Why growth rate differences persist

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Chapter 2

Literature survey

2.1 Introduction

The current chapter presents an overview of the economic literature on technology progress, international technology diffusion and productivity growth.[1] This literature has a long history and is quite extensive. The aim of the current chapter is to bring together the insights from different strands in order to show how the issue of international technology diffusion is embedded in the growth literature. The survey shows how the different theoretical and empirical approaches compare to each other. This forms the basis for the research in the next chapters, where the joint use of the different strands clarifies how international technology diffusion affects catching up and convergence.

The chapter starts with reviewing the work of economic historians and empirical scholars who explicitly studied individual cases of technology diffusion and their impact on growth (Section 2.2). These scholars demonstrated that technology diffusion is rather slow, and differs across countries, sectors and time periods. Growth differences can persist over a rather long time, but can also change radically, creating cases of 'leapfrogging' (taking over and falling behind). However, the approach of these empiricists is often descriptive, and does not explicitly describe the causal link between technology diffusion and macro-economic growth. This literature also often fails to translate the micro-economic insights to a macro-economic level.

In the 1950s and the 1960s, some early theoretical macro-economic growth models addressed innovation and human capital (Sections 2.3.1

[1]This chapter is an updated version of Rensman (1996).

and 2.3.2). These models were, in first instance, inspired by some 'stylized facts', but developed further independently from the empirical literature of the time. In this theoretical work, neoclassical and Keynesian doctrines competed with each other (Section 2.3.3). The neoclassical model of Solow became the starting point of empirical analysis for the emerging growth accounting literature (Section 2.3.4). The reduction of the large Solow residual, which was assumed to contain disembodied innovation, was a challenge for the growth accountants.

Unfortunately, these early models got stuck into the limited modeling techniques of that time and did not succeed to endogenize technological development and diffusion. The interest in long run growth modeling waned, all the more in the context of growth deceleration in the 1970s. Only by the 1980s, macro-economists renewed their interest in long run growth modeling and along with this, in its empirical foundations. The mainstream literature has now endogenized technological progress, enabling economists to explain the economic-historical observations of persistent growth differences and leapfrogging (Sections 2.4.1 to 2.4.3). Meanwhile, an alternative strand in the literature, evolutionary growth theory, developed almost independently (Section 2.4.4). The criticism of evolutionary economists of endogenous growth theory forces mainstream economists to pay more explicit attention to divergence, uncertainty, tacit knowledge and institutions. The modern growth theories boosted the building of new data sets and the growth regression literature on the impact of innovation and diffusion (Section 2.4.5).

After discussing these various strands in the growth literature, I shortly summarize how the issue of international technology diffusion is embedded in this literature, and how the different strands can be tied together (Section 2.5).

2.2 Comparative historical analysis of technology and growth

Long before formal growth theories assimilated issues like economies of scale, endogenous innovation and diffusion, economic historians and students of the history of technology dealt with these issues. Historically oriented economists tackled the issue of how and why countries or industries grow.[2] The literature is extensive and does not always show a clear direction of new thinking. Therefore, I do not discuss the literature in a strict chronological order, but focus on the main topics of economic-historical analysis, each with their own major concepts.

Catching up The concept of catching up is central to much of the economic-historical literature on economic growth of Western economies. Basically, it states that a 'follower' country tends to converge on a 'leader' country in terms of the latter's productivity level (Abramovitz, 1991, p.44). A follower experiences a technology gap with the leader, because it initially uses an average technology while the leader is at the technology frontier and exploits 'best practices' with higher productivity. The larger the gap, the larger the potential to catch up will be, as this potential will create incentives to catch up. The concept is strongly linked to the idea of Gerschenkron (1962) on the 'advantages of backwardness'. The gap creates a scope for imitation or absorption of the leader's technology. It does not only concern the replacement of obsolete capital by the best-practice technology. It also provides the opportunity to adopt additional knowledge surrounding the leading technology, such as management practices, educational improvements and institutional innovations (Abramovitz, 1991).

Path dependency However, catching up in productivity is not the same as catching up in technology (Broadberry, 1994a). The former does not necessarily mean that follower countries also increasingly resemble the leader in terms of the actual technology used. The leader's technology may diffuse to the follower, but the follower does not simply imitate. Instead the latter adapts the inherent knowledge to its own 'technology regime', which then progresses on its own 'path'. A technology regime or system is determined by the prevailing technology practices, factor proportions and market conditions.

The Habakkuk debate on the emergence of the US as an economic power in the nineteenth century led to this division between catching up in productivity and catching up in technology. Why and how did the United States catch up with the former economic leader, the United Kingdom? The thesis of Habakkuk (1962) states that because of relative labour scarcity, the nineteenth century American economy devel-

[2] A part of their work is supported by historical growth accounts which are discussed in Section 2.3.4.

oped capital-intensive mass production technologies in agriculture and manufacturing.[3] This capital-intensive technology was superior in productivity levels, and enabled the American economy to forge ahead of the UK in the late nineteenth century.

Temin (1966, 1971) objected against the idea of relative labour scarcity in US manufacturing. Since US interest rates were high at that time, capital was scarce, implying a lower capital intensity in manufacturing than in the UK, given that the two countries had common access to the same technologies. Temins argument became known as the labour scarcity paradox (compared to UK manufacturing, US manufacturing had a lower capital intensity but higher labour productivity).

Other historians responded to the paradox by suggesting that explanations might be found at industry level. First, only a number of industries developed capital intensive technologies, often due to complementarity with natural resources (Ames and Rosenberg, 1968; David, 1975; Cain and Paterson, 1985). Second, James and Skinner (1985) argue that capital substituted for (scarce) skilled labour. Industries which needed skilled labourers developed capital-intensive skilled labour-saving technology. These industries produced only 7% of US manufacturing output in 1850. Therefore the overall capital intensity in US manufacturing was comparatively low. Finally, Broadberry (1997b) argues that American mass production techniques could not be successfully applied at the same time in all industries.

Field (1985) argues that contemporary British visitors to US manufacturing industries used machinery intensity as a measure for capital intensity. But machinery is only a part of the total capital stock, which also consists of non-residential structures. The share of machinery in the capital stock was smaller in the US than in the UK. Total capital stocks constructed by Field reveals that by 1860, the US were less capital intensive than the UK, both in the overall economy and in manufacturing.

Maddison (2001) and O'Rourke and Williamson (2000) argue that a major source of catching up of the US to the UK level is not necessarily only capital accumulation but also international technology diffusion. However, this also raises the question why the early twentieth century UK did not catch up with the US, despite diffusion in the opposite direction.

Finally, David (1975) developed a model of path dependent develop-

[3] This is properly called the Habakkuk-Rothbarth thesis, also giving Rothbarth (1948) some of the credits.

ment, elaborated by Broadberry (1994a). A country initially chooses a technology which fits its factor proportions and market conditions.[4] Over time, subsequent investments bring about a cumulation of experience with this technology, which may even cause increasing returns to scale. The technology becomes increasingly embedded in the economy. As technology progresses, the economy will develop along a 'growth path' with more or less fixed factor proportions. Within boundaries, techniques may be replaced by each other. However, the country will not easily switch to a fundamentally different technology system, as the costs of such a switch will generally be too high.[5] As long as a follower country adjusts the leader's technology to its own technology system so that its productivity can continue to catch up with the leader's productivity, the two systems can coexist.

Technology congruence and social capability Why do countries not succeed to catch up in productivity, or even fall behind? In the search for an answer, Abramovitz' (1991) concepts of technology congruence and social capability come in particularly useful.

Technology congruence is the extent to which a follower country's factor proportions, nature and state of technology, and market conditions fit with the leader's technology characteristics (Abramovitz, 1991, p.45). This determines how easily the leader's technology may flow into the follower's economy and be embedded in production, or how costly it is for the follower to absorb foreign leader technology. Comparative advantage may impose restrictions on such international diffusion of technology.

Social capability (or technology competence) determines the ability to innovate and to absorb technology from elsewhere, and to adopt and adapt it to local circumstances. The literature gives very mixed and broad definitions of this concept. Three key forces are repeatedly mentioned, though. These forces are culture, government policy and institutions.

These factors are among other things the country's level and type of human capital, research institutions, financial institutions, attitudes,

[4]The country does not operate just one technique, but an array of techniques which resemble each other in the proportion of factors of production used, and which are dominant in most sectors of the economy.

[5]If factor proportions and market conditions change fundamentally, switching costs might decrease. For instance, post-war period conditions differ substantially from the late nineteenth century circumstances.

policy and organisation of the economy.[6] Policy as such actually does not provide absorptive capacity, though it may affect this capacity. Culture, reflected in social customs, traditions, norms and religions, is usually considered as quite elusive by economists. It only changes over a very long run, taking centuries (Williamson, 2000). Institutions and organisations may change within less than a century. In contrast to culture, it is possible to reform some institutions and organisations intentionally.

Technology congruence and social capability together determine the potential to catch up in the medium term. Realisation of the potential depends among other things on actual investment decisions of firms and individuals, educational organisations and the current engagement of government in innovation. Technology gap opportunities by themselves are self-limited in nature, as catching up decreases opportunities. However, in the long run, catch up opportunities change because the technology leader progresses. Moreover, technology systems and social capability gradually change, under the influence of actions of the same firms, individuals and organisations. This also changes the potential to catch up for followers.

Finally, the concept of a potential of 'latent knowledge' might explain why a follower country may ultimately succeed to surpass a leader, such as the nineteenth century US did (Abramovitz, 1991, p.43-44). Latent knowledge is frontier knowledge which is still non-existent but which may be developed. Some directions of technological progress may bear a larger potential of latent knowledge than other directions. It may happen that at a certain point of time, the most fruitful directions of technological progress fit well with a country's resource and factor endowments, market size, scale in production and other factors. Then a country may advance rapidly, depending on its scientific, engineering and administrative efforts. Nineteenth century US probably succeeded to reap such a potential of 'latent knowledge' in capital-intensive technology (Abramovitz and David 1973; Chandler, 1990).

These concepts point to a number of elements relevant for international technology diffusion. First, absorption of foreign leading technology ap-

[6]Social capability shows some overlap with the concept of social capital. However, social capital is a kind of asset, which like physical and human capital, can be accumulated, replaced and rented. Social capital is an asset of informal social rights which an agent acquires by investing in his social network. Its accumulation creates trust, norms and networks which improve efficiency through coordinated actions (Putnam, 1993).

pears not to be costless, nor automatic or inevitable (Gerschenkron, 1962; Abramovitz, 1991; Broadberry, 1997b). Second, absorption capacity partially depends on a follower country's own efforts. Free riding on the leader's technology is not possible. This is not only because simple copying of the leader's technology is unproductive for the follower's economy given differences in factor proportions and market conditions. It is also because adapting the leader's technology requires an understanding of the involved knowledge. This understanding is likely to be gained by means of own research efforts or human capital accumulation. Third, technology diffusion is uneven across countries and industries, depending on their technology congruence and capabilities. Fourth, technology diffusion is typically slow. If a country lacks technology congruence or falls short of capability to adopt, diffusion will be a long process. Finally, catching up in technology will not necessarily lead to catching up in productivity. Countries differ in their technology systems and social capability. Absorption of foreign technology implies adjustment of this technology to the local circumstances. The embeddedness of the technology in production will determine its productivity.

Endogenous innovation and diffusion Technology congruence and social capability determine how firms and individuals react to their environment and to international technology spillovers from abroad. Early micro-economic studies on technology diffusion show how costs and benefits of innovation and acquiring new knowledge determine innovation and diffusion.

Griliches (1957) looked at the adoption and diffusion of hybrid corn (a new agricultural 'technology') within and across US regions. He obtained an S-shaped diffusion curve based on a regression with data for US regions. Cross-region differences in the timing of adoption, rate of acceptance (the slope of the curve) and the equilibrium level of acceptance (the ceiling of the curve) are explained by differences in how profitable it is to shift to hybrid corn.

Schmookler (1966) and Mansfield (1968) also found evidence for the S-shaped diffusion curve at industry level. They also found that industries differ in the timing and rate of diffusion. Schmookler (1966) finds a high correlation between industrial spending on R&D and patent applications of the firms which made these expenditures. He stressed that inventions were determined by demand conditions. Saturation weighs more heavily than diminishing marginal returns to inventive activity, because investments are only made if they are profitable or expected to be so. On the supply side, technologies to produce the desired products are just selected out a pool of possible technologies, which differ across industries. Mansfield (1968), in contrast, emphasizes that both supply and demand forces are important. A new technology has to be both technically and economically feasible. He concludes that the rate of diffusion increases if innovations do not replace very durable equipment and if the industry is growing rapidly. This appears to be consistent with the hypothesis that rates of diffusion are higher in industries with more competition.

These early studies point to the restrictions of econometric work and data constraints (Griliches, 1992, 1994). Measurement problems concerning productivity and technology are numerous. For instance, total productivity is used as a proxy for technological change, which is a rather indirect measure. Total productivity captures other factors in addition to technological change, including measurement errors. Direct measures for capital, R&D and patents have their own restrictions. For instance, R&D statistics do not capture many small firms which do not register their innovative effort. Not all inventions are patented, the quality of inventions is not measured, and there are interindustry differences in the propensity to patent. Furthermore, assumptions made in regression analysis on technology and growth are not always realistic, including the neutrality of technological change, the absence of economies of scale, or disembodiment of technological change. Moreover, the regressions assume causality. And without an underlying growth theory, the implications of the micro-economic studies cannot be translated to the macro-economic level.

Shortcomings of the economic-historical literature “In economic history, more so perhaps than in other disciplines, everything is a matter of degree, and there are no absolutes” (Mokyr, 2005, p.75). This statement may capture a major problem of a large part of the economic-historical literature. Causal relationships are often not made explicit or formalized, possibly except for the cliometrics movement. Any supposed relationship often remains fuzzy because various feedback effects are mentioned, which blur the direction of the causation. This literature indeed points to the relative importance of certain forces behind international technology diffusion, such as institutions. It clearly demonstrates the relationship of these forces with economic growth, which are difficult to capture in a formal growth model. However, the economic-historical literature is relatively descriptive compared to formal theory, and does not always force to be explicit about the assumptions, direction and weight in causal relationships.

2.3 Early modeling and empirics

In the 1950s and 1960s, the first theoretical macro-economic growth models emerged which paid attention to technological progress and human capital (Section 2.3.1 and 2.3.2). Of all these models, the neoclassical Solow model with technological progress has been the most influential. Meanwhile, the neoclassical theory has continued to compete with Keynesian theory (Section 2.3.3). But the Solow model has typically become the starting point for the empirical analysis of growth, in particular for the emerging growth accounting literature (Section 2.3.4).

2.3.1 The Solow model with technology

Solow (1956) assumed fully disembodied, exogenous technological progress to explain sustained growth in the neoclassical framework.[7] He described technological progress as labour augmenting, using the simple aggregate production function $Y_t = F(K_t, A_t L_t)$, where output Y depends on technological change A_t, capital K_t and labour L_t.[8] Assuming the production function exhibits constant returns to scale, this can be rewritten as $Y_t/L_t = y_t = F(k_t, A_t)$, where k_t is the capital-labour ratio. In the steady state, growth of y_t is constant, so the average product of capital $y_t/k_t = f(A_t/k_t)$ should be constant (ceteris paribus). Technology A_t increases exponentially at a rate x. To keep the average product of capital constant, k_t should grow at the same rate.[9] That is, the capital-labour ratio is not constant in the long run. When defining the capital per effective unit of labour as $\tilde{k}_t = k_t/A_t = K_t/(A_t L_t)$, output per effective unit of labour can be written as $\tilde{y}_t = y_t/A_t = f(\tilde{k}_t)$. The growth rate of capital per effective unit of labour,assuming depreciation

[7]Properly called the Solow-Swan model, as it is also named after Swan (1956), who independently developed a comparable growth model.

[8]Harrod neutrality implies that relative input shares remain unchanged for a given capital-labour ratio. With Hicks neutrality, where $Y_t = A_t\ F(K_t, L_t)$, the ratio of the marginal products of capital and labour remains constant. In the Cobb-Douglas production function $Y_t = K_t^\alpha L_t^\beta$, Hicks and Harrod neutrality give the same results.

[9]Assuming zero population growth.

and labour growth being zero, runs as

$$\frac{d\tilde{k}_t/dt}{\tilde{k}_t} = \frac{sf(\tilde{k}_t)}{\tilde{k}_t} - x \tag{2.1}$$

where s is the savings rate. In the steady state, where $d\tilde{k}_t/dt = 0$, capital and output per effective unit of labour remains constant, but capital and output per worker (or labour productivity) grow at rate x in the long run. An increase in technology A_t namely raises the marginal product of capital, stimulating investment.

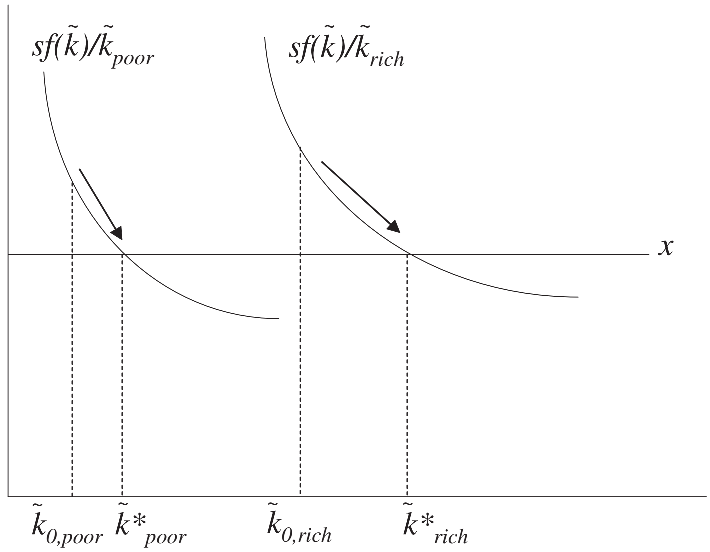
Convergence An important prediction of the Solow model is that a country's per capita growth rate decreases when it approaches the steady state, due to diminishing returns to capital. A country with a low initial $\tilde{k}_t$ will grow faster than a country with a higher initial $\tilde{k}_t$. This phenomenon is named β-convergence. β-convergence thus occurs when the partial correlation between real per capita income growth and its initial level is negative (Barro and Sala-i-Martin, 1995). β-convergence is a necessary but not sufficient condition for σ-convergence, which reflects falling dispersion of real per capital income across countries (Quah, 1993).

There is also a distinction between *absolute* β-convergence and *conditional* β-convergence. Absolute convergence implies that countries will end up with the same steady state value of $\tilde{k}^*$. If, however, countries differ in technology, savings or other parameters in the accumulation equation, then the resulting steady state values of income may differ across these countries. In Figure 2.1, a 'poor' country starts with a lower capital stock $\tilde{k}_0$ than a 'rich' country. The poor country ends up at a lower steady state value $\tilde{k}^*$ than the rich country, because their parameter values differ. In the following text, and in the next chapters of this thesis, the term 'convergence' refers to conditional β-convergence.

An implication of the Solow model for an open economy environment is that if capital is mobile, rich countries will invest in poor countries where capital-labour ratios are low and marginal returns to investments are high.

The Solow residual Solow (1957) used the production function with Harrod neutral technological progress, $Y_t = A_t\, F(K_t, L_t)$, to decompose output growth into the different contributions of capital, labour and

Figure 2.1: Conditional convergence in the Solow model



technology. Defining the relative shares of factors of production as $w_i = (dY_t/di_t)(i_t/Y_t)$ with i being K or L, Solow derived his famous equation

$$\frac{dY_t/dt}{Y_t} = \frac{dA_t/dt}{A_t} + w_K \frac{dK_t/dt}{K_t} + w_L \frac{dL_t/dt}{L_t} \tag{2.2}$$

or, in intensive form, assuming constant returns to scale and thereby implying $w_L = 1 - w_K$,

$$\frac{dy_t/dt}{y_t} = \frac{dA_t/dt}{A_t} + w_K \frac{dk_t/dt}{k_t} \tag{2.3}$$

The term $(dA_t/dt)/A_t$ is the so called Solow residual.[10] More formally, it is Total Factor Productivity (TFP) or Multi Factor Productivity (MFP) growth. Solow labeled the residual 'technical change' for convenience, but at the same time emphasized that it could contain other factors, such as "slowdowns, speed ups, improvements in the education of the

[10] The correct term should be the Abramovitz residual, following Abramovitz' earlier work in 1956.

labor force, and all sort of things", not in the least measurement errors (Solow, 1957, p.402). In an empirical application to American data, Solow found that capital accumulation accounted for less than one fifth of the doubling of output during the period 1909-1949. Total factor productivity growth 'explained' the remainder.

Shortcomings of the Solow model An important shortcoming of the Solow model is that in the steady state, additional savings do not matter for growth of per capita income, and that technological progress does do all the work (assuming zero population growth). This is rather counterintuitive, as capital is an important complementary factor, which also appears from the economic-historical literature. Moreover, the model implicitly states that technology is freely accessible for all countries so that cross-country growth rates of technology are equal in the long run. The model also exhibits a quick and smooth adjustment to the long run growth path. That is, new knowledge spreads immediately. However, transition is actually rather slow, even over half a century as empiricists already showed in the 1960s. In the meantime, economies are continuously confronted with shocks. Furthermore, empirical evidence shows that capital and technology alone cannot explain the magnitude of cross-country growth differences. Other forces seem to claim a role in this neoclassical model, such as human capital.[11]

The major deficiency of the Solow model in the context of technological progress is that it does not explain how disembodied technological progress originates. New technology falls like 'manna from heaven'. Within the neoclassical framework, one could also develop a model with all new technology embodied in capital, such as Solow's (1962) vintage model. But such a model still does not explain the origins of new knowledge in the new vintages.

2.3.2 Human capital models

Human capital theory has traditional roots in the economic literature, developed by among others Schultz (1961) and Becker (1964). Human capital may accumulate in two ways: through learning-by-doing and through education. But it may be not the accumulation, but the stock

[11] See Section 2.4.5 on empirical application by Mankiw et al. (1992) of the Solow model augmented with human capital.

of human capital that determines the capacity of an economy to develop and absorb new technology.

Learning by doing Arrow (1962) ascribed technical change to the effects of experience of workers in production, or learning by doing. Learning is not just a repetition of actions in production, but results in a steadily evolving pool of experience. Experience can be measured by investment because new equipment changes the environment, with new stimuli (Arrow, 1962, p.157). Investment affects production via experience in three ways: capital accumulation, embodiment of technological advances in the latest vintages, and stimulation of innovation. Innovation generates externalities causing a divergence between social and private returns to innovation. The new knowledge is a public good, and the market does not compensate the innovator. The accumulation of knowledge is an unintentional by-product of the accumulation of capital. The state of knowledge A depends on the total capital stock k or experience, the sum of the individual capital stocks of all firms

$$A_t = k_t^{\eta} \tag{2.4}$$

where $0 < \eta < 1$ is a technical parameter. k_t is given for an individual firm. Aggregate production (assuming the individual firms are all representative and aggregating their outputs) is described as (following Sala-i-Martin, 1990, p.18)

$$Y_t = f(K_t, L_t, k_t) = K_t^{\alpha} L_t^{(1-\alpha)} k_t^{\eta} \tag{2.5}$$

This implies constant returns to both K_t and L_t with a given k_t, but increasing returns to all inputs. In intensive form, the production function becomes $y_t = k_t^{\alpha} k_t^{\eta}$. Sala-i-Martin (1990) shows that the case in which $\alpha + \eta < 1$ results in a zero long run growth rate. Hence, increasing returns by themselves are not sufficient to generate persistent growth. Productivity growth might be constant if the growth rate of cumulative investment is constant.

Education Uzawa (1965) developed a two-sector model, with a production sector and an education sector. In this model, a part of the human capital is not used in production but is accumulated in the education sector. The cross-country differences in labour efficiency A and thus growth are due to differences in the growth rate of human capital accumulation. This model, however, implies that education, or the accumulation of human capital, will always have a positive effect on economic growth.

An alternative is to consider the stock of human capital as input. Nelson and Phelps (1966) wrote a short paper on the significance of the stock of human capital for the absorption capacity and technological catching up of countries. In fact, they formalized the catching up concept proposed by Gerschenkron (1962). The rate at which the gap between the technology frontier and the current level of productivity is narrowed depends on the level of human capital. Disembodied knowledge flows from the leader to the followers. But the smaller the distance to the leader, the slower the catching up growth will be. Formally (following Benhabib and Spiegel, 2005)

$$\frac{dA_t/dt}{A_t} = g(H_t) + c(H_t)\left(\frac{\hat{A}_t}{A_t} - 1\right) \tag{2.6}$$

where $(dA_t/dt)/dA_t$ is TFP growth, $g(H_t)$ the component of TFP growth depending on the level of education (or human capital stock) H_t in the country, and $c(H_t)(\hat{A}_t/A_t - 1)$ the rate of technology diffusion from the leader to the country. H_t affects the rate at which the gap $\hat{A}_t/A_t$ is closed. The leader has a higher human capital level. Technology diffusion is exponential, in that countries exhibit positive catching up with the leader. Despite scale affects and differences in human capital levels, all countries will eventually grow at the same rate. Divergent growth paths are not explained within this framework.

2.3.3 Heterodox economics

The Solow model was an alternative growth model to the Keynesian growth model of Harrod (1939) and Domar (1946). In the Harrod-Domar model, sustained positive growth is only achieved by chance, because the parameters which determine equilibrium are given. The natural growth rate (the sum of the population growth rate and the rate of technological progress) deviates nearly always from the warranted growth rate, the rate at which a growth path is guaranteed. The steady state is not necessarily stable, in contrast to the neoclassical result. Moreover, the capital-output ratio K/Y is constant, so that long run output growth depends on investments via savings. In the neoclassical model, this is certainly not the case.

Post-Keynesians like Kaldor (1961) and Robinson (1965) rejected the neoclassical framework with exogenous technological progress and separable production factors. They stated the factors of production are not perfect substitutable, and that the price mechanism does not work perfectly. Kaldor (1961), for instance, assumed that the savings rate depends on the functional income distribution between capital and labour, and that savings themselves are a linear function of technological progress. If the savings rate is fully dependent on capital income, then the K/Y ratio is constant. Then just one production technique exists and the saving rate depends on the returns on capital. In the neoclassical model, the marginal productivity of the factors of production K and L are equal to their factor prices. Therefore, a change in the real wage rate, profit rate or prices lead to a change in the capital intensity K/L, which in turn changes K/Y. In the Keynesian model, only price changes lead to a change in the savings rate.

Meanwhile, the neoclassical scholars extended the standard Solow model. For instance, Samuelson (1958) laid a microfoundation for the macro-economic model. The two-sector model of Meade (1961) is a straightforward extension of the Solow model. One result of Meade's explorations is that the growth path may be indeterminate because the equilibrium is not unique. Models with vintages in capital equipment took into account embodied technological change (Solow, 1962). Theories of the savings behaviour were developed by among others Cass (1965) and Koopmans (1965). Tobin (1965) combined real effects with monetary phenomena. Unfortunately, these models did not succeed to endogenize technological progress.

2.3.4 Growth accounting

Meanwhile, much empirical work on growth was done by growth accountants. This literature originally arose from the policy needs for empirical evidence on the contribution of the accumulation of factors of production to economic growth as measured in national accounts. Kuznets (1965), the NBER in the US, and Tinbergen (1942) in the Netherlands did much pioneering work in constructing growth accounts for several countries. The Solow model became the starting point for decomposing output growth into the contributions of production factors, though most growth accountants applied this framework in a pragmatic way. They aimed to reduce the large Solow residual, which was called the 'measure of our ignorance' (Abramovitz, 1991).

Reducing the Solow residual There are various ways to reduce the Solow residual, which may interact. First, the residual is partially reduced by accounting not only for the quantity of the factors of production, capital and labour, but also for quality improvements. A new vintage may contain new, better technology; newly hired labour may have a higher level of education, skills or experience. Solow (1957) shows that the residual explained 87.5% of American output growth between 1909 and 1949 (Table 2.1). But Abramovitz (1956) argues that accounting for quality improvements in capital might reduce the residual. What appears to be part of the shift in the production function (i.e. disembodied technological change) might actually be accumulation of real capital. During the 1950s, Fabricant (1954), Abramovitz (1956) and Kendrick (1956) are the most influential scholars who measure the changes in quantity and quality of capital and labour.

Table 2.1: Growth accounts of the United States (annual growth rates, between brackets: percentage of output growth explained by variable)

	Solow	Denison	Jorgenson/ Griliches	Kendrick	Maddison
	1957	1967	1972	1976	1991
Period	1909-1949	1950-1962	1950-162	1929-1969	1950-1973
Output	1.71 (100)	2.15 (100)	3.47 (100)	3.40 (100)	3.65 (100)
... Labour hours		-0.17 (-8)	0.37 (11)		0.81 (22)
... Labour quality		0.39 (18)	0.34 (10)		0.35 (10)
Total labour input		0.22 (10)	0.71 (20)	1.45 (43)	1.17 (32)
... Capital stock		0.60 (28)	1.30 (37)		0.98 (27)
... Capital quality			0.41 (12)		0.39 (11)
Total capital input		0.60 (28)	1.38 (49)	1.38 (41)	1.38 (38)
Total capital and labour input	0.21 (12)	0.79 (37)	2.42 (70)	2.83 (83)	2.54 (70)
Total factor productivity	1.50 (88)	1.36 (63)	1.03 (30)	0.57 (17)	1.11 (30)
Unexplained	1.50 (88)	0.76 (34)	1.03 (30)	0.57 (17)	0.77 (21)

Additional sources like foreign trade effects, economies of scale and demand fluctuations account for the difference between total factor productivity and the unexplained residual in the national accounts of Denison (1967) and Maddison (1991). Note: Denison (1967) adjusted total factor input for land (-0.03 per cent per year). Maddisons 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).

Second, the growth residual decreases further by accounting for more 'proximate sources' of growth besides capital, labour and human capital (see Table 2.2).[12] An important step forward, in particular for internationally comparable growth accounts, is made by Denison (1962, 1967). He introduces various new 'sources of growth' for the US and some European countries, such as improved allocation in resources and economies of scale. Still, 34% of output growth in the US between 1950 and 1962 remains to be explained (Table 2.1). According to Denison, advances in knowledge or general efficiency are difficult to measure directly. He argues that the residual contains these efficiency changes and disembodied technological change. Furthermore, it includes changes in the lag in the application of knowledge, and the interaction between the forces contained in the residual. Finally, the residual captures all measurement errors and omissions. Kendrick (1976, 1993) adds R&D to the traditional inputs, and reduces the residual further to 17% of output growth (Table 2.1). Maddison (1995a) also constructs accounts for a large number of countries. His residual accounts for less than 30% of US growth in the Golden Age period. For the period 1973-1987, he explains even 94% of output growth. For European countries, he calculates an explained part of more than two third (in most cases) since 1913.

Table 2.2: Maddison: Potential sources of growth

Proximate sources of growth	Accumulation of physical capital
	Accumulation of human capital and crude labour
	Increase in endowments (natural resources/energy)
	Initial conditions
	Advances in knowledge
	Increased openness
	Market structure and resources allocation
	Economies of scale
	Macroeconomic conditions and demand fluctuations
	Measurement errors and non-measurable factors
Ultimate sources of growth	Government policy
	Social changes
	Institutional and structural change

[12] Maddison's (1991) 'proximate' and 'ultimate' sources of growth resemble the concepts of technology congruence and social capability respectively (see Section 2.2).

Finally, measurement errors may also account for a part of the residual. Jorgenson and Griliches (1967) allege that Denison and other growth accountants faced serious measurement errors, which they aimed to 'eliminate', such as errors in aggregation, investment good prices, relative utilization, and aggregation of capital and labour services (Jorgenson, 1995, Table 3.9, p.84). Hence, following Jorgenson and Griliches, US output growth between 1945 and 1965 appears to be nearly fully explained by input growth, leaving a TFP residual of only 3% of output growth. Following a debate with Denison, Jorgenson and Griliches finally concluded that they had exaggerated the reduction of the the role of total factor productivity. Later calculations by Jorgenson and Griliches (1972) show the residual contributes 30% to output growth between 1950 and 1962, still lower than Denison's outcome (Table 2.1).

Historical and sectoral accounts Growth accounts have also contributed to growth analysis beyond post-war advanced economies at the macro-economic level. For instance, Maddison (2003) composed long run, internationally comparable time series on output, population, labour, capital and exports for a large group of countries across the world, generally from 1820 onwards. Long run, historical growth accounts enable economic-historical researchers to quantitatively assess the contributions of various factors behind growth. Therefore, the link between historical growth accounting and economic-historical literature is quite strong. Main scholars combining these two strands in the literature are, among others, Broadberry (1997b), Crafts (2003a), Abramovitz (1993) and David (1991).

Their calculations reveal that in the nineteenth century, capital accumulation, which in some cases is assumed to include embodied non-neutral technological progress, played a relatively large role in labour productivity growth. In the twentieth century, however, the role of total factor productivity growth increased (Abramovitz, 1993). The historical accounts also show that countries do not always follow converging growth paths or catch up. Rather, before 1870, divergence was more common, and between 1870 and the Second World War only weak convergence was found (Maddison, 2001). In the Golden Age between 1950 and 1973, catching up and convergence was strong within a club of advanced capitalist countries, but again divergence was the rule for the world as a whole.

Another important contribution of the growth accounting literature is the systematic decomposition of aggregate growth and factor inputs to the sectoral level, by among others Jorgenson (1995), Kendrick (1976), Maddison and Van Ark (1994) and Broadberry (1997b). In 1960, Salter already emphasized the importance of a sectoral approach. Macro-economic growth may not unveil heterogeneity across countries in specialization and the accompanying technological progress and diffusion, thereby presenting a too simple picture of how and why countries differ in growth experience. Sectoral shifts (or structural changes) over time are key to macro-economic performance (Van Ark, 1996). Depending on the nature of technological change (capital-deepening or labour-intensive) in the various sectors, sectoral factor intensities and prices might change, shifting inputs from lower- to higher-productivity sectors. International mobility and technology diffusion may mitigate such sectoral shifts, but country-specific effects remain very important too. Studies have shown that in the nineteenth century, high-productivity manufacturing played a dominant role in US growth, whereas services were relatively important in the UK. This suggests different technology regimes and path dependent developments (Broadberry, 1997a). Many post-war Western European economies experienced a shift to the service sector (Crafts and Toniolo, 1996).

Recent developments With the revival of growth theory in the 1980s (see Section 2.4), the issue of accounting explicitly for technological change and diffusion has come more to the forefront. For instance, estimation of the elasticity of substitution between factors of production and its impact on growth allows for increasing returns to scale due to innovation. Allowing for changes over time in the shares of factors of production in output gives room to non-neutral changes in efficiency. Hence, the 'modern' growth regressions provide a link between endogenous growth theory and growth accounts (Jorgenson, 1995). Still, growth accounts help to account for variables used in growth regressions, and can provide evidence of 'overexplanation' of growth, for instance because of interactions between the variables (Maddison, 1995a, p.13). Another recent issue is the measurement of the more elusive 'ultimate sources of growth', such as changes in institutions, policy and society (Maddison, 1991; Crafts and Toniolo, 1996). Growth accounts traditionally estimate proximate sources only.

Limitations of growth accounting The Solovian framework is a good starting point for quantitative growth analysis, but the subsequent refined decomposition depends on the data construction and the underlying assumptions. A main limitation of the growth accounts is that they do not explain the origin of the sources of growth. They do not explain differences in technological progress over time and levels of capital stocks between countries. Moreover, growth accounts do not always assimilate the insights of modern growth theory (see Section 2.4); this requires more laborious and econometric work such as the estimation of elasticity of substitution (Crafts, 2003b). Finally, accounting for technological change and diffusion still does not go far beyond the measurement of (domestic and foreign) R&D and patenting. Particularly for the service sector, this measurement issue is relatively important (Griliches, 1992).

Growth accounts provide much empirical evidence on growth and its 'sources'. The revival of growth theory boosted the data construction by growth accountants. It also put more emphasis on the need too collect data on technology. Data sets were designed, constructed and extended (see, for instance, Maddison, 2003). Growth accountants also refined the methods and procedures for constructing internationally comparable accounts (see, for instance, Inklaar et al., 2005). In turn, these data provide growth theorists the opportunity to test their theories with growth regressions.

2.4 Modern growth theory and empirics

Since the mid-1980s, economists regained interest in the explanation of long run growth and cross-country growth differences. Conditional β-convergence had not taken place and the exogeneity of technological progress in the Solow model was unsatisfactory. Moreover, an influential empirical study based on the Solow model by Mankiw et al. (1992) had shown that convergence does not take place without accounting for differences in human capital. From the late 1980s onwards, new neoclassical growth models were developed which attempted to endogenize technological progress (Section 2.4.1 and 2.4.2). In this framework, international technology diffusion and its costs and effects received more and more attention (Section 2.4.3). Meanwhile, evolutionary growth theory developed along the mainstream theory (Section 2.4.4). Some Post-Keynesians also constructed modern growth models. On the empirical side, much work was done by growth regression studies (Section 2.4.5), stimulated by expanding databases such as the Penn World Tables (Summers and Heston, 1991) and datasets on science and technology statistics from international organisations like the OECD. The increasing availability of data ultimately pushed the empirical testing and subsequent development of the new growth models forward.[13]

2.4.1 Endogenizing growth

Modern endogenous growth theory in the neoclassical tradition emerged from a number of studies which attempted to avoid diminishing returns to capital. They did so by assuming externalities from capital accumulation.

Constant returns to capital The most direct approach to endogenize growth in the neoclassical framework is a model with reproducible capital goods which generate long run growth. This follows the view that non-reproducible factors are not a key variable in the long run growth (Rebelo, 1991, p.518). In the 1980s and early 1990s, some models were developed in which the production function exhibits constant returns to inputs that can be accumulated (CRIA). An example is the AK-model of Rebelo (1991). In this model, the aggregate production function is perceived as $Y_t = A_t K_t$, that is, there are constant returns to capital.[14] The AK-model is a partial return to the Harrod-Domar model where marginal productivity of capital is also constant. In contrast to the Harrod-Domar model, however, labour supply is no bottleneck in the AK-model (Solow, 1994).

The AK-model has not become popular, as the assumption of constant returns to capital was not supported by empirical evidence, and the evolution of technology A remained unexplained. If nonreproducible inputs are necessary for growth, then increasing returns to scale (IRTS) arise.[15] However, a problem with such IRTS models is that no general equilibrium will result, because the increasing returns imply unlimited profits to production. Other models were developed to solve this prob-

[13] Meanwhile economists also developed modern models using the ideas of both the old Ramsey-Cass-Koopmans model and the modern endogenous growth theory; see for instance Heijdra and Van der Ploeg (2002). However, such analyses of savings behaviour and intertemporal choices are outside the scope of this thesis.

[14] In a Cobb-Douglas production function with constant returns to scale ($\alpha + \beta = 1$), the capital share α equals one.

[15] In the Cobb-Douglas case, $\alpha + \beta > 1$.

lem, such as model that incorporate knowledge spillovers (Romer, 1986) and rejection of perfect competition (Romer, 1990).

Knowledge externalities Romer (1986) modeled growth propelled by competition among firms investing in knowledge creation. While individual firms face diminishing returns to investment in knowledge, at the level of the economy as a whole increasing returns to knowledge emerge in production. This externality is due to unintentional Arrovian learning effects in production via the accumulation of capital (see Section 2.3.2). Entrepreneurs take the resulting national pool of knowledge as given and exploit this in production. The difference with the original Arrow (1962) model is that Romer assumed that the externalities from knowledge via capital accumulation compensate for the diminishing returns to capital (Romer, 1986, p.1016). In fact, this means that $\alpha + \eta = 1$ in Equation (2.5), in which case the model turns into an AK-like model. However, in contrast to the AK-model, knowledge accumulates with capital. The accumulators of capital do not earn a return on the accumulated knowledge, and the new knowledge is freely available.

Romer (1986) uses a Dixit-Stiglitz (1977) variant of the production function with product varieties or intermediates x_i in a continuum $[0,A]$. Final output is produced using labour L_t and intermediates x_i:

$$Y_t = L_t^{1-\alpha} \int_0^A x_i^{\alpha} di \tag{2.7}$$

with $0 < \alpha < 1$. In symmetric equilibrium, $x_i = x$ for all types of i. The value of x is the result of equating marginal cost of developing knowledge with (only) capital and marginal revenue from demand, or the marginal product of the intermediates. There is free entry into the intermediate goods sector, so that profits are zero. This determines the equilibrium value of A, the knowledge or technology level. The aggregate production function in the Romer (1986) model is then

$$Y_t = bL_t^{1-\alpha} A_t^{1-\alpha} K_t^{\alpha} \tag{2.8}$$

with coefficient $b > 0$. There are, in principle, IRTS in L_t and K_t. However, if $\alpha = 1$, the model is an AK-like model. Moreover, diminishing returns to capital are still possible (Sala-i-Martin, 1990). Furthermore, the free entry into the intermediate sector does not yield temporary monopoly profit for firms doing research. However, if technology diffusion spreads only gradually, the assumption of perfect competition breaks down.

Human capital externalities Lucas' (1988) model is also an AK-like model, but here K is defined broadly, including both physical and human capital. In contrast to the Romer model, the learning process is intentional. The economy in Lucas' model consists of two sectors, one for production and one for education. In the Arrow model, knowledge was generated in production, whereas in the Lucas model human capital accumulates by means of education in leisure time. Lucas applied Uzawa's (1965) assumption that the existing human capital is the only input in the education sector. The allocation of human capital between production and education is determined by the relative returns to human capital in each sector. Because leisure time is assumed to be constant, human capital changes in a fixed proportion to education in reaction to changes in output, so the returns to human capital accumulation are non-decreasing.

Formally, Lucas (1988) assumes that h is the skill level of a worker, which affects his productivity. In addition to this internal effect of human capital, he postulated an external effect from the average level of skills of the human capital stock in the economy,

$$h_a = \frac{\int_0^\infty hL(h)dh}{\int_0^\infty L(h)dh} \tag{2.9}$$

where $L(h)$ is the number of workers. h_a contributes to the productivity of all factors of production. If workers are all identical, h_a simply equals h. The production function can be written as as

$$Y_t = A_t K_t^\beta H_t^{1-\beta} h_{a,t}^\varphi \tag{2.10}$$

where $H_t = u_t h_t L_t$ is the effective workforce with u the fraction of non-leisure time. Knowledge accumulates in leisure time:

$$dh_t/dt = \phi h_t(1 - u_t) \tag{2.11}$$

with ϕ as the productivity parameter for studying. In this model, education is the driving force behind long run growth. The capital-output ratio will change due to the human capital accumulation. It may increase because more workers will use more sophisticated tools, but it may also decrease because productivity of knowledge acquisition is higher. The transitional dynamics of the model show that there is not always convergence to the steady state.

2.4.2 Endogenizing technological progress

In the models of Romer (1986) and Lucas (1988), growth is endogenous, but technological progress itself is not. Spillovers from knowledge and human capital accumulation help to avoid diminishing returns to the accumulation of capital, but these externalities are only part of the process. Indeed (broad) capital accumulation cannot be infinite in the long run. The most productive capital units will be used up first, and ultimately capital will exhibit diminishing returns. Hence there must be another source for non-zero long run growth, namely technological progress itself.[16] In case technological progress is endogenous, non-decreasing returns in broad capital may emerge in the long run.

An important assumption in the endogenization of innovation is that knowledge has public good characteristics. Knowledge is non-rival, in that the use of a piece of knowledge by one agent does not decrease the opportunity for other agents to use the same piece. Furthermore, knowledge is partially nonexcludable. The use of knowledge by other agents than the innovator may be prevented by patenting the knowledge. However, the knowledge in this patent will ultimately diffuse to other agents, who will be able to built on this knowledge. This is called the nonexcludability property. These public good characteristics of knowledge lead to knowledge spillovers. The research process is characterised by high fixed costs for inventing the first copy of a blueprint, and low marginal costs in subsequent reproduction. Therefore increasing returns and imperfect competition arise.

Increasing product variety Romer (1990) introduces rents from monopoly as an incentive for firms to innovate. He supposes that investments in research are necessary for product development, that is, firms have to pay sunk costs. These costs have to be compensated by monopoly rents. As there is free entry into the intermediate goods sector, there is monopolistic competition but no monopoly or oligopoly. As in the Romer (1986) model, final output is produced with labour and intermediate goods, but in the Romer (1990) model labour can also be used in research. Total labour L_t is the sum of labour input in production $L_{x,t}$ and labour input in research $L_{n,t}$. Putting $L_{n,t}$ into R&D yields designs or licenses for producing new intermediates. The state of

[16]Population growth may also be endogenized (see for instance Kremer, 1993), and other forces such as savings behaviour, but history shows technology seems to play a key role.

knowledge A_t is the current number of intermediate inputs. The sunk cost of producing x units of a given intermediate input is the price P_A for its design. The speed of innovation depends on the aggregate amount of research and the current state of knowledge (or number of designs)

$$dA_t/dt = \delta A_t L_{n,t} \tag{2.12}$$

with δ the productivity or research parameter. This is the key equation in the Romer (1990) model. Researchers can build on the current state of knowledge A_t, that is, there are spillovers from past research. In this sense, knowledge is non-rival. Furthermore, it is excludable as new varieties of intermediates are patented. The price P_A for design is determined by an arbitrage condition on labour input in production and research, with labour being indifferent between both types of activity in equilibrium. The value of the input of intermediates x follows from profit maximization by the local monopolists. The price P_A is the present value of the flow of monopoly profits (discounted at rate r),

$$P_A = \frac{1-\alpha}{\alpha}x \tag{2.13}$$

Deriving the steady state growth rate, Romer (1990) finds that this growth rate is positively affected by research activity δ and the size of the economy L_t, and negatively by the rate of time preference. As firms cannot fully internalize their contribution to product diversity, the knowledge spillovers reduce the incentive of these firms to invest in research. Therefore growth is below the social optimum.

Quality improvements A limitation of the Romer (1990) model is that it does not account for obsolescence of old intermediates x_i, that is, Schumpeterian creative destruction. Aghion and Howitt (1992) develop a model in which horizontal innovation (increasing the product variety) is replaced by vertical innovation (increasing product quality). They model the innovation process as is common in the patent-race literature (Reinganum, 1989). Innovation arises from the invention of a new variety of intermediate good that replaces the old one. The use of the new intermediate raises the technology parameter A_t by a constant factor $\gamma > 1$, the size of innovation. The innovations arrive randomly at the Poisson arrival rate λn, with $\lambda > 0$ the research productivity parameter and n the amount of labour used in research.[17] Successful innovations are monopolized until a new innovation occurs.

There are positive spillovers from the research activity, in that the innovator cannot fully internalize the rents from his or her innovation (the appropriability effect). Moreover, the knowledge pool can be used by other firms for the next innovation (intertemporal spillovers).[18] But there is also a negative spillover, namely the business stealing effect. The replacement of old intermediates by the new ones destroys the surplus of the old goods. The higher the chance or arrival rate of a new innovation is, the shorter the duration of monopoly profits, the smaller the payoff to innovation, and the larger the creative destruction effect.[19] The steady state growth rate increases with the research productivity parameter λ, research labour input n and the size of innovation γ. Because of the business stealing effect, growth may be excessive (above the social optimum), given the size of innovations. If the size of innovations is endogenized, it appears that underinvestment in R&D may also occur.

An important contribution of the Aghion and Howitt theory is the possibility of multiple equilibria, which represents an old historical concept. If growth is slow, firms tend to do little research because they cannot benefit from spillovers of another one's research activity (which is also low). With high growth, research efforts are larger. As for the Romer (1990) model, the basic model of Aghion and Howitt (1992) has its limitations, such as the assumptions on a steady state with balanced growth, and Harrod-neutral technological change. Aghion and Howitt (1998a) also indicate that their endogenous growth models do not fully incorporate the role of institutions.

Furthermore, the endogenous growth theory continued to lack empirical foundation. Jones (1995) argued that the steady rise of R&D intensity since the 1960s has not led to increasing but to constant or decreasing economic growth rates. Aghion and Howitt (1998a, 2005) however, argue that technological progress has become increasingly complex, requiring an ever-increasing R&D to maintain the same innovation rate as before. If population growth increases the size of the economy, the

[17] Assume a Cobb Douglas production function for final goods, $y_t = A_t x_t^{\alpha}$, and the total fixed stock of labour $L_t = x_t + n_t$, with x_t the amount of labour in final goods and n_t the research labour input.

[18] Incumbent innovators do not perform R&D because all other researchers have immediate access to the incumbent technology A.

[19] In the model, another negative effect of research comes from the upward pressure on wages for research labour, which decreases the monopoly profits.

number of imitations also increases, and thereby the allocation of R&D to more research areas.

Another issue is the distinction between incremental and radical innovations, or general purpose technologies (GPTs). Economic historians emphasize the different nature of major and minor innovations. Following up on their 1992 model, Aghion and Howitt (1998b) argue that a model with radical innovations show similar dynamics to a model with incremental innovations. There are three stages in the adoption of a new GPT: the introduction of the GPT, its use in manufacturing and its diffusion to other sectors. Aghion and Howitt (1998b) find that diffusion may be slow and that growth may slow down.

Finally, the issue of international technology diffusion has only recently been examined in more detail (see Section 2.4.3). In the basic Aghion and Howitt (1992) model, two independent economies have a strong tendency to diverge, as each will grow at its own rate determined by its own research effort. If a country X has a higher technology level than country Z, the two countries diverge even with the same size of innovations and research productivity. But with open economies, international technology transfer may lead to β-convergence (Aghion and Howitt, 1998a, p.68-70).

Human capital and bounded externalities In a slightly broader interpretation, the R&D in the models of Romer (1990) and Aghion and Howitt (1992) also include human capital input into the accumulation of knowledge. Skilled labour in the research sector fosters innovation. In addition, the Romer (1990) model built on Arrovian learning or externalities. The models of Stokey (1988), Lucas (1993) and Young (1993a, 1993b) focus more explicitly on the role of human capital in growth. Human capital generates bounded externalities, as learning is tied to physical bodies. Young (1993a, 1993b) built on the Aghion and Howitt (1992) model by combinng the two concepts of innovation and bounded learning by doing. After the introduction of a new technology, the inherent physical limit on its productivity slows down learning, unless a new innovation comes about. This is consistent with the historical evidence on long-lasting technological stagnation (Crafts, 1995). Aghion and Howitt (1992) also do not allow for the possibility that new technologies may complement older ones, which creates rents instead of destroying them.

2.4.3 International technology diffusion

The development of the endogenous growth theory inspired to develop open economy growth models with international technology diffusion. These models sometimes attempted to explain the existence and persistence of convergence clubs of poor, less poor and rich countries (Quah, 1997). International technology diffusion might also be an important source of convergence compared to convergence in capital-labour ratios, as economic history shows (Bernard and Jones, 1996a).

Technology may cross borders in a disembodied form, for instance via personal contacts in research (tacit knowledge transfer), blueprints, ideas, scientific principles, books, patents and so on. Here, a country's own research effort, or its human capital stock or accumulation, is supposed to enhance the adoption of leading-edge technology from abroad, and to overcome barriers to adoption. International technology diffusion may also occur via embodiment in traded goods or through international mobility of factors of production such as capital investments, capital goods, and skilled labour. This is a weaker form of international knowledge diffusion, but trade may not bring only technology embodied in traded intermediates but also increase the probability of international disembodied knowledge spillovers or cross-border learning (Keller, 2004).

Disembodied technology diffusion The first theories with international technology diffusion assumed that it creates a world knowledge pool which is accessible at (nearly) zero cost. Current researchers "stand on the shoulders of giants" (Caballero and Jaffe, 1993). But soon the models started to mention the importance of own R&D providing absorptive capacity. Here I discuss the model of Howitt (2000) which basically incorporates this concept.[20] Nelson and Phelps (1966) stated that human capital creates absorptive capacity. Howitt adopted this idea, but then for R&D, following Cohen and Levinthal (1989) in that R&D has a dual role for the firm: creating innovations and providing the ability to understand knowledge from elsewhere. Hence, an economy needs to invest in (domestic) R&D in order to build capacity to absorb foreign technology.

[20] Other models are developed by, for instance, Eaton and Kortum (1996, 1997, 1999), and Barro and Sala-i-Martin (1997). I discuss the Howitt (2000) model, of which the foundations are developed by Aghion and Howitt (1998a), as the model is the basis for the formal models developed in the current thesis (Chapters 4 and 5).

Howitt (2000) supposes there is a worldwide 'leading-edge technology' level

$$A_t^{\max} \equiv \max A_t^j(i) \mid i \in [0, N_t^j],\ j = i, ..., m \tag{2.14}$$

with countries j and intermediates or sectors i. An innovation in sector i of a country j at time t gives a new generation of that country's ith product, with its productivity equal to $A_t^{\max}$.[21] The country's average productivity parameter A_t grows at

$$dA_t/dt = \lambda n_t(A_t^{\max} - A_t) \tag{2.15}$$

with λn_t the Poisson arrival rate of innovation. If $A_t^{\max}$ would not grow, then the country's average productivity level A_t would converge to $A_t^{\max}$ as long as $\lambda n_t > 0$. However, if the leading edge $A_t^{\max}$ is continuously increasing at a rate g_t, then in the long run, more innovative economies will have higher productivity levels A_t because their intermediates are generally more up to date. Defining the country's distance or gap to the leading edge frontier as $a_t \equiv A_t/A_t^{\max}$, Howitt (2000) derives the convergence mechanism

$$da_t/dt = \lambda n_t(1 - a_t) - a_t g_t \tag{2.16}$$

An increase in n_t or R&D causes productivity growth to increase temporarily, but as the gap $(1 - a_t)$ narrows, innovations will raise average productivity by less and less, slowing down the growth rate of the average. In the long run, countries will converge to the same growth rate but their average productivity level will not.[22]

In the steady state countries will fall into two clubs. One club consists of countries with highly productive R&D, good education and a good intellectual property right protection. Their gap with the world's technology frontier will be constant in the long run, and they will grow at the frontier's growth rate. Countries in the second club have a relatively poor position in the underlying parameters and will not grow in the long run. They will not invest in R&D any more, and their technology gaps with the frontier will increase forever at the rate at which the frontier grows.

[21] Hence, the size of innovation in sector i will depend on how long it has been since the last innovation in that sector. In the Aghion and Howitt (1992) model, this size is a fixed constant, neglecting spillover from other sectors (Howitt, 2000).

[22] Howitt (2000) assumes there is no international trade in goods or factors, and that product variety increases through serendipitous imitation.

Like Howitt (2000), Benhabib and Spiegel (2005) draw upon the ideas of Nelson and Phelps (1966) on absorptive capacity. Benhabib and Spiegel (2005) assume the stock of human capital (or level of education) is a means to speed up technology diffusion, thereby leading to catch up in total factor productivity. They discuss two models, a Nelson-Phelps model in which countries catch up with the leader, and a model in which a country needs a minimum capital stock to catch up. They conclude that the latter model describes the catch up process well.

Krueger and Kumar (2004a) develop a model which distinguishes general education and skill specific, vocational education. General education is costly to obtain but enables workers to operate new production technologies. An economy with relatively more vocational education will grow slower in the long run. Moreover, the faster technology progresses, the larger the gap in growth will be between countries with general and vocational education.

Another recent study on international externalities is Klenow and Rodriguez-Clare (2005). In contrast to Howitt (2000), they start by renumerating empirical observations that countries in the long run do grow at the same rate. They argue that international technology spillovers must therefore be very substantial, despite differences in investment rates. They suppose that modest barriers to technology absorption might account for a large part of differences in total factor productivity. Furthermore, they emphasize that broad capital and technology are not always separable.

Appropriate technology and institutions With increasing interest in the ultimate sources of growth (see, for instance, Van de Klundert, 1997), mainstream economists attempt to formalize some of the economic-historical concepts on resistance or barriers to technology adoption, technology congruence and social capability to adopt. These models also draw upon the old ideas of Atkinson and Stiglitz (1969) on localized technological progress and learning.

Parente and Prescott (1994) discuss the role of barriers to technology adoption, of which the size differs across countries and over time. The larger the barriers, the greater investments or costs to adopt foreign leading technology. Basu and Weil (1998) develop an AK-like model in which technologies are specific to particular combinations of inputs. That is, foreign technologies have to be 'appropriate' to a country's factor proportions if they are to be absorbed. They assume that all technology is freely available and instantly transferred. There are non-linearities between savings and growth, which allows for the possibility of growth miracles (Lucas, 1993). A growth miracle occurs when a small change in savings leads to large changes in growth.

Caselli and Coleman II (2005) model both appropriateness and barriers to adoption. They assume that there is imperfect substitutability between skilled and unskilled labour, and that technology is not neutral in the use of skill. Technologies which use skilled labour more efficiently use unskilled labour less efficiently, and vice versa. The technology frontier is country-specific; richer countries experience lower barriers to adoption and a wider array of potential technologies. Caselli and Coleman II (2005) conclude that the role of barriers to adoption is more important than shows up from a model with factor-neutral technologies. This is because appropriate choice of technology mitigates the impact of differences in factor proportions, as countries suit their technology choice to their factor supplies.

Temple (1998) assumes that the relative efficiency function of a country j is dependent on a catch up effect (measured by the productivity relative to the world maximum level) and an appropriateness effect (represented by the relative capital-labour ratio):[23]

$$\psi_j = \psi\left(\frac{A_j}{\hat{A}}, \frac{(K/L)_j}{\hat{K/L}}\right) \tag{2.17}$$

The relative efficiency is decreasing in the first argument and increasing in the second. This captures the idea that research will be more productive the closer is a country's K/L-ratio to that of the leader. This model allows for multiple equilibria, and it breaks down the dichotomy between input and TFP levels.

Acemoglu et al. (2002) assume that absorption of technology from the world frontier is mainly done by older experienced managers, and that high-skilled (usually younger) managers engage in innovation. The model distinguishes two types of growth strategies by countries. Countries far below the frontier pursue an investment-based strategy, with little selection of high-skill managers, and larger and older firms, larger investments and enduring relationships. Countries closer to the frontier use an innovation-based strategy with better selection of managers.

[23] Temple (1998) notes that the appropriateness effect can also be reflected by other variables than the relative K/L ratio, such as the relative supply of skills, resource endowments and demand conditions.

Backward economies should not switch from investment to innovation too soon, but also should not fall into a trap. (Endogenous) policy and institutions appear to be crucial.

Vandenbussche et al. (2004) state that human capital has a level effect and a composition effect. An increase in the aggregate level of human capital (ceteris paribus) is always growth-enhancing. But conditional on the human capital level, the composition of human capital and the distance to the frontier determine growth. Skilled labour enhances growth to a larger extent when closer to the frontier, provided that innovation is more skill-biased than imitation. This implies that skilled human capital is a source for divergence.

Howitt and Mayer-Foulkes (2005) argue many endogenous growth models cannot explain persistent growth differences during a very long time period. In these models, all countries have the same growth rate in the long run. This contrasts historical evidence on divergence in the nineteenth and twentieth century. Howitt and Mayer-Foulkes (2005) assume that technology diffusion is difficult and skill-intensive, and absorptive capacity is required. They assume that skills are less effective in a technologically lagging country. They also assume that keeping in pace with the progressing technology frontier requires increasingly more skills. Hence a country's stock of effective skills depends on its distance to the frontier. The absorptive capacity of a laggard country may erode.

The model finally assumes the introduction of 'modern R&D' at a certain time t. Before this date, innovation arises from a form of pragmatic creativity, or 'implementation'. Both R&D and implementation are costly and skill intensive, but R&D draws more heavily on scientific knowledge and requires higher levels of skill. A switch from implementation to R&D requires surpassing a threshold skill level that increases with the frontier. In the long run equilibrium, there are three clubs of countries. The first consists of countries with leading technology; in the second club are follower countries with an initially sufficiently high critical threshold level of absorptive capacity to follow the leaders at a constant distance, and the third group falls further behind forever. Howitt and Mayer-Foulkes (2005) dispute that persistence of institutions explains persistent growth differences, as argued by Acemoglu et al. (2005). Institutions do have an effect on research and education, and in turn on absorption capacity.

Trade and mobile factors of production Extension of endogenous growth models with trade offers the possibility to model sector specific flows of technology, though this is still a less developed area of growth research. Countries specialize in trade and absorb the technologies they need for the products of their export sectors (Archibugi and Pianta, 1992). This specialization may lead to divergence in technological progress, and simple copying of foreign technology will become even more difficult. In some cases, specialization leads to structural shifts in the sectoral structure. Eventually, leapfrogging may occur. Comparative advantage becomes endogenous in a framework with trade and mobile factors of production.

A simple leapfrogging model is that of Brezis et al. (1993). A leader exploits a high-productive technology at the moment that a major innovation occurs. Because of its experience with the older high-productive technology, applying the new technology does not pay for the leader at that moment. However, for a follower country, adopting the innovation offers a potential to catch up during a learning process, until the follower ultimately passes the leaders in productivity. The model assumes that all this will happen if the follower country has relatively low wages (that is, learning costs in the adoption of the new technology are lower than in the leader country) and if the old technology has initially a higher productivity in the leader country. This multisector model of Brezis et al. (1993) is simple and appealing, but historically not always justified. For instance, when the US surpassed the leader UK around the turn of the nineteenth century, wages were relatively high in the US. Moreover, a leader country may be sometimes in a better position to learn from a new technology than a follower country. An example of such an advantage may be the recent developments in ICT in the US.

The new trade and geography literature (e.g. Fujita et al., 2001) provides some tools and concepts to model knowlege flows via trade in an endogenous growth framework. Grossman and Helpman (1991) model the impact of diffusion of technology from 'North' to 'South'. North conducts much R&D and creates specialized intermediates which are exported to the South, that invests much less or nothing in R&D. Or North's R&D efforts may create spillovers that leads to new intermediate inputs in South. Eaton and Kortum (2001, 2002) also apply a Schumpeterian model with trade. The modeling of international factor mobility has been less extensively developed. However, Lucas (1988) already mentions the impact of migration of labour.

2.4.4 Alternative growth theory

Evolutionary economics Evolutionary growth theory is developed partially because of discontent with mainstream growth theory. Though both strands of the growth literature find inspiration in Schumpeter's (1942) ideas in attaching a key role to innovation in long run growth, and though recent endogenous growth models pay more attention to phenomena like divergence and appropriate institutions, the two strands differ fundamentally (Fagerberg, 2003; Fagerberg and Verspagen, 2002).

First, endogenous growth theory starts from methodological individualism in which an individual, representative, rational agent acts upon perfect or at least predictable stochastic information. In evolutionary theory, a non-reducionist approach prevails; the micro- and macroeconomic levels interact with each other. The economy evolves through the actions of a population of heterogenous, boundedly rational agents finding their way via trial and error in largely uncertain environment. Firms operate in a national innovation system which consists of different domains of institutions, economy and technology exerting strong mutual influences (Freeman and Soete, 1987; Dosi et al., 1990). The influence of actors (selection environment) and other factors than technology (such as institutions) are important.

Second, in mainstream theory, knowledge is a non-rival and partially excludable good that spreads freely given certain legal arrangements that may limit the availability of public knowledge. Knowledge develops by means of learning by doing and R&D. Evolutionary economists suppose knowledge resides in firms as shared routines reproduced through practice (Nelson and Winter 1982). Knowledge is often tacit and embodied in the routines. Knowledge develops by means of a combination of various forms of learning with radical technological and organizational innovations. An unpredictable and complex environment guides the firms' strategies or capabilities.[24] This leads to two issues (Fagerberg and Verspagen, 2002). First, the distinction between radical and incremental innovations is crucial. Radical innovations disrupt existing structures and interdependencies. Incremental innovations depend on specific historical and institutional context. Second, innovation leads to

[24]Policy implications therefore also differ. Mainstream theory uses market failures as a legitimacy for policy. Evolutionary economists do not believe in the public good characteristics of knowledge and have other policy conclusions: increase variety of activity or actors (e.g. start ups); and increase the economy's capacity to absorb innovations to overcome inertia or resistance to new ways (Fagerberg, 2003).

divergence, imitation or diffusion to convergence.

A final difference is that mainstream theory considers convergence as a smooth transitional process towards the steady state, while evolutionary economics views economic growth as a process of continuous change. Evolutionary growth is a process of strong regularities and qualitative changes driven by firms, governments and other organizations, with a diverse set of motivations, decision rules and capabilities. Technology catching up is not a question of replacing obsolete technologies but a continuous transformation of technological economic and institutional structures. The speed of catching up depends on the economy's ability to transform social, institutional and economic structures (Fagerberg, 1987, 1994, 1995; Verspagen, 1991). One implication is that differences in economic growth are hard to predict (Fagerberg and Verspagen, 2002). Furthermore, in the long run, there needs not be convergence. Finally, structural growth and cyclical variation are not separable.

Post-Keynesian modeling Scott (1989) developed a Post-Keynesian growth model, which also builds on Arrovian learning effects. An important element in his model is that capital and technology investments are not separable. R&D is just one of the many forms of investments. He argues that because the future is uncertain, perceived investment opportunities are based on the present day situation. The rate of return to (knowledge) investment needs not to be depressed at a later date, as "all experience suggests that it does not" (Scott, 1992, p.625). However, elaborated neoclassical endogenous growth models also take physical capital accumulation into account, although it is still considered as a fundamentally different form of investment than R&D, exactly because of the properties of knowledge (nonrivalry and partial nonexcludability).

2.4.5 Growth regressions

The modern empirical growth literature from the 1980s onwards is rather bulky. Growth accountants continued to construct data and the new growth models stimulated further data research. Initially, growth regressions were applied in a rather ad hoc way on a large range of explanatory variables: capital, human capital, macro-economic variables, government, law, policy, social capital and so forth. But the modern growth models increasingly determine the specifications of the growth regressions by providing a structural framework.

With respect to international growth differences and technology diffusion, a number of regression approaches can be renumerated, based on their main focus and the underlying conceptual framework: conditional convergence; evolutionary technology gap models; trade, FDI and geography; and knowledge spillovers via own R&D and human capital.

This modern growth evidence seem to indicate that the following factors are of economic importance: initial conditions (initial per capita income), openness (although there are localization effects), the creation of absorptive capacity via own R&D and human capital, and different types of skill.[25]

Criticism on growth regressions Surveys of the modern evidence, such as Temple (1999), Durlauf and Quah (1999), Brock and Durlauf (2001), Keller (2004) and Durlauf et al. (2005), also discuss the negative aspects of the literature. This criticism concerns the robustness of the underlying cross-country or panel data and proxies for variables, the heterogeneity of the sample of countries, the selection of the explanatory variables, and the difficulties in interpretation of the regression results due to, for instance, simultaneity, endogeneity of the explanatory variables and multicollinearity.

The main problem is that the parameter estimates are unstable (Levine and Renelt, 1992; Durlauf and Quah, 1999). On the other hand, much of the variability in the results can be explained by the variation in the sample, the time period, and the used explanatory variables. There seems to be a number of variables that often turn out to be related to growth (such as initial per capita GDP). Moreover, the coefficients on the other variables might be significant conditional on the earlier mentioned variables. Another problem with regressions is that one or more of the explanatory variables are actually endogenous. Instrumental variables might be applied to control for this endogeneity, at least for certain variables.

Conditional convergence Early regressions aimed at the testing of β-convergence examine what determines cross-country differences and convergence in the rate of growth. These regression equations are often based on a Solovian model. Early regression of the growth of per capita income on the initial per capita income did not provide evidence for β-convergence. Subsequent studies added variables, sometimes inspired

[25] The role of institutions is also tested, although much work remains to be done.

by endogenous growth theory. This provided evidence on conditional convergence. In most regressions, two or more of four variables were included: a catching up variable such as the initial level of real per capita income, investments or capital intensity, population and education (see Table 2.3).

Table 2.3: Cross-country regression results

	Dowrick/ Nguyen 1989	Baumol et al. 1989	Barro 1991	Mankiw et al. 1992	Levine/ Renelt 1992	Wolff 1991	Verspagen 1991
test period	'50-'81	'50-'81	'60-'85	'60-'85	'60-'85	1880-1979	'60-'85
observations	63	57	55	98	86	6	90
R^2	0.38	0.41	0.63	0.46	0.73	0.81	0.31
s.e. regr.	1.06	0.30	0.01	0.33		0.01	
dependent variable	GDP/ capita	GDP/ capita	GDP/ capita	GDP per work.age person	GDP/ capita	rel.prod-uctivity growth	technol. gap
between parentheses	t-stat	t-stat	st.error	st.error	st.error	t-stat	t-stat
constant		1.04 (4.45)	0.04 (0.01)	3.04 (0.83)	20.50 (1.12)	-0.01 (1.64)	0.02 (4.67)
catch up variable	-0.78 (-3.10)	-2.41 (4.09)	-0.01 (0.00)	-0.29 (0.062)	-0.57 (0.12)	-0.08 (5.00)	-0.03 (5.80)
investment	0.11 (4.28)			0.52 (0.09)	10.15 (2.43)		
K/L ratio						0.40 (3.47)	
population	0.57 (3.53)	-14.88 (2.14)		-0.51 (0.29)	-0.02 (0.19)		
education		0.94 (2.60)		0.23 (0.06)			-0.09 (3.21)
primary education			0.02 (0.01)		0.99 (1.23)		
secundary education			0.02 (0.01)		1.07 (0.70)		
innovation							-0.01 (1.62)
more other variables?	no	no	yes	no	yes	yes	yes

Dowrick and Nguyen (1989) find that no overall convergence occurred in the period 1950-1981 in a group of 63 countries. There was some TFP catch up for richer countries. Poorer countries did not catch up because of relatively low investment rates. Baumol et al. (1989) introduce education, which was positively correlated with the growth of per capita GDP, whereas population growth turned out to have a negative coefficient, in contrast to Dowrick and Nguyen (1989). Barro (1991) splits the education variable into 1960 levels of primary and secondary schooling, both of which have a positive correlation with growth.

A famous study is Mankiw et al. (1992). They augment the Solow model with human capital, and show that conditional convergence takes place, as Barro (1991) also had concluded. They find that countries on average converge to their steady states at around 2% per year. The steady state levels vary across countries. Panel data studies find higher rates of convergence (e.g. Islam, 1995). However, panel study outcomes might be wrong, depending on whether they are dynamic panel estimates. When the estimation method is wrong, outcomes may be affected by a small sample bias, and the estimates are inconsistent.

The initial level of per capita GDP (the catching up variable) apparently has a robust negative relationship with growth, conditional on human capital accumulation or education. Levine and Renelt (1992) tested the regressions of other studies on the sensitivity of the estimations. They find sensitivity to be very high. They tested the Barro (1991) regressions again and find that only investment, initial income and the dummies for different regions or continents are significant. Moreover, they emphasize that the coefficients only show a correlation, and do not tell much about the direction of causality. Only within a structural framework or model (probably reduced form), something might be said on causality, provided that econometric problems are not too large, such as multicollinearity and endogeneity of the explanatory variables. Furthermore, the measurement of certain key variables, such as human capital, remains be difficult. Human capital, for instance, ideally includes formal education and on-the-job training. Hence, schooling data are only a proxy for human capital. The evidence on the relation between human capital and growth is rather weak.

Another study by Wolff (1991) covers a very long period (1880-1979). He uses a pooled cross section, without investment, education or population, and includes the relative initial level of productivity and the capital/labour ratio, together with country and period dummies. The coefficient on the initial productivity is negative and that of the capital/labour ratio positive. Capital intensity appears to be important for a country in the catch up process. The US became the world's technological leader when it surpassed the UK around the turn of the nineteenth century to the twentieth century.

Testing the technology gap model The technology gap concept in the evolutionary theory (see Section 2.4.4) is also tested. Seminal studies are Fagerberg (1987, 1988), Verspagen (1991) and Fagerberg and Verspagen (2002). The latter regress the growth rate of GDP on three variables: innovation (measured by patent growth), the potential for diffusion (the level of productivity or GDP per capita) and complementary factors that contribute to the exploitation of this potential, that is absorptive capacity (proxied by investments and industrial structure). They estimate this for a pool of 29 countries and three time periods 1966-1972, 1973-1983, and 1984-1995, including time-slope and time dummies. They conclude from the regression results that the scope for diffusion appears to be lower after 1983 than previously. Innovation is important, particularly in the last time period. A look at the differences between the US and other countries suggests that diffusion is important, even in the most recent period, but that it had become more difficult. Furthermore, innovation efforts have become particularly important in this recent period. This seems to indicate that the US (particularly its services sector) are forging ahead, possibly because of the impact of ICT. One criticism one might have on the technology gap approach is that catching up is measured by means of per capita GDP. This suggests a one-to-one relationship between technology diffusion and catch up in per capita GDP or labour productivity, while this may not be the case. Technology leadership is not the same as labour productivity leadership (see Broadberry, 1994a).

Diffusion via trade, FDI and geography Regression studies on trade-related and embodied international R&D spillovers helped to focus more attention on international knowledge spillovers (see Keller, 2004). Nadiri (1993) explores previous studies on international R&D spillovers and shows that there are significant spillovers effects and that these are growing over time. These spillovers flow via trade and multinational enterprises (Nadiri, 1993, p.35). Wolff and Nadiri (1993) find that R&D embodied in capital stock generates sizeable spillovers between sectors, whereby private R&D generates stronger spillovers than public R&D (see also Lichtenberg, 1992).

Jaffe et al. (1993) study whether spillovers are geographically localized. The advantage of being near other firms or universities might dominate the effect of openness of countries. Jaffe et al. (1993) find, on the basis of patent citations in the US market, that US patents are more often cited by other US patents than by foreign patents. Hence, spillovers are geographically bounded, and this localization effect fades only slowly over time. The localization effect is also found by Branstetter (2001), who uses micro-econometric data on R&D and patents on US and Japanese firms. Keller (2002) estimates spillovers conditional on distance and the country locations relative to each other. He finds that the decay of technology diffusion increases with distance, and that this decay is rather large. With every 1200 kilometers, there is a 50% drop in diffusion. Finally, this localization effect had become smaller over time, probably due to increasing economic integration. The question remains what the localization effect exactly does mean in an economic sense: trade costs, tacit knowledge transfer or other factors (Keller, 2004).

A seminal study on trade-related spillovers is that of Coe and Helpman (1995). They regress the (log of) total factor productivity of a country on domestic and foreign R&D stocks for a sample of 22 countries. The foreign stock is the bilateral import-share weighted R&D stocks of the country's trade partners. The more a country trades with countries with high R&D intensity, the more it is likely to receive high-productive knowledge embodied in intermediate goods imported from those countries. Coe and Helpman (1995) find the average elasticity of domestic TFP with respect to foreign R&D capital is 0.09. The importance of foreign R&D increases the more open the economy is, or the smaller its size. They argue that domestic R&D remains important in that it enhances the effective use of resources and the countrys ability to adopt foreign knowledge. Lichtenberg and Van Pottelsberghe de la Potterie (1998) also apply a trade-weighting system to aggregate foreign R&D capital. They find an average elasticity of domestic TFP with respect to foreign R&D capital of 0.11. Also here the more open a country is, the higher the elasticity. Lichtenberg and Van Pottelsberghe de la Potterie (2001) use FDI-weights instead of import-weights. Keller (1998) shows that the Coe and Helpman (1995) result can also be obtained with randomly created weights. So the evidence on imports as a conduit for knowledge spillovers is not robust. Subsequent studies have attempted to find a solution to this, but more research is needed (Keller, 2004). The empirical literature on FDI-related spillovers is even less conclusive on the robustness of the evidence. FDI by multinationals brings new or better technology to domestic firms. Recent micro-economic studies seem to point to a positive impact from FDI (Keller, 2004).

Eaton and Kortum (2001, 2002) are recent examples of endogenous models on trade-related spillovers. They assume that unit transport costs increase with geographical distance, so that the price of intermediates in remote (or poor) countries is high (that is, productivity is low). They show these effects are present, differences in the relative price of equipment appear to account for 25% of the productivity difference across the sample of 34 countries (Eaton and Kortum, 2001). However, this outcome is not consistent with actual international equipment good prices which are are relatively high in rich countries.

Diffusion via own R&D and human capital A final strand of modern growth empirics focusses on (disembodied) knowledge spillovers via own R&D and human capital. It highlights the role of absorptive capacity. The estimations suggest that absorptive capacity is economically important, and that this is only created by own efforts in R&D and the stock of skilled human capital. Free rider behaviour appears to be not possible.

Benhabib and Spiegel (1994) estimate (using data on a cross section of 78 countries for the period 1965-1985) that absorptive capacity, as measured by an interactive term between the productivity gap and the level of human capital, is statistically significant. More recently, Benhabib and Spiegel (2005) estimate a nonlinear specification of TFP for a cross section of countries between 1960 and 1995. They find that a logistic specification is the right one, that is, countries need a critical stock of human capital to catch up. Otherwise countries will grow slower than the leader. This appears also to be the case for the 22 out of 27 countries, for which the model predicts slower growth because of lack of human capital. Frantzen (2000) also finds in a cross section that education benefits absorptive capacity.

Eaton and Kortum (1996) find that inward technology diffusion increases with the level of human capital. Eaton and Kortum (1999) estimate that productivity growth due to domestic as opposed to foreign R&D is between 11 and 16% in Germany, France and the UK, about 35% for Japan and 60% for the US. Guellec and Van Pottelsberghe de la Potterie (2001) weigh foreign stocks of business R&D by (bilateral) technological proximity (of technological fields of patents). They state that effective absorption of certain technologies depends on own domestic research in those technologies. Their estimates reveal that the average elasticity of TFP with respect to foreign R&D is over 40%. This elasticity is higher the higher the own research intensity of the country under consideration.

Griffith et al. (2004) use panel data for industries in 12 OECD countries in the period 1971-1990. They find R&D to be statistically and economically significant for technology catching up and innovation. R&D plays a role in the convergence of TFP levels within industries across OECD countries, and this result appears to be robust. Human capital also plays a large role in productivity growth, but trade has only a small effect. Griffith et al. (2004) think that the reason why lagging countries do not invest more in R&D is because of inappropriate institutions or policies in these countries. Furthermore, they think interindustry technology diffusion should also be investigated in future economic research.

Rogers (2004) applies alternative proxies for absorptive capacity in a cross country sample over the period 1960-1995. The rate of technological catch up is determined by the size of the technology gap (proxied by the log of initial GDP per capita, the coefficient appears to be always negative and significant) and the level of absorptive capacity. The latter is proxied by the number of students overseas, telecommunications, publications, patent and trade data. These are potential channels of international technology diffusion. Depending on the estimation method, Rogers (2004) finds the study abroad proxy, or the telecommunications and publication proxies to be positive and significant. The proxies of trade openness and imports of equipment appeared to be not significant.

Appropriate technology models are tested by Caselli and Coleman II (2005) and Comin and Hobijn (2004). Caselli and Coleman II (2005) use data for 52 countries in 1988 in a calibration of their model to show that the relationship between the efficiency of skilled labour and income is stronger than that between unskilled labour and income, indicating a relative skill bias. The latter may even decline with income (absolute skill bias). Caselli and Coleman II (2002) find similar results on a time series application on US data from 1963 to 1992. Comin and Hobijn (2004) estimate a model in which differences in productivity levels at sectoral and aggregate level are explained by technologies in use. They use a broad range of technological adoption measures covering 17 technologies for 21 advanced countries over 180 years. They find that international differences in productivity are almost completely determined by the quality of the worst technology in use, rather than by the quality of the newest technology just adopted or by the number of technologies in use. They also find that the TFP component related to the range of technologies in use is highly correlated with overall sectoral TFP differences across countries.

Vandenbussche et al. (2004) also provide empirical results on their model that is built upon the endogenous growth theory. Their panel data cover 19 OECD countries for the period 1960-2000. Previous empirical research had shown no positive relationship between the initial schooling level and subsequent growth in rich countries. Vandenbussche et al. (2004) now show that the composition of human capital is important. Primary and secondary schooling (unskilled labour) and tertiary education (skilled labour) should be separated. In their empirical application it appears that tertiary schooling is causing economic divergence.

2.5 Conclusions

What has the literature to say about international technology diffusion and its impact on economic growth? What questions are still open?

Connecting different strands of theory and empirics Are there gains from a synthesis between different strands of growth theory and empirics? Scholars from various backgrounds have mentioned such gains (see for instance, Solow, 1994; Crafts, 1996; Barro, and Sala-i-Martin, 1995; Romer, 1994; Keller, 2004; Aghion and Howitt, 2005).

Endogenous growth theory seems to be a framework where ideas from all other different strands are brought together. But to economic historians and historical growth accountants, endogenous innovation and diffusion, externality effects from knowledge accumulation, accumulation of human capital and absorptive capacity have always been important concepts. These concepts have been taken up by the modern formal growth models, which has enriched the growth analysis. Unfortunately, the empirical basis of endogenous growth theory is still not very strong, despite the enormous growth of databases and proxies. Regression studies have recently made attempts, as the current literature survey shows.

For instance, it remains difficult to incorporate institutional settings into the models. Crafts (1996) does not believe the role of R&D to be so large. In historical perspective, capital accumulation and learning is more important than is usually thought in mainstream theory, and the influence of policies smaller than thought. Moreover, education, market size and R&D do not tell the whole story. The reaping of latent knowledge in certain directions of technological progress does also play its role. Furthermore, he thinks the role of international technology diffusion is overdone. Local circumstances and international differences in technology congruence act as a barrier to diffusion. Finally, theoretical niceties should not be overestimated. Kuznets (1965, p.5) emphasized that theory has to be considered as just a guide to further study of data construction and to direct future research.

To growth accountants and economic historians, endogenous growth theory offers the possibility of formalization and testing of empirical concepts. Formalization forces economic historians to be clear and explicit in their hypotheses on technology and growth. Growth theory serves a framework of analysis in which causal relationships are established. Growth accounts only quantify the relative contribution of variables to growth, assuming some relationship between these variables and growth. As Kuznets already stated (1965, p.81), "the wider view of the theory of economic growth advocated here forces recognition of the mutability of many partial doctrines that claim allegiance because they glorify, consciously of unconsciously, their conclusions. For this reason, and indispensable prerequisite for work toward such a theory is the fullest freedom in pursuit of testable findings, in continuous reformulation of interrelations in the light of additional evidence, and in the spread of accumulated results to ever-wider circles. In turn, this work might serve to reduce the obstacles stemming from the dogmatism that attaches to theories which claim eternal and universal validity."

The developments since the 1990s give reason for optimism about a collaboration between different strands of theory and empirics. Both acknowledge the key role of technological change in economic growth and that this has to be analyzed within a historical context. Historical case studies might reveal much of the peculiarities of technology, its diffusion and its impact on growth. However, the robustness of cases cannot be tested. "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" (Solow, 1994, p.52).

A growth model with international technology diffusion Which elements should a growth framework with international technology diffusion contain?

First of all, a long run view is essential to gain insight in the growth process and the role of international technology diffusion in this process. Driving forces in economy and society may require a long time for change before they are observed. Moreover, technology diffusion itself may be slow.

Second, disentangling international technology diffusion from local economic and social forces may clarify the mechanism of diffusion and growth. Because convergence and catching up are conditional on economic and social forces, productivity catching up and technology catching up are not synonymous. Technology flows to other countries, but it is often adapted by these countries and sometimes it may not be absorbed after all.

Third, the economic-historical literature points to two fundamental forces in the long run: technology incongruence and social capability. Technology incongruence arises when countries differ in factor proportions and market conditions. The choice of a technology system is usually forced by local circumstances, and its subsequent development is path dependent. Hence geography, sectoral structure and history matters in the explanation of economic growth differences. The second force, social capability, is created by among other things institutions. Particularly the institutions for human capital and research are apparently of crucial importance for capacity to absorb foreign leading technology. These include research, learning by doing, training on-the-job, vocational and general education.

Fourth, modern endogenous growth theory offers the possibility to test the impact of international technology diffusion on economic growth. A historical perspective may add insight to how the technology diffusion mechanism works. Recent growth models implicitly incorporate the concepts of absorptive capacity and appropriate institutions (Section 2.4.3), though this is still in its infancy. The current literature survey also suggests that econometric estimations should be based on a structural growth model in order to get an indication about causality and endogeneity. Misspecifications may blur the results. Finally the construction of data and proxies should not be undervalued.

There is a need for more attention to international technology diffusion and its mechanisms in the explanation of long run economic growth differences. This issue is still open, particularly the empirical foundations of a model with international technology diffusion (Howitt, 2002), and its historical and institutional settings. How does the mechanism of international technology diffusion work? What role do human capital and R&D play? And to what extent does international technology diffusion ultimately affect economic growth differences?

In the next three chapters, I develop a conceptual long run growth framework and two endogenous growth models with international technology diffusion. I test the framework and the models with data and highlight qualitative evidence on technology diffusion from the literature. The results of this research appears to largely confirm the current literature, and contributes to clarify the working of the mechanism of international technology diffusion in an historical perspective.