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**Innovation and Growth:
The Role of Labor-Force Qualification**

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Innovation and Growth: The Role of Labor-Force Qualification*

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Abstract

Endogenous innovation-based models of economic growth incorporate a scale effect predicting that larger economies grow faster and that population growth causes higher productivity growth. Recent models of semi-endogenous growth remove this scale effect but instead imply that productivity growth depends proportionally on population growth. This paper argues that an increasing qualification and not an increasing quantity of the labor force is decisive for productivity growth. The consequence of this reinterpretation of the role of the input factor labor is that growth can be enhanced by subsidizing education and hence labor-force qualification.

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1 Introduction

The recently published study of the “Programme for International Student Assessment” (PISA) has attracted great attention, particularly in Germany. The reason for the current interest is the unexpectedly poor performance of the 15 year old German adolescents. The study emphasized reading proficiency, basic mathematical skills, and basic scientific skills as performance measures. In reading proficiency, German adolescents only ranked 21st out of 31 countries. As can be seen in Table 1, the average performance in Germany was clearly lower than the OECD mean of 500 points, whereas the US, France, and the UK - as most western European countries - scored above the OECD average. In math as well as science skills Germany was 20th among the 31 countries and was again below the OECD mean.

Table 1: International Comparison of Educational Performance, 2000

Country	Reading	Math	Science
Germany	484	490	487
France	505	517	500
United Kingdom	523	529	532
USA	504	493	499

Source: OECD (2001a)

These disappointing results for German adolescents raise the question whether public policy is able to influence the educational performance. Therefore, Table 2 presents some additional data on public expenditures on education. Compared to the other countries listed above, the expenditure rate in Germany is the lowest. The difference does not primarily effect the universities, but more the primary and secondary schools. This evidence gives rise to the hypothesis that an enlargement of public expenditures is suitable to improve educational performance and thus to increase the qualification of the labor force.

The influence of the qualification of the labor force on economic growth is by now a hardly controversial stylized fact. In their empirical studies, Hanushek/Kimko (2000) and Barro (2001) have found that especially the quality, but also the quantity of schooling are positively related to subsequent economic growth. In modern growth theory, the role of education and qualification is well recognized, too. In his pionee-

Table 2: International Comparison of Public Expenditures on Education, relative to the GNP in %, 1998

Country	Public Expenditures on Education	Of which: Primary and Secondary Education	Of which: Tertiary Education
Germany	4.6	3.0	1.1
France	6.0	4.2	1.0
UK	4.9	3.4	1.1
USA	5.1	3.4	1.3

Source: OECD (2001b)

ring contribution to the endogenous-growth literature, Lucas (1988) has emphasized human capital accumulation by education as a decisive source of sustained growth.

Since the early nineties, however, endogenous growth theory is undoubtedly dominated by the innovation-based growth models which decisively build on innovation processes as the engine of productivity growth. Romer (1990), Grossman/Helpman (1991) and Aghion/Howitt (1992, 1998) were among the first to introduce dynamic general-equilibrium models which explain productivity growth by intentional R&D activities of private firms. According to their approach, technological change results from an endless sequence of vertical improvements of intermediate goods along a given quality ladder or, alternatively, from a continuing horizontal expansion of the variety of these intermediates. The innovation-based endogenous growth models share a common property which is well-known as the scale effect. This scale effect predicts that larger economies grow faster and that population growth causes higher productivity growth. This counterfactual prediction continues to hold in a related sense if the quantitative growth of the labor force is replaced by increasing qualification due to educational investment in human capital. Any enlargement of human capital now inevitably induces increasing productivity growth rates which is certainly at odds with the empirical evidence. For this reason, no successful attempts have been made to integrate the sustainable process of human capital accumulation, as suggested e.g. by the influential model by Lucas (1988), into the endogenous innovation-based growth models. Therefore, until recently, skill acquisition by the labor force on the one hand and technological innovations on the other hand were

treated separately as two alternative and independent engines of economic growth.

In the mid nineties, Jones (1995a) presented an influential empirical study in which he could find no support for the scale effect as predicted by the endogenous growth models. In response to this “Jones critique”, a new class of semi-endogenous growth models has emerged (see, e.g. Jones 1995b, 2002, Kortum 1997, Segerstrom 1998). As a distinguishing feature, these models remove the scale effect but instead imply that productivity growth depends proportionally on population growth. Without doubt, this property of the semi-endogenous growth models is at odds with the empirical findings, too. However, from a technical point of view, it opens the challenging possibility of integrating skill acquisition by the labor force in accordance with the empirical evidence if exogenous population growth is replaced by endogenous human capital accumulation. Only a few attempts in this promising direction have recently been made. Arnold (1998) and Blackburn/Hung/Pozzolo (2000) have integrated education in Romer’s (1990) variety-expansion model, Arnold (2002) education into Segerstrom’s (1998) quality-ladder model. The crucial assumption which removes the scale effect in the Arnold (2002) model is a continuing deterioration of the technological opportunities which results in a declining productivity of workers in the R&D sector. However, a historical analysis of the occurrence of technological innovations in different industries clearly shows that periods of increasing and decreasing technological opportunities have alternated. In our view, the existing empirical evidence is not convincing enough to support the hypothesis of a long-run declining trend in the R&D productivity.

In this paper, we therefore follow the suggestions by Arnold (1998, 2002) and Blackburn to focus on human-capital growth instead of population growth within the framework of a semi-endogenous growth model, but we prefer to build on another even more convincing specification which provides an alternative mechanism of eliminating the scale effect.¹ We adapt this mechanism from the latest generation of growth models as represented by Young (1998), Peretto (1998), Dinopoulos/Thompson (1998), Jones (1999), and Li (2002) who argue that the variety of (consumer or intermediate) products grows proportionally to the population of the economy. Extending an appropriate version of such a basic model by accounting for

¹ Another strand of the literature emphasizes the role of human capital in the absorption of new technology (see, e.g. Stokey 1991, Eicher 1996, Lloyd-Ellis/Roberts 2002).

endogenous accumulation of human capital instead of exogenous population growth yields some new insights about the importance of education and skill acquisition of the labor force. Most important, technological innovation and human capital accumulation are now simultaneously treated as twin engines of economic growth which are inextricably linked to each other.

The paper is organized as follows. Section 2 introduces the model. In Section 3, the steady-state growth equilibrium is derived and the factors explaining innovation and productivity growth are identified. Finally, Section 4 concludes.

2 The Model

2.1 Skill Acquisition and Spending Behavior of Households

In the household sector we assume that consumers share identical preferences and maximize their discounted utility from consuming a homogeneous good Y over an infinite time horizon. The time separable intertemporal utility function is given by

$$U(Y) = \int_0^{\infty} e^{-\rho t} \ln Y(t) dt,$$

where ρ is the common rate of time preference and the intertemporal elasticity of substitution equals one. There is a continuum of households in the interval $[0, 1]$, each of which is endowed with $H(t)$ units of human capital. By devoting $H_E(t)$ units to education, households can raise their human capital due to the Uzawa-Lucas technology

$$\dot{H}(t) = \kappa H_E(t), \tag{1}$$

where $\kappa (> \rho)$ denotes the efficiency of education. Thus, households maximize their discounted utility subject to the accumulation function (1) and to their dynamic budget constraint

$$\dot{A}(t) = r(t)A(t) + w(t)(H(t) - H_E(t)) + sw(t)H_E(t) - p_Y(t)Y(t),$$

where A denotes the value of asset holdings, r is the interest rate on these riskless assets, w is the wage rate, p_Y is the price of the consumer good, and s is an education

subsidy rate for foregone income. Public expenditures influencing the efficiency of education and subsidies to individuals in the education process are financed by a non-distorting lump-sum tax which is exogenously given for the households.

The current-value Hamiltonian of this dynamic optimization problem is given by

$$\begin{aligned} \mathcal{H} = & \ln Y(t) + \psi_1[r(t)A(t) + w(t)(H(t) - H_E(t)) + sw(t)H_E(t) - p_Y(t)Y(t)] \\ & + \psi_2[\kappa H_E(t)] \end{aligned}$$

where ψ_1 and ψ_2 are the costate variables of A and H . The necessary first-order conditions are given by

$$\mathcal{H}_Y = 1/Y(t) - \psi_1 p_Y(t) = 0, \quad (2)$$

$$\mathcal{H}_A = \psi_1 r(t) = \psi_1 \rho - \dot{\psi}_1, \quad (3)$$

$$\mathcal{H}_{H_E} = -\psi_1(1-s)w(t) + \psi_2 \kappa = 0, \quad (4)$$

$$\mathcal{H}_H = \psi_1 w(t) = \psi_2 \rho - \dot{\psi}_2. \quad (5)$$

Conditions (2) and (3) yield the Keynes-Ramsey rule

$$\dot{Y}/Y = r(t) - \dot{p}_Y(t)/p_Y(t) - \rho. \quad (6)$$

This optimal time path of consumption applies not only to a representative household but also to the aggregate economy. It proves convenient to impose a normalization of the price of the consumer good such that consumer expenditures $E(t)$ remain constant over time. Setting $E(t) = p_Y(t)Y(t) = 1$ implies from (6) that $r(t) = \rho$, i.e., the interest rate equals the rate of time preference which is assumed to be constant over time. Using this identity, we derive from (3), (4), and (5)

$$\dot{w}/w = \rho - \kappa/(1-s). \quad (7)$$

The larger the discount rate, the lower the efficiency of education, and the lower the education subsidy rate, the larger is the growth rate of (nominal) wages required by the labor force to invest in qualification.

2.2 The Consumer-Good Market

The consumption good is produced in a perfectly competitive market. For production, firms use intermediate goods which differ in variety and quality. The production function is given by

$$Y(t) = \left[\int_0^{N(t)} q(j, t)^{1-\alpha} x(j, t)^\alpha dj \right]^{1/\alpha}, \quad 0 < \alpha < 1, \quad (8)$$

where $N(t)$ denotes the number of varieties of intermediate goods that have been developed at time t , $q(j, t)$ and $x(j, t)$ denote the levels of quality and quantity of variety $j \in [0, 1]$ of the intermediates, and $\varepsilon = 1/(1 - \alpha) > 1$ is both the constant elasticity of substitution between varieties and the elasticity of demand for any single variety. Perfect competition in the supply of consumer goods ensures an equilibrium price p_Y equal to the minimum attainable unit manufacturing cost

$$p_Y(t) = \left[\int_0^{N(t)} q(j, t) p(j, t)^{-\frac{\alpha}{1-\alpha}} dj \right]^{-\frac{1-\alpha}{\alpha}}. \quad (9)$$

where $p(j)$ is the price of the intermediate good j . By applying Shephard's Lemma, the demand for each input j is derived as

$$x(j, t) = \frac{q(j, t) p(j, t)^{-\frac{1}{1-\alpha}} Y(t)}{\left[\int_0^{N(t)} q(j, t) p(j, t)^{-\frac{\alpha}{1-\alpha}} dj \right]^{\frac{1}{\alpha}}}. \quad (10)$$

Replacing $Y(t)$ in (10) by $E(t)/p_Y(t)$ with $E(t) = 1$ and p_Y from (9) yields

$$x(j, t) = \frac{q(j, t) p(j, t)^{-\frac{1}{1-\alpha}}}{\int_0^{N(t)} q(j, t) p(j, t)^{-\frac{\alpha}{1-\alpha}} dj}. \quad (11)$$

Each of these varieties is produced by specialized firms in non-competitive intermediate-goods markets to which we now turn.

2.3 The Intermediate-Goods Markets

We assume that all differentiated intermediate goods are produced subject to a constant-returns-to-scale technology with (qualified) labor H_X as the single input

factor. By an appropriate choice of units, production of one unit of each variety requires one unit of human capital. With this technology, marginal production costs at time t are equal to the wage rate $w(t)$. The supplier of variety j maximizes its flow profits

$$\pi(t, j) = (p(j, t) - w(t))x(j, t)$$

by charging an optimal price. The kind of price-setting behavior crucially depends on the intermediate-goods market structure which itself is characterized by the technological basic conditions. Each intermediate good can potentially be produced in a countably-infinite number of qualities. The quality grades of the intermediates are arrayed along the rungs of quality ladders which are assumed to be equal across markets. Each new generation of intermediate goods provides a λ times higher quality, where each upgrading factor $\lambda > 1$ is assumed to be exogenous and constant over time. The index

$$q(j, t) = \lambda^{m(j, t)} Q_\tau$$

represents the quality level achieved as a result of $m(j, t) = 0, 1, 2, \dots$ sequential upgrading innovations in market j at time t . Q_τ denotes the initial level of quality of the j th variety when it was introduced at time $\tau \leq t$. For convenience, we assume that this initial quality level equals the average quality of the existing product varieties, i.e.

$$Q_\tau = (1/N(\tau)) \int_0^{N(\tau)} q(j', \tau) dj'. \quad (12)$$

The quality improvements result from successful innovative activities undertaken in a separate R&D sector to be characterized below.

In the case of non-drastic innovations, the technological leaders charge a limit price $p(j, t) = \lambda^{\frac{1-\alpha}{\alpha}} w(t)$, thereby driving the followers out of the market. In the case of drastic innovations, however, the price decisions of technological leaders are constrained by competition from the producers of substitutive intermediate goods in the other markets. Facing the demand function in (11), the optimal pricing rule is then given by $p(t) = (1/\alpha)w(t)$. Therefore,

$$p(j, t) = \min\{1/\alpha, \lambda^{\frac{1-\alpha}{\alpha}}\} w(t), \quad (13)$$

depending on whether the quality innovation is drastic ($1/\alpha < \lambda^{\frac{1-\alpha}{\alpha}}$) or not. It is worth noting that, in both cases, intermediate firms charge an identical price $p(j, t) = p(t) \forall j$ for each product. Using the quality index (12), the demand function (11) can therefore be written as

$$x(j, t) = \frac{q(j, t)}{N(t)Q(t)p(t)}. \quad (14)$$

Substituting (14) into (8) and integrating the resulting expression yields

$$Y(t) = [N(t)Q(t)]^{\frac{1-\alpha}{\alpha}} / p(t). \quad (15)$$

The innovation processes, expanding variety N and rising quality Q are governed by the human-capital resources devoted to R&D. Following Li (2000, 2002), we assume that both types of innovation processes take place simultaneously.

2.4 The Innovation Processes

The quality of the intermediates can be upgraded by a sequence of innovations, each of which builds upon its predecessors. To produce a higher quality good, a blueprint is needed. These blueprints are developed by innovative firms in a separate R&D sector. The lure of monopoly rents drives potential entrants to engage in risky R&D projects in order to search for the blueprint of a higher quality intermediate product. The first firm to develop the new design is granted an infinitely-lived patent for the intellectual property rights. Competition therefore takes the form of a patent race between rival firms. Any newly discovered technology opens up the opportunity for all firms to search for the next innovation in this market. This implies an external spillover effect of technological knowledge since even laggard firms can equally participate in each patent race without having taken all of the rungs of the quality ladder themselves. It is only the patent protection which guarantees temporary appropriability of innovation rents. Each potential entrepreneur may target his research efforts at any of the continuum of state-of-the-art products, i.e. it may engage in any market. If it undertakes R&D at intensity $h(t)$ for a time interval of length dt , it will succeed in taking the next step up the quality ladder for the targeted product with probability $h(t)dt$. This implies that the number of realized innovations in each

industry follows a memoryless Poisson process with the arrival rate $h(t)$. The law of large numbers then implies that aggregate quality growth is deterministic and satisfies

$$g_Q = \dot{Q}(t)/Q(t) = h(t) \ln \lambda. \quad (16)$$

The arrival rate $h(t)$ of quality innovations is governed by the resources H_R of human capital invested into R&D. Following Grossman/Helpman (1991), the innovation production function is approximated by a linear specification where one unit of R&D intensity, $h(t)$, requires μ units of human capital per unit of time. The parameter $\mu > 0$ reflects the technological difficulties in the innovation process and is assumed to be constant and common to all markets. Since human capital devoted to R&D will be equally distributed to the mass of N industries, the industry-specific innovation rate is given by

$$h(t) = \frac{H_R(t)}{\mu N(t)}. \quad (17)$$

With respect to the variety expansion, we assume that the creation of new varieties depends linearly on the accumulated amount of human capital devoted to R&D.² The aggregate rate of variety expansion is given by

$$\dot{N}(t) = \theta H_R(t). \quad (18)$$

where θ indicates the pace of specialization of the economy. To close the model, we finally use the market-clearing condition for human capital

$$H(t) = H_X(t) + H_R(t) + H_E(t),$$

which can be devoted to production, to R&D and to education.

3 The Steady-State Growth Equilibrium

We restrict our attention to the steady-state growth equilibrium where the shares of human capital in the different sectors are constant over time. Aggregate human

² Li (2002) distinguishes between two different R&D sectors for quality and variety innovations and allows for knowledge spillovers between the two kinds of R&D activities. In contrast, Dinopoulos/Thompson (1999) assume that the creation of new varieties is the result of costless imitation.

capital devoted to production can be derived, using (12) and (14), as

$$H_X(t) = \int_0^{N(t)} x(j, t) dj = 1/p(t).$$

Since the mark-ups in the price-setting equation (13) are constant, independent of whether innovations are drastic or not, it follows that $g_p = g_w$. Therefore, the steady-state growth rates of human capital in all sectors are given by

$$g_H = g_{H_X} = g_{H_R} = g_{H_E} = -g_w. \quad (19)$$

From (15), the steady-state productivity growth rate can then be derived as

$$g_Y = \frac{1 - \alpha}{\alpha} (g_N + g_Q) + g_H. \quad (20)$$

Variety expansion and quality improvement of intermediates as well as human capital accumulation are the interrelated channels of productivity growth. From (7) and (19), human capital increases at the rate

$$g_H = \frac{\kappa}{1 - s} - \rho. \quad (21)$$

Variety expansion is directly linked to the growth of human capital. From (18), the ratio of human capital devoted to R&D, $k(t) = H_R(t)/N(t)$, is governed by the differential equation $\dot{k}(t) = g_H k(t) - \theta k(t)^2$. In the steady state with $k(t) = g_H/\theta$ the number of varieties is proportional to the level of accumulated human capital devoted to R&D:

$$N(t) = \frac{\theta H_R(t)}{g_H}. \quad (22)$$

The variety index therefore increases at the same rate as human capital

$$g_N = g_H. \quad (23)$$

Inserting (22) into (17) yields the arrival rate

$$h(t) = \frac{g_H}{\theta \mu} \quad (24)$$

and, from (16), the growth rate of the intermediates' quality index

$$g_Q = \frac{\ln \lambda}{\theta \mu} g_H. \quad (25)$$

Inserting (21), (23), and (25) into (20) finally yields the steady-state productivity growth rate

$$g_Y = \left[\frac{1}{\alpha} + \frac{(1-\alpha)\ln\lambda}{\alpha\mu\theta} \right] \left[\frac{\kappa}{1-s} - \rho \right]. \quad (26)$$

As is characteristic for all semi-endogenous growth models, the long-run growth rate is unrelated to scale. However, in accordance with the empirical evidence the explanation factors of the accumulation of both technological knowledge and human capital are derived as important determinants of growth. As can be seen from (26), the growth rate depends positively on the size of quality innovations λ , the efficiency of education κ , and the education subsidy rate s , but negatively on the difficulty of R&D μ , the pace of specialization θ and the discount rate ρ . The efficiency of education as well as the education subsidy rate not only accelerate the process of human capital accumulation but also the innovation processes. In this sense, the qualification of the labor force and the innovation activities of firms can be interpreted as twin engines of economic growth which are closely linked to each other.

4 Conclusion

Recent semi-endogenous growth models have accomplished a valuable task by removing the scale effect present in the endogenous growth models. A disturbing property of these models is, however, that the long-run growth rate depends proportionally on population growth. Without doubt, this property is at odds with the empirical evidence. The present paper has offered an alternative interpretation of the role of the input factor labor by replacing exogenous population growth by endogenous human capital accumulation. Therefore, consistent with the empirical evidence, the rate of productivity growth is not driven by population growth but by skill acquisition of the labor force. Investments in human capital and in technological innovations occur as twin engines of economic growth which are inextricably linked to each other. Hence, human-capital accumulation not only has a direct effect on productivity growth, but also an indirect effect via an acceleration of the innovation processes. The factors determining the skill acquisition of the work force are therefore as important as they

are in the endogenous human-capital growth model by Lucas (1988), but they are complemented by the factors determining innovative activities of firms.

The efficiency of education proves to be a very important source of growth. Subsidizing education is also suitable to positively influence the long-run growth rate. Through both of these channels education policy can play an important role in accelerating the process of human-capital accumulation on the supply and the demand side. Since human capital is an essential input factor for technological innovations, the presented model highlights the role of public expenditures on education for the dynamics of the innovation processes. The low education expenditure rates and the disappointing PISA results for the German adolescents, mentioned in the introduction, clearly call for a more active education policy in this country.

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II

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III

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