Innovation, Public Capital, and Growth

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Abstract

This paper studies interactions between innovation, public capital, and human capital in an OLG model of endogenous growth. Public capital affects growth through productivity, the diffusion rate of new technologies, innovation capacity, and human capital accumulation. Panel data regressions show that higher innovation performance promotes growth directly, whereas public capital (through quantity and quality effects) has both direct and indirect effects on growth by promoting human capital accumulation and raising innovation capacity. The direct growth effect operates in a nonlinear fashion, in line with "critical mass" models of infrastructure. Elasticity estimates derived from simultaneous equation techniques show that the general equilibrium effects of public capital on steady-state output per capita (which account for indirect effects though human capital and innovation) are significantly higher than those derived from single equation methods.

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1 Introduction

Increased globalization, through the adoption and adaptation of pre-existing technologies imported from more advanced countries, has led to a substantial acceleration in the pace of technological progress in developing countries. Imports of capital and intermediate goods—whose embodied technological knowledge allows domestic firms to employ more efficient production processes and to copy more advanced products—represented in 2002-04 between 6 and 13 percent of their GDP, compared to 5 and 9 percent in 1994-96 (see World Bank (2008)). The easing of restrictions on foreign direct investment (FDI) has also proved to be a powerful channel for technology diffusion. Indeed, a significant fraction of these inflows have helped to finance imported new machinery and equipment purchases in domestic affiliates of foreign firms, and to foster domestic R&D activities—eventually leading to greater exports of high-tech goods in a growing number of countries.

However, the capacity of developing countries to absorb foreign technologies improved at a slower pace. Human capital, a key determinant of a country's capacity to undertake the research necessary to develop new technologies and to understand, implement, and adapt imported technologies (see World Bank (2008) and Coe et al. (2009)), remains a key constraint. Another is access to physical infrastructure—including electricity networks, road infrastructure, fixed-line telephony, potable water, and sanitation networks. Lack of access to (or poor quality of) some types of infrastructure acts as a significant drag on the ability of firms to engage in research and development, bring new goods to markets, and reap the profits that the exploitation of new technologies may generate. For instance, lack of domestic transportation infrastructure, and inadequate access to telecommunications, may prevent firms from introducing new products and hamper economy-wide dissemination of new and more efficient technologies. Unreliable access to electricity may limit opportunities to use electronic equipment and other advanced devices used in research activities and cross-border knowledge sharing among researchers.[1] In a study of US counties in the early 19th century, Sokoloff (1988) found

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[1] Other important constraints include the regulatory environment and access to finance (or venture capital); see, for instance, United Nations (2007) and World Bank (2007, 2008).

that the introduction of water transportation (in the form of either the construction of a new canal or the dredging of a river) was followed by a sharp increase in the rate of patenting in counties adjacent to the waterway.

The link between human capital, innovation, and growth has been the subject of numerous analytical and empirical contributions. Starting from the seminal contributions of Romer (1990), Helpman and Grossman (1991), and Aghion and Howitt (1992), a number of studies have proposed integrated models in which R&D and human capital accumulation are engines of growth, by emphasizing the complementarity between these two factors for the process of development; these studies include Redding (1996), Arnold (1998), Funke and Strulik (2000), Strulik (2005), and Grossmann (2007). However, several of these papers assume implicitly that human capital is rival—a questionable assumption if (average) human capital is broadly interpreted as the stock of knowledge. In addition, if greater access to public capital promotes the acquisition of knowledge, the impact of human capital on innovation may result from the indirect effect of infrastructure. Accounting for these channels is important from the perspective of public policy.

At the same time, and surprisingly enough, the link between public capital, innovation, and growth has not received much attention. In one of the few existing contributions, Schiffbauer (2007) develops a Romer-type model in which government spending on infrastructure reduces transportation costs associated with intermediate goods. However, he does not discuss public policy, and the potential trade-offs associated with the provision of infrastructure and other services by the government. Yet, this is a critical issue; if governments have access to limited resources to cover their expenditure, different types of government interventions may entail dynamic trade-offs at the macroeconomic level—even though at the microeconomic or sectoral level these interventions are largely complementary. In addition, different types of government intervention may generate spillover effects on other sectors, which may have an indirect impact on innovation capacity. If indeed lack of infrastructure or low quality of tertiary education are key constraints on research and development activities, increasing spending on infrastructure or universities may ultimately prove to be more efficient to stimulate innovation than, say, subsidies to research activities in the private sector.

To address these issues, this paper develops an overlapping-generations (OLG) model in which education, public capital, and innovation are all determinants of long-run growth. In the model, public capital affects the economy in a number of ways—through productivity in the production of final goods (in the standard Barro (1990) tradition), but also through the diffusion rate of new technologies, innovation capacity, and the economy's ability to produce human capital. This last channel is consistent with a number of studies that have documented a positive impact of infrastructure services on educational attainment. As a consequence of these various channels, the trade-offs involved in the allocation of public spending are more involved; depending on production elasticities, the best way to foster innovation activity in the private sector is not necessarily through direct public subsidies.

Our analytical framework delivers several important testable implications with respect to the effects of public infrastructure and public R&D spending on economic growth. The former operates both directly and indirectly (through the capacity to innovate and the accumulation of human capital) while the latter depends on the way R&D spending is financed. Moreover, the impact of infrastructure may operate, both directly and indirectly, in a nonlinear fashion. We test these implications by using a sample of 38 industrial and developing countries for the period 1981-2008 with a variety of econometric procedures and alternative definitions of the key variables. The estimation techniques include standard panel regression techniques as well as techniques that address potential endogeneity (dynamic GMM techniques and 3SLS). The 3SLS system approach, in particular, allows us to capture some of the main interactions mentioned earlier. In addition, we also account for the impact of the quality of infrastructure on growth. To preview our results, we find that higher innovation performance is conducive to per capita income growth while the stock of public capital has both direct and indirect growth effects by raising both human capital and the capacity to innovate. We also find evidence of quality effects of infrastructure and empirical support for the "critical mass" hypothesis of public capital. Taking proper account of the government's budget constraint, and the joint determination of the key endogenous variables, our estimates also suggest that public spending on R&D contributes to growth by fostering innovation. Further, we use the coefficient estimates to calculate various elasticity parameters, thus offering a direct link to the theoretical model developed. Elasticity estimates derived from simultaneous equation techniques suggest that the general equilibrium effects of public capital on growth are significantly higher than those derived from single equation methods.

The paper continues as follows. Section II presents the model. Section III derives the equilibrium growth rate and studies the growth effects of a public subsidy involving an increase in the rate of R&D subsidies. Section IV presents our econometric methodology and findings. Section V offers some concluding remarks.

2 The Economy

We consider an OLG economy where individuals live for three periods, childhood, adulthood, and old age. Each individual is endowed with one unit of time in the first two periods of life, and zero unit in old age. Children allocate all their time to education. In adulthood, each individual has one child. Total population is thus constant and the size of each cohort is set to $\bar{N}$. Adults supply labor inelastically; thus, we abstract from time allocation issues, and wages in adulthood are the only source of income.[2] Savings can be held only in the form of physical capital. Agents have no other endowments, except for an initial stock of physical capital at $t = 0$, which is the endowment of an initial old generation.

In addition to individuals, the economy is populated by firms and a government. There are four sectors in the economy: the first produces a final good, the second intermediate inputs (which depreciate fully after use), the third human capital (which is nonrival), and the fourth conducts research and development (R&D). Labor is used in the production of the final good and new ideas, and moves freely across all sectors. In addition to labor, firms producing the final good use also human and private physical capital, public infrastructure, and intermediate goods. The good can be either consumed in the period it is produced, or stored to yield physical capital at the beginning of the following period.

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[2] See Grossmann (2007) for an R&D-based OLG model of growth with endogenous labor allocation. His focus is on a comparison between R&D subsidies to firms and the public provision of advanced education—an issue that also entails the type of tradeoffs in government spending alluded to earlier.

The government invests in infrastructure and spends on education, subsidies to innovation, and some other items. It finances its expenditure by taxing wages. It cannot borrow and therefore must run a balanced budget in each period. Finally, all markets clear and there are no debts or bequests between generations.

2.1 Households

Let c_{t+j}^t denote consumption at period $t+j$ of a person born at the beginning of period t, with $j = 1, 2$. Assuming that consumption of children is subsumed in their parents' consumption, the discounted utility of an individual born at t is given by

$$U_t = \ln c_{t+1}^t + \frac{\ln c_{t+2}^t}{1+\rho}, \tag{1}$$

where $\rho > 0$ is the subjective discount rate.

Because taxes are levied only on middle-aged workers, and the price of the final good is normalized to unity, the period-specific budget constraints are given by

$$c_{t+1}^t + s_{t+1} = (1-\tau)e_{t+1}w_{t+1}, \tag{2}$$

$$c_{t+2}^t = (1 + r_{t+2})s_{t+1}, \tag{3}$$

where w_{t+1} is the economy-wide wage rate, e_{t+1} individual human capital, $\tau \in (0, 1)$ a constant tax rate, s_{t+1} the savings rate, and r_{t+2} the rate of return on holding (physical) assets between periods $t + 1$ and $t + 2$.

2.2 Production of the Final Good

The final good is produced by identical competitive firms of mass 1, indexed by i. Production requires the use of effective labor, given by the product of average human capital of individuals born in $t - 1$, E_t, and employment, $N_{i,t}^Y$, private capital, $K_t^{P,i}$, public infrastructure, K_t^I, and a combination of M_t intermediate inputs (or brands), $x_{s,t}^i$, where $s = 1, ...M_t$. Although public capital is nonexcludable, it is partially rival because of congestion effects; for simplicity, congestion is taken to be proportional to the aggregate private capital stock, $K_t^P = \int_0^1 K_t^{P,i} di$.[3]

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[3] Measuring congestion in terms of the level of output, as in some other studies, yields qualitatively similar results.

In contrast to Romer's model, all newly invented technologies cannot be instantaneously used to produce goods. We assume instead that lack of access to infrastructure may hamper the adoption of new technologies into the production process of the final good. Insufficient access to electricity or telecommunications, for instance, may hold back the introduction and systematic use of newly-invented technologies in the production process. Thus, we define the diffusion rate, κ_t (which is the same for all firms, for simplicity), as

$$\kappa_t = \kappa(k_t^I), \tag{4}$$

with $k_t^I = K_t^I/K_t^P$ is the public-private capital ratio, $\kappa_t \in (0,1)$, $\kappa(0) = 0$, $\kappa' > 0$, and $\lim \kappa_{k_t^I \to \infty} = 1$. The endogeneity of κ_t implies that improved access to infrastructure exerts not only a direct (and by now standard) effect on output, but also an indirect effect, by enabling firms to adopt and exploit at a faster rate the gains from innovation, as measured by a greater variety of intermediate inputs.

The production function of firm i takes therefore the form

$$Y_t^i = (\frac{K_t^I}{K_t^P})^{\varepsilon}(K_t^{P,i})^{\alpha}(E_t N_{i,t}^Y)^{\beta}[\sum_1^{\kappa_t M_t}(x_{s,t}^i)^{\eta}]^{\gamma}, \tag{5}$$

where $\alpha, \beta, \gamma \in (0,1)$, $\eta \in (0,1)$, $\varepsilon > 0$, and $1/(1-\eta) > 1$ is the elasticity of demand for each intermediate good. This specific form implies that each new innovation involves the production of a new intermediate good (as in Romer (1990)), and that the elasticity of substitution between different intermediate goods is equal to one. In addition, the production function distinguishes between the returns to specialization, as measured by γ, and the parameter that determines the demand elasticity, η. We assume constant returns in private inputs, so that $\alpha + \beta + \gamma = 1$.

With the price of the final good normalized to unity, profits of firm i in the final sector, $\Pi_{i,t}^Y$, are given by

$$\Pi_{i,t}^Y = Y_t^i - (1+\Lambda_t)\sum_1^{\kappa_t M_t} p_t^s x_{s,t}^i - w_t^Y E_t N_{i,t}^Y - r_t K_t^{P,i},$$

where p_t^s is the price of intermediate good s, w_t^Y the wage rate in the final good production sector, and r_t the rental rate of private capital. As in Schiffbauer (2007), it is also assumed that transportation costs, Λ_t, distort the distribution of intermediate goods to producers of the final good.

Each producer maximizes profits subject to (5) with respect to private inputs, labor and capital, and demand for all intermediate goods $x^i_{s,t}$, $\forall s$, taking factor prices, M_t, and Λ_t as given. This yields

$$r_t = \alpha \frac{Y^i_t}{K^{P,i}_t}, \quad w^Y_t = \beta \frac{Y^i_t}{E_t N^Y_{i,t}}, \tag{6}$$

$$x^i_{s,t} = [\frac{\gamma \eta Z^i_t}{(1+\Lambda_t)p^s_t}]^{1/(1-\eta)}, \quad s = 1, ...M_t, \tag{7}$$

where

$$Z^i_t = Y^i_t / \sum_1^{\kappa_t M_t} (x^i_{s,t})^\eta. \tag{8}$$

Because each firm demands the same amount of each intermediate good, equation (7) implies that the aggregate demand for intermediate good s is

$$x_{s,t} = \int_0^1 x^i_{s,t} di = \int_0^1 [\frac{\gamma \eta Z^i_t}{(1+\Lambda_t)p^s_t}]^{1/(1-\eta)} di. \tag{9}$$

Because all firms producing the final good are identical and their number is normalized to unity, $K^P_t = K^{P,i}_t$, and $Z_t = Z^i_t$, $\forall i$, and the total demand for intermediate goods is the same across firms, $x^i_t = x_t$, $\forall i$. Moreover, in a symmetric equilibrium, $x^i_{s,t} = x^i_t$, $\forall s$. Thus, $\int_0^1 [\sum_1^{\kappa_t M_t} (x^i_{s,t})^\eta]^\gamma di = (\kappa_t M_t)^\gamma x^{\eta\gamma}_t$. Let also $N^Y_t = \int_0^1 N^Y_{i,t} di$ denote total labor employed in the production of the final good. Using these results, equation (5) and the constant returns to scale assumption imply that aggregate output of the final good is

$$Y_t = \int_0^1 Y^i_t di = \left\{ (k^I_t)^\varepsilon (\frac{K^P_t}{M_t})^\alpha (\frac{E_t N^Y_t}{M_t})^\beta \kappa^\gamma_t x^{\eta\gamma}_t \right\} M_t. \tag{10}$$

Thus, if the expression in brackets is constant in the steady state, the growth rate of output is equal in the long run to the growth rate of innovations.

Transportation costs are assumed to be a decreasing function of the public-private capital ratio:

$$\Lambda_t = \Lambda(k^I_t), \tag{11}$$

where $\Lambda(0) = \Lambda_M > 0$, $\Lambda' < 0$, and $\lim_{k_t^I \to \infty} \Lambda_t = 0$. Thus, from (7) and (11), access to infrastructure affects the demand for each intermediate input both directly (through its marginal product) and indirectly (through transportation costs).

2.3 Production of Intermediate Goods

Firms in the intermediate sector are monopolistically competitive. There is only one producer of each input s, and each of them must pay a fee to use the patent (design) of that input to R&D producers. Production of each unit of an intermediate good s requires θ units of the final good.

Once the fee involved in purchasing a patent has been paid, each intermediate-good producer sets its price to maximize profits, $\Pi_{s,t}^I$, given the perceived total demand function for its good (which determines marginal revenue), $x_{s,t}$:

$$\Pi_{s,t}^I = (p_t^s - \theta) x_{s,t}. \tag{12}$$

Substituting (9) in this expression and imposing $Z_t^i = Z_t$, $\forall i$, yields

$$\Pi_{s,t}^I = (p_t^s - \theta)[\frac{\gamma\eta Z_t}{(1+\Lambda_t)p_t^s}]^{1/(1-\eta)}.$$

Maximizing this expression with respect to p_t^s, taking Z_t and Λ_t as given, yields the optimal price as

$$p_t^s = p_t = \frac{\theta}{\eta}, \quad \forall s \tag{13}$$

which implies, using (9), that the optimal quantity of each intermediate good demanded by producers of the final good is

$$x_{s,t} = x_t = [\frac{\gamma\eta^2 Z_t}{(1+\Lambda_t)\theta}]^{1/(1-\eta)}. \quad \forall s \tag{14}$$

From the definition of Z_t^i in (8), in equilibrium $Z_t = Y_t/\kappa_t M_t x_t^\eta$. Substituting this expression in (14) yields

$$x_t = \frac{\gamma\eta^2}{(1+\Lambda_t)\theta}(\frac{Y_t}{\kappa_t M_t}). \tag{15}$$

Because k_t^I is constant in the steady state, so are κ_t and Λ_t. As shown in Appendix A, the ratio Y_t/M_t is also constant in the steady state; thus, the equilibrium quantity of each intermediate good is constant at $\tilde{x}$ as well along the balanced growth path.

Substituting (13) in (12) yields the maximum profit for an intermediate-good producer:

$$\Pi_t^I = (\frac{1}{\eta} - 1)\theta x_t, \tag{16}$$

which is constant in equilibrium if x_t is constant.

A potential producer of an intermediate input decides to enter the market by comparing the discounted stream of profits generated by producing that input, and the price that must be paid for the patent or new design, p_t^M. If the market for new designs is competitive, standard arbitrage implies that the price of a patent must be equal to the present discounted stream of profits that the producer of intermediate inputs could make by producing the intermediate input s. For simplicity, we assume that each producer of a new intermediate good is accorded a patent only for the period during which it is bought. The arbitrage condition requires therefore that

$$p_t^M = (\frac{1}{\eta} - 1)\theta x_t. \tag{17}$$

2.4 Human Capital Accumulation

Schooling is mandatory and agents allocate all of their time to education in the first period of their lives. Human capital is produced using a combination of government spending on education per worker, as well as the parent's human capital and public capital, in the latter case taking into account a congestion effect measured again in terms of the private capital stock:[4]

$$e_{t+1} = (\frac{G_t^E}{\bar{N}})^{\nu_1} E_t^{1-\nu_1} (\frac{K_t^I}{K_t^P})^{\nu_2}, \tag{18}$$

where $\nu_1 \in (0,1)$ and $\nu_2 > 0$. Because individuals are identical within a generation, a parent's human capital at t is equal to the average human capital of the previous generation, E_t. For tractability, the learning technology is assumed to exhibit constant returns to scale in government spending and human capital. In a symmetric equilibrium, we also have $e_t = E_t$.[5]

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[4] See Agénor (2011) for a review of the evidence on the impact of infrastructure on education outcomes.

[5] It could be assumed that, as in McDermott (2002), there is a spillover effect of the stock of ideas on learning, which would make the learning technology depend on M_t as well. However, as discussed in the next section, we do not find robust empirical evidence of the latter effect.

2.5 Research and Development Sector

Firms engaged in R&D generate designs for new intermediate inputs, using the same technology. There is no aggregate uncertainty in the innovation process.

The production of new designs depends on the existing stock of designs, effective labor, as well as government spending on R&D (measured in units of the final good), G_t^R, and access to (congested) public infrastructure:

$$M_{t+1} - M_t = (\frac{G_t^R}{E_t})^{\phi_1} (\frac{M_t}{E_t})^{\phi_2} (k_t^I)^{\phi_3} E_t N_t^R, \tag{19}$$

where N_t^R is total employment in the R&D sector, $\phi_1, \phi_2 \in (0,1)$, and $\phi_3 > 0$. As in Romer (1990), all R&D firms have free access to the existing stock of ideas, so that each innovation creates a positive externality for future research activities; however, this occurs with diminishing returns. In addition, it is scaled by average human capital, to account for the fact that, as general knowledge increases, the marginal benefit of an increase in the existing stock of ideas (or "specialized" knowledge) becomes less relevant to promote innovation.

Government spending on R&D (in the form of grants for financing lab equipment, improving research facilities, etc.) has a direct impact on the ability to discover or produce new ideas. It is scaled again by average human capital, to account for the fact that, as general knowledge increases, government spending—unless it keeps pace with the economy's available human capital stock—becomes less relevant for innovation activities.[6] To ensure that the marginal benefit of an increase in human capital on innovation activity remains positive, we impose $\phi_1 + \phi_2 < 1$.

Access to public capital also has a direct, positive effect on the ability to innovate. By fostering innovation today, public infrastructure also has a positive external effect on future research activity—in addition to the indirect effect operating through human capital accumulation. However, access to public capital is subject to congestion, as measured by the private capital stock.[7]

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[6] For instance, with the growth of knowledge, more and more sophisticated computer and lab equipment may be needed to perform research activities.

[7] Alternatively, it could be assumed that public capital is congested by the stock of designs, or equivalently the "size" of the research sector. This would not affect qualitatively our results.

R&D firms choose labor so as to maximize profits, Π_t^R, given the dynamics of innovation captured by (19), $N_t^R \geq 0$, and taking wages, w_t^R, the patent price, p_t^M, and the public-private capital ratio as given:

$$\max_{N_t^R} \Pi_t^R = p_t^M (M_{t+1} - M_t) - w_t^R E_t N_t^R.$$

The first-order condition is

$$w_t^R \geq \left\{ (\frac{G_t^R}{E_t})^{\phi_1} (\frac{M_t}{E_t})^{\phi_2} (k_t^I)^{\phi_3} \right\} p_t^M, \tag{20}$$

with equality if $N_t^R > 0$. In that case, and given the linearity of the innovation technology with respect to effective labor, (20) is also the zero-profit condition implied by free entry.

2.6 Government

As noted earlier, the government taxes only adult wages. It spends a total of G_t^I on infrastructure investment, G_t^E on education, G_t^R on R&D activities, and G_t^U on other items. All its services are provided free of charge. It cannot issue bonds and must therefore run a balanced budget:

$$G_t = \sum G_t^h = \tau e_t w_t \bar{N}, \qquad h = E, I, R, U \tag{21}$$

where w_t is the economy-wide wage.

Shares of public spending are all assumed to be constant fractions of government revenues:

$$G_t^h = \upsilon_h \tau e_t w_t \bar{N}, \qquad h = E, I, R, U \tag{22}$$

Combining (21) and (22) therefore yields

$$\sum_h \upsilon_h = 1. \tag{23}$$

Assuming full depreciation, public capital in infrastructure evolves according to

$$K_{t+1}^I = G_t^I. \tag{24}$$

2.7 Market-Clearing Conditions

The asset market clearing condition requires tomorrow's private capital stock to be equal to savings in period t by individuals born in $t-1$. Given that s_t is savings per household, and that the number of adults is $\bar{N}$, we have

$$K_{t+1}^P = \bar{N}s_t, \tag{25}$$

where for simplicity we assume full depreciation of physical capital.

With perfect labor mobility, $w_t^Y = w_t^R$; with full employment, labor market equilibrium requires

$$N_t^R + N_t^Y = \bar{N}. \tag{26}$$

Equation (20), holding with equality, can be used to determine the economy-wide equilibrium wage, w_t. If the patent price, and the ratios in the curly brackets on the right-hand side of that equation are all constant, then wages will also be constant.

Using equation (6) to substitute out for N_t^Y, equation (26) can be used to determine equilibrium employment in the R&D sector:

$$N_t^R = \bar{N} - \beta(\frac{Y_t}{E_t})w_t^{-1}, \tag{27}$$

which is constant if Y_t/E_t and w_t are constant. The allocation of labor across sectors is thus also constant.

3 Balanced Growth Path and Public Policy

A *dynamic equilibrium* for the model described above is a sequence of allocations $\{c_t^{t-1}, c_{t+1}^{t-1}, s_t\}_{t=0}^{\infty}$, physical capital stocks $\{K_t^P, K_t^I\}_{t=0}^{\infty}$, human capital stock $\{e_t\}_{t=0}^{\infty}$, factor prices $\{w_t, r_{t+1}\}_{t=0}^{\infty}$, prices and quantities of each intermediate input $\{p_t^s, x_{s,t}\}_{s=1,...M_t,t=0}^{\infty}$, available varieties, $\{M_t\}_{t=0}^{\infty}$, a constant tax rate and public spending shares such that, given initial stocks $K_0^P, K_0^I > 0$, $H_0 > 0$, and $M_0 > 0$, *a*) individuals maximize utility subject to their intertemporal budget constraint, taking prices as given; *b*) firms in the final-good sector maximize profits, choosing labor, private capital, and intermediate inputs, taking the public capital stock and input prices as given; *c*) intermediate goods producers set prices so as to maximize profits, while internalizing the effect of their decisions on the perceived demand curve for their product; *d*) producers of new designs in the R&D sector maximize profits by choosing employment, taking wages, patent prices, the initial stock of designs, as well as government spending on R&D, as given; *e*) the equilibrium price of each design extracts all profits made by the corresponding intermediate good producer; *f*) the government budget is balanced; and *g*) all markets clear.

A *balanced growth equilibrium* is a dynamic equilibrium in which *a*) c_t^{t-1}, c_{t+1}^{t-1}, s_t, K_t^P, K_t^I, E_t, Y_t, M_t, grow at the constant, endogenous rate $\boldsymbol{\gamma}$, implying that the human capital-private capital ratio, as well as the public-private capital ratio, are also constant; *b*) the rate of return on private capital r_t and the economy-wide wage rate w_t are constant; *c*) the price of intermediate goods p_t and the patent price p_t^M are constant; and *d*) the fractions of the adult labor force engaged in the production of the final good and ideas, $n_t^h = N_t^h/\bar{N}$, with $h = R, Y$, are constant and $n_t^R + n_t^Y = 1$.

The balanced growth rate of the economy is derived in Appendix A. The public-private capital ratio, k_t^I, is constant over time:

$$k_t^I = \frac{\upsilon_I \tau}{\sigma(1-\tau)} \equiv J, \quad \forall t \tag{28}$$

where $\sigma \in (0,1)$ is the savings rate, constant over time.

As also shown in Appendix A, the model can be condensed into a first-order linear difference equation system in $\hat{k}_t^P = \ln k_t^P$ and $\hat{z}_t = \ln z_t$, where $k_t^P = K_t^P/E_t$, and $z_t = E_t/M_t$. With a $\tilde{}$ used to denote steady-state values, the long-run growth rate of output per worker is given by

$$1 + \boldsymbol{\gamma} = \Psi(\tilde{k}^P)^{\alpha\nu_1/\Omega(1-\phi_1)}\tilde{z}^{\mu}, \tag{29}$$

where $\tilde{k}^P$ and $\tilde{z}$ are given in Appendix A, and

$$\Omega = 1 - \beta - \eta\gamma + \beta/(1-\phi_1) > 0,$$

$$\mu = \phi\nu_1 + \frac{\nu_1(\alpha + \beta\phi)}{\Omega(1-\phi_1)} > 0,$$

$$\Psi = (\upsilon_E\tau)^{\nu_1} J^{\nu_2} \left\{ \left\{ (\upsilon_R\tau\bar{N})^{\phi_1} J^{\phi_3} \frac{(\eta^{-1}-1)\gamma\eta^2}{[1+\Lambda(J)]\kappa(J)} \right\}^{\nu_1[1-\beta/\Omega(1-\phi_1)]/(1-\phi_1)} \right\}$$

$$\times[\frac{J^{\varepsilon}\kappa(J)^{1-\gamma}\beta^{\beta}}{[1+\Lambda(J)]^{\eta\gamma}\theta^{\eta\gamma}}(\gamma\eta^{2})^{\eta\gamma}]^{\nu_1/\Omega(1-\phi_1)}.$$

Equation (29) illustrates the multi-dimensional effect of infrastructure on economic growth. These effects are illustrated both directly, through higher output productivity, and indirectly, through the capacity to innovate, the ability to produce human capital, the greater diffusion of new technologies, and the lower transportation costs of intermediate goods. Therefore, equation (29) stresses the general equilibrium effects of infrastructure, which are likely to exceed the direct (Barro-type) productivity effects. Based on this observation, it would be useful to empirically estimate the total, or general equilibrium, effect of infrastructure on growth with the use of an appropriate estimation technique.

In addition, based on equation (29), the role of public policy on growth can be assessed in a fairly intuitive manner. An increase in the share of government spending on R&D financed by a cut in other spending ($d\upsilon_R = -d\upsilon_U$), or an increase in the share of spending on education financed in the same way ($d\upsilon_E = -d\upsilon_U$), unambiguously raises the growth rate. In the first case the ratio of human capital to the stock of designs falls, whereas it increases in the second. However, an increase in, say, the share of spending on R&D, financed by a cut in spending on either education ($d\upsilon_R = -d\upsilon_E$) or infrastructure ($d\upsilon_R = -d\upsilon_I$) has ambiguous effects on steady-state growth. Intuitively, although spending more on R&D leads to a more rapid pace in the production of new designs, lower spending on education or infrastructure hampers the production of productive inputs—the stock of human capital and public infrastructure.

The effect of infrastructure on growth may also operate in a nonlinear fashion, through the production of final goods, education, or innovation. Indeed, some contributions have highlighted the possibility that there may be "critical mass" effects or "network externalities" associated with infrastructure (see Röller and Waverman (2001), Czernich et al. (2009), Kellenberg (2009), and Agénor (2010)). These effects imply that the benefits of infrastructure vary with the level of infrastructure itself. Specifically, this could be captured here by assuming that the elasticities ε, ν_2, and ϕ_3 appearing in equations (5), (18), and (19), respectively, may change from a relatively low (and possibly insignificant value empirically) to a relatively large (and empirically significant) value, once the stock of infrastructure (scaled by either private capital, as in the model, or by population or production) is sufficiently high. It may be for instance that a telecommunications network must be sufficiently developed to promote interactions between researchers and foster innovation. Moreover, there could be multiple thresholds, with a corresponding range of elasticities. In such cases, the analysis of the growth effects of infrastructure would naturally need to account also for initial conditions and possible shifts in parameters.

Because of these theoretical ambiguities, it is important to examine empirically the link between innovation, human capital, infrastructure, and growth, while accounting explicitly for the government budget constraint—together with possible nonlinearities in the effects of infrastructure on the production of goods, human capital, and ideas. We seek to do this in the remainder of the paper.

4 Empirical Evidence

We now turn to an evaluation of the inter-relationship between the stock of public capital, human capital, innovation and per capita output growth while controlling for the effects of public spending on infrastructure, education, and R&D. This empirical evaluation offers a link to our theoretical structural model as it allows us to map the coefficient estimates to some key elasticities of the model, such as the elasticities of final goods, human capital and innovation outputs with respect to infrastructure. In addition, the empirical analysis allows us to derive estimates of both the direct and the general equilibrium effects of public capital on economic growth and on the steady-state level of output. We first describe our estimation methodology and present next some basic (linear) results. To assess the robustness of these results, we conduct a wide range of sensitivity tests, involving alternative estimation methods, changes in the definition of variables, and allowing for nonlinearities.

4.1 Estimation Methodology

The empirical analysis focuses on the growth effects of education, innovation, and of the level of access to infrastructure. Consistent with our theoretical framework, we take into account both the direct and indirect effects of these variables on growth. We do this by employing an empirical specification that estimates four equations, one for each of these key variables. These equations are estimated both in reduced form, independently of each other, and jointly as a system. The latter technique, by considering the simultaneous determination of the key variables, allows us to capture their main interactions alluded to earlier. In particular, the specification allows public capital to influence human capital, while at the same time capturing and identifying innovation as an important mechanism through which human capital, public capital, and public subsidies to R&D promote economic growth. This, in turn, allows for the estimation of the general equilibrium effect of the stock of infrastructure on economic growth.

One of the main channels of influence is represented by the active role of government in the sectors of education, innovation, and infrastructure through the allocation of public resources. This means that the impact of these policies on growth is transmitted through their effects on education, innovation, and infrastructure outcomes, respectively. Our empirical strategy allows for these indirect effects by imposing the government budget constraint in the (public and human) capital and innovation equations so as to treat the impact of some components of public spending (infrastructure, education, and R&D subsidies) in a consistent way and control for their financing method. These, in turn, allow the examination of the potential trade-offs governments may face between subsidies to R&D and the provision of infrastructure, education, and other services described in the theoretical model of the previous section.

As pointed out in a number of recent studies (see for instance Kneller et al. (1999), Adam and Bevan (2005), and Bose et al. (2007)), one needs to acknowledge that the elements of the government budget constraint are bound together through an identity, so that all but one need to be included in a regression in order to control for both the financing element and to avoid perfect multi-collinearity. If the variables of the budget constraint are expressed as fractions of GDP, the analysis considers the *level* effects of fiscal instruments. It is possible, however, to also test for the *composition* effects of public spending by expressing the expenditure elements as fractions of total public expenditure (see Devarajan et al. (1996)).[8] In both cases of composition and level effects, the coefficients on the remaining fiscal variables are understood as measuring these effects net of the effect of the excluded variable.

Given the above, our benchmark empirical setup, which dwells on our theoretical model and is in line with the empirical literature in each individual area, is represented by

$$\begin{aligned} g_{it} &= \alpha_0 + \alpha_1 initGDP_{it} + \alpha_2 innov_{it} + \alpha_3 infra_{it} + \alpha_4 educ_{it} \qquad (30)\\ &\quad + \sum_{k=1}^{m} \zeta_k X_{k,it} + \mu_i + \varepsilon_{it}, \\ innov_{it} &= \beta_0 + \beta_1 initGDP_{it} + \beta_2 infra_{it} + \beta_3 educ_{it} + \beta_4 patstock_{it} \qquad (31)\\ &\quad + \sum_{l=1}^{n-1} \lambda_l Z_{l,it} + \mu_i + u_{it}, \\ educ_{it} &= \gamma_0 + \gamma_1 initGDP_{it} + \gamma_2 infra_{it} + \gamma_3 patstock_{it} \qquad (32)\\ &\quad + \sum_{l=1}^{n-1} \lambda_l Z_{l,it} + \sum_{j=1}^{q} \theta_j W_{j,it} + \mu_i + v_{it}, \end{aligned}$$

$$infra_{it} = \delta_0 + \delta_1 initGDP_{it} + \delta_2 urban_{it} + \delta_3 popdens_{it} + \sum_{l=1}^{n-1} \lambda_l Z_{l,it} + \mu_i + z_{it}, \qquad (33)$$

where the notation is as follows: i (t) is the country (time) index; g_{it} denotes the growth rate of per capita real GDP; $initGDP_{it}$ denotes the logarithm of initial per capita GDP; $innov_{it}$ represents innovation output, which is traditionally measured by the total number of patent applications in logarithmic form;[9] $educ_{it}$ represents education; $infra_{it}$ denotes a measure of the stock of infrastructure (originally) in the telecommunications sector, proxied by the logarithm of the number of telephone lines; $patstock_{it}$ is the stock of "technical" knowledge generated, proxied by the logarithmic

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[8] As before, this necessitates the exclusion of one expenditure element while also requiring to control for the level effect of total expenditure.

[9] Patents have been described by some as an imperfect proxy of innovation, as they may not capture the whole range of innovation, or may have dissimilar "contents of ideas," with some patents containing many (or big) ideas and other relatively few (or less relevant) ideas (Pavitt (1988)). However, they are the only well-established source that reflects innovative activity (Trajtenberg (1990)). See Bottazi and Peri (2005) and Griliches (1990) for arguments in favor of the use of patents as a measure of innovation performance.

stock of a country's patents.[10] Following Akcomak and ter Weel (2009), we measure innovation with the number of patent applications filed to the European Patent Office (EPO) while education is measured by the share of tertiary level students in the total number of students, as primary and secondary education measures are not expected to matter significantly for innovation capacity.[11] We use a measure of access to telecommunications as our benchmark measure of infrastructure, as it has been found in several formal studies to be the main contributive infrastructure category to economic growth (see Bougheas et al. (2000), Röller and Waverman (2001), Esfahani and Ramirez (2003), Egert et al. (2009), and Kellenberg (2009)) and in less formal studies as an important determinant of innovation activity.[12] We do test, however, the validity of our benchmark findings to the use of different stocks of infrastructure.[13]

Variables $\{X_{k,it}\}_{k=1}^{m}$ represent a set of conditioning variables that have been identified in growth studies to explain a substantial variation in the data. These include the rates of fertility and inflation, trade openness, and private investment. $\{Z_{l,it}\}_{l=1}^{n-1}$ represents the set of fiscal variables in levels, measured as fractions of GDP. As explained earlier, the government budget identity in levels, $\sum_{l=1}^{n} Z_l = 0$, requires the exclusion of one fiscal factor Z_0 so that the coefficient $\lambda_l = z_l - z_0$, where z_l is the coefficient of variable Z_l, with z_0 unobserved, measures the marginal impact of the included factor Z_l, net of the marginal impact of the excluded factor Z_0. The set $\{Z_{l,it}\}_{l=1}^{n-1}$ comprises public spending on infrastructure, education, R&D, the remaining component of government spending, the budget deficit, and non-tax revenue; for consistency with the theoretical model, the excluded fiscal factor Z_0 is thus tax revenue.[14] The set $\{W_{j,it}\}_{j=1}^{q}$

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[10] See Table B1 in Appendix B for details on the construction of this measure as well as a description of all the variables involved in the empirical analysis.

[11] Later, we consider the sensitivity of our benchmark findings to patent applications filed to alternative patent offices.

[12] See, for instance, the index of innovation capacity developed by The Economist Intelligence Unit, and the Global Innovation Index developed by INSEAD and the Confederation of Indian Industries.

[13] The infrastructure variables are typically measured in terms of density (that is, telephone lines per capita, electricity production per capita, roads and railtracks in kilometres of length per capita). As Egert et al. (2009) point out, however, even if such consideration sounds meaningful for some types of infrastructure, the inclusion of fixed effects in the estimation allows the use of the raw level of infrastructure in the regression. For this reason, we measure infrastructure stocks in raw levels. Robustness tests reveal that results are insensitive to the use of measures that account for density.

[14] At a later stage, we also test for the composition effects of public spending.

includes a group of controls typically associated with educational attainment (life expectancy, population, and the rate of urbanization), while $popdens_{it}$ stands for the rate of population density. Finally, μ_i captures time-invariant country-specific effects, whereas ε_{it}, u_{it}, v_{it}, and z_{it} are the error terms.

The specification of the regression equations is based on the following considerations. Equations (30), (31), and (32) are the empirical counterparts to our structural specifications (29), (19) and (18).[15] The infrastructure equation (33) is also related to our theoretical model, and captures the direct link between stocks of infrastructure assets and government spending, as shown in equation (24). The introduction of the level of initial per capita GDP in equation (30) captures conditional convergence effects and, as shown below, allows for the derivation of the elasticity of the steady-state level of output per capita with respect to the stock of infrastructure.[16] In addition, the use of GDP level in equations (31)-(33) controls for the initial level of development.

The coefficients of interest are α_2, α_3, and α_4, as they reflect the growth impact of innovation, public capital, and human capital, respectively. We also pay attention to the inter-related effects of innovation, infrastructure, and education, captured through the coefficients β_2, β_3, and γ_2. Finally, we are interested in the effect of R&D subsidies on innovation as these materialize through the coefficient $\lambda_{R\&D}$ in equation (31). These coefficient estimates shed light on the importance of the stock of infrastructure, educational attainment and innovative practices for growth but also for fostering one another. At the same time, they allow an identification of the growth-promoting categories of public expenditure through the above transmission channels.

The coefficient estimates serve another purpose. They provide a link with our theoretical model as they can be used to derive the elasticities of human capital and innovation outputs with respect to their inputs, and in particular the stock of infrastructure (i.e., $\nu_1, \nu_2, \phi_1, \phi_2$, and ϕ_3). Furthermore, as described below, the GDP growth rate equation (30) allows us to calculate the elasticity of the steady-state level

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[15] In the education equation (32), we added the stock of patents to test for possible externalities in terms of human capital accumulation (as suggested by McDermott (2002)).

[16] Even though our theoretical analysis has focused on a balanced growth path in which transitional dynamics are ignored, the empirical counterpart of equation (29) accounts for conditional convergence to avoid the possibility of ommitted variable bias.

of per capita output with respect to infrastructure. In this way, our empirical analysis pins down the magnitude of some key elasticity parameters with a variety of estimation techniques, which as described below, can distinguish between direct and general equilibrium effects.

Even though the message of our theoretical model points toward an estimation technique where the main endogenous variables are jointly determined, we conduct our analysis both with single- and multiple-equation techniques. The reasoning is that the equation-by-equation estimation exercise provides the direct effects of the explanatory variables on the response variables. The simultaneous equations system, by contrast, provides both the direct and indirect, or general equilibrium, effects. Therefore, comparison between the estimates obtained by the two techniques gives an indication of the degree to which the two types of effects (direct vs. total) differ. This, in turn, may reflect the importance one needs to attach to the estimation of a structural model that takes into account general equilibrium effects. For instance, in terms of our theoretical model equation (29), estimation of the effect of infrastructure on GDP per capita growth (in equation (30)) as a single equation does not account for the fact that $\tilde{k}^P$ and $\tilde{z}$ adjust due to a change in the stock of infrastructure. The system regression, by contrast, does account for the possibility that both $\tilde{k}^P$ and $\tilde{z}$ may fluctuate in response to a change in the stock of infrastructure.[17] It is, therefore, useful to use both regression techniques (single vs. multiple) and compare their outcomes.[18]

We use four econometric procedures to estimate equations (30)-(33). The first is a standard panel regression technique controlling for unobserved country-specific effects using the fixed effects estimator. The remaining three estimation procedures are based on techniques that address potential endogeneity of the right-hand-side variables. Of these, the first two are dynamic GMM estimations that control for the endogeneity of

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[17] See expressions (A22) and (A23) in Appendix A.

[18] Note that neither of the two regression techniques can isolate the productivity effect of infrastructure on economic growth. As the term Ψ of equation (29) reveals, the coefficient estimate of infrastructure in the growth regression represents a composite of the productivity effect (ε), the effect on the diffusion rate of new inventions (through κ), the effect on costs of transportation (through Λ), and the elasticities of education and innovation with respect to infrastructure (ϕ_3 and ν_2). The single-estimation technique estimates exactly this composite effect, while the simultaneous equations method estimates this composite effect along with the indirect effect that arises through changes in $\tilde{k}^P$ and $\tilde{z}$. The latter represents the total effect, which is expected to exceed the direct effect in magnitude.

all the regressors, and the third (3SLS) is a joint estimation of equations (30)-(33) in a system that considers only the endogeneity of the key variables (public capital, human capital, innovation).[19]

The two dynamic procedures are the difference-GMM estimator developed by Arellano and Bond (1991) and the system-GMM estimator of Blundell and Bond (1998). Although these techniques have become popular in the growth literature in recent years, they do have their limitations. Difference-GMM is susceptible to a weak-instruments problem because lagged levels may not be highly correlated with their first differences, whereas system-GMM requires the instruments of the level equation to be orthogonal to the country-specific effects. Given their limitations, we choose to utilize both.

Another consideration associated with the two dynamic GMM estimators relates to the choice of the number of lags of the endogenous variables used as instruments. As Roodman (2009) points out, an excessive number of instruments can result in overfitting of the instrumented variables, thereby biasing the results towards those obtained by OLS. As a rule of thumb, the number of instruments is suggested not to exceed the number of countries. Typically, the way these problems are minimized is by subjecting the empirical model to sensitivity tests, with various sets of lags in line with the above restriction on the number of instruments. However, given that the number of countries in our sample is limited due to the availability of R&D data, this strategy is infeasible for system-GMM—even when we use the minimum number of lags restricted to the second period. We, therefore, can test our specification with a number of instruments consistent with the above rule of thumb only under difference-GMM.

Both of the GMM approaches we use are checked for the validity of the instruments by applying two specification tests. The first test is the Hansen (1982) J-test of overidentifying restrictions, which we use to examine the exogeneity of the instruments. To avoid dynamic panel bias we instrument for regressors that are not strictly exogenous. These include all the right-hand-side variables in equations (30)-(33). The second test is the Arellano and Bond (1991) test for serial correlation, the existence of which can cause a bias to both the estimated coefficients and standard errors.

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[19] We also control for country fixed-effects in the GMM and 3SLS estimation methods.

4.2 Data

Our data span 38 countries (a list of which is given in Appendix B) for the period 1981-2008. The choice of both the sample of countries and of the time period is restricted by the availability of data on public R&D expenditure as these are available for a long time series only for the OECD members (30) and affiliate countries (8). As our analysis entails growth regressions, we follow the standard approach of constructing 4-year period averages (1981-84, 1985-88, 1989-92,..., 2005-08) so as to minimize business cycle effects. This implies a maximum sample size of 266 observations, although we end up working with an unbalanced panel of as few as 124 observations for the innovation equation due to missing data. As Table B1 illustrates our data are drawn from a variety of sources that include the World Development Indicators (World Bank), Government Finance Statistics (IMF), Main Science and Technology Indicators (OECD), and UNESCO. Table 1 presents summary statistics of the variables used in the benchmark model of equations (30)-(33).

4.3 Benchmark Results

We begin our investigation by estimating equations (30)-(33) independently of each other with fixed-effects and with the two dynamic GMM procedures. Then, we allow for a simultaneous estimation of all four equations with 3SLS, using the sets of control variables described above. Recall that according to the theoretical mechanisms of the preceding section, the key variables of education and infrastructure stock may influence growth both directly and indirectly, while innovation operates only directly. In addition, the growth effect of public spending on R&D takes shape through innovation. Our benchmark findings are presented in Table 2.

We start with the stock of infrastructure equation (33), estimated with fixed effects, that appears in the set of columns (1). The stock of infrastructure is positively associated with the level of a country's development and the degree of urbanization, and negatively by the fiscal variables of infrastructure expenditure and the budget balance. At the same time, the remaining component (net of infrastructure) of public expenditure, the non-tax revenue, and the density of the population, do not seem to matter. As regards the effects of the fiscal variables, recall that we omit the category of tax revenue pertaining to the level effects of these variables, as a way of avoiding collinearity problems. This means that the estimated coefficient on each category of expenditure is a measure of the marginal impact on the stock of infrastructure of this type of spending when financed by the excluded financing component. In a similar way, the estimated coefficient on each included source of finance is a measure of the marginal impact on the stock of infrastructure of raising revenue from that source in order to offset a reduction in the excluded component. Our results suggest that the marginal impact of public infrastructure spending on the stock of infrastructure when financed by tax revenue is significantly negative, while the marginal effect of the rest of government expenditure is not statistically significant. On the revenue side, the marginal impact of increased government borrowing is significantly negative (at the 10 percent level), whilst the marginal impact of raising revenue from non-tax sources is not significantly different from zero.

The negative effect of infrastructure spending on the stock of infrastructure, which is of interest from the perspective of fiscal policy, hinges on three assumptions. First, it depends on the way infrastructure spending is financed. Second, because we do not control for potential endogeneity of infrastructure spending, the negative effect may reflect the lower commitment of governments to spend toward infrastructure in countries with a high infrastructure stock. Third, the effect may reflect the disassociation between infrastructure flows and stocks, as public infrastructure spending may have a different effect on the flow of infrastructure compared to its stock (see Agénor (2010)).

Turning to the education equation, greater life expectancy and a higher stock of infrastructure have a positive impact on education, while the rate of urbanization and the population size have a negative effect. The rest of the variables (level of development, marginal effect of fiscal variables, and stock of patents) have no explanatory power. The variables that appear to significantly influence education are in line with the findings of the related literature (see, for instance, Gupta et al. (1999)), while the sizable and highly significant positive effect of infrastructure stock supports our theoretical modelling.

Moving to the innovation equation, we observe strong positive effects of public

R&D expenditure, the stock of infrastructure, the stock of patents, and of education on innovation capacity. These findings suggest that channeling tax revenues toward R&D expenditure can lead to higher innovation performance, unlike the *flow of spending* toward infrastructure. In all, the results support the importance of infrastructure and education, as well as the use of R&D expenditure by the government, as a way of boosting innovation activity, not only directly but also through the accumulation of the stock of patents. These findings are in line with Prodan (2005), Ulku (2007*a*, 2007*b*), and Akcomak and ter Weel (2009) regarding the contribution of R&D intensity, measured either as public subsidies or as the share of R&D personnel employment in total employment. To our knowledge, however, no study before this one has examined the effect of the infrastructure stock on innovation activity.[20]

Finally, the estimation of the growth equation is supportive of the general findings in the literature as to the significance of income convergence effects and the growth-promoting impacts of higher levels of private investment and of a more outward-oriented trade policy. The results also reveal the strong influence of the key variables of our model on growth. The stock of infrastructure, the level of innovation, and the degree of educational attainment are all directly conducive to faster economic growth. If one also takes into account the indirect effects of these variables, as described above, then the positive impact of these key variables on growth is even greater in magnitude.[21] This is where one of our main contributions lies; although a number of studies in the literature have found that infrastructure is growth-enhancing (see Bougheas et al. (2000), Röller and Waverman (2001), Esfahani and Ramirez (2003), Calderón and Servén (2004), Straub (2008), and Egert et al. (2009)), none of them has accounted for the indirect channels outlined here. Overall, the empirical findings offer support to the assumptions of our theoretical model, in particular with regard to the production process of human capital and new designs.

One possible drawback of the results presented thus far is that they may be biased

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[20] Schiffbauer (2007) examined the effect of telecommunications infrastructure on the total public R&D expenditure (as a share of GDP). The latter, however, being a measure of innovation input, does not reflect innovation performance.

[21] Such estimates are offered below based on the results of the simultaneous equation estimation model.

by the endogeneity of some of the regressors. To overcome such a problem, the following two sets of columns present results that control for reverse causality. Column set (2) illustrates the difference-GMM regression, whereas set (3) presents the results of the 3SLS regression with the instrumented variables appearing in bold type.[22] In both of them, we observe the following consistent findings: *a*) a positive impact of public R&D subsidies on innovation activity; *b*) a positive effect of the stock of infrastructure on education outcomes, innovation activity, and economic growth; *c*) a positive impact of education on innovation; *d*) a positive effect of patents stock on innovation; and *e*) an enhancing effect of innovation capacity on economic growth. The effect of education on growth is not significant in the GMM estimation and (counter-intuitively) is found to have a negative effect in the 3SLS results, while the inflation rate picks up a negative sign under both estimation methods.[23] In addition, and in contrast to the results of the fixed-effects estimation, proper instrumentation of the government expenditure share to infrastructure unveils a statistically zero effect on the stock of infrastructure.[24]

Hansen's J-statistic, which examines the validity of the instruments in the GMM estimation, is also reported in Table 2. These specification tests cannot reject the hypothesis that the instruments are uncorrelated with the error term at a standard confidence level. Finally, the Arellano-Bond (1991) test rejects the hypothesis of no second-order serial correlation in the error term in all, but the innovation, regressions at any conventional level of significance.

As discussed earlier, the coefficient estimates reported in Table 2 are not only interesting for their qualitative impact (that is, the sign of the effect of the controlled

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[22] As discussed in the methodology section, the use of the system-GMM technique leads to overfitting of the intstrumented variables, thus questioning the validity of the instruments. For this reason we refrain from presenting these results. In general, however, the outcomes of the system-GMM regressions convey the same (qualitative and quantitative) information as the difference-GMM regressions.

[23] The insignificant growth effect of education is quite common in the growth literature across both heterogeneous country samples (Bose et al. (2007)) and homogeneous samples (Akcomak and ter Weel (2009) and Kneller et al. (1999)).

[24] The instruments used in the difference-GMM regression are the second-to-fifth lags of the instrumented variables (second and third for the education regression) using the 'collapse' option in STATA to create one instrument for each variable and lag distance, rather than one instrument for each time period, variable, and lag distance. This allows for a smaller number of instruments, even compared to the use of only the second lag as instrument for each one of the regressions. The latter, however, produces results equivalent to those reported.

variables), but also for their quantitative implications. First, the estimates can be used to calculate some key elasticity parameters that map into our theoretical model. Second, any differences in these elasticities across the single- and the multiple-regression estimations can be viewed as capturing the wedge between the direct and the general equilibrium effects. In what follows, we focus our attention on the elasticity parameters of the human capital accumulation equation (18), (ν_1, ν_2), and of the new designs production equation (19), (ϕ_1, ϕ_2, ϕ_3). Moreover, we obtain estimates of the long-run elasticity of the *level* of economic output per capita with respect to the stock of infrastructure.

Some of the coefficient estimates in Table 2 represent elasticities as both the dependent and the explanatory variables enter in logarithmic forms. This is true for the stock of patents and the stock of infrastructure in the innovation equation (31). Therefore, the coefficient estimates $\hat{\beta}_2$ and $\hat{\beta}_4$ correspond to the elasticity parameters ϕ_3 and ϕ_2 in our theoretical model.[25] The remaining elasticities are obtained with some further manipulation. The elasticity of human capital accumulation with respect to education spending (ν_1) is calculated around the mean values of these two variables by multiplying the coefficient estimate of education expenditure in the education regression $(\hat{\lambda}_{Educ})$ by the ratio of the mean value of education expenditure to the mean value of education. In a similar fashion, the elasticity of human capital accumulation with respect to the stock of infrastructure (ν_2) is calculated by dividing the coefficient estimate of the infrastructure stock in the education regression $(\hat{\gamma}_2)$ by the mean value of education. The elasticity of R&D production with respect to government spending on R&D (ϕ_1) is calculated by multiplying the coefficient estimate of R&D expenditure in the innovation regression $(\hat{\lambda}_{R\&D})$ by the mean value of R&D expenditure. Finally, following Angeles and Neanidis (2009), we use the implicit function theorem to obtain a measure of the elasticity of per capita output with respect to the stock of infrastructure at the steady state by dividing the coefficient estimate of infrastructure stock in the growth regression $(\hat{\alpha}_3)$ by the negative of the coefficient estimate of GDP per capita in the same regression $(\hat{\alpha}_1)$. Specifically,

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[25] A hat above a parameter denotes the coefficient estimate of that parameter.

$$\nu_1 = \hat{\lambda}_{Educ} \times \frac{\overline{educ\ exp}}{\overline{educ}}, \tag{34}$$

$$\nu_2 = \frac{\hat{\gamma}_2}{\overline{educ}}, \tag{35}$$

$$\phi_1 = \hat{\lambda}_{R\&D} \times \overline{R\&D\ exp}\ , \tag{36}$$

$$Output\ elasticity\ of\ infrastructure_{steady-state} = -\frac{\hat{\alpha}_3}{\hat{\alpha}_1}, \tag{37}$$

where *educ exp* denotes education expenditure as fraction of GDP, *R&D exp* stands for R&D expenditure as fraction of GDP, and a bar above a variable indicates its mean value.

Table 3 presents these elasticity parameters by using the coefficient estimates reported in Table 2, assigning a dash when a coefficient estimate is not statistically significant. The first thing to notice is that the elasticities are quite sizeable even for the single-equation estimation methods. The stock of infrastructure has a sizeable influence on both the accumulation of human capital and the production of innovative output as the respective elasticities are in the areas of 0.6-0.7 and 0.2-0.3. The first range of values is substantially higher than the parameter values used by Chen (2005) and Agénor (2011), while the second range is about half the size of the econometric estimate obtained by Sokoloff (1988).

Equally sizeable are the elasticities of innovative output with respect to public spending on R&D and to prior innovative contributions, as measured by the stock of knowledge. The values for these two elasticities lie between 0.2-0.3 and 0.4-0.7 respectively. Ulku (2007a) estimates elasticities of comparable magnitude (0.2 and 0.5 respectively) in a sub-sample of 26 OECD countries with a large market (defined as having aggregate GDP above the sample median value).[26]

Particular attention is reserved for the output elasticity of infrastructure which lies in the range of 0.1-0.2. These values are consistent with recent findings in the

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[26] In a related exercise, disaggregated at the sectoral level, Ulku (2007*b*) finds elasticity estimates of 0.1-0.2 for ϕ_1 and around 1 for ϕ_2 in the sectors of chemicals, drugs and medicine, machinery and transport, and electrical and electronics in 17 OECD countries.

literature, such as Röller and Waverman (2001) who find an elasticity of 0.15 for 21 OECD countries over 1970-1990, Shioji (2001) that estimates a long-run elasticity of 0.1-0.15 for US states and Japanese prefectures over four decades (1960s-1990s), Esfahani and Ramirez (2003) who find an elasticity of 0.1 for a panel of 75 countries over the period 1965-1995, and Kamps (2006) that estimates an average elasticity of 0.2 for 22 OECD countries over 1960-2001.[27]

As one moves from the single-equation regression coefficients to the simultaneous system of equations, we observe an increase in the size of every elasticity (with the exception of ϕ_2 which is at about the same level as the GMM estimate). Now even ν_1 takes up a positive value of 0.1, which is equal to the value used by Rioja (2005) and comparable to the estimates found by Gupta et al. (2002), which are in the range of 0.08-0.16.[28] In addition, ϕ_3 now is in line with the estimate of Sokoloff (1988). The elasticity of long-run per capita output with regard to infrastructure also rises to 0.26. This result suggests that a simultaneous equation model, which is better suited to account for indirect effects, represents a more accurate method of identifying the total effect of infrastructure. For this reason, the remaining of the analysis presents results based solely on this technique.[29]

4.4 Robustness

We examine the sensitivity of our benchmark results by re-running the regressions under various modifications. These include the use of alternative measures of innovation, various proxies for infrastructure, accounting for the quality of infrastructure, and testing for the presence of threshold effects related to infrastructure. Our basic findings survive all of these checks.

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[27] See Agénor (2011) for a more detailed discussion of the evidence on this parameter.

[28] To make the results in Gupta et al. (2002) comparable to our estimates, we calculated the elasticity ν_1 using the same technique as described earlier. Note that their estimates are based on gross primary and secondary enrollment rates.

[29] The results described in this section remain unchanged if instead of using the level effects of fiscal variables, we use the composition effects. The latter are obtained by introducing fiscal variables as shares of total public expenditure, while also controlling for the level effect of total government expenditure (see Devarajan et al. (1996)). The results are available upon request.

4.4.1 Alternative Measures of Innovation

The proxy for innovation we have used corresponds to the total number of patent applications filed to the European Patent Office (EPO) by year of filing, according to the inventor's country of residence (per million inhabitants). Even though the use of the residence of the inventor as the idea's country of origin is standard in the literature, many studies have proxied the generation of innovative ideas by the number of patent applications to the US Patent and Trademark Office (USPTO). Ulku (2007*a*, 2007*b*) suggests that this choice is typically guided by the fact that the US attracts the highest number of international patent applications, as it has the most dynamic market for technological innovation.[30] As such, US patents are thought to provide a good approximation for the rate of technological innovation of countries. In addition, Bottazi and Peri (2005) suggest a "cost-benefit" justification, in the sense that the USPTO likely attracts the most important innovations. By this reasoning, innovations with marginal use or with a low likelihood of profitability would not be worth the patenting cost in the US.

Apart from the number of patent applications submitted to the EPO and USPTO, one more patent indicator of inventive performance relates to the number of patent applications filed under the Patent Co-operation Treaty (PCT). The PCT "makes it possible to seek patent protection for an invention simultaneously in each of a large number of countries by filling an 'international' patent application." It thus represents a more global type of recognition and protection of patents. Given the variety of patent indicators, it is prudent to examine the validity of our benchmark findings against these alternative measures.

A first indication of the high comparability of the different innovation measures is offered by the correlation coefficients of the EPO patent applications with those filed at the USPTO and PCT. For our sample these are 0.88 and 0.87 respectively, both significant at the 1 percent level. A formal evaluation of the impact of these indicators

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[30] This is verified in our sample as the average number of total patent applications to the USPTO exceed that of the EPO by one-third. Accounting for the size of the population of the inventor's country of origin, however, reverses the order as patent applications to the EPO exceed those of the USPTO by a third. This offers indirect support for the use of the EPO filed patents as our benchmark measure.

is reported in Table 4 with regard to the 3SLS estimation, where the set in columns (1) repeats the findings of the benchmark innovation measure from Table 2 for ease of comparison. The results are in general supportive of our benchmark findings. Exceptions are that, for two of the three measures of innovation, education negatively affects innovation and R&D public spending improves innovation output. Other than these, the stock of infrastructure continues to promote education, innovation, and economic growth outcomes; the stock of patents improves innovation capacity; and innovation output has a positive effect on growth. These findings indicate that in the case of the alternative measures of innovation, the positive impact of infrastructure on growth operates only through the indirect channel of innovation improvements. Therefore, we can conclude that the choice of the innovation measure does not significantly impact upon the qualitative effects of the stock of infrastructure and of public R&D spending on growth.

The last statement is supported by the evidence reported in Table 5, which shows estimated elasticity values. These values do not differ widely across the three measures of innovation, particularly so for the elasticity of long-run output with respect to infrastructure, which varies between 0.22-0.27, while some variability is observed in the magnitude of the elasticities of R&D production, especially with respect to infrastructure.

4.4.2 Alternative Proxies for Infrastructure

In the foregoing analysis we have used the number of main telephone lines as our preferred measure of the stock of infrastructure, as this measure reflects the most widely used indicator in the literature (see for instance Easterly (2001), Röller and Waverman (2001), Loayza et al. (2005), Schiffbauer (2007), Kellenberg (2009)). At the same time, accessibility of telecommunication services seems to play a particularly important role on the ability to create new and more efficient technologies, and speed up their diffusion rate, within (and across economies) as outlined in our theoretical framework. Given, however, the increasing popularity of mobile phones since the mid-1990s our current estimates may not fully capture the influence of telecommunications networks. In order to account for this, we use the total number of mobile and fixed-line telephone subscriptions.[31]

The literature also offers some additional indicators of infrastructure. They mostly relate to the sectors of energy and transportation, measured by the amount of energy consumption, energy production, electricity production (or generating capacity), and the length of the road and/or rail network.[32] To explore the implications of the choice of the infrastructure sector for our benchmark results, we repeat our analysis by looking at the power sector and using as an indicator a country's electricity production capacity.

The results of these regressions are shown in Table 6. The use of the alternative infrastructure measures does not change our original conclusions in any meaningful way. The sole exception is that innovation's effect on growth turns out to be insignificant for the energy sector. Most importantly, however, the effect of the stock of infrastructure on education, innovation and growth outcomes continues to be positive and significant for both the telecommunications and the power sectors.

The insensitivity of the findings is also illustrated in Table 7 that presents estimated elasticity values. These values do not vary largely across the two infrastructure indicators, nor do they when compared with the initial infrastructure indicator of main telephone lines. However, worthy of note is that the elasticity of steady-state output per capita with respect to infrastructure jumps to a value of 0.4 for the energy sector.

4.4.3 Infrastructure Quality

A handful of papers go beyond measures of infrastructure stocks and consider issues of infrastructure quality and efficiency. Hulten (1996) develops an effectiveness index of infrastructure and finds a growth impact of more than seven times larger compared to that of the quantity of public capital. Esfahani and Ramirez (2003) show that the effectiveness of the stock of infrastructure on economic growth is affected by institutional factors. Calderón and Servén (2004) build a synthetic indicator of infrastructure qual-

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[31] Note though that line subscriptions are not strictly a physical measure of telecommunications infrastructure and may actually reflect an increase in use that represents congestion effects.

[32] Some studies have used in their analysis more than one indicator of infrastructure, independently of each other (Bougheas et al. (2000), Esfahani and Ramirez (2003)), whereas others have built synthetic indices of various dimensions of infrastructure by applying principal component analysis (Calderón and Servén (2004), Egert et al. (2009)). We prefer to use the former method as we wish to identify the impact of the different infrastructure categories on growth, through the production of human capital and new ideas.

ity and report an effect that is not significantly related to growth but does contribute to lower income inequality. More recently, Calderón (2009), using the same aggregate index of infrastructure quality, found a significant positive effect on growth for Africa.

Keeping in mind that having an operational and credible infrastructure network may be of equal importance as the physical presence of such a network, especially for the creation and distribution of new technologies, we add to our benchmark 3SLS regression indicators of infrastructure quality. These indicators are added in both the innovation and growth equations to capture the indirect and direct effects of infrastructure quality. We do this for both of the infrastructure sectors we have used in the previous section (telecommunications and energy) in order to examine whether the addition of the quality measures alters the impact of the quantity counterparts. Table 8 reports the results.

First, we add an indicator of quality in the services offered by the telecommunications network, measured by the number of telephone faults.[33] In line with the benchmark findings, the stock of infrastructure continues to have a positive and significant impact on the education, innovation and economic growth outcomes (with innovation still contributing significantly to growth). In addition to this quantity effect now the quality of the telecom network matters also directly for growth, as the poor quality of telecommunications diminishes growth. In the set of columns (2), we add as an indicator of quality in the power sector the percentage of electricity production that is *not* lost due to transmission and distribution problems. As in Table 6, the quantity of electricity production is conducive to education, innovation and growth. Also, as with the telecommunication services, better quality in the form of improved transmission and distribution of electric power has a direct positive effect on growth.

Table 9 shows the implied elasticity parameters once we control for infrastructure quality. The values are in general comparable with those of Table 7, which ignore quality considerations. The main feature of Table 9 is the sizeable elasticity of long-run per capita output with respect to the quality of infrastructure for electricity production,

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[33] Results are the same when we use either the number of main telephone lines or the number of mobile and fixed-line subscriptions as a measure of the quantity of the telecom infrastructure. Note that the addition of the quality measure, leads to a drop of the sample size by about 40 percent.

which takes up a value of 5.82. This estimate swamps its quantity counterpart and conveys information in line with the findings of Hulten (1996) as to the far greater importance of the quality of electricity power for economic performance. In general, however, these findings emphasize the dual influence of public infrastructure on growth as both the quality and the quantity of public capital are important determinants of economic performance.

4.4.4 Infrastructure Threshold Effects

A few studies in the infrastructure-growth literature have considered the potentially nonlinear nature of this relationship. On the theoretical side, Agénor (2010) developed a model where due to network externalities the degree of efficiency of infrastructure is increasing with the size of the public capital stock itself. An implication of such network effects is that the impact of infrastructure on growth may not be linear, but subject to threshold effects. In other words, the growth impact may be larger once a significant network size is achieved. These “critical mass” effects associated with public infrastructure have also been examined empirically. Röller and Waverman (2001) and Kellenberg (2009) examined nonlinearities related specifically to the telecommunications infrastructure. Even though they find on average a positive growth effect, the magnitude of the effect increases (doubles) in countries with high levels of telecommunications infrastructure, offering support to the presence of a critical mass at levels around universal service. In the same vein, Czernich et al. (2009) found that broadband matters for growth only above a threshold of 10 percent penetration rates. Bougheas et al. (2000) and Egert et al. (2009), on the other hand, report results that support the presence of diminishing returns on growth associated with the size of the telecommunication and transport infrastructure and telecommunication and energy infrastructure, respectively.

We take up the issue of nonlinearities in the infrastructure-growth relationship for all the measures of infrastructure used in the previous sections. As in the above studies, we test for threshold effects of infrastructure in the growth equation. Moreover, we test for such nonlinearities in the *innovation* equation in line with our earlier discussion. This consideration allows us to check for indirect threshold effects of infrastructure on growth through innovation.[34] This requires respecifying equations (30) and (31) as

$$
\begin{aligned}
g_{it} &= \alpha_0 + \alpha_1 initGDP_{it} + \alpha_2 innov_{it} + (\alpha_3 + \alpha_4 High) \times infra_{it} \qquad (38) \\
&+\alpha_6 educ_{it} + \sum_{k=1}^{m} \zeta_k X_{k,it} + \mu_i + \varepsilon_{it}, \\
innov_{it} &= \beta_0 + \beta_1 initGDP_{it} + (\beta_2 + \beta_3 High) \times infra_{it} \qquad (39) \\
&+\beta_5 educ_{it} + \beta_6 patstock_{it} + \sum_{l=1}^{n-1} \lambda_l Z_{l,it} + \mu_i + u_{it},
\end{aligned}
$$

where the dummy variable High corresponds to the classification defined in Table B1.[35] Given our findings of an increasing impact of infrastructure on both innovation and growth (i.e., $\beta_2, \alpha_3 > 0$), positive and significant coefficients for the interaction terms (β_3 and α_4) would support the network effects theory, whereas negative coefficients would support the diminishing returns hypothesis. Table 10 reports the findings.

For the telecommunications infrastructure (column set (1)) the results accord well with our benchmark findings.[36] Moreover, they illustrate the presence of diminishing returns of infrastructure on innovation and of network effects on economic growth. The parameter estimate β_2 indicates that important innovation effects from telecommunications infrastructure exist, particularly for countries with a relatively low stock to begin with. The positive innovation effects diminish in magnitude for higher levels of telecommunication infrastructure ($\beta_3 < 0$). The decline in magnitude is, however, small.[37] Further, the positive signs of α_3 and α_4 offer support to the findings of Röller and Waverman (2001) and Kellenberg (2009), both with regard to the critical mass story and the location of the threshold. As with innovation, however, the marginal growth impact of higher infrastructure—estimated at about 9 percent—is not sizeable.

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[34] We have also added public capital thresholds in the education equation but they have not been found to be statistically significant. As this addition has no bearing on the rest of the coefficient estimates, we chose to drop the thresholds from the education equation in favor of a more parsimonious model.

[35] The thresholds of the telecommunications sector follow Röller and Waverman (2001) and Kellenberg (2009). As for the energy sector, the dummy *High* corresponds to values that exceed the average value of our sample.

[36] The same is true when we use the number of mobile and fixed-line subscriptions instead.

[37] A joint test of the overall significance of high telecommunications countries reveals that there exists a statistically significant positive effect on innovation output at the 1 percent level.

The next set of columns examines the presence of nonlinear effects for the energy sector. The findings point to diminishing threshold effects on innovation ($\beta_3 < 0$) but only linear growth effects. As with telecommunications, the size of this declining effect is marginal. Turning to Table 11, we observe that the nonlinear effects just described have a minor impact on the estimated elasticities, preserving the general findings reported in the absence of threshold effects.

5 Concluding Remarks

This paper studied interactions between public capital, human capital, and innovation in a three-period OLG model of endogenous growth. In the model, public capital was shown to affect growth not only through productivity, but also through transportation costs, the diffusion rate of new technologies, the capacity to innovate, and the economy's ability to produce human capital. After deriving the steady-state growth rate of output, the model was used to illustrate the trade-offs involved in the allocation of public spending to R&D and other productive components, namely, infrastructure and education. The implications of the model are tested using a sample of 38 developed and developing countries for the period 1981-2008 and a variety of econometric procedures, including standard panel regression techniques as well as methods that address potential endogeneity problems (dynamic GMM and 3SLS techniques). Among other results, we found that higher innovation performance is conducive to per capita income growth while the stock of public capital has both direct and indirect growth effects, by raising the capacity to innovate and the rate of human capital accumulation. Taking proper account of the government's budget constraint, our estimates also suggest that public spending on R&D contributes to growth by fostering innovation. We also found that the quality of infrastructure matters (in line with other studies), and that the impact of infrastructure on innovation capacity appears to be subject to threshold effects. Finally, using our coefficient estimates we obtain values for various elasticity parameters. Elasticity estimates derived from simultaneous equation techniques show that the general equilibrium effects of public capital on steady-state output per capita (which accounts for indirect effects though human capital and innovation) are significantly higher than those derived from single equation methods, as reported in recent studies.

Our analysis has important implications for public policies aimed at fostering innovation and the design of growth-promoting public expenditure programs in general, for low- and middle-income countries. First, our theoretical framework and estimation results suggest that access to public capital can promote growth not only directly (through standard productivity effects), but also indirectly through its impact on human capital accumulation and the capacity to innovate. Moreover, the contribution of human capital to growth seems to operate mostly through its impact on innovation capacity; to the extent that access to infrastructure acts as constraint on the expansion of R&D activities, public spending on human capital may have little impact on growth. Second, for public infrastructure to have a sizable direct effect on growth, there must be enough of it for "critical mass" effects to kick in. Thus, for many low- and middle-income countries, to promote growth may require allocating sufficient government resources to boost the quantity and quality of public infrastructure, especially in telecommunications.[38]

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[38] Of course, this prescription assumes that investment in infrastructure is efficient enough; see Agénor (2010) for a further discussion.

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Appendix A NOT FOR PUBLICATION
Dynamic System and Steady-State Growth

Substituting for s_t from (2) in (3) yields the lifetime budget constraint,

$$c^t_{t+1} + \frac{c^t_{t+2}}{1+r_{t+2}} = (1-\tau)e_{t+1}w_{t+1}. \tag{A1}$$

Each individual maximizes (1) with respect to c^t_t and c^t_{t+1}, subject to the intertemporal budget constraint (A1) and $c^t_{t+1}, c^t_{t+2} > 0$. The first-order conditions give the standard Euler equation

$$\frac{c^t_{t+2}}{c^t_{t+1}} = \frac{1+r_{t+2}}{1+\rho}. \tag{A2}$$

Substituting this result in (A1) yields

$$c^t_{t+1} = (\frac{1+\rho}{2+\rho})(1-\tau)e_{t+1}w_{t+1}, \tag{A3}$$

so that

$$s_t = \sigma(1-\tau)e_t w_t, \tag{A4}$$

where $\sigma = 1/(2+\rho)$ is the marginal propensity to save.

Substituting this result in (25) yields

$$K^P_{t+1} = \sigma(1-\tau)e_t w_t \bar{N}. \tag{A5}$$

From (22) and (24),

$$K^I_{t+1} = \upsilon_I \tau e_t w_t \bar{N}. \tag{A6}$$

Combining (A5) and (A6), this expression yields

$$k^I_{t+1} = \frac{K^I_{t+1}}{K^P_{t+1}} = \frac{\upsilon_I \tau}{\sigma(1-\tau)} = J, \tag{A7}$$

which is constant over time.

From (6), (10), and (A7),

$$Y_t = J^\varepsilon \kappa(J)^\gamma \left\{ (\frac{K^P_t}{M_t})^\alpha (\frac{E_t}{M_t}\frac{\beta Y_t}{E_t w_t})^\beta x_t^{\eta\gamma} \right\} M_t = J^\varepsilon \kappa(J)^\gamma \beta^\beta x_t^{\eta\gamma}(k^P_t z_t)^\alpha (\frac{Y_t}{M_t})^\beta w_t^{-\beta} M_t,$$

where $k^P_t = K^P_t/E_t$ and $z_t = E_t/M_t$. Equivalently

$$(\frac{Y_t}{M_t})^{1-\beta} = J^\varepsilon \kappa(J)^\gamma \beta^\beta x_t^{\eta\gamma}(k^P_t z_t)^\alpha w_t^{-\beta}. \tag{A8}$$

From (15) and (A7),

$$x_t = \frac{\gamma\eta^2}{[1+\Lambda(J)]\theta\kappa(J)}(\frac{Y_t}{M_t}). \tag{A9}$$

Substituting this result in (A8) and rearranging yields

$$\frac{Y_t}{M_t}=[\frac{J^{\varepsilon}\kappa(J)^{1-\gamma}\beta^{\beta}}{[1+\Lambda(J)]^{\eta\gamma}\theta^{\eta\gamma}}(\gamma\eta^2)^{\eta\gamma}]^{1/(1-\beta-\eta\gamma)}(k_t^P z_t)^{\alpha/(1-\beta-\eta\gamma)}w_t^{-\beta/(1-\beta-\eta\gamma)},$$

that is,

$$\frac{Y_t}{M_t}=\Psi_1(k_t^P z_t)^{\alpha/\omega}w_t^{-\beta/\omega}, \tag{A10}$$

where

$$\omega=1-\beta-\eta\gamma>0$$

$$\Psi_1=[\frac{J^{\varepsilon}\kappa(J)^{1-\gamma}\beta^{\beta}}{[1+\Lambda(J)]^{\eta\gamma}\theta^{\eta\gamma}}(\gamma\eta^2)^{\eta\gamma}]^{1/\omega}>0.$$

From (17), (A7), and (A9),

$$p_t^M=(\frac{1}{\eta}-1)\theta x_t=(\frac{1}{\eta}-1)\frac{\gamma\eta^2}{[1+\Lambda(J)]\kappa(J)}(\frac{Y_t}{M_t}). \tag{A11}$$

From (22),

$$G_t^h=\upsilon_h\tau e_t w_t\bar{N}, \quad h=E,R \tag{A12}$$

Substituting (A11) and (A12) for $h=R$ in (20), holding with equality, and using (A7), yields

$$w_t=(\upsilon_R\tau w_t\bar{N})^{\phi_1}z_t^{-\phi_2}J^{\phi_3}(\frac{1}{\eta}-1)\frac{\gamma\eta^2}{[1+\Lambda(J)]\kappa(J)}(\frac{Y_t}{M_t}),$$

or

$$w_t=\Psi_2 z_t^{-\phi}(\frac{Y_t}{M_t})^{1/(1-\phi_1)}, \tag{A13}$$

with

$$\phi=\frac{\phi_2}{1-\phi_1}, \quad \Psi_2=\left\{(\upsilon_R\tau\bar{N})^{\phi_1}J^{\phi_3}(\frac{1}{\eta}-1)\frac{\gamma\eta^2}{[1+\Lambda(J)]\kappa(J)}\right\}^{1/(1-\phi_1)}>0.$$

Substituting (A13) in (A10) yields

$$\frac{Y_t}{M_t}=\Psi_3(k_t^P)^{\alpha/\Omega}z_t^{(\alpha+\beta\phi)/\Omega}, \tag{A14}$$

where

$$\Omega=\omega+\beta/(1-\phi_1)>0,$$

$$\Psi_3=\Psi_1^{\omega/\Omega}\Psi_2^{-\beta/\Omega}.$$

Substituting (A14) back in (A13) yields the equilibrium wage as a function of z_t and k_t^P:

$$w_t=\Psi_4(k_t^P)^{\alpha/\Omega(1-\phi_1)}z_t^{\mu_1}, \tag{A15}$$

where

$$\mu_1 = \phi + \frac{\alpha + \beta\phi}{\Omega(1-\phi_1)} > 0,$$

$$\Psi_4 = \Psi_2 \Psi_3^{1/(1-\phi_1)} > 0.$$

Now, from (18) and (A12) for $h = E$,

$$\frac{E_{t+1}}{E_t} = (\frac{G_t^E}{\bar{N}E_t})^{\nu_1} J^{\nu_2} = (\upsilon_E \tau w_t)^{\nu_1} J^{\nu_2},$$

or equivalently, using (A13) to eliminate w_t,

$$\frac{E_{t+1}}{E_t} = \Psi_5 z_t^{-\phi\nu_1} (\frac{Y_t}{M_t})^{\nu_1/(1-\phi_1)},$$

where

$$\Psi_5 = (\upsilon_E \tau)^{\nu_1} \Psi_2^{\nu_1} J^{\nu_2} > 0.$$

Substituting (A14) for Y_t/M_t yields

$$\frac{E_{t+1}}{E_t} = \Psi_6 (k_t^P)^{\alpha\nu_1/\Omega(1-\phi_1)} z_t^{\mu_2}, \tag{A16}$$

where

$$\mu_2 = \nu_1\mu_1 = \phi\nu_1 + \frac{\nu_1(\alpha + \beta\phi)}{\Omega(1-\phi_1)} > 0,$$

$$\Psi_6 = \Psi_5 \Psi_3^{\nu_1/(1-\phi_1)} > 0.$$

Using (A5), (A15), and (A16), the dynamics of k_t^P are determined by

$$k_{t+1}^P = \frac{\sigma(1-\tau)\bar{N}\Psi_4 (k_t^P)^{\alpha/\Omega(1-\phi_1)} z_t^{\mu_1}}{\Psi_6 (k_t^P)^{\alpha\nu_1/\Omega(1-\phi_1)} z_t^{\mu_2}},$$

or equivalently,

$$k_{t+1}^P = \Theta_P(k_t^P, z_t; J). \tag{A17}$$

Next, we need to determine the dynamics of z_t. Dividing (19) by M_t yields

$$\frac{M_{t+1}}{M_t} = 1 + (\frac{G_t^R}{E_t})^{\phi_1} z_t^{1-\phi_2} (k_t^I)^{\phi_3} N_t^R,$$

or equivalently, using (A7) and (A12) for $h = R$,

$$\frac{M_{t+1}}{M_t} = 1 + [(\upsilon_R \tau)^{\phi_1} J^{\phi_3}] w_t^{\phi_1} z_t^{1-\phi_2} N_t^R. \tag{A18}$$

To eliminate N_t^R from this expression, we can substitute (A13) for w_t in equation (27) to give

$$N_t^R = \bar{N} - \beta(\frac{Y_t}{M_t}) z_t^{-1} \Psi_2^{-1} z_t^{\phi} (\frac{Y_t}{M_t})^{-1/(1-\phi_1)},$$

or equivalently

$$N_t^R = \bar{N} - \frac{\beta}{\Psi_2}(\frac{Y_t}{M_t})^{-\phi_1/(1-\phi_1)} z_t^{-(1-\phi)}. \tag{A19}$$

Substituting (A14), (A15), and (A19) in (A18) yields

$$\frac{M_{t+1}}{M_t} = 1 + \Psi_7 (k_t^P)^{\alpha\phi_1/\Omega(1-\phi_1)} z_t^{\mu_3} [\bar{N} - \Psi_8 (k_t^P)^{-\alpha\phi_1/\Omega(1-\phi_1)} z_t^{-\mu_4}], \tag{A20}$$

where

$$\mu_3 = \phi_1\mu_1 + 1 - \phi_2,$$

$$\mu_4 = 1 - \phi + \frac{\phi_1(\alpha + \beta\phi)}{\Omega(1-\phi_1)} > 0,$$

$$\Psi_7 = (\upsilon_R \tau)^{\phi_1} J^{\phi_3} \Psi_4^{\phi_1} > 0,$$

$$\Psi_8 = \beta \Psi_2^{-1/(1-\phi_1)} \Psi_3^{-\phi_1/(1-\phi_1)} > 0.$$

Combining (A16) and (A20) yields

$$z_{t+1} = \frac{\Psi_6 (k_t^P)^{\alpha\nu_1/\Omega(1-\phi_1)} z_t^{1+\mu_2}}{1 + \Psi_7 (k_t^P)^{\alpha\phi_1/\Omega(1-\phi_1)} z_t^{\mu_3} [\bar{N} - \Psi_8 (k_t^P)^{-\alpha\phi_1/\Omega(1-\phi_1)} z_t^{-\mu_4}]},$$

or

$$z_{t+1} = \Theta_Z(k_t^P, z_t; J). \tag{A21}$$

In the steady state, k_t^P and z_t are constant; from (A17) and (A21), they are solutions of the system

$$\tilde{k}^P = \left\{ \frac{\sigma(1-\tau)\bar{N}\Psi_4 \tilde{z}^{\mu_1 - \mu_2}}{\Psi_6} \right\}^{1/\Phi}, \tag{A22}$$

$$\tilde{z} = \left\{ \frac{\Psi_6 (\tilde{k}^P)^{\alpha\nu_1/\Omega(1-\phi_1)}}{1 + \Psi_7 (\tilde{k}^P)^{\alpha\phi_1/\Omega(1-\phi_1)} \tilde{z}^{\mu_3} [\bar{N} - \Psi_8 (\tilde{k}^P)^{-\alpha\phi_1/\Omega(1-\phi_1)} \tilde{z}^{-\mu_4}]} \right\}^{-1/\mu_2}, \tag{A23}$$

where

$$\Phi = 1 - \frac{\alpha(1-\nu_1)}{\Omega(1-\phi_1)}.$$

By implication, E_t, M_t, and K_t^P (and thus K_t^I from (A7)) grow also at the same constant rate.

From (A14), in the steady state,

$$(\frac{\tilde{Y}}{M}) = \Psi_3 (\tilde{k}^P)^{\alpha/\Omega} \tilde{z}^{(\alpha - \beta\phi)/\Omega},$$

which implies that output grows also at the same rate as M_t and other aggregate variables.

From (A15), the steady-state wage rate is

$$\tilde{w} = \Psi_4(\tilde{k}^P)^{\alpha/\Omega(1-\phi_1)}\tilde{z}^{\mu_1}.$$

Thus, from (A2), (A3), and (A4), individual consumption (in both periods of life) and savings (in the first period) grow at the same rate as E_t and all other aggregate variables. From (6) the rental rate of capital is equal to $r_t = Y_t/K_t^P$ and is therefore constant in the steady state.

From (A16) and (A20), the growth rate of the economy is given by the equivalent forms[39,40]

$$\boldsymbol{\gamma} = \Psi_6(\tilde{k}^P)^{\alpha\nu_1/\Omega(1-\phi_1)}\tilde{z}^{\mu_2} - 1, \tag{A24}$$

$$\boldsymbol{\gamma} = \Psi_7(\tilde{k}^P)^{\alpha\phi_1/\Omega(1-\phi_1)}\tilde{z}^{\mu_3}[\bar{N} - \Psi_8(\tilde{k}^P)^{-\alpha\phi_1/\Omega(1-\phi_1)}\tilde{z}^{-\mu_4}], \tag{A25}$$

Equation (A24) corresponds to (29) in the text, with $\Psi = \Psi_6$ and $\mu = \mu_2$. After substitutions, we have

$$\Psi_6 = (\upsilon_E\tau)^{\nu_1}J^{\nu_2}\left\{\left\{(\upsilon_R\tau\bar{N})^{\phi_1}J^{\phi_3}\frac{(\eta^{-1}-1)\gamma\eta^2}{[1+\Lambda(J)]\kappa(J)}\right\}^{\nu_1[1-\beta/\Omega(1-\phi_1)]/(1-\phi_1)}\right\}$$

$$\times[\frac{J^{\varepsilon}\kappa(J)^{1-\gamma}\beta^{\beta}}{[1+\Lambda(J)]^{\eta\gamma}\theta^{\eta\gamma}}(\gamma\eta^2)^{\eta\gamma}]^{\nu_1/\Omega(1-\phi_1)},$$

$$\Psi_7 = (\upsilon_R\tau)^{\phi_1}J^{\phi_3}[\Psi_2]^{\phi_1}[\Psi_2^{-\beta/\Omega}]^{\phi_1/(1-\phi_1)}\left\{[\frac{J^{\varepsilon}\kappa(J)^{1-\gamma}\beta^{\beta}}{[1+\Lambda(J)]^{\eta\gamma}\theta^{\eta\gamma}}(\gamma\eta^2)^{\eta\gamma}]^{1/\omega}\right\}^{\omega\phi_1/\Omega(1-\phi_1)}$$

$$\times\left\{(\upsilon_R\tau\bar{N})^{\phi_1}J^{\phi_3}(\frac{1}{\eta}-1)\frac{\gamma\eta^2}{[1+\Lambda(J)]\kappa(J)}\right\}^{[\phi_1+\phi_1/(1-\phi_1)]/(1-\phi_1)},$$

$$\Psi_8 = \beta[\frac{J^{\varepsilon}\kappa(J)^{1-\gamma}\beta^{\beta}}{[1+\Lambda(J)]^{\eta\gamma}\theta^{\eta\gamma}}(\gamma\eta^2)^{\eta\gamma}]^{-\omega\phi_1/\omega\Omega(1-\phi_1)}$$

$$\times\left\{(\upsilon_R\tau\bar{N})^{\phi_1}J^{\phi_3}\frac{(\eta^{-1}-1)\gamma\eta^2}{[1+\Lambda(J)]\kappa(J)}\right\}^{-(1+\phi_1\beta/\Omega)/(1-\phi_1)^2}$$

To study the dynamic properties of the model, note that equations (A17) and (A21) form a first-order linear difference equation system in log-deviations from the steady state, $\hat{k}_t^P = \ln k_t^P$ and $\hat{z}_t = \ln z_t$, such that

$$\begin{bmatrix} \hat{k}_{t+1}^P \\ \hat{z}_{t+1} \end{bmatrix} = \begin{bmatrix} \Theta_P^1 & \Theta_Z^1 \\ \Theta_P^2 & \Theta_Z^2 \end{bmatrix} \begin{bmatrix} \hat{k}_t^P \\ \hat{z}_t \end{bmatrix}, \tag{A26}$$

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[39] From (A5) and (A6), two other equivalent expessions can be derived for the growth rate.

[40] Note that the solution displays the typical "scale effect" that is characteristic of Romer-type models of innovation and growth. This scale effect can be eliminated in various ways; see for instance Eicher and Turnovsky (2000), Dinopoulos and Thomson (2000), and Perez-Sebastian (2007).

where

$$\Theta_P^1 = \alpha(1-\nu_1)/\Omega(1-\phi_1) > 0,$$

$$\Theta_Z^1 = \mu_1 - \mu_2 = \phi + \frac{\alpha+\beta\phi}{\Omega(1-\phi_1)} - \phi\nu_1 - \frac{\nu_1(\alpha+\beta\phi)}{\Omega(1-\phi_1)},$$

The term Θ_Z^1 can be rewritten as

$$\Theta_Z^1 = \phi(1-\nu_1) + \frac{(1-\nu_1)(\alpha+\beta\phi)}{\Omega(1-\phi_1)} > 0.$$

We also have

$$\Theta_P^2 = \frac{\alpha\nu_1}{\Omega(1-\phi_1)}\left\{1 - \frac{A_1\phi_1}{\nu_1(1+A_1-A_2)}\right\},$$

$$\Theta_Z^2 = \mu_2 - 1 + \frac{A_2(\mu_3-\mu_4) - A_1\mu_3}{1+A_1-A_2},$$

where

$$A_1 = \Psi_7(\tilde{k}^P)^{\alpha\mu_1/\Omega(1-\mu_1)}\tilde{z}^{\mu_3}\bar{N},$$

$$A_2 = \Psi_7\Psi_8\tilde{z}^{\mu_3-\mu_4}.$$

In general, Θ_P^2 and Θ_Z^2 cannot be signed unambiguously; establishing stability and studying the transititional dynamics of the model require therefore numerical simulations.

Appendix B NOT FOR PUBLICATION

Country Sample and Data Sources

Country Sample (38)

Argentina, Australia, Austria, Belgium, Canada, China, Czech Rep., Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Japan, Korea, Luxembourg, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Romania, Russian Federation, Singapore, Slovak Rep., Slovenia, South Africa, Spain, Sweden, Switzerland, Turkey, United Kingdom, USA.

Table B1
Variables description and sources

Variable	Definition	Source
Benchmark Set		
Stock of infrastructure	Telephone lines.	World Bank, *WDI*
Education	Share of tertiary level students in the total number of all students, according to the International Standard Classification of Education 1976 and 1997 (ISCED-76, ISCED-97). For years 1981 to 1995 tertiary education includes ISCED-76 levels 5, 6 and 7. For years 1998 and after, tertiary education includes ISCED-97 levels 4, 5 and 6. The first level of each of the classifications covers programs that generally do not lead to a university degree but usually require successful completion of a program at the upper secondary level. The second level covers programs that lead to an award of a first university degree, and the third level covers programs that lead to an award of a second or further university degree.	UNESCO
Innovation	Total number of patent applications per million inhabitants filed to the European patent office (EPO) by year of filing, according to the inventor's country of residence. The reference date of the application is the priority date, which is the date of the first international filing of a patent and therefore the closest to the invention date.	OECD, *Main Science and Technology Indicators*
Growth	Annual percentage growth rate of GDP per capita based on constant local currency.	World Bank, *WDI*
Stock of patents	The stock of patents for country i is calculated using the perpetual inventory procedure in line with Bottazzi and Peri (2005) and Coe et al. (2009): $Stock_{it} = Innovation_{it-1} + (1-\delta)Stock_{it-1}$, where the depreciation rate, δ, is assumed to be 0.1 The initial value of the patent stock at time t_0 is calculated as $Stock_{it_0} = Innovation_{it_0} / (\delta + g_i)$, where g_i is the annual average logarithmic growth rate of patenting in country i from the earliest date data on patents are available (t_0) to 1995. For most of the countries $t_0 = 1977$.	
Initial GDP per capita	GDP per capita in constant 2000 USD for the first year of each period average.	World Bank, *WDI*
Infrastructure expenditure	Sum of fuel and energy, transportation, and communication expenditure of consolidated central government (% of GDP).	International Monetary Fund, *GFS*
Expenditure net of infrastructure exp.	Total expenditure of consolidated central government net of infrastructure expenditure (% of GDP).	International Monetary Fund, *GFS*
Education expenditure	Education expenditure of consolidated central government (% of GDP).	International Monetary Fund, *GFS*
Expenditure net of infrastructure and education exp.	Total expenditure of consolidated central government net of infrastructure and education expenditure (% of GDP).	International Monetary Fund, *GFS*
R&D expenditure	Gross domestic expenditure on research and development financed by the government (% of GDP).	OECD, *Main Science and Technology Indicators*
Expenditure net of	Total expenditure of consolidated central government net of infrastructure and	International Monetary

infrastructure and R&D exp.	R&D expenditure (% of GDP).	Fund, *GFS* and OECD, *Main Science and Technology Indicators*
Budget balance	Overall budget balance of consolidated central government (% of GDP).	International Monetary Fund, *GFS*
Non-tax revenue	Non-tax revenue of consolidated central government (% of GDP).	International Monetary Fund, *GFS*
Urban	Urban population (% of total).	World Bank, *WDI*
Population density	People per sq. km.	World Bank, *WDI*
Life expectancy	Life expectancy at birth, total (years).	World Bank, *WDI*
Population	Population, total.	World Bank, *WDI*
Investment	Gross fixed capital formation (% of GDP).	World Bank, *WDI*
Fertility rate	Fertility rate (births per woman), total.	World Bank, *WDI*
Trade	Trade (% of GDP).	World Bank, *WDI*
Inflation	Inflation, consumer prices (annual %).	World Bank, *WDI*
Sensitivity Set		
Innovation_USPTO	Defined the same way as "Innovation" but with regard to patent applications per million inhabitants filed to the United States patent and trademark office (USPTO).	OECD, *Main Science and Technology Indicators*
Innovation_PCT	Defined the same way as "Innovation" but with regard to patent applications per million inhabitants filed to the Patent Co-operation Treaty (PCT). The treaty makes it possible to seek patent protection for an invention simultaneously in each of a large number of countries by filling an "international" patent application.	OECD, *Main Science and Technology Indicators*
Mobile and fixed-line telephone subscription	Mobile and fixed-line telephone subscribers.	World Bank, *WDI*
Electricity production	Electricity production (kWh).	World Bank, *WDI*
Phone faults	Number of faults per year.	OECD, *Telecommunications Database*
% of transmission and distribution losses	Electric power transmission and distribution losses (% of output).	World Bank, *WDI*
Threshold_tellinespc	High: 40 or greater lines per 100 people.	Author's calculations
Threshold_mobfixsubpc	High: 50 or greater lines per 100 people.	Author's calculations
Threshold_elecprodpc	High: 7,500 or greater kWh per capita.	Author's calculations
Expenditure	Total expenditure of consolidated central government (% of GDP).	International Monetary Fund, *GFS*

Table 1
Summary statistics

Variable	Mean	Std. Dev.	Min	Max
Stock of infrastructure (per capita)	0.372	0.179	0.002	0.730
Education	15.03	7.21	0.498	35.86
Innovation	59.60	75.98	0.003	410.25
Growth	3.10	2.83	-8.28	12
Stock of patents (log)	6.94	2.47	1.09	12.39
Initial GDP per capita (log)	9.33	0.969	5.26	10.84
Infrastructure expenditure	1.69	1.06	0.062	6.48
Expenditure net of infrastructure exp.	31.34	11.30	9.93	58.70
Education expenditure	2.85	1.71	0.190	10.02
Expenditure net of infrastructure and education exp.	28.59	10.51	9.042	53.81
R&D expenditure	0.588	0.250	0.127	1.26
Expenditure net of infrastructure and R&D exp.	30.82	11.24	9.93	58.70
Budget balance	-1.44	5.29	-16.36	39.82
Non-tax revenue	8.81	6.82	-19.76	35.11
Urban	71.70	14.80	21.3	100
Population density	256.64	832.61	1.98	6413.06
Life expectancy	74.75	4.69	50.84	82.25
Population (log)	16.61	1.64	12.36	20.99
Investment	23.32	5.30	15.11	47.76
Fertility rate	1.84	0.576	1.14	4.55
Trade	75.12	52.54	14.30	447.89
Inflation	20.12	98.65	-0.477	1397.58
Quality of electric power	92.07	3.57	67.25	97.27

Note: A detailed description of the variables and their sources appears in Table B1.

Table 2
Benchmark findings

	(1) FE				(2) GMM-DIFF				(3) 3SLS			
	infrastructure	**education**	**innovation**	**growth**	**infrastructure**	**education**	**innovation**	**growth**	**infrastructure**	**education**	**innovation**	**growth**
Initial GDP per capita (log)	0.671	3.37	0.304	-9.30	**0.637**	**8.45**	**0.568**	**-12.16**	0.955	10.06	-0.750	-6.77
	(0.000)	(0.293)	(0.362)	(0.000)	**(0.347)**	**(0.122)**	**(0.004)**	**(0.000)**	(0.000)	(0.002)	(0.052)	(0.000)
Infrastructure expenditure	-0.202	0.571	-0.004		**-0.072**	**0.361**	**-0.098**		-0.156	0.409	0.109	
	(0.000)	(0.344)	(0.942)		**(0.439)**	**(0.565)**	**(0.004)**		(0.000)	(0.510)	(0.092)	
Expenditure net of infrastructure exp.	-0.009				**-0.001**				-0.013			
	(0.113)				**(0.944)**				(0.003)			
Education expenditure		0.181				**-0.098**				0.490		
		(0.618)				**(0.843)**				(0.069)		
Expenditure net of infrastructure and education exp.		0.156				**-0.165**				0.468		
		(0.074)				**(0.068)**				(0.000)		
R&D expenditure			0.585				**0.370**				0.629	
			(0.004)				**(0.027)**				(0.001)	
Expenditure net of infrastructure and R&D exp.			0.007				**0.017**				0.008	
			(0.378)				**(0.002)**				(0.394)	
Budget balance	-0.013	0.060	0.008		**-0.005**	**0.007**	**0.028**		-0.023	0.269	0.021	
	(0.067)	(0.591)	(0.345)		**(0.585)**	**(0.959)**	**(0.000)**		(0.040)	(0.009)	(0.040)	
Non-tax revenue	0.005	0.065	-0.017		**0.003**	**-0.083**	**-0.020**		0.008	0.036	-0.025	
	(0.187)	(0.353)	(0.002)		**(0.775)**	**(0.167)**	**(0.000)**		(0.022)	(0.561)	(0.000)	
Urban	0.056	-0.427			**0.139**	**-0.488**			0.017	-0.173		
	(0.000)	(0.014)			**(0.001)**	**(0.420)**			(0.068)	(0.247)		
Population density	0.001				**0.001**				0.001			
	(0.523)				**(0.893)**				(0.421)			
Life expectancy		1.54				**0.204**				1.11		
		(0.001)				**(0.801)**				(0.005)		
Population (log)		-25.72				**-48.47**				-35.16		
		(0.000)				**(0.001)**				(0.000)		
Stock of infrastructure (log)		8.86	0.337	0.945		**10.45**	**0.186**	**2.69**		**16.87**	**0.614**	**1.74**
		(0.000)	(0.044)	(0.051)		**(0.000)**	**(0.015)**	**(0.001)**		**(0.000)**	**(0.020)**	**(0.000)**
Stock of patents (log)		0.428	0.692			**4.36**	**0.476**			-1.62	0.428	
		(0.569)	(0.000)			**(0.021)**	**(0.000)**			(0.041)	(0.000)	
Education			0.015	0.104			**0.038**	**-0.008**			**0.075**	**-0.110**
			(0.039)	(0.002)			**(0.000)**	**(0.802)**			**(0.000)**	**(0.024)**
Innovation (log)				0.992				**1.30**				**1.14**
				(0.001)				**(0.000)**				**(0.019)**
Investment				0.134				**0.243**				0.182
				(0.003)				**(0.000)**				(0.000)
Fertility rate				-0.042				**1.01**				-1.11
				(0.953)				**(0.205)**				(0.046)
Trade				0.062				**0.082**				0.085
				(0.000)				**(0.000)**				(0.000)
Inflation				-0.001				**-0.002**				-0.038
				(0.421)				**(0.000)**				(0.010)
Countries / Observations	35 / 158	34 / 142	33 / 124	38 / 234	35 / 121	32 / 105	32 / 89	37 / 195	33 / 123	33 / 123	33 / 123	33 / 123
R^2	0.754	0.772	0.924	0.394					0.993	0.909	0.985	0.638
Number of Instruments					24	22	32	32				
Hansen J-statistic *(p-value)*					0.142	0.375	0.488	0.339				
AR(2) test *(p-value)*					0.420	0.003	0.300	0.405				

Notes: p-values in parentheses (based on two-step robust standard errors for the GMM technique). Constant term and country dummies (included in all regressions) not reported. Instrumented variables are in bold type. Instruments in regression (2): second-to-fifth period lag of instrumented variables (second-to-third for the education regression) using the “collapse” option to create one instrument for each variable and lag distance, rather than one for each time period, variable, and lag distance.

Table 3
Elasticities of human capital accumulation, R&D production, and steady-state output level

	FE	GMM-DIFF	3SLS
Human capital accumulation			
Education expenditure (v_1)	-	-	0.093
Stock of infrastructure (v_2)	0.589	0.695	1.122
R&D production			
R&D expenditure (φ_1)	0.344	0.217	0.369
Stock of patents (φ_2)	0.692	0.476	0.428
Stock of infrastructure (φ_3)	0.337	0.186	0.614
Growth of GDP pc			
Stock of infrastructure	0.101	0.221	0.257

Notes: Elasticity values based on coefficient estimates of Table 2. The elasticity of human capital accumulation with respect to education spending (v_1) is calculated by multiplying the coefficient estimate of education expenditure in the education regression by the ratio of the mean value of education expenditure to the mean value of education. The elasticity of human capital accumulation with respect to the stock of infrastructure (v_2) is calculated by dividing the coefficient estimate of infrastructure stock in the education regression by the mean value of education. The elasticity of R&D production with respect to government spending on R&D (φ_1) is calculated by multiplying the coefficient estimate of R&D expenditure in the innovation regression by the mean value of R&D expenditure. The elasticity of the steady-state output level with respect to the stock of infrastructure is calculated by dividing the coefficient estimate of infrastructure stock in the growth regression by the coefficient estimate of GDP per capita in the same regression. Mean values of variables can be found in Table 1. A dash corresponds to a coefficient estimate with no statistical significance.

Table 4
Testing the proxy of innovation: alternative definitions

	(1) European Patent Office (EPO)				(2) US Patent and Trademark Office (USPTO)				(3) Patent Co-operation Treaty (PCT)			
	infrastructure	**education**	**innovation**	**growth**	**infrastructure**	**education**	**innovation**	**growth**	**infrastructure**	**education**	**innovation**	**growth**
Initial GDP per capita (log)	0.955	10.06	-0.750	-6.77	0.929	3.48	-0.761	-5.64	0.955	7.25	0.490	-5.77
	(0.000)	(0.002)	(0.052)	(0.000)	(0.000)	(0.264)	(0.141)	(0.000)	(0.000)	(0.029)	(0.408)	(0.001)
Infrastructure expenditure	-0.156	0.409	0.109		-0.156	0.113	-0.224		-0.156	0.417	-0.028	
	(0.000)	(0.510)	(0.092)		(0.000)	(0.858)	(0.027)		(0.000)	(0.509)	(0.786)	
Expenditure net of infrastructure exp.	-0.013				-0.013				-0.013			
	(0.003)				(0.003)				(0.004)			
Education expenditure		0.490				1.46				0.847		
		(0.069)				(0.000)				(0.003)		
Expenditure net of infrastructure and education exp.		0.468				0.131				0.317		
		(0.000)				(0.153)				(0.000)		
R&D expenditure			0.629				0.091				0.535	
			(0.001)				(0.727)				(0.085)	
Expenditure net of infrastructure and R&D exp.			0.008				0.013				0.030	
			(0.394)				(0.366)				(0.051)	
Budget balance	-0.023	0.269	0.021		-0.011	0.065	0.004		-0.012	0.178	0.025	
	(0.040)	(0.009)	(0.040)		(0.047)	(0.566)	(0.818)		(0.041)	(0.077)	(0.134)	
Non-tax revenue	0.008	0.036	-0.025		0.008	0.106	0.021		0.008	0.053	0.008	
	(0.022)	(0.561)	(0.000)		(0.024)	(0.088)	(0.028)		(0.030)	(0.395)	(0.389)	
Urban	0.017	-0.173			0.018	-0.038			0.019	-0.155		
	(0.068)	(0.247)			(0.062)	(0.776)			(0.056)	(0.317)		
Population density	0.001				0.002				0.001			
	(0.421)				(0.297)				(0.576)			
Life expectancy		1.11				1.41				1.08		
		(0.005)				(0.000)				(0.005)		
Population (log)		-35.16				-32.36				-32.05		
		(0.000)				(0.000)				(0.000)		
Stock of infrastructure (log)		**16.87**	**0.614**	**1.74**		**9.49**	**1.09**	**1.51**		**14.13**	**2.18**	**1.30**
		(0.000)	**(0.020)**	**(0.000)**		**(0.000)**	**(0.003)**	**(0.001)**		**(0.000)**	**(0.000)**	**(0.015)**
Stock of patents (log)		-1.62	0.428			1.60	0.772			-0.223	0.618	
		(0.041)	(0.000)			(0.170)	(0.000)			(0.660)	(0.000)	
Education			**0.075**	**-0.110**			**-0.113**	**-0.016**			**-0.049**	**-0.122**
			(0.000)	**(0.024)**			**(0.000)**	**(0.777)**			**(0.034)**	**(0.027)**
Innovation (log)				**1.14**				**0.700**				**0.551**
				(0.019)				**(0.058)**				**(0.051)**
Investment				0.182				0.164				0.176
				(0.000)				(0.001)				(0.001)
Fertility rate				-1.11				-0.849				-1.13
				(0.046)				(0.311)				(0.206)
Trade				0.085				0.091				0.086
				(0.000)				(0.000)				(0.000)
Inflation				-0.038				-0.041				-0.047
				(0.010)				(0.005)				(0.001)
Countries / Observations	33 / 123	33 / 123	33 / 123	33 / 123	33 / 123	33 / 123	33 / 123	33 / 123	33 / 123	33 / 123	33 / 123	33 / 123
R^2	0.993	0.909	0.985	0.638	0.993	0.908	0.970	0.653	0.993	0.912	0.977	0.616

Notes: p-values in parentheses. Constant term and country dummies (included in all regressions) not reported. All regression results based on 3SLS technique. Instrumented variables are in bold type. The estimated coefficients of the endogenous variables are qualitatively the same when we use the rest of the estimation techniques.

Table 5
Elasticities of human capital accumulation, R&D production, and steady-state output level

	EPO	USPTO	PCT
Human capital accumulation			
Education expenditure (v_1)	0.093	0.275	0.160
Stock of infrastructure (v_2)	1.122	0.631	0.940
R&D production			
R&D expenditure (φ_1)	0.369	-	0.314
Stock of patents (φ_2)	0.428	0.772	0.618
Stock of infrastructure (φ_3)	0.614	1.09	2.18
Growth of GDP pc			
Stock of infrastructure	0.257	0.267	0.225

Notes: Elasticity values based on coefficient estimates of Table 4. For details see notes at bottom of Table 3.

Table 6

Testing the proxy of infrastructure: alternative measures

	(1) Mobile and fixed-line telephone subscription				**(2) Electricity production**			
	infrastructure	**education**	**innovation**	**growth**	**infrastructure**	**education**	**innovation**	**growth**
Initial GDP per capita (log)	2.70	0.781	0.257	-8.00	0.863	12.92	-1.089	-4.96
	(0.000)	(0.830)	(0.317)	(0.000)	(0.000)	(0.000)	(0.006)	(0.005)
Infrastructure expenditure	-0.112	-1.46	-0.022		-0.088	-0.969	0.074	
	(0.096)	(0.017)	(0.639)		(0.001)	(0.147)	(0.247)	
Expenditure net of infrastructure exp.	-0.013				0.008			
	(0.119)				(0.006)			
Education expenditure		0.595				0.518		
		(0.035)				(0.099)		
Expenditure net of infrastructure and education exp.		0.389				0.119		
		(0.000)				(0.161)		
R&D expenditure			0.791				0.440	
			(0.000)				(0.025)	
Expenditure net of infrastructure and R&D exp.			0.016				-0.005	
			(0.020)				(0.476)	
Budget balance	-0.017	0.182	0.018		0.008	-0.026	0.011	
	(0.118)	(0.064)	(0.017)		(0.038)	(0.808)	(0.280)	
Non-tax revenue	0.012	0.036	-0.017		0.001	0.153	-0.022	
	(0.093)	(0.567)	(0.000)		(0.510)	(0.023)	(0.001)	
Urban	0.001	0.106			0.002	0.029		
	(0.949)	(0.506)			(0.681)	(0.861)		
Population density	0.005				0.006			
	(0.196)				(0.000)			
Life expectancy		-0.540				1.34		
		(0.323)				(0.002)		
Population (log)		-28.44				-32.90		
		(0.000)				(0.001)		
Stock of infrastructure (log)		**11.52**	**0.435**	**1.61**		**13.00**	**0.635**	**2.08**
		(0.000)	**(0.001)**	**(0.000)**		**(0.021)**	**(0.095)**	**(0.000)**
Stock of patents (log)		-0.555	0.391			-1.84	0.405	
		(0.479)	(0.000)			(0.103)	(0.000)	
Education			**0.018**	**-0.185**			**0.093**	**-0.104**
			(0.087)	**(0.002)**			**(0.000)**	**(0.035)**
Innovation (log)				**1.50**				**0.728**
				(0.003)				**(0.145)**
Investment				0.197				0.207
				(0.000)				(0.000)
Fertility rate				-1.16				-1.32
				(0.043)				(0.019)
Trade				0.077				0.079
				(0.000)				(0.000)
Inflation				-0.031				-0.042
				(0.038)				(0.006)
Countries / Observations	33 / 123	33 / 123	33 / 123	33 / 123	33 / 123	33 / 123	33 / 123	33 / 123
R^2	0.978	0.897	0.994	0.608	0.996	0.896	0.983	0.652

Notes: p-values in parentheses. Constant term and country dummies (included in all regressions) not reported. All regression results based on 3SLS technique. Instrumented variables are in bold type. The estimated coefficients of the endogenous variables are qualitatively the same when we use the rest of the estimation techniques.

Table 7
Elasticities of human capital accumulation, R&D production, and steady-state output level

	Mobile and fixed-line subscriptions	Electricity production
Human capital accumulation		
Education expenditure (v_1)	0.112	0.098
Stock of infrastructure (v_2)	0.756	0.864
R&D production		
R&D expenditure (φ_1)	0.465	0.258
Stock of patents (φ_2)	0.391	0.405
Stock of infrastructure (φ_3)	0.435	0.635
Growth of GDP pc		
Stock of infrastructure	0.201	0.419

Notes: Elasticity values based on coefficient estimates of Table 6. For details see notes at bottom of Table 3.

Table 8
Accounting for the quality of infrastructure

	(1)				**(2)**			
	Mobile and fixed-line telephone subscription [phone faults]				**Electricity production [1 - % of transmission and distribution losses]*100**			
	infrastructure	**education**	**innovation**	**growth**	**infrastructure**	**education**	**innovation**	**growth**
Initial GDP per capita (log)	2.75	-7.28	-0.189	-17.19	0.858	14.01	-1.11	-5.69
	(0.000)	(0.191)	(0.598)	(0.000)	(0.000)	(0.000)	(0.006)	(0.001)
Infrastructure expenditure	-0.042	-1.56	-0.027		-0.088	-0.992	0.078	
	(0.692)	(0.102)	(0.677)		(0.001)	(0.138)	(0.230)	
Expenditure net of infrastructure exp.	-0.040				0.008			
	(0.001)				(0.009)			
Education expenditure		0.039				0.492		
		(0.959)				(0.119)		
Expenditure net of infrastructure and education exp.		0.842				0.130		
		(0.000)				(0.126)		
R&D expenditure			0.606				0.439	
			(0.004)				(0.040)	
Expenditure net of infrastructure and R&D exp.			-0.001				-0.005	
			(0.947)				(0.533)	
Budget balance	-0.032	0.443	0.006		0.008	-0.016	0.011	
	(0.018)	(0.001)	(0.508)		(0.039)	(0.875)	(0.287)	
Non-tax revenue	0.036	-0.124	-0.017		0.002	0.153	-0.022	
	(0.000)	(0.204)	(0.007)		(0.424)	(0.024)	(0.000)	
Urban	0.012	0.421			0.002	0.016		
	(0.748)	(0.326)			(0.699)	(0.921)		
Population density	0.009				0.006			
	(0.225)				(0.000)			
Life expectancy		-1.83				1.36		
		(0.073)				(0.002)		
Population (log)		-24.61				-31.19		
		(0.132)				(0.001)		
Stock of infrastructure (log)		**15.42**	**0.308**	**1.02**		**11.15**	**0.693**	**2.15**
		(0.000)	**(0.071)**	**(0.018)**		**(0.044)**	**(0.069)**	**(0.000)**
Quality of infrastructure			0.045	-0.573			-0.005	0.360
			(0.354)	(0.089)			(0.839)	(0.008)
Stock of patents (log)		-0.880	0.501			-1.71	0.396	
		(0.664)	(0.000)			(0.128)	(0.000)	
Education			**0.046**	**-0.232**			**0.094**	**-0.081**
			(0.001)	**(0.001)**			**(0.000)**	**(0.095)**
Innovation (log)				**4.52**				**0.594**
				(0.000)				**(0.221)**
Investment				0.390				0.218
				(0.000)				(0.000)
Fertility rate				0.866				-1.21
				(0.359)				(0.029)
Trade				0.053				0.083
				(0.002)				(0.000)
Inflation				-0.024				-0.034
				(0.135)				(0.024)
Countries / Observations	27 / 76	27 / 76	27 / 76	27 / 76	33 / 123	33 / 123	33 / 123	33 / 123
R^2	0.973	0.855	0.995	0.703	0.996	0.894	0.983	0.674

Notes: p-values in parentheses. Constant term and country dummies (included in all regressions) not reported. All regression results based on 3SLS technique. Instrumented variables are in bold type. The estimated coefficients of the endogenous variables are qualitatively the same when we use the rest of the estimation techniques.

Table 9
Elasticities of human capital accumulation, R&D production, and steady-state output level

	Mobile and fixed-line subscriptions	Electricity production
Human capital accumulation		
Education expenditure (v_1)	-	-
Stock of infrastructure (v_2)	1.02	0.741
R&D production		
R&D expenditure (φ_1)	0.356	0.258
Stock of patents (φ_2)	0.501	0.396
Stock of infrastructure (φ_3)	0.308	0.693
Quality of infrastructure	-	-
Growth of GDP pc		
Stock of infrastructure	0.060	0.377
Quality of infrastructure	0.033	5.82

Notes: Elasticity values based on coefficient estimates of Table 8. For details see notes at bottom of Table 3. The elasticity of the steady-state output level with respect to the quality of electric power is calculated by dividing the coefficient estimate of electric power quality in the growth regression by the coefficient estimate of GDP per capita in the same regression and multiply the finding by the mean value of the quality of electricity production.

Table 10
Testing for threshold effects of infrastructure

	(1)				**(2)**			
	Telephone lines				**Electricity production**			
	infrastructure	**education**	**innovation**	**growth**	**infrastructure**	**education**	**innovation**	**growth**
Initial GDP per capita (log)	0.949	9.40	-0.494	-8.22	0.863	14.60	-0.987	-4.87
	(0.000)	(0.004)	(0.163)	(0.000)	(0.000)	(0.000)	(0.012)	(0.000)
Infrastructure expenditure	-0.155	0.457	0.049		-0.088	-1.05	0.130	
	(0.000)	(0.458)	(0.410)		(0.001)	(0.114)	(0.049)	
Expenditure net of infrastructure exp.	-0.013				0.008			
	(0.003)				(0.007)			
Education expenditure		0.545				0.520		
		(0.040)				(0.081)		
Expenditure net of infrastructure and education exp.		0.475				0.127		
		(0.000)				(0.134)		
R&D expenditure			0.524				0.498	
			(0.004)				(0.007)	
Expenditure net of infrastructure and R&D exp.			0.004				-0.002	
			(0.656)				(0.733)	
Budget balance	-0.011	0.267	0.015		0.008	-0.016	0.007	
	(0.048)	(0.009)	(0.117)		(0.038)	(0.881)	(0.453)	
Non-tax revenue	0.009	0.024	-0.026		0.001	0.159	-0.026	
	(0.016)	(0.693)	(0.000)		(0.472)	(0.019)	(0.000)	
Urban	0.014	-0.227			0.002	-0.005		
	(0.128)	(0.125)			(0.773)	(0.972)		
Population density	0.002				0.006			
	(0.230)				(0.000)			
Life expectancy		1.01				1.34		
		(0.010)				(0.001)		
Population (log)		-34.30				-30.29		
		(0.000)				(0.000)		
Stock of infrastructure (log)		**18.05**	**0.507**	**1.70**		**10.03**	**0.775**	**2.06**
		(0.000)	**(0.039)**	**(0.000)**		**(0.026)**	**(0.036)**	**(0.000)**
Stock of infrastructure (log) - high			-0.022	0.087			-0.013	-0.001
			(0.000)	(0.003)			(0.000)	(0.927)
Stock of patents (log)		-1.58	0.484			-1.57	0.379	
		(0.044)	(0.000)			(0.133)	(0.000)	
Education			**0.077**	**-0.160**			**0.104**	**-0.100**
			(0.000)	**(0.002)**			**(0.000)**	**(0.056)**
Innovation (log)				**1.24**				**0.720**
				(0.010)				**(0.147)**
Investment				0.172				0.206
				(0.000)				(0.000)
Fertility rate				-1.60				-1.26
				(0.004)				(0.033)
Trade				0.091				0.079
				(0.000)				(0.000)
Inflation				-0.037				-0.041
				(0.010)				(0.008)
Countries / Observations	33 / 123	33 / 123	33 / 123	33 / 123	33 / 123	33 / 123	33 / 123	33 / 123
R^2	0.993	0.905	0.988	0.648	0.996	0.893	0.981	0.653

Notes: p-values in parentheses. Constant term and country dummies (included in all regressions) not reported. All regression results based on 3SLS technique. Instrumented variables are in bold type. The estimated coefficients of the endogenous variables are qualitatively the same when we use the rest of the estimation techniques.

Table 11
Elasticities of human capital accumulation, R&D production, and steady-state output level

	Telephone lines	Electricity production
Human capital accumulation		
Education expenditure (v_1)	0.103	0.098
Stock of infrastructure (v_2)	1.20	0.667
R&D production		
R&D expenditure (φ_1)	0.308	0.292
Stock of patents (φ_2)	0.484	0.379
Stock of infrastructure (φ_3)	0.507	0.775
Stock of infrastructure (φ_3) - high	0.485	0.762
Growth of GDP pc		
Stock of infrastructure	0.206	0.422
Stock of infrastructure - high	0.217	0.422

Notes: Elasticity values based on coefficient estimates of Table 10. For details see notes at bottom of Table 3.