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GROWTH AND CONVERGENCE THROUGH TECHNOLOGICAL INTERDEPENDENCE

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This paper presents a multi-country version of the Ramsey growth model with cross-country technological interdependence. The results rationalize several stylized facts about growth and convergence. First, individual countries tend to converge toward country-specific balanced growth paths rather than steady-state equilibria. Second, an economy that accounts for a smaller share of the world technology distribution harnesses the "advantages of backwardness" to catch up at a faster speed. Third, countries grow at different rates during the phase of transitional dynamics. However, technological interdependence creates a force toward cross-country convergence in the growth rate and stability of world income distribution in the long run. Finally, cross-country differences in structural characteristics and initial conditions lead to divergences in the level of income per capita.

Keywords: Convergence, Endogenous Growth, Technological Interdependence, Advantages of Backwardness

1. INTRODUCTION

The highly globalized world economy shows an overarching trend toward cross-country technological interdependence, where individual countries are simultaneously inventing and adopting each others technologies [e.g., European Commission (2013)]. In a world economy with technological interdependence, technological progress and economic growth in an individual country is not only a direct outcome of the fundamentals of its own but also depends on the characteristics of all other countries. This observation suggests that a better approximation of this reality might need a framework in which world technology depends on the

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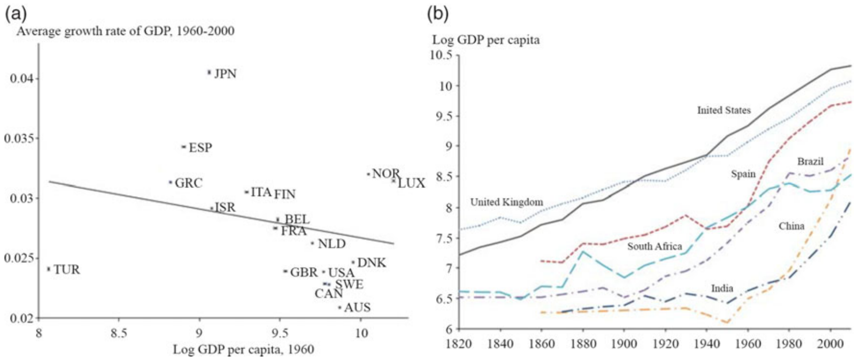

Source: OECD (2014) and World Bank (2017).

FIGURE 1. (a) Annual growth rate of GDP per capita between 1960 and 2000 versus log GDP per capita in 1960 for core Organisation for Economic Co-operation and Development (OECD) countries; (b) The evolution of income per capita in major economies, 1820-2000.

innovation efforts of all technologically interconnected countries, rather than on a single technology frontier country. For the analysis of growth and convergence in an interdependent world economy, the model incorporating cross-country technological interdependence provides a more satisfactory framework than the one with unidirectional technology diffusion from a single world frontier country [e.g., Nelson and Phelps (1966), Parente and Prescott (1994), Chu et al. (2014), Stokey (2015)].

This paper contributes to an analysis of growth and convergence through the lens of cross-country technological interdependence.[1] In doing that, we aim to rationalize the following stylized facts as shown in Figure 1. First, income per capita tends to increase along country-specific endogenous growth paths rather than to converge toward a common growth path or steady state. Second, an economy that, initially, had a low level of income tends to grow faster, and the correlation between the growth rate and the initial level is negative—the so-called β*-convergence* [e.g., Baumol (1986), Barro and Sala-i-Martin (1992), Galor (1996), Caselli et al. (1996)]. Third, although countries grow at different rates during transitional periods, there are more limited differences in sustained growth rates over recent years. Potential forces might exist in the world economy to ensure a relatively similar growth rate. Fourth and finally, the disparity in country-specific characteristics and initial conditions (e.g., preferences, technologies, population) could lead to cross-country divergence in the income level—the phenomenon coined as *club convergence* [e.g., Galor (1996), Azariadis (1996), Quah (1997)].[2]

We present a multi-country version of the Ramsey growth model, incorporating cross-country technological interdependence. Countries are technologically interdependent in the sense that the technology of individual economies both contributes to, and benefits from, a world technology pool. Technology diffusion from the world technology pool is determined by all technologically interdependent countries, rather than by a single world technology frontier that grows autonomously. This explicit account of cross-country technological interdependence is the main departure from the existing literature on technology diffusion and growth [e.g., Parente and Prescott (1994); Barro and Sala-i-Martin (1997); Chu et al. (2014); Benhabib et al. (2014); Stokey (2015); Acemoglu et al. (2006)].[3]

We show that the technologically interdependent world equilibrium is neither simply the equilibrium of each country on its own nor the equilibrium generated by unidirectional technology diffusion from a single frontier country. With cross-country technological interdependence, individual countries tend to grow along their country-specific balanced growth path, rather than converge toward the world technology frontier. A country with a wider technology gap can catch up at a faster rate by taking advantage of a greater amount of untapped knowledge in the rest of the world (RoW)—the so-called "advantages of backwardness" [e.g., Gerschenkron (1962), Rosenberg (1982), Abramovitz (1986)]. During the phase of transitional dynamics, individual countries grow at different rates, but the differences in growth rates are narrowing over time and will converge in the long run. Technological interdependence generates a pulling force to ensure cross-country convergence in growth rates. In particular, the common growth rate for cross-country convergence is endogenously determined by structural characteristics of all technologically interdependent countries rather than a single world frontier economy that grows autonomously. These results rationalize the stylized fact of convergence in growth rates as in Howitt (2000), Acemoglu and Ventura (2002), and Howitt and Mayer-Foulkes (2005).

The technologically interconnected world economy has a stable long-run distribution in technology and income that depends on the structural characteristics of all individual countries. An economy with greater indigenous innovation efficiency and knowledge absorption capacity tends to account for a larger share in the world distribution. Meanwhile, when other countries enhance the indigenous innovation efficiency and knowledge absorptive capacity, the country under consideration will end up with a smaller share in the world distribution. The long-run trend in the world income distribution depends only on fundamental characteristics, independently of initial conditions. This result is consistent with the insights offered in the seminal paper of Acemoglu and Ventura (2002).

The pulling force in the interconnected world economy, working through technological interdependence, creates a force toward convergence in the growth rate. However, cross-country differences in both fundamental characteristics and initial conditions lead to divergences in the level of technology and income. This result coincides with the evidence of σ-convergence: the level of income per capita diverges across countries over time [e.g., Bernard and Durlauf (1995, 1996), Quah (1996, 1997)]. While having an initial wider technology gap can generate a faster pace of catch-up ("advantage of backwardness"), an economy with inferior country-specific characteristics and initial conditions (e.g., lower indigenous innovation efficiency, weaker knowledge absorptive capacity, and lower initial technology levels) would end up with a lower level of technology and income per capita in the long run. This result provides an informed interpretation of the *club convergence*: income levels tend to converge to one another only among countries with similar structural characteristics and initial conditions but diverge between countries with quite different ones [e.g., Galor (1996), Azariadis (1996), Howitt (2000), Acemoglu and Ventura (2002), Howitt and Mayer-Foulkes (2005)].

Related Literature. This paper relates mostly to the influential studies on the distance to frontier, catching up, and convergence. Nelson and Phelps (1966) provide an early contribution of technology diffusion and growth where technology diffusion depends on human capital investment and the technology gap relative to the world technology frontier. Parente and Prescott (1994) propose a theory of economic development in which domestic barriers that retard the inflow of technology from the world frontier account for the income disparity across countries. Barro and Sala-i-Martin (1997) find that a follower grows relatively fast and tends to catch up to the leaders by imitation, which is cheaper than invention. As the pool of copiable technology decreases, the costs of imitation tend to rise, and the followers growth rate tends to fall. Hence, a pattern of conditional convergence emerges in this model of the diffusion of technology. Acemoglu et al. (2006) show that certain institutional arrangements and policies that might initially increase the growth and speed of convergence could then lead to slower growth and failure to converge to the world technology frontier. Benhabib et al. (2014) present a stylized model of distance to frontier, in which countries choose a portfolio of innovation and imitation that facilitates technology diffusion from the world frontier for domestic productivity improvement. Stokey (2015) shows that the economy might either keep path with the technology frontier (sustained growth) or converge to a minimal technology level that is independent of the world frontier (stagnation). Chu et al. (2014) develop a Schumpeterian growth model in which economic growth in the developing country is driven by both domestic innovation and transfers of foreign technologies from the world technology frontier. Acemoglu et al. (2017) analyze asymmetric growth and institutions in an interdependent world based on a model of technologically interconnected countries. Building on Schumpeterian growth models with technology transfers, Aghion and Howitt (1998), Howitt (2000), and Howitt and Mayer-Foulkes (2005) show that countries that converge to a common growth rate tend to have different productivity levels. These seminal works consider technology diffusion from a single world technology frontier that grows autonomously. In contrast, the focus of this paper is on cross-country technological interdependence. The world technology is determined by all interdependent countries rather than a single frontier one.[4]

This paper also connects with the literature on technology diffusion and adoption. Eaton and Kortum (1996, 1999, Eaton and Kortum (2001)) estimate

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the direction and magnitude of international technology diffusion. Caselli and Coleman (2001) examine the determinants of computer technology adoption. The linkages between productivity, technology adoption lags, and intensity of technology use are examined by, among others, Zeira (1998), Basu and Weil (1998), Acemoglu and Zilibotti (2001), Comin and Hobijn (2004, 2010), Schafer and Schneider (2015), Alesina et al. (2018), and Comin and Mestieri (2018). This strand of literature focuses on the process of technology diffusion and adoption, and the representations of linkages between technology diffusion and economic growth are parsimonious. In contrast, our analytical framework tends to be more disaggregated and provides richer specifications of the linkage between technology diffusion, growth, and convergence.

Layout. The rest of this paper is organized as follows. Section 2 presents the model. Section 3 characterizes the world equilibrium. Section 4 gives analytical results of growth and convergence. Section 5 provides calibrated simulations. Section 6 tests the theory empirically. Section 7 concludes.

2. THE MODEL

The framework builds on a multi-country version of the Ramsey growth model developed by Acemoglu (2009, Chapter 18), in which individual countries assimilate technology diffusion from a single world frontier country that grows autonomously at an exogenous rate. We differentiate our model by introducing cross-country technological interdependence, in which individual countries are technologically interdependent by simultaneously inventing and absorbing each other's technologies.[5] For a given country, technology diffusion from the RoW is determined by characteristics of all other countries, rather than by a single technology frontier country. Our explicit account of cross-country technological interdependence is the main departure from the existing literature which focus on unidirectional technology diffusions from a single world frontier country [e.g., Parente and Prescott (1994), Barro and Sala-i-Martin (1997), Acemoglu et al. (2006), Chu et al. (2014), Benhabib et al. (2014), Stokey (2015)].

Demographics and Preference. The world economy consists of J countries, indexed by $j = 1, 2, ..., J$. Each country admits a representative household. The number of populations within each representative household in country j at time t is given by $L_j(t) = L_j(0)\exp(n_j t)$, where $n_j := \dot{L}_j/L_j$ is the rate (constant) of population growth and $L_j(0) = 1$ the normalized initial condition.

The intertemporal utility is given by $\int_0^\infty \exp(-\rho_j t)L_j(t)u(c_j(t))dt$, where $u(.)$ is the instantaneous utility function. The household in the economy j at time t has an asset holding of $B_j(t)$ and the corresponding law of motion is given by $\dot{B}_j(t) = r_j(t)B_j(t) + w_j(t)L_j(t) - c_j(t)L_j(t)$, where $r_j(t)$ is the rate of return on assets, and $w_j(t)L_j(t)$ labor income earnings. Define by $b_j(t) := B_j(t)/L_j(t)$ the per capita assets, the law of motion for the asset holding is rewritten as $\dot{b}_j(t) = (r_j(t) -$

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$n_j)b_j(t) + w_j(t) - c_j(t)$. With a constant relative risk aversion utility function, the problem of the representative household in the economy j thus reads

$$\max_{[c_j(t),b_j(t)]_{t=0}^{\infty}} \int_0^{\infty} \exp(-(\rho_j - n_j)t)\frac{c_j(t)^{1-\theta_j} - 1}{1-\theta_j}dt \quad s.t.$$
$$\dot{b}_j(t) = (r_j(t) - n_j)b_j(t) + w_j(t) - c_j(t), \tag{1}$$

where $c_j(t) := C_j(t)/L_j(t)$ is the consumption per capita, ρ_j is the discount rate, and θ_j is the coefficient of relative risk aversion.

Production and Capital Accumulation. Each country admits a representative firm producing final goods with an aggregate production function as follows:

$$Y_j(t) = F\left(K_j(t), A_j(t)L_j(t)\right), \tag{2}$$

where $Y_j(t)$ and $K_j(t)$ are the outputs and physical capital stocks in country j at time t, respectively. The households supply labor $L_j(t)$ inelastically. The labor-augmenting technology, $A_j(t)$, is a country-specific and time-varying endogenous variable. The production technology $F(.,.)$ satisfies the standard neoclassical assumptions and exhibits constant returns to scale. We proceed by defining the income per capita:

$$y_j(t) := \frac{Y_j(t)}{L_j(t)} = \frac{A_j(t)L_j(t)}{L_j(t)}F\left(\frac{K_j(t)}{A_j(t)L_j(t)}, 1\right) = A_j(t)f(k_j(t)), \tag{3}$$

where $k_j(t) := \frac{K_j(t)}{A_j(t)L_j(t)}$ is the effective capital–labor ratio, and $f(k_j(t)) := F\left(\frac{K_j(t)}{A_j(t)L_j(t)}, 1\right)$ is the intensive form of the production function. Hence, the firm solves a problem of profit maximization as follows:

$$\max_{[K_j(t),L_j(t)]_{t=0}^{\infty}} F\left(K_j(t), A_j(t)L_j(t)\right) - R_j(t)K_j(t) - w_j(t)L_j(t), \tag{4}$$

where the firm optimally chooses capital stocks $K_j(t)$ and labor $L_j(t)$ to maximize profits given the rental rate of capital $R_j(t)$, the wage rate $w_j(t)$, and the labor-augmenting technology $A_j(t)$ in country j at time t. Given the production technology in (2), the stock of physical capital in country j is accumulated as follows:

$$\dot{K}_j(t) = F(K_j(t), A_j(t)L_j(t)) - C_j(t) - \delta_j K_j(t), \tag{5}$$

where δ_j is the rate of capital depreciation.

Technological Interdependence. Following the seminal works of Comin and Hobijn (2010) and Comin and Mestieri (2018), we consider that technological progress is driven by both undertaking indigenous innovation and absorbing foreign technology diffusion.[6] Hence, the law of motion for the technology in

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country j at time t is specified as follows:

$$\dot{A}_j(t) = \lambda_j A_j(t) + \sigma_j (A_{WTP}(t) - A_j(t)) = \lambda_j A_j(t) + \sigma_j \left(\sum_{i=1}^{J} A_i(t) - A_j(t) \right). \quad \textbf{(6)}$$

Here, the effect of indigenous innovation depends on the efficiency parameter λ_j and the existing technology level $A_j(t)$. The higher the current level of technology, the faster the pace of technological progress—the "standing on the shoulders of predecessor" effect [e.g., Romer (1990), Jones (1995, 1999)]. Meanwhile, technology diffusion is determined by knowledge absorptive capacity, σ_j, and the untapped technology in the world technology pool (WTP), $A_{WTP}(t) - A_j(t)$. In a technologically interdependent world economy, all individual countries feature complementary patterns of innovation specialization and thus contribute to the world technology as given by $A_{WTP}(t) = \sum_{i=1}^{J} A_i(t)$.[7] This specification is the point of departure from the existing literature that focuses on unidirectional technology diffusions from a single world frontier country.

Each country benefits from technology diffusion by assimilating untapped technology from the RoW according to the technology gap, $A_{WTP} - A_j$. A larger technology gap creates a greater amount of diffusion from the external world that potentially favors domestic technological progress—the "advantage of backwardness" proposed by Gerschenkron (1962). However, the "advantage of backwardness" does not necessarily mean that a country with a larger technology gap can absorb all untapped knowledge from abroad and immediately catch up. In fact, only part of the technologies available in the RoW can be absorbed effectively according to the country-specific knowledge absorptive capacity σ_j. In other words, a weaker knowledge absorptive capacity becomes an inhibitor that slows the effective adoption of technology diffusion, even if a greater amount of untapped technology is accessible in the external world [e.g., Zeira (1998), Comin and Hobijn (2004), Comin and Mestieri (2018), Alesina et al. (2018)]. λ_j and σ_j are country-specific, reflecting cross-country differences in structural characteristics.

The World Equilibrium. For the above-described growth model with cross-country technological interdependence, the world equilibrium is defined by the allocations $[c_j(t), b_j(t), K_j(t), L_j(t), A_j(t), R_j(t), w_j(t)]$ in country $j = 1, 2, ..., J$ at time $t \in [0, \infty)$, such that

i. The household chooses consumption and asset allocations $\left\{[c_j(t), b_j(t)]_{t=0}^{\infty}\right\}_{j=1}^{J}$ to maximize intertemporal utility subject to the budget constraint given by (1);
ii. The firm chooses capital and labor $\left\{[K_j(t), L_j(t)]_{t=0}^{\infty}\right\}_{j=1}^{J}$ to maximize profits given by (4);
iii. The stock of capital $\left\{[K_j(t)]_{t=0}^{\infty}\right\}_{j=1}^{J}$ is accumulated according to (5);
iv. The labor-augmenting technology $\left\{[A_j(t)]_{t=0}^{\infty}\right\}_{j=1}^{J}$ evolves according to (6);

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v. The rental rate of capital and the wage rate $\left\{[R_j(t), w_j(t)]_{t=0}^{\infty}\right\}_{j=1}^{J}$ are such that both capital and labor markets clear. The asset holding by the household is equal to the capital stock used by the firm, and the labor supplied by the household is equal to the labor demanded by the firm.

3. CHARACTERIZATION OF THE WORLD EQUILIBRIUM

Technology Gap. For analytical tractability, we define the proportional technology gap of country j relative to the world technology by:

$$a_j(t) := \frac{A_j(t)}{A_{WTP}(t)}, \tag{7}$$

where $a_j(t)$ is the share of country j in the world technology distribution. The law of motion for the technology (6) is thus rewritten by:

$$\dot{a}_j(t) = \sigma_j - \left(\sigma_j - \lambda_j + g_{WTP}(t)\right) a_j(t), \tag{8}$$

where the rates of technological progress specific to the world and an individual country are given, respectively, by:[8]

$$g_{WTP}(t) := \frac{\dot{A}_{WTP}(t)}{A_{WTP}(t)} = \sum_{j=1}^{J} \left(\left(\lambda_j - \sigma_j\right) a_j(t) + \sigma_j\right),$$

$$g_j(t) := \frac{\dot{A}_j(t)}{A_j(t)} = \lambda_j + \sigma_j \left(\frac{1}{a_j(t)} - 1\right). \tag{9}$$

Combining (8) with (9), the law of motion for the proportional technology gap is determined by:

$$\dot{a}_j(t) = \sigma_j - \left(\sigma_j - \lambda_j + \sum_{j=1}^{J} \left(\left(\lambda_j - \sigma_j\right) a_j(t) + \sigma_j\right)\right) a_j(t). \tag{10}$$

Effective Capital–labor Ratio. Define consumption per effective unit of labor in country j at time t as $\bar{c}_j(t) := \frac{C_j(t)}{A_j(t)L_j(t)}$. The law of motion for the capital stock given in (5) is thus rewritten by $\dot{k}_j(t) = f(k_j(t)) - \bar{c}_j(t) - \left(n_j + \delta_j + g_j(t)\right) k_j(t)$, where $g_j := \dot{A}_j/A_j$ is the rate of technological progress, $n_j := \dot{L}_j/L_j$ the rate of population growth, and δ_j the rate of capital depreciation. Substituting the second expression of (9) to replace $g_j(t)$, we derive the law of motion for the effective capital–labor ratio as follows:

$$\dot{k}_j(t) = f(k_j(t)) - \bar{c}_j(t) - \left(n_j + \delta_j + \lambda_j + \sigma_j \left(\frac{1}{a_j(t)} - 1\right)\right) k_j(t). \tag{11}$$

Euler Equation of Consumption. Solving the problem given by (1) yields the Euler equation: $\dot{c}_j(t)/c_j(t) = \theta_j^{-1}\left(r_j(t) - \rho_j\right)$, and the transversality condition: $\lim_{t\to\infty} \exp(-(\rho_j - n_j)t)\mu_j(t)b_j(t) = 0$. Meanwhile, solving the problem given by (4) determines the rental rate of capital and the wage rate as: $R_j(t) = f'(k_j(t))$,

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and $w_j(t)/A_j(t) = f(k_j(t)) - k_j(t)f'(k_j(t))$. The equilibrium rate of return on capital assets is given by $r_j(t) = R_j(t) - \delta_j = f'(k_j(t)) - \delta_j$. The Euler equation of consumption can thus boils down to:

$$\frac{\dot{\bar{c}}_j(t)}{\bar{c}_j(t)} = \frac{\dot{c}_j(t)}{c_j(t)} - \frac{\dot{A}_j(t)}{A_j(t)} = \frac{1}{\theta_j}\left(f'(k_j(t)) - \delta_j - \rho_j\right) - \lambda_j - \sigma_j\left(\frac{1}{a_j(t)} - 1\right), \quad \mathbf{(12)}$$

where $\bar{c}_j(t) = \frac{c_j(t)}{A_j(t)} = \frac{C_j(t)}{A_j(t)L_j(t)}$ is consumption per effective unit of labor. The growth rate depends on the marginal product of capital $f'(k_j(t))$, and the rate of technological progress $\dot{A}_j(t)/A_j(t)$ is given by (9).

Transitional Dynamics. The world equilibrium is characterized by the time path of the technology gap, effective capital–labor ratio, and consumption per effective unit of labor $\left\{[a_j(t), k_j(t), \bar{c}_j(t)]_{t=0}^{\infty}\right\}_{j=1}^{J}$. Starting from the initial condition $[a_j(0), k_j(0), \bar{c}_j(0)]_{j=1}^{J}$, $\left\{[a_j(t), k_j(t), \bar{c}_j(t)]_{t=0}^{\infty}\right\}_{j=1}^{J}$ evolve according to the equations (10)–(12) and converge toward the corresponding steady state $[a_j^*, k_j^*, \bar{c}_j^*]_{j=1}^{J}$. The stationary conditions of (10)–(12) determine $[a_j^*, k_j^*, \bar{c}_j^*]_{j=1}^{J}$ as follows:

$$\begin{aligned} a_j^* &= \frac{\sigma_j}{\sigma_j - \lambda_j + g_{WTP}^*}, \qquad f'(k_j^*) = \delta_j + \rho_j + \theta_j g_{WTP}^*, \\ \bar{c}_j^* &= f(k_j^*) - \left(\delta_j + n_j + g_{WTP}^*\right) k_j^*, \end{aligned} \quad \mathbf{(13)}$$

where the superscript "*" corresponds to the long-run balanced growth path[9] and $g_{WTP}^* := \dot{A}_{WTP}^*/A_{WTP}^*$ is the long-run trend rate of world technological progress endogenously determined by:

$$\sum_{j=1}^{J} \frac{\sigma_j}{\sigma_j - \lambda_j + g_{WTP}^*} = 1. \quad \mathbf{(14)}$$

Here, g_{WTP}^* depends on structural characteristics of all interdependent countries in the world economy.

For any given initial condition of technology $[A_1(0), A_2(t), ..., A_J(0)]$, if there are some countries, say country j, of which the initial value of the technology gap is not equal to the steady state, that is, $\frac{A_j(0)}{\sum_{j=1}^{J} A_j(0)} := a_j(0) \neq a_j^* = \frac{\sigma_j}{\sigma_j - \lambda_j + g_{WTP}^*}$, then the technologically interdependent world equilibrium has transitional dynamics from the initial condition toward the long-run balanced growth. Furthermore, the transitional dynamics are saddle-path stable. Given the initial values of $[a_j(0), k_j(0)]_{j=1}^{J}$, there is a stable manifold that determines the initial value of $[\bar{c}_j(0)]_{j=1}^{J}$, such that from the initial condition $[a_j(0), k_j(0), \bar{c}_j(0)]_{j=1}^{J}$, $\left\{[a_j(t), k_j(t), \bar{c}_j(t)]_{t=0}^{\infty}\right\}_{j=1}^{J}$ evolve according to (10), (11), and (12) and converge toward the long-run steady state $[a_j^*, k_j^*, \bar{c}_j^*]_{j=1}^{J}$ determined by (13) (Appendix A provides details).

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4. GROWTH AND CONVERGENCE

4.1. Convergence in the Growth Rates

In the long-run world equilibrium, proportional technology gap, consumption per effective unit of labor, and effective capital–labor ratio tend to be constant $[a_j(t), k_j(t), \bar{c}_j(t)] = [a_j^*, k_j^*, \bar{c}_j^*]$ as given by (13). Hence, we derive the following result.

PROPOSITION 1. *In a technologically interdependent world equilibrium, there is cross-country convergence in the growth rates of technology, consumption per capita, and income per capita, that is,*

$$\frac{\dot{y}_j^*}{y_j^*} = \frac{\dot{c}_j^*}{c_j^*} = \frac{\dot{A}_j^*}{A_j^*} = \frac{\dot{A}_{WTP}^*}{A_{WTP}^*} := g_{WTP}^*, \tag{15}$$

where $y_j := Y_j/L_j = A_j f(k_j)$, $c_j := C_j/L_j = A_j\bar{c}_j$, *and* A_j *are income per capita, consumption per capita, and technology, respectively. The common growth rate for cross-country convergence is the long-run trend rate of world technological progress* g_{WTP}^* *as determined by (14).*

Proposition 1 shows that Ramsey growth with cross-country technological interdependence can generate a trend of convergence in growth rates. This result rationalizes the empirical fact that there are more limited differences in the long-run sustained growth rates, though countries tend to grow at different rates during the phase of transitional dynamics [e.g., Baumol (1986), Williamson (1996)]. This paper isolates technological interdependence as a mechanism for cross-country convergence. This novel perspective complements the existing studies explaining convergence through the lens of international trade or technology transfers from the world technology frontier [e.g., Howitt (2000), Acemoglu and Ventura (2002), Howitt and Mayer-Foulkes (2005)]. Furthermore, the growth rate for convergence is endogenous and depends on the structural characteristics of all individual countries in a technologically interdependent world economy. This result departs from the existing literature, which views each economy as converging to the growth rate of a single world frontier country that advances technology autonomously [e.g., Parente and Prescott (1994), Barro and Sala-i-Martin (1997), Acemoglu et al. (2006), Chu et al. (2014), Benhabib et al. (2014), Stokey (2015)].

In a world equilibrium with cross-country technological interdependence, the common growth rate for convergence depends on structural characteristics of all individual countries. The following result gives the comparative static effects of indigenous innovation efficiency and knowledge absorptive capacity.

COROLLARY 1. *The comparative static effects of indigenous innovation efficiency* λ_j *and knowledge absorptive capacity* σ_j *on the common growth rate for cross-country convergence* g_{WTP}^* *are given, respectively, by*

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$$\frac{\partial g^*_{WTP}}{\partial \lambda_j} = \frac{\sigma_j}{\left(\sigma_j - \lambda_j + g^*_{WTP}\right)^2 \sum_{i=1}^{J} \frac{\sigma_i}{\left(\sigma_i - \lambda_i + g^*_{WTP}\right)^2}} > 0, \quad \textbf{(16a)}$$

$$\frac{\partial g^*_{WTP}}{\partial \sigma_j} = \frac{g^*_{WTP} - \lambda_j}{\left(\sigma_j - \lambda_j + g^*_{WTP}\right)^2 \sum_{i=1}^{J} \frac{\sigma_i}{\left(\sigma_i - \lambda_i + g^*_{WTP}\right)^2}} > 0. \quad \textbf{(16b)}$$

Proof. See Appendix B. ■

The interdependent world economy tends to grow at a larger rate if some national economies improve their indigenous innovation efficiencies and knowledge absorptive capacities. As technological interdependence drives cross-country convergence to the rate of world technological progress, the improvement in structural characteristics of one country has a positive effect in promoting the long-run growth of other countries.

4.2. World Technology Distribution

In a technologically interconnected world, changes in one country's structural characteristics affect another country's position in the world technology distribution. While technological interdependence ensures cross-country convergence in the rate of technological progress, there tends to be divergence in the world technology distribution due to cross-country disparity in fundamental characteristics. Specifically, following the first expression of (13), the long-run distribution of the world technology boils down to $a^*_j = A^*_j / A^*_{WTP} = \sigma_j / \left(\sigma_j - \lambda_j + g^*_{WTP}\right)$. The following result shows the effect of country characteristics on the world technology distribution.

PROPOSITION 2. *The within- and cross-country effects of country characteristics on the world technology distribution are given, respectively, by:*

$$\frac{\partial a^*_j}{\partial \lambda_j} = \left(\sum_{i \neq j} \frac{\sigma_i}{\left(\sigma_i - \lambda_i + g^*_{WTP}\right)^2}\right) \frac{\partial g^*_{WTP}}{\partial \lambda_j}$$

$$= \frac{\left(\sum_{i \neq j} \frac{\sigma_i}{\left(\sigma_i - \lambda_i + g^*_{WTP}\right)^2}\right) \sigma_j}{\left(\sigma_j - \lambda_j + g^*_{WTP}\right)^2 \sum_{i=1}^{J} \frac{\sigma_i}{\left(\sigma_i - \lambda_i + g^*_{WTP}\right)^2}} > 0, \quad \textbf{(17a)}$$

$$\frac{\partial a^*_j}{\partial \sigma_j} = \left(\sum_{i \neq j} \frac{\sigma_i}{\left(\sigma_i - \lambda_i + g^*_{WTP}\right)^2}\right) \frac{\partial g^*_{WTP}}{\partial \sigma_j}$$

$$= \frac{\left(\sum_{i \neq j} \frac{\sigma_i}{\left(\sigma_i - \lambda_i + g^*_{WTP}\right)^2}\right) \left(g^*_{WTP} - \lambda_j\right)}{\left(\sigma_j - \lambda_j + g^*_{WTP}\right)^2 \sum_{i=1}^{J} \frac{\sigma_i}{\left(\sigma_i - \lambda_i + g^*_{WTP}\right)^2}} > 0, \quad \textbf{(17b)}$$

$$\frac{\partial a_i^*}{\partial \lambda_j} = -\frac{\sigma_i}{\left(\sigma_i - \lambda_i + g_{WTP}^*\right)^2} \frac{\partial g_{WTP}^*}{\partial \lambda_j} = -\frac{\frac{\sigma_i}{\left(\sigma_i - \lambda_i + g_{WTP}^*\right)^2} \sigma_j}{\left(\sigma_j - \lambda_j + g_{WTP}^*\right)^2 \sum_{i=1}^{J} \frac{\sigma_i}{\left(\sigma_i - \lambda_i + g_{WTP}^*\right)^2}} < 0, \quad \textbf{(17c)}$$

$$\frac{\partial a_i^*}{\partial \sigma_j} = -\frac{\sigma_i}{\left(\sigma_i - \lambda_i + g_{WTP}^*\right)^2} \frac{\partial g_{WTP}^*}{\partial \sigma_j} = -\frac{\frac{\sigma_i}{\left(\sigma_i - \lambda_i + g_{WTP}^*\right)^2} \left(g_{WTP}^* - \lambda_j\right)}{\left(\sigma_j - \lambda_j + g_{WTP}^*\right)^2 \sum_{i=1}^{J} \frac{\sigma_i}{\left(\sigma_i - \lambda_i + g_{WTP}^*\right)^2}} < 0, \quad \textbf{(17d)}$$

where $\frac{\partial a_j^*}{\partial \lambda_j}$ and $\frac{\partial a_j^*}{\partial \sigma_j}$ are the effect of the country j's indigenous innovation efficiency and knowledge absorptive capacity on this country's technology share. $\frac{\partial a_i^*}{\partial \lambda_j}$ and $\frac{\partial a_i^*}{\partial \sigma_j}$ are the country j's indigenous innovation efficiency and knowledge absorptive capacity on another country i's technology share.

Proof. See Appendix C. ∎

Proposition 2 emphasizes that we should often consider the world economy as an interconnected equilibrium in which one country's technological position depends on characteristics of all other countries, not simply an equilibrium of each country on its own. While technological interdependence creates a force driving convergence in the growth rates, the shares that different countries account for in the world technology distribution tend to diverge due to cross-country disparity in fundamental characteristics. This result coincides with the insights offered by the seminal works of Howitt (2000), Acemoglu and Ventura (2002), and Howitt and Mayer-Foulkes (2005). More specifically, an economy with a stronger capacity to undertake indigenous innovation and absorb technology diffusion will end up with a larger share in the world technology distribution. Furthermore, changes in a particular country's characteristics have effects on another country's technological position. The negative cross-country effect suggests that improvement in one country's indigenous innovation efficiencies and knowledge absorptive capacity will shrink the share of other countries in the world technology distribution.

4.3. Divergences in Levels

The pulling force in the interconnected world economy, working through technological interdependence, drives technological progress and ensures cross-country convergence in the long-run growth rates. However, we will show below that there tends to be cross-country divergence in the aggregate level, owing to cross-country disparity in fundamental structural characteristics. For analytical tractability, we use the relative ratio between countries (proportional level differences) as a proxy for cross-country divergence and obtain the following proposition.

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PROPOSITION 3. *The technology ratio between any given two countries $i, j = 1, 2, ..., J$ is determined by:*

$$\frac{A_i^*}{A_j^*} = \frac{\frac{\sigma_i}{(\sigma_i - \lambda_i + g_{WTP}^*)}}{\frac{\sigma_j}{(\sigma_j - \lambda_j + g_{WTP}^*)}}, \tag{18}$$

the capital ratio between countries is determined by:

$$\frac{K_i^*}{K_j^*} = \frac{\frac{\sigma_i}{(\sigma_i - \lambda_i + g_{WTP}^*)}}{\frac{\sigma_j}{(\sigma_j - \lambda_j + g_{WTP}^*)}} \cdot \frac{f'^{-1}\left(\delta_i + \rho_i + \theta_i g_{WTP}^*\right)}{f'^{-1}\left(\delta_j + \rho_j + \theta_j g_{WTP}^*\right)} \cdot \frac{L_i^*}{L_j^*}, \tag{19}$$

and the consumption ratio between countries is determined by:

$$\frac{C_i^*}{C_j^*} = \frac{\frac{\sigma_i}{(\sigma_i - \lambda_i + g_{WTP}^*)}}{\frac{\sigma_j}{(\sigma_j - \lambda_j + g_{WTP}^*)}} \cdot \frac{f(f'^{-1}\left(\delta_i + \rho_i + \theta_i g_{WTP}^*\right)) - \left(\delta_i + n_i + g_{WTP}^*\right) f'^{-1}\left(\delta_i + \rho_i + \theta_i g_{WTP}^*\right)}{f(f'^{-1}\left(\delta_j + \rho_j + \theta_j g_{WTP}^*\right)) - \left(\delta_j + n_j + g_{WTP}^*\right) f'^{-1}\left(\delta_j + \rho_j + \theta_j g_{WTP}^*\right)} \cdot \frac{L_i^*}{L_j^*}, \tag{20}$$

where $f'^{-1}(\cdot)$ is the inverse function (denoted by "$^{-1}$") of the derivative (denoted by "$\prime$") of the intensive-form production function $f(k) := F\left(\frac{K}{AL}, 1\right)$. $[\lambda, \sigma, \delta, \theta, \rho]$ are indigenous innovation efficiency, knowledge absorptive capacity, capital depreciation rate, coefficient of relative risk aversion, and rate of time preference, respectively. g_{WTP}^* is the long-run trend rate of world technological progress determined by (14). The labor ratio between countries is given by $L_i^*/L_j^* = \exp\big((n_i - n_j)t^*\big)$, where n is the growth rate of labor and t^* is the time point in the long-run balanced growth phase. Cross-country differences in structural characteristics $[\lambda, \sigma, \delta, \theta, \rho, n]$ lead to cross-country divergence in the level of technology, capital stocks, and consumption, and the divergence becomes wider as time proceeds $t^* \to \infty$.

Proof. See Appendix D. ∎

Proposition 3 shows that the aggregate levels of technology, capital stocks, and consumption tend to diverge, owing to cross-country disparity in structural characteristics such as indigenous innovation efficiency and knowledge absorptive capacity. The following result gives the comparative static effects.

PROPOSITION 4. *The cross-country divergence in technology, capital stocks, and consumption, measured by A_i^*/A_j^*, K_i^*/K_j^* and C_i^*/C_j^*, respectively, depends on indigenous innovation efficiency and knowledge absorptive capacity $[\lambda_i, \sigma_i, \lambda_j, \sigma_j]$.*

i. *The comparative static effects of $[\lambda_i, \sigma_i, \lambda_j, \sigma_j]$ on divergence in technology are given by:*

$$\frac{\partial(A_i^*/A_j^*)}{\partial\lambda_i} > 0, \quad \frac{\partial(A_i^*/A_j^*)}{\partial\sigma_i} > 0, \quad \frac{\partial(A_i^*/A_j^*)}{\partial\lambda_j} < 0, \quad \frac{\partial(A_i^*/A_j^*)}{\partial\sigma_j} < 0. \tag{21}$$

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ii. If the following condition holds

$$\frac{\theta_i}{k_i^* f''(k_i^*)} - \frac{\theta_j}{k_j^* f''(k_j^*)} + \frac{1}{a_i} \sum_{j \neq i} \frac{\sigma_j}{\left(\sigma_j - \lambda_j + g_{WTP}^*\right)^2} - \frac{1}{a_j} \frac{\sigma_j}{\left(\sigma_j - \lambda_j + g_{WTP}^*\right)^2} > 0, \tag{22}$$

the comparative static effects of $[\lambda_i, \sigma_i, \lambda_j, \sigma_j]$ *on divergence in capital stocks are given by:*

$$\frac{\partial(K_i^*/K_j^*)}{\partial \lambda_i} > 0, \quad \frac{\partial(K_i^*/K_j^*)}{\partial \sigma_i} > 0, \quad \frac{\partial(K_i^*/K_j^*)}{\partial \lambda_j} < 0, \quad \frac{\partial(K_i^*/K_j^*)}{\partial \sigma_j} < 0. \tag{23}$$

Otherwise the comparative static effects are opposite, that is,

$$\frac{\partial(K_i^*/K_j^*)}{\partial \lambda_i} < 0, \quad \frac{\partial(K_i^*/K_j^*)}{\partial \sigma_i} < 0, \quad \frac{\partial(K_i^*/K_j^*)}{\partial \lambda_j} > 0, \quad \frac{\partial(K_i^*/K_j^*)}{\partial \sigma_j} > 0. \tag{24}$$

iii. If the following condition holds

$$\begin{aligned} &\frac{1}{\bar{c}_i^*}\left(\left((\theta_i - 1)g_{WTP}^* + \rho_i - n_i\right)\frac{\theta_i}{f''(k_i^*)} - k_i^*\right) \\ &\quad - \frac{1}{\bar{c}_j^*}\left(\left((\theta_j - 1)g_{WTP}^* + \rho_j - n_j\right)\frac{\theta_j}{f''(k_j^*)} - k_j^*\right) \\ &\quad + \frac{1}{a_i^*}\sum_{j \neq i}\frac{\sigma_j}{\left(\sigma_j - \lambda_j + g_{WTP}^*\right)^2} - \frac{1}{a_j^*}\frac{\sigma_j}{\left(\sigma_j - \lambda_j + g_{WTP}^*\right)^2} > 0, \end{aligned} \tag{25}$$

the comparative static effects of $[\lambda_i, \sigma_i, \lambda_j, \sigma_j]$ *on divergence in consumption are given by:*

$$\frac{\partial(C_i^*/C_j^*)}{\partial \lambda_i} > 0, \quad \frac{\partial(C_i^*/C_j^*)}{\partial \sigma_i} > 0, \quad \frac{\partial(C_i^*/C_j^*)}{\partial \lambda_j} < 0, \quad \frac{\partial(C_i^*/C_j^*)}{\partial \sigma_j} < 0. \tag{26}$$

Otherwise the comparative static effects are opposite, that is,

$$\frac{\partial(C_i^*/C_j^*)}{\partial \lambda_i} < 0, \quad \frac{\partial(C_i^*/C_j^*)}{\partial \sigma_i} < 0, \quad \frac{\partial(C_i^*/C_j^*)}{\partial \lambda_j} > 0, \quad \frac{\partial(C_i^*/C_j^*)}{\partial \sigma_j} > 0. \tag{27}$$

Proof. See Appendix E. ■

Proposition 4 shows that an economy with higher indigenous innovation efficiencies and knowledge absorption capacities tends to have a higher technology level as compared to other countries. However, increases in one country's indigenous innovation efficiencies and knowledge absorption capacities might not necessarily lead to a larger stock of capital and a higher level of consumption as compared to other countries. As Proposition 4 shows, when conditions (22) and (25) are met, the improvement of one country's indigenous innovation efficiencies and knowledge absorption capacities can generate a larger stock of capital and a higher level of consumption relative to other countries.

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The intuition of (22) is as follows. The effect of indigenous innovation efficiency λ_i on country i and j's effective capital–labor ratio through the channel of world technological progress is characterized by $\frac{1}{k_i^*}\frac{\partial k_i^*}{\partial \lambda_i} = \frac{\theta_i}{k_i^* f''(k_i^*)}\frac{\partial g_{WTP}^*}{\partial \lambda_i}$ and $\frac{1}{k_j^*}\frac{\partial k_j^*}{\partial \lambda_i} = \frac{\theta_j}{k_j^* f''(k_j^*)}\frac{\partial g_{WTP}^*}{\partial \lambda_i}$, respectively. If $\frac{\theta_i}{k_i^* f''(k_i^*)} - \frac{\theta_j}{k_j^* f''(k_j^*)} > 0$, an increase in λ_i generates a positive effect to widen cross-country differences (between country i and j) in the effective capital–labor ratio, that is, $\frac{\partial (k_i^*/k_j^*)}{\partial \lambda_i} = \frac{k_i^*}{k_j^*}(\frac{\theta_i}{k_i^* f''(k_i^*)} - \frac{\theta_j}{k_j^* f''(k_j^*)})\frac{\partial g_{WTP}^*}{\partial \lambda_i} > 0$. Meanwhile, the effect of indigenous innovation efficiency λ_i on country i and j's technology gap through the channel of world technological progress is characterized by $\frac{1}{a_i^*}\frac{\partial a_i^*}{\partial \lambda_i} = (\frac{1}{a_i^*}\sum_{j\neq i}\frac{\sigma_j}{(\sigma_j - \lambda_j + g_{WTP}^*)^2})\frac{\partial g_{WTP}^*}{\partial \lambda_i}$ and $\frac{1}{a_j^*}\frac{\partial a_j^*}{\partial \lambda_i} = \frac{1}{a_j^*}\frac{\sigma_j}{(\sigma_j - \lambda_j + g_{WTP}^*)^2}\frac{\partial g_{WTP}^*}{\partial \lambda_i}$, respectively. If $\frac{1}{a_i}\sum_{j\neq i}\frac{\sigma_j}{(\sigma_j - \lambda_j + g_{WTP}^*)^2} - \frac{1}{a_j}\frac{\sigma_j}{(\sigma_j - \lambda_j + g_{WTP}^*)^2} > 0$, an increase in λ_i will widen the cross-country differences in the technology gap, that is, $\frac{\partial (a_i^*/a_j^*)}{\partial \lambda_i} = \frac{a_i^*}{a_j^*}(\frac{1}{a_i}\sum_{j\neq i}\frac{\sigma_j}{(\sigma_j - \lambda_j + g_{WTP}^*)^2} - \frac{1}{a_j}\frac{\sigma_j}{(\sigma_j - \lambda_j + g_{WTP}^*)^2})\frac{\partial g_{WTP}^*}{\partial \lambda_i} > 0$. Combining the effects on both effective capital–labor ratio and technology gap, we can accordingly show an increase in λ_i will widen the cross-country difference in capital stock if the sufficient condition (22) is met, because we have $\frac{\partial (K_i^*/K_j^*)}{\partial \lambda_i} = (\frac{a_i^*}{a_j^*}\cdot\frac{\partial (k_i^*/k_j^*)}{\partial \lambda_i} + \frac{k_i^*}{k_j^*}\cdot\frac{\partial (a_i^*/a_j^*)}{\partial \lambda_i})\frac{L_i^*}{L_j^*}$. A similar reasoning applies to the sufficient condition (25) ensuring the comparative static effects on cross-country divergence in consumption given in (26).

4.4. Advantage of Backwardness

The analysis proceeds by understanding cross-country growth patterns from the perspective of "advantage of backwardness," that is, a technologically backward economy tends to catch up at a faster pace [e.g., Gerschenkron (1962)]. Specifically, the technology position of a given country $j = 1, 2, ..., J$ in the world distribution is measured by the proportional technology gap $a_j(t) = \frac{A_j(t)}{\sum_{j=1}^{J} A_j(t)}$, and transition dynamics along the stable saddle path is determined by:

$$a_j(t) = a_j(0)\exp(-|\chi_j|t) + a_j^*\left(1 - \exp(-|\chi_j|t)\right), \tag{28}$$

where the technology gap starts from the initial condition $a_j(0)$ and converges toward the long-run steady state a_j^*, and the speed of transition dynamics is governed by the negative stable eigenvalue χ_j (Appendix A provides details):

$$\chi_j = -g_{WTP}^* - (\lambda_j - \sigma_j)(a_j^* - 1) = -\left(\frac{\sigma_j}{a_j^*} + (\lambda_j - \sigma_j)a_j^*\right) < 0. \tag{29}$$

We thus establish the following proposition to explain the advantage of economic backwardness.

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PROPOSITION 5. *A technologically backward country j with a smaller share in the world technology distribution,* $a_j^* := A_j^* / \sum_{j=1}^{J} A_j^*$, *takes the "advantage of backwardness" to converge toward its corresponding balanced growth path at a faster speed.*

Proof. See Appendix F. ■

A country that is relatively "backward" tends to make faster transitions to its corresponding long-run balanced growth path, and this is because technologically backward economies, with access to a larger amount of untapped knowledge in the RoW, can assimilate foreign technology diffusion to advance their domestic technology level. The pulling force attributable to the Gerschenkron's "advantage of backwardness" tends to be stronger to facilitate catching up at a faster pace [e.g., Gerschenkron (1962)]. This result can shed light on the stylized fact of β*-convergence*: an economy that initially had a low level of income tends to grow faster, and the rate of income growth over time and the initial income level are correlated negatively [e.g., Baumol (1986), Barro and Sala-i-Martin (1992), Galor (1996), Caselli et al. (1996), Barro (2015)]. Note that, while technologically backward economies can harness the "advantage of backwardness" to experience a fast pace of transitional dynamics, their long-run growth trend will still converge to the growth rate that is common to all interdependent countries. Also, technologically backward economies will end up with a lower position in the world technology distribution, owing to their lower indigenous innovation efficiency and knowledge absorptive capacity.

5. QUANTITATIVE ANALYSIS

5.1. Model Calibration

Parameterization. The quantitative analysis considers the world economy as three countries/regions: the USA, the EU, and the RoW. The model is calibrated using the Penn World Table (PWT) version 9.1 database which covers 182 countries between 1950 and 2017 [Feenstra et al. (2015)]. The calibrated parameters are given in Table 1. The average growth rates of labor are estimated as $n_{US} = 1.4\%$, $n_{EU} = 0.5\%$, $n_{RoW} = 2.0\%$. The average rates of capital depreciation are set at $\delta_{US} = 3.82\%$, $\delta_{EU} = 3.56\%$, and $\delta_{RoW} = 3.36\%$ according to the PWT. The rate of time preference is set at a standard value $\rho = 0.02$ [e.g., Grossmann et al. (2013), van der Ploeg and Withagen (2014)]. We use $\theta = 2$ as an implied coefficient of relative risk aversion that is within the consensus range 1–3 [e.g., Mehra and Prescott (1985), Epstein and Zin (1991), Acemoglu et al. (2012)].[10] The production technology is specified as a Cobb–Douglas function, $Y = F(K, AL) = K^{\beta}(AL)^{1-\beta}$. The corresponding intensive-form representation is $F\left(\frac{K}{AL}, 1\right) := f(k) = k^{\beta}$, where the factor share of labor income is given by $1 - \beta$. We use the PWT database to calculate the factor share of labor compensation in GDP, and the average values over the period 1950–2017 are estimated as 0.62,

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TABLE 1. Calibrated parameters for quantitative analysis

Description	Parameter	Value		
		j=US	j=EU	j=RoW
Indigenous innovation efficiency	λ_j	0.03	0.025	0.02
Knowledge absorptive capacity	σ_j	0.02	0.015	0.01
Output elasticity of capital	β_j	0.38	0.39	0.4
Growth rates of labor	n_j	0.014	0.005	0.02
Rate of capital depreciation	δ_j	0.038	0.036	0.034
Coefficient of relative risk aversion	θ_j	2	2	2
Rate of time preference	ρ_j	0.02	0.02	0.02
Initial values of technology gap	$a_j(0)$	0.289	0.385	0.326
Initial values of effective capital–labor ratio	$k_j(0)$	22.98	11.22	2.65

0.61, and 0.6 for the USA, the EU, and RoW, respectively. Hence, the output elasticities of capital (the factor share of capital) are set at $\beta_{US} = 0.38$, $\beta_{EU} = 0.39$ and $\beta_{RoW} = 0.4$.

We calibrate the parameters of indigenous innovation efficiency and knowledge absorptive capacity as follows. We collect the date of intangible capital stocks from the PWT database as a measurement of the technology level. The PWT 9.1 documents the data of intangible capital stocks over the period 1950–2017.[11] As Figure 2(a)–(c) shows, we fit the trend of intangible capital stocks for the USA, the EU, and RoW using the law of motion for the technology given by (6) with the calibrated parameters $\lambda_{US} = 0.03$, $\lambda_{EU} = 0.025$, $\lambda_{RoW} = 0.02$, $\sigma_{US} = 0.02$, $\sigma_{EU} = 0.015$, and $\sigma_{RoW} = 0.01$. Aggregating the three countries/regions gives the calibration for the world as shown in Figure 2(d). With the parameters $[\lambda_j, \sigma_j]_{j=US,EU,RoW}$, the long-run trend rate of world technological progress is endogenously determined by:

$$\sum_{j=US,EU,RoW} \frac{\sigma_j}{\sigma_j - \lambda_j + g^*_{WTP}} = 1 \quad \Rightarrow \quad g^*_{WTP} = 0.055.$$

The calibrated parameters also satisfy the condition $\sigma_j < \lambda_j < g^*_{WTP}$, given that the technology gap is less than unity, $\sigma_j/(\sigma_j - \lambda_j + g^*_{WTP}) < 1 \Rightarrow \lambda_j < g^*_{WTP}$. Undertaking indigenous innovation contributes more to domestic technological progress than absorbing foreign technology diffusion (no free riding behavior).

Boundary Conditions. We use the PWT data of intangible capital stocks for the year 1950 (14,341, 19,130, and 16,199 in millions 2011 USD for the USA, the EU, and RoW, respectively) to estimate the initial condition of technology gaps as $[a_{US}(0), a_{EU}(0), a_{RoW}(0)] = [0.289, 0.385, 0.326]$. With the PWT data of physical capital $K_j(0)$ and labor $L_j(0)$, we use the formula $k_j(0) = K_j(0)/(A_j(0)L_j(0))$ to calculate the initial condition of the effective capital–labor ratio as $[k_{US}(0), k_{EU}(0), k_{RoW}(0)] = [22.98, 11.22, 2.65]$. Hence, the initial values of predetermined state variables $[a_j(0), k_j(0)]_{j=US,EU,RoW}$ give the initial condition

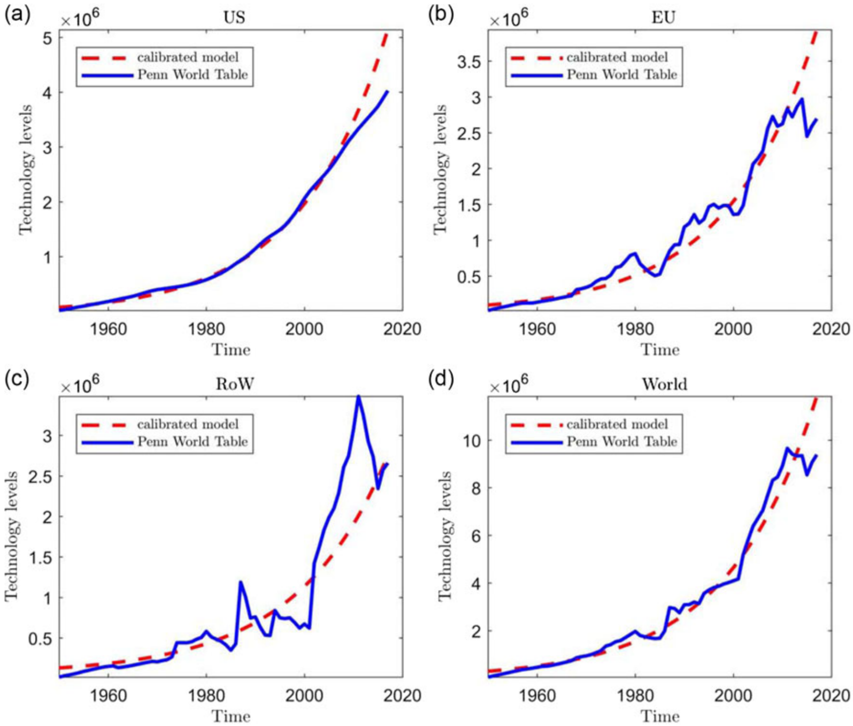

FIGURE 2. Panel (a) fits the US data of intangible capital stocks using the law of motion for the technology (6) with the calibrated parameters $\lambda_{US} = 0.03$ and $\sigma_{US} = 0.02$. Panel (b) fits the EU data of intangible capital stocks using the law of motion for the technology (6) with the calibrated parameters $\lambda_{EU} = 0.025$ and $\sigma_{US} = 0.015$. Panel (c) fits the RoW data of intangible capital stocks using the law of motion for the technology (6) with the calibrated parameters $\lambda_{RoW} = 0.02$ and $\sigma_{RoW} = 0.01$. Panel (d) gives the calibration for the world technology by aggregating the USA, the EU, and RoW.

of differential equations (10)–(12). Meanwhile, we use (13) to compute the long-run Balanced Growth Path (BGP) and establish the terminal condition as follows:

$$a_j^* = \frac{\sigma_j}{\sigma_j - \lambda_j + g_{WTP}^*}, \qquad k_j^* = \left(\frac{\delta_j + \rho_j + \theta_j g_{WTP}^*}{\beta_j}\right)^{\frac{1}{\beta_j - 1}},$$
$$\bar{c}_j^* = \left(k_j^*\right)^{\beta_j} - \left(\delta_j + n_j + g_{WTP}^*\right) k_j^*.$$

This boils down to $[a_{US}^*, a_{EU}^*, a_{RoW}^*] = [0.44, 0.33, 0.23]$, $[k_{US}^*, k_{EU}^*, k_{RoW}^*] = [3.72, 4.07, 4.44]$, and $[\bar{c}_{US}^*, \bar{c}_{EU}^*, \bar{c}_{RoW}^*] = [1.25, 1.34, 1.33]$.

Solving Transitional Dynamics. With the initial and terminal conditions, we solve the differential equations numerically with the boundary value problem characterized by (10)–(12). As Figure 3 shows, there is a stable saddle path that determines the initial value of $[c_j(0)]_{j=US,EU,RoW}$ endogenously, given the initial

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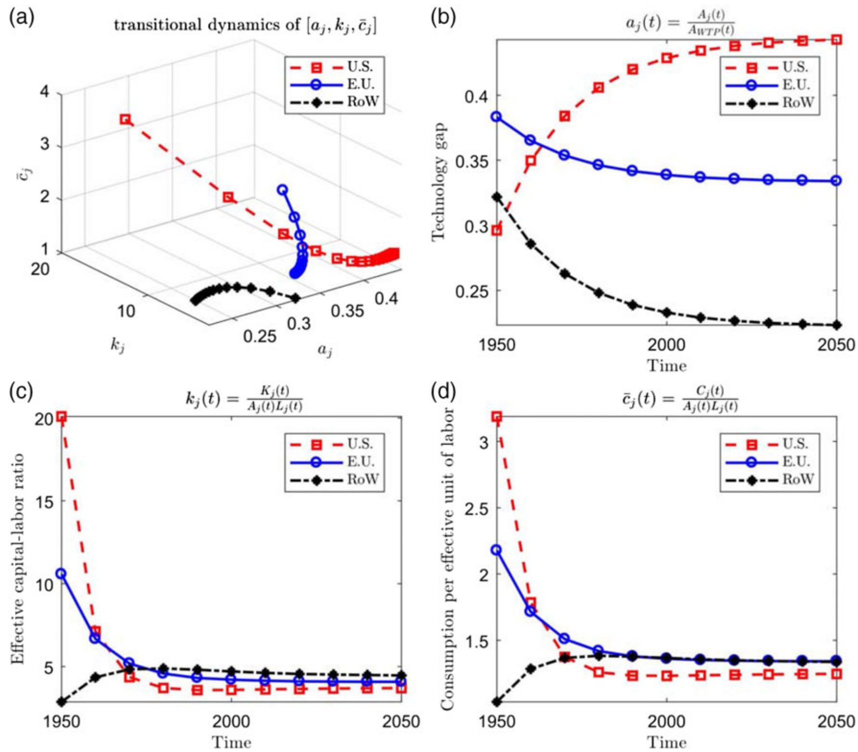

FIGURE 3. Panel(a) depicts transitional dynamics of technology gap a_j, effective capital–labor ratio k_j, and consumption per effective unit of labor $\bar{c}_j$. Panel (b) plots the time path of technology gap $a_j(t) = A_j(t)/A_{WTP}(t)$. Panel (c) plots the time path of effective capital–labor ratio $k_j(t) = K_j(t)/(A_j(t)L_j(t))$. Panel (d) plots the time path of consumption per effective unit of labor $\bar{c}_j(t) = C_j(t)/(A_j(t)L_j(t))$. The dashed red, solid blue, and dash-dotted black lines correspond to the USA, the EU, and RoW, respectively.

values of predetermined state variables $[a_j(0), k_j(0)]_{j=US,EU,RoW}$. Then, starting from the initial condition $[a_j(0), k_j(0), \bar{c}_j(0)]_{j=US,EU,RoW}$, the world equilibrium evolves along the stable saddle path of transitional dynamics toward the long-run balanced growth phase $[a_j^*, k_j^*, \bar{c}_j^*]_{j=US,EU,RoW}$.

5.2. Simulation Results

Convergence in Growth Rates. Figure 4(a), (b), and (c) shows the cross-country pattern of convergence in the growth rates of technology, income, and consumption per capita, respectively. The USA, the EU, and RoW with different structural characteristics and initial conditions increase their technology and income levels at different rates during the phase of transitional growth. However, the difference is narrowing over time, and there tends to be cross-country convergence in

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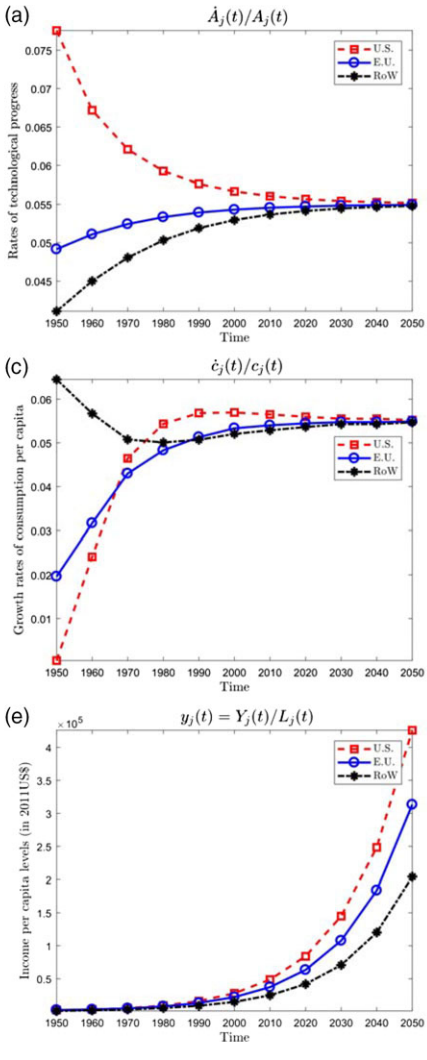

FIGURE 4. Panel (a), (b), and (c) plots cross-country convergence in the rate of technological progress $\dot{A}_j/A_j$, the growth rate of income per capita $\dot{y}_j/y_j$, and the growth rate of consumption per capita $\dot{c}_j/c_j$, respectively. Panel (d), (e), and (f) plots cross-country divergence in the level of technology A_j, income per capita $y_j(t) = Y_j/L_j$, and consumption per capita $c_j = C_j/L_j$, respectively. The solid red, dashed blue, and dotted black line corresponds to the USA, the EU, and RoW, respectively.

the long-run growth trend with all three countries/regions converging to a common growth rate of 5.52%. Technological interdependence provides the pulling force that ensures a similar growth rate across countries in the long-run sustained growth. This quantitative result coincides with the analytical finding of convergence obtained in Proposition 1.

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Divergence in Levels. Although technological interdependence plays a role to generate cross-country convergence in the growth rates, the level of technology and income tends to diverge, owing to cross-country disparity in fundamental characteristics and the initial conditions of economic development. As Figure 4(d), (e), and (f) show, advanced economies, such as the USA and the EU, with higher indigenous innovation efficiencies and knowledge absorptive capacities, tend to generate higher levels of technology. Then, divergence in technology leads to cross-country differences in the level of income and consumption per capita. These results are in agreement with the analytical findings obtained in Proposition 3: cross-country disparities in structural characteristics lead to divergence in technology and income levels. Put differently, individual countries with different fundamental characteristics and initial conditions tend to grow along their country-specific balanced growth path, rather than converge toward a common growth path (e.g., the growth rate of the world technology frontier). Accordingly, our findings strengthen the viability of *club convergence* as a competing hypothesis with unconditional convergence: countries that differ in their structural characteristics and initial conditions may cluster around different steady-state/balanced growth equilibria [e.g., Galor (1996)].

World Technology Distribution. Starting from the initial condition of world technology distribution $[a_{US}(0), a_{EU}(0), a_{RoW}(0)] = [0.29, 0.38, 0.33]$, the USA and the EU will continue to have dominant shares in the world technology, while the contribution made by the RoW will decline. The long-run world technology distribution will end up with $[a^*_{US}, a^*_{EU}, a^*_{RoW}] = [0.44, 0.33, 0.22]$. This result suggests that technologically advanced economies with strong capacities to undertake indigenous innovation and absorb technology diffusion tend to account for larger shares in the long-run world technology distribution. In contrast, countries with relatively backward innovative capacity end up with a lower position in the world technology distribution.

Comparative Statics. Figure 5 shows the comparative static effects of technology characteristics on cross-country divergence. As shown in Figure 5(a), when the USA improves its indigenous innovation efficiency and knowledge absorptive capacity, the pace of technological progress tends to be faster in that country, widening the technology gap for both the EU and RoW relative to the USA. Meanwhile, Figure 5(b) shows that the faster technological progress in the USA also drives capital accumulation at a relatively larger rate as compared to that in both the EU and RoW. Hence, the capital ratio of the EU and RoW relative to the USA becomes smaller as a result of an increase in US indigenous innovation efficiency and knowledge absorptive capacity. Similar comparative statics results are reached for consumption and income as shown in Figure 5(c)–(f). The divergence between the EU/RoW and the USA tends to widen when the USA increases its indigenous innovation efficiency and knowledge absorptive capacity.

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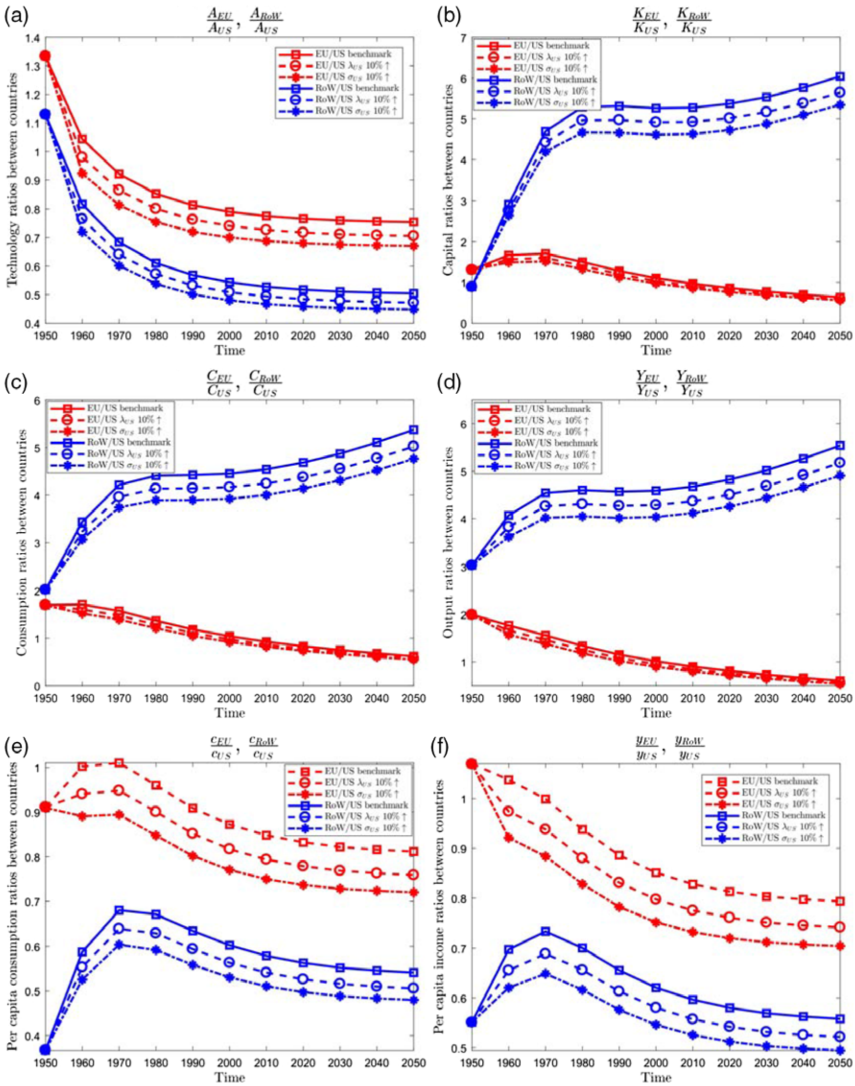

FIGURE 5. Panel (a) plots the comparative statics for technology ratios between the USA, the EU, and RoW. Panel (b) plots the comparative statics for capital ratios between the USA, the EU, and RoW. Panel (c) plots the comparative statics for consumption ratios between the USA, the EU, and RoW. Panel (d) plots the comparative statics for output ratios between the USA, the EU, and RoW. Panel (e) plots the comparative statics for per capita consumption ratios between the USA, the EU, and RoW. Panel (f) plots the comparative statics for per capita income ratios between the USA, the EU, and RoW. The comparative static effects of structural characteristics are examined by considering 10% increases in the parameters of the US indigenous innovation efficiency and knowledge absorptive capacity from the benchmark values $\lambda_{US} = 0.03$ and $\sigma_{US} = 0.02$.

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6. EMPIRICAL TESTS

6.1. Empirical Strategy

This section describes empirical tests for the theoretical results obtained in previous sections. In our empirical analysis, we adopt intangible capital stock as a proxy indicator of technology. The reasons for this treatment are twofold. First, our Ramsey growth framework has factored into physical capital, that is, K_j in the production function (2). It is important to include intangible capital and link it to A_j in our empirical analysis. This follows from the fact that the advanced economy such as the USA and the EU has shifted toward service- and technology-based industries, which has made intangible assets such as innovative products, brands, patents, software, customer relationships, databases, and distribution systems increasingly important.

Second, in our growth model with cross-country technological interdependence, the technology level A_j is a stock variable that is cumulative over time (as described by the law of motion for technology), and technology across economies can be aggregated to be the world technology, that is, $A_{WTP}(t) = \sum_{j=1}^{J} A_j(t)$. These features can be captured using intangible capital which is both accumulative over time and aggregatable across countries. In contrast, total factor productivity as used in traditional growth accounting literature to measure technology is neither accumulative over time nor aggregatable across countries and is thus not applicable to our model. The method of using intangible capital as a proxy of technology builds on the literature of intangible capital and growth accounting including, among others, Corrado et al. (2009), Corrado and Hulten (2010), Nakamura (2010), Corrado and Hulten (2014), Eisfeldt and Papanikolaou (2014), Peters and Taylor (2017), Chen (2018), and Kogan and Papanikolaou (2019). It is widely acknowledged in these studies that intangible capital is closely related to total factor productivity, and the growth rates of output per worker are found to increase at a similar rate as that of intangible capital.

Specifically, we test the following three results obtained in the theoretical expositions. First, there is cross-country convergence in the rate of technological progress. Second, a country with a stronger capacity to undertake indigenous innovation and absorb technology diffusion tends to have a larger share in the world technology pool (a higher level of technology relative to other countries). Third, a country's structural characteristics affect its relative technology level. To test these results formally, we estimate the following equations:

$$\Delta \ln A_j(t) = a_j - c_j \left(\ln A_j(t-1) - d \ln A_{WTP}(t-1)\right) + \theta_1 \Delta \ln A_j(t-1) + \theta_2 \Delta A_{WTP}(t-1) + \vartheta_j(t), \quad \textbf{(30a)}$$

$$\Delta A_j(t) = e_j - f_j \left(A_j(t-1) - d_j A_{WTP}(t-1)\right) + \theta_3 \Delta A_j(t-1) + \theta_4 \Delta A_{WTP}(t-1) + \epsilon_j(t), \quad \textbf{(30b)}$$

$$d_j = \gamma_0 + \gamma_1 HK_j + \gamma_2 ISQ_j + \delta_j, \quad \textbf{(30c)}$$

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where $A_j(t)$ is country j's technology level in period t, $A_{WTP}(t-1)$ is the world technology pool in period $(t-1)$, HK_j is country j's initial human capital stock, and ISQ_j is country j's initial institutional quality. Equation (30a) characterizes a panel cointegration model for all countries in the sample. The long-run equilibrium relationship is $\ln A_j(t-1) = d \ln A_{WTP}(t-1)$, with the coefficient of cointegration denoted by d. As Proposition 1 indicates, technology converges to a common growth rate across countries in the long run, and this common growth rate is equal to the growth rate of the world technology pool. This result suggests that the cointegrating coefficient should be equal to one, $d = 1$, since d corresponds to the ratio of $A_j(t)$ which is the rate of technological progress in the economy j and the rate of the progress of the world technology $A_{WTP}(t)$.

Furthermore, we use the level of technology $A_j(t)$ in (30b), instead of the natural logarithm of the technology $\ln A_j(t)$ in (30a). The long-run relationship is $A_j(t-1) = d_j A_{WTP}(t-1)$, where d_j denotes the coefficient of cointegration that is country-specific. In particular, the values of d_j represent the share that a country j accounts for in the world technology pool in the long run. The specification given in (30b) is used to test the theoretical results in the proposition : a country with a stronger capacity to undertake indigenous innovation and absorb foreign technology diffusion accounts for a larger share in the world technology distribution. Then, we could test whether the value of d_j is greater when the capacity of innovation and absorption is stronger. Finally, (30c) examines how the value of d_j is influenced by variables that reflect a country's structural characteristics in terms of the capacity of indigenous innovation and technology adoption. Specifically, we test for the effect of human capital HK_j and institutional quality ISQ_j on the value of d_j.

6.2. Data

The data source for our empirical tests is the latest version of the PWT 9.1 which contains data for variables required in the estimation. PWT 9.1 categorizes all capital in an economy into four types and provides data for each of them in the sample. These four types are (1) residential and nonresidential structure; (2) machinery and non-transport equipment; (3) transport equipment, and (4) other assets including software, intellectual property products, and cultivated assets. According to the study of Corrado et al. (2009), the intangible capital consists of three main categories: computerized information (software), intellectual property (R&D), and economic competency (advertising, staff training, and organization capital). The category "other assets" in the PWT 9.1 reflects the intangible capital conceptualized by Corrado et al. (2009). Therefore, we use the values of the "other assets" as a proxy for the intangible capital stock, which is the proxy for the technology level. In general, intangible capital consists of the stock of immaterial resources that enter the production process and is important for the creation and improvement of products as well as production processes [Arrighetti et al. (2014)]. It has been identified in the existing literature that intangible capital plays an increasingly important role in determining firm productivity and economic performance [Marrocu et al. (2012)].

We also collect data for factors that may potentially determine a country's indigenous innovation efficiency and knowledge absorptive capacity: human capital stock HK_j and institutional quality ISQ_j. We include these two variables based on the findings in Comin and Hobijn (2004) that the most important determinants of the speed at which a country adopts technologies are the country's human capital endowment, type of government, degree of openness to trade, and adoption of predecessor technologies. Since institutional quality covers a measure of trade openness, we do not include another measure of trade openness separately. When estimating (30c), we use the initial values of the variables in the year 1970 which is the earliest year with all the variables required in the estimation. The human capital index in the year 1970 is obtained from PWT 9.1 and is used as a proxy for an initial value of the human capital stock. Initial values of institutional quality are measured by the economic freedom index in 1970, obtained from Fraser Institute's Economic Freedom Database. The database reports a chain-linked summary index that is the average of five subindices: (1) size of government; (2) legal structure and property rights; (3) access to sound money; (4) freedom to trade internationally; and (5) regulation of credit, labor, and business.

6.3. Estimation Methods

The estimation is conducted in STATA 15. We run panel cointegration regressions based on the specifications in (30a) and (30b), and the ordinary least squares estimation for (30c). The empirical results are presented in Tables 2–4.

As we have 180 countries over 45 years (1970–2014) in the sample, the panel is of a large-N and large-T structure. There are several approaches to estimate the regression equation for a heterogeneous dynamic panel with both large N and large T. At one extreme, a fixed-effect (FE) estimation approach could be used in which the time series data for each group are pooled and only the intercepts are allowed to differ across groups. However, if the slope coefficients are not identical, the FE approach produces inconsistent and potentially misleading results. At the other extreme, the model could be fitted separately for each group, and a simple arithmetic average of the coefficients could be calculated. This is the mean group (MG) estimator proposed by Pesaran and Smith (1995). With this estimator, the intercepts, slope coefficients, and error variances are all allowed to differ across groups. In between the two extremes, Pesaran et al. (1999) propose a pooled mean group (PMG) estimator that combines both pooling and averaging. This intermediate estimator allows the intercept, short-run coefficients, and error variances to differ across the groups but constrains the long-run coefficients to be equal across groups.

We adopt the PMG estimator for (30a) and the MG estimator for (30b). The reason for using the two estimators above, respectively, is that for (30a) a common relationship is tested for all countries in the sample, that is, in the long

TABLE 2. The cointegration test of (30a)

d	1.2*** (0.33)
Cointegration tests, under a null of no cointegration	Gt = −2.14 (p-value=0.000) Ga = −10.42 (p-value=0.000) Pt = −22.34 (p-value=0.006) Pa = −5.86 (p-value=0.00)
Number of observations	7113
Number of groups	180
Observations per group avg	40
Test $d = 1$	$F = 1.81$ (p-value=0.18)

Note. Standard errors in parenthesis. Significance levels are denoted as *of 10%, **of 5%, ***of 1%.

TABLE 3. The cointegration test of (30b)

All test statistics of panel cointegration are distributed $N(0, 1)$ under a null, of no cointegration and diverge to negative infinity.	$v = 7.36$ rho = −1.654 $t = 2.68$ adf = −2.125

run, whether the growth rate of an individual country's technology level is equal to that of the world technology pool. Therefore, in the long-run relationship, the coefficient d is common across countries, and the suitable estimator is the PMG estimator. In contrast, (30b) identifies a pairwise relationship between each country and the world in terms of relative technology levels. In the long run, each country ends up with different technology levels relative to world technology. Therefore, the coefficient d_j varies across countries, and the more suitable estimator is the MG estimator.

6.4. Results

In Tables 2 and 3, we can see that the test statistics for the cointegration test with the null of no cointegration are all statistically significant, thus rejecting the null of no cointegration. This finding suggests that there exist long-run relationships as specified in (30a)–(30b). In Table 4, the F-statistic is 1.81 and the associated p-value is 0.18. The test fails to reject the null at conventional significance levels that d is equal to 1 and therefore supports the result that growth rates of technology level are equal across economies in the long run.

In Table 4, we regress the values d_j of individual countries on a country's structural characteristics variables. The results suggest that both human capital and institutional quality are important factors determining a country's relative technology level in the long run. In other words, human capital is an essential input required for indigenous innovation and technology absorption, and institutional quality is also critical in shaping regulatory policy frameworks that enhance

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TABLE 4. The effect of explanatory variables on d_j, estimation of (30c)

Dependent variables	d_j
HK_j	0.44**(0.20)
ISQ_j	0.23**(0.11)
Number of observations	53
R-squared	0.32

Note. Standard errors in parenthesis. Significance levels are denoted as *of 10%, **of 5%, ***of 1%.

both domestic innovation and the absorption of knowledge spillovers from the RoW. These empirical results support the analytical findings in our model and are consistent with the theoretical works on the determinants of technology adoption [e.g., Parente and Prescott (1994), Comin and Hobijn (2004), Stokey (2015)].

It is worth noting that the sample size used to estimate (30c) is smaller than that used to estimate (30a) and (30b) because of limited data available for measuring institutional quality. Another caveat is that we are estimating the long-run relationship using an error correction specification in (30c) for the sample from 1970 to 2014. Although the sample period is long, it is possible that the economies are still in the phase of transitional dynamics and have not entered the BGP yet. Therefore, when interpreting the estimation results, we should bear this caveat in mind.

7. CONCLUSION

The key takeaways from our analysis and findings are as follows. The world equilibrium with technological interdependence is neither simply the equilibrium of each country on its own nor the equilibrium resulting from unidirectional technology diffusion from a single frontier country that grows autonomously. Different countries grow at different rates during transitional dynamics but converge toward a common growth rate in the long run. The pulling force of technological interdependence ensures convergence in the long-run growth rates. The common growth rate for convergence is endogenously determined by structural characteristics of all individual countries in the world economy, rather than by a single frontier country that grows autonomously. Cross-country disparities in structural characteristics and initial conditions lead to divergence in technology and income levels, though technological interdependence ensures convergence in the growth rate. This finding rationalizes *club convergence*: the income levels tend to converge among countries that are identical in structural characteristics and initial conditions but diverge between countries with quite different characteristics and initial conditions.

There are still important caveats. First, our model focuses on specifications of technological interdependence, and the structural characteristics such as indigenous innovation efficiencies and knowledge absorptive capacities are described in exogenous, parsimonious representations. One important direction for extensions is to provide endogenous specifications of indigenous innovation efficiency and knowledge absorptive capacity and to relate them to deeper determinants, such as R&D learning [e.g., Cohen and Levinthal (1989)], intellectual property rights [e.g., Marchese et al. (2019), Iwaisako (2020)], trade barriers [e.g., Parente and Prescott (1994)], education and human capital [e.g., Nelson and Phelps (1966), Stokey (2015), Chu et al. (2019), Dutt and Veneziani (2020)], labor market regulations [e.g., Alesina et al. (2018)], appropriate technology [e.g., Basu and Weil (1998), Acemoglu and Zilibotti (2001)], financial development [e.g., Trew (2014), Sunaga (2019)], and institutional arrangements [e.g., Acemoglu et al. (2006, 2017), Li et al. (2020)]. Second, there can potentially be cross-country linkages through the channel of international capital flows, besides the channel of technological spillovers and interdependence as emphasized in this paper. We expect that there might still be a cross-country pattern of convergence in the growth rates when international capital flows are introduced. But cross-country capital flows provide a channel for widening divergence in levels. Countries with a smaller rate of time preference (a high degree of patience) tend to maintain a positive asset position and consume the larger share of net world outputs, while countries with a larger rate of time preference (a low degree of patience) run a persistent current account deficit and consume less at later dates. The established results of both convergence in growth rates and divergence in levels might be robust. We leave details expositions of these areas for future research.

NOTES

1. The growth accounting literature shows that cross-country differences in income cannot be solely explained by differences in the physical or human capital, and technology differences across countries are likely to be at the heart of cross-country income differences [e.g., Barro (1991), Mankiw et al. (1992), Galor and Tsiddon (1997), Hall and Jones (1999), Galor (2005), Madsen (2008), Jones (2016)].

2. Cross-country differences in productivity and income have increased dramatically over the last 200 years. The average income ratio between Maddisons Western countries and the non-Western countries was 1.9 in 1820 and increased to 7.2 by 2000 [e.g., Maddison (2003)].

3. Without taking technological interdependence into account, the world behaves as an integrated economy rather than an interdependent collection of economies. There is no interaction between countries, and they simply grow in tandem. It would have sufficed to look at one economy only and analyze its growth compared with that of the world leader. Hence, the growth model would become a single-country one, and the equilibrium would be specific to each country on its own, rather than an interdependent world equilibrium.

4. We also acknowledge a strand of literature that examines growth and convergence through the channel of international trade such as Krugman (1979), Ventura (1997), Acemoglu and Ventura (2002), and Prettner and Strulik (2016).

5. For analytical simplicity, the focus of our analysis is on cross-country linkages through the channel of technological spillovers and interdependence. Cross-country interactions through the channel of international capital flows are omitted.

6. While indigenous innovation plays a critical role in improving technical efficiency, an additional source is to be found in the adoption of technologies already developed in other countries according

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to macroeconomic evidences [e.g., Coe and Helpman (1995), Coe et al. (1997), Eaton and Kortum (1999)].

7. European Commission (2013) shows the trend of complementarity in the specialization patterns of three major world areas in the decade 2000–2010. The European Research Area is characterized by a marked specialization in transport and mechanical-related technologies. Asia is markedly specialized in Information and communications technology (ICT) and nanotechnology, and the USA presents a profile of strong specialization in pharmaceuticals, biotechnology, space, and the more service-oriented segments of ICT.

8. Dividing both sides of (6) by $A_j(t)$ obtains $\dot{A}_j(t)/A_j(t) = \lambda_j + \sigma_j \left(A_{WTP}(t)/A_j(t) - 1\right) = \lambda_j + \sigma_j \left(a_j(t)^{-1} - 1\right)$, and substituting it into $g_{WTP}(t) := \dot{A}_{WTP}(t)/A_{WTP}(t) = \sum_{j=1}^{J} (A_j(t)/A_{WTP}(t))(\dot{A}_j(t)/A_j(t)) = \sum_{j=1}^{J} a_j(t)\dot{A}_j(t)/A_j(t)$ derives (9).

9. In the long-run phase of balanced growth, variables with effective levels $[a_j^*, k_j^*, barc_j^*]$ are stationary, and variables with aggregate levels $[c_j(t), b_j(t), K_j(t), L_j(t), A_j(t)]$ increase in a balanced growth pattern.

10. As we tend to put our focus on cross-country disparity in technological characteristics such as indigenous innovation efficiencies and knowledge absorptive capacities, the rate of time preference and the coefficient of relative risk aversion are set at the same level across the three countries/regions.

11. Intangible capital consists of the stock of immaterial resources that enter the production process and are important for the creation or improvement of products as well as production processes [e.g., Arrighetti et al. (2014)]. The intangible capital is playing an important role in the productivity and performance of the economy [e.g., Marrocu et al. (2012)] . The intangible capital consists of three main categories: computerized information, intellectual property, and economic competency such as advertising, staff training, and organization capital [e.g., Corrado et al. (2009)].

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APPENDIX A: TRANSITIONAL DYNAMICS STABILITY

Local stability of transitional dynamics is investigated by evaluating the Jacobian matrix of (10), (11) and (12) at the steady state $[a_j^*, k_j^*, \bar{c}_j^*]$:

$$\begin{bmatrix} \frac{\partial \dot{k}_j}{\partial k_j} & \frac{\partial \dot{k}_j}{\partial a_j} & \frac{\partial \dot{k}_j}{\partial \bar{c}_j} \\ \frac{\partial \dot{a}_j}{\partial k_j} & \frac{\partial \dot{a}_j}{\partial a_j} & \frac{\partial \dot{a}_j}{\partial \bar{c}_j} \\ \frac{\partial \dot{\bar{c}}_j}{\partial k_j} & \frac{\partial \dot{\bar{c}}_j}{\partial a_j} & \frac{\partial \dot{\bar{c}}_j}{\partial \bar{c}_j} \end{bmatrix} = \begin{bmatrix} f'(k_j^*) - \left[n_j + \delta_j + \lambda_j + \sigma_j\left(\frac{1}{a_j^*} - 1\right)\right] & \frac{\sigma_j k_j^*}{\left(a_j^*\right)^2} & -1 \\ 0 & -g_{WTP}^* - \left(\lambda_j - \sigma_j\right)\left(a_j^* - 1\right) & 0 \\ \frac{1}{\theta_j}\bar{c}_j^* f''(k_j^*) & \frac{\sigma_j \bar{c}_j^*}{\left(a_j^*\right)^2} & 0 \end{bmatrix}. \tag{A1}$$

The determinant of the Jacobian matrix (A1) boils down to a three-order polynominal equation as follows:

$$\left(\chi_j + g_{WTP}^* + (\lambda_j - \sigma_j)(a_j^* - 1)\right) \times \left(\chi_j^2 - \left(f'(k_j^*) - n_j - \delta_j - \lambda_j - \sigma_j\left(\frac{1}{a_j^*} - 1\right)\right)\chi_j + \frac{\bar{c}_j^* f''(k_j^*)}{\theta_j}\right) = 0, \tag{A2}$$

where the root of the polynominal equation, χ_j, corresponds to the eigenvalue of the Jacobian matrix (A1). The three-order polynominal equation has three roots, and one of the three eigenvalues takes the form $\chi_j = -g_{WTP}^* - (\lambda_j - \sigma_j)(a_j^* - 1) = -\left(\frac{\sigma_j}{a_j^*} + (\lambda_j - \sigma_j)a_j^*\right) < 0$, where the second equality follows from the first expression of (13), that is, $g_{WTP}^* = \lambda_j - \sigma_j + \sigma_j/a_j^*$. $\lambda_j > \sigma_j$ pins down the negative sign. Meanwhile, given that $\bar{c}_j^* f''(k_j^*)/\theta_j < 0$ in (A2), the other two eigenvalues are one positive and one negative. The negative eigenvalues of the Jacobian matrix thus establish the saddle-path stability of transitional dynamics.

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APPENDIX B: PROOF OF COROLLARY 1

To prove $\partial g^*_{WTP}/\partial\lambda_j > 0$, differentiating (14) with respect to λ_j yields

$$\frac{\sigma_j}{\left(\sigma_j-\lambda_j+g^*_{WTP}\right)^2}\frac{\partial\left(\sigma_j-\lambda_j+g^*_{WTP}\right)}{\partial\lambda_j}+\sum_{i\neq j}\frac{\sigma_i}{\left(\sigma_i-\lambda_i+g^*_{WTP}\right)^2}\frac{\partial\left(\sigma_i-\lambda_i+g^*_{WTP}\right)}{\partial\lambda_j}=0,$$

and simplifying the terms yields (16a). Similarly, differentiating (14) with respect to σ_j yields

$$\frac{1}{\sigma_j-\lambda_j+g^*_{WTP}}-\frac{\sigma_j}{\left(\sigma_j-\lambda_j+g^*_{WTP}\right)^2}\frac{\partial\left(\sigma_j-\lambda_j+g^*_{WTP}\right)}{\partial\sigma_j}$$
$$-\sum_{i\neq j}\frac{\sigma_i}{\left(\sigma_i-\lambda_i+g^*_{WTP}\right)^2}\frac{\partial\left(\sigma_i-\lambda_i+g^*_{WTP}\right)}{\partial\sigma_j}=0,$$

and simplifying the terms yields (16b), where the positive sign follows from $g^*_{WTP}-\lambda_j>0$ given by (14).

APPENDIX C: PROOF OF PROPOSITION 2

Differentiating the first expression of (13) with respect to λ_j yields

$$\begin{aligned}\frac{\partial a^*_j}{\partial\lambda_j}&=\left(\frac{\sigma_j-\lambda_j+g^*_{WTP}}{\sigma_j}\right)^{-2}\left(\frac{1}{\sigma_j}-\frac{1}{\sigma_j}\frac{\partial g^*_{WTP}}{\partial\lambda_j}\right)\\&=\left(\frac{\sigma_j-\lambda_j+g^*_{WTP}}{\sigma_j}\right)^{-2}\left[\frac{\left(\sigma_j-\lambda_j+g^*_{WTP}\right)^2\sum_{i=1}^{J}\frac{\sigma_i}{\left(\sigma_i-\lambda_i+g^*_{WTP}\right)^2}-\sigma_j}{\sigma_j\left(\sigma_j-\lambda_j+g^*_{WTP}\right)^2\sum_{i=1}^{J}\frac{\sigma_i}{\left(\sigma_i-\lambda_i+g^*_{WTP}\right)^2}}\right],\end{aligned}\tag{C1}$$

where (16a) is used to replace $\partial g^*_{WTP}/\partial\lambda_j$ in the first equality of (C1), and the nominator in the last term on the right-hand side of (C1) can be simplified as:

$$\begin{aligned}&\left[\left(\sigma_j-\lambda_j+g^*_{WTP}\right)^2\sum_{i=1}^{J}\frac{\sigma_i}{\left(\sigma_i-\lambda_i+g^*_{WTP}\right)^2}\right]-\sigma_j\\&=\left(\sigma_j-\lambda_j+g^*_{WTP}\right)^2\sum_{i\neq j}\frac{\sigma_i}{\left(\sigma_i-\lambda_i+g^*_{WTP}\right)^2}.\end{aligned}\tag{C2}$$

We hence obtain (17a). Similarly, differentiating the first expression of (13) with respect to σ_j yields

$$\begin{aligned}\frac{\partial a^*_j}{\partial\sigma_j}&=\left(\frac{\sigma_j-\lambda_j+g^*_{WTP}}{\sigma_j}\right)^{-2}\left(\frac{g^*_{WTP}-\lambda_j}{\sigma_j^2}-\frac{1}{\sigma_j}\frac{\partial g^*_{WTP}}{\partial\sigma_j}\right)\\&=\left(\frac{\sigma_j-\lambda_j+g^*_{WTP}}{\sigma_j}\right)^{-2}\left(\frac{g^*_{WTP}-\lambda_j}{\sigma_j}\right)\left[\frac{\left(\sigma_j-\lambda_j+g^*_{WTP}\right)^2\sum_{j=1}^{J}\frac{\sigma_j}{\left(\sigma_j-\lambda_j+g^*_{WTP}\right)^2}-\sigma_j}{\sigma_j\left(\sigma_j-\lambda_j+g^*_{WTP}\right)^2\sum_{i=1}^{J}\frac{\sigma_i}{\left(\sigma_i-\lambda_i+g^*_{WTP}\right)^2}}\right].\end{aligned}\tag{C3}$$

Using (C2) to simplify the terms of (C3) yields (17b).

We proceed by differentiating the first expression of (13) with respect to λ_j yields

$$\frac{\partial a_i^*}{\partial \lambda_j} = -\left(\frac{\sigma_i - \lambda_i + g_{WTP}^*}{\sigma_i}\right)^{-2}\left(\frac{1}{\sigma_i}\frac{\partial g_{WTP}^*}{\partial \lambda_j}\right) < 0,$$

$$\frac{\partial a_i^*}{\partial \sigma_j} = -\left(\frac{\sigma_i - \lambda_i + g_{WTP}^*}{\sigma_i}\right)^{-2}\left(\frac{1}{\sigma_i}\frac{\partial g_{WTP}^*}{\partial \sigma_j}\right) < 0,$$

and using (16a) to replace the expression of $\frac{\partial g_{WTP}^*}{\partial \lambda_j}$ yields (17c) and (17d).

APPENDIX D: PROOF OF PROPOSITION 3

First, imposing the stationary condition on $\dot{a}_j/a_j = \dot{A}_j/A_j - \dot{A}_{WTP}/A_{WTP}$ yields $\dot{A}_i^*/A_i^* = \dot{A}_j^*/A_j^* = \dot{A}_{WTP}^*/A_{WTP}^* := g_{WTP}^*$ for countries $i, j = 1, 2, ..., J$. Given $\dot{A}_i^*/A_i^* = \dot{A}_j^*/A_j^* = \dot{A}_{WTP}^*/A_{WTP}^*$, we have $A_i^*/A_j^* = a_i^*/a_j^*$. Then substituting the first expression of (13) yields (18). Second, following the second expression of (13), we derive

$$\frac{k_i^*}{k_j^*} = \frac{f'^{\,-1} \times \left(\delta_i + \rho_i + \theta_i g_{WTP}^*\right)}{f'^{\,-1}\left(\delta_j + \rho_j + \theta_j g_{WTP}^*\right)},$$

which yields (19). Finally, following the last expression of (13), we have

$$\frac{c_i^*}{c_j^*} = \frac{A_i^*}{A_j^*}\frac{\bar{c}_i^*}{\bar{c}_j^*} = \left(\frac{\frac{\sigma_i}{(\sigma_i - \lambda_i + g_{WTP}^*)}}{\frac{\sigma_j}{(\sigma_j - \lambda_j + g_{WTP}^*)}}\right)$$

$$\times\left(\frac{f(f'^{\,-1}\left(\delta_i + \rho_i + \theta_i g_{WTP}^*\right)) - \left(\delta_i + n_i + g_{WTP}^*\right) f'^{\,-1}\left(\delta_i + \rho_i + \theta_i g_{WTP}^*\right)}{f(f'^{\,-1}\left(\delta_j + \rho_j + \theta_j g_{WTP}^*\right)) - \left(\delta_j + n_j + g_{WTP}^*\right) f'^{\,-1}\left(\delta_j + \rho_j + \theta_j g_{WTP}^*\right)}\right),$$

which yields (20).

APPENDIX E: PROOF OF PROPOSITION 4

Given that $A_i^*/A_j^* = a_i^*/a_j^*$, differentiating a_i^*/a_j^* with respect to λ_i, σ_i, λ_j and σ_j yields

$$\frac{\partial(a_i^*/a_j^*)}{\partial \lambda_i} = \frac{1}{a_j^*}\frac{\partial a_i^*}{\partial \lambda_i} - \frac{a_i^*}{(a_j^*)^2}\frac{\partial a_j^*}{\partial \lambda_i} > 0, \qquad \frac{\partial(a_i^*/a_j^*)}{\partial \sigma_i} = \frac{1}{a_j^*}\frac{\partial a_i^*}{\partial \sigma_i} - \frac{a_i^*}{(a_j^*)^2}\frac{\partial a_j^*}{\partial \sigma_i} > 0, \quad \textbf{(E1a)}$$

$$\frac{\partial(a_i^*/a_j^*)}{\partial \lambda_j} = \frac{1}{a_j^*}\frac{\partial a_i^*}{\partial \lambda_j} - \frac{a_i^*}{(a_j^*)^2}\frac{\partial a_j^*}{\partial \lambda_j} < 0, \qquad \frac{\partial(a_i^*/a_j^*)}{\partial \sigma_j} = \frac{1}{a_j^*}\frac{\partial a_i^*}{\partial \sigma_j} - \frac{a_i^*}{(a_j^*)^2}\frac{\partial a_j^*}{\partial \sigma_j} < 0, \quad \textbf{(E1b)}$$

where the signs of (E1a)–(E1b) are determined following $\frac{\partial a_i^*}{\partial \lambda_i} > 0$, $\frac{\partial a_j^*}{\partial \lambda_i} < 0$, $\frac{\partial a_i^*}{\partial \sigma_i} > 0$, $\frac{\partial a_j^*}{\partial \sigma_i} < 0$, $\frac{\partial a_i^*}{\partial \lambda_j} < 0$, $\frac{\partial a_j^*}{\partial \lambda_j} > 0$, $\frac{\partial a_i^*}{\partial \sigma_j} < 0$ and $\frac{\partial a_j^*}{\partial \sigma_j} > 0$ as given by (6.1).

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For the within-country effect, differentiating the second and third expression of (13) with respect to λ_j and σ_j yields

$$\frac{\partial k_j^*}{\partial \lambda_j} = \frac{\theta_j}{f''(k_j^*)} \frac{\partial g_{WTP}^*}{\partial \lambda_j} < 0, \tag{E2a}$$

$$\frac{\partial k_j^*}{\partial \sigma_j} = \frac{\theta_j}{f''(k_j^*)} \frac{\partial g_{WTP}^*}{\partial \sigma_j} < 0, \tag{E2b}$$

$$\frac{\partial \bar{c}_j^*}{\partial \lambda_j} = \left(\left((\theta_j - 1) g_{WTP}^* + \rho_j - n_j \right) \frac{\theta_j}{f''(k_j^*)} - k_j^* \right) \frac{\partial g_{WTP}^*}{\partial \lambda_j} < 0, \tag{E2c}$$

$$\frac{\partial \bar{c}_j^*}{\partial \sigma_j} = \left(\left((\theta_j - 1) g_{WTP}^* + \rho_j - n_j \right) \frac{\theta_j}{f''(k_j^*)} - k_j^* \right) \frac{\partial g_{WTP}^*}{\partial \sigma_j} < 0, \tag{E2d}$$

where $(\theta_j - 1) g_{WTP}^* - n_j > 0$ with $\theta_j > 1$, and the negative sign follows from $f''(k_j^*) < 0$, $\partial g_{WTP}^* / \partial \lambda_j > 0$, and $\partial g_{WTP}^* / \partial \sigma_j > 0$. Meanwhile, for the cross-country effect, differentiating the second and third expression of (13) with respect to σ_j and λ_j yields

$$\frac{\partial k_i^*}{\partial \lambda_j} = \frac{\theta_i}{f''(k_i^*)} \frac{\partial g_{WTP}^*}{\partial \lambda_j} < 0, \tag{E3a}$$

$$\frac{\partial k_i^*}{\partial \sigma_j} = \frac{\theta_i}{f''(k_i^*)} \frac{\partial g_{WTP}^*}{\partial \sigma_j} < 0, \tag{E3b}$$

$$\frac{\partial \bar{c}_i^*}{\partial \lambda_j} = \left[\left((\theta_i - 1) g_{WTP}^* + \rho_i - n_i \right) \frac{\theta_i}{f''(k_i^*)} - k_i^* \right] \frac{\partial g_{WTP}^*}{\partial \lambda_j} < 0, \tag{E3c}$$

$$\frac{\partial \bar{c}_i^*}{\partial \sigma_j} = \left[\left((\theta_i - 1) g_{WTP}^* + \rho_i - n_i \right) \frac{\theta_i}{f''(k_i^*)} - k_i^* \right] \frac{\partial g_{WTP}^*}{\partial \sigma_j} < 0, \tag{E3d}$$

where the negative sign follows from $(\theta_i - 1) g_{WTP}^* + \rho_i - n_i > 0, f''(k_i^*) < 0$, $\frac{\partial g_{WTP}^*}{\partial \lambda_j} > 0$ and $\frac{\partial g_{WTP}^*}{\partial \sigma_j} > 0$.

For the comparative static effect on $\frac{K_i^*}{K_j^*} = \frac{k_i^*}{k_j^*} \frac{A_i^*}{A_j^*} \frac{L_i^*}{L_j^*} = \frac{k_i^*}{k_j^*} \frac{a_i^*}{a_j^*} \frac{L_i^*}{L_j^*}$, differentiating $\frac{K_i^*}{K_j^*}$ with respect to λ_i and σ_i yields

$$\frac{\partial (K_i^*/K_j^*)}{\partial \lambda_i} = \left(\frac{a_i^*}{a_j^*} \cdot \frac{\partial (k_i^*/k_j^*)}{\partial \lambda_i} + \frac{k_i^*}{k_j^*} \cdot \frac{\partial (a_i^*/a_j^*)}{\partial \lambda_i} \right) \frac{L_i^*}{L_j^*}, \tag{E4}$$

where the first term in the right-hand side of (E4) is given by:

$$\frac{a_i^*}{a_j^*} \cdot \frac{\partial (k_i^*/k_j^*)}{\partial \lambda_i} = \frac{a_i^*}{a_j^*} \cdot \left(\frac{1}{k_j^*} \frac{\partial k_i^*}{\partial \lambda_i} - \frac{k_i^*}{(k_j^*)^2} \frac{\partial k_j^*}{\partial \lambda_i} \right) = \frac{a_i^*}{a_j^*} \frac{k_i^*}{k_j^*} \left(\frac{\theta_i}{k_i^* f''(k_i^*)} - \frac{\theta_j}{k_j^* f''(k_j^*)} \right) \frac{\partial g_{WTP}^*}{\partial \lambda_i},$$

and the second term in the right-hand side of (E4) is given by:

$$\frac{k_i^*}{k_j^*} \cdot \frac{\partial (a_i^*/a_j^*)}{\partial \lambda_i} = \frac{k_i^*}{k_j^*} \cdot \left(\frac{1}{a_j^*} \frac{\partial a_i^*}{\partial \lambda_i} - \frac{a_i^*}{(a_j^*)^2} \frac{\partial a_j^*}{\partial \lambda_i} \right)$$

$$= \frac{a_i^*}{a_j^*} \frac{k_i^*}{k_j^*} \left(\frac{1}{a_i^*} \sum_{j \neq i} \frac{\sigma_j}{\left(\sigma_j - \lambda_j + g_{WTP}^* \right)^2} - \frac{1}{a_j^*} \frac{\sigma_j}{\left(\sigma_j - \lambda_j + g_{WTP}^* \right)^2} \right) \frac{\partial g_{WTP}^*}{\partial \lambda_i}.$$

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We thus simplify (E4) as:

$$\frac{\partial(K_i^*/K_j^*)}{\partial\lambda_i} = \frac{a_i^*}{a_j^*}\frac{k_i^*}{k_j^*}\frac{L_i^*}{L_j^*}\frac{\partial g_{WTP}^*}{\partial\lambda_i} \times \left(\frac{\theta_i}{k_i^* f''(k_i^*)} - \frac{\theta_j}{k_j^* f''(k_j^*)} + \frac{1}{a_i^*}\sum_{j\neq i}\frac{\sigma_j}{\left(\sigma_j-\lambda_j+g_{WTP}^*\right)^2} - \frac{1}{a_j^*}\frac{\sigma_j}{\left(\sigma_j-\lambda_j+g_{WTP}^*\right)^2}\right),$$

and obtain the condition (22). Similarly, we can show that $\frac{\partial(K_i^*/K_j^*)}{\partial\sigma_i} > 0$, $\frac{\partial(K_i^*/K_j^*)}{\partial\lambda_j} < 0$, and $\frac{\partial(K_i^*/K_j^*)}{\partial\sigma_j} < 0$ if the condition (22) holds.

For the comparative static effect on $\frac{C_i^*}{C_j^*} = \frac{\bar{c}_i^*}{\bar{c}_j^*}\frac{A_i^*}{A_j^*}\frac{L_i^*}{L_j^*} = \frac{\bar{c}_i^*}{\bar{c}_j^*}\frac{a_i^*}{a_j^*}\frac{L_i^*}{L_j^*}$, differentiating $\frac{C_i^*}{C_j^*}$ with respect to λ_i and σ_i yields

$$\frac{\partial(C_i^*/C_j^*)}{\partial\lambda_i} = \left(\frac{a_i^*}{a_j^*}\cdot\frac{\partial(\bar{c}_i^*/\bar{c}_j^*)}{\partial\lambda_i} + \frac{\bar{c}_i^*}{\bar{c}_j^*}\cdot\frac{\partial(a_i^*/a_j^*)}{\partial\lambda_i}\right)\frac{L_i^*}{L_j^*}, \tag{E5}$$

where the first term in the right-hand side of (E5) is given by:

$$\frac{a_i^*}{a_j^*}\cdot\frac{\partial(\bar{c}_i^*/\bar{c}_j^*)}{\partial\lambda_i} = \frac{a_i^*}{a_j^*}\cdot\left(\frac{1}{\bar{c}_j^*}\frac{\partial\bar{c}_i^*}{\partial\lambda_i} - \frac{\bar{c}_i^*}{(\bar{c}_j^*)^2}\frac{\partial\bar{c}_j^*}{\partial\lambda_i}\right)$$
$$= \frac{a_i^*}{a_j^*}\frac{\bar{c}_i^*}{\bar{c}_j^*}\left[\frac{1}{\bar{c}_i^*}\left(\left((\theta_i-1)g_{WTP}^*+\rho_i-n_i\right)\frac{\theta_i}{f''(k_i^*)} - k_i^*\right) - \frac{1}{\bar{c}_j^*}\left(\left((\theta_j-1)g_{WTP}^*+\rho_j-n_j\right)\frac{\theta_j}{f''(k_j^*)} - k_j^*\right)\right]\frac{\partial g_{WTP}^*}{\partial\lambda_i},$$

and the second term in the right-hand side of (E5) is given by:

$$\frac{\bar{c}_i^*}{\bar{c}_j^*}\cdot\frac{\partial(a_i^*/a_j^*)}{\partial\lambda_i} = \frac{\bar{c}_i^*}{\bar{c}_j^*}\cdot\left(\frac{1}{a_j^*}\frac{\partial a_i^*}{\partial\lambda_i} - \frac{a_i^*}{(a_j^*)^2}\frac{\partial a_j^*}{\partial\lambda_i}\right)$$
$$= \frac{a_i^*}{a_j^*}\frac{\bar{c}_i^*}{\bar{c}_j^*}\left(\frac{1}{a_i^*}\sum_{j\neq i}\frac{\sigma_j}{\left(\sigma_j-\lambda_j+g_{WTP}^*\right)^2} - \frac{1}{a_j^*}\frac{\sigma_j}{\left(\sigma_j-\lambda_j+g_{WTP}^*\right)^2}\right)\frac{\partial g_{WTP}^*}{\partial\lambda_i},$$

We thus simplify (E5) as:

$$\frac{\partial(C_i^*/C_j^*)}{\partial\lambda_i} = \frac{a_i^*}{a_j^*}\frac{\bar{c}_i^*}{\bar{c}_j^*}\frac{L_i^*}{L_j^*}\frac{\partial g_{WTP}^*}{\partial\lambda_i}\left[\frac{1}{a_i^*}\sum_{j\neq i}\frac{\sigma_j}{\left(\sigma_j-\lambda_j+g_{WTP}^*\right)^2} - \frac{1}{a_j^*}\frac{\sigma_j}{\left(\sigma_j-\lambda_j+g_{WTP}^*\right)^2} + \frac{1}{\bar{c}_i^*}\left(\left((\theta_i-1)g_{WTP}^*+\rho_i-n_i\right)\frac{\theta_i}{f''(k_i^*)} - k_i^*\right) - \frac{1}{\bar{c}_j^*}\left(\left((\theta_j-1)g_{WTP}^*+\rho_j-n_j\right)\frac{\theta_j}{f''(k_j^*)} - k_j^*\right)\right].$$

and obtain the condition (25). Similarly, we can show that $\frac{\partial(C_i^*/C_j^*)}{\partial\sigma_i} > 0$, $\frac{\partial(C_i^*/C_j^*)}{\partial\lambda_j} < 0$, and $\frac{\partial(C_i^*/C_j^*)}{\partial\sigma_j} < 0$ if the condition (25) holds.

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APPENDIX F: PROOF OF PROPOSITION 5

For the negative eigenvalue given by (29), $\frac{\sigma_j}{a_j^*} + (\lambda_j - \sigma_j)a_j^*$ is decreasing in a_j^* when a_j^* is within the range $a_j^* \in \left[0, \sqrt{\sigma_j(\lambda_j - \sigma_j)}/\sigma_j\right]$. As the value of the technology gap decreases $a_j^* \downarrow$, the absolute value of the negative eigenvalue increases $|\chi_j| \uparrow$, thus translating into a larger speed of convergence and a shorter time of transitional dynamics.

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