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Human capital, R&D, and competition in macroeconomic analysis

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Abstract in English

Long-run per capita economic growth is driven by productivity growth. Major determinants of productivity are investments in education and research, and the intensity of competition on product markets. While these ideas have been incorporated into modern growth theories and tested in empirical analyses, they have not yet found their way to applied macroeconomic models used to forecast economic developments. In this paper, we discuss various options to include human capital, R&D, and product market competition in a macroeconomic framework. We also study how policy can affect the decisions to build human capital or to perform research, and how competition policy impacts on macroeconomic outcomes. We finally sketch how these mechanisms can be implemented into the large models used at CPB.

Key words: Human capital, R&D, competition, applied macroeconomic models

Abstract in Dutch

De lange-termijn economische groei per hoofd van de bevolking wordt bepaald door de productiviteitsontwikkeling. Belangrijke determinanten van productiviteit zijn onderwijs en onderzoek, en concurrentie op productmarkten. Hoewel deze ideeën centraal staan in de moderne groeitheorie en empirisch zijn getest, hebben ze nog niet hun weg gevonden naar de toegepaste macromodellen die worden gebruikt bij economische voorspellingen. In dit document bespreken we diverse manieren om menselijk kapitaal, onderzoek en ontwikkeling, en concurrentie op productmarkten in een macro-economisch model in te bouwen. Ook onderzoeken we hoe beleid kan doorwerken in de beslissing om te investeren in menselijk kapitaal of onderzoek uit te voeren, en hoe concurrentiebeleid kan doorwerken in de macro-economie. Tenslotte schetsen we mogelijkheden om deze mechanismen in de CPB-modellen op te nemen.

Steekwoorden: Menselijk kapitaal, onderzoek en ontwikkeling, concurrentie, toegepaste macromodellen

Een uitgebreide Nederlandse samenvatting is beschikbaar via www.cpb.nl.

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Preface

The topic of economic growth is perhaps one of the most fundamental issues in macroeconomics. Important channels to raise living standards are the promotion of human capital formation (say, education), research and development and product market competition. While there is a substantial literature on the determinants of productivity, such mechanisms are usually ignored in applied macroeconomic models because of a lack of quantitative knowledge. This study reviews the literature and sketches options to implement human capital, R&D, and competition in the CPB models.

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This report should be seen as a position paper to explore the macroeconomic impact of productivity-drivers such as human capital, R&D, and product market competition. A lot more work is needed before we have sufficiently reliable quantitative results to use in our macroeconomic models. In parallel projects we already started to experiment with endogenous productivity in CPB models, and these efforts will be continued in future work.

Henk Don, director CPB

Summary

In this paper, we try to bring the modern literature on productivity and the world of macroeconomic modelling in closer proximity. A country's long-run per capita growth rate is driven by productivity growth. Major determinants of productivity are investments in education and research. Also the market structure in which firms are embedded is relevant, both for the decision to adopt an existing technology and to develop new technologies through research and development (R&D) efforts. While these ideas have been incorporated into modern growth theories and tested in empirical analyses, they have not yet found their way to the empirical macroeconomic or macroeconometric models used to analyse economic policy. Briefly, we propose a two-step strategy:

- The first step is to study the macroeconomic effects of human capital, R&D, and competition. This is the topic of Chapter 2.
- The second step is to study the link between policy and human capital, R&D, and competition. This is the topic of Chapter 3.

In Chapter 4, we review if and how human capital, R&D, and market structure are considered in applied macroeconomic models used at CPB and other policy research institutes.

Review of theories on productivity

What is the macroeconomic impact of changes in human capital, R&D, or the intensity of product market competition? Chapter 2 explores the important mechanisms as proposed in the economic literature. Human capital can be introduced as an additional production factor, contributing to equilibrium production levels in a neoclassical growth model and to the balanced growth rate in an endogenous growth framework. Human capital can also play a productive role in terms of the absorption capacity to assimilate new technologies. Growth empirics indicate that an increase in average educational attainment of the population by one year increases long-run per capita output by about 6%. If education is subject to decreasing returns, the impact on per capita output might be smaller in countries with high education levels such as the Netherlands. R&D can be introduced either as a separate production factor, or through its impact on total factor productivity. Empirical studies point out that R&D generates substantial returns, both in terms of innovation and through adoption of existing technologies. Finally, the impact of increased product market competition on macroeconomic performance can operate through two channels: improvements in static and dynamic efficiency. The potential gains from improved dynamic efficiency can be important, as innovation is increased. While increases in human capital, R&D, and product market competition can improve macroeconomic performance, it can take a long time before these benefits arrive, as for instance it takes time to build human capital.

Effects of government policy

How can policy affect the formation of human capital and R&D activity, and what is known about the relationship between competition policy and macroeconomic outcomes? We distinguish between human capital policies aimed at enrolment (a quantity indicator) and educational quality. Examples of enrolment policies are changes in the compulsory schooling age and financial aid to encourage higher education enrolment. Policies designed to improve educational quality include class size reductions and merit pay for teachers. Especially early childhood interventions have been found effective, both in terms of raising average years of education and improving student performance. R&D policies include subsidy programs to encourage private R&D, but also instruments to make better use of the existing knowledge base. Estimates on the effectiveness of R&D subsidies show substantial variation, and outcomes will depend on (country-) specific institutional arrangements. Finally, the literature on the macroeconomic impact of competition policy generally finds positive effects in terms of GDP or total factor productivity. Unfortunately, convincing policy evaluation studies are scarce, and little is known about the causal impact of these instruments. In the design of new policy, one could take into account the possibilities for a proper evaluation based on natural or controlled experiments. This is helpful to evaluate the causal impact of policy some time after its implementation (so-called ex post policy evaluation). Such a strategy should enable evidence-based policy design in the future.

Productivity in applied macroeconomic models

How do existing applied macroeconomic models deal with productivity and the role of human capital, R&D, and product market competition? The CPB models MIMIC and WORLDSCAN distinguish workers of different skill levels, and MIMIC also specifies a training sector for employees. Exogenous R&D expenditures and the role of international R&D spillovers are considered in the WORLDSCAN model. The intensity of product market competition in terms of exogenous mark-up pricing can be studied in JADE, SAFE, MIMIC, and WORLDSCAN (in which differentiated varieties of consumer goods are specified). ATHENA has exogenous mark-ups, but also allows for entry and exit of firms. Models used at other policy institutions tend to ignore these issues. Notable exceptions are the LINKAGE model of the Worldbank (where workers can be skilled or unskilled, and where mark-up pricing can be studied in combination with entry/exit of firms), and the MULTIMOD model of the IMF (which has been extended with R&D and R&D spillovers).

1 Introduction

The topic of economic growth is perhaps one of the most fundamental issues in macroeconomics. Economic growth directly affects the living standards of the population, and thereby the welfare level. The search for the fundamental determinants behind the growth process is an ongoing research theme. Production can be expanded through investments in factor inputs (such as physical capital) and through employment growth, but also by improvements in productivity. By working in a smarter way, more can be produced with given factor inputs. Also, new products and services can generate a higher value added for their users. Economists agree that the long-run growth potential in per capita income is determined by advances in productivity. A theory on economic growth is therefore a theory on productivity growth. There are, broadly speaking, two dominant growth theories: neoclassical growth models and endogenous growth models. Neoclassical growth models assume that productivity growth is exogenous, arising as 'manna from heaven'. This view is challenged since the birth of new or endogenous growth theory in the early 1980s. According to new growth theory, long-run economic growth is affected by deliberate economic behaviour and human actions such as innovation and education. The debate whether long-run economic growth patterns can best be explained from traditional or endogenous growth theory is far from settled, but the notion that education and innovation can contribute to economic growth, at least during a certain time span, is now widely accepted among economists.

Most macroeconomic models used at CPB assume exogenous productivity growth, in line with neoclassical growth theory.[1] Potential productivity benefits associated with investments in education and innovation are not taken into account. This feature has led to criticism. For example, in the run-up to elections, political parties submit their election platforms to CPB for an evaluation of the economic impact of the proposed policy changes. In the CPB-models, the assumption of exogenous productivity growth implies that additional expenditures on, say, education do not yield long-run productivity improvements and are therefore potentially 'undervalued'. In fact, the returns to education are implicitly set at zero. However, research on the benefits of education consistently produces substantial returns to education. Similar examples can be given for expenditures on R&D. However, while the benefits from schooling and R&D can be large, it typically takes a long time before these gains arrive, and also the costs associated with the investments need to be taken into account.

In this paper we discuss various mechanisms to endogenise productivity, and to study the effects of policy. Particular attention is given to the role of education, R&D and market structure for the macroeconomic performance. The following steps need to be taken:

[1] More precisely, changes in total factor productivity or labour-augmenting technological progress are exogenous in most CPB models (except WORLDSCAN). Macroeconomic labour productivity depends on the capital-labour ratio (and possibly some other factors).

- We need to introduce a link between inputs such as knowledge, R&D and human capital and the output variable of interest (e.g. economic growth);
- We need to evaluate the impact of policy on the decisions to invest in education and R&D, and on the market structure.

The proposed research strategy is as follows. In Chapter 2 we look at the literature on productivity. In particular, we review studies on the connection between (i) human capital and economic growth, (ii) R&D and economic growth, and (iii) market structure and economic growth. Chapter 3 deals with the effects of policy on education, R&D, and market structure. In Chapter 4 we recapitulate how productivity is incorporated in the CPB models, and in important macroeconomic models used throughout the world. Some final thoughts are presented in the Epilogue.

2 Review of theories on productivity

What is the macroeconomic impact of changes in human capital, R&D, or the intensity of product market competition? Human capital can be introduced as an additional production factor, contributing to equilibrium production levels in a neoclassical growth model and to the balanced growth rate in an endogenous growth framework. Human capital can also play a productive role in terms of the absorption capacity to assimilate new technologies. Growth empirics indicate that an increase in average educational attainment of the labour force by one year increases long-run per capita output by about 6%. R&D can be introduced either as a separate production factor, or through its impact on total factor productivity. Empirical studies point out that R&D generates substantial returns, both in terms of innovation and through adoption of existing technologies. Finally, the impact of increased product market competition on macroeconomic performance can operate through two channels: improvements in static and dynamic efficiency. The potential gains from improved dynamic efficiency can be important, as innovation is increased. While increases in human capital, R&D, and product market competition can improve the macroeconomic performance, it can take a long time before these benefits arrive, as for instance it takes time to build human capital.

2.1 Neoclassical growth theory

It is helpful to first consider the standard neoclassical growth model as developed by Solow (1956). This theory assumes a production function of the type

$$Y = Af(K, L) \tag{2.1}$$

where Y is output, A is Total Factor Productivity (TFP), K is physical capital, and L is labour. Labour productivity is defined by Y/L. Changes in TFP (A) are called Hicks neutral technological change.[2]

Another widely used neoclassical production function takes the form

$$Y = f(K, EL) \tag{2.2}$$

E is an efficiency-index. For a given capital stock K and labour input L, changes in E lead to changes in labour productivity. Increases in E are thus referred to as labour-augmenting technological progress, also called Harrod neutral technological change.

Let x denote the rate of technological progress (either Hicks or Harrod neutral). Population growth increases the labour force at rate n. Long-run economic growth is equal to population growth and technological progress, n+x. As n and x are exogenously determined, it is referred to as *exogenous growth*. The short-run rate of economic growth can deviate from the balanced

[2] See Barro and Sala-i-Martin (p. 32-33, 1995) for a more elaborate discussion.

growth rate when the economy is adjusting towards a new equilibrium (transition dynamics). In the neoclassical view, each country has access to the world technology (A or E). New knowledge immediately spreads around the world without costs. An important prediction of this model is international convergence in output levels: poor countries grow faster than rich ones. Another prediction is that when capital is mobile, advanced economies should invest in poor countries where capital is scarce and the marginal returns to investment are high.

2.2 Human capital

2.2.1 Human capital in a neoclassical framework

According to human capital theory (developed by Schultz (1961) and Becker (1964)), education enhances a person's skill level and thereby his or her human capital. A higher skill level in the workforce increases the production capacity. Although this sounds very straightforward, systematic research on how to incorporate human capital in theories of growth started only about two decades ago.

As especially the neoclassical prediction of international convergence in per capita production levels is not supported by the data, Robert Lucas asked 'Why doesn't capital flow from rich to poor countries?' (Lucas, 1990). His answer is that differences in returns to physical capital (as implied by the neoclassical growth model) become much smaller when account is taken of differences in human capital across countries: physical capital tends to move towards countries with more human capital. In the 1990s the standard neoclassical growth model has been revised by introducing human capital. For instance, Mankiw et al. (1992) propose a Cobb-Douglas production function of the form

$$Y = K^{\alpha} H^{\beta} (EL)^{1-\alpha-\beta} \tag{2.3}$$

where H is the human capital stock of the workforce, α is the production elasticity of physical capital, β is the production elasticity of human capital ($\alpha+\beta<1$ to maintain exogenous balanced growth), and $1-\alpha-\beta$ is the production elasticity of labour. Mankiw et al. use enrolment rates, but the human capital stock can also be determined from a macro-Mincer equation of the form

$$H = e^{\pi(s)} \tag{2.4}$$

where s is average years of schooling. As there is no heterogeneity, all individuals in this economy have a similar schooling level. Various forms for the function π can be chosen. Caselli (2004) uses a piecewise linear function with slope 0.13 for $s \leq 4$, 0.10 for $4<s\leq 8$, and 0.07 for $s>8$ (i.e. decreasing marginal returns to schooling). Bosworth and Collins (2003) assume a 7% return to each year of schooling.

This extension has several implications. First, the average skill level in the workforce has an impact on the production level. An increase in the average years of schooling increases the human capital stock *H*, and thereby the production level *Y*. Second, when markets are competitive, factor returns are given by their marginal product,

$$r = \frac{\partial Y}{\partial K} = \alpha K^{\alpha-1} H^{\beta} (EL)^{1-\alpha-\beta} \tag{2.5}$$

$$w_{EL} = \frac{\partial Y}{\partial EL} = (1-\alpha-\beta) K^{\alpha} H^{\beta} (EL)^{-\alpha-\beta} \tag{2.6}$$

where *r* is the return to physical capital, and w_{EL} is the wage rate. So the human capital stock not only affects the wage rate, but also the interest rate (when the economy is closed; the case of an open economy is discussed in Section 2.2.4). Increases in the human capital stock thereby also lead to increases in the interest rate, and to adjustments in the physical capital stock. Third, changes in the stock of human capital only have a temporary impact on the growth rate; the balanced growth rate is again determined by the exogenous rate of labour-augmenting technical progress and population growth.

2.2.2 Human capital and endogenous growth

So far we have assumed that long-run economic growth is exogenous. An increase in human capital leads to higher production levels, but does not affect the balanced growth rate. Policies and deliberate actions to build human capital only have a transitory impact on economic growth, and the balanced growth rate is determined by parameters that cannot be manipulated. Lucas (1988) proposes to introduce endogenous growth through human capital accumulation. We will be brief in our summary; for an elaborate treatment of the analysis the reader is referred to Lucas (1988) and to Barro and Sala-i-Martin (1995). Suppose that the production function takes the form

$$Y = K^{\alpha} (uH)^{1-\alpha} \tag{2.7}$$

where *H* is human capital and *u* is time devoted to production. How is human capital accumulated? Schooling and experience gained at the work floor are two well-known ways to build human capital. The former is often labelled as learning-or-doing (as time devoted to schooling competes with production time), and the latter as learning-by-doing (Lucas, 1988). Suppose that each employee is allotted with one unit of time, which can be used for production or learning. Learning-or-doing can be modelled as

$$\gamma_H = B(1-u) - \delta \tag{2.8}$$

where γ_H is the growth rate of human capital, 1-u is the time devoted to learning, B is the transformation rate of learning into human capital and δ is depreciation of human capital. The core of the model responsible for endogenous growth is that there are constant returns to scale with regard to *reproducible* factor inputs physical capital and human capital. The balanced growth rate in this economy is given by

$$\gamma^* = (1/\theta)(B - \delta - \rho) \tag{2.9}$$

where 1/θ is the intertemporal elasticity of substitution and ρ is the rate of time preference. Consumer preferences and the human capital accumulation technology determine together the long-run growth rate. As economic growth is determined from structural parameters, growth is called *endogenous*.[3] Notice that human capital is a purely private commodity in this analysis. Increases in human capital translate into higher wages, and there are no external effects. So there is no reason (in terms of economic efficiency) for government interference in this framework. The widespread argument that the government should support education because education is good for growth is therefore not valid in the Lucas-economy without spillovers.

Lucas also considers a model with human capital externalities. Production is affected by the average human capital stock $\overline{H}$, i.e.

$$Y = K^{\alpha}(uH)^{1-\alpha}\overline{H}^{\psi} \tag{2.10}$$

where ψ captures the size of the spillover effect. Individuals base their human capital investment decision on the private marginal product of human capital, taking the average human capital stock as given. The social marginal product of human capital takes the effect of individual human capital investments on the average human capital stock into account. In the presence of human capital spillovers there is a wedge between the private and the social marginal product of human capital. Without government action, there will be underinvestment in human capital from a social viewpoint.

2.2.3 Time to build human capital

Building human capital takes time. When using models with human capital for policy analysis and forecasts, one should take account of the time lag between the investment in human capital and the moment when the human capital can be used for productive purposes. Two aspects are important. First, the time lag depends on the schooling level. For instance, while an increase in tertiary education enrolment will lead to a higher inflow of skilled workers on the labour market after, say, four to six years, early childhood interventions will only materialise after ten to

[3] There is also a class of models exhibiting 'semi-endogenous' growth, in which the balanced growth rate is determined by parameters that are typically viewed as invariant to policy manipulation, but where productivity growth is tied to the discovery of new designs through R&D by rational, profit-maximising agents (see Jones, 1995).

fifteen years. Second, due to cohort effects, an extension of the schooling period only gradually changes the average educational attainment of the labour force. The effects of an extension of the compulsory schooling age will have its full impact on the average schooling level in the workforce only after about 50 years.

Let us return to a discrete time version of the Lucas (1988) model with learning-or-doing. The human capital accumulation function is

$$H(t) = H(t-1)[B(1-u(t))+1-\delta] \qquad (2.8')$$

In words, it is assumed that schooling in year *t* generates productive human capital in year *t*. It is also assumed that schooling refers to schooling of the whole labour force (agents are identical; there are no overlapping generations). An adjusted version of this human capital accumulation technology where account is taken of time lags could take the following form

$$H(t) = H(t-1)[\sum_{\tau=0}^{t} \lambda_\tau B(1-u(\tau))+1-\delta] \qquad (2.8'')$$

where $\tau \leq t$ denotes the time when the schooling has taken place, and λ_τ measures the impact of schooling in year τ on the human capital stock in year *t*. More complex specifications could take account of different transformation rates of learning into human capital formation and different depreciation rates at different schooling levels (e.g. primary, secondary, and tertiary).

2.2.4 Human capital in an open economy

The Netherlands is a small and open economy. This openness may have several implications. First, international mobility of production factors will induce international arbitrage of factor returns. It is commonly believed that financial capital is much more mobile than human capital, so we would not expect massive migration to France if the French earn a somewhat higher college premium than the Dutch. And even financial capital is not perfectly mobile internationally. But let us assume that the interest rate applying for the Netherlands is determined on the world capital market. In an economy with a production technology such as (2.3), the stocks of physical capital are determined from

$$r^* = \alpha \left(\frac{K}{EL} \right)^{\alpha-1} \left(\frac{H}{EL} \right)^{\beta} \qquad (2.11)$$

where r^* is the world interest rate. Second, the notion of the Netherlands as a small open economy has implications for human capital policy. For instance, international differences in public contributions to higher education could lead to student migration (which is not necessarily undesirable). In that case, some coordination of higher education policies can be efficient.

2.2.5 Human capital and technology adoption

In the endogenous growth model by Lucas (1988), sustained economic growth is due to the *accumulation* of human capital over time. An alternative view is that a country's human capital *stock* affects the rate of economic growth. For instance, in Romer's (1990) analysis, innovations are generated by the human capital stock, and Nelson and Phelps (1966) assume that the human capital stock determines the ability to assimilate new technologies.[4] One way to model the idea that human capital builds absorptive capacity is to link the level of total factor productivity to the human capital stock, i.e.

$$A = A(H) \tag{2.12}$$

with $A'>0$. Whether it is the stock of human capital or its accumulation that is important for growth is a testable empirical question, to which we turn next.

2.2.6 Empirical relationship between human capital and economic growth

Since the emergence of international datasets on major macroeconomic variables such as the Penn World Tables by Heston and Summers, a large empirical literature on the determinants of growth emerged. It is not our aim to review this literature, and the interested reader is referred to e.g. Krueger and Lindahl (2001) and Temple (1999). Instead, some influential papers are mentioned, and we will summarise the major findings. When studying the determinants of economic growth it is helpful to distinguish two approaches: a structural approach and a non-structural approach.

Non-structural approach

The first approach is basically inspired by the idea of letting the data speak. Take a group of countries, collect data on whatever indicator that may affect economic growth, and run regressions to obtain quantitative relationships. Robert Barro and Xavier Sala-i-Martin have popularised this approach, including conventional economic variables such as investment shares, human capital, and initial income, but also not so conventional variables such as black market premium and political instability (cf. Barro, 1991; Barro and Sala-i-Martin, 1995).[5]

What is the relationship between education and economic growth in this approach? Barro and Sala-i-Martin (1995) distinguish primary, secondary, and tertiary education, and study the relationship between educational attainment and economic growth for a large sample of countries. They do not find a significant effect from primary education of males and females on economic growth. For males a significant relationship is found for secondary and tertiary education. An increase in male secondary attainment by one standard deviation (0.68 year) corresponds to a 1.1%-point increase in economic growth. An increase in male tertiary

[4] A recent empirical test of the Nelson-Phelps model is presented in Benhabib and Spiegel (2003).

[5] Earlier, this approach was followed in Kormendi and Meguire (1985) and Grier and Tullock (1989).

education by one standard deviation (0.091 year) is estimated to raise economic growth by 0.5%-point. They thus find a convex relationship between educational attainment and economic growth. A somewhat peculiar result is that female educational attainment is bad for economic growth. A possible explanation provided by Barro and Sala-i-Martin is that less female attainment signifies more backwardness, and a higher growth potential through the convergence mechanism. Another (perhaps more convincing) explanation is that the regression results suffer from multi-collinearity when both male and female attainment are included (cf. Krueger and Lindahl, 2001).

The apparent advantage of these so-called Barro-regressions is that the method can be useful to detect mechanisms that have been ignored by theorists. However, the inclusion of indicators is to some extent ad hoc. Also, the empirical results may depend on the included list of variables. Indeed, Levine and Renelt (1992) have shown that only few variables appear with robustly significant coefficients. They find a positive and robust correlation between average economic growth and the share of investment in GDP. Also the conditional convergence hypothesis (from Mankiw et al., 1992) is supported: a robust, negative correlation is found between initial per capita GDP and growth over the 1960-1989 period when the initial level of human capital investment is included. No robust correlation with growth is found for a broad array of other indicators.[6]

Structural approach

The second approach is to derive the econometric model directly from a theoretical model. According to Aghion and Howitt (1998), it is useful to distinguish between level effects and growth effects of the human capital stock.

Level effects

Let us first discuss economic models where the human capital stock affects the production level, or – in first-differences – changes in the human capital stock affect production growth.

As mentioned before, Mankiw et al. (1992) extend the standard neoclassical growth model with human capital. Investments in human capital are measured by using a schooling variable, namely the percentage of the labour force enrolled in secondary education (primary and tertiary education are not considered).[7] The econometric results show that the inclusion of human capital improves the fit of the model. A representative outcome of their analysis is the following production function

$$Y = K^{1/3} H^{1/3} L^{1/3} \qquad (2.13)$$

[6] A response to the critical analysis in Levine and Renelt (1992) can be found in the paper 'I just ran two million regressions' by Sala-i-Martin (1997).

[7] Mankiw et al. (1992) use UNESCO data on the fraction of the eligible population (aged 12 to 17) enrolled in secondary school. They then multiply this enrolment rate by the fraction of the working-age population that is of school age (aged 15 to 19).

This implies a production elasticity of human capital of 1/3: 1% more human capital translates into 1/3% higher production. It is important to note that in equilibrium, the human capital stock affects a country's production level, but not the rate of economic growth. Changes in the stock of human capital will lead to transition dynamics, and this predicts a positive relationship between human capital accumulation and economic growth during the transition period. While Mankiw et al. do find evidence for such a positive relationship for the total country sample, their results are not robust to changes in the country sample. No significant relationship between human capital investments and GDP growth (per working-age person) is found for the OECD countries.

Data on educational enrolment may suffer from measurement problems, and noisy data can lead to a downward bias in the regression results. De la Fuente and Doménech (2000) construct new data on attainment levels by removing some peculiarities (probably due to definition changes) in the Barro and Lee (1996) data. The new dataset by De la Fuente and Doménech includes 21 OECD countries over the period 1960-1990. De la Fuente and Doménech (2000, 2001) use this new data to empirically investigate the relationship between production and human capital, both in levels and in first differences. They find a production elasticity of human capital of 0.271 (statistically significant), which is close to the earlier findings by Mankiw et al. (1992). Also Temple (1999) finds an insignificant connection between changes in human capital and economic growth at first instance, but he finds a significantly positive relationship when outliers are eliminated from the data: "in the 64 countries that remain in the sample, there is a reasonably strong correlation between increases in human capital and output growth, just as one would expect" (p. 133). Finally, Bassanini and Scarpetta (2001) investigate the relationship between human capital accumulation and economic growth for a panel of 21 OECD countries between 1971 and 1998. They find that one extra year of schooling increases the long-run per capita output level by about 6%. This is an average effect however. If education is subject to decreasing returns, the impact on per capita output might be smaller in countries with higher levels of educational attainment (such as the Netherlands).

Growth effects

A second approach is to investigate the interaction between the human capital stock and technological change. Benhabib and Spiegel (1994) introduce a model where human capital affects TFP through two channels. First, following Romer (1990), human capital can directly influence TFP by increasing the capacity to innovate. Second, following Nelson and Phelps (1966), human capital affects the speed of technological catch-up and diffusion of knowledge. The empirical results by Benhabib and Spiegel suggest that the human capital level has a positive effect on GDP growth. A 1% larger stock of human capital corresponds to an increase in the growth rate by about 0.13%. The authors furthermore find that countries with a larger human capital stock show faster technological catch-up. When the country sample is divided into three sub-samples, it is found that the innovation-effect dominates for the richest 26 countries, while for the poorest third of the countries only the adoption-effect plays a role. Both effects are insignificant for the intermediate-income countries. Another study investigating interactions between education and technological change is Barro and Sala-i-Martin (1995). They also find that catch-up growth is faster when the initial human capital stock is larger.

Quality of human capital

International comparison of schooling data is difficult. One year of schooling in Tanzania is not the same as one year of schooling in the Netherlands. Barro (1991) tries to take account of differences in educational quality, by including student-teacher ratios and adult literacy rates. Barro and Sala-i-Martin (1995) use expenditures on education as a fraction of GDP as a proxy for educational quality. They find a positive relationship between public spending on education and economic growth. The estimation suggests that a one standard deviation increase in public spending on education as a fraction of GDP (i.e. about 1.5%-point) raises the annual growth rate by 0.3%-point. Hanushek and Kimko (2000) use as a proxy for the quality of the labour force the average performance on an international mathematics and sciences test. They find a strong relationship between the quality of the labour force and the rate of economic growth: a one standard deviation increase in the test score corresponds to a 1.46%-point higher growth rate.[8]

Table 2.1 summarises the findings on the empirical connection between education and economic growth. Earlier studies typically find a positive relationship between educational attainment (as a proxy for the human capital stock) and subsequent economic growth, and an insignificant effect from educational investments on the growth rate. These results suffer from measurement errors in human capital data (which are worsened when first differences are taken) and specification problems (cf. Krueger and Lindahl, 2001). More recent studies that aim to deal with these two issues tend to find a positive relationship between changes in human capital and economic growth, and no relationship between educational attainment and subsequent growth.

[8] Wößmann (2003) presents a review on human capital indicators, paying particular attention to international quality-differences.

Table 2.1 Summary of growth empirics

Study	Human capital data	Dependent variable	Human capital stock	Change in human capital
Barro and Sala-i-Martin (1995)	Barro and Lee (1993)	Growth in per capita income	+ for males – for females	0
Mankiw, Romer and Weil (1992)	UNESCO	Growth in income per worker		0
Benhabib and Spiegel (1994)	Kyriacou (1991)	Growth in per capita income		0
		Growth in TFP	+	
Temple (1999)	Kyriacou (1991), elimination of unrepresentative observations	Growth in per capita income		+
De la Fuente and Doménech (2000, 2001)	Revised version of Barro and Lee (1996)	Per capita income level	+	
		Growth in per capita income		+
Bassanini and Scarpetta (2001)	Revised version of Barro and Lee (1996)	Growth in per capita income		+
Krueger and Lindahl (2001)	World Values Survey	Growth in per capita income		+

Finally, it should be noted that in the growth empirics discussed above it is assumed that causality runs from human capital to economic growth. However, according to human capital theory people invest in education in order to increase their expected future income. This would imply a reverse causal relationship between human capital and income in macro-regressions: economic growth induces people to invest in human capital. Bils and Klenow (2000) indeed find evidence that an increase in the returns to schooling leads to a higher enrolment rate.

2.3 Research and development

2.3.1 Conceptual issues

Productivity can increase through better skills, but also through an improved technology. Earlier empirical evidence made some authors conclude that technology improvements are of minor importance. However, the way this was measured (growth accounting) may have been misleading, attributing a smaller fraction of growth to innovation than its true contribution (Aghion and Howitt, 1998, Chapter 12). At present, it is widely acknowledged that technology improvements are an important force behind long-run economic growth.

Technological know-how, or rather knowledge in general, comes in many forms (see also David Romer (Section 3.4, 2001). It is useful to think of a continuum of types of knowledge, ranging from highly abstract to highly applied. At one end of the spectrum is broadly applicable, basic scientific knowledge, such as the Pythagorean theorem and the theory of quantum mechanics. At the other end is knowledge about specific goods, such as how to open your safe. In between there is great diversity. Hence, the accumulation of knowledge is a complex phenomenon, and there is no unified explanatory theory.

Still, as emphasised by Paul Romer (1990), many types of knowledge are *non-rival*, i.e. the use of an item of knowledge in one application does not hinder its use in another application. Consequently, the production and allocation of knowledge cannot be completely governed by competitive market forces. Once an item of knowledge has been discovered, the marginal cost of supplying it to an additional user is zero. The rental price of knowledge would thus be zero in a competitive market, and the creation of knowledge cannot be motivated by the prospect of private economic gain.

Romer (1990) further mentions that knowledge is heterogeneous along a second dimension: *excludability*. A good is excludable if it is possible to prevent others from using it. Conventional private goods like clothing are excludable. In the case of knowledge, excludability depends both on the nature of the knowledge itself and on economic institutions governing property rights. Patent laws give inventors rights over the use of their inventions, copyright laws disallow the copying of books. Meanwhile, some knowledge is sufficiently complex that it can be kept secret without copyright or patent protection, and other knowledge is so easy to retrieve that no effective legal protection is possible.

2.3.2 R&D in a neoclassical framework

Nonneman and Vanhoudt (1996) develop a neoclassical growth model with human capital, physical capital, and technological know-how. Investments in technological know-how are measured by gross domestic expenditures on R&D as a fraction of GDP. Nonneman and Vanhoudt assume that the market for technological know-how works perfectly (there are no external effects or economies of scale). They estimate a production function of the type

$$Y = AK^{\alpha}H^{\beta}T^{\chi}L^{1-\alpha-\beta-\chi} \qquad (2.14)$$

where T stands for technological know-how, and α, β, and χ are production elasticities of physical capital, human capital, and technological know-how. A representative result is

$$Y = AK^{1/3}H^{3/20}T^{3/35}L^{2/5} \qquad (2.15)$$

This means that a 1% increase in the stock of technological know-how would yield an increase in output of about 0.09%.

Some comments are in order. First, the assumption of Nonneman and Vanhoudt that knowledge is a ‘normal’ economic commodity, tradable on markets, does not correspond to insights from modern growth theory, and can lead to misspecification of their econometric model. Nonneman and Vanhoudt express their model in per capita units, dividing all terms by

L. If the market for technological know-how fails and knowledge has aspects of a public good, then it is the total stock of technological know-how that matters for per capita income. Second, changes in the stock of technological know-how, like changes in the stock of physical and human capital, have only a temporary impact on the growth rate; the balanced growth rate is again determined by the exogenous rate of labour-augmenting technical progress and population growth.

2.3.3 R&D and endogenous growth

A number of authors have suggested that new ideas are the engine of growth. It is not our purpose here to systematically review the literature (a concise review is available in Klenow and Rodriguez-Clare, 2004). Instead we will briefly mention some milestones in the development of endogenous growth models with R&D.

A pioneer in the area of endogenous growth is Paul Romer. Romer (1990) emphasises the public-good character of knowledge: ideas, designs, and blueprints are in principal non-rival. However, they may be made excludable through protection by patent law and copyright law. Firms engaged in R&D are then able to protect their inventions during a certain time period and may reap the benefits from their investments. The prospect of (temporary) monopoly profits encourages firms to invest in R&D.

Suppose that the production function takes the form

$$Y = A\sum_{j=1}^{N} K_j^{\alpha} L^{1-\alpha} \qquad (2.16)$$

where K_j is input of the jth type of the specialised intermediate good, and N is the number of varieties of the capital goods (cf. Romer (1990), Barro and Sala-i-Martin (1995)). Technological progress yields an expansion in N. In equilibrium, the production function can be rewritten to

$$Y = ANK^{\alpha} L^{1-\alpha} \qquad (2.17)$$

Thus, technological change in the form of a steady increase in N is not subject to diminishing returns, and this property of the production function is essential to generate endogenous growth. The next step in the analysis is to study the expansion in the variety of products. New growth models assume that this expansion requires deliberate effort in the form of research and development. For instance, Barro and Sala-i-Martin assume that the cost to create a new type of product is fixed at η units of Y. However, most models assume some randomness in the discovery of new products (generating fluctuations at the aggregate level).

Two other economists who made important contributions on the link between R&D and economic growth are Philippe Aghion and Peter Howitt. Aghion and Howitt (1992) develop an endogenous growth model with creative destruction (based on the ideas of Schumpeter). R&D

efforts can lead to innovations, i.e. improvements in the general purpose technology. Protection by patent law gives a firm the monopoly right to market a new product. The prospect of monopoly profits encourages firms to develop new and better products, so that the innovating firm can enter the market and the incumbent monopolist is replaced (Schumpeterian creative destruction). Economic growth is determined by the speed of the innovation process. The market solution may not correspond to the socially optimal solution. In the model by Aghion and Howitt, economic growth can be too high or too low. On the one hand, intertemporal knowledge spillovers can reduce R&D investments below the optimal level. By assumption, entrepreneurs only look at the returns to R&D during the life span of their company. The firm is replaced when another entrepreneur develops a better product, but this innovation builds forth on knowledge embodied in the previous product generation. Innovators thus stand on the shoulders of giants. The positive externality of intertemporal knowledge spillover leads to private returns falling short of social returns to R&D, depressing R&D activity below its socially optimal level. On the other hand, by assumption entrepreneurs do not consider the consequences of innovation for the profits of incumbent firms. Innovation yields improved products, and the existing product is driven out of the market (business stealing). The lost profits are not reflected in the private return, but they do reduce the social return to R&D. The negative externality of creative destruction thereby leads to private returns exceeding the social return, possibly triggering excessive R&D activity.

One way to model the idea that R&D matters for growth is to introduce a relationship between TFP and the R&D stock (cf. Griffith et al., 2000, 2004), i.e.

$$A = A(T) \tag{2.18}$$

where *A'*>0. The production function then looks like

$$Y = A(T)K^{\alpha}L^{1-\alpha} \tag{2.19}$$

This equation says that countries with a larger R&D stock have a higher level of total factor productivity. Or, taking first differences, countries with higher R&D investments experience faster TFP growth.

The relationship between R&D and TFP as expressed in equation (2.18) can reflect two effects: innovation and adoption. R&D is an essential factor in the innovation process, and R&D helps firms to build absorption capacity, i.e. the ability to exploit knowledge spillovers (cf. Cohen and Levinthal, 1989). This concept of absorption capacity captures the idea that one has to do basic research oneself in order to understand results of other researchers.

2.3.4 Time to research and develop

Similar to the accumulation of human capital (Section 2.2.3), it should be noted that research and development of new products is a time consuming process. Especially for basic research it can be a long way before new insights can be applied in new products, processes, or services. But also for more applied research it holds that it can take a long time to further develop a prototype product, and to bring the product to the market. We can take account of such time lags by specifying the law of motion (in discrete time) of the stock of technological knowledge as

$$T(t) = \sum_{\tau=0}^{t} \lambda_\tau R\&D(\tau) + (1-\delta)T(t-1) \qquad (2.20)$$

where λ_τ has a similar interpretation as before. Again, this accumulation function can be refined. For example we may want to distinguish between applied and basic research (or, perhaps more pragmatic, between public and private research). It can be expected that applied research contributes faster to the stock of technological know-how than basic research.

2.3.5 Empirical relationship between R&D and economic growth

Returns to R&D

There is by now a substantial literature on the impact of R&D on output. Cameron (1998) presents an overview of the empirical literature on the returns to R&D. The impact is often estimated to be quite high. A typical estimate of the social rate of return to R&D would be in the order of 20 to 30 percent when estimated at the industry level, and can be much higher economy-wide (Jones and Williams (1998) even mention an economy-wide social rate of return of around 100%). Estimated private returns to R&D are in the order of 7-14%.[9] Discrepancies between marginal private and marginal social returns to R&D imply that the incentives for firms to invest in R&D are sub-optimal. Jones and Williams (1998) conclude that there is substantial underinvestment in R&D: “optimal R&D spending as a share of GDP is more than two to four times larger than actual spending” (p. 1121).[10]

However, empirical estimates of the returns to R&D are not undisputed. First, the estimates are subject to measurement errors. For example, econometric specifications do not allow to make a distinction between intended and unintended spillovers, while only unintended spillovers are a market failure. In other words, knowledge flows which carry a market price and knowledge flows which are not priced cannot be distinguished in the statistics (cf. Cornet and Van de Ven, 2004).

[9] Some studies report much higher estimates of the private returns to R&D (up to 30%, see e.g. the discussion in Griffith, 2000). This also raises the question why arbitrage, i.e. exploiting profitable investment opportunities so that rates of return are driven down to normal levels, does not take place. Perhaps a somewhat higher rate of return to R&D can be explained from the risk premium demanded for the often substantial uncertainties of R&D endeavours. On the other hand, when risks of research projects are uncorrelated, the market might be able to reduce the aggregate risk through risk pooling. Rates of return to R&D in the order of 30% are therefore not very plausible.

[10] For the Netherlands, Van Leeuwen and Van der Wiel (2003) find that ICT spillovers are important.

Second, estimates on the returns to R&D might be unreliable due to specification problems. For instance, Comin (2004) warns that there are many factors omitted in the typical regression that simultaneously affect TFP growth and the innovators' incentives to invest in R&D, and mentions as the most obvious candidates anything that enhances disembodied productivity, like managerial and organisational practices. When these factors are ignored, the estimated returns to R&D are biased upwards. Comin pioneers an alternative approach in an attempt to overcome the difficulties that beset the econometric framework. He starts from the free-entry condition for innovators and the fact that most R&D innovations are embodied. Upon calibrating his model to US data he finds that the annual contribution of R&D to productivity growth is smaller than three to five tenths of one percentage point. His analysis implies that, if the innovation technology takes the form assumed in the literature, the actual US R&D intensity may be close to the socially optimal one. Overall we can conclude that while most studies suggest substantial private and social returns to R&D, these results are not undisputed.

R&D and economic growth

Overviews of the literature on R&D and economic growth can be found in Cameron (1998) and Jones and Williams (1998). Here we confine ourselves to a study of Griffith et al. (2000, 2004) in which particular attention is paid to the 'two faces' of R&D (cf. Cohen and Levinthal, 1989). Griffith et al. investigate TFP convergence in a panel of industries across 13 OECD countries over the 1970-1990 period. For each industry, the distance to the technological frontier is used as an indicator for potential technology transfer, where the technological frontier is defined by the country with the highest TFP in the corresponding industry. Adoption of technology is then reflected in international convergence of TFP-levels, also called catch-up growth. The direct effect of R&D shifts the technological frontier. The researchers find that both R&D and human capital are important for movements towards and shifts of the technological frontier. The authors present estimates of the total social return to R&D, and the return due to adoption / imitation. Being the technological leader in most industries, the returns to R&D in the USA are almost fully determined by the direct innovation-effect. The return to R&D from technology adoption is only 0.5%. Also for the Netherlands it is found that the innovation-effect is more important than the adoption-effect.[11] Technology adoption is a major determinant of the social return to R&D for the Scandinavian countries, Italy, Japan, and the UK.

[11] In contrast, Keller (2004) finds that only about 4.7% of Dutch productivity growth can be attributed to Dutch R&D, suggesting that foreign sources of technology are much more important.

2.4 Product market competition

2.4.1 Competition in a framework with exogenous growth

Competition and market structure

The neoclassical model assumes perfect competition: the economy comprises of many identical firms, which are price takers on a perfectly competitive product market. Output prices equal marginal production costs in this model. In this section we want to consider the macroeconomic impact of competition, and therefore we need to relax the neoclassical assumption of perfect competition, and introduce market power. The most well-known form of market dominance is when there is only one firm in the market, i.e. a monopoly. Such a monopoly will maximise its producer surplus, and charge prices above marginal costs. Interestingly, under certain assumptions, entrance of one other firm can completely destroy monopoly power, and in equilibrium the two firms charge the competitive price (i.e. prices equal to marginal costs). This is known as the Bertrand paradox (cf. Tirole, 1988). Two firms can also strategically interact in Cournot competition, where they choose their produced quantities simultaneously. The Industrial Organisation (IO) literature deals with such strategic interactions between competing firms in more detail, and we refer the interested reader to Tirole (1988) for an extensive treatment.

Another way to study the role of competition and its macroeconomic impact is to consider an economy where firms compete monopolistically, while the number of firms is assumed to be large so that one can ignore strategic interactions. Dixit and Stiglitz (1977) provide an analytical framework. In the Dixit-Stiglitz framework product prices exceed marginal costs, and the mark-up depends on the intensity of competition. The assumption of monopolistic competition implies the presence of entry barriers such as fixed production costs. An interesting aspect of the Dixit-Stiglitz framework is that intensified competition can take various forms, such as closer substitutability of the goods, lower fixed costs of production, or more firms (see also Smulders and Van de Klundert, 1995).

Competition and technology adoption

While it is often argued that the benefits from improved static efficiency in terms of consumer prices are modest,[12] gains associated with the adoption of new technology can be much larger. The neoclassical model assumes that technology is a public good, arising as manna from heaven. New technologies immediately spread around the world, and firms can access and implement the new technology without incurring any costs. Total factor productivity is therefore identical for all firms and for all countries.[13] This is unrealistic as, for given factor inputs, some firms are able to produce more than others. Also at the macroeconomic level there

[12] For instance, Matheron and Maury (2004) estimate the welfare cost of monopolistic competition between 0.4 and 1.2% of consumption.

[13] Or, in models with labour-augmenting technological change it is assumed that the efficiency index for labour is identical for all firms and for all countries.

is convincing evidence for large international differences in TFP-levels, e.g. Hall and Jones (1999). Therefore, in the words of Edward Prescott, we need a theory of TFP (Prescott, 1998). Many explanations for TFP differences have been proposed in the literature, such as differences in the legal framework, social capital, climate, political structure, openness, and intensity of competition, on which we want to focus here.

Several studies have investigated the connection between competition and the adoption of new technologies (see Canton et al. (2002) for an overview). For example, the connection between competition and TFP can be studied in a principal-agent framework. Nickell (1996) notes that more intense competition in the product market may increase the opportunities for shareholders to effectively monitor the performance of managers (i.e. reduce principal-agent problems) by providing yardsticks or sharpen incentives (as profits become more sensitive to managerial effort in a more competitive environment). An opposite effect of competition is also possible (at least in theory): Martin (1993) develops a Cournot model where X-inefficiency increases with the number of firms. The idea is that marginal revenues decline when there are more active firms, so the principal has less incentives to monitor agents and managerial slack increases. However, in an empirical analysis of the implementation of the Single Market Program in Europe, Griffith (2001) finds that the resulting increase in product market competition led to an improvement in overall levels of efficiency. Interestingly, stronger efficiency gains occurred in firms where management and ownership were separated (say, 'principal-agent type of firms').

By-and-large, to study the macroeconomic connection between competition and technology adoption we could assume that TFP is a function of the intensity of competition, i.e.

$$A = A(COMP) \tag{2.21}$$

where *COMP* is an indicator for the intensity of product market competition. A change in competition will affect the economy's total factor productivity and aggregate production possibilities.

Competition and R&D

The intensity of competition can also influence firms' decisions to invest in R&D. This, in turn, affects dynamic efficiency. To study the macroeconomic effects of such a connection between competition and R&D, we could consider an extended version of the model in Nonneman and Vanhoudt (1996). Nonneman and Vanhoudt consider R&D expenditures as exogenous. We conjecture that research activity is a function of the competition intensity, i.e.

$$R\,\&\,D = R\,\&\,D(COMP) \tag{2.22}$$

In fact, what we do here is an attempt to endogenise R&D activity, and instead of providing a structural model we take the short-cut of a reduced form relationship. In the model by Nonneman and Vanhoudt, R&D adds to the production capacity in a similar way as the other production factors (i.e. it is a rival and excludable input in the production process; see also our earlier discussion), and therefore firms find it profitable to invest in it. We do not have strong opinions about the functional form of this relationship between competition intensity and R&D. Competition can discourage R&D, when firms find it harder to reap the returns from their R&D benefits when price competition is fierce. Competition can also be conducive for R&D, for instance when firms compete dynamically in a more Schumpeterian sense. And perhaps the relationship between competition and R&D is nonlinear, positive at some level of competition and negative at other levels. Empirical research on the relationship between competition and innovation is scarce, and does not provide uniform results. The properties of the (augmented) neoclassical production function (Equation 2.14) imply that a change in competition intensity will change the stock of technological know-how and the long-run production potential in the economy. This will lead to transitory changes in economic growth, until the new equilibrium is restored. For an elaborate discussion on the relationship between competition and innovation, the reader is referred to Baumol (2002).

2.4.2 Competition and endogenous growth

In Equation 2.22 we postulated a relationship between competition and R&D, or dynamic efficiency of the firm. Theory provides two explanations for such a relationship, which we will discuss here.[14]

The first mechanism describes competition between innovating entrants and incumbent firms (Aghion and Howitt, 1992; see also Section 2.3.3). An innovating entrant can capture the entire market, and drive the incumbent monopolist out of business. R&D investments by potential entrants are thus driven by the prospect of (temporary) monopoly profits. Instead, incumbent firms only enjoy an incremental increase in profits when they innovate. Under certain conditions it therefore holds that only entrants innovate (the so-called Arrow's replacement effect). Entrants destroy incumbents when they leapfrog them through fundamental innovation. In the course of time, the economy consists of a sequence of temporary monopolists, with ever increasing efficiency. Competition is characterised by creation and destruction. The competitive process is described by two determinants, i.e. the return on investment in R&D (as reflected in the firm's mark-up) and the expected lifetime. If there is no mark-up, there is no innovation and macroeconomic productivity stagnates. Firms live eternally.

[14] Kamien and Schwartz (1975) and Cayseele (1998) present surveys on the empirical relationship between competition and innovation.

In contrast, if the entrants can earn a monopoly profit on their R&D-investments, the Schumpeterian process of creative destruction will yield innovation and economic growth.[15]

The second mechanism describes competition between incumbent firms (Aghion et al., 2001; Aghion and Howitt, 2005). Implicitly, there are large barriers to market entry, so there are no entrants. Incumbents innovate based on their expected incremental profits. These are the profits on innovation less the profits they would have earned without innovation. The incumbents differ in efficiency. If the most efficient firms innovate, they cannot be imitated by their rivals. Therefore, they can always earn a monopoly mark-up. The firms with lower efficiency than the most efficient firms can catch up. Competition is measured by imitation costs. Higher imitation costs imply less competition, because lagging firms are discouraged to catch up and become fiercer competitors. For all firms it holds that profits (without innovation) increase if competition intensity decreases. Then, more competition intensity stimulates the most efficient firms to innovate, while the lagging firms are discouraged. In the course of time, firms mutually change positions in a process of jumping forward and catching up. In equilibrium, the distribution of efficiencies of the firms needs to be stable. Particular combinations of parameters may lead to an inverted U-shape between competition and innovation. That is, innovation activity is maximised somewhere between perfect competition and monopoly.

2.5 Interactions between human capital, R&D, and competition

An advantage of formalising human capital, R&D, and competition in a macroeconomic framework is that interactions can be studied (see for instance Redding (1996) and Bucci (2003)). Such interactions can also have consequences for the effectiveness of economic policy. In particular, three types of interactions are distinguished:

- Human capital and R&D;
- Human capital and competition;
- R&D and competition.

The interactions between R&D and competition have already been discussed in Section 2.4, and here we will confine ourselves to a discussion of the other two types of interactions.

First, the stock of human capital can interact with an economy's R&D activity. The major input into the R&D process is highly skilled labour. As we will see in the next chapter, government policies to stimulate R&D typically take the form of demand side subsidies, i.e. subsidies for firms in order to reduce the costs of R&D. Romer (2000) has argued that such

[15] A slightly different approach analyses the impact of monopolistic competition, where entrants do not destroy incumbents, but they gain market share at the cost of the market shares of incumbents (Grossman and Helpman, 1991). The main conclusions remain unchanged.

R&D subsidies will not work when the supply of scientists is inelastic. In case of fixed supply of researchers, R&D subsidies will result in higher wages of R&D employees, and not in increased R&D activity. It would then be more effective to encourage the supply of scientists, by making it more attractive for students to choose research-oriented graduate programs, for instance by offering generous fellowships to students in natural sciences or engineering. Another potentially interesting interaction between human capital and R&D is related to educational production. Loosely put, it takes high skilled labour to produce high skilled people. Extension of the higher education sector means less high skilled workers in other sectors in the economy.

Second, the human capital stock may interact with the competition intensity. One example of such an interrelationship is also discussed in Section 2.4, i.e. when skilled labour forms the major input in the R&D process, and competition refers to dynamic competition in the sense of Schumpeterian creative destruction. Abundance of skilled labour can drive down the wages of researchers, making R&D less costly. This in turn could encourage R&D activity, speed up the innovation process, and intensify dynamic competition in the industry. Another example is earlier discussed in the context of technology adoption (cf. Canton et al., 2002): learning to operate new technologies (which may be a more specific form of human capital) is more attractive when employees work for more competitive firms.

3 Effects of government policy

How can policy affect the formation of human capital and R&D activity, and what is known about the relationship between competition policy and macroeconomic outcomes? We distinguish between human capital policies aimed at enrolment (a quantity indicator) and educational quality. Especially early childhood interventions have been found effective, both in terms of raising average years of education and improving student performance. R&D policies include subsidy programs to encourage private R&D, but also instruments to make better use of the existing knowledge base. Estimates on the effectiveness of R&D subsidies show substantial variation, and outcomes will depend on (country-)specific institutional arrangements. Finally, the literature on the macroeconomic impact of competition policy generally finds positive effects in terms of GDP or total factor productivity. Unfortunately, convincing policy evaluation studies are scarce, and little is known about the causal impact of these instruments. Application of new methods in the field of experimental economics should enable evidence-based policy design in the future.

3.1 Human capital[16]

How does policy affect education, and hence the accumulation of human capital? There are two channels through which policy can operate: through enrolment, that is, a measure of educational quantity, or through the impact on educational quality.

The outline of this section is as follows. First, in Section 3.1.1 we briefly review the various reasons for public intervention in the education sector, with particular reference to education spillovers. Subsequently, in Section 3.1.2 we try to sketch how the important policy interventions affect educational quantity (i.e. enrolment and/or educational attainment) and quality, distinguishing among interventions at different levels of education. Section 0 concludes.

3.1.1 Rationale for public intervention in education[17]

Governments all over the world intervene substantially in education. Various reasons for public intervention in education have been identified in the literature. One can think of paternalistic motives, and equity (i.e. income-distributional) considerations. The most important motivation for public intervention in education, however, is the occurrence of market failures (efficiency motives). Examples of market failures in education are externalities, capital market constraints,

[16] We focus solely on education here, and do not consider policy in the context of the other components of human capital formation, encompassing (work-related) training, experience and learning-by-doing. One reason for this omission is that the scope for public intervention regarding these other types of human capital formation is generally assumed to be relatively limited, particularly when compared to education. Furthermore, due to certain econometric problems, reliable estimates of the impact of policy on training participation, and subsequently of the effect of training on productivity, earnings and economic growth are rather scarce, as argued by Donselaar et al. (2003). However, we should bear in mind that post-school learning is an important source of human capital formation, accounting for as much as one third to one half of all skill formation in a modern economy (cf. Heckman, 2000).

[17] The reader is referred to Van der Steeg (2005) for a more comprehensive analysis of the various rationales for government intervention in education, and of externalities in particular.

insurance market imperfections, and imperfect information and transparency problems (cf. CPB and CHEPS, 2001).[18] Here, we will briefly focus on education spillovers. The idea of education externalities is that the benefits of individually acquired education may not be restricted to the individual, but might spill over to others as well, accruing at higher levels of aggregation (e.g. the public). Spillovers, if not already internalised by public intervention, may drive a wedge between the social and private rate of return to education.

The relevant question is whether there is any empirical evidence for the prevalence of positive externalities of education at current levels of policy efforts, and if so, how large these spillovers are. Based on reviews of the recent literature on human capital spillovers by Venniker (2000), Temple (2001) and CPB and CHEPS (2001), we can draw the following conclusions. First, empirical evidence is rather scarce. Second, economic literature is ambiguous about the existence of human capital externalities at current levels of public intervention, delivering some indications for positive externalities, but not very strong and undisputed. Examples of studies finding that private and social returns to education are roughly the same at current levels of government intervention are Gemmel (1997), Blundell et al. (1999), Ciccone and Peri (2000), and Acemoglu and Angrist (2001).[19]

Third, looking more specifically at different types of education spillovers, we observe that the lack of (consistent) evidence is particularly eminent for spillovers from an individual's education to higher wages and productivity of others (i.e. *static* externalities), and in the form of technological progress and diffusion of new technologies (i.e. *dynamic* externalities).

Fourth, with respect to so-called *non-pecuniary* (or social) external benefits of education, evidence is somewhat more consistent and promising, particularly concerning the effects of education on crime reduction (e.g. Lochner and Moretti, 2004) and health outcomes.[20] It should be stressed that these non-pecuniary spillovers are abstracted from in standard (*macro-Mincer*) estimations of social returns to education, as these returns are generally measured in terms of effects on GDP or productivity. This implies that social returns to education may exceed private returns if we take into account these non-pecuniary spillovers. However, we are unaware of any attempts to incorporate these non-pecuniary spillovers in an econometric analysis.

We may conclude that on the basis of the available empirical literature on education spillovers it is difficult to make precise statements about the optimal scale at which governments should intervene in education, at least on efficiency grounds. Moreover, the scale at which certain spillovers can be reaped may differ across education levels and types, as well

[18] Different types of market failures may require different types of public interventions as well. For example, capital market imperfections can be solved by means of public provisioning of loans to students, whereas the occurrence of education externalities may call for government subsidisation of education.

[19] Moretti (2004a; 2004b) are notable exceptions to this literature, finding evidence for significant positive spillovers of (higher) education at the city level on wages and productivity. For instance, Moretti (2004a) finds that a one percentage point increase in the supply of college graduates raises high school drop-outs' wages by 1.9%, high school graduates wages by 1.6%, and college graduates wages by 0.4%.

[20] See Wolfe and Haveman (2002) for a comprehensive overview of these social spillovers from education.

as across socio-economic groups (cf. Krueger and Lindahl, 2001). This has repercussions for the optimal *allocation* of government budgets.

Apart from efficiency motives to intervene in education, equity or income-distributional considerations may act as an important additional motivation. Tinbergen (1975) argued that there is a role for governments in reducing wage inequality by means of education subsidies. The central idea is that raising the average number of years of education (or, more particularly, increasing enrolment at *higher* levels of education), will make low-skilled workers scarcer, raising their wages, whereas the higher supply of highly educated workers reduces their wages. In other words, the higher relative supply of skilled workers resulting from education policy reduces wage inequality by lowering the private monetary return to education. There is some empirical work that seems to support this mechanism (e.g. Dur and Teulings, 2001; Teulings and Van Rens, 2003), showing that a rise in average educational attainment lowers the private return to education. However, the literature has identified a number of reasons why education policy designed to reduce income inequality may be counterproductive.[21] One reason is that a larger relative stock of skilled workers may induce the development of new technologies that are more complementary to skilled workers. If this mechanism is at work, stimulating skill formation with education policy does not only lead to an increased supply of skilled workers, but also to an increased (relative) demand for skilled workers.

3.1.2 Effects of education policy

How does policy affect education, and thereby the accumulation of human capital?[22] There are basically two channels through which education policy can operate: through educational quantity or through the impact on educational quality. Educational quantity is usually expressed in enrolment levels or average years of schooling. Educational quality has been traditionally measured by input measures such as teacher-student ratios, teachers' human capital or total public expenditures on education. A more recent strategy, however, is to evaluate educational quality in terms of output indicators measuring the performance of students and graduates. Towards this end, test scores in areas like maths, reading and science are often used. The idea is that when students in one country outperform students in another, provided they are in the same grade, we can assume that they have enjoyed schooling of higher quality, irrespective whether this higher quality comes from higher teacher-student ratios, the quality of teachers, other expenditures on education or other unobservable factors specific to the production of human capital.

[21] It is not our goal to discuss these reasons here. For a comprehensive overview of factors that undermine the effectiveness of education policies in reducing wage inequality, the reader is referred to Jacobs (2004).

[22] The macroeconomic impact of education policy in terms of productivity and economic growth will not be discussed here. Instead, we have chosen a two-step methodology: this section shows how policy inflicts on (the quantity and quality of) education, whereas Section 2.2.6 shows how education, or more broadly seen, human capital may affect macroeconomic outcomes such as productivity and economic growth.

There exists a rich empirical literature in which measurements of educational quantity (e.g. average years of schooling) as well as educational quality (e.g. test scores) are taken as the determinants of macroeconomic performance, which is usually expressed in the level of GDP per capita and/or its growth rate. See Section 2.2.6 for a discussion of the main outcomes of this literature. The apparent relationship between the state of an educational system and macroeconomic performance makes the question as to how policy affects the quantity and quality of education all the more relevant.

Table 3.1 presents a brief overview of the outcomes of studies measuring the causal effect of various types of public interventions.[23] We distinguish among the effects on enrolment levels (i.e. the quantity channel) and measurements of student performance (i.e. the quality channel). Besides categorising education policies according to their particular *focus* (i.e. quantity versus quality), we also subdivide educational interventions according to the different *stages* of the education career in which they are carried out. To this end, we distinguish among interventions during pre-compulsory schooling (or early childhood interventions), compulsory schooling (i.e. primary and secondary education), and post-compulsory schooling (i.e. tertiary education), as indicated in the first column of table 3.1. Thus, in the presence of a government education budget constraint, aside from the choice of a particular *type* of intervention (i.e. *how* to intervene?), policymakers are also concerned with the *timing* of educational interventions (i.e. *when* to intervene?).

How can the effects of a particular intervention be measured? Unfortunately, convincing policy evaluation studies are scarce. Much of the traditional evaluation literature does not fulfil the requirements of internal validity, in the sense that so-called *endogeneity bias* is present.[24] In table 3.1, we have confined ourselves to a presentation of studies using a (quasi-)experimental design. These studies exploit exogenous variation in interventions in education produced by natural or controlled experiments to evaluate their impact, thereby correcting for endogeneity of educational inputs.[25] In the design of new policy, one could take into account the possibilities for a proper evaluation based on natural or controlled experiments. This is helpful to evaluate the causal impact of policy some time after its implementation (so-called ex post policy evaluation). Such a strategy should therefore enable evidence-based policy design in the future.

What can we learn from table 3.1?[26] First, it appears from table 3.1 that the vast majority of interventions are designed to affect educational *quality*. This can be explained as follows. Some

[23] In this paper, we are only interested in the main effects of various interventions in terms of enrolment and student performance. A more in-depth analysis of the outcomes of these evaluation studies is already carried out in Webbink (2005) and Webbink and Hassink (2002).

[24] The key question in internal validity is whether observed changes in outcomes can be attributed to the intervention (i.e. the cause) and not to other possible causes.

[25] For a more in-depth discussion of the problems of measuring causal effects of educational interventions, the reader is referred to Webbink (2005).

[26] We are mainly interested in its implications for simulations of interventions in a macro model.

interventions of which the impact on educational quality is reported in table 3.1 may indeed have affected (or were designed to affect) educational quantity as well, but then its impact was not studied. A more profound reason is that the studies presented in table 3.1 evaluate the effectiveness of interventions carried out in advanced economies only, mostly in the US, and not in developing countries. Since advanced economies have often reached the upper limits of enrolment, at least in primary and -though somewhat less - in secondary education, (recent) public interventions in these countries are focused mostly on improving educational quality.[27] In other words, contrary to developing countries, the scope for raising enrolment or average years of education is relatively limited in developed countries.[28]

A second conclusion from table 3.1 is that early childhood interventions appear to be relatively more effective, both in terms of raising average years of education, as well as in improving student performance. When modelling early childhood interventions in a macro model, however, it is important to realise that the time lag between the intervention and labour market entrance of the students targeted with it is much longer than in the case of interventions during compulsory schooling, or (even more significant) during post-compulsory schooling. This means that the macroeconomic benefits of early childhood interventions, if any, materialise in the long term.

Third, considering interventions in the stage of compulsory and post-compulsory schooling, the picture arising from table 3.1 is mixed. The effectiveness of interventions in these stages of the education life-cycle differ not only *across* different types of interventions (e.g. extensions of instruction time appear to be more effective than more computer facilities), but also *within* a certain class of interventions (e.g. a larger class size, or performance incentives for students in higher education). Effects found in one program need not occur when exactly the same program is implemented in another city, region, country, on a larger scale, or in another time period. Furthermore, differences in program design and execution could also be an explanation for contrasting results within a certain class of interventions.

A final remark is that a cost-benefit analysis is absent in most evaluation studies presented in table 3.1. Some interventions may yield positive effects in terms of improvements in student performance or enrolment, but may have considerable costs due to the large expenditures incurred in those programs. Moreover, as argued by Carneiro and Heckman (2003), for many large-scale interventions it is essential to account for general equilibrium effects that reverse or diminish partial equilibrium effects.

[27] In the Netherlands for instance, 92% of all people aged 16 were engaged in full-time education in the year 2000 (89% in 1980), and that of 18-year olds amounted to 64% (46% in 1980), whereas enrolment of 24-year olds stood at 17% (9% in 1980) (SCP, 2004).

[28] This is not to deny that there is still some potential to raise educational quantity in industrialised countries, for instance by raising enrolment in tertiary education, or by lowering dropout rates in secondary education, that are in some cases substantial.

Table 3.1 Effectiveness of public interventions in education by type and level (based on studies with an (quasi-) experimental approach)

Timing (level)	Intervention (type) + country[3]	Literature	Effect Quality[7]	Effect Quantity[7]
Pre-Compulsory				
	early childhood interventions			
	several pre-school intervention programs (e.g. full-day child care, home visits, pre-school program) (US)	Heckman (2000);Currie (2001)[5]	+	+[16]
Compulsory[1]				
	'classical' education inputs			
	instruction time (school hours)			
	- Israel	Lavy (1999a)	+	
	- NL	Leuven et al. (2004a)	+[8]	
	- Sweden	Lindahl (2001)	+	
	expenditure per pupil (US)	Guryan (2001)	n.s./+[9]	
	class size reduction			
	- Israel	Angrist and Lavy (1999)	+	
	- NL	Dobbelsteen et al. (2002)	n.s.	
	- US	Krueger (1999, 2003)	+	
	- US	Hoxby (2000a)	n.s.	
	- US	Krueger and Whitmore (2001)	+	
	- various countries	Wößmann and West (2005)	n.s./+[10]	
	teacher training/acquisition			
	- Israel	Angrist and Lavy (2001)	n.s./+[11]	
	- US	Jacob and Lefgren (2004a)	n.s.	
	teacher testing/certification (US)	Angrist and Guryan (2003)	n.s.[12]	
	computer facilities			
	- in elementary and middle schools (Israel)	Angrist and Lavy (2002a)	n.s.	
	- in primary schools (NL)	Leuven et al. (2004b)	-	
	internet investment subsidy	Goolsbee and Guryan (2002)	n.s.	
	organisational changes			
	school-going age extension (Sweden)	Meghir and Palme (1999)		+
	competition (vouchers/school choice)			
	- US	Hoxby (2002)	+	
	- US	Cullen et al. (2003)	n.s.	
	- US	Krueger and Zhu (2003)	n.s.	
	performance incentives[4]			
	- merit pay for teachers (Israel)	Lavy (2003)	+	
	- merit pay for schools (Israel)	Lavy (2002)	+	n.s.[17]
	peer group (changes in class heterogeneity)			
	- Israel	Lavy (1999b)	+	
	- US	Hoxby (2000b)	+	
	teachers' grading standards (US)	Figlio and Lucas (2000)	+	

Table 3.1	**Continued**			
	specific projects for students at risk			
	- cash bonus for high school matriculation for low-achieving students (Israel)	Angrist and Lavy (2002b)	+	
	- additional instruction to underperforming students (Israel)	Lavy and Schlosser (2004)	n.s./+[13]	
	- funding for extra personnel for primary schools with disadvantaged students	Leuven et al. (2004b)	n.s.	
	- student counselling and financial incentives for minority students (US)	Taggart (1995); Heckman (2000)	+	
	- several dropout prevention programs (US)	Dynarski et al. (1998)[6]	n.s.	n.s.
	- remedial summer education (US)	Jacob and Lefgren (2004b)	n.s./+[14]	
Post-Compulsory[2]				
	tuition fees			
	- US	Heckman et al. (1998),		– (0.07)[18]
	- US	Cameron and Heckman (2001)		– (0.02-0.05)[18]
	- US	Dynarski (1999)		– (0.03)[17]
	financial support (loans/ grants)			
	- California college grant program (US)	Kane (2003)		+
	- social security student benefit (US)	Dynarski (1999)		+
	- SOFES loan program (Mexico)	Canton and Blom (2004)	+	
	performance incentives for students			
	- reward for 1st year college completion(NL)	Leuven et al. (2003)	n.s./+[15]	
	- performance-based grant system (NL)	Belot et al. (2004)	+	

Sources: partly adapted from Webbink and Hassink (2002); Webbink (2005).

Notes:

1 Primary and secondary education.

2 Tertiary education.

3 US = United States, NL =Netherlands.

4 The reader is referred to Canton and Webbink (2004) for a discussion of evaluations of interventions based on performance incentives.

5 Heckman and Currie have reviewed several (quasi-)experimental evaluation studies of various early childhood intervention schemes.

6 Dynarski et al. (1998) have reviewed sixteen dropout prevention programs carried out in the US, of which eight middle-school programs and eight high-school programs. These programs were generally ineffective in lowering the dropout rate or improving student performance. However, some positive results were found for a limited number of intensive middle school programs and for high school GED programs.

7 + significant positive effect on performance; n.s. no effect; - significant negative effect on performance.

8 Positive effects on test scores apply only to pupils with lower educated parents and minority children.

9 Test scores are positively affected for 4th-grade students, but increased spending showed no effect on 8th-grade test scores

10 Class-size effects are estimated on mathematics and science achievement in 18 countries. Significant positive effects of smaller class size were found for only two countries (Iceland and Greece). Wößmann and West (2005) conclude that class-size effects in one school system cannot be interpreted as a general finding for all school systems.

11 Positive effects are found for secular schools, but effects on student performance in religious schools are insignificant.

12 Effects have been studied on teacher quality as an indirect measure of educational quality.

13 Remedial education improved the performance of sixth graders, but not of third graders.

14 Cash bonuses for high school matriculation (this is a prerequisite for university admission) are effective when provided to an entire school, but not when given to individually selected students within the school.

15 Positive effects are found for students with high math skills and for students with higher educated fathers when given a ‘high’ reward.

16 The quantity effect of early childhood interventions refers to the direct effect on average years of schooling due to the extra classes in the pre-school stage, but also to the indirect effect caused by increased high school graduation rates and/or lower dropout rates.

17 The quantity effect refers to the impact on the dropout rate.

18 Presented numbers are enrolment elasticities.

3.1.3 Conclusions

When modelling education in a macro context, one should take account of:

- Possible external effects of education;
- Effects on income distribution;
- Varying effects by education level in terms of size and type;
- Possibly decreasing returns to the expansion of education;[29]
- A distinction between the quantity and quality component of education;
- Bounded growth of educational quantity (particularly in developed countries);
- In principle unbounded growth of educational quality.

When modelling education *policy* in a macro-context, one should take account of the following notions:

- A distinction between policies aimed at raising enrolment or average years of education (quantity) and policies aimed at raising student performance (quality) could be workable;
- Timing of intervention matters: pre-school interventions appear to be more effective than interventions in later stages of the education cycle;[30]
- The type of intervention under consideration matters as well: at each stage of the education cycle the government can mostly choose from a whole menu of interventions. Measurements of effectiveness vary not only between different types of interventions, but also *within* a certain class of interventions (class-size reductions for example).
- Macroeconomic effects of interventions in the early stage of the education life cycle in terms of labour market outcomes materialise much later than effects of interventions in for instance tertiary education.

3.2 Research and development

In the previous subsection, we have discussed the impact of government policy on human capital. Here we will focus on another important factor in terms of its potential impact on the process of economic growth, notably research and development (R&D). The outline of this section is as follows. First, in Section 3.2.1 we briefly discuss the rationale for public intervention in R&D, both from a theoretical and an empirical perspective. Subsequently,

[29] As mentioned by Sianesi and Van Reenen (2002), the incremental value of additional education in countries where average length of education is already high is less obvious, and probably depends largely on the type and quality of education.

[30] Another argument in favour of early interventions in education is that early investments raise the productivity of later investments, as argued by Carneiro and Heckman (2003): *'Learning begets learning, skills (both cognitive and non-cognitive) acquired early on facilitate later learning'*.

Section 3.2.2 reviews the most important policy instruments in the area of R&D and sheds some light on their effectiveness. Section 3.2.3 concludes.

3.2.1 Rationale for public intervention in research and development

Several market failures have been identified in economic theory as a justification for public interference with R&D (e.g. Romer, 1986; Lucas, 1988; Jaffe, 1996). Most often mentioned are external effects, capital market constraints following from asymmetries in information between capital markets and R&D spenders, and insurance market imperfections.[31]

Let us briefly focus on R&D spillovers.[32] The theoretical literature discerns several channels along which R&D spills over from one firm, sector or country to another, both positive and negative. We can distinguish among the following two types of *positive* R&D spillovers, due to which incentives of companies to invest in R&D may be too weak (relative to the social optimum):

- *Knowledge spillovers*: the revenue from R&D is (technological) knowledge. This knowledge has, at least to some extent, features of a public good: it is non-rivalrous and only partially non-excludable. Once invented, other companies, both competitors and companies operating in other sectors (e.g. suppliers), may imitate ideas produced by the innovating company.[33] The *standing on the shoulders of giants* effect of knowledge spillovers benefits other firms through knowledge leaks, imperfect patenting and movement of skilled labour to other firms (cf. Cameron, 1998). However, as emphasised by Cohen and Levinthal (1989), acquiring the results of other firms' R&D requires research effort (and costs) by the recipient firm. Rather than thinking of R&D (knowledge) spillovers as exogenous, a firm needs to invest in its *absorptive capacity* (i.e. the firm's ability to identify, assimilate and exploit knowledge developed elsewhere) in order to gain from knowledge spillovers from other firms. Leahy and Neary (2004) specify a model of the absorptive capacity process and show that this costly absorption, while raising the returns to own R&D, lowers the effective spillover coefficient.[34]

[31] Information asymmetries (about the quality of planned R&D projects) between providers of capital and firms engaged in R&D may lead to moral hazard problems and adverse selection. We refer to Canton et al. (2005) for a more detailed analysis of capital market imperfections in the market for R&D. Insurance market imperfections arise when firms are unable to insure themselves against the risks involved in R&D investments, neither by building up a sufficiently diversified research portfolio nor by contracts with insurance companies. *Ceteris paribus*, both market failures lead to underinvestment in R&D relative to what is socially optimal.

[32] For a more comprehensive review of the R&D spillover literature, the reader is referred to Griliches (1992) and Cameron (1996). Our goal here is just to present the main (theoretical) arguments for government intervention in the market for R&D.

[33] However, intellectual property rights and delays in the dissemination of ideas enable the innovator to appropriate a share of the rents from a new idea.

[34] Moreover, Cohen and Levinthal (1989) argue that own R&D's contribution to a firm's absorptive capacity (i.e. the "second face of R&D") has an important implication for R&D policy, notably, that the negative incentive effects of intra-industry knowledge spillovers (i.e. underinvestment in R&D) may not be as great as supposed. This means that the benefits of policies designed to mitigate these negative incentive effects, such as patent policies, may be not as great as generally assumed either.

- *Rent (or surplus) spillovers*: the firm carrying out R&D is not able to appropriate the entire consumer surplus associated with the good it creates. Full appropriation would only be possible if the innovating firm can price discriminate perfectly to downstream users (Cameron, 1998). However, a firm cannot charge every customer the maximum price each customer is willing to pay. This implies that downstream industries or consumers benefit from R&D efforts by upstream industries. Also, the importance of these rent spillovers increases with the intensity of competition, as in a perfectly competitive market consumers are able to capture the entire surplus.

On the other hand, theory also identifies two *negative* types of R&D spillovers, potentially leading to private overinvestment in R&D:

- *Business stealing effect*: new ideas resulting from R&D efforts by one company can make existent production processes and products of competitive firms obsolete, even if these new ideas are only marginally better. This process of Schumpeterian creative destruction may cause the current innovator to receive the entire flow of rents, while the past innovator is forced out of the market. The resulting profit loss of the past innovator is not internalised by the current innovator. This business stealing effect may raise private incentives to invest in R&D relative to social incentives. The fact that the past innovator takes into account the possibility of dynamic competition (i.e. being forced out of the market) in its decision to innovate does not make this argument invalid (Aghion and Howitt, 1992).

- *Duplication externality* (or *congestion externality*): companies are sometimes engaged in patent races, in which multiple firms run parallel R&D programs in the hope of being the first to succeed in patenting a new good or process (Jones and Williams, 2000). This duplication of research efforts is also called the stepping on toes effect, and it reduces the average productivity of R&D in an economy.

If positive R&D spillovers dominate negative externalities, leaving aside other market failures, the social rate of return will exceed the private rate of return to R&D. In that case we can state that there is private underinvestment in R&D (relative to the social optimum).[35]

What does the empirical literature tell us? The majority of studies finds that social returns substantially exceed private returns to R&D at current levels of public intervention, so that (positive) R&D spillovers are both prevalent and important (cf. Griliches, 1992; Nadiri, 1993; Jones and Williams, 1998; Cameron, 1998, Canton, 2002). Jones and Williams (1998) even

[35] However, there is the possibility that *existing* policies have already internalised R&D spillovers, thereby eliminating the gap between the social and private rate of return that would have existed in the absence of any policy intervention. Moreover, there is also a risk of (over-) internalisation of R&D spillovers due to institutions initiated by the market. Examples of these institutions are patents, technology licenses, and R&D-cooperation of firms (i.e. research joint ventures) (cf. Leahy and Neary, 1999; Kamien and Zang, 2000).

argue that conservative estimates of R&D spillovers (i.e. the discrepancy between social and private returns to R&D) suggest that optimal R&D investment in the US is at least four times actual investment.[36]

If the available estimates of the social and private returns to R&D are true, this would imply that current levels of public interference with R&D are too low. Stated otherwise, these large spillovers would justify a reallocation of public funds to R&D. However, as already noted in Section 2.3.5, the high social and private returns to R&D found in the literature are not undisputed and should be treated with caution. Nonetheless, there would appear to be at least some scope for additional social gains from increased public interference with R&D. The potential benefits of an interference should be compared to the costs (higher taxes and government failure).

In addition to the question how much R&D should be stimulated, the government also needs to decide what type of R&D can best be promoted. It is important to realise that R&D is a heterogeneous phenomenon, and that rates of return on R&D and the size of spillovers may vary across different types of R&D. The main findings, as summarised in OECD (2003), are as follows. First, the returns to *process* R&D are higher than the returns to *product* R&D. Second, rates of return on *private* R&D are much higher than those on *public* financed R&D. Third, *basic* R&D generally yields higher returns than *applied* R&D. Fourth, returns to R&D vary between industries, with R&D in research-intensive sectors having higher returns. Finally, the size of R&D spillovers appears to depend not only on the type of R&D, but also on geographical distance to the firm carrying out R&D. As argued by Cameron (1998), R&D spillovers tend to be localised, with foreign economies gaining significantly less from domestic innovation than other domestic firms.[37]

[36] Jones and Williams (1998) have derived an endogenous growth model in the spirit of Romer (1990), which incorporates all four of the earlier mentioned R&D externalities, notably knowledge spillovers, rent spillovers, the *stepping on toes* effect, and *creative destruction*. In a more recent paper, Jones and Williams (2000) develop a different endogenous growth model, this time in the tradition of Stokey (1995), in which they incorporate the same four distortions to R&D to tackle the issue of over- or underinvestment in R&D. Again they find that there is typically underinvestment in R&D relative to what is socially optimal, unless duplication externalities are very large and the equilibrium real interest rate is extremely high.

[37] This does not imply that domestic firms do not profit from foreign R&D. There is some debate, however, on the impact of foreign R&D knowledge on domestic productivity (relative to domestic R&D spillovers), as well as the mechanisms through which this occurs. Coe and Helpman (1995), for example, in a sample for 22 OECD countries, find that foreign R&D has a positive and quantitatively large effect on domestic productivity, and argue that these international R&D spillovers are stronger the more open an economy is to foreign trade. Keller (1998), however, questions the assumption that international trade flows are the (main) channel of foreign technology diffusion. Keller uses random shares to create the counterfactual foreign knowledge stock instead of the bilateral import shares used by Coe and Helpman, and finds similarly high coefficients and levels of explained variation in productivity. Furthermore, two country studies on international R&D spillovers are worth mentioning. First, Jacobs et al. (2002) find evidence for spillovers from foreign R&D in the Netherlands, but these are small relative to domestic inter-industry spillovers (TFP elasticities are 3 and 15%, respectively). Second, Griffith et al. (2004) show that US-based R&D positively affected total factor productivity of UK firms in the 1990s, and that these spillovers were larger in industries whose TFP gap with the US was greater. The reader is referred to Cincera and Pottelsberghe de la Potterie (2001) and Keller (2004) for an elaborate survey of both macro and micro level studies of international R&D spillovers.

These observations have important policy implications not only for the types of R&D that governments should promote, but also, on the issue of the magnitude of foreign R&D spillovers, whether policy should be aimed at assimilating foreign technologies rather than stimulating domestic investment in R&D.

3.2.2 Effects of R&D policy

Apart from the legitimacy of R&D policy, we are interested in two other issues. First, what instruments may governments use to affect the level and/or the average (social) rate of return to R&D in the economy? And second, is it possible to draw some general conclusions about the (relative) effectiveness of these instruments from the empirical literature? Whereas there is a rich literature on the first question, the second question is somewhat more complicated. Good ex-post evaluation studies of the various R&D policy instruments, that is, studies with a (quasi-)experimental design, are scarce.[38] Cornet and Van de Ven (2004) argue that policy experiments, in which some (randomly chosen) firms are disposed to a certain treatment, may yield interesting insights into the effectiveness of R&D policies.[39]

Policy instruments

Let us turn to the first question and start with an overview of the various instruments governments generally use to affect the level of R&D investment in the economy, either directly or more indirectly. The level of R&D investments depends on the quality of basic institutions, such as patent systems or the financial sector. This implies that there is a role for policy in these areas. However, we restrict ourselves to the following categories of policy instruments:

- Fiscal incentives (i.e. R&D tax credits);
- Public funding of private-performed R&D (e.g. public grants, government procurement contracts);[40]
- Public performed R&D (e.g. public research laboratories; university research);
- ‘Framework’ policy (e.g. education policy, competition policy, labour market policy, trade policy).[41]

[38] Examples of studies with a (quasi-)experimental design in the area of education are shown in Section 3.1.2.

[39] These kinds of experiments are very common for evaluating the effectiveness of new medicines for instance.

[40] Government procurement contracts generally are financial outlays to procure research results that are expected to assist the public agency in better defining and fulfilling its mission objectives. Examples can be found in public aerospace or defense. Public grants are the primary mechanism for funding exploratory research for the advancement of knowledge and fostering emerging technologies (cf. David et al., 2000).

[41] We have labelled this category framework policy, because it refers to policy of which the principal focus is not to stimulate R&D activity in the economy.

These factors are under direct control of the government and are easier to incorporate in macro-models than for instance patent laws or financial sector regulations. The first two instruments are *directly* targeted at stimulating business R&D. Fiscal incentives and public funding of private performed R&D directly lower the costs of research of firms.[42] On the other hand, research carried out in public research laboratories and in universities lower the costs and uncertainty of private research in a more indirect way, for instance by helping firms to understand the technological opportunities that are available (cf. Guellec and Van Pottelsberghe de la Potterie, 2003).[43]

Finally, the fourth category of policy instruments (i.e. framework policy) contains policies that have no direct focus on R&D, but that may play an important role in affecting the level (or productivity) of R&D activity indirectly. Let us briefly discuss the interactions between R&D and policy in the two other main areas discussed in this chapter, that is, education and competition. First consider education policy. Scientists and engineers can be seen as the main input for R&D. This implies that, in addition to policies aimed at raising R&D activity from the *demand* side, there is a potential role for (higher) education policy in stimulating R&D activity from the *supply* side by increasing the supply of scientists and engineers. Supply side constraints may arise from a relatively inelastic supply of scientists and engineers, reflecting the time to acquire the necessary human capital.[44] A more general argument for the importance of education policy is that empirical studies show a strong interaction between human capital and R&D. Economic theory has also made clear that human capital and R&D activity are complements: R&D is more effective the more skilled the labour force is (cf. Redding, 1996; Goldin and Katz, 1998; Bucci, 2003).

A second example of framework policies is competition policy. It is widely believed that the degree of competition in a market affects the incentives for firms to innovate, and, thus, to engage in R&D activities. This implies that competition policy may be used to affect the level of R&D that is undertaken in certain markets. However, the recent literature shows that the relationship between competition and innovation (and hence, R&D) is not unambiguous. Different effects may work against each other (e.g. the *escape competition* effect and the *Schumpeterian* (surplus appropriability) effect, cf. Aghion et al., 2002). It is not clear which

[42] The primary difference in execution between these two policy instruments is that tax incentives typically allow the private firms to choose projects, whereas direct subsidies for R&D are often accompanied by a government directed choice, either because the government spends the funds directly, or because the funds are distributed via grants to firms for specific projects or research areas (David et al., 2000).

[43] Moreover, stimulating business R&D is generally not the only or the principal goal of research carried out in public research laboratories and universities. For example, universities may carry out research projects that yield significant social returns, but in which the private sector shows no interest. The wedge between private and social returns is likely to be highest in basic research (i.e., the type of research typically carried out in universities), rather than in applied research.

[44] An example of the importance of education policy in shaping the conditions for effective R&D policy is provided by Romer (2000). He argues that existing institutional arrangements in higher education in the US have limited the supply response of scientists and engineers that was necessary to make the R&D subsidies work that stimulated private sector demand of scientists and engineers.

effect dominates in a particular market with a certain degree of competition.[45] This has implications for the optimal design of competition policy, at least if it is to stimulate innovation, and implicitly, the level of R&D activity.

Effectiveness of R&D policy

The effectiveness of R&D policy can be evaluated by two indicators. The first indicator is the aggregate amount of R&D *activity*.[46] Stated otherwise, how much *additional* R&D is stimulated by one dollar of government money? The second indicator is the marginal (social) rate of return to R&D. What is the productivity of these additional R&D investments? It should be noticed that the majority of evaluation studies only focuses on the *additionnality* of R&D policy, and not so much on its impact on the social rate of return to R&D.

A priori, the theoretical impact of government policy is not evident. Let us first consider the impact of government policy on the *level* of R&D activity. There are several reasons why policy instruments do not always lead to additional (private) R&D, and hence effectiveness may be lowered:[47]

- Substitution;
- Input price effect;
- Fungibility.

First, public funded R&D may complement private R&D by providing knowledge that is helpful to firms. This will stimulate private R&D. However, it may also directly substitute for private funding of R&D projects that would have been undertaken anyway in the absence of this public funded R&D.

Second, government R&D policy may also crowd out private R&D indirectly by increasing the demand of R&D, which may lead to higher costs of research inputs, and hence, a lower rate of return. This crowding out effect will become more significant the more inelastic the supply of research inputs. Goolsbee (1998) mentions that the majority of R&D spending is just salary payments for R&D workers. Because their labour supply is quite inelastic, he argues, a significant fraction of government funding of R&D goes directly into higher wages of

[45] Aghion et al. (2002) develop a Schumpeterian growth model predicting that the relationship between product market competition and innovation has an inverted U-shape. The main idea is that, at low levels of competition, the *escape competition* effect dominates, and more competition leads to higher incentives to innovate (in order to take the lead over your rivals), whereas at high levels of competition, the *Schumpeterian* effect dominates, such that more competition reduces incentives to innovate. Aghion et al. (2002) have confronted the prediction of this inverted U-relationship with UK firm level data on competition and innovation activities (measured both, by the amount of patents and by R&D spending), and seem to find empirical support for this prediction. However, the empirical literature on this issue is still thin and developing, so that strong conclusions are unwarranted at the moment...

[46] The amount of R&D *activity*, or the volume of R&D investments, should be distinguished from R&D *expenditures*, in the sense that the latter also carries a price component.

[47] We refer to Cornet and Van de Ven (2004) for a more extensive treatment of this issue.

researchers.[48] When faced with these higher research costs, firms shift their funding to alternative investments. This implies that, even if government funding raises the total amount of R&D expenditures in the economy, the *real* amount of R&D activity (adjusted for the higher cost of research) increases less. Goolsbee states that, because of this wage effect, conventional estimates of the effectiveness of R&D policy may be 30 to 50% too high.[49]

A third reason why R&D policy may not lead to additional R&D is that part of the reported R&D expenditures may just be a relabelling of existing activities to R&D, so as to make them qualify for policy instruments such as tax deductions. This is also called fungibility.
Besides having an ambiguous impact on the *level* of R&D, government policy may also change the *composition* of R&D, and, thereby, the average (social) rate of return to R&D. For instance, public R&D may perfectly substitute for private R&D, thereby leaving total R&D unaffected. Yet, the average impact of R&D may be lowered if the return to this additional public R&D is lower than the return to private R&D. In an ideal situation, policy triggers research projects with the highest social rate of return. However, two factors may limit the effectiveness of R&D policy in this respect: lack of information on part of the government about the social returns to R&D of particular projects, and the pressure of lobby groups (cf. Cornet and Van de Ven, 2004). This may lead to government support of undesirable R&D projects, that is, projects with a low social rate of return.

Above, we have sketched some *theoretical* arguments showing how the effectiveness of R&D policies may be lowered. Whereas it is useful to understand these mechanisms, simulating R&D policies in a macro model requires insights in how effective these policies really are. Is it possible to derive some general conclusions from the available empirical studies?

The majority of evaluation studies of R&D policy has focused either on the effectiveness of fiscal incentives (e.g. Mohnen, 1999; Hall and Van Reenen, 2000), or on the impact of public *funding* of private performed R&D (e.g. Capron and Van Pottelsberghe de la Potterie, 1997; David et al., 2000, Garcia-Quevedo, 2004). Much less is known about the effects of public *performed* research on private R&D activity, that is, research conducted in government labs or universities.[50]

Most of the available evaluation studies of R&D programs have not been based on microeconomic techniques, but instead on case studies and interviews with project managers. These kinds of studies suffer from the objection that the results are often not representative or

[48] The reader is referred to Jacobs and Webbink (2004) for a discussion of the current labour market situation of R&D workers in the Netherlands.

[49] Marey and Borghans (2000) have estimated this wage effect for the Netherlands. They find that one euro additional expenditure on business R&D increases wages by 20 to 30 eurocents.

[50] If studied, the effectiveness of the various instruments is often studied separately. However, instruments are generally used simultaneously, and it is important to take account of interactions between the instruments. For instance, those policies affecting applied research, such as R&D tax credits, may enhance the efficiency of instruments oriented towards basic research, as they may strengthen the absorptive capacity of recipient firms. As argued by Guellec and Van Pottelsberghe (2003), the different tools thus constitute a system, and their efficiency can best be captured by analysing the system as a whole.

(upward) biased, as argued by Klette et al. (2000). Evaluation studies based on controlled or natural experiments are rather scarce.[51] With respect to the findings reported below, it should be stressed that in all studies there is a lot of unexplained variation in the estimated returns or elasticities. This is due to the heterogeneity of the empirical models used (e.g. regarding time periods, data sources, the level of aggregation (e.g. firms, industries, countries), and econometric techniques). Furthermore, it may reflect differences in the effectiveness of R&D programs, which are all very specific in nature. This makes it difficult to simulate a specific government program in a macro-model. Whereas it is not our purpose to discuss all the ins and outs of the results found in the empirical literature, let us summarise the main findings.

Fiscal incentives

The effectiveness of fiscal incentives to stimulate private R&D is measured by the so-called *tax price elasticity*. This indicator can be interpreted as the amount of additional R&D that is generated by one dollar of tax deduction. As could be expected, there is a good deal of variety in econometric estimates of this tax price elasticity, ranging from 0.1 to 2. In a review of the literature, Hall and Van Reenen (2000), however, conclude that the most plausible estimates of the tax price elasticity are around unity, which signifies that each dollar forgone in tax credit for R&D stimulates a dollar of additional R&D. Mohnen (1999, p.12) has also reviewed the existing econometric estimates of the tax price elasticity: “The existing evidence about the effectiveness of R&D tax incentives, although it is mixed, seems to tilt towards the conclusion that they are not terribly effective in stimulating more R&D than the amount of tax revenues foregone.” Finally, Bloom et al. (2000) estimate an econometric model using panel data on tax changes and R&D spending in eight industrialised countries to examine the impact of R&D tax credits on the level of R&D investment. They find that, in the short-run, a 10% fall in the cost of R&D stimulates 1% additional R&D, whereas in the long run, R&D increases by over 10%.

Is there any empirical evidence on the effectiveness of R&D tax incentives in the Netherlands? The most important government program to stimulate private R&D activity in the Netherlands is the WBSO, a wage tax credit for R&D labour.[52] The WBSO is a generic instrument, for which about three-quarters of all companies engaged in R&D in the Netherlands apply (Brouwer et al., 2003). Estimates of the effectiveness in terms of the extra amount of R&D activity generated by one Euro of this wage tax credit vary. Brouwer et al. (2003) find a tax price elasticity of unity on the basis of an instrumental variable analysis. Bureau Bartels

[51] As mentioned by Klette et al. (2000), evaluating the impact of R&D policies, one has to face the question of what would have taken place without the program, and this makes it an exercise in counterfactual analysis. Consider for instance large scale R&D subsidy programs. Neither the firms receiving support, nor those applying can be considered random draws. Public authorities may be more inclined to support firms that are already carrying out R&D and that have good innovative ideas. Constructing a valid control group in this setting is quite challenging. Klette et al. (2000) conclude that a more careful inference of the magnitude of the impact parameters of interest can be made drawing from the recent advances in the evaluation literature in labour market econometrics (e.g. Heckman et al., 1998; Angrist and Krueger, 1999).

[52] The abbreviation WBSO stands for ‘Wet vermindering afdracht loonBelasting en premie volksverzekeringen, onderdeel Speur- en Ontwikkelingswerk’, which means: Reduction of contributions wage taxes and social insurance act, part research and development.

(1998) use another methodology by conducting interviews with managers of the firms that received the wage tax credit. This study finds that only two-thirds of the WBSO subsidy was spent on additional R&D.

Cornet (2001), however, lists four arguments why the additionality of the WBSO may be overestimated in the literature: substitution, fungibility (or relabelling), the input price (or wage) effect, and selection effects.[53] The first three effects have been explained earlier. Selection effects may occur because firms generally propose those projects with the highest expected returns. Taking into account the uncertainty about the size of these effects, Cornet (2001) arrives at about 50 percent as a lower bound for the additionality of the WBSO, and about 100 percent as an upper bound. In addition, Cornet argues that a full cost-benefit analysis requires knowledge of the social rate of return on the extra R&D induced by the instrument, which is difficult to measure.[54] This lack of knowledge on the size of these crucial impact parameters (i.e. additionality, and the social rate of return on additional R&D) complicates simulations of tax incentive schemes (or, in fact, any other R&D policy program) in a macro model.[55]

Public funding of private performed R&D

The relevant question when determining the effectiveness of public funding of R&D is whether it complements private R&D activity or substitutes for private performed R&D. The literature is not unambiguous on this issue.[56] Let us discuss the main findings.

David et al. (2000) find that one third (11 out of 33) of the empirical studies they review report net substitution of public funded R&D for private R&D. Garcia-Quevedo (2004) finds that a little less than one quarter (17 out of 74) of the reviewed studies report substitutability.[57] Both David et al. and Garcia-Quevedo find that substitution is far more prevalent among the studies conducted at the firm level, than among those carried out at the industry or country level.[58]

Guellec and Van Pottelsberghe de la Potterie (2003) find that one dollar of public funding of private performed R&D by means of grants or public contracting stimulates 0.70 dollar of private R&D (cf. Table 3.2).[59] They simultaneously analyse the effects of the four earlier mentioned policies (i.e. fiscal incentives; public funding of private R&D; public research in

[53] Cornet (2001) supposed on the basis of the scare empirical literature that the fungibility and the input price effect jointly account for about one third of additional R&D expenditures due to the WBSO.

[54] Cornet takes 20 percent as the lower bound, and 60 percent as the upper bound for the social rate of return on extra R&D generated by the WBSO. We refer to Cornet (2001) for the reasoning behind taking these boundaries.

[55] An example of a computable general equilibrium model with R&D and R&D tax incentives is Russo (2004).

[56] Studies differ according to the level of aggregation (firms; industries; countries), time-period under consideration, type of data (cross-section; time-series), and econometric methodology.

[57] This does not imply that the remaining studies report complementarity, because another quarter of the studies under consideration find an insignificant relationship between public funding of R&D and private R&D activity.

[58] Another interesting result found by Garcia-Quevedo and David et al. is that crowding out of private R&D is more often found in studies for the US than in studies for other countries.

[59] This value is the *average* amount invested by private decision makers when they receive one dollar of subsidies. However, we would like to stress that the relative importance of positive spillovers and negative crowding out effects of public funding of R&D may differ substantially across industries, as well as across countries.

government labs; research performed by universities) on private R&D outlays in one framework, using data for 17 OECD countries.

Capron and Van Pottelsberghe de la Potterie (1997) have reviewed a large number of studies and conclude the following: "Despite the heterogeneity of the empirical models referred to in the literature, which makes any comparison exercise hazardous, the balance seems to tilt towards the recognition of a complementary effect between the two sources of funds. However, there are some indications that in some industries, or in some countries, government R&D is a substitute for private R&D."[60]

Research performed in the public sector

An interesting question is whether the private sector benefits from publicly performed research. Cohen et al. (2002) find that public research positively affects industrial R&D, but that the magnitude of this effect varies by industry and firm size. After controlling for industry effects, the impact of public research on industrial R&D is greatest for larger firms as well as for start-ups.

However, we have seen earlier that publicly performed research consists of two categories, notably, research conducted in public research laboratories and university research. Relatively little is known about the separate effects of each of these two categories of public R&D on private R&D outlays. One of the notable exceptions is the earlier mentioned study of Guellec and Van Pottelsberghe de la Potterie (2003). They find that, for the group of 17 OECD countries as a whole, an extra dollar of R&D conducted in government labs crowds out 44 cents of private R&D, whereas a dollar spent on academic research lowers private R&D expenditure by 18 cents (see table 3.2).[61] An important drawback of the study of Guellec and Van Pottelsberghe de la Potterie (2003) is that it does not sufficiently take into account the longer term effects of R&D policies, such as knowledge spillovers (cf. Venniker and Canton, 2004). For instance, it may take a few years before basic knowledge developed in universities spills over to firms. This implies that the net effect of university research on private R&D outlays may not be that negative, or may even be positive in the long term.

[60] For example, a country-level study of Capron and Van Pottelsberghe de la Potterie (1997) finds that the marginal impact of public funded R&D on private R&D activity is significantly negative (i.e. substitution) for Canada, France and Italy, insignificant for Germany and Japan, whereas it is positive (i.e. complementarity) for the UK. The interested reader is referred to Capron and Van Pottelsberghe (1997) and Garcia-Quevedo (2004) for a comprehensive review of the results of many other empirical studies on this issue.

[61] These average marginal effects may mask potentially large international differences. As mentioned by Venniker and Canton (2004), the marginal effect of an extra dollar of public money in countries characterised by a relatively low ratio of private R&D outlays to public outlays, which is the case in the Netherlands for instance, will be smaller (in absolute terms).

An example of a study finding a positive effect of university research on private (industry) R&D is Jaffe (1989). Using US state-level data, and controlling for population and economic activity, Jaffe finds a positive elasticity of 0.7.[62]

Table 3.2 Effects of R&D policy on private R&D outlays[1]

	Public funding	Fiscal incentives[2]	Government labs	University research
Short-term elasticity	0.07	0.29	– 0.07	– 0.04
Long-term elasticity	0.08	0.33	– 0.08	– 0.05
Marginal effect of an extra dollar[3]	0.70		– 0.44	– 0.18

Source: Guellec and Van Pottelsberghe de la Potterie (2003). The table is taken from Venniker and Canton (2004).

Notes:

1 Based on data on 17 OECD-countries from 1983 to 1996.

2 Tax outlays have been measured by an index, and should not be interpreted in monetary (dollar) terms. The reader is referred to Guellec and Van Pottelsberghe de la Potterie (2003) for an explanation of the construction of this index.

3 This is calculated as the elasticity times the ratio of the relevant government outlays and private R&D outlays over all 17 countries in 1997.

3.2.3 Conclusions

When modelling R&D in a macro-context, one should take account of:

- (Substantial) positive external effects of R&D (i.e. social rate of return exceeds private rate of return to R&D).
- Interactions of competition and the stock of human capital with the level and/or returns to R&D.

When modelling R&D *policy* in a macro-context, one should take account of the following notions:

- Policy may impact upon the level of R&D activity as well as upon the rate of return to R&D.
- A whole array of different types of policies exists to impact upon R&D activity, either directly or more indirectly. The effects of each of these different types of interventions vary in terms of magnitude and character. Empirical evidence on the (relative) effectiveness of these different policies based on sound evaluation studies (i.e. studies with a (quasi-) experimental design) is scarce.
- Even when considering a certain type of intervention (e.g. tax credits), it is difficult to draw conclusions on its effectiveness. This is because R&D programs are often very specific in nature, and the effects of a particular program often depend on program design and management. Moreover, effects found for one particular intervention need not to occur when exactly the same intervention is carried out in another region or country, on a larger scale, in another time period, or in another industry (this is the concern of external validity).

[62] However, as mentioned by Jaffe, there are some caveats in the data used, and one cannot interpret these results structurally, in the sense of predicting the resulting change in industrial R&D if university research spending were exogenously increased.

- There may be time lags in the effects of R&D policies. For instance, public R&D may directly crowd out private R&D, whereas the knowledge spillovers of this public R&D to firms only materialise after some years. It is important to take these lag structures into account when modelling R&D policies in a macro-model.

3.3 Product market competition

In this section, we discuss the impact of competition policy. As competition is not a production factor, we confine ourselves to a description of the impact of competition policy on several important macroeconomic indicators. Table 3.3 presents a summary. The empirical evidence presented in the table suggests that regulatory reform has been beneficial for efficiency. Both level and growth effects seem to be relevant. It should be noted that it is not straightforward to derive welfare implications from these results. There will be a time lag between the regulatory reform and the efficiency gain (see Matheron and Maury (2004) for a simulation analysis to quantify the welfare cost of monopolistic competition in an endogenous growth framework), and possible adjustment costs are not taken into account.

CEPR and IFS (2003) review a number of important product market regulations and reforms at the level of the aggregate economy, such as:

- Ease of starting a new business;
- Trade;
- State involvement in the economy;
- Administrative burden on business.

First, the ease of starting a new business can affect entry, and thereby competition within an industry (although Geroski (1995) finds that entry has only a modest effect on average price-cost margins). Data on the ease of starting a new business are for instance available from the Fraser Institute and the OECD. According to the Fraser Institute index, it is relatively easy to start a new business in Finland and the US (respectively 8.8 and 8.4 on a 10 point scale in 2000). The Netherlands has an index of 7.6 in the year 2000. Second, according to economic theory, lowering import barriers will increase the degree of competition. An important indicator for trade barriers is the average import tariff rate. There is little variation in tariff rates across EU countries, as rates were largely harmonised within the European Community. Third, CEPR and IFS include several aspects of government involvement in the economy, such as government transfers and subsidies as a percentage of GDP, government enterprises and government investment as a percentage of total investment, price controls, and public procurement as a percentage of GDP. Finally, to proxy for the administrative burden on business, CEPR and IFS use the Fraser Institute index of “Time senior management spends with government bureaucracy". The Netherlands performs very well on this indicator, i.e. the burden is considered to be low by the surveyed managers and entrepreneurs (2000 data).

Table 3.3 Product market liberalisation and performance

Study	Country / period	Explanatory variable	Performance variable	Effects found	Method
Emerson et al., 1988	EU, medium-term	Implementation of Single Market	GDP	+ 4.1%	Simulation
Industry Commission, 1995	Australia, long-run	Deregulation (implementation of the Hilmer report)	GDP	+ 5.5%	Simulation
Lipschitz et al., 1989	Germany, annually	Deregulation	GDP	+ 0.3%	Simulation
Van Sinderen et al., 1994	Netherlands, annually	Deregulation	GDP	+ 0.5%	Simulation
OECD, 1997	8 OECD countries, long-run	Regulatory reform in electricity, air travel, road freight, telecom, and retail	GDP		Simulation
	US			+ 0.9%	
	Japan			+ 5.6%	
	Germany			+ 4.9%	
	France			+ 4.8%	
	UK			+ 3.5%	
	Netherlands			+ 3.5%	
	Spain			+ 5.6%	
	Sweden			+ 3.1%	
Goff, 1996	US, 1950-1992	Index of regulatory intensity	GDP	– 0.9% (annually)	Econometric
Koedijk and Kremers, 1996	11 EU countries, 1981-1993	Index of strictness of product market regulation	GDP per capita growth	Negative	Descriptive
			TFP growth	Negative	
			Labour productivity growth	Negative	
Gwartney and Lawson, 1997	115 countries	Index of degree of economic freedom	GDP per capita	Positive	Descriptive
			GDP per capita growth	Positive	
Dutz and Hayri, 1999	52 countries, 1986-1995	Index of pro-competitive policy environment	GDP per capita growth	Positive	Econometric
Edwards, 1998	93 countries, 1980-1990	Index of openness to trade	TFP growth	Positive	Econometric

Source: Ahn (2002).

CEPR and IFS conduct a regression analysis to investigate the influence of the competition indicators on mark-ups. The data include 12 OECD countries over the 1985-2000 period. Briefly, their findings are as follows. In most regressions, mark-ups are lower when it is easier to start a new business and when there are less price controls, but also when average tariff rates are higher (which is counterintuitive). The results are economically important. For instance, the coefficient on “ease of starting a new business” equals about -0.021 (Table 9 in CEPR and IFS, 2003), suggesting that competition policies that increase the index by 1 (on a 10 point scale) would reduce the mark-up by about 2.1 percentage points. This corresponds to about an 8% fall in the average mark-up over value added.

4 Productivity in applied macroeconomic models

How do existing applied macroeconomic models deal with productivity and the role of human capital, R&D, and product market competition? The CPB models MIMIC and WORLDSCAN distinguish workers of different skill levels, and MIMIC also specifies a training sector for employees. Exogenous R&D expenditures and the role of international R&D spillovers are considered in the WORLDSCAN model. The intensity of product market competition in terms of exogenous mark-up pricing can be studied in JADE, SAFE, MIMIC, and WORLDSCAN (in which differentiated varieties of consumer goods are specified). ATHENA has exogenous mark-ups, but also allows for entry and exit of firms. For our purpose interesting models used at other policy institutions are the LINKAGE model of the Worldbank (where workers can be skilled or unskilled, and where mark-up pricing can be studied in combination with entry/exit of firms), and the MULTIMOD model of the IMF (which has been extended with R&D and R&D spillovers).

4.1 Applied macroeconomic models

In this chapter we review how productivity is incorporated in a number of macroeconomic models. The models covered are listed in table 4.1 (models in use at CPB) and table 4.2 (a selection of models used at other institutes). Their nature ranges from national, one-sector, temporal, quarterly macroeconometric models like MORKMON II of De Nederlandsche Bank (DNB) to multi-country, multi-sector, intertemporal general-equilibrium models like LINKAGE of the World Bank.

Table 4.1 Models used at CPB

Model	Description
ATHENA	Macroeconometric model to analyse medium- and long-run sectoral developments in the Dutch economy (see CPB, 2005)
GAMMA	Intertemporal applied general equilibrium model to analyse ageing in the Dutch economy (see Draper and Westerhout, 2002)
JADE[a]	Macroeconometric model to analyse long-run developments in Dutch economy (see CPB, 2003a)
MIMIC	Applied general-equilibrium model to analyse structural labour market implications of changes in the tax and social security system (see Graafland et al., 2001)
SAFE[a]	Macroeconometric model to analyse short-run developments in the Dutch economy (see CPB, 2003b)
WORLDSCAN	Applied general-equilibrium model to analyse long-run developments in the world economy (see CPB, 1999)

[a] Recently, JADE and SAFE have given birth to SAFFIER, a model suitable for short-term and long-term analysis. SAFFIER closely resembles its parents.

Table 4.2 Models used at other institutes

Model	Description
LINKAGE (The World Bank, Washington D.C.)	Multi-country, multi-sector dynamic applied general-equilibrium model (see Van der Mensbrugghe, 2003)
MESEMET (Ministry of Economic Affairs, The Hague)	Applied general-equilibrium model of the Dutch economy with endogenous technology (see Van Bergeijk et al., 1997)
MORKMON II (De Nederlandsche Bank, Amsterdam)	Macroeconometric quarterly one-sector model of the Dutch economy (see Fase et al., 1992)
MULTIMOD (IMF, Washington, D.C.)	World econometric model used by the IMF (see Bayoumi et al., 1999)
NiDEM (NIESR, London)	Macroeconometric model of the UK economy (see Hubert and Pain, 2001; Pain and Young, 2004)

A common feature of all models considered is that productivity *growth* is either exogenous or, when it is endogenous, tends to a constant value (determined by exogenous variables and parameters) in the long run. However, the *level* of labour productivity may be the outcome of endogenous choices with respect to investments in physical capital, human capital, and in R&D. The attention paid to the determinants of the level of productivity varies somewhat with the focus of the models; still, a general conclusion is that the subject has received scant attention so far. In recent years, several institutes have built experimental or special-purpose versions of their models that do incorporate features of the new growth theory. However, most of the insights gained from the recent theoretical and empirical work on economic growth must still find their way into the applied models.

4.2 Human capital

4.2.1 CPB Models

The macroeconometric models ATHENA, JADE, and SAFE do not take explicit account of human capital. Still, in these models wage levels do differ between sectors of industry, reflecting differences in the composition of sectoral employment with respect to age, gender, and skill. The applied general-equilibrium models GAMMA, MIMIC, and WORLDSCAN do account for labour heterogeneity in at least one respect.

GAMMA focuses on the impact of ageing on the economy. To that end, it disaggregates the (potential) labour force (persons 15-64 years of age) into fifty year classes. The age-productivity profile, coinciding with the age-wage profile, is exogenous and constant. Average labour productivity varies with shifts in the age distribution of the labour force.

MIMIC focuses on the impact of the tax and social security system on the labour market. It contains a rather detailed labour supply module, distinguishing the potential labour force with respect to age (two classes), gender, marital status, main source of income (work or some kind of benefit) and - most relevant for our purpose - three skill groups, unskilled, low-skilled and high-skilled labour. In other parts of the model the breakdown is less detailed. For example, labour demand is broken down only to the three skill groups.

In MIMIC, upon leaving the educational system (that has not been modelled) and entering the (potential) labour force, an age cohort has a given skill distribution. In general, the average skill level of the young cohort will be higher than that of the old, retiring cohort. Compared to models with homogeneous labour, MIMIC thus explains part of the increase of (labour) productivity to a rising skill level of the working population (as a result of investment in human capital), so that a smaller share is attributed residually to exogenous (labour-augmenting) technical progress.

Moreover, the skill distribution of the age cohorts is not fixed once and for all. Unskilled and low-skilled workers may enrol in training programs (to improve their productivity and employability while staying in the same skill group) or post-initial schooling programs (to climb the skill ladder). As skills become obsolete at some non-zero rate, even high-skilled workers have an incentive to enrol in training programs (in MIMIC, they may not enrol in schooling programs). Net income differentials provide the incentives for training and schooling. Hence, changes in the progressiveness of income taxes have some impact on human capital formation, but only on human capital formation after the completion of initial schooling. Ultimately, a given change in the tax structure leads to a stable deviation from the skill distribution originally imported into MIMIC.

WORLDSCAN distinguishes between two kinds of labour: high-skilled and low-skilled. The relative supply of these two types of labour is exogenously determined outside the model. For OECD-countries it is assumed that the share of high-skilled workers is constant at 50%. The production functions are of the nested CES-type. Both types of labour enter the production function in the value-added nest,[63] together with capital and a fixed production factor. Technical progress is assumed to be TFP-enhancing, implying there are no differences in labour-augmenting technical progress between high- and low-skilled workers. On the sectoral level, labour productivity can change as a result of factor substitution. On the macroeconomic level, labour productivity also depends on relocation of high- and low-skilled labour among sectors.

4.2.2 Other models

Like other macroeconometric models for short-term forecasting and policy analysis, MORKMON II of DNB does not pay attention to human capital.

Inspired by Den Butter and Wollmer (1996), Van Bergeijk et al. (1997) extend MESEM, the applied general-equilibrium model for the Dutch economy of the Ministry of Economic Affairs, with endogenous technology in ways suggested by new growth theory to obtain MESEMET. In this model, value added is a Cobb-Douglas function of effective labour and effective capital. Effective labour itself is a CES function of 'raw labour' L and human capital H with conditional (that is, for constant quantity of effective labour) Allen partial elasticity of substitution equal to 0.55 in the base line version of the model. Human capital is treated as a public good. It evolves according to

[63] Value added is a Cobb-Douglas function that is a CES function with Allen partial elasticity of substitution equal to one.

$$d \ln H = \alpha_1 d \ln H_{-1} + \alpha_2 d \ln I_p + \alpha_3 d \ln RD_p + \alpha_4 d \ln RD_g + \alpha_5 d \ln E_g - \alpha_6 d \ln T_i, \qquad (4.1)$$

where I_p is private investment (in physical capital), RD_p is private R&D, RD_g is public R&D, E_g is public expenditure on education, and T_i is the marginal tax rate on labour income. The first term represents depreciation, the second term represents a positive external effect of learning-by-doing, and the third and fourth term represent a positive external effect of R&D-activities on the human-capital stock, which Van Bergeijk et al. (1997) call learning-by-designing. Naturally, public expenditures on education increase the stock of human capital. Finally, high marginal taxes discourage investment in human capital through a negative effect on the rate of return.

The values of crucial parameters are highly uncertain, giving the researcher a wide range of choice. For example, compared to Van Bergeijk et al. (1997), Den Butter and Wollmer (1996) opt for a lower value of 0.8 for the partial elasticity of substitution between effective labour and effective capital, and simultaneously for a higher value of 1.25 for the (conditional) partial elasticity of substitution between raw labour and human capital. They find that a boost to human capital *reduces* the demand for raw labour, while Van Bergeijk et al. (1997) find that it *raises* the demand for raw labour. This divergence is for a great part due to the differing assumptions about the elasticities of substitution just mentioned (naturally, other differences in parameters and model specification play a role as well).

LINKAGE, the applied general-equilibrium model used by the World Bank, distinguishes between unskilled and skilled labour. Aggregate labour is a substitute for capital in the value-added production functions. However, the model user has the option to introduce a third skill group, that of highly skilled labour, to which some part of skilled labour is allotted; highly skilled labour is a complement to capital in the production of value added.

4.3 Research and development

4.3.1 CPB Models

In Lejour and Nahuis (2000), the possibility of R&D spillovers was added to WORLDSCAN in a way that resembles the approach of Bayoumi et al. (1999) (see below). TFP-growth of a sector is modelled as a function of its own R&D-stock, the R&D-stock of the other sectors in the economy (using input-output coefficients as weights), and the trade-weighted R&D-stock of the foreign sectors. Lejour and Nahuis (2000) construct TFP-measures using growth accounting techniques, and estimate the equations for all regions and sectors using R&D-data. Lejour and Nahuis find significant rates of return to own R&D and spillovers within the economy, and positive but insignificant interregional spillovers.

These equations for TFP are used in the WORLDSCAN model. The R&D expenditures are assumed to be a constant proportion of value added of each sector. The model is used by Lejour and Nahuis (2000) in a simulation exercise to analyse the effects of trade liberalisation. They find that the introduction of R&D in WORLDSCAN increases the effects of trade liberalisation.

The TFP-equations were re-estimated by Tang and Lejour (2004) and the new version of the model was used in CPB (2004) to analyse the relationship between the German and Dutch economies. Furthermore, the model was used in a study on climate change policies (Bollen, 2004).

4.3.2 Other models

MESEMET includes technology capital, the output of R&D activities, in the production function of value added in a similar way to human capital. Effective capital is a CES function of public capital and composite private capital; the latter in its turn is a CES function of physical capital and technology capital, which is a CES function of public and private technology capital. The production function thus contains three public goods, human capital, public (physical) capital, and public technology capital, next to three private goods. The properties of the model[64] are highly dependent on the values of the (conditional) Allen partial elasticities of substitution at all levels of the production tree. Both Van Bergeijk et al. (1997) and Den Butter and Wollmer (1996) perform sensitivity analyses that testify to the great uncertainty surrounding the outcomes of their simulation exercises.

Two foreign models particularly relevant for us are NiDEM and MULTIMOD. Special-purpose versions of these models have been built that incorporate some features of the new growth theory. These will be discussed next.

Bayoumi et al. (1999) introduce R&D spillovers in the MULTIMOD model of IMF. Each country has a Cobb-Douglas production function,

$$\ln Y = \ln A + \alpha \ln K + (1-\alpha)\ln L, \quad 0 < \alpha < 1, \tag{4.2}$$

where A is total factor productivity TFP (of course, the parameters and variables differ across countries, and the variables differ across time, but the subscripts have been deleted). Based on work by Coe and Helpman (1995) and by Coe et al. (1997), Bayoumi et al. (1999) endogenise total factor productivity A by relating it to the domestic and foreign R&D capital stocks and to the share of imports in GDP. For small industrial countries, the following equation is used:

$$\ln A = \phi + 0.08 \ln S^D + 0.26 m \cdot \ln S^F - 3.18 m, \tag{4.3}$$

where ϕ is a country-specific constant, S^D is the domestic R&D capital stock, S^F is the foreign R&D capital stock, and m is the import share. A 1% increase in the domestic R&D

[64] Formally, under the assumption of cost minimisation one may derive mixed demand functions for the private inputs with the prices of the private inputs and of the quantities of the public inputs as arguments (next to the level of production); moreover, one may derive shadow-price equations for the public inputs with the same list of arguments.

capital stock leads to a 0.08% TFP increase. Trade acts as a carrier for knowledge spillovers and thus foreign R&D capital affects TFP through its interaction with the import share *m*. In addition, imports affect domestic TFP directly, the intuition being that foreign knowledge can be embodied in new products. The elasticities of the foreign R&D capital stock and the import share depend on the level of the other variable because of the interaction term. At the sample averages, the elasticity of TFP with respect to foreign R&D capital is about 0.08 and the elasticity with respect to the import share is roughly zero. Following a shock, economic growth returns to the same steady-state value in the long run, but adjustment can take very long indeed (eighty years). The R&D/GDP ratio is an exogenous variable. An increase in this ratio raises TFP, which boosts the return to investment in the physical capital stock and thus triggers higher investments. General-equilibrium effects thus reinforce partial-equilibrium effects. For example, raising the R&D/GDP ratio by 0.5%-point increases US output by more than 9% in the long run, about three quarters of which is due to productivity increases and the remainder to induced higher investments.

Hubert and Pain (2001) adopt a similar approach but deviate from the work of Bayoumi et al. (1999) in two important respects. First, they represent the technology by a two-factor CES production function, with technical progress (TP) assumed to be labour augmenting at rate λ, over time t. Second, they add a measure of the level of activity of foreign-owned firms to the list of determinants of domestic technical progress. The idea that foreign direct investment is one of the main transmission mechanisms behind the diffusion of knowledge, both codified and tacit, across national borders is borne out by their estimation results on industry-level panel data for the UK manufacturing sector. Hubert and Pain (2000) have reported econometric evidence that the mechanism is also at work in the financial-services and distribution sectors of the UK economy.

Based on this work, Pain and Young (2004) endogenise the level of technology in the NiDEM model of NIESR by relating it to the stock of foreign direct investments (SFDI). Under constant returns to scale, the first-order condition that the marginal product of each input should equal its real price can be used to derive a long-run log-linear labour demand equation of the form:

$$\ln(L_t / Y_t) = c - (1-\sigma)\lambda t - \sigma \ln(W_t / P_t), \tag{4.4}$$

where L denotes labour demand, Y value added output, W the wage rate, P the value added price, and σ the elasticity of substitution. Pain and Young (2004) next replace λt by

$$\lambda t = \lambda_T TIME + \lambda_F \ln(SFDI / P)_{t-1}. \tag{4.5}$$

In this specification TP will grow at a constant rate if foreign assets do. Pain and Young embed the long-run equilibrium relationship implied by equations (4.3) and (4.4) in a dynamic errorcorrection model. They use the estimation results of Hubert and Pain (2001) in their simulation analyses. A 1% change in the stock of manufacturing FDI eventually raises the level of labour-augmenting TP in the manufacturing sector by 0.32%; for the financial-services and distribution sector the elasticity is 0.135.

In the LINKAGE model of the World Bank, technical progress is labour augmenting. There is no explicit role for R&D. The model does allow for the possibility that the extend to which some country may enjoy international knowledge spillovers is positively correlated with the 'openness' of the economy as measured by the EXports/GDP ratio. The specification is

$$\lambda_t = (1 + \chi_t + \textit{other terms}) \cdot \lambda_{t-1}, \tag{4.6}$$

$$\chi_t = \varphi \cdot (EX_t / GDP_t)^{\eta}, \tag{4.7}$$

where λ is the productivity factor. The parameter φ determines the degree to which productivity depends on openness and is fixed in the calibration procedure by the model user. The elasticity η may be put equal to zero to switch the mechanism off and make productivity exogenous.

4.4 Product market competition

4.4.1 CPB models

None of the CPB models has been built with applications to competition policy in mind, so it causes no surprise that they contain few elements that are relevant for this purpose. GAMMA assumes perfect competition on product markets. In the other models, firms set prices in imperfectly competitive markets; in fact, markets are populated with Bertrand oligopolies or monopolistic competitors, as the case may be. Mark-ups are constant in JADE, SAFE, and MIMIC at fairly low levels; implicitly, the implied pure profits are just sufficient to compensate for sunk costs (which are not present explicitly). In WORLDSCAN, each sector in a region produces exactly one variety. Since the varieties are imperfect substitutes, sectors are able to charge a (constant) mark-up over their marginal costs. The number of firms (varieties) is fixed. ATHENA is more advanced in the description of market structure. Firms within an industry charge a (constant) mark-up over marginal costs, as in WORLDSCAN. The mark-up may or may not be sufficient to cover the fixed costs, and therefore the firms may make profits or losses. The number of firms then adjusts, through entry or exit, until there are no long-run profits. In this way, the number of firms in an industry is made endogenous.

4.4.2 Other models

LINKAGE provides the user with a choice with respect to the returns to scale in production. They may be constant, in which case there is perfect competition on product markets. Or they may be increasing through the presence of fixed costs, in which case there are positive mark-ups of prices over marginal cost. In the latter case, the user has another choice to make: either fixed mark-ups go together with endogenous profits, or zero-profit conditions make the mark-ups endogenous (as in contestable markets).

5 Epilogue

This chapter presents some final thoughts with regard to the implementation of human capital, R&D, and product market competition in applied macroeconomic models. Such an exercise calls for a number of strategic choices which have to be made by the researcher. We want to wind up our analysis by sketching some of these strategic modelling decisions.

Complexity: A cost-benefit analysis

Whenever a new issue is addressed in a macroeconomic model, it becomes more complex to analyse and more costly to build and maintain. Such a decision whether or not to extend the model should therefore be based on a cost-benefit appraisal, where various implementation strategies can be considered. A practical approach is to add an exogenous variable whose value is determined separately (e.g. in a sub-model or econometric analysis). This will be easier to implement, but ignores interactions with other variables in the model.

Human capital

Let us first consider human capital in macroeconomic analysis. One needs to decide whether to consider exogenous or endogenous growth. It should be noticed that changes in the human capital stock will affect economic growth in a neoclassical growth framework during the transition period. These transition dynamics can be a lengthy process. In fact, the time horizon of forecasting will typically be shorter than the full adjustment process to the new equilibrium path. The dynamic properties of exogenous and endogenous growth models may therefore be not so different in the short-run. However, endogenous growth models typically generate non-stationary time series for important macroeconomic variables such as production, consumption and investments. Another strategic choice refers to the degree of heterogeneity in the work force. Allowing for two or more different skill levels among employees enables the researcher to investigate wage inequality (and corresponding equity consequences), and to consider skill-biased technical change (cf. Acemoglu, 2002). It also opens up the possibility to study changes in the fraction of skilled or unskilled workers. However, the schooling decision can also be investigated in a framework with a homogeneous labour force (cf. Lucas, 1988). Also, a complication of multiple skill levels is that the researcher needs to pick parameter estimates for the substitutability in production between skill levels, as well as between each skill level and the physical capital stock. A final example of strategic modelling decisions with regard to human capital is whether or not to introduce an education sector. This implies the specification of an education production function, linking inputs in the education process to outputs. The advantage of such a structural approach is internal consistency, the possibility to explore general equilibrium effects, and transparency. The problem here is that educational outcomes will be affected by a myriad of factors, such as teacher training, class size, funding system, competitiveness of the education market, peer effects, etc., and it is not possible to incorporate all these mechanisms into the education production function.

Research and development

The introduction of R&D in applied macroeconomic models is less straightforward than human capital. New knowledge appears in many guises, some in the form of embryonic scientific insights with a strong public good character and others in more tacit or embodied (and thereby rival and excludable) form. New knowledge can find its way to productive uses along several paths, such as via embodied knowledge in advanced machinery or through improved organisation of logistic processes. In macroeconomic analyses we have to try and represent the important facets of the R&D process, while keeping the broader economic picture and the technical feasibility of the model in mind. An important strategic choice is again whether one wants to consider exogenous or endogenous growth. In an extended version of the neoclassical model a la Nonneman and Vanhoudt (1996), the stock of technological know-how (resulting from R&D investments in the past) affects the production capacity, but not the long-run growth potential. Changes in the R&D stock will change the equilibrium production level, and generate transitional dynamics until the new balanced growth path is reached. In endogenous growth models such as Aghion and Howitt (1992), R&D investments determine the pace of economic growth. Also, the researcher needs to choose how R&D affects the production capacity. There are (at least) three possibilities: (i) we can introduce the knowledge stock as a separate production factor into the production function, (ii) we can allow for quality ladders in the physical capital stock, where more recent machinery embodies more state-of-the-art knowledge, and (iii) we could assume that research benefits firms through total factor productivity. All these three possibilities seem feasible, though a bit more creativity (or a lot of hard work) may be needed to follow the quality ladder approach in an existing macroeconomic model with only one type of physical capital. The first approach basically treats R&D as a private commodity, in a similar fashion as the physical capital stock. The third approach has the advantage that it is rather straightforward and flexible. And by imposing a connection between TFP and R&D, we could study issues connected to adoption of existing technologies (R&D helps firms to move towards the technological frontier), as well as endogenous growth processes in a Schumpeterian style (R&D shifts the technological frontier outwards). A final thought here is whether or not to specify the research sector. Scientists and engineers are the major input in the research process, and a straightforward modelling assumption would be that researchers are the only input (as in Aghion and Howitt, 1992). Incorporation of the research sector allows us to study labour market effects from changes in research activity, and this can be interesting because public programs to support R&D often take the form of subsidies or tax benefits to reduce the labour costs of researchers.

Competition

Finally we present some thoughts about how competition and competition policy can be dealt with in macroeconomic analysis. As we have seen, the macroeconomic impact of competition can be studied in both exogenous and endogenous growth models. An interesting aspect of competition in Schumpeterian growth models such as in Aghion and Howitt (1992) is that (dynamic) competition and economic growth are intimately intertwined: competition manifests itself in creative destruction of incumbent firms, and the innovating firm becomes the new market leader. A somewhat simplified version of this mechanism can be studied in an extended neoclassical growth model with (i) inclusion of R&D, while R&D is linked to some indicator of the competition intensity, or (ii) TFP linked to competition. Second, how should we deal with the notion that product market competition is not perfect? As we have discussed in Section 2.4.1 we could consider a market with only a few firms, while these firms compete with each other through strategic interaction (i.e. Bertrand or Cournot competition). An alternative is found in the Dixit-Stiglitz approach, where firms compete monopolistically (without strategic interaction), and consumers have a taste for variety. In equilibrium, firms are symmetric and mark-ups identical. A short-cut could be to introduce mark-up pricing, and link the mark-up to the intensity of competition and perhaps a set of other institutional characteristics such as entry barriers and the administrative burden for companies. Following the work of Boone (2000a, 2000b) and Aghion and Howitt (2005), competition will be intertwined with efficiency differences across firms in the same industry. This would allow us to study the dynamics of catching-up towards the most efficient firms. Finally, intensified competition may imply that factors of production need to be reallocated. Moving people to new jobs and capital to new firms or branches is costly. For workers these costs are for instance unemployment allowances during the period of job-switching, and training costs. Also the capital stock is not flexible due to rigidities of old vintages. The period of adjustment is often rather long, and adjustment costs precede the economic benefits. Switching costs for consumers can also be seen as costs of more competition.

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