological and technical change. The former type of change concerns invention, know why things work as they do (discovery), while the latter involves innovation, know how to make things work (application). Invention and innovation are two subsequent stages influencing the technological frontier. After the discovery and introduction of a new technology further improvements can be made and costs reduced through learning effects. Then other firms, foreign or domestic, can adopt the technology more easily. In this phase the new technology is diffused and the productivity levels in an economy using the average practice

are affected. No sharp boundaries can be drawn between the three stages of invention, innovation and diffusion because of feedback mechanisms. The recent literature on technology considers invention as a part of innovation and both are considered as elements in one process together with diffusion (OECD, 1991). Innovation and diffusion can both be determined by demand and supply factors. Schmookler (1966) was convinced that demand determines the application of new techniques, whereas others think supply forces stronger.

Diffusion of technologies within or among countries can enhance productivity growth. In nineteenth century Britain the technological path was determined by learning effects from increasing returns and exogenous changes in the environment, together with economies of scale. International spillovers were less important to the UK in the previous century (Crafts, 1995a). At that time clusters of macro-inventions, which were exogenous and unpredictable, led to chain reactions of micro improvements in the long run. Rosenberg (1976) stated that the cumulative effects of minor technological changes upon cost reduction were larger than effects of major technological changes. This was in sharp contrast with the theory of Schumpeter, who emphasized the major breaks.

The British developments stood in contrast to the systematic R&D and applied scientific research which are predominant nowadays, such as happened in the US from the 1880s on. The US benefited from a cluster of innovations in the 1880s, which was an opportunity to reap economies of scale in a resource and capital intensive mass-production system, used in newly organized giant firms. These developments enabled the US to establish the private organization and public infrastructure necessary to operate in emerging science-based industries, although the US was not the leader in the scientific area at the beginning of the twentieth century (Nelson and Wright, 1992).

Rosenberg (1982) argued that improvements in technology will not necessarily be incorporated in production immediately, but will be adopted with a lag. David (1991) shares Rosenberg's opinion in his own story on dynamos and computers. This was the only way to solve the so called productivity paradox. This paradox refers to the many innovations in the information technology in the 1980s and 1990s, which do not seem to have been translated in accelerated productivity growth (OECD, 1992). There seems to be a less strong link between technological progress and productivity growth than was assumed before. Several theories were developed on the solution of the paradox. Some scholars, such as Griliches (1994), imputed the paradox to the measurement problem of data of the service sector, where most of the productivity increase had occurred.

40

However, according to scholars like David (1991) the link between technological progress and productivity does exist, but diffusion of technological knowledge occurs only slowly. In Salter's (1960) opinion, diffusion is slow due to costs arising from uncertainty and fixed costs surrounding the adoption of an innovation, vintage effects and the heterogeneity of firms and markets, which complicate the copying of one's another technology. These costs arise because diffusion is more than imitating a new production method or new variety or better quality of a product. It also involves an economic incentive to adopt it, which is an innovation by itself. In the diffusion process, a treshold level of costs exists where the new and old technologies are competitive. After passing this level adoption rates of the new technology may be increasingly sensitive to further improvements.

The economic importance of diffusion stems from the difference between social and private returns. This difference implies that gaps between countries in objects (that is, capital goods) and ideas are not closed (Romer, 1993). Countries at the technological frontier are followed by others, which try to catch up with these leaders by borrowing frontier technologies and exploit them within their own social environment. To catch up, a backward country will have to choose a particular technology with specific characteristics within a specific institutional setting. This choice is made by firms at a microeconomic level, which affects the macroeconomic character of a society's technological path (David, 1975).

A labour intensive technological system will follow another path than one system which is capital intensive. It is difficult to swith to another technology, because of information and coordination problems and technological interrelationships. A chosen technology will thus be deepened rather than shifted. The path forms an irreversible process which determines the long-run productivity rates. Although the possibility of imitation or borrowing allows for catch up growth, the growth rates will differ between countries. Broadberry (1994b) describes the technological systems of the US, UK and Germany. The productivity development in the different countries is given in table 4 of Appendix B. In the nineteenth century the US economy exhibited a technology system necessary for mass production, namely one which uses machinery and resources intensively. In contrast, craft production was often profitable in the UK, that specialized in a skilled-labour intensive technology. Those technological systems coexisted, as long as they could adopt new techniques. Innovation elsewhere may undermine the position of one's own technology. However, one's another technology system cannot be just imitated, because the cumulative or path-dependent character of the technological progress is specific to the country. So technologies cannot just be copied by other countries (Fagerberg, 1994).

Hence, different strategies in technology development are possible, on the condition that investments are made in specific skills to reap economies of scale and scope inherent to each technology system (Broadberry, 1994b). The extent to which a country is able to exploit existing technologies depends on its social capability and technological congruence (Abramovitz, 1991). Technological congruence is the extent to which the country can apply the new technology of the leader to its own circumstances, while technological competence or social capability determines the absorption and exploitation of technologies. Both elements determine the society's potential to catch up. The realisation or exploitation of growth opportunities is determined by more factors, such as the speed of technology diffusion, macroeconomic conditions, structural changes (such as a shift between sectors) and the institutional framework. As Gerschenkron (1962) argued, the process of overcoming "the lack of preconditions for economic progress" is stimulated by the existence of "advantages of backwardness" or a catch-up opportunity, but this is a costly process (p. 51) because it requires an rearrangement of country-specific institutions.

Fogel (1964) made a provocative argument with respect to the path an economy can follow. He stated that railways in the American states in the nineteenth century were not necessary to take a lead in agricultural production. Instead, the railways were an embodied technological development, which was exploited as largely as possible. Disembodied technological progress was reflected by the fact that cheaper transportation became possible in the previous century through a cluster of innovations, whatever form this transportation would take. "...the fact that the condition of cheap transportation was satisfied by one innovation [railways] rather than another [water, wagons] determined, not whether growth would take place, but which of many possible growth paths would be followed" (p. 237). A certain chance element plays a role, but just within the technological developments.

Technological progress is embedded in the country-specific organizational structure of economy, which consists of firms, networks and institutions. The firms, which differ mutually in the capability to innovate, learn and adopt, play a key role in the choice of the technological path (Chandler, 1990). Human capital accumulated in those firms is very important, too. Furthermore, the institutional environment of the firms affects their performance. The use of average practice technologies instead of frontier technologies is caused by institutional barriers. "[L...]ocation on a technological trajectory may be less important than the efficiency with which the advantages of that location are pursued. This, in turn, depends on institutional features (broadly defined) that may be more or less appropriate

for a given pattern of specialization" (Ergas, 1987, p. 233). It is difficult, however, to quantify the effects of institutional aspects.

In short, a follower country has the possibility to catch up because of the possibility to borrow technology cheaply from the leader and because of greater opportunities than the leader to change institutions. The possibility to catch up provides a potential advantage, which is realised, depending on the social capability and technological congruence. Human capital, international trade, market structure, social stability and government policy and other factors interact and change over time, affecting the productivity growth rate. The path-dependency of technological change is essential in the explanation of productivity growth differentials between countries.

4.3 Growth accounting

Exploring sources of growth

Growth accounting is an analysis of the decomposition of the growth rate of a dependent variable such as GDP per hour worked in different possible 'sources' of growth. Such sources are among other things changes in the input of physical and human capital, scale effects, foreign trade and the institutional environment. A residual remains after accounting for these factors. Abramovitz (1956) calls this part a "measure of our ignorance" (Abramovitz, 1991, p. 133). In the successive studies from the 1950s on, the residual is reduced from 90 per cent to even less than 40 per cent, but it still accounts for a large part of the economic growth. Technological progress is usually assumed to account for a large part of the residual, in addition to factors which could not be measured and measurement errors. Growth accounting is not a theory of growth, because it fails to explain how the sources relate to growth (Barro and Sala-i-Martin, 1995, p. 352).

Tinbergen (1942) constructed the first growth accounts for several countries, with labour and capital as the driving forces behind growth. He referred to the unexplained residual as 'total factor productivity' growth. At that time, availability of accurate data was still a great problem. In the US the NBER did much pioneering work in growth accounting. In 1957, Solow constructed the model that directed the attention of many neo-classical economists to technological change. They emphasized the role of physical capital and investment and the long run adaptive capacity of the economy, whereas for Keynesians like Kaldor (1961) demand aspects like factor and commodity prices also remained essential. In the 1950s various scholars began to measure changes in quantity and quality of capital and labour. Fabricant (1954), Abramovitz (1956), and Kendrick (1956) are a few of the most influential authors in this area. Some growth accountants, such as Jorgenson (1995), followed the neo-classical ideas strictly, whereas others used a more eclectic approach with national and sectoral data.

Abramovitz (1956) included new factors like education and research as inputs in his growth accounts. However, according to Maddison (1995), Solow's paper (1957) was more influential. In this paper the residual is assumed to represent technological change, although other factors also played a role in this residual. Solow assumed that technological progress is fully disembodied, so that all technological change appears in a shift of the production function. Later Solow (1962) developed a vintage model with an effective stock of capital in which all technological progress is embodied. In his 1957 paper, Solow measured the residual with time series of Goldsmith for

the US. Table 1 summarizes his results and compares them to other studies, which I will discuss below. In Appendix B detailed accounts are presented for interested readers. Solow concluded that technological change is uncorrelated with the capital-labour ratio, so that over this

Table 1. Growth accounts of the US
(growth rates in % per year; between parentheses as a % of growth rate)

	Solow (1957)	Denison (1967)	Jorgenson &Grilich. (1972)	Kendrick (1976)	Maddison (1991)
period	1909-1949	1950-1962	1950-1962	1929-1969	1950-1973
1.Output	doubled	2.15 (100)	3.47 (100)	3.4 (100)	3.65 (100)
2.Total labour hours	NA	-0.17 (-8)	0.37 (11)	NA	0.81 (22)
3.Labour quality	NA	0.39 (17)	0.34 (10)	NA	0.35 (10)
4.Capital stock	NA	0.60 (27)	1.30 (37)	NA	0.98 (27)
5.Capital quality	NA	NA	0.41 (12)	NA	0.39 (11)
6.Total labour input	NA	0.22 (10)	0.71 (21)	1.45 (43)	1.17 (32)
7.Total capital input	NA	0.60 (27)	1.38 (41)	1.38 (41)	1.38 (38)
8.Total factor input	NA (12.5)	0.79 (36)	2.42 (70)	2.83 (84)	2.54 (70)
9.TFP (Total factor productivity)	1.50 (87.5)	1.36 (64)	1.03 (30)	0.57 (17)	1.11 (30)
10.Unexplained	1.50 (87.5)	0.76 (34)	1.03 (30)	0.57 (17)	0.77 (21)

Source: Appendix B. After accounting for the contribution from capital and labour in quantitative and qualitative terms, the growth rate of output can be decomposed in the growth rate of total factor input and total factor productivity. The latter is decomposed by Denison (1967) and Maddison (1991) in additional sources like foreign trade effects, economies of scale and demand fluctuations. After this decomposition a residual remains unexplained (line 10). In the other three studies no other sources of growth are added, so the residual remains equal to TFP. Furthermore, Denison (1967) adjusted total factor input for land (-0.03 per cent per year). Maddison's data (1991, table 5.3 and 5.10) are weighted with 0.7 for total labour input (growth rate 1.67), 0.23 for non-residential capital (growth rate 5.01) and 0.07 for residential capital stock (growth rate 3.29).

period, shifts in the aggregate production function can be considered as neutral. Technical change accelerated after 1929. Over forty years technology changed with 1.5 per cent per year on the average. Furthermore, labour productivity, real GNP per man hour, is doubled from $0.623 to $1.275. Total factor productivity or the change in technology $A°/A$ increased with 80 per cent from 1,000 to 1,809 (indexed) over the same period. Dividing the 1949 value for output per man hour, $1.275, by 1.809 results in GNP per man hour net of technical change: $0.705. Thus, 12.5 per cent of the increase is thanks to the capital accumulation per man hour, while 87.5 per cent comes from technical change (see table B.5). Solow (1957, p. 412, fn. 5) refers to Abramovitz (1956) and emphasises measurement problems like that of improvement in the quality of the labour input, which must be a result of real capital formation of some kind. A lot of what appears to be part of the shifts in the production function represents the accumulation in real capital. An important step forward in growth accounting, in particular on an internationally comparative basis, was made by Denison (1962, 1967). Denison introduced various new 'sources', which were considered as important by contemporary scholars, but which were not included in growth accounts yet. The basis of Denison's work was formed by the theories of Solow (1956, 1957, 1962) and Schultz (1961). The latter developed the concept of human capital, like Mincer and Becker. Denison (1967) constructed growth accounts for the US (see table 1) and some European countries. After deducting the contribution of the inputs capital, labour and land and adjusting for changes in their quality, total factor productivity (TFP) growth accounted for 64 per cent of the growth rate in 1950-1962. Denison added other determinants of growth like improved allocation in resources (13 per cent of TFP) and economies of scale (16 per cent of TFP). Two ways were thus open for growth accountants to reduce the residual: by adding new sources of growth and by accounting for embodiment of technological change in adjusting for quality, composition and the like. However, 34 per cent still remained unexplained as a residual in Denison's account of the US.

According to Denison advances in knowledge are difficult to measure directly. After accounting for all possible measurable sources, the residual must therefore contain advances of knowledge (general efficiency) and the change in the lag in the application of knowledge, together with measurement errors and omissions. For instance, the residuals include the "interaction" between the contribution of factors included in the residual and other factors such as the technological knowledge which is not embodied in capital. The interaction is however "too trifling ... to impair comparisons" (p. 281, fn. 8). Table B.7 in Appendix B presents the contribution of the residual in different countries. Denison's estimates of the residual value it less than 50 per cent, even less than 40 per cent of the growth in national income per person

employed. Measured as a percentage of output per unit of input, the residual is somewhat higher.

Jorgenson and Griliches (1967) tried to reduce the residual to zero by measuring capital and labour in efficiency units (Choi, 1983), which capture improvements in quality. Jorgenson and Griliches stated that the economic theory underlying the measurement of total factor productivity has not been fully exploited. Furthermore, they alleged that Denison and other growth accountants had made measurement errors, which gave serious biases. Jorgenson and Griliches eliminated those 'errors' in aggregation, investment good prices, relative utilization, aggregation of capital services and aggregation of labour services (Jorgenson, 1995, table 3.9, p. 84).

Jorgenson and Griliches assumed perfect competition and employed a constant returns production function. Similar to Denison, technical change equaled a shift of the production function and the growth rate of total factor productivity was the difference between the growth rates of real product and that of real factor input. In measuring capital, Jorgenson and Griliches used the flow prices of capital services, not the asset prices of the capital stock. Their estimation resulted in an average annual growth rate in total output of 3.59 (originally 3.49) in the US private domestic economy in the period 1945-1965 and a growth rate of 3.47 (originally 1.83) for total input. The residual decreased to 0.10 a year, i.e. 3 per cent of growth rate in output, in contrast to the original estimate of 1.60, i.e. 46 per cent. Jorgenson and Griliches concluded that growth in real factor input rather than growth in total factor productivity was the predominant source of growth in real product.

The publication of this 1967 paper was the start of an intensive debate with Denison in economic journals. This discussion led Jorgenson and Griliches to conclude that they had exaggerated in reducing the residual to zero, although they still disagreed with Denison in the way of measuring physical capital and believed that one has to refine and extend the growth accounts to minimize the residual: "The resulting estimates of growth in total factor productivity are closer to Denison's estimates than our original ones, but still significantly lower. .... [H]owever, ... : Growth in total input is a major rather than a minor source in the growth of national output" (Jorgenson, 1995, p. 102). According to Jorgenson and Griliches (1972) real product increased in the period 1950-1962 with an average annual rate of growth of 3.47 and real factor input with a rate of 2.42. Total factor productivity increased with 1.03, i.e. 30 per cent of the total output growth rate (see table 1). Above all, Jorgenson constructed sectoral accounts and his refinements of these accounts remain of great value, as becomes clear from the collected papers of Jorgenson (1995). Denison only considered total economy. In section 4.5 ideas underlying the sectoral approach will be described.

Kendrick (1976, 1993) and Maddison (1972 to 1995) provided more detailed growth accounts following Abramovitz, Solow, Denison and Jorgenson and Griliches. Kendrick (1976) added R&D to the traditional inputs physical capital, human capital and inventories. Like Jorgenson he disaggregated his data to the sectoral level. His estimations appeared to confirm the neo-classical view of a constant capital-output ratio. Tables 1, B.8 and B.9 demonstrate his results. Physical and human tangible and intangible capital contributed for a large part to the national growth. Table B.9 shows that the residual decreased to between 10 per cent and 20 per cent of the growth rate. Human capital (including R&D) and nonhuman capital contributed to growth with 41 to 45 per cent and 37 to 42 per cent respectively (Kendrick, 1993). His conclusion is that the including real intangible capital increases the contribution of real human capital to growth. The residual is reduced because improvements in quality of labour are accounted for by human capital. In short, according to Kendrick total factor productivity growth is not zero although the largest part of growth comes from broad (both physical and human) capital accumulation.

Maddison (1995) composed time series on GDP, population, labour, capital and exports for 56 countries. Summers and Heston (1991), the OECD, the World Bank, the IMF and other institutions also gathered figures on among other things consumption expenditures and saving rates and used a sample of countries, though not for such a long period as Maddison. The growth accounts in Maddison's 1991 book, in which the growth accounts cover 16 countries, showed his efforts to refine the measurements. Table B.10 describes the different forces behind growth according to Maddison and shows that the residual was reduced to less than 30 per cent for the US (see also tables 1 and B.11). In the period 1973-1987 the explained part even rises to 94 per cent of the total growth in GDP. On average, 77 per cent of the total growth in GDP can be explained. Growth accounts are made not only for advanced countries, but also for developing countries, by among others Hofman, Elias and Langoni on Latin American countries and accounts for among others Korea. Those are not discussed in this literature survey, which concentrates on developed countries.

The revival in growth theory, stimulated by articles of Baumol (1986), Romer (1986) and Lucas (1988), was of great importance because the greater explanatory power allocated to technical change was not "tackled very seriously" by growth accountants. But (country-specific) institutional factors remain difficult to model and difficult to test. Furthermore, policies are difficult to distinguish from institutions. Maddison (1995) distinguishes between proximate and ultimate sources of growth (p. 50). Institutions, political and economic order, policies and technological diffusion from leaders to followers are ultimate sources. Growth accounts only estimate the

proximate sources: land, capital, labour and their productivity changes, eventually added with other sources like foreign trade effects. The residual accounts for disembodied technological progress.

In his recent book Maddison (1995) argued that although there is good progress in growth accounting, these often cover only the twentieth century and are not yet constructed for many countries. Exceptions are, for example, Abramovitz (1993) and David (of which the figures are gathered in Abramovitz, 1993) for the US from 1800 onwards. Maddison (1995) constructed figures on GDP and population which go back to 1820 for advanced countries. In such a setting the long run developments and their nature in different countries become clear. Those figures will provide a new starting point for future research on long periods and for extensions to more countries. In table B.12 the computations of Maddison (1995) for the US are presented.

From the first growth accounts onwards, Abramovitz and David commented at several occasions on developments in growth accounting with various case studies. In Abramovitz' paper (1993) historical data constructed by David are given. Table B.13 presents his results. In this way Abramovitz focused attention on long-run developments, free from temporary fluctuations, political changes and measurement errors. Table B.13 shows the relative importance of capital accumulation in the nineteenth century. The same development can be observed from Maddison's figures (table B.12). In the twentieth century, TFP growth gains more importance, although its share in GDP growth seems to decline after 1966 (or 1973 in Maddison's account, table B.12). In the nineteenth century technological progress appears to be heavily embodied in physical capital, while in the twentieth century the emphasis shifted to human or intangible capital (Abramovitz, 1993).

The growth accounts can be modified to cope with theoretical assumptions, together with the endogenizing of technological change. "The growth accounting approach can also be used to test the findings of econometricians who use the regression approach to causal analysis" (Maddison, 1995, p. 13). If, for instance, a new factor is added to the growth accounts which is used in a regression, the growth accounts could make obvious whether growth is 'overexplained' or not. Overexplanation can occur because of the interaction between the different variables. Then restrictions have to be imposed on the coefficients or the structure of the model has to be changed. Jorgenson was also interested in econometric models of economic growth to give a more analytical role to the sources-of-growth method. In section 4.4 studies of technological change with the help of regressions, cross country or time serial, are discussed. These empirical analyses are important in that they might link the formal endogenous growth theory and the growth

accounting. Such an integration will be proposed in the conclusion of this paper.

Limitations of growth accounting

Although growth accounts give insight in the relative impact of different sources on growth, they have their limitations. The first is the difficulty of correct measurement and definition of variables. For example, what is 'capital'? Which data have to be used to measure capital? How have the data to be deflated? The choice of international Purchasing Power Parities, weighting of the factors starting from a basis year, and the measurement of services causes problems. Measurement errors can arise from the lack of accurate data. Moreover, the impact of some variables on growth can be lagged in time (OECD, 1991). Griliches (1994) observes data problems in measuring R&D and patents (see section 4.6). A related problem is the difficulty to measure the impact of the institutional framework. How to solve this problem is not clear yet. Furthermore, maybe one has to measure technology directly, using data on R&D, patents and the like as a proxy for technological change, in order to gain more insight in its relative influence (see section 4.6).

Second, growth accounts lack a theoretical basis (Grossman and Helpman, 1991) and cannot explain the precise relationship between productivity growth and factors of which it is assumed that they influence productivity growth. Although accounts cannot identify causal relationships and assumptions such as the neo-classical production function and weights for the determinants are imposed, they give insight in the relative influence of different determinants of productivity growth. Another problem with the accounts is that because of their aggregative character, national or sectoral, they cannot uncover the uneven distribution of technology across countries or sectors. Nevertheless, a sectoral approach will make the distribution of productivity changes between internationally competing sectors better known to us, as will be argued in section 4.5.

Third, the new insights of modern growth theory are not entirely applied in growth accounts, whereas growth regression acquire all those results (section 4.4). For instance, the initial conditions of an economy are important in the race to catch up with technological leaders (Dowrick, 1995). The role of government policies trying to enhance productivity growth are not highlighted in the growth accounts. Furthermore, according to Roeger (1995) the inclusion of an indicator for the market structure, the mark up, appears to reduce the traditional residual, which now contains not only TFP growth but also the mark up. Other studies have indicated strong links between exports,

innovation and economic performance of firms, instead of a strong link between innovation and R&D.

To summarize, table 2 lists determinants that play a role in the decomposition of productivity growth. This selection is not exhaustive. One point of attention is that the relative influence of those sources of growth can change in time and place. In the nineteenth century for example, physical capital had a relatively large impact on economic growth, while in the twentieth century human capital accumulation or education became more important. Furthermore, the coefficients in the estimated regressions are sensitive to the choice of the observed countries. If we consider only the OECD countries, then we will draw different conclusions about the importance of some factors than if we also include African countries or South American countries. We will also get other results if we consider sectoral differences.

Table 2. Potential sources of growth

_____
Proximate sources of growth

Accumulation of physical capital
Accumulation of human capital and crude labour
Technological change or advances in knowledge
Increased openness
Initial conditions
Endowments (natural resources and energy)
Market structure and resource allocation
Economies of scale
Macroeconomic conditions and fluctuations in demand
Measurement errors and non-measurable factors

_____
Ultimate sources of growth

Government policy
Social changes
Institutional and structural changes

_____

4.4 Growth regressions

Cross country and panel studies

Cross country and time series studies can determine the role of explanatory variables like capital, investment and education or test the prediction of the standard neoclassical model that conditional convergence will take place. Until recently most empirical studies did not test endogenous models of technological change (Pack, 1994). In section 4.6 some recent studies are discussed. Cross country regressions estimate growth differentials, while panel studies describe the effects of changes in the characteristics of an economy.

Cross country growth studies based on the Solow models tried to verify the β-convergence hypothesis. Regressions of the growth rate of real per capita income or labour productivity on the initial level of the dependent variable did not confirm this hypothesis. DeLong (1992) argued that the results may be valid for advanced countries today, but not for the richest countries in the nineteenth century (Fagerberg, 1994). Later other variables indicated by endogenous theory and growth accounting studies were taken

into account. Now the growth regressions test the validity of the catch up concept and the conditional convergence hypothesis. Examples of cross country studies are those of Romer (1990), Barro (1991) and Helliwell and Chung (1992). In most regressions four basic variables are incorporated: a catch up variable such as the initial level of real per capita income, investments, population growth and education. Sometimes the latter two variables are not included together.

Table 3 presents some results of cross country regressions. Dowrick and Nguyen (1989) regress the average annual growth rate of real GDP on the catch-up variable Y_{1950} (the log of 1950 per capita GDP), the annual growth rate of population 1950-81 and the average percentage share of gross investment in GDP. The estimation method is OLS and t-statistics are presented in parentheses in table 3.[5] The countries are selected on the basis of their income level in 1950. The data come from the Summers and Heston tables (1984). The population growth rate is used as a proxy for the employment growth. A regression of GDP per capita on Y_{1950} gives a striking result: it shows a positive relationship, so that 63 countries seem to have been diverged since 1950. In the estimation in table 3 a negative correlation exists, conditional on other variables. Although no convergence occurred, there was TFP catch-up for all but the very poor, at a similar rate as in the OECD groups of 24 countries (in another regression). The divergence is caused by the relatively low investment rates in poor countries according to Dowrick and Nguyen. In 1950 to 1973 an acceleration in growth was observed, after 1973 economic growth slowed down. No clear distinction can be made between TFP catch-up and income convergence with the regression in the table. Therefore Dowrick and Nguyen divided the period 1950 to 1981 in subperiods to obtain insight in this problem. Their results are not discussed here and the reader is referred to their article.

The Baumol et al. (1989) regressions introduced education. Table 3 shows that population growth was negatively correlated with output growth. In the Dowrick-Nguyen regression this correlation was positive. The positive effect of education on productivity growth was part of the 'population' variable in this regression. Baumol et al. disentangled the influence of population growth and education level, where population growth becomes counterproductive. Barro (1991) focused on education and divided the labor force in high and low educated people. The human capital proxies are the 1960 primary and secundary school enrollment rates based on UN data. Holding those variables constant (and others, which are less significant), the

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[5] David Romer (1996) pointed out the fact that standard t-statistics are not suited properly, because the estimates of the parameter for the catch-up variable are biased negatively. A better measure would be the Dickey-Fuller unit root test (p. 176-177).

estimated coefficient on 1960 per capita GDP is negative and highly significant. Barro first carried out a regression for a sample of 98 countries, which is restricted to 55 countries in the estimation represented in table 3. Each country had an initial per capita GDP exceeding $1000. Comparing the results of both estimations shows that the coefficient of initial income changes

Table 3. Cross country regression results

	Dow-rick & Nguyen (1989)	Baumol et al. (1989)	Barro (1991)	Man-kiw et al. (1992)	Levine & Renelt (1992)	Wolff (1991)	Verspa-gen (1991)
period	'50-'81	'50-'81	'60-'85	'60-'85	'60-'85	1880-1979	'60-'85
number of observat.	63	57	55	98	86	6	90
R^2	.38	.41	.63	.46	.73	.81	.31
s.e. of the regression	1.06	.30	.0109	.33	NA	.011	NA
dependent variable	real GDP per capit.	real GDP per capit.	real GDP per capit.	GDP per working-age pers.	real GDP per capit.	relative productivity growth	tech-nology gap
between parenthes.	t-statistic	t-statistic	standard error	standard error	standard error	t-statistic	t-statistic
constant		1.041 (4.45)	.0406 (.007)	3.04 (.83)	2.05 (1.12)	-.011 (1.64)	.0149 (4.67)
catch-up variable	-.78 (-3.1)	-2.409 (4.09)	-.0065 (.001)	-.289 (.062)	-.57 (.12)	-.078 (5.00)	-.0294 (5.8)
investment	.114 (4.28)			.524 (.087)	10.15 (2.43)		
K/L-ratio						.395 (3.47)	
population variable	.57 (3.53)	-14.88 (2.14)		-.505 (.288)	-.02 (.19)		
education (primary and secundary) variables		.935 (2.6)	.0211 (.008) .018 (.007)	.233 (.06)	.99 (1.23) 1.07 (.70)		-.0876 (3.21)
innovation indicator							-.0055 (1.62)
government			-.122 (.003)		-6.8 (2.3)		
export indicator					-.03 (.041)		

56

other variables	no	no	yes	no	yes	yes	yes

(from -0.0075 to -0.0065, with standard errors changing from 0.0012 to 0.0010) a little. Barro argued that increases in initial GDP per capita and contemporary increases in human capital per person do not have a strong link with subsequent increases in the dependent variable. But holding all other variables constant, initial GDP per capita and human capital have a robust relationship with growth, respectively.

Barro had also taken other proxies for human capital. Furthermore, government consumption is negatively related to per capita growth. Barro found that high tax rates and other activities of government distort the market, while it does not stimulate growth (and investment) significantly. According to other estimations however, there is little correlation between public investment and growth. As Levine and Renelt (1992) state, "... many indicators of policy, taken individually or in groups, are correlated with growth, but the relationship between growth and any particular indicator ... is typically fragile" (p. 948). Barro estimated the impact of such indicators on growth, but did not find a robust relationship.

The model of Mankiw et al. (1992), which is of a Solow type, was augmented with human capital (see chapter 2). Their study showed that conditional convergence takes place between countries. Barro (1991) drawed the same conclusion. A robust negative relationship between initial GDP per capita and the growth of GDP per capita exists, conditional on other variables. This is however only true if human capital or education is included. Education variables have a robust correlation with growth in GDP per capita (Barro, 1991). Investments and initial income are not linked strongly according to Levine and Renelt (1992).

Levine and Renelt (1992) tested regressions of other scholars on the sensitivity of the estimations of those regressions for small changes in conditioning variables, and they showed that the regressions are very sensitive for the inclusion of these variables. One of the regressions they comment on is that of Barro (1991). He used several variables to test relationships which are predicted in economic theory. But Barro did not use all these variables in one estimation, because one of his restrictions is a maximum number of variables in one equation, namely eight. Levine and Renelt find this assumption a reasonably one, but in Barro's paper the different equations include different variables or groups of variables. Then one does not know which equations are more or less reliable. So Levine and Renelt combine some groupings in one estimation, of which the results are represented in the table. This shows that only investment, initial income and the dummies for different regions or continents are significant.

They conclude that the relationship between macroeconomic variables and long run growth was fragile. Levine and Renelt emphasize that a robust partial correlation does not say anything about the direction of the causality

58

between the variables. "The crucial, though nettlesome, issue of empirically identifying causal channels has not been adequately addressed by the cross-country growth literature" (p. 944). Dowrick (1995) also argues that it is better to try to identify structural relationships between various sources and to estimate the growth equation accordingly. Problems of endogeneity and simultaneous causation are often ignored. The impact of a variable cannot be captured within a single equation framework.

Two other estimations are presented in table 3. Wolff (1991) has estimated a growth regression over a period of 100 years with a pooled cross section. The basic variables investment, population and education are not taken into account. He used only a catch up variable, the relative initial level of productivity, and the capital-labour ratio as inputs, together with country and period dummies. The influence of the initial level is negative, while the capital intensity has a positive influence on productivity growth. The capital-labour ratio appears to be important for a country in the catch up race. The US became the technological leader of the world instead of the UK in 1900 when its capital intensity surpassed that of the UK by three times.

Evans (1995) and Quah (1994) have criticized the use of OLS in growth regressions. Evans states that OLS cannot estimate coefficients consistently, except under highly implausible conditions. Deviations of those conditions can produce large biases. He applied an alternative estimation method to the data on 78 countries over a period from 1964 to 1980, and the results showed that the estimates by this alternative are twice as large in magnitude as the estimated coefficients by OLS. "This result suggests that many of the inferences reached in the empirical growth literature are invalid and may be seriously misleading. In particular, inferences that economies either do not converge or converge slowly toward their unconditional means appear to result from biased estimates", so Evans concludes (p. 1). This has important consequences for the estimation of growth regressions. Verspagen's (1991) results are obtained with a nonlinear method. The education variable has a negative correlation with productivity growth.

The problems of cross country studies are avoided in panel studies by among others Ben-David (1995) and Kuper (1995). Ben-David showed that countries with strong trade links and large trade volumes experience income convergence. The convergence rate is also influenced by the trade volume between the partners. This evidence, in correspondance with the Heckscher-Ohlin theorem, would be a "measure of reassurance to the advocates of free trade" (p. 21). Kuper (1995) shows that relative convergence takes place among countries which move to a world steady state. Those countries have a growth rate higher than the average rate and an income lower than the average level. Countries in Latin America experience relative divergence. The

conclusion is that the gap between Asia and Latin America is widening, while African countries and the OECD states have a stable development.

Limitations of growth regressions

Cross country regression copes with simultaneity problems, multicollinearity and a lack of degrees of freedom. The right hand variables in the regression are jointly determined. Too few exogenous variables exist in cross country data sets to establish causality between the variables under consideration. The independent variables are correlated, so that measurement errors will work through the estimations. The residual can contain information about those correlations. Moving to panel studies, one meets another problem, namely that of business cycles, which will make the variables more volatile. However, to get a full picture of productivity growth and its determinants, cross country regressions and time series could be used next to each other, because growth differentials vary in time and in place.

Historical economists have always emphasized the complexity and richness of the dynamics of technological change. Part of this complexity is the interaction between the variables influencing technological change and, hence, economic growth. Physical and human capital accumulation can influence technological progress by embodying new knowledge in new equipment or bodies, but technological progress can in turn influence capital accumulation by enhancing its efficiency and profitability (see for instance Kremer, 1993). How can we disentangle the different sources of growth in such a way that the decomposition accounts for interaction between them? This interaction problem is more than a measurement problem in growth regressions. It indicates the necessity of modelling by means of a system of simultaneous equations.

Furthermore, growth regressions are very sensitive to data problems like the growth accounts and sensitive to the choice of time and space. The results themselves are volatile. For example, DeLong and Summers (1991) and DeLong (1992) tried to measure the size of the link between growth and machinery investment. They concluded that there is a strong relationship between the variables. Albers et al. (1994) however found that this link is very sensitive to the choice of countries and time periods. Only within homogenous groups some convergence will take place, but then the results may be due to sample selection biases. Moreover, Jorgenson (1995) argues that the aggregate production function is useful in modelling long-run economic growth trends, but its assumptions are inconsistent with empirical evidence since 1973. A sectoral approach would explain the developments better. In section 4.5 the background of the sectoral approach is described. Furthermore, the old standard models are easier to test than the models with R&D. According to Romer (1994) the R&D model must, however, be preferred on theoretical grounds. Finally, more attention must be given to international technological spillovers in future research. International trade or

integration of economies leads to more diffusion and innovation and larger economies of scale (Romer, 1990).

4.5 Global diffusion and sectoral specialization

Investment in knowledge is important for a firm in order to gain a comparative advantage. Intangible investments involve education, R&D, patents, software and marketing or management. Education is embodied in human capital and tied to physical bodies, while disembodied knowledge is reflected in the remaining intangibles. Ideas generated from the latter intangibles are nonrival and partially excludable (see chapter 3). Knowledge spillovers arise from intangible investments, so that increasing returns to scale and imperfect competition can exist. The spillover benefits can be enhanced by investments in physical capital, such as hardware or computers, telecommunication infrastructure and environment (Minne, 1995).

The knowledge that a firm possesses has been obtained by various internal and external means. Internal sources are R&D of the firm itself, non-technical research and experiences in production or learning by doing. Human capital investments will be very important. By diffusion the firm can acquire external knowledge. It can, possibly supported by government, buy patents or licences from abroad and use external services. Interfirm agreements are even more important nowadays. The firm can also procure equipment and intermediates in which new knowledge is embodied. Finally, free exchange of knowledge in informal relationships between researchers will spread knowledge across firms, sectors and nations. The firm must however be able to adopt this knowledge and this is dependent on the social capability of its environment (SER, 1995).

This subdivision can be linked up with the distinction between foreign and domestic knowledge. Domestic research generates new ideas which can be patented and it enhances the adoption of foreign R&D. The capability to adopt is very important for the diffusion and exploitation of knowledge in a profitable way. Foreign knowledge can be acquired directly by licences or learning and indirectly via importing embodied knowledge. Evidence shows that for small countries foreign know-how is very important and that open economies benefit more from productivity enhancing spillovers from abroad than closed economies. International technology spillovers are thus crucial and should earn more attention in studies on growth differences between countries. Coe and Helpman (1993) for example estimate foreign returns on R&D relatively large compared with domestic returns (section 4.6).

Through international spillovers the world economy's knowledge is becoming more and more a general knowledge pool, accessible for many at (nearly) zero cost. The growth of this pool accelerates because the path-dependency of technological progress causes cumulation of ideas which are 'build on the giants' shoulders' (Caballero and Jaffe, 1993). Convergence in scientific knowledge is taking place now. In the past decades a transition from

internationalisation to globalisation took place (OECD, 1992).[6] The globalisation of the world economy is reflected in international trade. This development is caused by different factors, among which two are the most important. Those are deregulation of finance and political developments which enhanced liberalisation of international trade, and technological progress which increases the pressure in global competition. Those developments have various consequences. For instance, international investments become more important than international trade itself. Furthermore, international capital flows have been increased strongly and multinationals have gained economic power which was inconceivable before.

According to Guile and Brooks (1987) the concept of a competitive nation with a particular endowment is less applicable now because of the globalisation. In traditional theories a 'national system of innovation' determines the growth differential with other countries. By now international technological spillovers between countries are so large that little economic advantage can be acquired by applying common technologies. Nevertheless, Porter (OECD, 1992) argues that a national structure remains important for firms, because an economy exists of a mix of connected clusters of firms, of which the specific features reflect the economy's comparative advantage. Empirical studies show that international polarisation takes place, where the relative position of countries in dissaggregated fields is still marked by growing divergence and specialization (Archibugi and Pianta, 1992).

The divergence is caused by the differences in nature and institutions of the national innovation system as well as in the social capability. Comparative advantage has to be obtained by specialization at the sectoral level. Sustained comparative advantage at sectoral level can be acquired from the interaction between the determinants in the environment. Because of the specific features of this environment and the path-dependency of the technological development in a cluster, the innovation system will be difficult to copy by foreigners. The easiest and cheapest way to develop specific technological knowledge is to collaborate within clusters with other firms which possess relevant knowledge and are prepared to share it, because of the large capital investments which are required. The exploitation of economies of scale and scope in one particular field, whatever this field will be, appears to be important to obtain non-zero profits in a market with product differentiation and imperfect competition.

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[6] 'Globalisation' might not be the right term. Various scholars prefer 'regionalisation' or 'mondialisation'. Moreover, the used meaning of 'globalisation' determines where the trend had started. Most people place this start in the beginning of the nineties, but in this literature survey one can see globalisation as the increasing openness of economies with respect to technologies and trade, which has already set in the previous century.

Salter (1960) already emphasized the importance of a sectoral approach: "... in fact, one of the points which the statistical analysis seeks to establish is the extreme variety of growth between industries, and the complexity of the relationships between the level and composition of output. It is important, therefore, that we extend our understanding of these problems, both because they are significant in their own right, and as a step towards a less over-simplified aggregative analysis" (p. 2). Englander and Gurney (1994) argue that industry level data provide information on whether convergence has proceeded unevenly across industries due to regulation or structure. In Appendix B, table B.15 presents some figures about the developments within three major sectors since 1960. The table shows that the growth rates of labour productivity differ significantly among the three sectors in both the Netherlands and the US. Furthermore, the relative increase in sectoral labour productivity with regard to the other two sectors differs between the countries.

Growth theorists argue that the shift of employment between sectors with different productivities is one of the main factors behind productivity growth. Marshall (1920) already predicted clustering to enhance efficiency in production. According to Krugman (1991) chance plays a large role in the development of such clusters. Which location and technology will be used is the consequence of coincidence and not of taste, technology development or factor endowments. An example is Silicon Valley in the US. Such core industries will, however, form the spearheads in international competition. Kuznets (1981) emphasises the sectoral or structural change in the composition of among others trade and demand variables. According to Mansfield (1968) a change in technology can lead to displacement of workers; hence income and substitution effects will emerge. However, clustering of firms will follow and in the longer run the consequence of the shift can be positive through acquisition of a comparative advantage.

Inter- and intrasectoral differences reflect the complexity of economic patterns. Those differences are caused by the coexistence of different technology systems and by the uneven rates of diffusion and exploitation of technologies in different sectors. According to OECD (1992) inter-industry spillovers are more important than intra-industry spillovers. The productivity of firms depends more on innovations elsewhere than the own innovations. Table 3.5 in Archibugi and Pianta (1992) shows this trend very clearly. Industries with similar technology systems experience larger spillovers than those which are not close with regard to technology. Industries are also unequally affected by spillovers. Industries with relatively high R&D shares show a positive relationship between their own R&D and rival innovations. Own research enhances the capability to adopt ideas from abroad. If the firms only purchase innovations, this has less impact on economic efficiency.

The sectoral approach has already been used by various scholars. For instance, at the University of Groningen, the International Comparisons on Output and Productivity (ICOP) project is striving for comparable industry level accounts complementary to the accounts of the International Comparisons Project (ICP), which is carried out by among others Summers and Heston (1984). The ICP approach compares expenditure prices, while the ICOP estimates are based on producer prices. The ICOP accounts, developed by among others Maddison and Van Ark (1994) involve real output changes (in comparative levels) in agriculture, mining, manufacturing and services. For a comparison between countries, appropriate purchasing power parities are used to convert national estimates into a common numeraire. The ICOP comparisons have been mainly bilateral until now, because most attention of the project researchers is directed to international technology diffusion and the process of catch up with the leading countries by followers. An example of sectoral growth accounting with respect to structural change is the paper of Van Ark (1994). One conclusion drawn in this article is that intrasectoral changes in productivity are the major factor in explaining productivity growth at the aggregate level in post war Europe. The structural changes are narrowly defined as shifts in employment between high and low productivity sectors. Kuznets' definition of structural change is broader and includes also changes in trade and demand patterns in different sectors. In section 4.6, spillover studies, originating from both empirical and theoretical side or combining them, are discussed. They also applied firm or industry level data.

4.6 Technological spillovers

This section discusses various studies which apply data on R&D, patents and licenses. Schmookler (1966) and Mansfield (1968) were one of the first scholars who saw the advantages of a microeconomic approach which should endogenize as much of technological change as was possible. Griliches (1994) applied their ideas and measured technological indicators of R&D efforts, patenting and licenses. Minne (1995) and others also measured foreign and domestic R&D. Growth theorists made use of the efforts of these studies. Among others Lichtenberg (1992), Wolff and Nadiri (1993) and Jaffe et al. (1993) estimated the magnitude of knowledge spillovers and returns on R&D efforts, sometimes distinguishing foreign and domestic returns. Caballero and Jaffe (1993), Coe and Helpman (1993) and various others constructed models with endogenized technology, founded on the most recent growth theories of among others Aghion and Howitt (1992, 1996) which also apply ideas of historically oriented economists. They tried to verify the Schumpeterian models with help of data on technology.

66

R&D and patent data

The Schmookler and Mansfield studies tried to quantify relationships between technology data and economic growth at industry level. A sectoral viewpoint can yield new insights in economic relationships and structures, as is discussed in section 4.5. Schmookler's (1966) goal was to explain variations in invention an space and over time. He used patents as a proxy for inventions. This was justified as long as one beared in mind that not all inventions are patented, that some inventions are not measured and that there are differences in quality of inventions. Unfortunately, he lacked independent measures of inventions: "...in most instances the choice is not between patent statistics and better data, but between patent statistics and no data" (p. 198). Patent statistics are used as an index, so that only large differences appear to be significant. Case studies are more accepted, but these studies have their own problems.

Schmookler found a high correlation between industrial spending on R&D in 1953 and patent applications of the firms which made these expenditures. Furthermore, he found an imperfect correspondence between patent statistics and other forms of knowledge, such as the difference between independent and corporate inventions, empirical and scientific driven inventions, inventions made by individuals and in laboratoria, and full time and part time inventions. Schmookler was convinced that inventions were determined by demand conditions, illustrating this argument with the example of the horseshoe. The S-shaped growth curve of an industry, which is also valid for inventions, reflects demand forces. The saturation phase would be more restrictive than diminishing marginal returns to inventive activity. The relationship between investments and innovations demonstrates that the latter are a result of past decisions on investments and that they in turn generate new investments. Investments are only made if they are profitable or expected to be profitable. On the supply side, within the industries, technologies to produce the desired products are selected out of a pool of possible technologies. Schmookler stated that "the combination of a richer knowledge base underlying the product technologies of some industries and possible shifts in the characteristics desired in inventions thus results in substantial interindustry variation in the patent-sales ratio" (p. 212).

Mansfield (1968) emphasized both demand and supply forces underlying an innovation. A new technology had to be economically and technically attractive, otherwise it would remain a potentiality. The growth rate of total productivity was a function of the R&D-sales ratio, the growth rate of output and the amplitude of cyclical fluctuations. The relationships were, however, not causal, but only tentative correlations. Furthermore,

technological change must be embodied in new equipment to be utilized. Mansfield concluded that the rate of diffusion increased if innovations did not replace very durable equipment and if the industry was growing rapidly. His findings on interindustry differences in productivity terms and in technologies were consistent with the hypothesis that rates of diffusion are higher in less concentrated industries.

Mansfield's measurement problems remained numerous, like for Schmookler (1966) and later researchers like Griliches (1992, 1994). The measurement of total productivity, such as he did, was an indirect method to measure technological change. Moreover, total productivity captured other factors than technological change, as is discussed in chapters 2, 3 and section 4.3. Other measurement problems were the definition of capital and the assumptions underlying the analyses such as the neutrality of technological change and absence of economies of scale. Finally, the extent to which technological change was embodied was difficult to measure.

According to Griliches (1992), three measurement issues arised from the analysis of productivity growth and its sources. First, the relative growth of the sector of private services, government and other public institutions had increased the measurement problem. The products of this sector were not defined well and its productivity was and is still very difficult to measure. The consequence is that a growing part of historical accounts are badly or not measured at all. A second problem is the deflation of variables. Third, how do we measure technological change? Griliches (1994) used data on R&D to indicate the development of technology, not because they are such a good indicator, but because our understanding "is constrained by the extent and quality of the available data" (p. 2).

In Griliches' opinion a part of the difficulty to estimate the impact of variables on productivity growth is due to the misinterpretation of data caused by "inadequate attention to how they are produced" (p. 2). Therefore, the observed decline in the patent-R&D ratio was not really due to exhaustion of inventive opportunities, but mainly due to interpretation problems. The economy's structure had changed and the collection of data had not kept pace with it. There was "little professional agreement on what is to be measured and how" (p. 14).

Griliches (1994) argued that the estimations of R&D spillovers affecting productivity growth in various studies like Wolff and Nadiri (1993) showed that they were real, but that their magnitudes were modest and not enough to account for the bulk of the residual. The same was valid for studies which tried to embody technological change in capital accumulation. After analysis of data on R&D, Griliches concluded that there was no real decline in relative expenditures on R&D, but that there was a widening gap between

social and private returns, due to the internationalization of R&D, increased competition and the change in the exchange rates.

Schmookler (1966) had concluded that "we can now predict within comparatively narrow limits the number of inventions that will be made in capital goods fields, and there is reason to suppose that, with further research, a similar statement about invention in consumer goods fields will also prove possible"   (p. 215). Griliches (1994), however, argued that invention and innovation are fundamentally uncertain, so that the emergence of a particular innovation will be unpredictable. A "fully 'endogenous' theory of technological change" (p. 18) is very unlikely. Solow (1994, p. 52) also observed this problem. However, in Griliches' (1994) opinion, future researchers will have to explain the residual better ex post.

Finally, Griliches advocated the expansion of the framework of the analysis of productivity growth and its sources. Disequilibria and the measurement of knowledge and other externalities must be at the centerpoint of attention in such an extension. He argued that modern growth theories are right in emphasizing the role of knowledge externalities, but that they cannot explain the developments in the past two decades, because there is "no reason to believe that they [knowledge externalities] have declined over time" (p. 16). A more fruitful approach would be the development of models of externalities which are "models of interaction between different actors in the economy" (p. 16). An example is that of Jaffe et al. (1993), who examined the citation-patents ratio and scientific literature, but according to Griliches these data are just a small part of the exchanges in informal networks.

Externality studies

Nadiri (1993) explored studies to find evidence on R&D investment, especially the question of diminishing returns on inventive activities, the relationship with productivity and the return on R&D, and the magnitudes of spillovers on firm, industry or country level. Nadiri concluded that one could neither say that there are diminishing returns on innovation nor that there are no diminishing returns, because the used yardsticks of patent numbers and R&D were unadequate and caused measurement problems (see Nadiri, 1993). However, studies often showed that the rates of return to own R&D are high and that there are significant spillover effects from R&D, so that Nadiri supposed that diminishing returns to innovation are less plausible (p. 34). Furthermore, R&D affected the growth rates of output and TFP positively and strongly, although the magnitude of its impact varied in space. Moreover, R&D investments interact with other inputs. The average rates of return on R&D vary among the studies between 20 to 30 per cent at firm level and between 10 to 30 per cent at industry level. Evidence also demonstrated that

since the 1970s TFP growth had slowed down and R&D expenditures decreased.

With respect to R&D spillovers, Nadiri found significant international spillover effects, growing over time. On average, the social rate of return is 50 per cent. Within the OECD, many technology transfers took place, especially via multinationals. Technologies were diffused in various ways: ".. They may take the form of intra- and interindustry relationships, interdependence between public and private sector investment, supplier and purchaser connections, and geographical location, as well as between domestic firms and firms in other countries through international technology market trade and multinational enterprises" (p. 35). Finally, spillovers also induce changes in structures of production and rate of profitability, next to productivity growth. R&D spillovers account for more than half of TFP growth. Nadiri concluded that there is some underinvestment in R&D, although high rates of return are required to compensate for uncertainty surrounding the innovation.

Wolff and Nadiri (1993) studied the relationships between R&D, technological change and intersectoral linkages. They found that R&D embodied in capital stock generated sizeable spillovers among all sectors. Furthermore, suppliers and purchasers in manufacturing experienced close links in their growth rates of TFP. Sectors which were strongly linked also had relatively higher R&D expenditures and higher TFP growth rates. Finally, Wolff and Nadiri concluded that private R&D provided stronger spillover effects than total (embodied) R&D, which included governmental R&D. Lichtenberg (1992) drawed the same conclusion about the difference in returns on governmental and private R&D.

As mentioned above, Griliches (1994) advocated the approach used in Jaffe et al. (1993). The latter observed that various studies were carried out on the relationship between R&D expenditures (own or imported) and productivity growth, but that these studies did not analyse the geographical localization of the knowledge spillovers, while the question was important enough: "...Is there any advantage to nearby firms, or even firms in the same country, or do spillover waft into the ether, available for anyone around the globe to grab?" (p. 577). Krugman (1991) and Marshall (1920) already acknowledged the role of localization (see section 4.5). In the growth literature of the 1980s knowledge was assumed to spill over within a country, but not between countries. Only when Grossman and Helpman (1991) explicitly recognized the importance of international technological spillovers, the interest in localization was renewed. Jaffe et al. (1993) argued that spillovers "leave a paper trail in the form of citations" (p. 595), which is geographically localized. They found significant effects of localization. This localization fades over time, but only slowly. The technological character of the patents cited did not seem to affect the localization process, but Jaffe et al.

thought better measurements would generate new insights. Finally, Jaffe et al. did not find strong evidence of differences in localization around universities and firms. According to the authors, more research on the phenomenon of localization was required.

Endogenous technological change: the first little steps

The convincing power of models developed by among others Romer (1990), Grossman and Helpman (1991), Aghion and Howitt (1992, 1996) and Young (1993a, 1993b), turned more scholars to models with Schumpeterian elements, which incorporate elements like uncertainty and variety of products. The Aghion and Howitt models (1992, 1996) provide good starting points of empirical studies which estimate the impact of innovation on productivity and output growth. Caballero and Jaffe (1993) and Coe and Helpman (1993) also acquired new insights which largely affected the way of thinking of various others. Eaton and Kortum (1995) are another illustration of the new road taken nowadays. They studied the relative role of foreign and domestic sources of innovation, a distinction which is important in a globalizing world. Not only growth theorists were beginning to approach the empirical area, but the empirical scholars themselves also applied ideas used in modern growth models, for instance Crafts (1995b).

Jaffe's et al. (1993) emphasis on the role of international technological spillovers can be retrieved in Coe and Helpman (1993) and Eaton and Kortum (1995). Coe and Helpman proved that the interaction between international trade and foreign R&D generated significant international R&D spillovers among trade partners. Foreign knowledge spills over via learning, organisation and production processes, or indirect by importing embodied technological knowledge. Domestic R&D, however, remains important in that it enhances the effective use of resources and the country's ability to adopt foreign knowledge. The estimates of Coe and Helpman showed that TFP growth was affected by both foreign and domestic R&D, where foreign R&D affects domestic productivity more the more open the economy to international trade or the smaller it is. This result has already been discussed in section 4.5.

Caballero and Jaffe (1993) developed a multisectoral model in the spirit of both Grossman and Helpman (1991) and Aghion and Howitt (1992). The title of their study expresses the ideas they borrowed from early scholars like Schmookler (1966) and Schumpeter (1934). Schmookler's idea of the inventor is that of an agent who used knowledge of the past. In the model of Caballero and Jaffe new knowledge emerged from the existing pool (the giants' shoulders). The Schumpeterian element in the model was reflected in the process of creative destruction, in which innovation is endogenous.

Caballero and Jaffe captured this process by the rate of decline of entrepreneurial profits, which depends positively on "the degree of substitutability between new and old goods and on the pace at which new goods are introduced" (p. 17). Caballero and Jaffe applied R&D, patent and citation data for their estimations of knowledge spillovers.

The results of their estimations indicated a speeding up of the rate of diffusion in this century. The foreign knowledge spillovers "approximately balance the increased rate of knowledge obsolescence that they also create" (p. 69). However, Caballero and Jaffe also predicted a decreased private productivity of research inputs. They were also puzzled with the observation that the patent-R&D ratio had fallen, like Griliches (1994). Caballero and Jaffe argued that if the size of patents increased enough, the idea-R&D ratio did not necessarily fall. They found this difficult to prove for the last decades, although the size of patents had grown since the beginning of this century. Furthermore, Caballero and Jaffe demonstrated that the rate of invention and the growth rate of productivity move closely together. The model can explain some of the slowdown in aggregate productivity and the fall in patent numbers since the 1970s, but the result is sensitive to changes in the assumptions of the model.

Eaton and Kortum (1995) carried on with the research on international spillovers by Lichtenberg (1992), Coe and Helpman (1993) and Caballero and Jaffe (1993) and combined them with ideas expressed by historically oriented economists like Gerschenkron (1962). The estimation results on the capital-output ratio suggested that productivity in manufacturing sectors of industrialized countries (Germany, France, UK, Japan and the US) is affected by the ability to adopt more productive technologies rather than by capital accumulation. Eaton and Kortum developed a model which fitted the post-war developments of manufacturing productivity well. They concluded that after the Second World War countries converged technologically, conditional on their ability to adopt.

Crafts (1995b) took the historical viewpoint of the empirist and drawed lessons for economic history from theoretical modelling, combining them with insights from history. According to Crafts, growth theory had little to offer before the mid-1980s. After that time the new growth models provided a deeper understanding of growth processes and were able to exchange ideas with economic history literature (p. 3). Crafts (1995b), however, did not explored the most recent models of creative destruction and concentrated on models like that of Grossman and Helpman (1991). Crafts encouraged better quantification of institutional variables. He also argued that the role of R&D as opposed to learning, and that of patents and market size as opposed to other determinants of profitability of innovations is exaggerated somewhat in modern growth models, while the emphasis on international

technology transfers is overdue (p. 45). Moreover, Schumpeterian growth models had to take into account the fact that trends in growth rates often change between epochs, as can be seen between the Golden Age and the slowdown period in the past two decades.

Conclusion

The previous chapters have shown that many economists believe that technological progress plays an important role in productivity growth (in Kuznets' opinion this statement is a truism (1965, p. 61)), though it is not the sole determinant. As Denison (1993) wrote: "If one were forced to choose a single growth source as most important in the long run, the choice would have to be advances in knowledge" (p. 58). After the introduction in chapter 1, chapters 2 and 3 displayed the theories of neoclassical economists, whereas in chapter 4 the empirical approaches of various scholars were described.

A co-operation between theoretical and empirical approaches

The theoretical and empirical views should collaborate to benefit from each others results. An advantage for the modern growth theory to look at empirical studies is that the plausibility of endogenous growth theory can be tested with the help of historical growth accounts (Solow, 1994). Until now, most tests of growth theory concern the validity of the Solow type model and its assumptions, such as Mankiw et al. (1992) have done. Endogenous growth theory however has no strong empirical basis yet. A few efforts have been made in this direction by among others Aghion and Howitt (1992). Furthermore, the role of dynamic returns to scale, externalities from R&D, the accumulation of human capital and endogenous innovation have always been crucial in the empirical area. Those elements seem to be taken up by recent growth theory, which has enriched the analysis. Moreover, a look on history would give the theory a broader insight in the richness and dynamics of interactions between technology (and other economic variables) and economic growth. The traditional neoclassical models are too simple in this respect (Pack, 1994). Theoretical niceties, however, must not be overestimated. Kuznets (1965) emphasized that theory has to be considered as just a guide to further study of data and to direct future research (p. 5).

The gains for economic historians and other empirists come from the possibility to formalize their insights in a structural model, which will clear some fuzzy and vague empirical hypotheses. The formal framework will also force them to be consequent in their ideas on technology, which are sometimes badly arranged. Their ideas about catch up, convergence and social capability are still difficult to incorporate in a growth regression. However, the first efforts are made by among others Caballero and Jaffe (1993). Moreover, growth accounting is no theory of growth. The accounts can only describe the relative influence of economic variables on productivity growth. They cannot explain why those particular variables are determining

the growth rates, or which causal relationship exists between the variables and labour productivity growth. The accounts only assume some relationship between variables. Those assumptions are deduced from theory. This can become a problem, if growth accounts are used to test theory. Only theory can explain the causality between observed variables. However, the growth accounts can serve as an complement to growth regressions. They are a first step towards the analysis of the more ultimate causes of growth, although those causes are very difficult to stylize.

The recent developments, from 1990 onward, give reason for some optimism with respect to a collaboration between different views. Why this has not happened systematically yet, may be the consequence of the spirits of the past decades and developments in economic science. Nowadays, economists from both sides acknowledge that endogenous technological change has a crucial role in economic growth and that it has to be seen in a historical context. An example is the article of Eaton and Kortum (1995), as discussed in section 4.6. Solow (1994) wrote: " The best source of empirical material may be historical case studies, but then the test of truth is bound to be fuzzy. The best bet, no doubt, would be collaboration between model-builders and those who use informal methods, to compromise between one side's need for definiteness and the other side's sense of complexity" (p. 52).

Path-dependent technological change in a growth model

From both points of view some key elements are deduced that must be incorporated in an 'integrated' model. On the one hand, modern growth theory, discussed in chapter 3, offers some interesting subjects. Until now, most empirical studies which test growth theory (section 4.4), have only tested the traditional model with exogenous technological change, as described in chapter 2 (Solow, 1994). Now the modern line of research must be taken up and technological progress has to be incorporated in an endogenous model. In order to form an idea of technological developments, data on patents, licenses and R&D are of great value, as appeared from section 4.6. The idea of technological indicators in growth regressions is an appealing one and the companying measurement problems have to be tackled seriously. Recent growth models are more realistic and incorporate Schumpeterian ideas. Furthermore, human and physical capital accumulation and increasing returns to scale must also have a role in a formal model, so that spillovers from technology and learning by doing can be modelled in this way.

On the other hand, three aspects deduced from recent empirical results have to be emphasized in future research. First, a long period has to be considered to catch small changes in variables, such as Kuznets (1965, p. 5) emphasized. Only then the path-dependency of economic development,

emphasized in section 4.2, can be highlighted. Maddison's (1995) figures and that of other growth accountants (section 4.3) show that some variables only change very slowly over time. The supply side of the economy, where the adaptive capacity is adjusted in the long run, will thus determine growth, while the demand side with fluctuations in factors and prices of commodities will be relatively less important. The lagged impact of inventions can be taken into account, together with institutional changes which affect productivity growth. Another aspect that is linked with the long run view, is the notion of epochs in growth, as is sketched in section 1.2. Each period has its own specific features which affect productivity growth and with which a researcher has to work.

Second, international technology spillovers or diffusion appear to be very important (section 4.6), causing growth differences between countries and sectors. Formal theorists like Grossman and Helpman (1994) have already included those spillovers in their models. Next to imperfect competition, increasing returns to scale and incomplete allocation they emphasize the international interdependence of countries. Third, a sectoral approach, discussed in section 4.5, would enrich the analysis of the complex changes in the world economy. Jorgenson's (1995) sectoral approach is also combined with estimations of growth regressions. The role of institutions should also to be taken into account, although this will be very difficult. Some have argued that technology (its change and nature), institutions (the 'network'), and the tension between both forces determine the course of technological development and the trend in productivity growth rates.

76

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Appendix A The Ramsey-Cass-Koopmans model

In this appendix the neoclassical model is placed in an infinite horizon optimizing framework, in which intertemporal choices of consumption are made. This framework is developed by Cass (1965) and Koopmans (1965) and founded on the model of Ramsey (1928).

Consumers maximize their intertemporal utility subject to the accumulation equation and initial conditions, with $c = C/L$ and $k = K/L$:[7]

$$\text{Max } U(0) = {}_0\!\int^{\infty} e^{-(\rho-n)t}[u(c_t)]dt = {}_0\!\int^{\infty} e^{-(\rho-n)t}[(c_t^{1-\sigma}-1)/(1-\sigma)]dt \qquad (A.1)$$

subject to

$$k^{\circ} = f(k) - c - nk - \delta k \qquad \text{and} \qquad k_0 > 0.$$

(A.2)

The instantaneous utility $u(c_t)$ is a CIES function, which warrants a constant elasticity of marginal utility in steady state, so the growth rate of consumption will be constant.[8] The discount rate ρ represents the impatience of current generations to consume now and taking care less of future generations. Population grows with exogenous rate n. Produced goods Y are consumed or invested: $Y=C+I$, with $I = dK/dt - \delta K$, δ being the depreciation rate. If depreciation is zero, this would not affect the outcome of the model fundamentally. In chapter 2, depreciation is assumed to be zero. Because $Y=C+I$, investments are equal to savings. If $k = K/L$, then the resource constraint of k° must be satisfied. The per capita production function $f(k)$ satisfies the Inada conditions. The Cobb Douglas production function is an example of such a production function. Further, for $U(0)$ to be bounded, the term inside the integral must go to zero as t goes to infinity. This implies that the discount rate is larger than n.

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[7] In this case the households produce the good. In a market eco nomy firms pay the factors of production their marginal rate. If these earnings are substituted in an individual budget constraint, the r esulting outcome of such a market model is the same as that of the household economy.

[8] CIES means 'constant intertemporal elasticity of substitution'. This utility function warrants that the elasticity of substitution σ is constant intertemporally. The elasticity is equal to $\sigma = -u'(c)/[u''(c)xc]$, which is the reciprocal of the elasticity of ma rginal utility. From the Euler equation, which runs as $f'(k) = \rho - [(u''(c)xc)/u'(c)]x(c^{\circ}/c)$, follows that to find a steady state in which $f'(k)$ and c°/c are constant, the intertemporal ela sticity of substitution must be co nstant.

To solve the maximization problem, a Hamiltionian is set up. The first order conditions are derived from the Hamiltonian. The Euler equations are used to deduce the condition for consumption growth:

$$\gamma_c = c^\circ/c = \sigma^{-1}(f'(k) - \rho - \delta), \tag{A.3}$$

which can be rewritten as $\rho + \sigma\gamma_c = f'(k) - \delta$. The left hand side is the rate of return to consumption, the right hand side the return on investment. An optimizing individual consumer is indifferent between both returns in equilibrium. If the production function is a Cobb Douglas without technological progress, then $Y = K^\alpha L^\beta$. In the neoclassical model there are constant returns to scale: $\alpha + \beta = 1$. In per capita terms the production function is $y = k^\alpha$. The equations (A.2) and (A.3) become

$$k^\circ = k^\alpha - c - nk - \delta k \tag{A.2}'$$
and
$$\gamma_c = \sigma^{-1}(\alpha k^{-(1-\alpha)} - \rho - \delta).$$
(A.3)'

In steady state the growth rates of capital and consumption are constant. The growth rate of capital-labour ratio is equal to $k^{\alpha-1} - c/k - n - \delta$. Taking logs and derivatives of c/k (after rearranging) we get the result that the growth rates of k and c must be equal to each other. Then they have to be zero, otherwise there will be no steady state. In steady state

$$f'(k) = \rho + \delta. \tag{A.4}$$

With Harrod neutral technological progress, the Cobb-Douglas production function is with constant returns to scale

$$Y = F(K, AL) = K^\alpha AL^{1-\alpha}. \tag{A.5}$$

Defining 'effective labour' as $L_t' = L_0 e^{(n+x)t}$, we have a production function in effective labour units $y_t' = f(k_t')$ with $k_t' = K_t/L_t'$ (as described in chapter 2). The accumulation equation runs as follows:

$$k'^\circ = Ak^\alpha - c' - nk' - \delta k'. \tag{A.2}''$$

Here $u(c_t')$ is defined in effective labour units in the intertemporal utility function. After setting up the Hamiltonian and deriving the first order

conditions the following steady state condition for consumption results (the growth rate of k and c being zero):

$$f'(k') = \rho + \sigma x + \delta. \tag{A.4)'}$$

Appendix B Empirical studies of growth

Table B.1 Development of GDP per capita
(in 1990 International Dollars)

	1820	1870	1900	1913	1950	1973	1992
France	1218	1858	2849	3452	5521	12940	17959
Germany	1112	1913	3134	3833	4281	13152	19351
Netherlands	1561	2640	3533	3950	5850	12763	16898
UK	1756	3263	4593	5032	6847	11992	15738
USA	1287	2457	4096	5307	9573	16607	21558
Japan	704	741	1135	1334	1873	11017	19425

Source: Maddison (1995), table 1.3, p. 23.

Table B.2 Phases of per capita real GDP growth, 1820-1992
(annual average compound growth rates)

	1820-70	1870-1913	1913-50	1950-73	1973-92
France	0.8	1.5	1.1	4.0	1.7
Germany	1.1	1.6	0.3	5.0	2.1
Netherlands	1.1	0.9	1.1	3.4	1.4
UK	1.2	1.0	0.8	2.5	1.4
USA	1.3	1.8	1.6	2.4	1.4
Japan	0.1	1.4	0.9	8.0	3.0

Source: Maddison (1995), table 3.2, p. 62.

Table B.3. Rate of growth of labour productivity, 1870-1992
(annual average compound growth rates of GDP per hour worked)

	1870-1913	1913-50	1950-73	1973-92
France	1.7	1.9	5.1	2.7
Germany	1.9	0.6	6.0	2.7
Netherlands	1.3	1.3	4.8	2.2
UK	1.2	1.6	3.1	2.2
USA	1.9	2.5	2.7	1.1
Japan	1.9	1.9	7.7	3.1

Source: Maddison (1995), table 3.13a, p. 79.

Table B.4 Broadberry (1994a): Manufacturing output per person employed
(UK = 100)

	US/UK	Ge/UK	Jap/UK
1869	203.8		
1875		100.0	
1879	187.8		
1889	195.4	94.7	
1899	194.8	99.0	
1907	190.0	106.4	20.7
1913	212.9	119.0	24.4
1920	222.8		27.0
1925	234.2	95.2	25.1
1929	249.9	104.7	32.2
1935	207.8	*102.0	38.8
1937	*208.3	99.9	39.4
1950	262.6	96.0	19.9
1958	250.0	111.1	35.5
1968	242.6	120.0	72.5
1975	207.5	132.9	102.9
1980	192.8	140.2	133.8
1985	182.3	121.5	140.0
1987	188.8	107.8	137.4
1989	177.0	105.1	*143.1

Source: Broadberry (1994a), table 1, p. 293. The symbol * marks the benchmark year from which the time series are extrapolated. In the original table figures are given in brackets behind the numbers of some of the years. Those figures, now deleted, are actual benchmark comparisons.

Table B.5 Solow (1957): Technological change

	(1) share of property in income	(2) private non-farm GNP p. man hour (1939 $)	(3) employed capital per man hour	(4) technolog. change [Δ(2)/(2) - (1)xΔ(3)/(3)]	(5) technology A(t) [from (4)]
1909	0.335	0.623	2.06	-0.017	1.000
1919	0.354	0.767	2.47	-0.076	1.157
1929	0.332	0.895	3.06	-0.043	1.251
1939	0.347	1.034	2.66	0.050	1.514
1949	0.326	1.275	2.70	--	1.809

Source: Solow (1957), table 1, pp. 406-407. Table B.5 is an abridged version. In table 1 (Solow, 1957), the sign of technological change (column (4)) is often positive, so this abridged version gives a somewhat distorted picture.

Table B.6 Denison (1967): US growth of national income per person
employed, 1950-1962

Sources of growth	Contribution to growth rate in % points	% in distribution of growth rate among sources of growth
National income	2.15	100
Total factor input	0.79	36
Labour	0.22	10
Capital	0.60	27
Land	-0.03	-1
Output per unit of input	1.36	64
Advances of knowledge	0.75	34
Improved allocation resources	0.29	13
Economies of scale	0.36	16
Irregularities in demand	-0.04	
Adjusted growth rates		
National income	2.19	
Output per unit of input	1.40	

Source: Denison (1967), tables 21-1 and 21-2, pp. 298-299. This table is an abridged version of the original table of Denison. The contribution of labour is divided in four categories in the original table: employment (-), hours of work (-0.17, -8%), age-sex composition (-0.10, -5%) and education (0.49, +22%). Capital contributes in four ways to the growth rate: dwellings (0.21, +10%), international assets (0.04, +2%), nonresidential structures and equipment (0.29, +13%) and inventories (0.06, +3%). With respect to 'Advances in knowledge', in growth accounts of countries of North Western Europe an additional factor is given, namely 'changes in lag in application of knowledge, general efficiency, and errors and omissions (reduction in age of capital and other sources)'. Together those factors form the Residual. 'Improved allocation of resources' is divided in three categories: contraction of agricultural inputs (0.25, +11%), contraction of nonagricultural self-employment (0.04, +2%) and reduction of international trade barriers (-). 'Economies of scale' contributes to growth via growth of national market measured in US prices (0.30, +14%) and independent growth of global markets (0.06, +3%). The growth rates of sources expressed in percentages of national income are the adjusted growth rates, corrected for 'demand irregularities'.

Table B.7 Denison (1967): The residual, 1950-1962

	Growth in labour productivity	Residual in %	Growth in output per unit input	Residual in %
France	4.80	33	3.67	41
Germany	5.15	31	4.43	36
Netherlands	3.65	34	2.79	42
UK	1.63	46	2.41	67
US	2.15	34	1.36	55

Source: Denison (1967), tables 21.1, 21.2, 21.9 - 21.14, 21.17, 21.18 (pp. 298-315).

Table B.8 Kendrick (1976): Major components of US growth, 1929-1969
(average annual percentage rates of change)

	1929-69	1929-48	1948-69
Real GNP, adjusted	3.4	2.7	4.0
Real total capital	2.8	2.2	3.5
Tangible	2.4	1.8	3.1
Intangible	3.8	3.2	4.3
Residual	0.6	0.5	0.5

Source: Kendrick (1976), table 5.1, p. 113.

Table B.9 Kendrick (1993): Sources of growth in the US

	1929-69	1929-48	1948-69
Real GNP, adjusted	3.4	2.2	4.0
Human capital, weighted	1.45	1.12	1.79
% of growth	42.6	41.5	44.8
Nonhuman capital, weight.	1.38	1.00	1.67
% of growth	40.6	37.0	41.8
Total capital services	2.83	2.12	3.46
Residual	0.57	0.58	0.54
% of growth	16.8	21.5	13.5

Source: Kendrick (1993), p. 143, supplemented with 'Real GNP, adjusted'.

Table B.10 Maddison (1991): GDP growth in the US, 1913-1987
(annual average compound % contributions to GDP growth)

	1913-50	1950-73	1973-87
GDP	2.79	3.65	2.51
Augmented factor input	1.53	2.54	2.55
Foreign trade effect	0.04	0.07	0.07
Structural effect	0.29	0.12	-0.11
Technology diffusion	0.00	0.00	0.00
Scale	0.08	0.11	0.08
Energy effect	0.00	0.01	-0.18
Natural resources windfall	0.00	0.00	0.00
Total explained	1.94	2.86	2.41
Unexplained residual	0.83	0.77	0.10

Source: Maddison (1991), table 5.19, p.159. The contribution of the factor 'structural effect' in the column of the period 1913-1950 is actually computed over the period 1909-1939.

Table B.11 Maddison (1991): Unexplained percentage of growth, 1913-1987

	1913-50	1950-73	1973-87
France	49	37	29
Germany	13	38	28
Japan	6	14	6
Netherlands	5	18	30
UK	26	25	42
USA	30	13	4
Average	21	24	23

Source: Maddison (1991), table 5.20, p. 160. In this table percentages of growth which are explained are given. In table B.11 the unexplained parts are presented.

Table B.12 Maddison (1995): Growth performance US, 1820-1992
(average annual compound growth rates)

	1820-70	1870-1913	1913-50	1950-73	1973-92	1820-1992
GDP / hour worked	1.10	1.88	2.48	2.74	1.11	1.81
TFP	-0.15	0.33	1.59	1.72	0.18	0.63
Natural resources	1.41	0.01	0.01	0.00	0.00	0.41
Total hours	3.09	2.02	0.35	1.15	1.27	1.77
Nonres. capitalstock	5.46	5.53	2.01	3.27	3.13	4.18

Source: Maddison (1995), table K-2, p. 255.

Table B.13 Abramovitz (1993): Labour productivity growth in the US,
1800-1989   (growth rates in % per year)

	labour productivitygrowth	growth of share of K/L-ratio	Total Factor Productivity growth	share of TFP in growth
David				
1800–1855	0.42	0.22	0.20	0.48
1855–1890	1.06	0.70	0.36	0.34
1890–1927	2.01	0.62	1.40	0.69
Kendrick				
1890–1927	2.00	0.51	1.49	0.74
1927–1966	2.67	0.56	2.14	0.79
1966–1989	1.40	0.62	0.78	0.54

Source: Abramovitz (1993), table 1, p. 223. The figures in the three periods from 1800 to 1927 are estimations of David (revised). The period 1890-1927 is added to provide for overlap with Kendrick's estimates from 1890 to 1989, which are derived by Abramovitz from Kendrick's constructions or based on his data. For details, see Abramovitz (1993).

Table B.14 Development of R&D per person employed
($ in 1985 relative prices)

	1960	1973	1987
France	207	448	761
Germany	179		848
Japan	89	342	757
Netherlands	291	514	687
UK	343	480	650
USA	809	814	1074

Source: Maddison (1991), table 5.15, p. 152.

Table B.15 Sectoral labour productivity growth
(Gross value added per person employed)

	1909-48	1950-73	1973-87
Agriculture/Forestry/Fishery			
Netherlands	NA	6.0	4.4
USA	1.6	5.4	2.4
Industry			
Netherlands	NA	5.6	1.5
USA	1.5	2.2	1.1
Services			
Netherlands	NA	1.8	0.4
USA	1.0	1.4	0.2

Source: Maddison (1991), table 5.13, p. 150.