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Original Article

Knowledge gaps, convergence, and growth

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Abstract

This article presents a growth model with international knowledge spillovers arising from learning-by-investing externalities, explaining patterns of income convergence and growth. Technology adoption in follower economies depends on relative capital intensity, with spillovers enhancing productivity only when capital gaps with frontier economies are moderate. Using global data, we show that capital intensity largely determines growth, consistent with the model's predictions. Income growth differentials relative to the US arise only below a threshold of capital disparity, independent of human capital or innovation. These findings highlight the critical role of embodied learning and technology absorption in driving growth for lagging economies.

Keywords: multi-country AK model; cross-country knowledge transmission; endogenous adoption; convergence.

JEL classifications: F43, F63, O11, O41, O47

1. Introduction

An important empirical question in the growth literature concerns whether poorer countries are catching up with richer ones and whether international income differentials are narrowing, the so-called *convergence hypothesis*.[1] This question has been central to both theoretical and empirical research, as it speaks directly to the explanation of international differences in living standards and the appropriate modeling of modern growth processes (Johnson and Papageorgiou 2020).

Neoclassical growth theory explains cross-country differences in income growth through transitional dynamics: countries with lower capital–labor ratios should grow faster because of the higher marginal productivity of capital. By contrast, endogenous growth models emphasize externalities, human capital accumulation, and innovation. While these models do not rule out unconditional convergence, they imply that income differences may persist when absorptive capacity or knowledge diffusion is unevenly distributed. At the same time, they also allow for convergence when poorer countries accumulate human capital or adopt technologies at sufficiently rapid rates. Whether observed patterns conform to these mechanisms remains an empirical question.

[1] In the growth literature, convergence refers to the process by which poorer economies grow faster than richer ones. The distinction is between conditional convergence—where economies converge to parallel growth paths if they do not share the same fundamentals but have access to the same technology—and absolute (or unconditional) convergence—where all economies converge to the same growth path regardless of initial conditions. See Barro and Sala-i Martin (2005).

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The early empirical literature provided little support for unconditional convergence. Instead, it found either divergence of poor countries relative to rich ones (Barro 1991; Pritchett 1997) or evidence of conditional convergence toward country-specific steady states (Barro and Sala-i Martin 1991, 1992; Mankiw, Romer, and Weil 1992). Other contributions identified convergence within particular sectors, most notably manufacturing (Madsen and Timol 2011; Rodrik 2012). At the aggregate level, however, data from the 1970s onward indicated convergence in efficiency but divergence in productivity relative to the frontier economy (the United States), with East Asia as the main exception (Battisti et al., 2022).

More recently, a new wave of studies has documented evidence of unconditional convergence since the mid-1990s (Kremer, Willis, and You 2021). These findings indicate that emerging-market and middle-income countries have grown faster than advanced economies—a pattern labeled "Wilde convergence" by Roy, Kessler, and Subramanian (2016)—and that low-income countries have caught up with richer ones at an estimated rate of 0.7 per cent per year (Patel, Sandefur, and Subramanian 2021). The latter result is particularly notable, as it contrasts with Barro's "iron law" of 2 per cent (Barro 2012). Patel et al. also show that convergence has followed an inverted-U pattern, with middle-income countries growing faster than either rich or poor economies, and that growth trajectories have become more regular, with fewer sharp accelerations and collapses. This renewed evidence raises the question of what has driven global convergence since the 1980s and which theoretical frameworks best account for it. While some explanations emphasize institutional and policy adoption facilitated by ICT diffusion (Kremer, Willis, and You 2021), others stress the role of technology diffusion in the spirit of Gerschenkron's "advantage of backwardness" (Gerschenkron 1962), more consistent with endogenous growth theory.

This article contributes to the latter line of research by developing a multi-country endogenous growth model with endogenous and potentially costly technology adoption that explains the recent convergence process. The model integrates an AK production structure with monopolistic competition and threshold-based technology adoption, drawing on the externality framework of Arrow (1962), Frankel (1962), and Romer (1986). A key contribution of the model is to show how convergence and divergence can arise within a single Romer-style learning-by-investing framework once technology adoption is subject to endogenous threshold costs, with the relative capital intensity of follower economies determining whether adoption is profitable. While similar patterns can emerge in other growth models through mechanisms such as fixed costs, trade integration, or alternative frictions, this article demonstrates that such dynamics can be generated in a parsimonious extension of the Romer (1986) structure.

Following Romer (1986) and Greiner and Semmler (1996), we interpret the capital stock as a proxy for the economy's knowledge base, so that capital accumulation not only expands physical capacity but also embodies productivity-enhancing technological improvements. We assume the existence of a single frontier economy that advances the global technological frontier, while follower economies can absorb frontier knowledge through international spillovers only if their capital per worker exceeds a threshold that renders adoption profitable given its sunk cost.

The model delivers a range of outcomes. When the capital gap is very large, the follower cannot absorb frontier knowledge and unconditional divergence results, consistent with Barro (1991) and Pritchett (1997). When the gap is moderate, the follower gains access to the frontier's knowledge pool, generating conditional convergence toward parallel growth paths (Barro and Sala-i Martin 1992; Mankiw, Romer, and Weil 1992). Finally, when followers share the frontier's fundamentals, the model predicts a *near-frontier* convergence process, similar to Kremer, Willis, and You (2021) and Patel, Sandefur, and Subramanian (2021). Here, due to adoption costs, the benefits of adopting the very latest technologies are outweighed by the costs, leading to "Wilde convergence" (Roy, Kessler, and Subramanian 2016), where followers match the leader's growth rate but maintain a permanently lower income level.

We test these predictions empirically using a global sample of 179 economies over the period 1950–2019. A panel dynamic regression supports the model's explanatory power. Our results show that; (1) differences in capital stocks relative to the frontier account for much of the variation in long-run growth; (2) the effect of relative capital endowment vanishes beyond a threshold; (3) knowledge embodied in capital contributes distinctly from disembodied R&D-based knowledge; *iv* a *near-frontier* equilibrium can be empirically identified, consistent with our theoretical prediction.

This work relates to several strands of literature. First, it contributes to the extensive research on endogenous growth models with knowledge spillovers (Romer 1986; Lucas 1988; Stokey 1988, 1991; Romer 1990; Tamura 1991; Aghion and Howitt 1992; Greiner and Semmler 1996; Howitt 1999). Our main contribution is to extend the Frankel (1962)-Romer (1986) learning-by-investing framework to a multicountry setting, in which international spillovers arise but adoption is subject to a threshold determined endogenously by the necessary, irrecoverable sunk costs that lagging countries must bear to absorb new technologies. Second, we add to the literature on cross-country technological interdependence (Rivera-Batiz and Romer 1991; Eaton and Kortum 1999; Klenow and Rodriguez-Clare 2005; Acemoglu, Aghion, and Zilibotti 2006; Ertur and Koch 2007, 2011; Moll 2008; Alvarez 2017; Jin and Zhou 2022; Kleinman et al., 2023). In contrast to Ertur and Koch (2007), who assume that all countries can generate new knowledge and focus primarily on steady states, our model distinguishes frontier from follower economies and analyzes transitional dynamics, thereby capturing both convergence and divergence. Third, the article relates to the empirical literature testing growth models (Madsen 2008; Ang and Madsen 2011; Venturini 2012). In this context, we show that an extended AK model with knowledge spillovers can replicate observed convergence patterns over the last four decades.

Our findings underscore the importance of relative capital intensity in shaping convergence dynamics. Countries with capital per worker within roughly one-quarter of the US level can leverage embodied knowledge diffusion, while those below this threshold remain excluded. This mechanism explains why some developing economies have sustained catch-up while others have not. Moreover, even those near the frontier may converge in growth rates without eliminating income gaps, as the profitability of adopting frontier technologies diminishes. These dynamics are consistent across the income distribution and robust to alternative specifications, including the role of disembodied knowledge and the instability of growth spells in less developed countries.

The article is organized as follows. Section 2 develops the two-country AK model with cross-country knowledge externalities and endogenous technology adoption, characterizing its dynamic equilibrium and steady-state growth path. Section 3 investigates the dynamic properties of the steady state, identifying the theoretical conditions under which the model generates divergence, conditional convergence, and the *near-frontier* equilibrium that prevents absolute convergence. Section 4 conducts a regression analysis on a global sample of countries to empirically validate the role of learning-by-investing and capital-embodied knowledge spillovers in driving convergence. Section 5 examines the applications of our study and discusses its policy implications. Finally, Section 6 concludes.

2. The two-country framework

Consider an asymmetric world economy composed of two countries: a technology-frontier (or *leader*) country, indexed by ℓ, and a non-technology-frontier (or *follower*) country, indexed by f. In each country, households supply labor inelastically and accumulate capital assets, while firms produce a final good by aggregating a continuum of intermediate components, each produced by a local monopolist using physical capital and labor services.

To accommodate endogenous growth, we assume that productivity rises through learning-by-investing externalities that result from knowledge spillovers. However, we differentiate frontier and non-frontier economies by two spillover types: (*i*) *Localized knowledge spillovers*, through which increases in a country's own stock of knowledge enhance its economic growth; (*ii*) *Cross-country knowledge spillovers*, through which advances in labor productivity in the frontier country are transmitted to the non-frontier country.

The model is set in continuous time. However, for convenience, we omit time subscripts when no confusion arises.

2.1 Preferences and consumption

Each country $i = \ell, f$ is populated by an infinitely-lived representative household, comprising a continuum L_i of identical individuals who provide labor services in exchange for wages. The size of each household grows over time at a constant rate ν, and all individuals globally share the same rate of time preference, ρ.

The representative household in country i maximizes the discounted flow of lifetime utility:

$$U_i = \int_0^\infty e^{-(\rho-\nu)t} \log c_i dt, \qquad \rho > \nu,$$

subject to the flow budget constraint:

$$\dot{k}_i = (r_i - \delta - \nu)k_i + \pi_i + w_i - c_i, \tag{1}$$

where k_i is the household i's capital stock, r_i is the rental rate of capital, δ is the depreciation rate of capital, π_i is per capita profits from the intermediate producers, w_i is the wage rate, and c_i is consumption expenditure. The necessary and sufficient conditions for an interior optimum are:

$$\dot{c}_i = (r_i - \delta - \rho)c_i \tag{2}$$

$$\lim_{t\to\infty} \left\{ e^{-\int_0^t [r_i(z)-\delta-\nu]dz} \frac{k_i(t)}{c_i(t)} \right\} = 0, \tag{3}$$

for all $i = \ell, f$.

Equation 2 is the standard consumption Euler equation, dictating that consumption grows when the net return on capital $(r_i - \delta)$ exceeds the discount rate (ρ). Equation 3 is the transversality condition, which ensures intertemporal optimality.

2.2 Technologies and production

The production sector of each country i comprises two vertically integrated sectors: a final-good sector, producing an homogeneous good, denoted by Y_i; an intermediate sector made out of a unit continuum $\omega \in [0, 1]$ of independent industries, each of which produces a country-specific differentiated component.

The final good is produced under perfect competition according to the Constant Elasticity of Substitution (CES) technology:

$$Y_i = \left[\int_0^1 Y_i(\omega)^\varrho d\omega \right]^{1/\varrho}, \tag{4}$$

where $\varrho \in (0, 1)$ is a given parameter capturing the degree of substitutability between the differentiated component and $Y_i(\omega)$ is the quantity of the ωth component used for the production of the final good of economy i.

The goal of each final-good producer is to maximize its profits subject to the technology constraint in (4). Denoting by $p_i(\omega)$ the relative price of the ωth component in terms of the final good, we have that first-order conditions for profit maximization lead to the following Marshallian demand function:

$$Y_i(\omega) = p_i(\omega)^{1/(\varrho-1)} Y_i. \tag{5}$$

The intermediate sector is operated by a continuum ω of local monopolists, each of which produces its differentiate component by assembling labor and physical capital according to the Cobb–Douglas technology:

$$Y_i(\omega) = \left[\frac{A_i L_i(\omega)}{1-\alpha}\right]^{1-\alpha} \left[\frac{K_i(\omega)}{\alpha}\right]^\alpha, \tag{6}$$

where $\alpha \in (0, 1)$ is the output elasticity of capital, supposed—for simplicity—to be the same across countries, $L_i(\omega)$ and $K_i(\omega)$ are, respectively, the industry-specific levels of employment and physical capital, and A_i is a country-specific labor-augmenting technology parameter, whose analytical properties will be described later on in Section 2.4.

Because the Cobb–Douglas technology in (6) is linear homogeneous in labor and capital, it follows that the (minimum) total cost function of the typical intermediate monopolist ω is linear in firm's output and given by:

$$C_i[Y_i(\omega)] = \left(\frac{w_i^{1-\alpha} r_i^{\alpha}}{A_i^{1-\alpha}}\right) Y_i(\omega). \tag{7}$$

Given (7), the objective of the typical intermediate firm is to maximize profits subject to the Marshallian demand schedule in (5). Solving this maximization problem leads to the following expressions for the optimal supply and maximized operating profits:

$$Y_i(\omega) = \left(\frac{w_i^{1-\alpha} r_i^{\alpha}}{\varrho A_i^{1-\alpha}}\right)^{1/(\varrho-1)} Y_i := \tilde{Y}_i \tag{8}$$

$$\Pi_i(\omega) = (1-\varrho)\left(\frac{w_i^{1-\alpha} r_i^{\alpha}}{\varrho A_i^{1-\alpha}}\right)^{\varrho/(\varrho-1)} Y_i := \tilde{\Pi}_i \tag{9}$$

From (8) and (9), we can conclude that all intermediate monopolists produce and sell the same quantity and earn identical operating profits. This symmetry allows us to drop the index ω from the variables and focus the remainder of the analysis on the symmetric equilibrium, where $Y_i(\omega) = \tilde{Y}_i$ and $\Pi_i(\omega) = \tilde{\Pi}_i$ hold at each moment of time.

2.3 Factor prices and final output

By applying Shepherd's lemma to (7), and then using (8) to eliminate $Y_i(\omega)$ from the resulting equations, it follows that the conditional demands for labor and capital of each intermediate producer ω can be written as:

$$L_i(\omega) = (1-\alpha)\varrho\left(\frac{w_i^{1-\alpha} r_i^{\alpha}}{\varrho A_i{}^{1-\alpha}}\right)^{\varrho/(\varrho-1)} \frac{Y_i}{w_i} := \tilde{L}_i \tag{10}$$

$$K_i(\omega) = \alpha\varrho\left(\frac{w_i^{1-\alpha} r_i^{\alpha}}{\varrho A_i{}^{1-\alpha}}\right)^{\varrho/(\varrho-1)} \frac{Y_i}{r_i} := \tilde{K}_i. \tag{11}$$

As (10) and (11) show, intermediate firms in each country i demand the same amounts of labor and capital, so $K_i(\omega) = \tilde{K}_i$ and $L_i(\omega) = \tilde{L}_i$ for all $\omega \in [0, 1]$. Integrating over all industries and imposing market clearing (where total demand equals the fixed supply L_i and K_i), we can interpret (10) and (11) as the aggregate labor and capital demands for economy i.

Because in this symmetric equilibrium $Y_i(\omega) = \tilde{Y}_i$ applies for all ω, from (4) it follows that aggregate output satisfies $Y_i = \tilde{Y}_i$ at all times t. Substituting from (8) into this expression, and recalling that the final good serves as the model's numeraire, we obtain:

$$\frac{w_i^{1-\alpha} r_i^{\alpha}}{\varrho A_i^{1-\alpha}} = 1. \tag{12}$$

Equation (12) can be interpreted as a zero-profit condition for the final-good sector. Consequently, inserting this condition into (10) and (11), we have that the equilibrium levels of wages and rental rate of capital of each economy i can be expressed as:

$$w_i = \frac{(1-\alpha)\varrho Y_i}{L_i} \tag{13}$$

$$r_i = \frac{\alpha\varrho Y_i}{K_i}. \tag{14}$$

Finally, by substituting (13) and (14) into the zero-profit condition (12), it follows that the level of the final good is determined by the following labor-augmenting Cobb–Douglas production function:

$$Y_i = (1-\alpha)^{\alpha-1}\alpha^{-\alpha}(A_i L_i)^{1-\alpha} K_i^{\alpha}. \tag{15}$$

2.4 Learning-by-investing and cross-country knowledge externalities

To accommodate endogenous growth into the model, we assume that each country's productivity A_i is driven by learning-by-investing externalities generated by capital accumulation (Arrow 1962; Romer 1986). Unlike the leader, however, the follower can benefit from international knowledge spillovers if its intermediate sector can successfully assimilate technical knowledge from the frontier (Parente and Prescott 1994, 2002; Alfaro, Kalemli-Ozcan, and Volosovych 2008). To do so, intermediate producers in the follower country must incur a sunk cost, expressed in units of the final good, to correctly adapt the foreign technology for domestic use.

Formally, we assume that the productivity index of intermediate firms are given by:

$$\mathrm{A}_\ell = \mathrm{A}_\ell^{1/(1-\alpha)} k_\ell \tag{16}$$

$$\mathrm{A}_f = \mathrm{A}_f^{1/(1-\alpha)} k_f \cdot \mu(\kappa_f), \tag{17}$$

where $\mathrm{A}_i > 0$ (with $\mathrm{A}_f < \mathrm{A}_\ell$) is a catch-all parameter capturing all institutional and domestic factors contributing to the production efficiency of economy i, $k_i := K_i/L_i$ is its capital-to-labor ratio of economy i, $\kappa_f := k_\ell/k_f$ denotes the capital stock ratio between the leader and the follower (capturing the technological distance from the frontier), and $\mu(\cdot)$—with $\mu'(\cdot) > 0$ and $\mu''(\cdot) < 0$—is an absorption function reflecting the follower's ability to translate leader-generated technological knowledge into productivity gains.

The shape of $\mu(.)$ depends on whether intermediate firms in the follower economy decide to adopt technical knowledge from the leader. Adoption requires the payment of a sunk cost, expressed in terms of the final good, which we assume increases with the technology gap κ_f and is given by[2]:

$$F_f = \phi \kappa_f \cdot Y_f, \tag{18}$$

where $\phi \in (0,1)$ is exogenous. The absorption function is defined as follows:

$$\mu(\kappa_f) := \begin{cases} \kappa_f^{\psi_f} & \text{if } F_f \text{ is borne} \\ 1 & \text{if } F_f \text{ is not borne} \end{cases}, \tag{19}$$

where $\psi_f \in [0,1)$ is an absorption parameter that captures the extent to which the follower can effectively assimilate the leader's knowledge.

The following lemma establishes the conditions under which intermediate firms in the follower economy find it profitable to adopt technological knowledge from the leader.

Lemma 1 *Define:*

$$\tilde{\phi} := \frac{(1-\varrho)\psi_f(1-\alpha)}{[1+\psi_f(1-\alpha)]^{[1+\psi_f(1-\alpha)]/[\psi_f(1-\alpha)]}} < 1.$$

If $\phi < \tilde{\phi}$, there exists a closed interval, $[\tilde{\kappa}_1, \tilde{\kappa}_2]$, such that: (i) *if $\kappa_f \in [\tilde{\kappa}_1, \tilde{\kappa}_2]$, the intermediate firm does find it optimal to invest in technology adoption;* (ii) *if either $\kappa_f < \tilde{\kappa}_1$ or $\tilde{\kappa}_2 < \kappa_f$, the intermediate firm does not find it optimal to invest in technology adoption.*

Proof. See Supplementary Appendix A.

The lemma above identifies two threshold levels of $\tilde{\kappa}_f$, denoted by $1 < \tilde{\kappa}_1 < \tilde{\kappa}_2$. These thresholds define the interval within which follower firms find it optimal to adopt foreign technology. If $\kappa_f > \tilde{\kappa}_2$, the knowledge gap between the leader and the follower is too wide, so the costs of adopting foreign technology exceed the potential gains. Conversely, if $1 < \kappa_f < \tilde{\kappa}_1$, the gap is too narrow and the incremental profits from adoption are insufficient to cover the fixed costs. Therefore, intermediate producers in the

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[2] More generally, the sunk cost of adoption can be can be written as: $F_f = \Phi(\kappa_f) \cdot Y_f$, where $\Phi'(\cdot) > 0$ and $\Phi''(\cdot) \geq 0$. However, for ease of exposition, in this article we restrict attention to the linear specification: $\Phi(\kappa_f) := \phi \kappa_f$.

follower country adopt foreign technology only when κ_f lies within the interval $[\tilde{\kappa}_1, \tilde{\kappa}_2]$, where the additional profits from adoption outweigh the costs.

Letting $y_i = Y_i/L_i$ denote per capita income in country i at time t, from (15), (16), (17) and (19), we have that—at the aggregate level—each country's per capita income can be written as:

$$y_\ell = (1-\alpha)^{\alpha-1}\alpha^{-\alpha}A_\ell k_\ell \tag{20}$$

$$y_f = (1-\alpha)^{\alpha-1}\alpha^{-\alpha}A_f k_f \cdot \begin{cases} \kappa_f^{\psi_f(1-\alpha)} & \text{if } \kappa_f \in [\tilde{\kappa}_1, \tilde{\kappa}_2] \\ 1 & \text{if } \kappa_f \notin [\tilde{\kappa}_1, \tilde{\kappa}_2] \end{cases}. \tag{21}$$

According to (21), as long as $\kappa_f \in [\tilde{\kappa}_1, \tilde{\kappa}_2]$, technological advancements in the frontier economy contribute to the expansion of the follower country's knowledge base, thereby increasing its per capita income. However, for values of κ_f outside the interval, the follower country behaves as a standard AK economy.

2.5 Equilibrium dynamics

2.5.1 Derivation of the equilibrium system.

In this section, we study the dynamic properties of the equilibrium. In doing this, we will focus on the special case in which $\kappa_f \in [\tilde{\kappa}_1, \tilde{\kappa}_2]$, such that the follower country possesses the initial knowledge base to absorb the leader's technology.

The dynamic system of the model can be constructed as follows. Firstly, we determine the equilibrium factor prices in each country by substituting Equations (20) and (21) into (13) and (14); this yields:

$$r_\ell = \varrho(1-\alpha)^{\alpha-1}\alpha^{1-\alpha}A_\ell, \quad r_f = \alpha\varrho(1-\alpha)^{\alpha-1}\alpha^{-\alpha}A_f\kappa_f^{\psi_f(1-\alpha)} \tag{22}$$

$$w_\ell = \varrho(1-\alpha)^{\alpha}\alpha^{-\alpha}A_\ell k_\ell, \quad w_f = \varrho(1-\alpha)^{\alpha}\alpha^{-\alpha}A_f k_f \kappa_f^{\psi_f(1-\alpha)}. \tag{23}$$

Then, we use (12), (20) and (21) into (9) to obtain the following pair of expressions for the (aggregate) profits[3]:

$$\tilde{\Pi}_\ell = (1-\varrho)(1-\alpha)^{\alpha-1}\alpha^{-\alpha}A_\ell k_\ell L_\ell, \quad \tilde{\Pi}_f = (1-\varrho-\phi\kappa_f)(1-\alpha)^{\alpha-1}\alpha^{-\alpha}A_f k_f \kappa_f^{\psi_f(1-\alpha)}L_f. \tag{24}$$

Finally, to obtain the closed-form dynamic system, we substitute from (22), (23) and (24) into (1), (2) and (3) to obtain the following 4×4 system of differential equations:

$$\frac{\dot{k}_\ell}{k_\ell} = (1-\alpha)^{\alpha-1}\alpha^{-\alpha}A_\ell - \frac{c_\ell}{k_\ell} - \nu - \delta \tag{25}$$

$$\frac{\dot{k}_f}{k_f} = (1-\phi\kappa_f)(1-\alpha)^{\alpha-1}\alpha^{-\alpha}A_f\kappa_f^{\psi_f(1-\alpha)} - \frac{c_f}{k_f} - \nu - \delta \tag{26}$$

$$\frac{\dot{c}_\ell}{c_\ell} = \varrho(1-\alpha)^{\alpha-1}\alpha^{1-\alpha}A_\ell - \delta - \rho \tag{27}$$

$$\frac{\dot{c}_f}{c_f} = \varrho(1-\alpha)^{\alpha-1}\alpha^{1-\alpha}A_f\kappa_f^{\psi_f(1-\alpha)} - \delta - \rho. \tag{28}$$

with transversality conditions given by:

$$\lim_{t\to\infty}\left\{e^{-[\varrho(1-\alpha)^{\alpha-1}\alpha^{1-\alpha}A_\ell - \delta - \nu]t}\frac{k_\ell(t)}{c_\ell(t)}\right\} = 0 \tag{29}$$

$$\lim_{t\to\infty}\left\{e^{-\int_0^t[\alpha\varrho(1-\alpha)^{\alpha-1}\alpha^{-\alpha}A_f\kappa_f(z)^{\psi_f(1-\alpha)} - \delta - \nu]dz}\frac{k_f(t)}{c_f(t)}\right\} = 0. \tag{30}$$

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[3] In deriving the expressions (25) and (26), we assumed that firms' profits are evenly distributed among household members, such that $\pi_i = \tilde{\Pi}_i/L_i$. We then substituted $\tilde{\Pi}_i$ using (24).

Definition 1 *A dynamic equilibrium for the two-country AK model with international knowledge transmission can be defined as a set of infinite sequences of allocations* $\{c_\ell, c_f, k_\ell, k_f\}_{t\in[0,\infty)}$ *that:* (i) *satisfies* (25)–(28); (ii) *fulfills the inequality constraints* $c_f \geq 0$, $c_\ell \geq 0$, $k_f \geq 0$, $k_\ell \geq 0$; *and* (iii) *satisfies the transversality conditions* (29)–(30).

Equations (26) and (28) shows how changes in the knowledge gap κ_f may influence the dynamics of the equilibrium paths of k_f and c_f. Consequently, to solve the model for the long-run equilibrium, it is convenient to reduce the dynamic system from four to three dimensions and focus on the following re-scaled variables: the consumption-to-capital ratio of the frontier economy, $x_\ell := c_\ell/k_\ell$, the consumption-to-capital ratio of the non-frontier economy, $x_f := c_f/k_f$, and the cross-country knowledge gap, $\kappa_f := k_\ell/k_f$.

Combining (25)–(28) yields the following 3×3 dynamic system in κ_f, x_f, and x_ℓ:

$$\frac{\dot{\kappa}_f}{\kappa_f} = x_f - x_\ell + (1-\alpha)^{\alpha-1}\alpha^{-\alpha}\left[A_\ell - (1-\phi\kappa_f)A_f\kappa_f^{\psi_f(1-\alpha)}\right] \tag{31}$$

$$\frac{\dot{x}_f}{x_f} = x_f - (1-\alpha\varrho-\phi\kappa_f)(1-\alpha)^{\alpha-1}\alpha^{-\alpha}A_f\kappa_f^{\psi_f(1-\alpha)} - (\rho-\nu) \tag{32}$$

$$\frac{\dot{x}_\ell}{x_\ell} = x_\ell - (1-\alpha\varrho)(1-\alpha)^{\alpha-1}\alpha^{-\alpha}A_\ell - (\rho-\nu), \tag{33}$$

In system (31)–(33), the variables x_ℓ and x_f are the non-predetermined (jump) variables, while κ_f is the predetermined (state) variable. Therefore, for any given $\kappa_f(0) \in [\tilde{\kappa}_1, \tilde{\kappa}_2]$, the dynamic system (31)–(33) completely characterize the transitional dynamics of our two-country AK model with international knowledge transmission.

2.5.2 *Characterization of the steady state.*

Let an asterisk ("*") denote steady-state values of the endogenous variables.

Definition 2. *A steady-state equilibrium for the two-country world economy consists of a set of infinite sequences of allocations* $\{c_\ell, c_f, k_\ell, k_f\}_{t\in[0,\infty)}$ *satisfying* Definition 1, *such that:* (i) *The variables* x_ℓ, x_f, *and* κ_f *are constant over time;* (ii) *Individual consumption expenditures* (c_ℓ *and* c_f) *and capital stocks* (k_ℓ *and* k_f) *grow at the common constant rate* g.

The steady state is obtained by setting the equations in system (31)–(32) equal to zero and solving the resulting 3×3 static system for the three endogenous variables: κ_f^*, x_f^*, and x_ℓ^*. This yields the following result:

Proposition 1. *If* $\kappa_f(0) \in [\tilde{\kappa}_1, \tilde{\kappa}_2]$, *then the model predicts a unique steady-state equilibrium where:*

i) *The knowledge gap* κ_f^* *is strictly greater than one and equal to:*

$$\kappa_f^* = \left(\frac{A_\ell}{A_f}\right)^{1/[\psi_f(1-\alpha)];} \tag{34}$$

ii) *The consumption-to-capital ratios of the leader and follower country are respectively given by:*

$$x_\ell^* = \rho - \nu + (1-\alpha)^{\alpha-1}\alpha^{-\alpha}(1-\alpha\varrho)A_\ell \tag{35}$$

$$x_f^* = \rho - \nu + (1-\alpha)^{\alpha-1}\alpha^{-\alpha}(1-\alpha\varrho)A_\ell[1 - \frac{\phi}{1-\alpha\varrho}\left(\frac{A_\ell}{A_f}\right)^{1/[\psi_f(1-\alpha)]}]; \tag{36}$$

iii) *The unique steady-state growth rate of the world economy coincides with that of the leader and is given by:*

$$g^* = \varrho(1-\alpha)^{\alpha-1}\alpha^{1-\alpha}A_\ell - \delta - \rho; \tag{37}$$

iv) *The steady-state growth path is (asymptotically) saddle-path stable.*

Proof. See Supplementary Appendices B and C.

Proposition 1 highlights several key implications. Sustained long-run growth (part (*iii*)) depends critically on the frontier's efficiency level, A_ℓ. Persistent knowledge gaps arise from differences in economic institutions, captured by the ratio $A_\ell/A_f > 1$ (part (i)). Furthermore, due to the fixed absorption cost, consumers in the follower country must save more, resulting in a lower consumption-to-capital ratio (part (*ii*)).

As for the income ratio, y_ℓ/y_f, Proposition 1 shows that the rise in cross-country income inequality can also be attributed to efficiency differences, as captured by[4]:

$$\frac{y_\ell^*}{y_f^*} = \left(\frac{A_\ell}{A_f}\right)^{1/[\psi_f(1-\alpha)]} = \kappa_f^*. \tag{38}$$

Finally, the dynamic adjustment to the steady state follows the stable path (part (*iv*)):

$$\kappa_f(t) = \kappa_f^* + [\kappa_f(0) - \kappa_f^*]e^{\widehat{\lambda}t}, \tag{39}$$

$$x_f(t) = x_f^* + \vartheta[\kappa_f(0) - \kappa_f^*]e^{\widehat{\lambda}t}, \tag{40}$$

$$x_\ell(t) = x_\ell^*, \tag{41}$$

where $\widehat{\lambda} < 0$ is the stable eigenvalue of the Jacobian matrix of the linearized system, and $\vartheta > 0$ is a function of exogenous parameters.[5]

From (41), we have that the frontier economy remains on its steady-state growth path at all times. In contrast, from (39)–(40), it follows that the non-frontier economy may experience temporary deviations from its balanced path, gradually adjusting at a rate governed by the magnitude of the eigenvalue $\widehat{\lambda}$, which—in turn—depends on the absorption parameter ψ_f.

In conclusion, while standard AK models predict constant growth without transitional dynamics, our two-country framework incorporating cross-country knowledge spillovers features a unique, asymptotically stable, steady-state growth path reminiscent of the neoclassical growth model. However, unlike the neoclassical framework where growth is exogenous, the global growth rate in this model is endogenously determined through knowledge spillovers facilitated by capital accumulation.

Given the central role of ϕ and ψ_f in driving the model's catching-up behavior, the next section explores the transitional dynamics to identify the conditions that generate the observed convergence and divergence patterns.

3. Determining convergence patterns

To illustrate the conditions under which a specific convergence pattern may arise in the long run, consider first the case where the initial knowledge base is sufficiently low, such that $\kappa_f(0) \notin [\tilde{\kappa}_1, \tilde{\kappa}_2]$. This implies that adapting the leader's knowledge is too costly for the follower, that is, $\phi > \tilde{\phi}$. In this situation, each country behaves as an isolated technological "island": starting from its own initial capital stock, $k_i(0)$, it immediately jumps onto its individual steady-state growth path and remains there indefinitely.

When $\kappa_f(0) \notin [\tilde{\kappa}_1, \tilde{\kappa}_2]$, Equation (38) implies that $y_\ell/y_f \to \infty$ whenever $A_\ell > A_f$. This is the "unconditional divergence" result predicted by standard AK models *à la* Romer (1986), and empirically supported by Barro (1991) and Pritchett (1997) for the decades before the 1990s.[6] However, as shown by Barro and Sala-i Martin (1991, 1992) and Mankiw, Romer, and Weil (1992), this prediction is rejected by both regional and cross-country data, which instead support "conditional" convergence—that is, convergence in growth rates rather than income levels.

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[4] To obtain (38), it suffices to divide (20) by (21), and then substitute from (34) into the resulting equation.

[5] See Supplementary Appendix C for the analytical expressions of $\widehat{\lambda}$ and ϑ.

[6] Divergence arises when $\psi_f = 0$ because, without cross-country productivity externalities, the two economies grow independently at $g_i^* = \alpha A_i - \rho - \delta$, with $g_\ell^* > g_f^*$ since $A_\ell > A_f$.

Table 1. Baseline parametrization.

Parameter	Value	Description
ν	0	Net population growth rate
α	0.33	Capital share in production
ρ	0.05	Discount rate/time preference
A_ℓ	0.2044	Efficiency index of the leader economy
A_f	0.1718	Efficiency index of the follower economy
ψ_f	0.062	Knowledge absorption parameter
ϱ	0.75	CES elasticity parameter
ϕ	0.0005	Sunk cost parameter for knowledge adoption
δ	0.0354	Capital depreciation rate

Table 2 . Steady-state quantities under the benchmark parametrization.

Variable	κ_f^*	x_f^*	x_ℓ^*	g^*
Value	66.7	0.327	0.34	0.01

To examine whether the model also predicts "conditional" convergence, we now consider the case $\kappa_f(0) \in [\tilde{\kappa}_1, \tilde{\kappa}_2]$, such that $\phi \leq \tilde{\phi}$. Here, $\widehat{\lambda} < 0$ and $\vartheta > 0$, implying that the two countries are linked through knowledge transmission. If the world economy starts with a relative capital intensity such that $\kappa_f(0) \leq \tilde{\kappa}$, then the ratio y_ℓ/y_f is no longer explosive and monotonically converges to its long-run value given by (38). The model thus predicts convergence in growth rates but not necessarily in per capita income levels, consistent with the "conditional convergence" literature.

Finally, since all cross-country differences in macroeconomic fundamentals are summarized by the parameter A_i, the follower can narrow the gap with the leader by adopting policies that offset $A_f - A_\ell$. This would turn "conditional" convergence into "absolute" convergence. Kremer, Willis, and You (2021) refer to this as the "converging-to-convergence" hypothesis; that is, a medium-term scenario where "institutional homogenization" drives convergence in development-friendly policies rather than in income levels.

To assess to what extent the "converging-to-convergence" hypothesis can be responsible for the low convergence speed estimated by Patel, Sandefur, and Subramanian (2021), in the rest of this section we calibrate our two-country model using the following set of exogenous parameters based on data for the US economy (see Table 1).

To set the rate of time preference and the output elasticity of capital, we follow the bulk of growth literature and assume $\rho = 0.05$ and $\alpha = 0.33$. Moreover, since demographic growth is not key in shaping the transition paths of the model, for simplicity we set $\nu = 0$. To calibrate the efficiency parameters A_ℓ and A_f, we set $A_\ell = 0.2044$ so as to get the same average growth rate in purchasing power parity (PPPs) GDP per worker of 1% shown by the US economy between 1960 and 2010 (source: Penn World Tables, PWT 10.0), and $A_f = 0.1718$ to get a initial gap in knowledge stocks, $\kappa_f(0)$, of about 66.7, which roughly corresponds to the capital per worker ratio USA and China in 1978 (source: Penn World Tables, PWT 10.0). The fixed cost of adaptation is then set to $\phi = 0.0005$ (0.5 per-thousand) so that to have the interval $[\tilde{\kappa}_1, \tilde{\kappa}_2] \sim [1.05, 83.8]$ containing the initial knowledge gap $\kappa_f(0) = 66.7$.

As for the depreciation rate, we set $\delta = 0.0354$ to match the average annual rate for the US economy between 1960 and 2010. The absorption parameter $\psi_f \approx 0.062$ is then calibrated to replicate the slow convergence speed documented by Patel, Sandefur, and Subramanian (2021) and Kremer, Willis, and You (2021). Finally, we set $\varrho = 0.75$ to yield a markup of 1.33 (a 33 per cent unit profit), which aligns with standard empirical estimates (Hall 2018; Edmond, Midrigan, and Xu 2023).

Table 2 reports the steady-state equilibrium quantities.

Suppose that, at a certain moment of time, the non-frontier country manages to increase its efficiency parameter, A_f, from 0.1718 to 0.2040, thereby closing the knowledge gap with the leader enough to reach the lower bound of the adoption interval, $\bar{\kappa}_1 = 1.05$.[7]

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[7] Indeed, because acquiring technology is costly, the maximum level of equality to which the follower country can aspire coincides with the lower bound of the interval, $\bar{\kappa}_1 \approx 1.05$, as any further acquisition of knowledge would entail an absorption cost exceeding the associated benefit. This result can be explained by noting that when the follower country's stock of knowledge is nearly identical to that of the leader, acquiring additional knowledge becomes increasingly complex and, therefore, prohibitively costly.

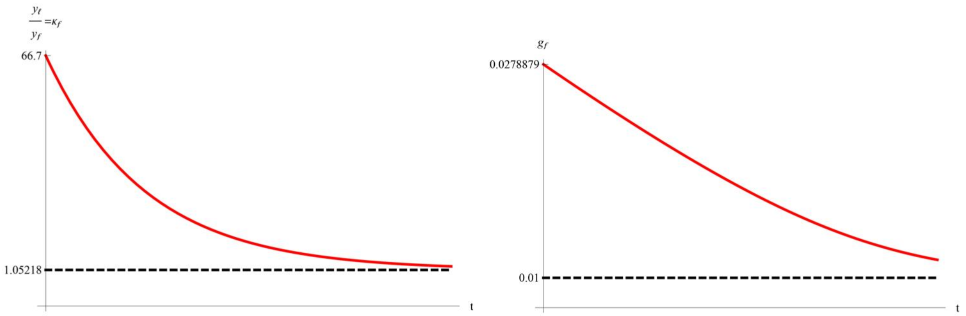

Figure 1. Adjustment paths of income ratio y_n/y_s (left) and growth rates (right). The "dotted" line in the diagram on the right indicates the growth rate of the frontier economy and the "thick" line the growth rate of the non-frontier economy.

The adjustment dynamics generated by κ_f are portrayed in the left chart in Fig. 1. As the figure shows, this permanent increase in A_f leads to a smooth adjustment toward the new long-run equilibrium value of the relative capital stock $\kappa_f^* \approx 1.05$. During the entire transition, the growth rate of the frontier economy remains constant at $g^* = 0.01$, while that of the non-frontier economy temporarily deviates from its long-run value of 1% (See the right chart in Fig. 1). This implies two further corollary results: (*i*) the frontier country remains on its equilibrium path throughout; (*ii*) during the adjustment, the non-frontier economy always grows faster than the frontier economy ("Wilde"-convergence).

A pivotal implication of this result is that even if the follower country consistently shrinks the efficiency and institutional gap with the leader (i.e., $A_f \rightarrow A_\ell$), the income ratio y_ℓ/y_f converges not to unity, but to the lower bound of the technology adoption interval, $\bar{\kappa}_1 \approx 1.05$. This indicates the persistence of a steady-state income gap of approximately 5 per cent, implying that full income equality—and therefore absolute convergence—remains out of reach.

The economic intuition for this lies in the endogenous nature of technology adoption. As the follower narrows the knowledge gap, the marginal benefit of adopting additional frontier technology diminishes. However, the sunk cost of adoption, $\phi\kappa_f$, increases with proximity to the frontier. Consequently, there exists a point—defined by $\bar{\kappa}_1$—where the costs of further adoption rationally outweigh the benefits for follower firms. The follower economy therefore settles into a *near-frontier* equilibrium, where it grows at the same rate as the leader but sustains a permanently lower level of income per capita. This self-limiting mechanism inherently curtails the potential for absolute convergence.[8]

Finally, to quantify the convergence speed predicted by the model, we log-linearize (31)–(33) around the steady state and calculate the half-time. Our simulation confirms the existence of one stable (negative) eigenvalue and two unstable (positive) eigenvalues (see Table 3), establishing the saddle-path stability of the steady state. However, because the modulus of the negative eigenvalue is very close to zero, the implied half-life is very large, amounting to 169 years. This result aligns with the findings of Patel, Sandefur, and Subramanian (2021) and Kremer, Willis, and You (2021) that poor economies tend to catch up with rich ones only slowly over time.

4. Empirical analysis

Now, we conduct an econometric test to validate the main predictions of our theoretical framework by performing a dynamic panel regression analysis. Our model indicates that, in the long run, the growth rate of per capita income is positively related to the gap in capital endowment between the lagging and the frontier economy. This gap is expressed as the inverse ratio of the laggard's capital intensity compared to the frontier economy (κ).

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[8] One could argue that full convergence might be achieved if A_f were instantaneously adjusted to match exactly A_ℓ (i.e., 0.2044). However, during the transition, the value of κ_f would reach its lower bound, κ_1, before reaching 1. As a result, firms' incentives to implement leader-produced knowledge would disappear before perfect equality ($\kappa_f = 1$) is attained, thereby halting the transformation from conditional to unconditional convergence. Indeed, if we model the knowledge gap closing gradually with an adjustment function of the form $Z(A_\ell, A_f) = A_f e^{-\vartheta t} + A_\ell(1 - e^{-\vartheta t})$, where $\vartheta > 0$, the follower's approach to the lower threshold is smoother. This smoother transition clarifies the point at which the marginal benefits of further technology absorption no longer outweigh the costs, guiding firms to cease implementing the leader's technological knowledge.

Table 3. Eigenvalues of the Jacobian matrix of the linearized system.

	1	2	3
eigenvalue, λ	– 0.0041	0.328	0.34
eigenvector, Λ	91.8	3.06	–0.0532
	1	1	0.982
	0	0	1

According to our model, the relative capital intensity should facilitate knowledge spillovers through learning by investing. This, in turn, would enhance efficiency levels and ultimately lead to an increase in the rate of growth of GDP per capita. Accordingly, as an economy develops and its income level rises, the role of relative capital in driving growth should diminish. This is because the scope of knowledge spillovers tends to shrink as the economy expands. Therefore, if our model holds true, when we account for differences in productivity and income levels, the relationship between relative capital and the rate of income growth should weaken.

In this section, we aim to validate these predictions by presenting various pieces of evidence. We utilize data from the PWT 10.0 and primarily focus on measuring per capita income as GDP in 2017 million US dollars (in millions of chained PPP) per inhabitant. Relative capital endowment refers to the ratio between the per person capital stock of USA, which serves as our frontier economy, and the same measure of capital intensity in countries that are lagging behind (in millions of chained US PPP). The time frame considered in this analysis spans from 1950 to 2019, during which data is available for a sample of 179 countries.

4.1 Descriptive evidence

As first evidence, in Fig. 2 we report the scatter plots between the growth rate of GDP per capita and relative capital (left-hand side), and between the growth rate of GDP per capita and initial value of income per capita taken in logs (right-hand side). In all charts, observations are obtained as averages at country level over the full time period, and are based on size weights reflecting the levels of income, so to mitigate the impact of outlying behavior of poorer countries. In both graphs, the red solid line identifies the linear fit, whilst the red dotted line is obtained from a quadratic regression. The figures point to a positive correlation between relative capital endowment and income growth ($y = 0.003 + 0.007\times$), and a negative correlation between income growth and its initial level ($y = 0.12 - 0.013\times$). As expected, richer countries—which are denoted by larger circles—benefit from a weaker effect of relative capital and have a slower convergence process. Not less relevantly, there is a group of poor countries, identified by the small circles, that falls well below the linear fit, explaining why the quadratic interpolation may provide a better approximation for these relationships. This issue has been pointed out, among others, by Patel, Sandefur, and Subramanian (2021) in studying global income convergence.[9]

4.2 Benchmark regressions

We support more rigorously our theory by developing a panel dynamic regression analysis. The stochastic version of our (long-run) equilibrium relationship is defined as:

$$\Delta \log y_{it} = a_{i0} + b \log \kappa_{it} + c \log X_{it} + F_t + \varepsilon_{it} \tag{42}$$

where i denotes countries ($i = 1, \ldots, 179$), t years ($t = 1950, \ldots, 2019$). X is a vector including various controls that we introduce below, whilst F_t captures the effect of un-observable factors affecting income dynamics, that we primarily model with common time dummies.[10] a_{i0} are country fixed effects and ε_{it} spherical error terms.

Table 4 presents the estimates for the long-run relationship between relative capital and income growth. These estimates are derived from the short-run coefficients obtained through the implementation of an Auto-Regressive Distributed Lags (ARDL) model. This procedure is robust to reverse

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[9] Figure A1 of Supplementary Appendix E illustrates that the relationship between income growth and relative capital over time, showing how it weakens when accounting for cross-country differentials in productivity and income.

[10] The effect of dummies is modeled by expressing all variables as deviations from their cross-sectional mean.

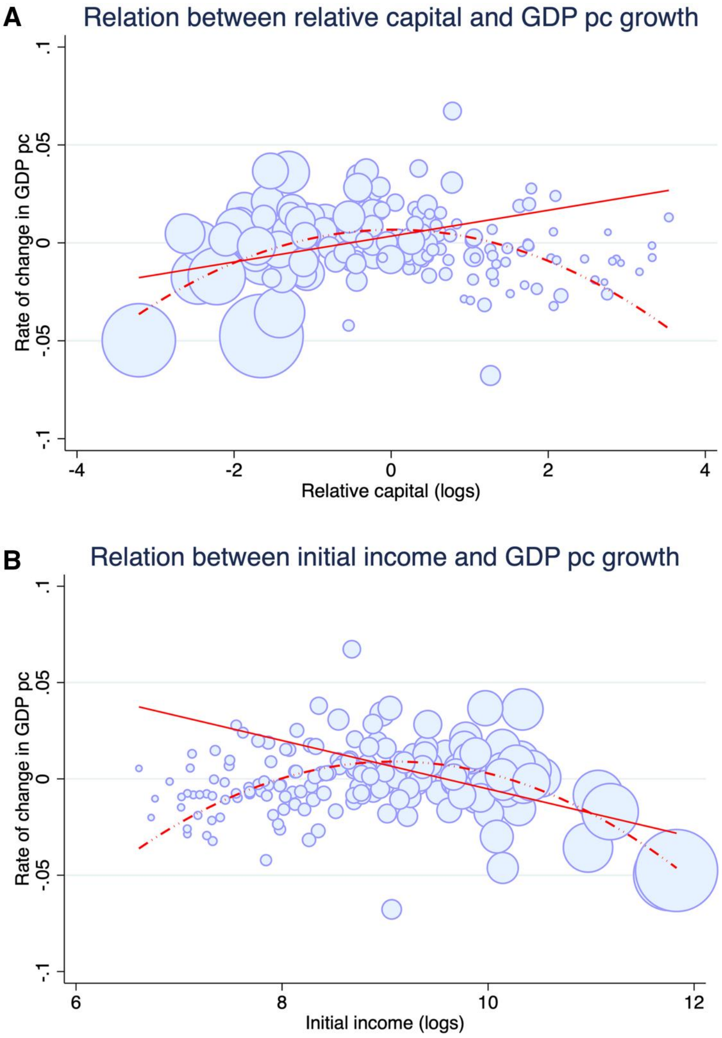

Figure 2. Linear and quadratic fit between GDP p.c. (per capita) growth, relative capital, and initial income (country means using GDP p.c. as weights, 1950–2019).

causality and other important econometric issues (dynamic adjustment, heterogeneity, the integration order of the variables, etc.).[11]

Our baseline regression in column (1) considers the annual rate of change of GDP per inhabitant as dependent variable whilst in column (2) we utilize GDP per worker as an alternative measure of income. In column (3), we narrow down the regression sample to countries with an average population greater than 0.350 million inhabitants and to those with at least one million inhabitants in column (4), as in Johnson and Papageorgiou (2020). In columns (1) through (4), we assume homogeneity across countries in the impact of relative capital. In column (5), we relax this assumption and allow the coefficient of the explanatory variable to vary across the units of our panel sample. To estimate the parameters for each panel unit, we employ the Mean Group estimator, that is, we run the regression country by country and calculate the cross-sectional mean of the parameter b of (42) (see Pesaran and Smith 1995). Further, we introduce heterogeneity in the impact of un-observable shocks across countries in column (6). We approximate these with the cross-sectional means of all the variables in the model

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[11] In all regressions, the parameter that measures the speed of adjustment towards the long-run cointegration equilibrium is negative and significant indicating that there is a stable relationship (stochastic trend) governing the dynamics of the variables.

Table 4. Long-run estimation of the relationship between relative capital and GDP per capita growth (full sample).

	(1)	(2)	(3)	(4)	(5)	(6)
Relative capital	0.013^{***}	0.009^{**}	0.011^{***}	0.012^{***}	0.038^{***}	0.017^{**}
	(0.004)	(0.004)	(0.003)	(0.003)	(0.012)	(0.007)
Income per person	GDP p.c.	GDP p.w.	GDP p.c.	GDP p.c.	GDP p.c.	GDP p.c.
Population	No limit	No limit	>0.35 M	>1 M	>1 M	>1 M
Slope heterogeneity	No	No	No	No	Yes	Yes
Un-observable shocks	TD	TD	TD	TD	TD	CCE
Observation	9,350	8,503	8,545	7,804	7,804	7,216
R-squared	0.981	0.978	0.971	0.957	0.681	0.584
Number of countries	179	177	162	147	147	147

Long-run estimates derived from an Auto-Regressive Distributed Lags (ARDL) specification including country fixed effects and controls for un-observable shocks, namely time dummies (TD) or common correlated effects (CCE). The dependent variable is the annual rate of change in Gross Domestic Product per capita (GDP p.c.) or in Gross Domestic Product per worker (GDP p.w.). All right-hand side variables are in logs. Relative capital is the ratio between the US per person capital stock and that of the follower country. Population thresholds: 0.35 M (average population, 350,000 inhabitants); 1 M (average population, 1 million inhabitants). The lag order of the variables is set to four ($= T^{1/3}$, T is the number of time points of the analysis). Column (6) reports the mean group estimates robust to the outliers. Standard errors robust to heteroskedasticity and first-order autocorrelation in parentheses. ***, **, and * significant at 1%, 5%, and 10%.

(so-called Common Correlated Effects, CCEs) and, contrarily to when using dummy dummies, we allow the impact of these factors to change across economies.[12]

Our long-term regression analysis largely confirms the positive relationship between relative capital and income growth. Based on our benchmark estimates in column (4), a ten-percentage (one-off) difference (in logs) in the capital intensity between leader and follower would generate a 0.12 per cent faster rate of income growth for the latter. Notably, our benchmark estimates are conservative with respect to the results of the regressions that account for heterogeneity in slope coefficients (columns (5) and (6)). The results in column (6) are particularly important as they are obtained as means robust to outliers (see Bond, Leblebicioğlu, and Schiantarelli 2010), and hence mitigate the effect of countries with unusually large coefficients. The simple mean of individual coefficients would be 0.180 (S.E. 0.007), while the median value 0.019 (S.E. 0.008). Furthermore, it is important to observe that the regression in column (6) corresponds to an open-economy specification as it incorporates the cross-country (unweighted) means of both the dependent variable and the regressor (i.e., the CCE terms) to account for the effect of cross-sectional dependence. These additional terms capture the average disparity in rates of economic growth and capital accumulation between frontier and laggards, ensuring thus that the coefficient of relative capital does indeed reflect the impact of learning-by-investing spillovers.

Next, we examine how the results vary based on the capital intensity of the different groupings of countries (Table 5). Firstly, we exclude from this estimation those countries with a capital stock per person higher than USA for all the time horizon, $\kappa < 1$ (ten countries; column (2)). According to our model, these countries should not experience significant benefits from knowledge spillovers. The estimates in column (2) support this prediction, as they do not differ significantly from those in column (1) based on the larger sample. Secondly, we analyze the impact of relative capital on economies that have had capital intensity lower than the United States all along the time interval between 1950 and 2019, $\kappa > 1$ (116 countries; column (3)). These countries have not completed the catching-up process toward the frontier and hence can be considered as "ongoing followers." For these countries, relative capital has an effect in line with our previous estimates. Thirdly, we narrow down the regression analysis to economies that, starting from a lower input intensity, have achieved (or even surpassed) the level of capital stock per person of the leading economy during the sample period, $\kappa \rightarrow 1$ (21 countries; column (4)). For this group, hereinafter labelled as "completed catching-up" countries, the impact of relative capital is more pronounced, and this may explain their ability to catch up and reach the capital intensity of USA.

Following the anecdotal evidence presented in Fig. 2, in column (5) we acknowledge the possibility of a nonlinear relationship between relative capital and income growth. Our objective is to explore

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[12] The estimator used in column (6) corresponds to the cross-sectionally augmented ARDL approach studied by Chudik and Pesaran (2015). The coefficients of CCEs are omitted from the table for the sake of brevity.

Table 5. Long-run relationship between relative capital and GDP per capita growth by follower status.

	(1)	(2)	(3)	(4)	(5)
Relative capital	0.012***	0.012***	0.011***	0.020**	
	(0.003)	(0.003)	(0.003)	(0.008)	
Below threshold					0.038***
					(0.008)
Above threshold					0.012
					(0.013)
Threshold					4.3
Lower bound					3.4
Upper bound					5.8
Countries	All	Catching-up	Ongoing catching-up	Completed catching-up	All
Observation	7,804	7,294	6,073	1,221	7,808
R-squared	0.957	0.955	0.958	0.902	–
Number of countries	147	137	116	21	157

Long-run estimates derived from an Auto-Regressive Distributed Lags (ARDL) specification including country fixed effects and time dummies. The dependent variable is the annual rate of change in real Gross Domestic Product per capita (GDP p.c.). All right-hand side variables are in logs. Relative capital is the ratio between the US capital stock per capita and that of the follower country. Slope parameters are assumed homogeneous. The lag order of the variables is set to four ($= T^{1/3}$, where T is number of time points of the series). Estimates consider countries with an average population greater than one million inhabitants. Standard errors robust to heteroskedasticity and autocorrelation in parentheses. ***, **, and * significant at 1%, 5%, and 10%.

whether there exists a threshold for relative capital beyond which the effect of the factor on the growth rate of GDP per capita changes. We identify endogenously this threshold with the procedure developed by Kremer, Bick, and Dieter (2013) for panel dynamic regressions.[13] This estimation confirms the expectation of a positive relation between relative capital and GDP per capita growth only for countries with a relative capital intensity not too high, that is, with a gap in logged capital stock p.c. lower than the estimated value of 4.3. Beyond this threshold, no significant impact is found for our key regressor. This finding suggests that the difference in capital intensity between laggard and frontier economies should not be too wide, as otherwise the former would not be able to benefit from knowledge spillovers embedded in capital inputs. Below the identified threshold, relative capital is estimated with a long-run effect of 0.038, which is higher than what we run in the regression based on the full sample of countries assuming homogeneous slope parameters (columns (1)–(4)).

To evaluate the plausibility of the estimated threshold, in Fig. 3 we illustrate the quadratic interpolation of the country-specific coefficients derived from Mean Group regression underlying estimates in Table 4. The fit is plotted against the distribution of relative capital along our sample of countries. In order to provide a comprehensive analysis, we consider the distributions against minimum values (red), against mean values (green), and the maximum values (blue).[14] The shaded area in the graph represents the 95 per cent confidence interval for the quadratic fit over the mean value of the relative capital (green line). Notably, in all the three scenarios, the interpolation curve exhibits a bell-shaped pattern. Furthermore, the parameter distribution, conditionally to the mean, reaches its maximum around a value relative close to the estimated threshold of 4.3. Consistent with the predictions of our model, relative capital does not exhibit a statistically significant effect for those economies with a capital intensity similar to USA ($\kappa \sim 1$). In line with our estimates above, the parameter value of relative capital falls between 0.04 and 0.05 just below the threshold ($\kappa < 4.3$), and turns again insignificant for values of capital intensity exceeding the threshold ($\kappa > 4.3$).

Our theory posits that disparities in capital intensity relative to the frontier (κ "not much" larger than 1) should lead to higher levels of total factor productivity and income. Therefore, we re-assess the empirical model's results including these variables (Table 6). Column (1) presents our benchmark estimates shown above. In column (2), we consider the productivity value of each country relatively to the frontier's levels. In column (3), we introduce the lagged level of productivity as a control, following

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[13] Kremer, Bick, and Dieter (2013) apply the procedure devised by Hansen (1999) to dynamic panel data using forward orthogonal deviation transformations to remove fixed effects and preserve the distributional properties required for applying the original methodology, that was devised by static regressions.

[14] The graph restricts the sample to countries with relative capital intensity, κ_f, smaller or equal to 10, to exclude the possibility that those lying at the very bottom-end of the distribution, that may have an anomalous performance, affect the results of our analysis.

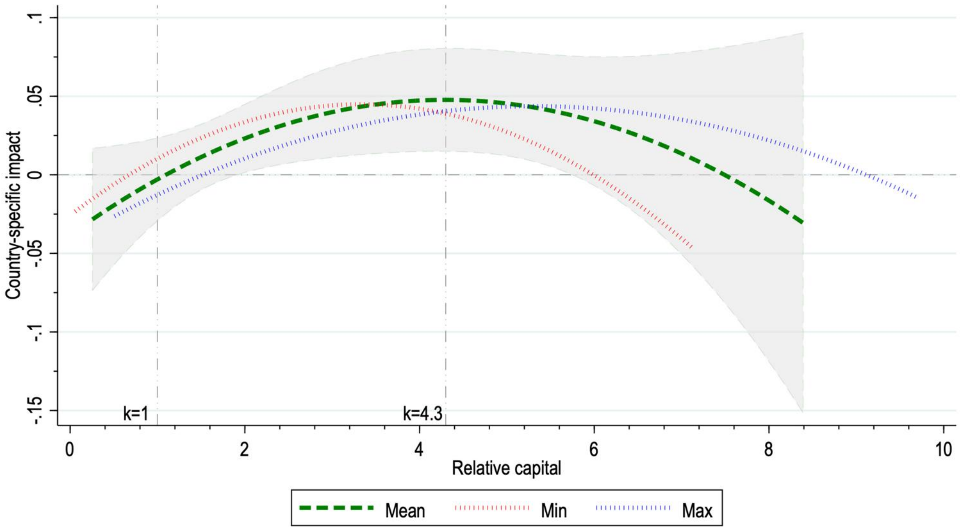

Figure 3. Growth effect of relative capital along the distribution and the threshold.

Quadratic regression fit of the country-specific (long-run) coefficients yielded by the regression robust-to-outliers reported in column (5), Table 4. The green line interpolates the long-run coefficients against the mean value of relative capital of each country. The red line uses the distribution of the minimum level of relative capital, whist the red line uses the maximum level. The shadowed area identifies the 95% confidence interval for the quadratic fit over the mean value of relative capital (green line). The graph restricts the sample to countries with a capital intensity smaller or equal to 10.

Equation (37) of the theoretical model. Columns (4) and (5) incorporate relative income (namely, GDP p.c.) and the lagged level of GDP p.c. In column (6), we combine both relative measures of productivity and income. Finally, the last two columns present the results for the baseline regression and the regression with controls for countries with a capital intensity not "too far" from the US levels (i.e., below the threshold of 4.3 for κ). Taken as a whole, the impact of relative capital weakens when controls are introduced, resulting insignificant in the regression focused on countries lying above the threshold ($\kappa < 4.3$). The coefficient size of relative productivity that emerges from these regressions is not far from estimates in earlier works (Kneller and Stevens 2006; Madsen, Islam, and Ang 2010). Estimates in the last two columns clearly indicate that differences in capital endowment translate into a positive income growth effects by closing the gap in income and productivity with the frontier. The former of these effects would be due to convergence via a differential rate of capital accumulation; the latter would be due to technology transfers via learning-by-investing of capital-embodied knowledge. This is in line with the evidence in Fig. A1.

4.3 Robustness regressions

As a first check, we assess the robustness of our main results to omitted variables. For instance, there could be some forms of disembodied knowledge, not incorporated in capital equipment, that spills over across economies and affect the rate of income growth, but that our regression model is not able to control for. In Table 7, we address this issue for countries below the threshold ($\kappa < 4.3$). In columns (2) and (3), we interact relative capital, respectively, with relative productivity and relative income. These two additional terms are not statistically significant, indicating that there are no unaccounted knowledge transfers, channeled by learning-by-investing processes between the leader and follower economies. In columns (4)–(7), we control for human capital and innovation capabilities, as well as the interplay between these variables and relative productivity. Since the latter is measured as the Distance to the Frontier (i.e., USA), it is hereinafter denoted as DTF for brevity. The index of human capital is sourced by PWT and reflects the years of primary, secondary and tertiary education across different population cohorts. Innovation capabilities are measured in terms of patent propensity, defined as ratio between patent applications, provided by the World Intellectual Property Office (WIPO), and the population level. Both measures of human capital and innovation are expressed as the inverse ratio to the levels observed in USA.

Table 6. Long-run estimation with controls, below and above the threshold ($\kappa = 4.3$).

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
						Below tde tdreshold ($\kappa < 4.3$)		
Relative capital	0.012***	0.005***	0.009***	−0.024***	−0.039***	−0.018***	0.027***	−0.006
	(0.003)	(0.002)	(0.003)	(0.005)	(0.005)	(0.002)	(0.008)	(0.004)
Relative productivity (DTF)		0.009*				0.054***		0.036***
		(0.005)				(0.006)		(0.007)
Productivity level (1-yr lag)			0.022***					
			(0.006)					
Relative income				0.060***		0.052***		0.053***
				(0.005)		(0.003)		(0.005)
Income level (1-yr lag)					−0.089***			
					(0.006)			
Observation	7,804	5,509	5,509	5,509	5,509	5,509	3,231	3,155
R-squared	0.957	0.260	0.624	0.251	0.916	0.251	0.960	0.237
Number of countries	147	110	110	110	110	110	73	68

Long-run estimates derived from an Auto-Regressive Distributed Lags (ARDL) specification including country fixed effects and time dummies. The dependent variable is the annual rate of change in real Gross Domestic Product per capita (GDP p. c.). All right-hand side variables are in logs. Relative capital (or TFP or GDP p.c.) is the ratio between the US level of per capita stock (or productivity or GDP p.c.) and the corresponding value of the follower country. DTF denotes distance to frontier (or relative productivity with respect to the US). Slope parameters are assumed as homogeneous. The lag order of the variables is set to four ($= T^{1/3}$, where T is number of time points of the series). Estimates consider countries with an average population greater than one million inhabitants. Standard errors robust to heteroskedasticity and autocorrelation in parentheses. ***, **, and * significant at 1%, 5% and 10%.

Table 7. Long-run estimation controlling for disembodied knowledge spillovers, below the threshold ($\kappa < 4.3$).

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
								Below median κ	**Above median** κ
Relative capital	−0.006	−0.012***	−0.005	−0.011**	−0.009***	−0.008*	−0.006**	−0.015**	−0.002
	(0.004)	(0.004)	(0.007)	(0.005)	(0.003)	(0.005)	(0.003)	(0.007)	(0.006)
Relative productivity (DTF)	0.036***	0.043***	0.034***	0.046***	0.046***	0.035***	0.031***	0.046***	0.035***
	(0.007)	(0.013)	(0.007	(0.009)	(0.008)	(0.007)	(0.005)	(0.010)	(0.010)
Relative income	0.053***	0.057***	0.048***	0.057***	0.057***	0.059***	0.060***	0.068***	0.045***
	(0.005)	(0.006)	(0.007)	(0.006)	(0.004)	(0.006)	(0.004)	(0.009)	(0.006)
Relative capital × DTF		−0.005							
		(0.007)							
Relative income × Relative income			0.005						
			(0.007)						
Relative human capital				−0.048***	−0.051***				
				(0.017)	(0.011)				
Relative human capital × DTF					0.006				
					(0.019)				
Relative patenting						−0.003***	−0.003***		
						(0.001)	(0.001)		
Relative patenting × DTF							0.001		
							(0.002)		
Observation	3,155	2,841	2,841	2,841	2,755	2,805	2,719	1,680	1,475
R-squared	0.237	0.212	0.222	0.206	0.223	0.211	0.233	0.251	0.222
Number of countries	68	54	54	54	51	53	50	34	34

Long-run estimates derived from an Auto-Regressive Distributed Lags (ARDL) specification including country fixed effects and time dummies. The dependent variable is the annual rate of change in real Gross Domestic Product per capita (GDP p. c.). All right-hand side variables are in logs. Relative capital (or TFP or GDP p.c. or human capital or patenting) is the ratio between the US level of per capita stock (or productivity or GDP p.c. or human capital or patents) and the corresponding value of the follower country. DTF= Distance to frontier (relative productivity). Slope parameters are assumed as homogeneous. The lag order of the variables is set to four ($= T^{1/3}$, where T is number of time points of the series). Estimates consider countries with an average population greater than one million inhabitants and an average relative capital intensity lower than the threshold ($\kappa < 4.3$). Standard errors robust to heteroskedasticity and autocorrelation in parentheses. **, **, and * significant at 1%, 5% and 10%.

The main effect of these variables should capture transfers from the frontier of knowledge (so-called disembodied) which depends on cross-country differentials in educational levels and technology base. Conversely, the interaction between these measures with the DTF should reveal whether technology transfers are easier for countries with higher or lower levels of production efficiency (relative TFP). The results indicate that the gap in the endowment of knowledge inputs (human capital and patenting) does not translate into an income growth premium. Rather, in line with endogenous growth theories (Lucas 1988; Romer 1990; Aghion and Howitt 1992), a greater difference in these inputs is found to widen the gap in the growth rate of GDP per capita between the leader and follower economy. Additionally, the interaction terms between knowledge inputs and the DTF are insignificant, leaving unchanged the pattern of long-run effects associated with relative productivity and income.

Further, we investigate whether countries experience different gains from relative capital, depending on their structural differences. Some countries may not share the same technology with the frontier and have a persistently high capital intensity ratio, κ. To address this, we replicate our benchmark regression (column (1)) by dividing countries into two groups based on their average relative capital: those below and above the median value of κ (column (8) and (9)). The idea is that countries with a capital intensity closer to that of USA (i.e., below the median value of κ) may benefit more from knowledge spillovers, leading to faster income growth and convergence. The results of Table 7 mildly support this expectation, as the coefficient sizes of our key regressors are slightly larger for the former group of countries. Note that our estimates remain robust even after controlling for trade openness (export/GDP), returns to capital (internal interest rate), and capital obsolescence (average depreciation rate; source: PWT 10.0). These additional checks are not included here for the sake of brevity, but are available from the authors upon request.

One may wonder whether our results are robust to, or can help explain, other growth patterns recently identified in the literature. In particular, significant attention has been given to growth spells or accelerations—episodes in which GDP growth rates deviate from their long-term trends (Pritchett 2000). The high volatility of in the rate of change of GDP per capita in these economies reflects underlying instability in their fundamentals, which, in turn, reduces the effectiveness of standard growth drivers. Growth spells, which are common to most least-developed countries, tend to be recurrent in these economies, making their duration the primary factor contributing to their negative impact (Hausmann, Pritchett, and Rodrik 2005). In the context of our analysis, it is crucial to determine whether the learning-by-investing mechanism and the capital threshold we have identified reflect the intrinsic characteristics of economies with unstable growth. These economies are likely to be concentrated at the lower end of the capital (income) distribution, where such instability may reinforce persistent underdevelopment.

In Table 8, we examine whether the effect of relative capital on income growth is influenced by growth spells. Specifically, we reestimate the main regressions from the previous table, using a measure of growth spells as the dependent variable. Following Pritchett et al. (2016), we define growth spells as absolute deviations from the world's average rate of change in GDP per capita. We distinguish between temporary and persistent deviations, with the latter defined as those lasting at least five consecutive years. This analysis is conducted separately for countries below and above the capital threshold κ to determine whether the threshold emerges as a consequence of income growth instability, whether conversely growth spells arise due to a lack of international knowledge transfer, or whether these processes are unrelated. Our main finding—that relative capital drives increases in relative income, likely through embodied knowledge spillovers—is largely confirmed. However, these regressions offer additional insights. First, below the threshold, technology transfers from the frontier appear unrelated to long-lasting growth spells, as indicated by the insignificance of the relative productivity parameter in column (4). Above the threshold, the factors driving income growth (column (6)) and growth spells (columns (6) and (7)) are similar. Overall, this evidence supports the validity of the threshold in distinguishing different development regimes, identifying the range of countries where investment and learning-by-investing remain crucial drivers of growth.

Another well-established finding in the literature is that income distribution exhibits a degenerate pattern, with heterogeneous convergence dynamics across groups of countries. This has historically fueled two main lines of research: one on convergence clubs and another on the distributional properties of global income growth (Quah 1997; Canova 2004). These studies examine whether countries with

Table 8. Long-run estimation of income growth and growth spells.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Below the threshold ($\kappa < 4.3$)				Above the threshold ($\kappa > 4.3$)			
Dep. variable	**Income growth**		**Growth spells All**	**Growth spells > 5 years**	**Income growth**		**Growth spells All**	**Growth spells > 5 years**
Relative capital	0.028***	−0.006	−0.008*	−0.000	0.001	−0.026***	−0.029***	−0.030***
	(0.008)	(0.004)	(0.004)	(0.004)	(0.003)	(0.005)	(0.004)	(0.005)
Relative productivity		0.036***	0.037***	0.001		0.077***	0.087***	0.075***
		(0.007)	(0.007)	(0.007)		(0.012)	(0.012)	(0.013)
Relative income		0.053***	0.058***	0.039***		0.054***	0.059***	0.058***
		(0.005)	(0.005)	(0.005)		(0.007)	(0.007)	(0.008)
Observation	3,830	3,155	3,100	3,155	3,885	2,017	1,961	2,017
R-squared	0.967	0.237	0.489	0.618	0.947	0.275	0.570	0.692
Number of countries	87	68	68	68	84	44	43	44

Long-run estimates derived from an Auto-Regressive Distributed Lags (ARDL) specification including country fixed effects and time dummies. The dependent variable is the annual rate of change in real Gross Domestic Product per capita (GDP p. c.) in column (1)-(2), and (5)-(6), and the excess of GDP p.c growth over the annual world average in columns (3)-(4) and (7)-(8). Regressions in column (4) and (8) considers episodes of growth spells of more than 5 years. All right-hand side variables are in logs. Relative capital (or TFP or GDP p.c. or human capital or patenting) is the ratio between the US level of per capita stock (or productivity or GDP p.c. or human capital or patents) and the corresponding value of the follower country. Slope parameters are assumed as homogeneous. The lag order of the variables is set to four,= $T^{1/3}$), where T is number of time points of the series. Estimates consider countries with an average population greater than one million inhabitants, an average relative capital intensity lower than the threshold ($\kappa < 4.3$) in columns (1)-(4), and relative capital intensity higher than the threshold ($\kappa > 4.3$) in columns (5)-(8). Standard errors robust to heteroskedasticity and autocorrelation in parentheses. ***, **, and * significant at 1%, 5% and 10%.

similar economic or institutional fundamentals tend to self-select and converge toward the same equilibrium, as well as which distribution best characterizes global income growth. Depending on a country's position within the distribution, the forces driving economic growth may vary. In robustness checks (Table A1 of Supplementary Appendix E), we run a quartile dynamic regression and further document that relative capital is a key driver of income growth: this factor fuels relative income convergence for countries at the lower end of the income growth distribution: these countries likely have lower GDP per capita and remain well below the threshold κ.

5. Discussion

This section highlights the relevance of our findings in explaining leapfrogging phases across different country groups. we start by providing anecdotal examples that illustrate the connection between the magnitude of the technology gap—proxied by the relative capital stock per worker—and the emergence of a country's convergence process. Then, we discuss the policy interventions derived from our analysis.

5.1 Technology acquisition and convergence: country evidence

Our analysis classified countries into groups according to their capital intensity relative to the frontier. A first group comprised countries whose capital intensity was permanently higher than that of the U. S., keeping them below the threshold ($\kappa < 1$ in all years) and therefore outside the scope of our study. A second group consisted of diverging economies characterized by persistently low capital intensity, remaining above the threshold ($\kappa = 4.3$, or 1.45 in logs), denoted as "no-catching-up." A third group encompassed "ongoing catching-up" economies, which initially had capital intensity slightly above the threshold but gradually reduced much of their income gap with the frontier. Finally, some economies started below the frontier in terms of capital intensity, but eventually completed the catching-up process.

Figure 4 shows the dynamics of the log of relative capital stock per worker, κ_f, and relative income per capita, $\log(y_\ell/y_f)$, for four representative countries: Pakistan (no-catching-up), China (ongoing

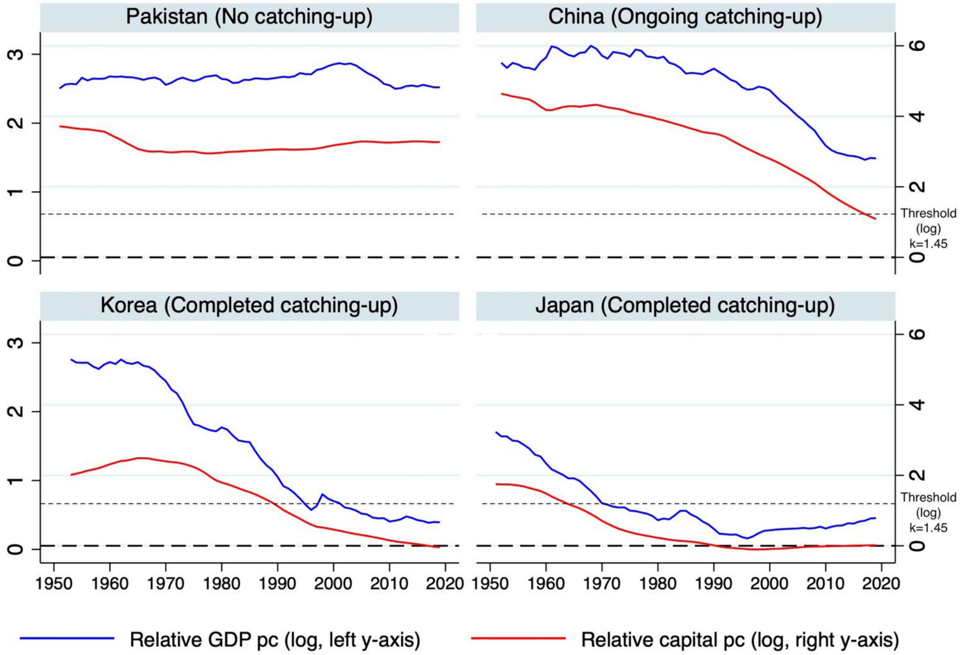

Figure 4. Relative capital stock per worker dynamics in China, Japan, South Korea, and Taiwan. Data for κ are displayed in logarithmic scale, with $\log(\kappa_f) = 0$ indicating completed convergence. Relative capital threshold = 1.45 (in logs); 4.3 in absolute terms.

catching-up), and Japan and South Korea (completed catching-up). The figure highlights starkly different trajectories. Pakistan exhibits no convergence, reflecting its failure to reduce the technology gap. By contrast, Japan and South Korea experienced sustained capital deepening, enabling full convergence, while China has reached an advanced stage and is approaching completion.

A crucial finding is that the evolution of the income gap mirrors that of relative capital, and that convergence concludes, with relative income becoming stationary, once relative capital falls below the threshold. Countries cross this point at different times: Japan in the early 1960s, South Korea in the mid-1980s, and China in the early 2010s. After crossing, each economy began developing leading technologies in key sectors, with the role of government diminishing and private firms emerging as the main drivers of development.

Japan's trajectory exemplifies this process. Following decades of overseas knowledge acquisition (Odagiri and Goto 1996), Japan became a leader in consumer electronics in the 1960s, in automobiles in the 1970s and 1980s (Watanabe and Honda 1992), and in robotics and precision manufacturing in the 1980s (Kumaresan and Miyazaki 1999; Dekle 2020). South Korea's "Miracle on the Han River" followed a similar pattern, beginning with shipbuilding in the 1980s (Kim 1991), expanding into electronics and automobiles in the 1990s, and achieving global leadership in semiconductors and display technology by the 2010s (Soh, Koh, and Aridi 2023). China's trajectory has been more recent: from e-commerce, renewable energy, and high-speed rail leadership in the 2010s (Gaida et al., 2024), to advances in 5G (Harwit 2023), biotechnology, and electric vehicles, and artificial intelligence in the 2020s (Allison et al., 2021; Bazavan and Huidumac-Petrescu 2023; Atkinson 2024).

5.2 Policy implications

Our results underscore the importance of sustained physical capital accumulation—whether domestically produced or imported—and the absorption of embodied knowledge as engines of growth.[15] Three types of policies follow: (1) public incentives for capital formation or reduced barriers to investment,

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[15] For analyses of fiscal policy in AK models, see Aghion and Howitt (1998), Barro and Martin (2004), Jones and Manuelli (2005) in closed economies, and Turnovsky (2011) in open economies.

(2) openness to capital goods imports, and (3) education and training policies that enhance absorptive capacity.

Governments can adapt these policies to their stage of development. Economies with low capital intensity (above the threshold) may require temporary tax incentives for investment and greater trade openness. Where openness has already been maximized, fiscal incentives should be maintained over longer horizons. In either case, successful absorption of embodied knowledge depends on a workforce capable of adapting to new technologies, making technical education, and vocational training crucial.

For countries below the threshold or approaching the near-frontier equilibrium, policies should prioritize domestic innovation and productivity growth by reforming institutions and market structures, as their income gaps stem more from high adoption costs than from technological limitations.

6. Concluding remarks and future extensions

In this article, we developed a growth framework with endogenous cross-country knowledge diffusion through learning-by-investing and technology adoption. We showed that the model reproduces the main long-run growth patterns and income convergence documented in the literature and validated its predictions using a broad sample of industrialized, developing, and underdeveloped economies.

Our results highlight the central role of differences in capital intensity in explaining cross-country disparities in income growth. Capital accumulation facilitates the absorption of technological knowledge and promotes convergence, but only when the relative capital gap vis-à-vis the frontier remains below a critical threshold. Using ARDL techniques, we estimate this threshold and find that knowledge transfers are highly likely when a follower country's relative capital stock lies within, approximately, twenty-five.

We further establish, through extensive robustness checks, that international technology diffusion is not primarily driven by cross-country variation in human capital or innovation inputs. Instead, our findings indicate that embodied learning-by-investing constitutes the dominant channel of convergence for countries that are lagging behind yet remain sufficiently close to the technological frontier. Importantly, the framework developed in this article is also consistent with episodes of renewed divergence. When shocks, structural changes, or institutional weakening widen the capital gap beyond the adoption threshold, follower economies may again be excluded from frontier knowledge spillovers, leading to divergence even after periods of convergence. This mechanism offers a coherent interpretation of recent observations suggesting that the global convergence process has become more uneven and heterogeneous across country groups.

Although analytically tractable, our analysis rests on simplifying assumptions that open several avenues for future research. First, the model assumes a single global technological leader driving frontier knowledge. However, Debarsy and Ertur (2019) identify one global leader (USA) alongside two regional leaders (Germany and Japan). Extending the framework to incorporate multiple technological leaders would allow for a richer representation of heterogeneous diffusion channels and the emergence of regional convergence clubs.

Second, the structure of international technological interdependence is captured in reduced form. A more detailed treatment would model the complex interactions between leaders and followers within a dynamic global network, potentially calibrated using trade-flow-based interaction matrices and empirical measures of technological connectedness (Fronzetti Colladon et al., 2024).

Finally, the framework abstracts from changes in the composition of capital, particularly the rising importance of intangible assets (Corrado et al., 2022). Intangibles—such as software, R&D, and brand equity—typically involve sunk costs, scale effects, and firm specificity (Haskel and Westlake 2018), which may limit their effectiveness as carriers of embodied international spillovers. Understanding whether, and through which channels, intangible investment contributes to cross-country technology diffusion remains an important avenue for future research.

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Supplementary data

Supplementary data are available at *Journal of Economic Geography* online.

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