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Infrastructure and Industrial Development with Endogenous Skill Acquisition

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Abstract

The link between infrastructure and industrial development is studied in an OLG model with endogenous skill acquisition. Industrial development is defined as a shift from an imitation-based, low-skill economy to an innovation-based, high-skill economy, where ideas are produced domestically. Imitation generates knowledge spillovers, which enhance productivity in innovation. Changes in industrial structure are measured by the ratio of the variety of imitation- to innovation-based intermediate goods. The model also distinguishes between basic infrastructure, which helps to promote learning by doing and productivity in imitation activities, and advanced infrastructure, which promotes knowledge networks and innovation. Numerical experiments, based on a calibrated version for a low-income country, show that changes in the level and composition of public investment in infrastructure may have significant effects on the structure of the labor force and the speed of industrial development.

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1 Introduction

Much research on growth and development during the past decades has focused on structural transformation, a process that has been characterized as the reallocation of economic activity and employment across three broadly-defined production sectors (agriculture, industry, and services) and the movement of population from rural to urban areas.[1] A key insight of the literature is that accounting for the sectoral composition of output is crucial for understanding a variety of outcomes associated with the process of development. This includes changes in productivity, the composition of the labor force, and wage inequality.[2] In particular, it has been shown that structural transformation involves not only a decline in the share of agriculture and extractive mining, mirrored by an increase in the share of industry and modern services in output, but also a shift between and within sectors from lower- to higher-productivity activities.

Some contributions to the literature on structural transformation have focused on the process of industrialization, and more specifically the role of manufacturing industries (as opposed to mining or construction) in promoting rapid and sustained growth. Indeed, the evidence collected by Szirmai (2012) and others suggests that—with the exception of a few small countries that benefited from the successful management of natural resource windfalls—virtually all countries that have sustained high growth rates for decades since the 1950s did so by building highly competitive manufacturing industries and by experiencing very rapid penetration of export markets in manufacturing. In fact, economic historians, most prominently Maddison (1991), have long argued that in the history of the world economy rarely has a country been able to develop without engaging in manufacturing: transforming first from a primarily agrarian society to one

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[1] Kuznets (1959) is an early reference on structural transformation. Another notable contribution is Syrquin and Chenery (1989), who provided a comprehensive review of post-war industrialization patterns. Herrendorf et al. (2013) offer a recent review of the literature, whereas Buera and Kaboski (2012*a*, 2012*b*) and Uy et al. (2013) provide recent analytical contributions.

[2] The literature on *economic* transformation (reviewed by Greenwood and Seshadri (2005) for instance) refers to a broader set of issues, including changes in fertility patterns and women's labor allocation between home and market production.

that is more industry driven, before relying on services as an engine for growth and employment. Moreover, as documented by Rodrik (2013), manufacturing industries tend to exhibit *unconditional* convergence, in the sense that industries that start further away from the world productivity frontier tend to experience significantly faster productivity growth. This occurs even without conditioning on the usual variables, such as initial income per capita, human capital, and institutional quality. Put differently, manufacturing has often proved to be a key engine for growth, even in the presence of poor institutions, weak governance, and bad policies.[3]

Several reasons may help to explain why manufacturing industries play such a critical role in the process of industrial change and economic development (see UNIDO (2009, 2011)). An important one is that manufactured goods are highly tradable and the technology that enables their production (at least in the case of light manufacturing) often requires abundant raw labor but relatively few specialized skills, which can be transferred across borders if they are not available locally. Tradability and limited skill requirements have indeed allowed a number of countries to initiate a rapid transition to manufacturing by engaging in labor-intensive imitation activities, based on imported technology from advanced countries. Through learning-by-doing effects manufacturing has often proved to be a major conduit for the diffusion of technologies, not only across countries but also between sectors of the economy. More generally, by providing an ever greater variety of inputs (some of which are in the form of new capital goods), with an ever greater degree of technological sophistication, the manufacturing sector helps to build knowledge that may fuel the expansion of a variety of production sectors.

This paper contributes to the ongoing debate on industrialization and growth by developing a two-period overlapping generations (OLG) model of endogenous growth and horizontal innovation à la Romer (1990), with three main characteristics that are broadly consistent with some of the facts discussed earlier. First, in line with Segerstrom (1991), Currie et al. (1999), Acemoglu et al. (2006), Vandenbussche et al.

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[3] Rodrik's results also suggest that countries with better institutions and policies experience faster rates of productivity growth in manufacturing, and therefore benefit from a more rapid rate of conditional convergence.

(2006), and Perez-Sebastian (2007), we account for two types of design activities: those based on imitation and those based on homegrown innovation. Both of these activities produce blueprints for intermediate-good producers. Imitation involves essentially copying foreign ideas and adapting foreign technology, whereas innovation involves inventing new ideas. Thus, unlike studies focusing on structural transformation, our analysis of the process of industrial development does not focus on the relative contribution of manufacturing to the whole economy. Indeed, rather than focusing on the composition of *final output*, we focus on the composition of the range of *intermediate inputs*, created through imitation and innovation activities, that firms use in producing final goods. From that perspective, industrial development takes the form of an increase over time in the relative contribution of more technology-intensive intermediate goods in the production process of manufactured goods. Industrial transformation is thus fundamentally the result of the transition from imitation to innovation, or equivalently of a reallocation over time of resources to more skill- and technology-intensive production of designs and development activities.

Our analysis also accounts for the existence of a learning externality associated with imitation activities, which tends to stimulate (at least in an initial phase) productivity in the innovation sector. If this effect is sufficiently strong, imitation may be the main source of productivity growth in the early stages of development, with innovation taking over later on in time. This feature of our analysis highlights the fact that the international diffusion of technology, and the promotion of imitation activities based on the non-rivalrous use of ideas, may help a poor country to absorb knowledge embedded in products invented in the rich world. Technological imitation by low-income developing countries with a limited pool of skilled workers may thus account for their success at an early stage of industrialization, as noted earlier. In that sense, imitation activities can serve as a "stepping stone" for innovation, as emphasized in some contributions (see for instance Glass (2010), Lorenczik and Newiak (2012), and Agénor and Dinh (2013)).[4] Beyond a certain point, however, these benefits tend to

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[4] Glass (2010) builds a product-cycle model in which an exogenous fraction of industries has to engage in imitation before being able to target the market for innovations. By contrast, Agénor and Dinh (2013) consider learning spillovers between separate imitation and innovation sectors, as we do here. Lorenczik and Newiak (2012) discuss how policies targeted at intellectual property rights affect

fade, thereby reducing over time the marginal gain associated with present imitation effort. It becomes therefore crucial to find new ways to increase productivity in the innovation sector and avoid falling into a middle-income growth trap (see Agénor and Canuto (2012)).

Second, the process of skill acquisition is endogenized. In standard fashion, individuals choose to invest in (advanced) education depending on the relative returns to schooling. While imitation requires only unskilled labor, innovation requires high-skilled labor.[5] At the same time, the process of industrialization itself—especially in the early stages, through the learning externality associated with imitation activities, as noted earlier—increases the demand for high-skilled labor, which puts upward pressure on skilled wages and induces more individuals to invest in education.[6] Thus, there is a two-way interaction between industrialization and the quality of the labor force. At the same time, however, if learning externalities are sufficiently strong, investment in human capital is not a prerequisite for promoting growth in its initial stages.[7] Once the process of imitation takes off, it contributes to the accumulation of knowledge available to all workers in the economy, raising productivity and wages in the innovation sector, thereby promoting investment in skills and the expansion of the innovation sector. Thus, as in Vandenbussche et al. (2006), our analysis highlights the importance of distinguishing between different types of human capital and their allocation across sectors at different stages of economic development. However, we also go beyond their analysis by accounting explicitly for the process through which skill acquisition occurs, instead of assuming (as they do) that the distribution of the labor force is given exogenously and constant over time. In doing so we bring to the fore the

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the process through which imitation can help to promote innovation.

[5] Cross-country evidence suggests the existence of a close correlation between export sophistication and the percentage of the labor force that has completed tertiary education (see World Bank (2009)). This is consistent with the specification of an innovation sector that uses skilled labor only.

[6] This feature of the model is consistent with the evidence in Madsen et al. (2010). Using data for 55 developing and developed countries, they found that innovation is an important factor for growth in OECD countries, whereas growth in developing countries is driven by imitation. Furthermore, the interaction between educational attainment and the distance to the world technological frontier is a significant determinant of growth in the overall sample. A similar result is obtained by Madsen (2014) for productivity growth in industrial countries.

[7] This is consistent for instance with Gómez (2011), who unlike Funke and Strulik (2000) found that the sequencing between human capital formation and innovation can be reversed.

two-way interaction between a country's own development process—which depends on learning spillovers across sectors, rather than distance to the technological frontier *per se*—and human capital formation.

Third, the model accounts for the composition of infrastructure, or public capital, and its impact on production and design activities. Specifically, we distinguish between *basic* infrastructure (which consists of roads, energy, basic telecommunications, and water and sanitation) and *advanced* infrastructure, which consists of advanced information and communication technologies (ICTs) in general, and high-speed communication networks in particular. Basic infrastructure helps to promote productivity in the final good and imitation sectors, whereas advanced infrastructure benefits mainly the innovation sector. One reason for the latter effect is that access to high-speed broadband, in particular, facilitates the buildup of knowledge networks, thereby promoting the dissemination of ideas within and across borders (see Romer (2010) and Agénor and Canuto (2012)). This is consistent with recent research, which shows that ICTs and innovation are closely interlinked (see Cardona et al. (2013) and Baquero Forero (2013)) and that ICTs have a strong, albeit possibly nonlinear, impact on growth (Czernich et al. (2011) and Oulton (2012)). Baquero Forero (2013), in particular, found that countries with more investment in two specific technologies, mobile telephony and internet infrastructure, are closer to the global technological frontier.[8]

These features of the model, and the analysis that they lead to, shed useful light on the nature of the ongoing debate on industrialization and the role of manufacturing in low-income countries. This is especially relevant to countries in Sub-Saharan Africa, where the relative importance of the manufacturing sector has declined almost continuously in recent decades (see Page (2012)). As documented by UNIDO (2011, Table 1), in Africa the share of manufacturing in GDP fell from 15.3 percent in 1990 to 12.8 percent in 2000 and 10.5 percent in 2008. The diversity and sophistication of the region's manufacturing sectors have also declined, and it continues to be marginalized

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[8] The evidence also suggests that broadband internet is a necessary, but not sufficient, condition for the positive impact of ICTs on innovation and growth. As noted earlier, the model highlights the availability of high-skilled labor as an important determinant of innovation. Yet, access to high levels of human capital is neither necessary nor sufficient to promote innovation and growth; a low level of productivity in the innovation sector may be due to a lack of access to (advanced) infrastructure.

in global manufacturing trade: its share in global manufacturing value added fell from 1.2 percent in 2000 to 1.1 percent in 2008.[9] The distinction between imitation and innovation, and the associated implication regarding the diversification of inputs that we emphasize, is important to highlight the phases of development that countries in the region may go through.

Accounting for endogenous skill acquisition allows us to also account for the fact that Africa lags substantially behind other developing country regions in skills and vocational training. The gross enrolment ratio at the tertiary level is only 6 percent in the region and recent increases in the number of higher education graduates have often been at the expense of quality (African Development Bank (2012, Chapter 6), UNECA (2013, Chapter 2)). Where they exist, technical and vocational skills development systems suffer from a shortage of qualified staff, obsolete equipment, poorly-designed programs, and weak links with the labor market. According to some recent estimates (see Messinis and Ahmed (2013)), and despite substantial spending on education in several countries, synthetic measures of human capital and cognitive skills in the region have deteriorated almost continuously since the early 1980s—a potential hindrance to cross-border technology diffusion and assimilation.

Finally, introducing public capital allows us to account for the fact that African countries have very poor transport, communication and energy infrastructure. As recognized by many observers, poor access to basic infrastructure remains a major obstacle to the development of competitive manufacturing industries in the region and acts as a significant drag on economic growth. Indeed, it is estimated that Africa loses about 1 percentage point per year in per capita income growth as a result of its infrastructure deficit (UNIDO (2012)). And according to Foster and Briceño-Garmendia (2010), the high cost of infrastructure in Africa increases significantly trade costs and reduces the productivity of African firms. At the same time, our analysis helps to emphasize that the type of infrastructure that is needed to promote growth does change in between the initial and later phases of development.

The remainder of the paper is organized as follows. Section 2 presents the model,

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[9] By contrast, in developing Asia, that share rose from 13 percent to 25 percent during the same period. See Memedovic and Lapadre (2009) for a structural decomposition analysis of these changes.

which is a two-period overlapping generations (OLG) model of endogenous growth and horizontal innovation (as in Romer (1990)). A key feature of the model, as noted earlier, is the learning externality associated with imitation, which tends to promote innovation activities and growth. The strength of this externality determines the speed at which industrial transformation occurs. The balanced growth equilibrium is defined in Section 3 and the steady-state solution is presented in Section 4. Section 5 calibrates the model for a low-income country, characterized by an initial situation where the proportion of skilled workers is small, the innovation sector is embryonic (so that most of the skilled workers are engaged in the production of final goods), access to basic infrastructure is limited, access to advanced infrastructure is almost nonexistent, and the cost of acquiring skills is high. Section 6 focuses on experiments involving changes in the level and composition of public investment in infrastructure and studies the transitional dynamics associated with these changes. The final section draws together the policy implications of the analysis and offers some concluding remarks.

2 The Model

The economy that we consider is populated by individuals with different innate abilities, who live for two periods: adulthood and old age. Population is constant at $\bar{N}$. Each individual is endowed with one unit of time in the first period of life, and zero units in old age.

There are five production sectors in the economy: one producing a homogeneous final good, two producing intermediate goods (*core* and *enhanced* inputs, from now on), and two creating designs (*imitation* and *innovation* sectors, from now on) used for the production of each of the two categories of intermediate inputs. The final good is produced by combining both private and public inputs, and is used for consumption, private and public investment, and the production of intermediate goods. Public inputs consist of basic infrastructure (essentially high-speed telecommunications). Both types of services are provided free of charge but are subject to congestion. Production in the design sectors combines public and private (labor) inputs as well, but in different ways.

Firms in the final good and design sectors are perfectly competitive, whereas those in the intermediate good sectors are monopolistically competitive, each producing (as in Romer (1990)) a differentiated variety of good. The total number of blueprints existing at a certain point in time coincides with the number of intermediate input varieties available in the economy, and represents the stock of (nonrival) knowledge. Knowledge is non-appropriable, so designers have access to that information for free. But they cannot sell the knowledge gathered from a design to future potential designers either. As in Agénor and Dinh (2013), knowledge accumulated in the imitation sector creates an externality that promotes productivity in both design sectors, but this benefit is subject to diminishing marginal returns.

There are two categories of labor in the economy, skilled and unskilled. Individuals are born unskilled and must decide at the beginning of adulthood whether to become skilled or remain unskilled for the rest of their adult life. Becoming skilled involves both time and pecuniary costs. Labor (either skilled or unskilled) is perfectly mobile between the final good and design sectors, and wages adjust to clear both segments of the labor market.

2.1 Individuals

Individuals have identical preferences but are born with different abilities, indexed by a. Ability (or talent) is observable at birth by all and follows a continuous, time-independent distribution. For tractability, a is assumed to follow a Pareto (Type I) distribution, defined over $a \in [a_m, \infty)$, with a density function $f(a) = \theta a_m^\theta / a^{1+\theta}$ and a cumulative distribution function $F(a) = 1 - (a_m/a)^\theta$, where $a_m > 1$ denotes the lowest ability and $\theta > 2$ is the tail index.[10] Average ability is thus $a_m\theta/(\theta-1)$. Each individual maximizes utility and decides whether to enter the labor force as an unskilled worker or (after undergoing training) a skilled worker. The individual's ability determines his or her relative cost of acquiring skills.

Specifically, an adult with ability a can enter the labor force at the beginning of period t as an unskilled worker and earn the wage w_t^U, which is independent of the worker's ability. Alternatively, the individual may choose to spend first a fraction of time $\varepsilon \in (0, 1)$ of his or her time endowment at the beginning of adulthood in training

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[10] The assumption $\theta > 2$ ensures that the ability distribution has a finite variance.

(or higher education) and enter the labor force for the remainder of the period as a skilled worker, earning the effective market wage $a^{\chi}w_t^S$. For simplicity, training involves no direct pecuniary cost and during training workers also earn no income. There are no barriers to entry in the design sectors, so any individual can work there if he or she is willing to do so.[11]

Let $c_{t+j}^{h,t}$ denote consumption at period $t+j$ of an individual working at wage w_t^h, where $h = U, S$, born at the beginning of period t, with $j = 0, 1$. The individual's discounted utility function is given by

$$U_t^h = \eta_C \ln c_t^{h,t} + \frac{\ln c_{t+1}^{h,t}}{1+\rho}, \quad h = U, S \tag{1}$$

where $\rho > 0$ is the discount rate and $\eta_C > 0$ a preference parameter.

The period-specific budget constraints, which depend on the sector of employment in adulthood, are given by

$$c_t^{U,t} + s_t^U = (1-\tau)w_t^U, \tag{2}$$

$$c_t^{S,t} + s_t^S = (1-\tau)(1-\varepsilon)a^{\chi}w_t^S, \tag{3}$$

$$c_{t+1}^{h,t} = (1+r_{t+1})s_t^h, \quad h = U, S \tag{4}$$

where s_t^h is savings of type-h worker, $1 + r_{t+1}$ the rate of return on holding assets between periods t and $t+1$, $\tau \in (0,1)$ the tax rate, and $\chi \in (0,1)$ a productivity parameter.

As shown in the Appendix, using (A36) and solving the individual optimization problem for $h = S, U$ gives the optimal consumption and savings solutions. Substituting these results in (1) gives the indirect utility functions V^h; the critical value a_t^C—the threshold level of ability which is such that all individuals with ability $a < a_t^C$ choose to remain unskilled—is thus obtained by setting $V^S = V^U$:

$$a_t^C = (\frac{\theta-1}{\theta})[\frac{w_t^U}{(1-\varepsilon)w_t^S}]^{1/\chi}. \tag{5}$$

This equation describes an increasing and convex relationship between the wage ratio w_t^U/w_t^S and a_t^C.

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[11] Perfect labor mobility between the final good sector and the design sectors implies that there is a single, economy-wide wage for each category of labor.

The productivity of unskilled workers is equal to unity, independently of their abilities. The (effective) supply of unskilled labor, N_t^U, is thus equal to

$$N_t^U = \bar{N}\int_{a_m}^{a_t^C} f(a)da = a_m^\theta \left[-a^{-\theta}\right]_{a_m}^{a_t^C} \bar{N} = [1-(\frac{a_m}{a_t^C})^\theta]\bar{N}. \tag{6}$$

The raw supply of skilled labor is $\bar{N}\int_{a_t^C}^\infty f(a)da = (a_m/a_t^C)^\theta \bar{N}$. However, we must account for the average productivity of workers with ability $a \in [a_t^C, \infty)$ who have undergone training, which is equal to $\theta a_t^C/(\theta-1)$. Thus, the effective supply of skilled labor at time t, N_t^S, can be defined as

$$N_t^S = \bar{N}\int_{a_t^C}^\infty af(a)da = \theta a_m^\theta \left[\frac{a^{1-\theta}}{1-\theta}\right]_{a_t^C}^\infty \bar{N} = \frac{\theta a_m^\theta}{\theta-1}(a_t^C)^{1-\theta}\bar{N}. \tag{7}$$

2.2 Final Good

Production of the final good (manufacturing), Y_t, requires the use of (effective) skilled labor, $N_t^{S,Y}$, unskilled labor, $N_t^{U,Y}$, private capital, K_t^P, basic public infrastructure, K_t^B, and a combination of core intermediate inputs, $x_{s,t}^I$, with $s \in (0, M_t^I)$, and enhanced intermediate inputs, $x_{s,t}^R$, with $s \in (0, M_t^R)$. Within each category, inputs are substitutes to one another.

Let X_t be a composite intermediate input defined as

$$X_t = [\int_0^{M_t^I} (x_{s,t}^I)^\eta ds]^{\nu/\eta} \cdot [\int_0^{M_t^R} (x_{s,t}^R)^\eta ds]^{(1-\nu)/\eta}, \tag{8}$$

where $\eta \in (0,1)$ and $1/(1-\eta) > 1$ is (the absolute value of) the price elasticity of demand for each intermediate good, and $\nu \in (0,1)$. Thus, the composite intermediate input exhibits constant returns to scale with respect to core and enhanced inputs.

The production function is specified as

$$Y_t = [\frac{K_t^B}{(K_t^P)^{\zeta_K}\bar{N}^{\zeta_N}}]^\omega [(1-\varepsilon)N_t^{S,Y}]^{\beta^S}(N_t^{U,Y})^{\beta^U} X_t^\gamma (K_t^P)^\alpha, \tag{9}$$

where $\beta^S, \beta^U, \alpha, \gamma \in (0,1)$, $\omega > 0$, $\zeta_K, \zeta_N > 0$, $\alpha = 1-(\beta^S+\beta^U)-\gamma$, and K_t^P is the aggregate private capital stock. This specification implies that there are constant returns in private inputs and that basic public capital is partially rival and subject to congestion, measured by the aggregate private capital stock and population size. The strength of congestion effects is measured by the parameters ζ_K and ζ_N.

Assuming that private capital depreciates fully during each period, profits of the representative firm are given by

$$\Pi_t^Y = Y_t - \int_0^{M_t^I} P_t^{I,s} x_{s,t}^I ds - \int_0^{M_t^R} P_t^{R,s} x_{s,t}^R ds - w_t^S (1-\varepsilon) N_t^{S,Y} - w_t^U N_t^{U,Y} - r_t K_t^P,$$

where $P_t^{I,s}$ ($P_t^{R,s}$) is the price of core (enhanced) intermediate good s and r_t the (net) rental rate of private capital. The final good is used as the numéraire and its price is normalized to unity.

Subject to (8) and (9), profit maximization with respect to labor, private capital, and quantities of all intermediate goods $x_{s,t}^j$, $\forall s$, taking as given factor prices and M_t^j, $j = I, R$, yields

$$w_t^S = \beta^S \frac{Y_t}{(1-\varepsilon) N_t^{S,Y}}, \quad w_t^U = \beta^U \frac{Y_t}{N_t^{U,Y}}, \tag{10}$$

$$r_t = \alpha(\frac{Y_t}{K_t^P}), \tag{11}$$

$$x_{s,t}^j = (\frac{\gamma \nu^j Z_t^j}{P_t^{j,s}})^{1/(1-\eta)}, \quad s = 1, ...M_t^j, \tag{12}$$

$$Z_t^j = Y_t / \int_0^{M_t^j} (x_{s,t}^j)^\eta ds, \tag{13}$$

where $j = I, R$, $\nu^I = \nu$, and $\nu^R = 1 - \nu$.

2.3 Intermediate Goods

As noted earlier, there are two sets of intermediate goods producers: those producing core inputs (index I), based on blueprints produced by the imitation sector, and those producing enhanced inputs (index R), based on designs produced by the innovation sector. Each firm produces one, and only one, horizontally-differentiated intermediate good. In both cases, production of each unit of intermediate good requires one unit of the final good.[12]

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[12] It could be assumed, as in Daido and Tabata (2013) for instance, that access to basic infrastructure helps to promote production of intermediate goods. However, as long as the production process for each type of inputs remains the same, this would not make qualitative differences to our analysis, given the specification of the production function of final goods.

The two sectors are treated symmetrically. Each producer in sector $j = I, R$ must purchase a patented design from the respective design sector (imitation or innovation). Once the patent is bought, each producer sets its price to maximize profits, given the perceived demand function for its good (12), which determines marginal revenue. Under a symmetric equilibrium, profits are given by $\Pi_t^j = (P_t^j - 1)x_t^j$ or using (12) and (13), $\Pi_t^j = (P_t^j - 1)[\gamma\nu^j Y_t / P_t^j M_t^j (x_t^j)^\eta]^{1/(1-\eta)}$, $j = I, R$. In standard fashion, the solution yields the optimal price as

$$P_t^{j,s} = \frac{1}{\eta}. \ \forall s = 1, ...M_t^j, \quad j = I, R \tag{14}$$

Using (12), the quantity demanded at this price is $x_{s,t}^j = (\gamma\eta\nu^j Z_t^j)^{1/(1-\eta)}$, $\forall s$, that is, noting that under symmetry $\int_0^{M_t^j} (x_{s,t}^j)^\eta ds = M_t^j (x_t^j)^\eta$,

$$x_t^j = \gamma\eta\nu^j (\frac{Y_t}{M_t^j}), \quad j = I, R \tag{15}$$

with maximum profit given by

$$\Pi_t^j = (1 - \eta)\gamma\nu^j (\frac{Y_t}{M_t^j}). \ \ j = I, R \tag{16}$$

For simplicity, we assume that intermediate-input producing firms last for only one period and that patents are auctioned off randomly (and at no cost) to a new group of firms in each period. Thus, each producer of a new intermediate good holds a patent only for the period during which it is bought, implying monopoly profits during that period only; yet patents last forever.[13] By arbitrage, therefore, the patent price Q_t^j is

$$Q_t^j = \Pi_t^j. \ \ j = I, R \tag{17}$$

2.4 Design Sectors

Designs are produced in two sectors: an imitation sector, which employs only unskilled labor, in quantity $N_t^{U,I}$, and an innovation sector, which employs only skilled labor, in quantity $N_t^{S,R}$. There is no aggregate uncertainty in either sector. In the imitation sector, local firms invest resources in order to absorb and adapt the information needed to replicate new products invented abroad. Thus, imitation differs from innovation in

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[13] See Agénor and Canuto (2012) for a more detailed discussion of this assumption.

that the number of goods that can be copied at any point in time is limited in part to the rate at which imitable goods are being discovered elsewhere.

Both imitation and innovation create two kinds of knowledge. First, *private* knowledge, which is acquired (for a price) by intermediate goods firms to produce a new production input. Second, *public* knowledge, which spills over to other firms in the imitation and innovation sectors—in ways specified later—and increases productivity there. In addition, there is an externality from imitation for innovation. This is consistent with the idea, alluded to earlier, that imitation can be a *stepping stone* for true innovation.

Consider the imitation sector first. The aggregate technology is defined as

$$M_{t+1}^{I} - M_{t}^{I} = A_{t}^{I}(\frac{N_{t}^{U,I}}{\bar{N}})(1+g^{W})^{\kappa^{I}}, \tag{18}$$

where A_t^I is a productivity factor, and $g^W > 0$ the growth rate of the stock of designs available internationally that can be effectively imitated in the country under consideration. The technology parameter $\kappa^I \in (0,1)$ is assumed to be less than unity, to capture the fact that the growth in imitable goods worldwide entails diminishing marginal benefits for domestic imitation. In addition, as in Chen and Funke (2013) for instance, the international knowledge pool available for copying is assumed to grow at an exogenous rate.[14] Finally, to eliminate scale effects, it is the *ratio* of unskilled workers to total population that is taken to affect activity in that sector.[15]

Productivity in imitation activities depends on the economy's stock of imitated designs and access to basic infrastructure:

$$A_{t}^{I} = (k_{t}^{B})^{\phi_{1}^{I}} M_{t}^{I}, \tag{19}$$

where $k_t^B = K_t^B/K_t^P$, and $\phi_1^I \in (0,1)$. Thus, as in Romer (1990), each design creates

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[14] A more general specification would be to assume, as in Perez-Sebastian (2007) for instance, that as distance from the world technological frontier of imitated goods decreases, imitation becomes more expensive. This would mitigate the benefits of imitation over time but would not eliminate those that occur in the early stages, as we discuss later.

[15] See Dinopoulos and Segerstrom (1999). As in Di Maria and Stryszowski (2009), it could also be assumed that a fraction of the skilled labor force is involved in adapting existing (imported) technologies. However, this would complicate significantly the analysis without adding much additional insight.

a positive externality for future imitation activities.[16] Access to basic public capital is subject to (proportional) congestion, measured by the private capital stock.

Firms in the imitation sector choose labor so as to maximize profits, $\Pi_t^I = Q_t^I(M_{t+1}^I - M_t^I) - w_t^U N_t^{U,I}$, subject to (18), and taking the wage rate, the patent price, Q_t^I, and productivity A_t^I, as given. The first-order condition with strictly positive employment is given by

$$w_t^U = (\frac{Q_t^I A_t^I}{\bar{N}})(1+g^W)^{\kappa^I}. \tag{20}$$

Consider now the innovation sector. The aggregate technology is defined as

$$M_{t+1}^R - M_t^R = A_t^R[\frac{(1-\varepsilon)N_t^{S,R}}{\bar{N}}], \tag{21}$$

where A_t^R is productivity, which depends on access to advanced infrastructure and *both* stocks of technological knowledge—with innovation creating a stronger spillover effect than imitation:

$$A_t^R = (k_t^A)^{\phi_1^R}(M_t^R + \phi_2^R M_t^I), \tag{22}$$

where $k_t^A = K_t^A/K_t^P$, $\phi_1^R \in (0,1)$, and $\phi_2^R > 0$. For tractability, access to advanced infrastructure is again taken to be congested by the private capital stock.

This specification accounts for an efficiency gain associated with imitation: the more a country engages initially in copying foreign technology, the more its workers become familiar with existing innovations made abroad, and the easier it is to engage in original innovation. These trade-related, knowledge spillovers and their cross-sectoral impact on the capacity to innovate have been well documented in the literature.[17] However, this spillover may weaken over time if the ratio M_t^I/M_t^R itself decreases over time, which occurs if the innovation sector—precisely as a result of knowledge spillovers—expands at a relatively faster rate.

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[16] We therefore abstract from duplication externalities, as discussed in some of the literature (see for instance Gancia and Zilibotti (2005) and Gómez and Sequeira (2013)). However, much of the evidence on these externalities relates to industrial countries.

[17] See Keller (2004) and World Trade Organization (2008, Chapter 2). The case considered here corresponds to what is usually referred to in the trade literature as "active" spillovers, when the importing country acquires the knowledge embodied in the imported good (whether intermediate or final), often through a process of reverse engineering.

Firms in the innovation sector also choose labor so as to maximize profits, $\Pi_t^R = Q_t^R(M_{t+1}^R - M_t^R) - w_t^S(1-\varepsilon)N_t^{S,R}$, subject to (21), and taking the wage rate, the patent price, Q_t^R, and productivity as given.

The first-order condition with positive employment is given by

$$w_t^S = \frac{Q_t^R A_t^R}{\bar{N}}. \tag{23}$$

2.5 Government

The government levies a tax on wages at the rate τ, invests a total of G_t^B and G_t^A on basic and advanced infrastructure, and spends G_t^U on other items. Its services are provided free of charge. It cannot issue debt claims and must therefore run a balanced budget:

$$G_t = \sum G_t^i = \tau \left[w_t^U N_t^U + (1-\varepsilon) a^{\chi} w_t^S N_t^S \right]. \tag{24}$$

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

$$G_t^i = \upsilon_i \tau \left[w_t^U N_t^U + (1-\varepsilon) a^{\chi} w_t^S N_t^S \right], \tag{25}$$

where $\upsilon_i \in (0,1)$, $\forall i = A, B, U$.

Combining (24) and (25) therefore yields

$$\sum_i \upsilon_i = 1. \tag{26}$$

Assuming that public capital depreciates fully during each period, both stocks evolve according to

$$K_{t+1}^i = \varphi_i G_t^i, \quad i = A, B \tag{27}$$

where $\varphi_i \in (0,1)$ is an efficiency parameter, which measures the extent to which investment flows translate into actual accumulation of public capital (see Agénor (2010, 2012)).

2.6 Market-Clearing Conditions

To close the model requires specifying the equilibrium conditions between aggregate savings and investment, and between supply and demand in the markets for skilled and unskilled labor.

The savings-investment balance requires the capital stock in $t+1$ to be equal to savings in period t by individuals born in $t-1$:

$$K_{t+1}^{P} = s_t^U N_t^U + s_t^S N_t^S. \tag{28}$$

Equilibrium of the market for unskilled labor implies that workers are employed either in the production of the final good or in the imitation sector, that is, $N_t^{U,Y} + N_t^{U,I} = N_t^U$, or equivalently, in terms of ratios,

$$\theta_t^{U,Y} + \theta_t^{U,I} = \theta_t^U, \tag{29}$$

where $\theta_t^U = N_t^U/\bar{N}$ is the total supply of unskilled labor in proportion to total population. Subsequently, from (6) and normalizing a_m to unity for simplicity, we obtain

$$\theta_t^U = 1 - (a_t^C)^{-\theta}. \tag{30}$$

This equation implies a positive relationship between a_t^C and θ_t^U.

Similarly, equilibrium of the market for skilled labor implies that workers are employed either in the production of the final good or in the innovation sector, that is, $N_t^{S,Y} + N_t^{S,R} = N_t^S$, or equivalently, in relative terms,

$$\theta_t^{S,Y} + \theta_t^{S,R} = \theta_t^S, \tag{31}$$

where $\theta_t^S = N_t^S/\bar{N}$ is the total supply of skilled labor, measured in efficiency units, in proportion to total population. From (7) this is equal to

$$\theta_t^S = \frac{\theta}{\theta - 1}(a_t^C)^{1-\theta}. \tag{32}$$

Because $\theta > 1$, this equation implies a negative relationship between a_t^C and θ_t^S.

Figure 1 summarizes the production structure of the model, the impact of public capital, and the distribution of labor across sectors.

3 Balanced Growth Equilibrium

In this economy an *equilibrium with imperfect competition* is a sequence of consumption and saving allocations $\{c_t^{h,t}, c_{t+1}^{h,t}, s_t^h\}_{t=0}^{\infty}$, for $h = U, S$, private capital stock $\{K_t^P\}_{t=0}^{\infty}$, public capital stocks $\{K_t^A, K_t^B\}_{t=0}^{\infty}$, prices of production inputs $\{w_t^U, w_t^S, r_{t+1}\}_{t=0}^{\infty}$, prices and quantities of intermediate inputs $\{P_t^{s,j}, x_{s,t}^j\}_{t=0}^{\infty}$, $\forall s \in (0, M_t^j)$ and $j = I, R$, existing varieties, $\{M_t^I, M_t^R\}_{t=0}^{\infty}$, such that, given initial stocks $K_0 > 0$, $K_0^A, K_0^B > 0$, and $M_0^I, M_0^R > 0$,

a) all individuals, skilled or unskilled, maximize utility by choosing consumption subject to their intertemporal budget constraint, taking factor prices and the tax rate as given;

b) firms in the final good sector maximize profits by choosing labor, capital, and intermediate inputs, taking input prices as given;

c) intermediate input producers set prices so as to maximize profits, while internalizing the effect of their decisions on the perceived aggregate demand curve for their product;

d) producers in the design sectors maximize profits by choosing how much labor to hire, taking wages, patent prices, productivity, and population, as given;

e) the equilibrium (patent) price of each blueprint extracts all profits made by the corresponding intermediate input producer; and

f) all markets clear.

A *balanced growth equilibrium* is an equilibrium with imperfect competition in which

a) $\{c_t^{h,t}, c_{t+1}^{h,t}, s_t^h\}_{t=0}^{\infty}$, for $h = U, S$, and K_t^P, K_t^A, K_t^B, Y_t, M_t^I, M_t^R, w_t^U, w_t^S, grow at the constant, endogenous rate $1 + \gamma^Y$, implying that the knowledge-capital ratios, as well as the public-private capital ratios, are also constant;

b) the net rate of return on capital r_{t+1} is constant;

c) the price of intermediate goods P_t^j and the patent prices Q_t^j, $j = I, R$, are constant;

d) the threshold level of ability below which individuals choose to remain unskilled, a_t^C, is constant; and

e) the fractions of the skilled and unskilled labor force employed in manufacturing (and thus in the design sectors), $\theta_t^{U,Y}$ and $\theta_t^{S,Y}$, are constant.

4 Dynamics and Steady-State Growth

As shown earlier, the threshold level of ability above which individuals choose to acquire skills depends on the wage ratio (see equation (5)). In the Appendix, the wage ratio is shown to be given by

$$\frac{w_t^U}{w_t^S} = \beta(1-\varepsilon)(\frac{\theta_t^{S,Y}}{\theta_t^{U,Y}}), \tag{33}$$

where $\beta = \beta^U/\beta^S$. Thus, the unskilled-skilled wage ratio varies inversely with the relative supplies of skilled and unskilled labor in the final good sector.

Substituting this result in (5) implies that in equilibrium the threshold level of ability, a_t^C, is given by

$$a_t^C = (\frac{\theta - 1}{\theta})[\beta(\frac{\theta_t^{S,Y}}{\theta_t^{U,Y}})]^{1/\chi}. \tag{34}$$

The Appendix also shows that the public-private capital ratios are constant over time and given by

$$k_t^i = J^i = \frac{\varphi_i \upsilon_i \tau}{\sigma(1-\tau)}, \quad i = A, B \tag{35}$$

where $\sigma \in (0,1)$ is the family's propensity to save, defined as

$$\sigma = \frac{1}{1 + \eta_C(1+\rho)} < 1. \tag{36}$$

To determine the growth rate, the first step is to derive the restrictions on the congestion parameters in (9). In a symmetric equilibrium,

$$X_t = [(M_t^I)^{1/\eta} x_t^I]^{\nu}[(M_t^R)^{1/\eta} x_t^R]^{1-\nu}. \tag{37}$$

From (15), $x_t^j = \gamma\eta\nu^j(Y_t/M_t^j)$, for $j = I, R$. Substituting these results in (37) yields

$$X_t = \gamma\eta\nu^{\nu}(1-\nu)^{1-\nu}[(M_t^I)^{\nu(1-\eta)/\eta}(M_t^R)^{(1-\nu)(1-\eta)/\eta}]Y_t,$$

or equivalently, noting that $(K_t^P)^{(1-\eta)/\eta} = (K_t^P)^{1/\eta}/K_t^P$, we obtain

$$X_t = \Lambda_1(m_t^I)^{\nu(1-\eta)/\eta}(m_t^R)^{(1-\nu)(1-\eta)/\eta}(\frac{Y_t}{K_t^P})(K_t^P)^{1/\eta},$$

where $m_t^j = M_t^j/K_t^P$, $j = I, R$ and $\Lambda_1 = \gamma\eta\nu^{\nu}(1-\nu)^{1-\nu}$. Substituting this expression in (9) yields

$$Y_t = (1-\varepsilon)^{\beta^S}(\theta_t^{S,Y})^{\beta^S}(\theta_t^{U,Y})^{\beta^U}\bar{N}^{\beta^S+\beta^U-\omega\zeta_N} \tag{38}$$

$$\times(k_t^B)^{\omega}\left\{\Lambda_1(m_t^I)^{\nu(1-\eta)/\eta}(m_t^R)^{(1-\nu)(1-\eta)/\eta}(\frac{Y_t}{K_t^P})\right\}^{\gamma}(K_t^P)^{\alpha+\gamma/\eta+\omega(1-\zeta_K)}.$$

Generating endogenous growth requires imposing the following restrictions on the congestion parameters ζ_K and ζ_N: $\beta^S+\beta^U-\omega\zeta_N=0$ and $\alpha+\gamma/\eta+\omega(1-\zeta_K)=1$. Thus, the level of output becomes:

$$Y_t=\frac{(J^B)^{\omega/(1-\gamma)}\Lambda_2}{[(\theta_t^{S,Y})^{\beta^S}(\theta_t^{U,Y})^{\beta^U}]^{-1/(1-\gamma)}}\left\{(m_t^I)^{\nu(1-\eta)/\eta}(m_t^R)^{(1-\nu)(1-\eta)/\eta}\right\}^{\gamma/(1-\gamma)}K_t^P, \tag{39}$$

where $\Lambda_2=[(1-\varepsilon)^{\beta^S}\Lambda_1^{\gamma}]^{1/(1-\gamma)}$. Equation (39) is thus linear in the private capital stock.

The Appendix shows that the dynamic system that drives the economy consists of two first-order difference equations in m_t^I and m_t^R and nine static equations:

$$m_{t+1}^I=\left[1+(J^B)^{\phi_1^I}(1+g^W)^{\kappa^I}\theta_t^{U,I}\right]m_t^I \tag{40}$$

$$\times\left\{\sigma(1-\tau)Q_t^I\theta_t^U(J^B)^{\phi_1^I}m_t^I(1+g^W)^{\kappa^I}\right.$$

$$\left.+\sigma(1-\tau)(1-\varepsilon)(\frac{\theta a_t^C}{\theta-1})^{\chi}Q_t^R\theta_t^S(J^A)^{\phi_1^R}m_t^R[1+\phi_2^R(\frac{m_t^I}{m_t^R})]\right\}^{-1},$$

$$m_{t+1}^R=\left[1+(J^A)^{\phi_1^R}[1+\phi_2^R(\frac{m_t^I}{m_t^R})](1-\varepsilon)\theta_t^{S,R}\right]m_t^R \tag{41}$$

$$\times\left\{\sigma(1-\tau)Q_t^I\theta_t^U(J^B)^{\phi_1^I}m_t^I(1+g^W)^{\kappa^I}\right.$$

$$\left.+\sigma(1-\tau)(1-\varepsilon)(\frac{\theta a_t^C}{\theta-1})^{\chi}Q_t^R\theta_t^S(J^A)^{\phi_1^R}m_t^R[1+\phi_2^R(\frac{m_t^I}{m_t^R})]\right\}^{-1},$$

$$\frac{Y_t}{K_t^P}=\frac{(J^B)^{\omega/(1-\gamma)}\Lambda_2}{[(\theta_t^{S,Y})^{\beta^S}(\theta_t^{U,Y})^{\beta^U}]^{-1/(1-\gamma)}}\left\{(m_t^I)^{\nu(1-\eta)/\eta}(m_t^R)^{(1-\nu)(1-\eta)/\eta}\right\}^{\gamma/(1-\gamma)}, \tag{42}$$

$$Q_t^j=(1-\eta)\gamma\nu^j(\frac{Y_t}{K_t^P})(m_t^j)^{-1},\quad j=I,R \tag{43}$$

$$a_t^C=(\frac{\theta-1}{\theta})[\beta(\frac{\theta_t^{S,Y}}{\theta_t^{U,Y}})]^{1/\chi}, \tag{44}$$

$$\theta_t^U=1-(a_t^C)^{-\theta}, \tag{45}$$

$$\theta_t^S=\frac{\theta}{\theta-1}(a_t^C)^{1-\theta}, \tag{46}$$

$$\theta_t^{S,Y} = \frac{\beta^S (J^A)^{-\phi_1^R}}{(1-\varepsilon)(1-\eta)(1-\nu)\gamma}[1+\phi_2^R(\frac{m_t^I}{m_t^R})]^{-1}, \tag{47}$$

$$\theta_t^{S,R} = \theta_t^S - \theta_t^{S,Y}, \tag{48}$$

$$\theta_t^{U,Y} = \frac{\beta^U (J^B)^{-\phi_1^I}}{(1-\eta)\nu\gamma}(1+g^W)^{-\kappa^I}, \tag{49}$$

$$\theta_t^{U,I} = \theta_t^U - \theta_t^{U,Y}. \tag{50}$$

Given its complexity, stability of this system cannot be studied analytically. Nevertheless, stability can be checked numerically, once the model is calibrated.

In the steady state, the growth rates of imitation- and innovation-based knowledge are equal. From the static conditions (42)-(50), Y_t/K_t^P, Q_t^I, Q_t^R, a_t^C, θ_t^U, θ_t^S, $\theta_t^{S,Y}$, $\theta_t^{S,R}$, $\theta_t^{U,Y}$ and $\theta_t^{U,I}$ are also constant. Thus, the steady-state growth rate of output is the same as the growth rate of knowledge and the growth rates of the capital stocks.

The long-run growth rate, $1+\boldsymbol{\gamma}^Y$ can be written in several equivalent ways. In particular, as shown in the Appendix,

$$1+\boldsymbol{\gamma}^Y = (J^B)^{\phi_1^I}(1+g^W)^{\kappa^I}\tilde{\theta}^{U,I}, \tag{51}$$

$$1+\boldsymbol{\gamma}^Y = (J^A)^{\phi_1^R}[1+\phi_2^R(\frac{\tilde{m}^I}{\tilde{m}^R})](1-\varepsilon)\tilde{\theta}^{S,R}. \tag{52}$$

From the solutions (40)-(50), we can define an index of industrial transformation as $m_t = m_t^I/(m_t^I + m_t^R)$ and an index of public capital allocation, $k_t = k_t^B/(k_t^A + k_t^B)$.

5 Calibration

To study the transitional dynamics of the model and the steady-state effects of public policy, we calibrate it as follows. On the household side, the annual discount rate is set at 0.04, as is standard in the literature. Interpreting a period as 25 years in this framework yields an intergenerational discount rate of $\rho = 1.04^{25} - 1 = 1.667$ and an intergenerational discount factor of $1/2.667 = 0.375$. In line with the evidence on private savings for low-income countries, the family's propensity to save, σ, is set at 0.06. Consequently, we consider a low-income country where households are close to the subsistence level of consumption. Solving (36) backward for the preference parameter

η_C and given the value of the intergenerational discount factor, the calibrated value of η_C is 5.87.

Time allocated to advanced schooling, ε, is set at 0.15. This corresponds to an average number of years in higher education of 3.8. The parameter that measures the efficiency of training, χ, is set at 0.5; experiments with higher or lower values of χ affected mainly the speed of convergence, not the qualitative features of the results. The tail index parameter, θ, is set at 2.1, a common value in the trade literature.

In the final good sector, the elasticity of production with respect to basic public capital, ω, is set at 0.17, which is the long-run value estimated through meta-regression analysis by Bom and Ligthart (2014) for core public capital at the national level.[18] The elasticity of production with respect to unskilled labor, β^U, is set at 0.2, the elasticity with respect to skilled labor, β^S, at 0.35, and the elasticity of production with respect to private capital, α, at 0.3, which is standard in the literature (see Agénor (2011)). By implication, the elasticity of output with respect to the composite intermediate good, γ, is equal to 0.15. This is substantially lower than the value of 0.36 used by Funke and Strulik (2000) and Sequeira (2011) for instance, but it is more appropriate for a low-income country where, to begin with, the share of intermediate goods is relatively small, compared to capital and, especially, labor. We also assume that the relative share of imitated goods in the composite intermediate good X_t, as measured by ν (which, when multiplied by γ, measures the relative share of that input in final production), is set at 0.9.

In the intermediate good sectors, the parameter η (which determines the price elasticity of the demand for intermediate goods) is set to 0.61, similar to the value used by Iacopetta (2011) and Chen and Funke (2013). This implies an elasticity of substitution between intermediate inputs of about 2.6, which corresponds also to the value found by Acemoglu and Ventura (2002).

In the imitation sector, the growth rate of the international pool of blueprints available for imitation, g^W, is set at 0.02, as in Chen and Funke (2013). The elasticity with respect to the growth rate of imitable goods worldwide, κ^I, is set initially at

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[18] Note that other studies, based on simultaneous equation methods, obtain substantially higher values; see Agénor and Neanidis (2010) for instance.

0.35, in line again with Chen and Funke (2013). The elasticity with respect to basic infrastructure, ϕ_1^I, is set at 0.1, which is slightly lower than the estimate referred to above for the production of final goods.

In the innovation sector, parameter ϕ_1^R, which measures the response to advanced infrastructure, is set at 0.1. The parameter measuring the externality associated with the stock of imitative knowledge, ϕ_2^R, is also set equal to 0.1. There is not much evidence in the literature on either one of these parameters; accordingly, they are both set initially to low values and sensitivity analysis is reported later on.

The tax rate on wage income is calculated as follows. From the calculations in Baldacci et al. (2004, p. 530), the average ratio of tax revenues to GDP for low-income countries is 0.151. This value is divided (to match the model's definition) by $\beta^U + \beta^S = 0.55$, which corresponds to the share of labor income in final output. Thus, the effective tax rate is $\tau = 0.151/0.55 = 27.4$ percent. By definition, and because the model does not consider deficit financing, this is also the share of government spending in output. The share of government investment in basic infrastructure, υ_B, is set equal initially to 6.5 percent, and the share of investment in advanced infrastructure to 0.5 percent, as in Agénor and Dinh (2013). Thus, much of public investment is initially devoted to core infrastructure.

To estimate the efficiency parameters of public spending, φ_A and φ_B, we use the median value estimated by Dabla-Norris et al. (2012) for a sample of 71 developing countries, that is, 0.4.[19] Thus, we assume that initially 60 percent of both types of investment is "wasted", in the sense that it does not transform into public capital.

Parameter values are summarized in Table 1. Given these values, and starting values for the dynamic variables, the model is solved iteratively (in its nonlinear form) to generate a steady-state equilibrium with $\Delta m_{t+1}^j = 0$, $j = I, R$. The resulting steady-state values of some of the main variables are shown in Table 2. The proportion of unskilled workers in the population, θ^U, is equal to 0.95 whereas the (effective) proportion of skilled workers, θ^S, is equal to 0.049. The absolute share of the unskilled

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[19] An alternative approach is to use the governance index defined in Baldacci et al. (2008, Table 1) which, once normalized to be between 0 and 1, gives a value of 0.5. However, the results are not highly sensitive to that change. An extension of the analysis could be to consider different values for φ_A and φ_B.

labor force in final good production, $\theta^{U,Y}$, is equal to 0.7, which implies that the share of that type of labor in the imitation sector, $\theta^{U,I}$, is 0.25. Similarly, the share of the (effective) skilled labor force in the final good sector, $\theta^{S,Y}$, is equal to 0.036, which implies that the share of that type of labor in the innovation sector, $\theta^{S,R}$, is 0.013. The ratio of imitation-based goods to private capital is equal to $m^I = 1.4$, whereas the ratio of innovation-based goods to private capital is set equal to $m^R = 0.2$. By implication, our index of industrial structure, $m = m^I/(m^I + m^R)$, is initially equal to 0.87. Using formula (45), the threshold level of ability, a^C, is 4.16. The unskilled-skilled wage ratio is normalized to 0.8, which implies an education premium equal to 25 percent, in line with the evidence for developing countries (see Agénor (2006)). The solution also yields initial steady-state values of the public-private capital ratios in basic and advanced infrastructure equal to $k^B = 0.16$ and $k^A = 0.01$, respectively, implying that the index of the composition of public capital is $k = 0.928$; access to advanced infrastructure is relatively scarce to begin with. Based on these values, the steady-state growth rate of final output (on an annual basis) is calibrated at 2.4 percent. That value corresponds to the average growth rate in Sub-Saharan Africa over the period 1990-2010 (see Agénor and Dinh (2013)) and is obtained by adding a multiplicative constant in the relevant equation.

Thus, as in Agénor and Dinh (2013), the low-income economy that we calibrate is characterized initially by *a*) a positive but low growth rate in income per capita; *b*) an embryonic innovation sector and a relatively more developed imitation sector; *c*) a high cost of acquiring skills; *d*) a labor force consisting mostly of unskilled workers, employed in both the imitation sector and final good production (and more so in the latter); *e*) a small fraction of skilled workers in the labor force, employed almost entirely in final good production (in line with the assumption that the innovation sector is negligible in size); *f*) limited availability of basic infrastructure and almost nonexistent advanced infrastructure; and *g*) correspondingly a relatively low share of public investment in basic infrastructure and a much lower one on advanced infrastructure. At the same time, both stocks of public capital are relatively small in proportion to the private capital stock.

6 Policy Experiments

To illustrate the role of public policy in promoting growth and industrial transformation, we focus on public investment in basic and advanced infrastructure. As discussed earlier, a key aspect of the model is the differentiated impact of public capital: while basic infrastructure (roads, energy, and basic telecommunications) has a positive impact on the production of final goods and imitation activities, advanced infrastructure (advanced information and communication technologies, ICTs) helps to promote innovation activities only. The channels through which public investment operates depend therefore on the type of capital that is being built. In addition, there are possible trade-offs between the two types of investment. We consider both of these issues in turn.

To characterize the results of our experiments, we focus on the following variables: the share of unskilled labor, θ^U, the share of unskilled labor in the imitation sector, $\theta^{U,I}$, the share of the (effective) skilled labor force, θ^S, the share of skilled labor in the innovation sector, $\theta^{S,R}$, the industrial structure index defined earlier, $m = m^I/(m^I + m^R)$, and the growth rate of final output.

6.1 Changes in the Level of Public Investment

Consider first a permanent, budget-neutral increase in the share of spending on basic infrastructure, υ_B, from an initial value of 0.065 to 0.075, financed by a cut in unproductive spending ($d\upsilon_B + d\upsilon_U = 0$). Figure 2 reports the results of this experiment for two different values of the parameter φ_B, which measures the degree of efficiency of investment in basic infrastructure, 0.4 and 0.5. The first impact of this policy is to increase the marginal product of unskilled labor, and therefore labor demand as well as the economy-wide wage for that category of workers. At the initial level of skilled wages, this tends to mitigate incentives for individuals to acquire skills, and therefore to reduce the (effective) supply of skilled labor. This, in turn, tends to dampen activity in both the innovation and the final good sectors. At the same time, the demand for labor rises more significantly in the imitation sector as a result of a larger productivity effect. The share of unskilled labor employed in that sector therefore rises initially, by more than a percentage point, and matching to a large extent the increase in the wage ratio (as implied by (33)).

However, during the transition, these initial effects are reversed. By raising productivity in the innovation sector, the learning effect contributes to raising wages for skilled labor. The unskilled-skilled wage ratio starts falling, thereby inducing more individuals to invest in higher education. The adjustment process involves a falling (increasing) share of unskilled (skilled) labor in the population, as illustrated in Figure 2. The stronger the learning effect, the faster the increase in the supply of skilled labor during the transition, and the stronger the expansion in innovation activities. Nevertheless, this effect is not strong enough (given the direct benefit of improved access to basic infrastructure for imitation) to prevent the industrial structure from shifting toward imitation activities over time. On impact, and despite the adverse effect associated with the reduction in the supply of skilled labor, the growth rate of final output increases significantly due to the productivity effect associated with a higher stock of basic infrastructure. Over time, this effect on the marginal product of labor fades out, but the increase in the composite intermediate input helps to sustain activity. In the long run, the change in the growth rate of output converges to a value of about 0.5 percentage points. When the increase in investment on basic infrastructure is coupled with an improvement in the efficiency of that category of spending, all of these effects are magnified.

The results therefore illustrate the fact that imitation (promoted by higher public investment in basic infrastructure) may indeed be a key source of productivity growth in the early stages of development—in both the imitation and innovation sectors. In the model, the learning effect associated with imitation is magnified by the endogeneity of labor supply—as productivity increases in the innovation sector through the learning externality, wages there tend to increase; in our calibration, this effect is strong enough to reverse the initial drop in the skilled-unskilled wage ratio, and as a result the transitional dynamics are characterized by an increase in the supply of skilled labor—which further stimulates activity in the innovation sector. However, the learning spillover associated with imitation and the shift in the structure of the labor force are not strong enough (at least for the range of parameters considered here) to generate growth in the innovation sector that is fast enough to have a substantial impact on the industrial structure; in the end, investment in basic infrastructure benefits largely imitation activities.

Consider now a permanent, budget neutral increase in the share of spending on advanced infrastructure, υ_A, from an initial value of 0.005 to 0.02, financed again by a cut in unproductive spending $(d\upsilon_A + d\upsilon_U = 0)$. Starting from a low base, we consider therefore an ambitious program to promote access to advanced telecommunications and other information technologies.

Figure 3 shows the results of this policy for alternative values of the parameter ϕ_2^R, which measures the strength of the externality associated with imitation activities for the innovation sector: the benchmark value of 0.1 and higher value of 0.2 and 0.4. Because labor market outcomes are not affected significantly by changes in ϕ_2^R, for simplicity the figure reports only changes in the industrial structure index and the growth rate of final output.

As mentioned earlier, advanced infrastructure benefits only innovation activities; it has no direct effect on production elsewhere in the economy. Thus, on impact the higher stock of advanced infrastructure raises productivity and wages only in the innovation sector. The fall in the unskilled-skilled wage ratio promotes investment in skills. The increase in labor demand in the innovation sector is therefore satisfied not only by an increase in the overall supply of skilled labor but also by a reallocation of skilled workers away from the final good sector. This tends to mitigate activity in that sector. The reduction in the supply of unskilled labor, coupled with the reallocation of skilled labor toward innovation activitites, combine to generate a substantial fall in the growth rate of final output on impact.

Over time, once again, these initial effects are reversed. The reduction in the supply of unskilled labor tends to mitigate the initial drop in the unskilled-skilled wage ratio. As a result, the proportion of individuals seeking higher education falls over time. This dampens the initial increase in activity in the innovation sector and promote activity in the imitation sector, as more unskilled workers shift toward the latter. Nevertheless, during the transition the expansion in innovation activitites is high enough to ensure that the industrial structure continues to shift toward this type of activities. This is to a very significant extent the consequence of the learning effect: as activity in the imitation sector expands, it also helps to sustain activity (albeit at a decreasing rate) in the innovation sector. Indeed, as shown in the figure, the stronger the learning effect (the higher ϕ_2^R is), the faster the reduction in the industrial index. While the growth rate of final output falls initially (as noted earlier), it recovers gradually during the transition and turns slightly positive in the long run. At the same time, and given our calibration, alternative values of ϕ_2^R do not seem to make much difference in terms of labor market outcomes and the path of output growth.

To summarize, increased investment in advanced infrastructure does generate a more rapid process of industrial transformation and accelerated growth, consistent with the evidence discussed earlier. In the model, the benefits of a higher stock of public capital are magnified by a shift in the composition of the labor force toward higher skill levels. However, this process occurs endogenously through changes in productivity and higher wages—rather than, say, through education subsidies—which act as signals to individuals about the returns to education. Moreover, the stronger the learning externality associated with imitation, the faster the transition toward an innovation-based economy.[20]

6.2 Changes in the Composition of Public Investment

To illustrate potential trade-offs between different types of public investment, we now consider the case, once again, of a permanent increase in the share of spending on advanced infrastructure, υ_A, from an initial value of 0.005 to 0.02, but this time financed in a 20 percent proportion by a cut in investment in basic infrastructure, υ_B. The results of this experiment are displayed in Figure 4. Because qualitatively the effects of this policy are similar to those shown in Figure 3, we focus here again on two variables, the industrial transformation index and the growth rate of final output. In addition, we do so for two different values of ϕ_1^R, the parameter that measures the response

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[20] It is important to note also that these results do not depend on the assumption that advanced infrastructure has no effect on activity in the final good sector. In practice, of course, this type of infrastructure is likely to benefit all sectors of activity. However, as long as the effect on innovation (as measured by ϕ_1^R) is relatively stronger, the qualitative nature of the results illustrated in Figure 3 would remain unchanged.

of innovation activity for advanced infrastructure (the benchmark value of 0.1 and a higher value of 0.15), and two different values of ϕ_2^R, the parameter that measures the strength of the learning externality associated with imitation in the innovation sector (the benchmark value of 0.1 and a higher value of 0.2). The benchmark experiment, in which the increase in the share of spending on advanced infrastructure is financed by a cut in unproductive spending, is also shown in the figure (continuous red line) for comparative purposes.

These experiments illustrate two main results. First, financing higher investment in advanced infrastructure by a cut in investment in basic infrastructure can be detrimental to growth. The reason is of course because in the model basic infrastructure benefits directly the production of final goods; a cut in that category of investment has therefore an immediate adverse effect on production. However, while this effect can be significant on impact (to the extent that it magnifies the adverse effects of a higher υ_A described earlier) it is mitigated by the increase in the supply of intermediate goods over time. Second, as shown in Figure 4, the combination of lower spending on basic infrastructure (which has an adverse effect on activity in the imitation sector) and higher spending on advanced infrastructure (which promotes directly innovation) is quite effective in terms of inducing a shift toward an innovation-based economy—despite the fact that reduced activity in the imitation sector mitigates (for ϕ_2^R given) learning spillovers. Third, higher values of both ϕ_1^R and ϕ_2^R are associated with faster rates of industrial transformation, as measured by the ratio of the variety of imitation- to innovation-based intermediate goods but, given our calibration, this appears to come with little additional benefits in terms of growth in the long run.

The drop in steady-state growth displayed in Figure 4 could of course be mitigated, or even reversed, if the fraction of υ_A financed by a cut in υ_B is smaller, if ϕ_1^R is higher, or if advanced infrastructure were to affect final output. Indeed, the assumption in equation (9) is that only basic infrastructure affects directly the production of final goods. This is a reasonable assumption for a low-income country where the stock of advanced public capital is scarce to begin with. But even in such conditions the *marginal* impact of improved access to advanced infrastructure on the manufacturing sector could be sizable. For instance, better access to high-speed telecommunication networks could help to improve significantly the management of supply chains in real time, thereby boosting efficiency in the production of manufactured goods (see Park et al. (2013)). This could be captured by replacing K_t^B in (9) by the weighted average $(K_t^B)^{\alpha_G}(K_t^A)^{1-\alpha_G}$, where $\alpha_G \in (0,1)$ and now $\alpha_G < 1$ instead of unity. Alternatively, as can be inferred from the results in Figure 2, higher steady-state growth could be achieved by significant improvements in the efficiency of investment in both types of infrastructure.

The broader lesson from these experiments is that, during an initial stage, when the supply of skilled labor is relatively scarce, investing in basic infrastructure may be a critical step to promote growth and initiate a process of industrial development, based on replicating foreign technologies and adapting them to local markets. As this imitation process gathers pace, and learning spillovers become significant, wage signals become strong enough to induce individuals to invest in higher education. These results are consistent with the evidence which suggests that investments in education, training and new technologies are closely related, and are associated with higher productivity (Mattalia (2012)). However, this may not be enough to promote further industrial diversification, in the form of a sustained reduction in the ratio of the variety of imitation- to innovation-based intermediate goods. To achieve this goal, a shift in the composition of public investment toward more advanced infrastructure, which is critical to foster further increases in productivity in the innovation sector, may be needed (see Agénor and Dinh (2013)). At the same time, the productivity-enhancing effect of advanced infrastructure raises the demand for skilled labor, which further promotes innovation. It is possible that the resulting shift in the industrial structure may not be sufficient to increase the growth rate of output to a substantially higher level on a permanent basis—especially if the increase in spending on advanced infrastructure is financed by a cut in investment in basic infrastructure. To do so governance reform aimed at improving investment spending efficiency and at reallocating spending away from unproductive uses may also be required.

7 Concluding Remarks

In this paper the link between public capital and industrial development was studied in an OLG model with endogenous skill acquisition. Industrial development is defined as a shift from an imitation-based, low-skill economy to an innovation-based, high-skill economy, where technological progress occurs through the domestic invention of ideas. In the model, productivity in innovation is enhanced through a knowledge spillover from imitation. Changes in industrial structure are measured by changes over time in the ratio of imitation-based and innovation-based production inputs, rather than changes in the relative share of manufacturing production in total final output, as often done in studies of economic transformation. The model also endogenizes individual decisions to acquire skills and distinguishes between basic infrastructure, which helps to promote learning-by-doing and productivity in imitation activities, and advanced infrastructure, which promotes knowledge networks and innovation.

Numerical experiments, based on a calibrated version for a low-income country, showed that changes in the level and composition of public investment, as well as learning externalities, may have significant effects on the structure of the labor force and the speed of industrial development. Our experiments suggest that the scope for imitation-based learning has significant implications for the pace of industrial change. In the early stages of development, when skilled labor is in short supply and unskilled labor is abundant, investing in core infrastructure may be a critical step to initiate a process of industrial development and growth based on imitating imported technologies. As this imitation process unfolds, learning externalities gather pace and begin to benefit skilled labor productivity and spur innovation. In doing so, wage signals are strengthened and induce more individuals to invest in higher education. In that sense, large investments in human capital are not critical to promote growth during the early stages of development; human capital accumulation becomes instead a by-product of industrial development.

At the same time, however, beyond an initial stage learning spillovers may not be enough to promote industrial diversification away from imitation-based to innovation-based activities. To that end, a shift in the composition of public investment toward more advanced information and communication technologies, which is critical to promote knowledge networks and ensure sustained increases in labor productivity in the innovation sector, may become essential. To the extent that a lack of resources may force a reduction in the basic infrastructure investment needed to bring about this shift, governance reform (aimed at improving efficiency of investment spending and at reallocating public expenditure away from nonproductive uses) may also be needed to avoid adverse effects on growth.[21] These results provide important lessons for policymakers in low-income countries that are now considering ways to speed up the process of industrial development.

Finally, although our analysis focused on a set of initial conditions that characterizes today's low-income countries, it may also have some broader historical relevance. Some recent studies—such as Iacopetta (2010) and Gómez (2011) for instance—have argued that a transition path involving a phase of innovation first, and human capital accumulation second, is more consistent with the historical evidence for today's developed countries, at least during the first phase of the Industrial Revolution (1760-1830). Indeed, as documented by Galor (2005), literacy rates did not increase much during that time. However, in the second phase of the Industrial Revolution, the demand for skilled labor in the growing industrial sector rose markedly. To satisfy the increasing skill requirements in the process of industrialization, human capital formation improved substantially.[22] This two-way interaction is consistent with our analysis of the interplay between imitation, innovation, and skill acquisition in promoting sustained growth. At the same time, however, there are important differences in our view between the experience of developed countries during the past two centuries, the growth process of today's middle-income countries since the end of World War II, and the type of policies that today's low-income countries should implement to catch up with richer economies. Our analysis has drawn attention to the critical role that public infrastructure and its composition can play in promoting growth and industrial transformation.

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[21] Alternatively, public-private partnerships in infrastructure provision may be pursued, although the performance of these arrangements has been mixed in developing countries.

[22] Galor (2005, p. 274) also noted the possibility of a positive feedback between the rate of technological progress and the level of education, when ability is endogenous.

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Table 1

Calibrated Parameter Values: Benchmark Case

Parameter	**Value**	**Description**
Households		
ρ	1.667	Intergenerational discount rate
σ	0.06	Family's propensity to save
η_C	5.87	Preference parameter, consumption in adulthood
ε	0.15	Time allocated to schooling
χ	0.5	Productivity parameter (efficiency of training)
θ	2.1	Pareto index, ability distribution
Final Goods		
ω	0.17	Elasticity wrt to public-private capital ratio
β^U	0.2	Elasticity with respect to unskilled labor
β^S	0.35	Elasticity with respect to skilled labor
α	0.3	Elasticity with respect to private capital
γ	0.15	Elasticity with respect to composite intermediate input
ν	0.9	Share of core inputs in composite intermediate input
Intermediate goods		
η	0.61	Substitution parameter, intermediate goods
Imitation sector		
κ^I	0.35	Elasticity wrt distance from technology frontier
ϕ_1^I	0.1	Elasticity wrt basic public infrastructure
g^W	0.02	Growth rate of world stock of imitable goods
Innovation sector		
ϕ_1^R	0.1	Elasticity wrt advanced public infrastructure
ϕ_2^R	0.1	Learning effect, stock of imitated goods
Government		
τ	0.274	Effective tax rate on wages
υ_A	0.005	Share of spending on advanced infrastructure
υ_B	0.065	Share of spending on basic infrastructure
φ_A, φ_B	0.4	Efficiency parameters, public investment

Table 2

Initial Steady-State Values of Key Variables

Variable	**Value**	**Description**
θ^U	0.95	Share of unskilled labor force in population
$\theta^{U,Y}$	0.7	Share of unskilled labor force in final good production
$\theta^{U,I}$	0.25	Share of unskilled labor force in imitation sector
θ^S	0.049	Share of skilled labor force in population
$\theta^{S,Y}$	0.036	Share of skilled labor force in final good production
$\theta^{S,R}$	0.013	Share of skilled labor force in innovation sector
k^A	0.01	Advanced infrastructure-private capital ratio
k^B	0.16	Basic infrastructure-private capital ratio
k	0.928	Index of public capital composition
m^I	1.4	Imitation-based goods-private capital ratio
m^R	0.2	Innovation-based goods-private capital ratio
m	0.87	Index of industrial transformation
a^C	4.16	Threshold level of ability
w^U/w^S	0.8	Unskilled-skilled wage ratio

Figure 1
Public Capital, Production Structure, and Labor Allocation

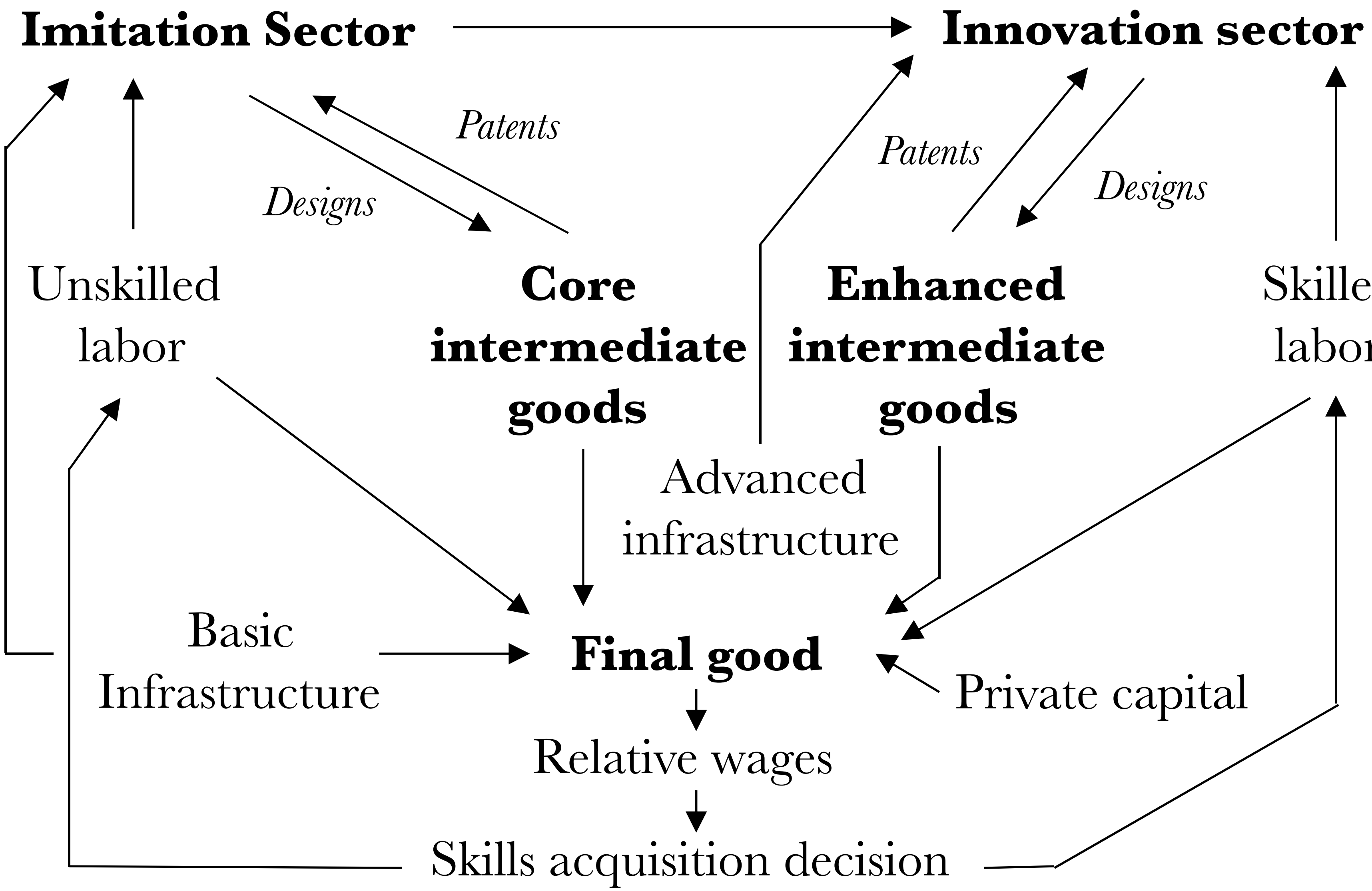


Figure 2

Permanent Increase in Share of Spending on Basic Infrastructure

(Absolute deviations from baseline)

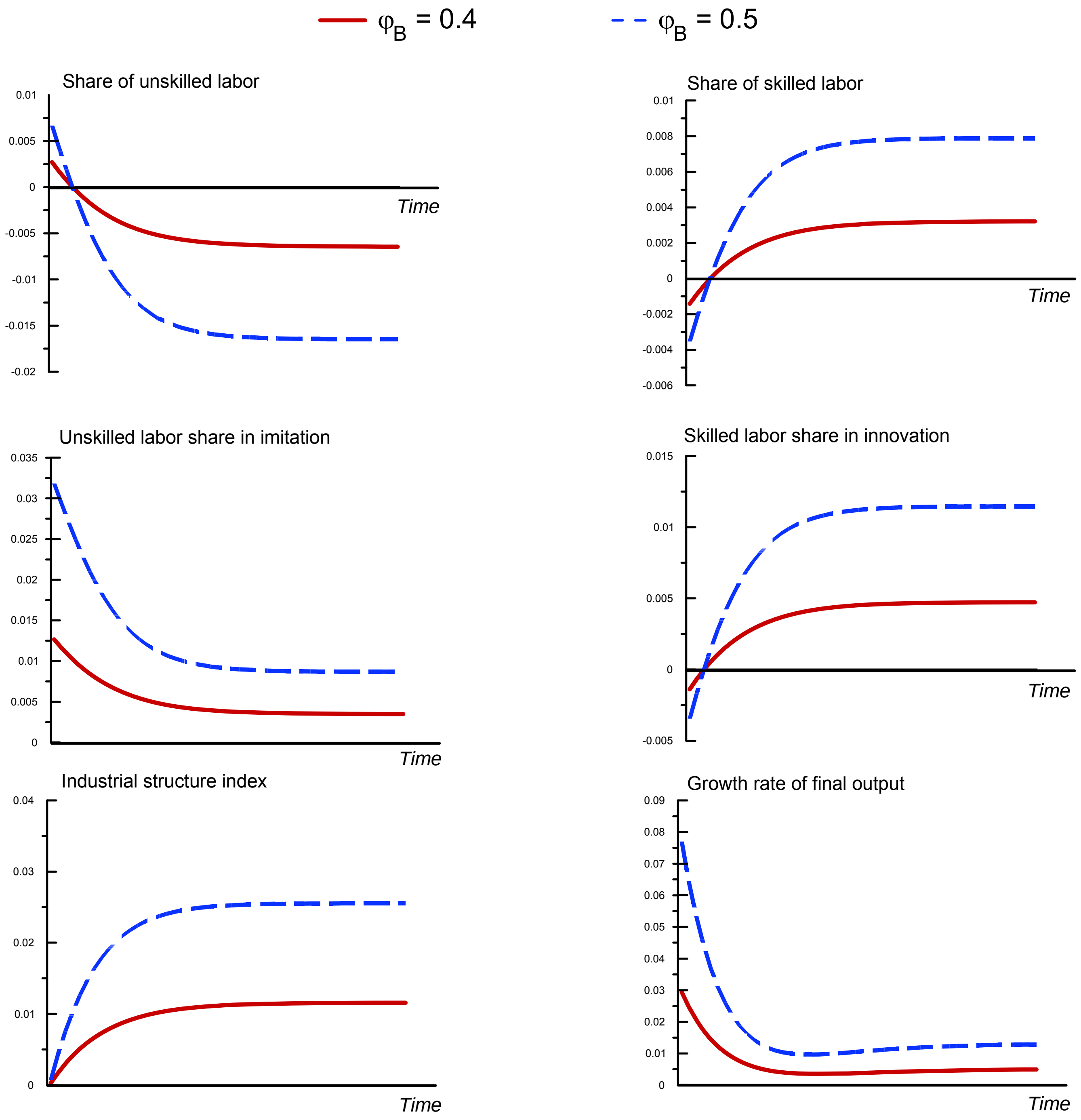
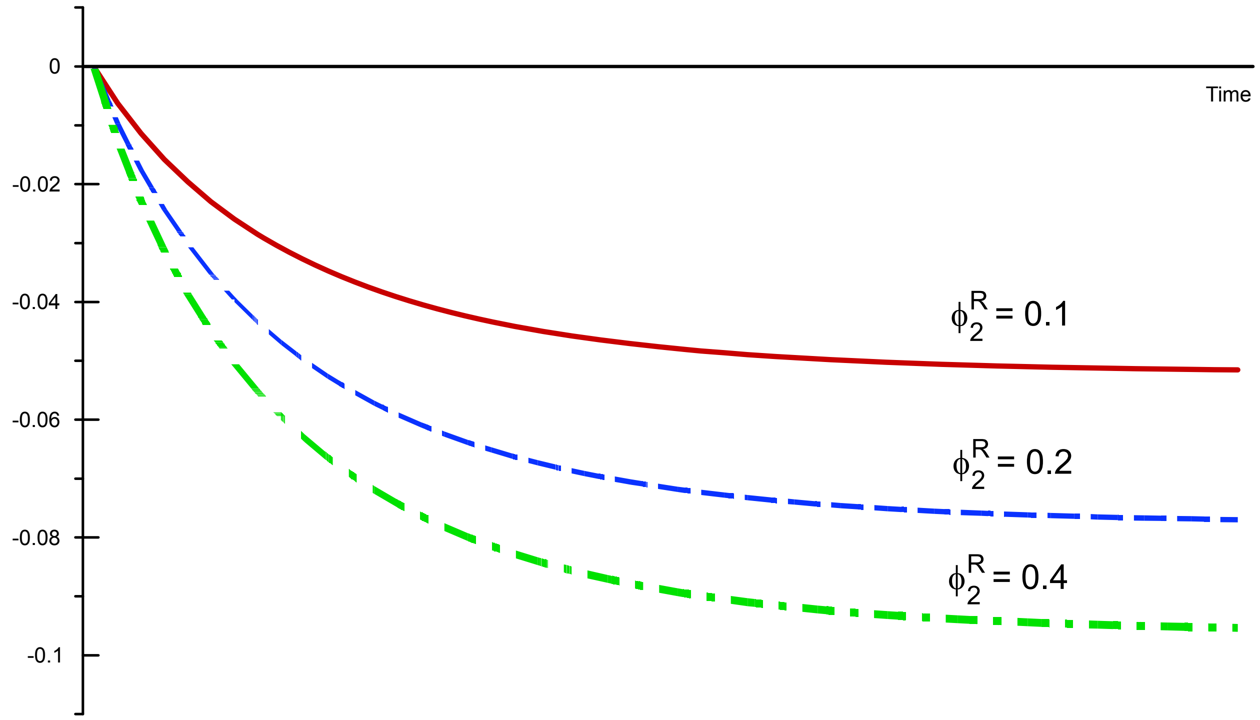


Figure 3

Permanent Increase in Share of Spending on Advanced Infrastructure

(Absolute deviations from baseline)

Industrial Transformation Index



Growth rate of final output

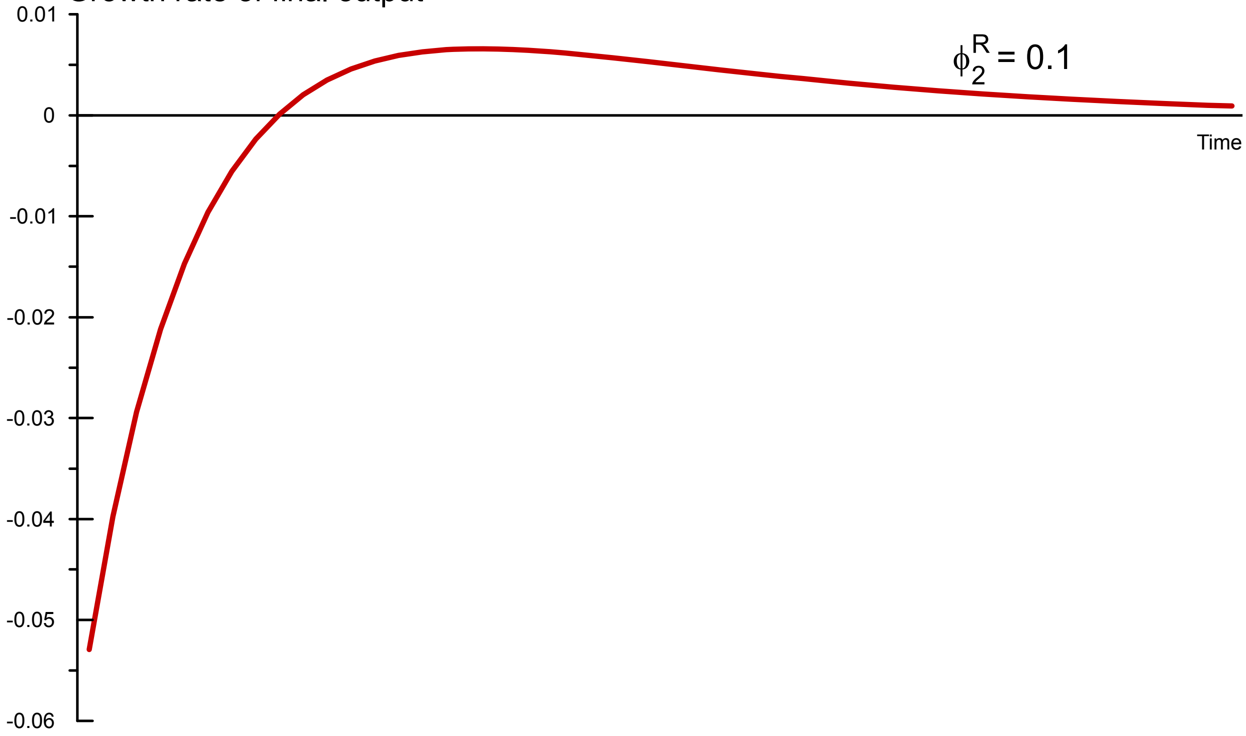
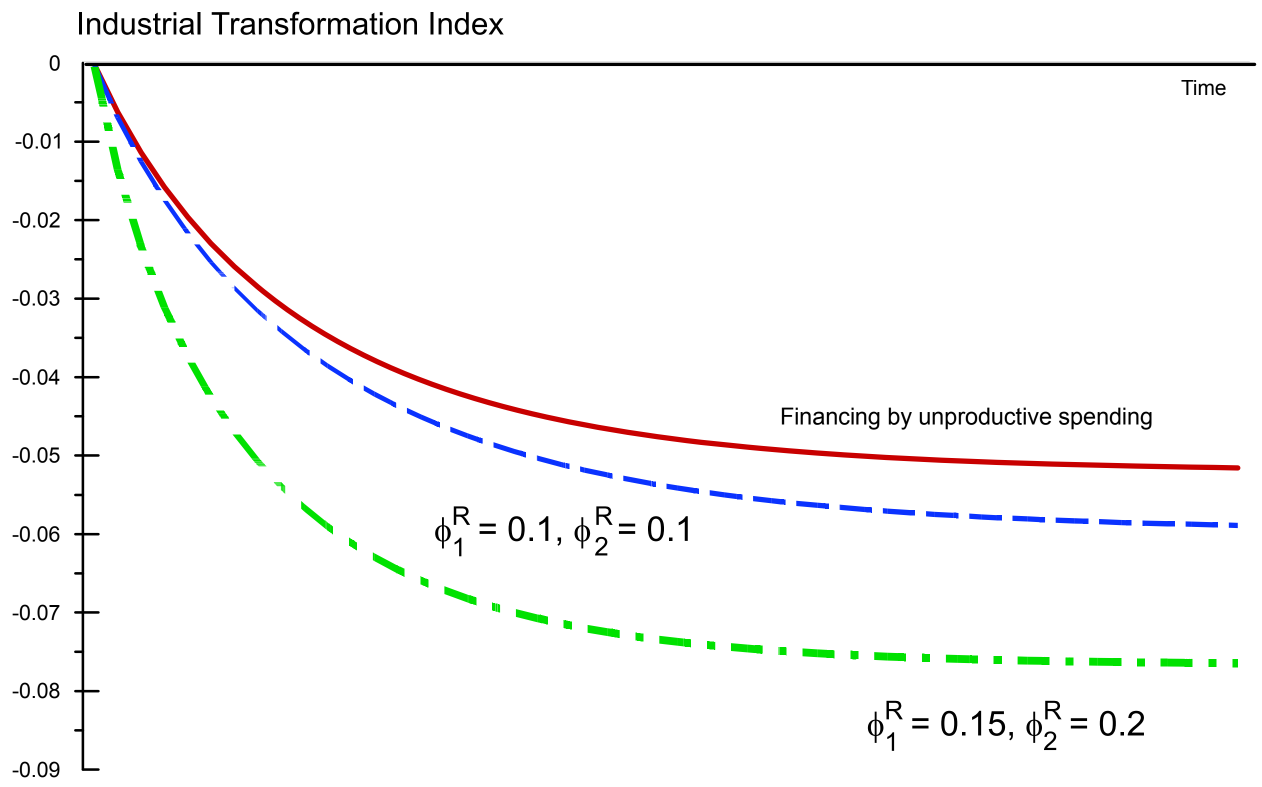
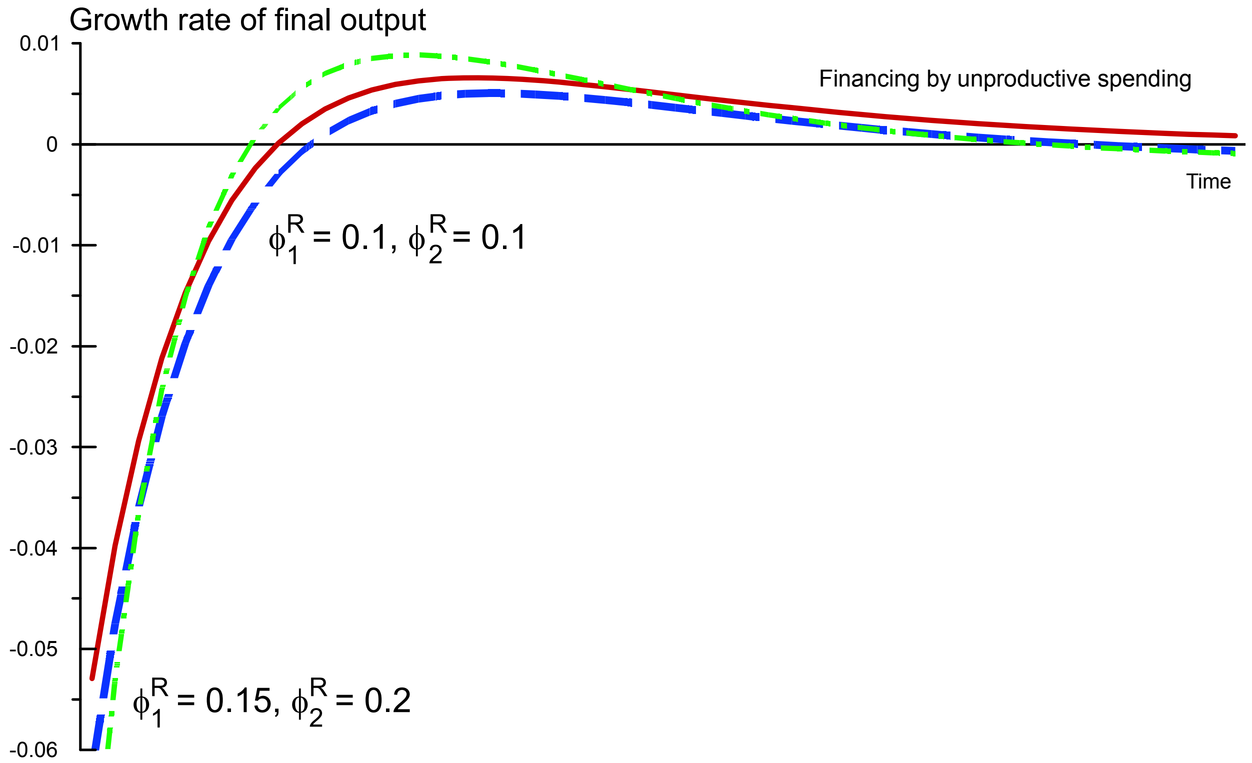


Figure 4

Permanent Increase in Investment in Advanced Infrastructure
Financed Partly by a Reduction in Investment in Basic Infrastructure
(Absolute deviations from baseline)


Industrial Transformation Index


Growth rate of final output