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Engines of Growth: Education and Innovation

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Abstract

The paper presents a dynamic general-equilibrium model of education, quality and variety innovation, and scale-invariant growth. We consider endogenous human-capital accumulation in an educational sector and quality and variety innovation in two separate R&D sectors. In the balanced growth equilibrium education and innovation appear as in-line engines of growth and government can accelerate growth by subsidizing education or by enhancing the effectiveness of the educational sector.

Keywords: Education, quality and variety innovation, scale-invariant growth

JEL Classification: O2, O3

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1 Introduction

Today it is widely accepted that human-capital accumulation and technological progress are the two most important engines of economic growth. In his pioneering contribution to the emerging New Growth Theory, Lucas (1988) emphasized human-capital accumulation by education as decisive source of endogenous growth. In their empirical studies, Hanushek, Kimko (2000), Barro (2001), and Hanushek, Wößmann (2008) have found that quantity and even more quality of schooling is positively related to subsequent economic growth. Since the early nineties, however, endogenous growth theory is undoubtedly dominated by the R&D-based growth models which build exclusively on innovation dynamics as engine of growth. Romer (1990), Grossman, Helpman (1991) and Aghion, Howitt (1992, 1998) were among the first to introduce dynamic general-equilibrium models to explain per-capita growth by intentional R&D activities of private firms. According to these models, technological change results either from an endless sequence of vertical improvements of consumer goods or, alternatively, from a continuing horizontal expansion of the variety of goods.

The R&D-based endogenous growth models of the first generation share a common property which is well-known as the scale effect. The scale effect predicts that larger economies grow faster and that population growth causes increasing per-capita growth rates. This counterfactual prediction of increasing growth rates persists if labor input is replaced by human-capital input. In this case, accumulation of human capital inevitably induces increasing per-capita growth rates which is certainly at odds with empirical evidence. For this reason, no successful attempts have been made to integrate the sustainable process of human-capital accumulation into the first-generation R&D-based growth models. Instead, education on the one hand and innovation on the other hand were treated separately as two alternative and independent engines of economic growth (see, e.g., the standard text book of Barro, Sala-i-Martin 2003).

Jones (1995a) presented an influential empirical study in which he could find no support for the scale effect as predicted by the first-generation 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 second-generation growth models remove the scale

effect but instead imply that per-capita growth depends proportionally on the exogenous growth of the labor force. Without doubt, this property of the semi-endogenous growth models is at odds with empirical findings, too. However, from a technical point of view, the model has opened the challenging possibility of reintroducing human-capital accumulation in accordance with the empirical evidence. The idea is to replace exogenous population growth by endogenous human capital accumulation. Several attempts in this promising direction have been made. Arnold (1998) and Blackburn, Hung, Pozzolo (2000) have integrated education in Romer's (1990) variety-expansion model, whereas Arnold (2002) has incorporated education into Segerstrom's (1998) quality-ladder model. The crucial assumption which removes the scale effect in the Segerstrom-Arnold approach is a continuing deterioration of the technological opportunities which results in a declining productivity of workers in the R&D sector. Variety innovations are excluded from the analysis.

In this paper, we follow the suggestions of Arnold (1998, 2002) and Blackburn, Hung, Pozzolo (2000) to focus on human-capital growth rather than on population growth within the framework of a semi-endogenous growth model, but we build on a more convincing specification which provides an alternative mechanism of eliminating the scale effect.¹ We adopt this mechanism from the latest generation of growth models as represented by Young (1998), Peretto (1998), Dinopoulos, Thompson (1998), Jones (1999), and Li (2002), which assume that the variety of products grows proportionally to the population of the economy. Extending an appropriate variant of such a basic model by accounting for endogenous accumulation of human capital instead of exogenous population growth yields some new insights regarding the impact of education on innovation and growth (see also Strulik 2005). In particular, human-capital accumulation and technological innovation appear as in-line engines of growth. To point out the intrinsically stochastic character of technological innovation, we assume that not only quality innovations but also variety innovations are governed by Poisson processes with endogenously determined arrival rates. To the best of our knowledge this is a novel feature of our model.

The remainder of the paper is organized as follows. Section 2 introduces the integrative growth model. In Section 3, the balanced growth equilibrium is derived and the

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

factors explaining education, innovation and growth are identified. Finally, Section 4 concludes.

2 The Model

We consider an economy consisting of a continuum of firms, each producing a differentiated consumer good. The goods are sold to households who have preferences for quantity, quality and variety. Improvements of quality and extensions of variety appear stochastically with intensities increasing in the R&D efforts of firms. Households are endowed with human capital which can be accumulated by education. Thus, there are two engines of growth which are closely linked to each other: education and innovation.

2.1 Education and Spending Behavior of Households

There is a continuum of households indexed by $[0, 1]$ which live forever and inelastically supply human-capital services in exchange for wage payments. They share identical preferences and maximize their discounted utility

$$U = \int_0^{\infty} e^{-\rho t} \ln C \, dt, \quad (1)$$

where $\rho > 0$ is the constant subjective discount rate and

$$C = \left[\int_0^N q(j)^{1-\alpha} x(j)^\alpha dj \right]^{1/\alpha}, \quad 0 < \alpha < 1, \quad (2)$$

is a quality-augmented Dixit-Stiglitz consumption index which measures instantaneous utility. It reflects the households' preferences for quantity $x(j)$ and quality $q(j)$ of the demanded goods available in a continuum of industries indexed on the interval $j \in [0, N]$ as well as their love for variety of horizontally differentiated goods indicated by N . The preferences reflect a unit intertemporal elasticity of substitution and a constant elasticity of substitution $1/(1 - \alpha)$ between any two products across industries.

The utility maximization problem of a representative household can be solved in two steps. The first step is to solve the across-industry static optimization problem at each point of time. Maximizing the consumption index (2) subject to the budget constraint

$$I = \int_0^N p(j)x(j)dj ,$$

where I denotes consumption expenditure and $p(j)$ the price of product j , yields the individual demand functions

$$x(j) = \frac{q(j)p(j)^{-\frac{1}{1-\alpha}} I}{\int_0^N q(j)p(j)^{-\frac{\alpha}{1-\alpha}} dj} \quad (3)$$

for all products j . Hence, the consumption index (2) can be rewritten as

$$C = I/p^C ; \quad p^C \equiv \left[\int_0^N q(j)p(j)^{-\frac{\alpha}{1-\alpha}} dj \right]^{-\frac{1-\alpha}{\alpha}} , \quad (4)$$

where p^C is the price index of consumption goods. The second step is to solve the dynamic optimization problem of consumer spending. Households supply human-capital services to education, production, and R&D. By devoting H^E units to education, they raise their human capital according to the Uzawa-Lucas technology

$$\dot{H} = \kappa H^E - \delta H , \quad (5)$$

where $\kappa (> \delta + \rho)$ denotes the effectiveness of the educational system and δ represents the constant depreciation rate of human capital. The dynamic budget constraint of each household (worker) is given by

$$\dot{A} = rA + w(H - H^E) + \sigma w H^E - I - T , \quad (6)$$

where A denotes the value of asset holdings, r is the nominal interest rate, w is the nominal wage rate for a worker employed either in production or in R&D, and $\sigma \in [0, 1)$ denotes an education subsidy rate for foregone income. The subsidies are publicly financed by a non-distorting lump-sum tax T . Each household considers this tax as fixed and maximizes its discounted utility (1), given (4), subject to the accumulation function (5) and the dynamic budget constraint (6).

Choosing labor as the numeraire, i.e. normalizing the wage rate to $w = 1$, the current-value Hamiltonian of the control problem reads

$$\mathcal{H} = \ln I - \ln p^C + \psi_1[rA + (H - H^E) + \sigma H^E - I - T] + \psi_2[\kappa H^E - \delta H] ,$$

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

$$\mathcal{H}_I = 1/I - \psi_1 = 0 , \tag{7}$$

$$\mathcal{H}_A = \psi_1 r = \psi_1 \rho - \dot{\psi}_1 , \tag{8}$$

$$\mathcal{H}_{H^E} = -\psi_1(1 - \sigma) + \psi_2 \kappa = 0 , \tag{9}$$

$$\mathcal{H}_H = \psi_1 - \psi_2 \delta = \psi_2 \rho - \dot{\psi}_2 . \tag{10}$$

Conditions (7) and (8) lead to the well-known Keynes-Ramsey rule

$$g_I = \dot{I}/I = r - \rho ,$$

which explains the growth rate of consumption expenditure by the difference between the interest and the discount rate. Further, we derive from (9) and (10) the constant costates' growth rates

$$\dot{\psi}_1/\psi_1 = \dot{\psi}_2/\psi_2 = -[\kappa/(1 - \sigma) - \delta - \rho] < 0$$

and hence from (8) the constant interest rate

$$r = \kappa/(1 - \sigma) - \delta ,$$

such that the Keynes-Ramsey rule can be rewritten as

$$g_I = \kappa/(1 - \sigma) - \delta - \rho > 0 . \tag{11}$$

The larger the effectiveness of education and the lower the discount and depreciation rates, the larger is the growth rate of consumer spending. Public expenditure is appropriate to enlarge this growth, independently of whether devoted to subsidize education, σ , or to raise the effectiveness of education, κ .

2.2 The Product Markets

Each product line is initially created by a horizontal basic innovation. Once a new variety is available on the market, its quality can be improved by vertical innovations. The quality grades are arrayed along equidistant rungs of a quality ladder. Each new generation of products provides a quality level, λ times higher than the previous one, where the size of technological jumps realized quality innovations is assumed to be constant over time and equal across all industries.² Thus the quality of the top-of-the-line product in industry j is given by

$$q(j) = q_0(j)\lambda^{m(j)} , \quad (12)$$

where $m(j)$ is the number of innovations realized in industry j up to the present. All existing consumer goods are produced subject to a constant returns to scale technology with human capital as single input. By an appropriate choice of units, production of one unit of each variety requires one unit of human capital, independently of its quality. Therefore, each firm has a constant marginal cost equal to the normalized wage rate, and the supplier of the highest quality of variety j maximizes the flow of profits given by

$$\pi(j) = [p(j) - 1]Lx(j)$$

with $x(j)$ specified in (3). The price-setting behavior of the technology leaders depends on the industrial structure which in turn is determined by the technological basic conditions. In this paper we restrict our analysis to the case of drastic quality innovations such that the price decisions of the leaders are constrained by competition from the producers of substitute goods supplied in the other industries.³ The constant price elasticity of demand, $-1/(1 - \alpha)$, implies monopolistic competition at prices $p(j) = 1/\alpha$ being the same across all the industries $j \in [0, N]$. Defining the average quality of all existing varieties by

$$Q = (1/N) \int_0^N q(j) dj , \quad (13)$$

² An extension of the model that allows for stochastic rung distances within and across industries and, hence, for heterogeneity of industries is discussed in Minniti, Parello, Segerstrom (2011) and Stadler (2012).

³ In the alternative case of non-drastic quality innovations the leading firms would charge limit prices since each industry leader is exactly one step ahead (see, e.g., Li 2001).

we derive from the individual demand functions (3) the industry demands

$$Lx(j) = \alpha ILq(j)/(NQ) , \quad (14)$$

and, hence, the flow of profits

$$\pi^Q(j) = (1 - \alpha)IL\lambda q(j)/(NQ) \quad (15)$$

to be expected by the firm succeeding in the next quality innovation.

The innovation dynamics in terms of both rising quality Q and expanding variety N are governed by the amount of human-capital resources devoted to R&D. In order to consistently integrate several variants of R&D-based growth models we assume that both types of innovative activities are undertaken simultaneously and that the numbers of quality and variety innovations rise according to sector-specific Poisson processes with endogenously determined arrival rates.

2.3 Quality-upgrading Innovations

The quality of the consumer goods can be upgraded by a sequence of innovations, each building on its predecessors. To produce a higher quality product, a blueprint is needed, which is developed by innovative firms in a vertical R&D sector. The opportunity of realizing temporary monopoly rents drives potential entrants to engage in risky R&D projects in order to search for the blueprint of a higher quality product. The first firm to develop the higher quality product is granted an infinitely-lived patent for the intellectual property rights. Since the incumbent firms have no incentive to invest in R&D in order to attain a two-step quality advantage over their nearest competitors, competition takes the form of sequential patent races between potential entrants and can be interpreted as a continuing process of creative destruction in the sense of Schumpeter (see Reinganum 1985). Every quality innovation establishes the opportunity for all firms to search for the next vertical innovation in this industry. This implies an external spillover effect of technological knowledge since even laggard firms can equally participate in each patent race without having climbed all rungs of the quality ladder themselves. It is only the patent protection which guarantees temporary appropriability of innovation rents. Each firm may target its research efforts at any of the continuum of state-of-the-art products, i.e. it

may engage in any industry. If a firm undertakes R&D at intensity $h^Q(j)$ for an infinitely small time interval of length dt , it will succeed in taking the next step up the quality ladder for the targeted product j with probability $h^Q(j)dt$. This implies that the number of realized quality innovations in each industry follows a Poisson process with the arrival rate $h^Q(j)$. We attempt to integrate several aspects discussed in the literature and suggest the rather general specification

$$h^Q(j) = \frac{\xi^Q LH^Q(j)}{q(j)}, \quad \xi^Q \equiv N^{\varepsilon_N} Q^{\varepsilon_Q}, \quad \varepsilon_N, \varepsilon_Q > 0, \quad (16)$$

where the arrival rate is assumed to depend proportionally on the amount of human capital $LH^Q(j)$ devoted to R&D activities in order to realize a quality improvement in industry j . The quality term $q(j)$ in the denominator of (16) represents a negative externality of industry specific innovation successes in the past by indicating that the realization of further quality innovations becomes progressively more difficult as the level of the achieved quality rises. The term ξ^Q captures a positive externality of the economy-wide knowledge created in the past through variety and quality innovations.

If a firm succeeds in a quality innovation it attains the stock market value $V^Q(j)$. To participate in a patent race firms have to employ human capital in their research labs. An entrepreneur who devotes $LH^Q(j)$ units of human capital to vertical R&D at cost $LH^Q(j)$ for a time interval of length dt attains the patent value $V^Q(j)$ with probability $[\xi^Q LH^Q(j)/q(j)]dt$. The entrepreneur can finance this R&D venture by issuing equity claims that pay nothing in the case that the research effort fails but entitle the claimants to the income stream $\pi^Q(j)$ if the effort succeeds. Free entry into each patent race requires

$$V^Q(j) = q(j)N^{-\varepsilon_N}Q^{-\varepsilon_Q}. \quad (17)$$

Absence of arbitrage opportunities on the stock market implies that the expected return on equities of quality innovators must equal the return on an equal size investment in a riskless bond, i.e.

$$r = \pi^Q(j)/V^Q(j) + \dot{V}^Q(j)/V^Q(j) - h^Q(j).$$

Since the risks associated with industrial research efforts are idiosyncratic, equity holders can earn a safe return by holding a well-diversified portfolio of firms' shares

in different industries. Using (15) and (17), the no-arbitrage condition can be written as

$$r = (1 - \alpha)ILL\lambda N^{-(1-\varepsilon_N)}Q^{-(1-\varepsilon_Q)} - \varepsilon_N g_N - \varepsilon_Q g_Q - h^Q . \quad (18)$$

It becomes obvious that the arrival rate is independent of the industry, i.e. $h^Q(j) = h^Q \forall j$. Due to this property and the assumption that the quality of product j jumps up from $q(j)$ to $\lambda q(j)$ whenever an innovation occurs, the time derivative of average technology is

$$\dot{Q} = (1/N) \int_0^N (\lambda - 1)q(j) h^Q dj = (\lambda - 1)h^Q Q ,$$

such that the quality growth rate

$$g_Q = (\lambda - 1)h^Q \quad (19)$$

is proportional to the vertical innovation rate h^Q . We now turn to variety innovations.

2.4 Variety-expanding Innovations

Each product line is initially created by a horizontal basic innovation. To avoid an unpalatable effect of declining average quality as a result of the introduction of new varieties, we assume that the initial quality level of a variety innovation, $q_0(j)$, equals the average quality at this time such that the expected flow of profits is given by

$$\pi^N = (1 - \alpha)ILLQ_0/(NQ) , \quad (20)$$

where Q_0 is the expected average quality at the moment of introducing a variety innovation. In tradition of the models introduced by Romer (1990) and Grossman, Helpman (1991) variety innovations are usually assumed to follow a deterministic process.⁴ However, there is no plausible reason to suppose riskless variety innovation, in particular if quality innovation is treated as risky at the same time. We therefore

⁴ In their simplified models, Aghion, Howitt (1998) and Dinopoulos, Thompson (1999), and Stadler (2003) even assume that variety innovations are pure results of costless imitation.

assume that the number of variety innovations follows a Poisson process, too. In order to apply the law of large numbers we assume that variety innovation is not only occurring in a single industry but takes place in all industries of the economy (see, e.g., Li 1998). Each firm undertaking horizontal R&D at intensity h^N for a time interval of length dt will succeed in creating a new product line with probability $h^N dt$. This implies that the number of realized variety innovations follows a Poisson process with the arrival rate h^N . By close analogy with (16) we use the specification

$$h^N = \frac{\xi^N LH^N}{Q}, \quad \xi^N \equiv N^{\eta_N} Q^{\eta_Q}, \quad \eta_N, \eta_Q > 0, \quad (21)$$

where the arrival rate depends proportionally on the amount of human capital LH^N devoted to horizontal R&D activities. The industry specific quality term in the denominator of (16) is replaced by average quality Q since variety search takes place at the rungs of different quality ladders. The term ξ^N captures a positive externality of the economy-wide knowledge created in the past through variety and quality innovations. A firm which devotes LH^N units of human capital to horizontal R&D at cost LH^N for a time interval of length dt attains the patent value V^N with probability $[\xi^N LH^N / Q]dt$. Free entry into each patent race requires

$$V^N = N^{-\eta_N} Q^{1-\eta_Q}, \quad (22)$$

Once the quality of a new variety is improved by a vertical innovation it becomes obsolete.⁵ Absence of arbitrage opportunities on the stock market implies that the expected return on equities of variety innovators must equal the return on an equal size investment in a riskless bond, i.e.

$$r = \pi^N / V^N + \dot{V}^N / V^N - h^Q, \quad (23)$$

where the right-hand side is the rate of return on equities of variety innovators, consisting of the dividend rate, the capital gains and the risk of losing the profits

⁵ Li (2000) imposes that the quality innovators have to pay a fixed fraction of their profit as royalty to the variety innovators. We do not follow this suggestion. In our view, it not realistic to assume that all quality innovators on the different rungs of the quality ladders have to pay a royalty to a firm replaced a long time ago.

due to a quality innovation in the future. Using (20) and (22), this no-arbitrage condition can be written as

$$r = (1 - \alpha)IL(Q_0/Q)N^{-(1-\eta_N)}Q^{-(1-\eta_Q)} - \eta_N g_N + (1 - \eta_Q)g_Q - h^Q, \quad (24)$$

where the ratio (Q_0/Q) is constant over time. The mass of horizontally differentiated products at time t is then determined by

$$N = \int_0^t h^N d\tau,$$

implying $\dot{N} = h^N$ (by the law of large numbers) and thus the variety growth rate

$$g_N = h^N/N. \quad (25)$$

Note that, in contrast to the quality-growth scenario (19), a constant variety growth rate requires an increasing horizontal innovation rate h^N .

3 The Balanced Growth Equilibrium

To close the model, we finally use the market-clearing condition for human capital

$$LH = LH^E + LH^X + LH^Q + LH^N, \quad (26)$$

which can be devoted to education, production, and both types of R&D. From (14) we obtain aggregate human capital employed in production,

$$LH^X = \int_0^N Lx(j)dj = \alpha IL,$$

from (16) human capital devoted to vertical innovation,

$$LH^Q = \int_0^N q(j)h^Q N^{-\varepsilon_N} Q^{-\varepsilon_Q} dj = h^Q N^{1-\varepsilon_N} Q^{1-\varepsilon_Q},$$

and from (21) and (25) human capital devoted to horizontal innovation,

$$LH^N = h^N N^{-\eta_N} Q^{1-\eta_Q} = g_N N^{1-\eta_N} Q^{1-\eta_Q},$$

such that (26) reads

$$LH = LH^E + \alpha IL + h^Q N^{1-\varepsilon_N} Q^{1-\varepsilon_Q} + g_N N^{1-\eta_N} Q^{1-\eta_Q} . \quad (27)$$

We restrict our attention to the balanced growth equilibrium where the shares of human capital in the different sectors remain constant over time. A first implication is that the steady-state growth rate of human capital is equal to the one of consumer spending as determined in (11) and therefore

$$g_H = g_I = \kappa / (1 - \sigma) - \delta - \rho . \quad (28)$$

This constant growth implies for the households' education choice in (5)

$$H^E / H = (g_H + \delta) / \kappa = 1 / (1 - \sigma) - \rho / \kappa . \quad (29)$$

The share of time households spend in the educational sector depends negatively on the rate of time preference ρ , but positively on the rate of education subsidy and on the effectiveness of the educational system.

Further a balanced path with constant growth rates g_N and g_Q requires

$$\begin{aligned} g_H &= (1 - \varepsilon_N)g_N + (1 - \varepsilon_Q)g_Q \\ &= (1 - \eta_N)g_N + (1 - \eta_Q)g_Q , \end{aligned}$$

such that

$$g_N = \frac{\eta_Q - \varepsilon_Q}{(1 - \varepsilon_N)(1 - \eta_Q) - (1 - \varepsilon_Q)(1 - \eta_N)} g_H \quad (30)$$

and

$$g_Q = \frac{\varepsilon_N - \eta_Q}{(1 - \varepsilon_N)(1 - \eta_Q) - (1 - \varepsilon_Q)(1 - \eta_N)} g_H . \quad (31)$$

Thus the growth rates of quality Q and variety N depend not only on the exogenously given on the spillover parameters but also on the endogenous growth rate of human capital as determined in (28). By aggregating the individual demands (3) across industries, imposing $p(j) = 1/\alpha$ and using the average quality index (13), we derive the quality-augmented consumption index

$$C = \alpha [NQ]^{\frac{1-\alpha}{\alpha}} I$$

which grows at the rate

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

Inserting (28), (30), and (31) finally yields the scale-invariant growth rate⁶

$$g_C = \left[\frac{1 - \alpha}{\alpha} \frac{\varepsilon_N - \varepsilon_Q - \eta_N + \eta_Q}{(1 - \varepsilon_N)(1 - \eta_Q) - (1 - \varepsilon_Q)(1 - \eta_N)} + 1 \right] [\kappa / (1 - \sigma) - \delta - \rho] .$$

Variety expansion and quality improvement of the products as well as human capital accumulation are the interrelated channels of growth. Most important, the dynamics of quality and variety innovations decisively depend on the pace of human capital accumulation.

As is characteristic for semi-endogenous growth models, the long-run growth rate is unrelated to scale. However, in accordance with empirical evidence the explanatory factors of the accumulation of both human capital and technological knowledge are derived as important determinants of growth. As can be seen, the growth rate depends positively on market power $1/\alpha$, the subsidy rate σ , and the effectiveness of the education system κ but negatively on the subjective discount rate ρ and the depreciation rate δ .

The effectiveness of education as well as the education subsidy rate not only accelerate the pace of human-capital accumulation but also the dynamics of quality and variety innovation. In this sense, human-capital accumulation of households and innovations as a result of intentional R&D activities of firms can be interpreted as in-line engines of economic growth.

4 Conclusion

Recent semi-endogenous growth models have accomplished a valuable task by removing the scale effect present in the first-generation endogenous growth models. A

⁶ This “qualitative” model can easily be transformed into a more conventional “quantitative” growth model if the innovative products are treated as intermediate inputs into the production of a single, final consumer good (see Grossman, Helpman 1991, Chap. 5).

disturbing property of these non-scale 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. An intriguing alternative is to replace exogenous population growth by endogenous human-capital accumulation. In this modified interpretation economic growth is not driven by growth of the labor force but by education of the workers. Human-capital resources devoted to education and R&D appear as engines of economic growth which are inextricably linked to each other. As was shown, human-capital accumulation has not only a direct growth effect, but also an indirect effect via an acceleration of quality and variety innovations.

It turns out that subsidizing education and improving the effectiveness of education are suitable policies to raise the long-run growth rate. Indeed, education policy plays a decisive role in public growth policy. According to the well-known results derived by Lucas (1988), an effective education accelerates human-capital accumulation as a main engine of growth. At the same time, however, since human capital is an essential input into horizontal and vertical R&D, education also accelerates the innovation dynamics such that education and innovation appear as in-line engines of economic growth.

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