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A model of sequential reforms and economic convergence: The case of China ☆

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ABSTRACT

Motivated by China's experience, a growth model is developed to explain the repeated interaction between economic reforms and growth in a developing country. Convergence occurs until the developing country reaches a bottleneck, then convergence stops unless the institution is improved. After the reform, convergence resumes until a new bottleneck is encountered, which triggers another reform, and so on. Using recursive methods, I show analytically that, in a perfect international credit market, each reform occurs when the new growth bottleneck just becomes binding; the reform size changes monotonically over time; there are finite reforms and convergence is unceasing until the last constraint binds, so a permanent GDP gap may exist. The model also implies that a politically more powerful government should adopt more gradual reforms. In an imperfect credit market, convergence can be delayed and an initially richer economy can be more likely to adopt insufficient reforms.

1. Introduction

The last several decades witnessed institutional transitions in China, India, Russia, Vietnam, and many other developing countries. Some were successful and managed to converge to the richest economies, but others failed. To understand why, Rodrik (2005) reviews a vast pertinent literature of reforms and economic accelerations. He finds that economic accelerations (not mere recoveries from recessions) typically occur after certain binding institutional bottlenecks are relaxed. Moreover, to ignite economic convergence in a developing economy may only need a small institutional or policy change, but to sustain the convergence it would require a process of *cumulative institutional building* along the way:

> "*In the long run, the main thing that ensures convergence with the living standards of advanced countries is the acquisition of high-quality institutions. The growth-spurring strategies have to be complemented over time with a cumulative process of institution building to ensure that growth does not run out of steam…*"

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This also echoes the increasingly popular view that institutions are fundamental causes of long-run growth (see Acemoglu, Johnson, and Robinson (2005); Hall and Jones (1999); North (1990)). Surprisingly, however, there exist few, if any, theoretical models that explicitly characterize how economic convergence occurs with an *endogenously cumulative process of institutional building* in the standard growth/convergence framework.[1] In this paper I aim to help fill this gap.

China is a case in point for such investigations. It has undertaken gradualist reforms and achieved spectacular convergence in the past three decades. In this process there is a salient feature: a policy or institutional reform ignites economic convergence, which continues until the economy meets a new binding constraint. Then another reform is undertaken to eliminate this new growth obstacle. Convergence resumes afterwards until another new binding constraint arises, so on and so forth. In other words, economic convergence triggers, and is also sustained by, endogenous and successive institutional reforms.[2]

In this paper, I develop a formal model to capture precisely this interactive process between economic growth (convergence) and sequential relaxations of newly-binding constraints, which is so far only informally described in the literature. The focus is on the analytical characterization of their mechanical interactions. I discipline the modeling by making minimum deviations from standard growth models. To maintain tractability, I put forth a highly parsimonious model to address two normative questions: what is the first-best reform scheme and how does it interact with economic convergence? The model is adapted from the endogenous growth framework developed by Lucas (1988, 2009). The issues addressed here are also closely related to the question how to eliminate barriers to adopting better foreign technology (see Parente and Prescott (1994, 2000)).[3]

In the existing growth literature, economic convergence is usually studied with institutions and policy barriers taken as exogenous and time-invariant (Barro & Sala-I-Martin, 1992; Ngai, 2004; Stokey, 2012). My approach is different in that the barrier is an endogenous policy variable instead of an exogenous parameter. Economic reforms are modeled as endogenous reduction of this barrier variable. Similar to Lucas (2009), there is a developing economy and an exogenously growing developed economy. Growth occurs with the accumulation of human capital, which should be interpreted as a proxy for the composite of all the production factors and technology. The initially large gap in human capital (and GDP) allows the poor economy to catch up thanks to knowledge spillover or technology diffusion. The new element in my model is that convergence stops when the gap shrinks to a threshold value, which depends on the barrier variable. This convergence bottleneck is referred to as a binding convergence constraint.

Economic reforms are costly. Each reform entails a fixed cost and a variable cost. The fixed cost may reflect how efficient the decision process of a reform is. For example, it includes all the implicit and explicit size-independent cost to formulate a reform plan and the cost to get the reform proposal formally approved. The variable cost includes all the rest of the implicit and explicit social cost associated with the reform and it is a convex function of the reform size, so the reform cost increases disproportionately more as the reform becomes more radical. Given the reform cost function, the benevolent social planner, or Ramsey government, formulates a barrier adjustment scheme, which specifies when and how much to change this barrier variable to maximize social welfare.

Using recursive methods, I analytically characterize this non-stationary dynamic optimization problem to show how economic growth triggers barrier reduction (institutional reforms) and how reforms feedback on factor accumulation and growth dynamics. The model is able to generate the pattern of repeated interactions between reforms and growth observed in reality (outlined above). In addition, four main results are obtained. First, each reform occurs precisely when the convergence constraint becomes binding. Second, the magnitude and frequency of reforms are both monotonic over time. More precisely, if the reform size decreases (increases) over time, the frequency of reforms increases (decreases) over time. Third, the number of reforms is finite and the successive reforms support an unceasing convergence until the convergence constraint binds permanently. In the long run, a GDP gap may still exist but the two countries will have the same growth rate.[4] Fourth, when the international credit market is imperfect, reforms may be delayed and the resulting convergence process can be punctuated and intermittent. In addition, there may exist an advantage to backwardness in reforms. That is, an initially richer economy is sometimes more likely to undertake insufficient reforms, because growth bottleneck is reached too soon, even before enough saving is accumulated. Following Parente and Prescott (2000), I place more emphases on level effect than growth effect in the analysis.[5]

The model developed here highlights the importance of cumulative and sequential reforms that underlie the entire process of economic convergence. At a superficial level, the course of convergence still appears to be fully dictated by human capital accumulation without any explicit role for the barrier variable, seemingly identical to the existing convergence literature with exogenous barriers. However, at a deeper level, my model mechanism strongly echoes the view of Acemoglu et al. (2005) and

[1] Acemoglu, Aghion, and Zilibotti (2006) show that, in order to achieve sustained development, the growth mode should switch from an investment-based strategy to an innovation-based strategy when a country gets closer to the world technology frontier. However, they do not emphasize the “cumulative process” of sequentially relaxing the new institutional constraints.

[2] Section 2 provides two concrete motivating stories to illustrate this pattern in China. For more discussions, also see Roland (2000), Naughton (2007), Rodrik (2010), Xu (2011), and Lin (2012). This pattern of repeated interactions between convergence and reform is also widely observed in other economies that succeeded in catching up after World War II (Rodrik, 2005; Wade, 1990; World Bank, 2005).

[3] Klenow and Rodriguez-Clare (2005) provide a survey for human capital learning externality and economic growth. This paper is also closely related to discussions on human capital and technology diffusion by Benhabib and Spiegel (2005). Stokey (2012) examines explicitly the different roles played by human capital and technology diffusion in the catch-up process.

[4] The above three results are all based on the assumption that the international credit market is perfect, which also implies that households' risk attitude or intertemporal elasticity of substitution does not affect any of these results, because uncertainty is fully insured away by the international market and the optimal reform schemes are not constrained by the short-run financial ability thanks to the international borrowing. The GDP time path remains unchanged, but the consumption growth rate depends on the intertemporal elasticity of substitution. However, refer to footnote 11 and Appendix 10 for more discussions.

[5] In growth models with human capital learning externality (without institutional change), a standard result is that the developing and the developed countries grow at the same speed on the balanced growth path, as implied by the law of motion in the human capital diffusion (Klenow & Rodriguez-Clare, 2005). But the level difference can be still enormous. Parente and Prescott (2000) argue that it is important to look at the level effect as well.

Rodrik (2005) by demonstrating explicitly that, beneath the GDP dynamics, the fundamental force that ignites and sustains economic convergence is actually the successive reforms in institutions or policies. These reforms sequentially eliminate newly-arising binding constraints *along with* the process of convergence, the empirical relevance of which is repeatedly established and stressed in the growth and transition literature (Hausmann, Rodrik, & Velasco, 2008; Lin, 2012; Qian, 2003; Rodrik, 2005, 2010; World Bank, 2005). Unfortunately, so far few attempts, if any, have been made to formalize this important idea in the pertinent growth and reform literature.

The model also sheds light on optimal reform strategies. Reforms should be made at the point of "crisis", which occurs when the convergence constraint is binding within the model, because further convergence is jeopardized at that moment. This prediction is consistent with the empirically-verified "crisis hypothesis" in the reform literature, but the mechanism is different from the political economy argument (Alesina, Ardagna, & Trebbi, 2006; Drazen & Grilli, 1993). Another implication of the model is that the optimal reform scheme depends on the administrative power of the government, as it determines the relative importance of the fixed and variable reform costs. A strong government, which may be authoritarian, tends to formulate and implement a reform plan more quickly than a weak government, so the fixed cost for each reform is smaller, ceteris paribus. The opposite can be true for the variable cost of reform, because a weak government is more likely to have already negotiated with different parties to minimize the negative consequences for any given reform size.[6] This intrinsic asymmetry, according to the model, implies that the economy with a stronger government *should* have a more gradual reform, because the fixed cost is relatively small, so it pays to increase the number of reforms and reduce the size for each reform, mainly to avoid the variable cost with a large reform size (because of convexity). The opposite is true for a weaker government because the fixed cost is so high that it is optimal to have either no reform or relatively "lumpy" reforms.

These results are diametrically opposite to the standard "Washington Consensus", which recommends that all imperfect institutions must be reformed thoroughly and simultaneously at the fastest speed regardless of the cost structures of reforms or the strength of government, which is called "shock therapy". It would imply that convergence should come after thorough reforms and that no binding constraint will ever occur afterwards.[7]

How capital investment is affected by fixed and variable adjustment costs has been intensively discussed in the textbook investment model with convex adjustment cost functions and in the more sophisticated (S, s) inventory models. However, methodologically, a distinctive feature of my model is that it studies the "capacity adjustment" instead of "flow adjustment". Recall that (S, s) inventory models examine how to adjust the inventory "flow" under the constraint that the "container" has an exogenous capacity, but what is optimally adjusted in this paper is the capacity of the "container" rather than the "flow" itself. Notice that my model does not directly adjust human capital as it cannot jump discontinuously, which is different from physical capital investment in the pertinent investment literature.

In this regard, Parente (1994) is similar to the (S, s) model because the choice variable is the technology level per se instead of the capacity or ability of technology adoption. A more important difference between Parente's model and mine is the budget constraint. In his model the adjustment cost is the loss of expertise; the cost is not paid explicitly with physical resources, hence the budget constraint problem is circumvented. In contrast, reforms require physical resources in my model. I show that different degrees of international credit market perfectness, which affects the budget constraint of the reformer, have significant impact on reform strategies and growth dynamics.

The existing academic literature on reforms and transitions typically focuses on one, or at most two, specific institution or policy change(s) at a time. The merit of this approach is that it allows for explicitly incorporating more institutional details into the analysis,[8] but this separate treatment of different reforms does not help organize our thinking about the interactive process of all different reforms and convergence at different development stages of the sort we observe in China and many other economies. It is this interactive process that I try to formalize and shed light on. Dewatripont and Roland (1992), Wei (1997), Lau, Qian, and Roland (2000), Caselli and Gennaioli (2008), among others, study the optimal sequencing of reforms by analyzing how to make it politically feasible to gain enough support to push forward different reforms in the presence of multiple groups with conflicting interests; these models are not formulated in an explicit growth framework, so it is not clear how reforms and convergence interact. Moreover, they focus on the role of political constraints rather than the sequentially binding growth bottlenecks. My paper complements this literature by helping bridge the gap between the two different, often orthogonal, strands of literature: economic convergence and sequential reforms.

The rest of the paper is organized as follows: Section 2 provides two specific motivating stories from China. Section 3 describes the general setting of the model economy. Sections 4 and 5 examine the optimal reform and the associated growth dynamics when the international credit market is perfect and imperfect, respectively. Section 6 concludes by discussing some possible avenues for future research.

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[6] A recent growing literature emphasizes the importance of state capacity and the shortcomings of a weak government in economic development; see Blanchard and Shleifer (2001), Acemoglu (2005), Besley and Persson (2009).

[7] The "Washington Consensus" has received wide criticism as it is incapable of explaining many empirical facts including, for example, the stagnation of the average developing countries in 1980–1998, although they all followed the prescriptions of the "Washington Consensus" (Easterly, 2001). The skepticism reached its peak after the former Soviet Union and some other Eastern European countries experienced unexpectedly huge economic difficulties after adopting the shock therapy. In sharp contrast, China achieved unexpected success by adopting a more pragmatic and piece-meal reform strategy; see Stiglitz (1998), Rodrik (2005, 2010), World Bank (2005), Xu (2011) and Lin (2012).

[8] See, for example, Murphy, Shleifer, and Vishny (1992), Lin (1992), Barberis, Boycko, Shleifer, and Tsukanova (1996), Banerjee, Ghatak, and Gertler (2002), Easterly (2005), and Wang (2013). Excellent surveys include Xu (2011) and Roland (2000).

2. Motivating stories from China

This section provides two concrete motivating Chinese stories to illustrate how the reduction of growth barrier (reform) interacts with economic convergence (growth) and what the reform costs may consist of in reality. International comparison is also made to highlight the distinctive features of these Chinese cases and to further explain how the economic mechanisms work under different conditions.

The first story is about the development process of a potato industry in Anding county in Northwest China. Before the Household Responsibility System (HRS) was adopted in the late 1970s, all the farmers worked for the commune and were paid equally regardless of individual effort. Naturally the output was low and people could not even feed themselves. After the agricultural reform, HRS was implemented, which allowed individual households to claim their residuals after fulfilling a fixed quota. This reform solved the incentive problem, which was the main institutional bottleneck for growth at that stage, so output grew rapidly. However, the next growth hurdle appeared soon: the land was too infertile to raise the output of traditional crops such as wheat or sorghum. To dismantle this growth bottleneck, the local government invited some agricultural experts from Beijing to seek solutions. It was soon discovered that some types of potatoes were magically suitable for the land conditions of that region. Those potatoes were introduced into Anding, together with the information about how to grow them efficiently. Aggregate agricultural output increased tremendously afterwards. Farmers could not only feed themselves but also have surplus potatoes to sell.

Now came the new growth bottleneck: local farmers had no price information. Consequently, farmers could only sell their surplus potatoes at low prices to a handful of local intermediaries with monopoly power. To overcome this bottleneck, the county government of Anding established an office located in Zhengzhou, one of the major national potato markets and far away from Anding, to help collect the potato price information, which would be posted and made freely accessible to all the farmers in Anding. As the information hurdle was dismantled, local farmers got good prices for their surplus potatoes and output skyrocketed. However, the fast output growth soon created a new growth bottleneck: long-distance transportation had to rely on trains, but only two carts were allocated to Anding. It was impossible for the local farmers or the local government to fundamentally change the way how the whole railway system should operate. However, after some personal contact and negotiations between the Anding government and China's Ministry of Railways, four more carts were added to the trains and the transportation constraint was effectively relaxed, after which potato output continued to climb. Witnessing the success of Anding's potato industry, the neighboring counties started to mimic the practice of potato business in Anding, so even six carts soon became insufficient. Then local people cooperated with the local government and found an innovative way to store potatoes during the harvest season. They also tried to produce and export higher value-added processed potato products rather than just raw potatoes, which led to further growth in the local GDP (see Zhang and Hu (2014)).

In this story, we can see clearly that industrial development encountered distinctive bottlenecks at different stages: production incentives, technology constraints, information hurdle, transportation capacity, storing technology, and so on. Most of these binding constraints were directly or indirectly due to institutions or policies. Continuous economic growth (or convergence to richer regions) became admissible only when the new binding constraints were dismantled. Moreover, the constraints are sequentially binding. A growth constraint that became binding later would not have become binding if the economy had not developed after the earlier growth-binding barriers were eliminated. In other words, economic growth triggered the arrival of new binding constraints and hence called for further changes in institutions or policies (reforms). Meanwhile, reforms relaxed the growth bottlenecks and sustained economic growth. These are the key characteristics which must be captured by the theoretical model to be developed.

It is also important to understand the associated reform costs in this story.[9] For example, the introduction of the HRS involves both fixed and variable reform costs. The fixed cost may include all the time, fiscal, and administrative resources spent in reaching the decision to implement the HRS by the local government, whereas the variable cost may include, depending on how thorough and how quick the reform is, all the time, fiscal, political, administrative, legal cost when the government officials implemented the HRS in the field as well as all the cost shouldered by the households in the entire process. Similarly, to remove the price information hurdle, the fixed cost again may include all the cost the county government spent in learning about the growth bottleneck and reaching the decision to get involved and take specific actions to solve this problem, that is, to help collect and disseminate price information for the local farmers, whereas the variable cost includes the cost to establish an office in Zhengzhou and maintain its daily operations as well as the profit loss suffered by the middle men, etc. Alternatively, the local government could choose to also set offices in other major potato markets, provide both the current price information and the price forecasting services, and even sponsor telephone lines to each potato producer directly connected to the Zhengzhou office to avoid transmission delays, and so on. That would be certainly more attractive from the potato producers' perspective, but the variable cost would be much higher. Similar cost analyses can be made for the other reform steps, but skipped here for the space constraint.

Note that the fixed cost for each reform (or relaxation of growth barriers) is relatively small because local government in China has strong economic incentives and sufficient fiscal and administrative power to make quick decisions to propose and initiate economic reforms. The above story also suggests that it is too costly, both financially and politically, to eliminate all the potential growth constraints in one step. Consequently, economic reforms are piece-meal, sequential, and timely. It stands in stark contrast with India, which features political decentralization and economic centralization, exactly the opposite to China, so the Indian local government is much weaker in the sense that it has more limited fiscal power and reform proposals typically take much longer time to get approved due to the pressure from different vested interest groups via the democratic process (see, Bardhan, 2010; Wang (2013)).

[9] The reform cost function will be formally introduced and interpreted in Section 3.

The relatively high fixed cost of reforms in India could explain why its reforms (such as infrastructure building) are typically much less frequent than China at the local government level.

Although this is a story about only one particular industry in a particular region, the interactive process of economic convergence and successive removal of binding obstacles is a general pattern in China's industrial development. The associated reform costs and their impact on the reform patterns are also quite representative. These elements are crucial for us to understand the general logic behind the sequential reforms and economic growth at the local level when the cost structure of reforms is dictated by the political institutions and the economic nature of the associated activities.

The second motivating story is a brief narrative of China's major reforms and aggregate growth at the national level in the past 35 years.[10] The primary goal is to illustrate how sequential reforms and economic growth repeatedly interact with each other at the macro scale. Different from the first story, now the national government plays a key role and the reforms move across sectors and regions as the entire economy grows. The cost structures of those reforms could be analyzed analogously as in the first story.

More specifically, China's economic acceleration started by the rural reform in the late 1970s, when farmers' incentives to work were stimulated after the abolishment of the collectivization mode and the universal adoption of the Household Responsibility System across the country. Rural productivity and total output increased dramatically after the incentive constraint was relaxed (Lin, 1992). However, economic growth soon led to a new bottleneck: as more farmers were released from the agricultural production, further growth required that more industrial jobs be created for them, but it was unconstitutional to establish private firms at that time and the Hukou system virtually prohibited rural labor from migrating into urban areas. This bottleneck was circumvented by the institutional innovation of the semi-public Township-and-Village Enterprises (TVEs), which were ideologically more acceptable. Without fundamentally changing the constitution or law enforcement, this reform facilitated rural industrialization and significantly contributed to the aggregate growth (Qian, 2003).

After the Tiananmen event in 1989, western countries imposed both financial and technological sanctions on China, and the liberalization reforms in China were radically challenged by the political conservatives and hence were suspended, followed by the stagnant growth performance. The market-oriented reform and open-door policies resumed after Deng Xiaoping's South Tour in 1992. Special economic zones were established and favorable policies were introduced to attract foreign direct investment, which effectively released the financial and technological constraints so the catch-up growth continued (Lin, 2012). All the economic development paved the way for the reform of inefficient State-Owned Enterprises (SOEs), which were then the major growth obstacle for the urban areas and for the country at large. Massive SOE reforms started in the late 1990s. However, China adopted a gradual approach by keeping the large SOEs, especially those in the upstream industries (such as energy, raw materials, and banks), and letting go small-and-medium-sized SOEs, which were mostly concentrated in the downstream industries (such as labor-intensive manufacturing and consumption-oriented services such as hotels and restaurants) (Li, Liu, and Wang (2012)). Deregulation of downstream industries resulted in resource reallocation from bankrupt SOEs to more productive private firms, which enabled China to continue its high growth rate (Song, Storesletten, and Zilibotti (2011)). However, a new growth bottleneck will arise when the labor cost increases to a certain level, because the downstream private firms have to pay markup prices for some key intermediate inputs and services monopolized by upstream SOEs. Without reforming the upstream SOE monopoly, the downstream private sectors would be strangled and lose the international competitiveness, so the economic convergence would also stop (Li et al. (2012)).

Notice that, diametrically opposite to the Chinese experience, the former Soviet Union followed the recommendation of the Washington Concensus and adopted a “shock therapy” by privatizing all the SOEs overnight, which incurred decade-long high unemployment, economic recessions and huge social cost. This is because China was politically centralized, ensuring that the central government remained powerful and, therefore, was able to steer the reforms steadily (with low fixed cost of reforms and low variable cost for any given reform size), whereas the former Soviet Union became politically decentralized in the 1990s, and the de facto power fell to the hands of a few political oligarchies or even the mafia, so the central government was extraordinarily weak during the transition period (Blanchard & Shleifer, 2001). It implies high fixed cost of reforms, as the decision making process for orderly reforms was difficult, so radical reforms were a more natural equilibrium choice. In addition, the former Soviet Union received generous foreign aid and low-interest loans to support its shock therapy, which made it financially feasible to even implement overly large-size reforms (Stiglitz, 1998). However, China received much less foreign aid to directly finance its institutional reforms, which made it even more necessary to economize the reform sizes in each step. It suggests that the accessibility to international credit market may also play an important role and hence should be theorized.

To summarize, the above two motivating stories highlight the interactive process of successive reforms and economic convergence. The brief comparison with India and the former Soviet Union indicates that the reform cost structures closely depend on the political institutions as well as the perfectness of international credit market. The Chinese experiences, especially the economic logic, are not necessarily unique. Wade (1990), Canda (2006), Rodrik (2005) and World Bank (2005) all provide convincing cross-country case studies and empirical evidence showing that mild policy (or institutional) changes sometimes can activate an industry or even a whole economy and that the industry or the whole economy keeps developing as the sequentially-binding growth bottlenecks are eliminated one by one via policy changes or institutional reforms. Complementary to this view, Hausmann et al. (2008) and Rodrik (2010) further advocate the approach of growth diagnostics and they find that the binding institutional constraints for growth indeed not only differ across different countries but also vary over time along with economic development for the same country.

[10] A complete narrative of China's economic development is beyond the scope of this paper, and many other important features of the Chinese economy are not highlighted here. For more detailed treatment, see Qian (2003), Naughton (2007), Rodrik (2010), Xu (2011), Lin (2012), and the references cited there.

3. Model environment

Although the two detailed motivating stories are both from China, the logic of the model is more general. Consider a developing economy populated by a unit mass of identical households. A representative household maximizes the total present value of discounted utility:

$$\int_0^\infty c(t)e^{-\rho t}dt, \tag{1}$$

where ρ is the discount rate. The assumption of infinite inter-temporal elasticity of substitution helps us focus on the institutional change problem by making the consumption analysis trivial.[11] A representative household is endowed with one unit of labor, which is inelastically supplied to produce one homogeneous good with the following technology:

$$f(h,G) = mh^{\alpha}G^{1-\alpha},$$

where h is the human capital and G represents the public goods and services provided by the government. Suppose G is financed by the tax revenues on the output at rate τ, then $\tau f(h,G)$, which implies

$$f(h,G(h,\tau)) = \tau^{\frac{1-\alpha}{\alpha}}m^{\frac{1}{\alpha}}h.$$

Without loss of generality, we can normalize parameter m such that the above equation is reduced to

$$\widetilde{f}(h) = h,$$

that is, one unit of human capital ultimately can produce one unit of final good, which is storable and can be either consumed or used to pay the cost of institution adjustment. Human capital in this model should not be interpreted too literally and narrowly. It should be interpreted as a proxy for the composite of all the intangible cumulative production factors and technology embodied in the labor.[12] The initial human capital is h_0.

There is also a developed economy with the same one-to-one production technology. $H(t)$ denotes its per capita human capital stock at time t, which grows exogenously at a constant exponential speed g_H. $H(0)$ is normalized to unity. Due to the positive externality in human capital or adoption of external better technology, $h(t)$ increases up to a limit determined by an institutional barrier variable, $\delta(t)$. As in Parente and Prescott (1994, 2000), Lucas (2009) and Stokey (2012), variable $\delta(t)$ captures all the pertinent policy and institutional factors that affect diffusion, adoption, and operation of technology (and human skills) at time t. It may include international factors such as trade barriers, FDI policies, intellectual property rights protections, academic and business exchange programs, international media controls, and domestic factors which affect working incentives, allocation efficiency, information hurdles, public good provision, monopoly, etc. (see Klenow and Rodriguez-Clare (2005) for a more comprehensive treatment). A larger $\delta(t)$ means a worse institution. δ_0 denotes the initial barrier value. The law of motion for $h(t)$, and hence the GDP of the developing country, is given by

$$\dot{h}(t) = \mu h(t)\Phi\left(\frac{h(t)}{H(t)},\delta(t)\right)\cdot \dot{H}(t),$$

where μ is a positive parameter dictating the growth rate of domestic human capital net of depreciation in autarky; $\Phi\left(\frac{h(t)}{H(t)},\delta(t)\right)$ captures all the underlying economic forces of convergence, which depends on the gap in human capital $\frac{h(t)}{H(t)}$ and the barrier variable $\delta(t)$.[13] In particular, I assume

$$\Phi\left(\frac{h(t)}{H(t)},\delta(t)\right) \equiv \begin{cases} \frac{h(t)}{H(t)}, & \text{if} \quad \frac{h(t)}{H(t)} < \frac{\eta}{\delta(t)}, \\ 0, & \text{otherwise} \end{cases}$$

[11] Consumption dynamics would be different with a non-degenerate CRRA utility function. However, it turns out that the equilibrium reforms and output path would remain exactly the same for the general CRRA utility function when the international credit market is perfect in this deterministic environment. Please refer to Appendix 10 for the formal proof. The intuition is the following. The Ramsey government decomposes its dynamic decision into two separate steps: first, it tries to maximize the representative household's total life-time income via optimal reforms; second, dynamic consumption decisions will be made subject to the inter-temporal budget constraint because of the perfect international credit market. However, the analysis becomes much more complicated when the international credit market is imperfect, but such complication does not seem promising to pursue for new insights, especially because this paper wants to emphasize the level effect instead of the growth effect and the focus is on institutional reforms rather than consumption behaviors. Please refer to Appendix 10 for more details.

[12] The textbook treatment of the endogenous time allocation decisions on human capital accumulation does not yield any new insights for the purpose of this paper, so I choose to abstract away this dimension of complication.

[13] Of course, institutional barriers differ in nature and change over time, but for our purpose all the different barriers and the related reforms must be incorporated into a unified and tractable framework, so different pertinent institutions are captured by a single variable, $\delta(t)$, in this model, just for analytical simplicity.

which says that, for any given institutional barrier $\delta(t)$, a larger gap in human capital (a smaller $\frac{h(t)}{H(t)}$), which can be also equivalently interpreted as gap in technology or GDP in this model, generates a stronger tendency for convergence because the foreign pool of ideas to tap is larger from the developing country's point of view. This is a standard conditional convergence assumption justified by theoretical and empirical support (see Barro and Sala-I-Martin (1992) and the aforementioned growth literature). On the other hand, for any given GDP gap $\frac{h(t)}{H(t)}$, a worse institution (larger barrier $\delta(t)$) tends to admit more limited room for the catch-up growth of the developing country. In the Chinese motivating stories in Section 2, such barriers are in the forms of incentive constraints by farmers, information hurdle and limited transportation capacity due to insufficient provision of public goods and service, illegal status of private firms at the early stage of market-oriented reforms, international economic sanction, barriers to FDI and trade, inefficient financial sector, upstream SOE monopoly, and so on.

Positive parameter μ is the speed of convergence. η is another positive parameter useful for comparative statics analysis. A higher η implies a longer time to enjoy the convergence for any given institution barrier and gap in per capita GDP. One possible interpretation for η could be the population ratio of the developing economy relative to the developed economy, which captures the scale effect. However, convergence is conditional on that $\frac{h(t)}{H(t)} < \frac{\eta}{\delta(t)}$ holds, that is, the convergence constraint is not binding.[14] Define $x(t) \equiv \frac{h(t)}{H(t)}$, then the above two equations yield

$$\frac{dx(t)/dt}{x(t)} = \begin{cases} \mu, & \text{if} \quad x(t) < \dfrac{\eta}{\delta(t)} \\ 0, & \text{otherwise} \end{cases} \quad \text{and} \quad x(0) = h_0. \tag{2}$$

So the gap between the two countries shrinks at a constant exponential speed μ until the gap hits the critical value $\frac{\eta}{\delta(t)}$, at which point convergence stops unless the institutional barrier variable $\delta(t)$ is adjusted downward. This is what I mean by "institutional improvement" or "reform".[15]

The reform cost has two components: a variable cost and a fixed cost. More precisely, when $\delta(t)$ is adjusted from δ to δ' in a single step, the cost is given by

$$C(\delta, \delta') = \begin{cases} A\left(\dfrac{\delta}{\delta'}\right)^{\phi} + B, & \text{if} \;\; \delta \neq \delta' \;\; \text{and} \;\; \delta' \geq \eta \\ \infty, & \text{if} \;\; \delta' < \eta \\ 0, & \text{if} \;\; \delta = \delta' \end{cases}, \tag{3}$$

where parameters A and B are both positive. $\phi > 1$, so the adjustment cost function is convex in the adjustment size, $\frac{\delta}{\delta'}$. No adjustment $(\delta = \delta')$ naturally incurs no cost. Eq. (3) also imposes a lower bound for δ', which is to rule out the leapfrogging of the developing economy by merely exploiting international human capital externality or adopting existing technologies. So $x(t) \leq 1, \ \forall t$.

The reform cost depends on the structural details of the political institutions, so Eq. (3) should be interpreted as a reduced form for the overall cost associated with reforms. A bigger reform is more costly, as is captured by the variable cost, $A\left(\frac{\delta}{\delta'}\right)^{\phi}$. Given the size of barrier adjustment, countries that implement reforms mainly through administrative orders and centralized planning are more likely to create larger distortions and hence incur a higher social cost, so A would be larger, compared with the pro-market reform strategies in a more deregulated economy. On the other hand, the fixed cost B may include all the opportunity costs of proposing a reform plan and getting it passed in the legislature. B is large if intensive multilateral bargaining and negotiations are always involved in each reform process. The more powerful and politically consolidated the central government, the smaller the fixed cost B.[16] Dixit (2004) explicitly discusses costs of institution-building, and he argues that setting up formal institutions (such as legal rules and democratic political systems) requires high fixed costs B but low marginal (variable) costs (smaller A), whereas informal institutions (such as moral codes and common practice) are the opposite.

Reform reversals (upward adjustment of δ) are allowed, but a benevolent government has no incentive to do so, and hence the relevant adjustment must be downward. The functional space for the reform policy function is

$$\Delta \equiv \{\text{real function } \delta(t) : \mathbb{R}_+ \rightarrow [\eta, \delta_0] \text{ such that } \delta(0) = \delta_0\}.$$

Conventional reasoning implies that $\delta(t)$ must be a step function due to the convexity of cost function and positive fixed cost B. More precisely, the Ramsey government needs to find a bounded and weakly decreasing sequence $\{\delta_i\}_{i=0}^{\infty}$ and the corresponding

[14] Lucas (2009) assumes that $\dot{H}(t)/H(t) = g_H$ and $\dot{h}(t) = g_H h(t)^{1-\theta} H(t)^{\theta}$, which imply that convergence never stops and that in the long run there exists no speed difference $\left(\lim_{t\to\infty} \frac{\dot{h}(t)}{h(t)} = \dot{H}(t)/H(t) = g_H\right)$ or level difference $\left(\lim_{t\to\infty} \frac{h(t)}{H(t)} = 1\right)$. In contrast, in my model, convergence would stop if the binding learning constraint is not endogenously relaxed in time (via adjustment of $\delta(t)$) and there may exist long run level difference $\left(\lim_{t\to\infty} \frac{h(t)}{H(t)} < 1\right)$, as will be clear soon.

[15] It is not too much difficult to generalize the human capital evolution equation such that the binary-value function (2) becomes a multi-value step function (or a continuous function in the limit) so that the convergence speed also depends on the gap. For simplicity, the developing economy never grows at a speed lower than the developed economy by construction, same as Lucas (2009). One possible way to incorporate the possibility of "falling behind" (widening gap) is to introduce stochastic growth rate such as Geometric Brownian Motion into Eq. (2), which is challenging due to the non-existence of fixed point of policy function in the associated Hamilton–Jacoby–Bellman equation due to the non-stationary nature of this dynamic reform problem, as is clear later. Also see Stokey (2012).

[16] Blanchard and Shleifer (2001) argue that one important reason that the decentralization economic reform was successful in China but failed in Russia in the 1990s is that China was more politically centralized; hence every step of the reform was under the control of the strong central government, whereas the Russian central government at that time was too weak to maintain orders or implement effective reforms, and the reforms turned chaotic.

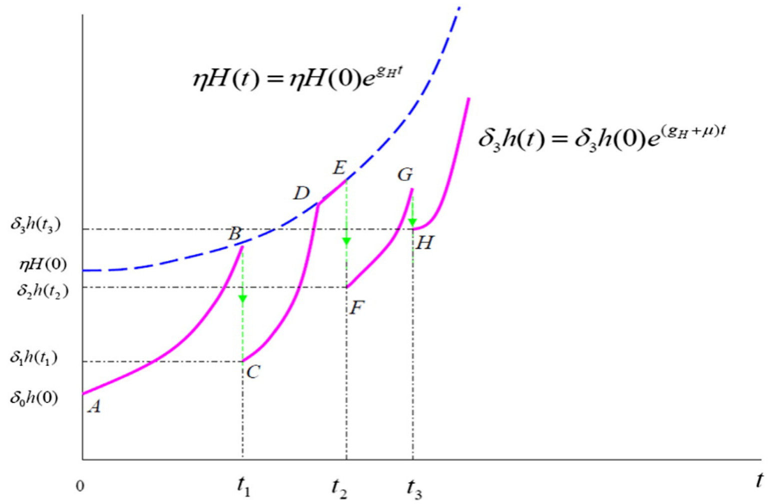

Fig. 1. A possible reform scheme. Note: The horizontal axis is time t and the vertical axis is function values. The dashed (blue) curve plots the product of population ratio η and the developed economy's human capital stock $H(t)$. The solid (pink) curve is the product of the developing economy's human capital stock $h(t)$ and barrier variable $\delta(t)$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

adjustment time sequence $\{t_i\}_{i=0}^{\infty}$ with given δ_0 and $t_0 = 0$, where δ_i and t_i stand for, respectively, the value of the barrier variable right after the ith adjustment and the time of that adjustment.

Fig. 1 depicts what a possible (not necessarily optimal) adjustment path would look like. The dashed curve plots $\eta H(t)$, which grows at the exponential speed g_H. The solid curve is $h(t)\delta(t)$, which is the developing economy's human capital stock multiplied by the barrier variable $\delta(t)$. At time 0, the developing economy is at point A. No institutional adjustment is made, so Eq. (2) implies that $h(t)$ grows at the exponential speed $g_H + \mu$ until time t_1, when the solid line hits the dashed line at point B. That is, the convergence constraint becomes binding. The barrier variable is adjusted downward from δ_0 to δ_1 at time t_1, so $\delta(t)h(t)$ jumps down to point C. Note that human capital cannot jump. The adjustment cost $C(\delta_0,\delta_1)$ is paid at t_1. After this reform, the convergence constraint is relaxed so $h(t)$ continues to grow at speed $g_H + \mu$ until the convergence constraint becomes binding again at point D. Since no reform is made, convergence stops and $h(t)$ can only grow at speed g_H afterwards.[17] So the solid curve overlaps with the dashed curve. The second reform is made at time t_2, at which point the developing economy jumps from point E to point F due to the downward change of the barrier variable to δ_2. The convergence resumes. At time t_3, the convergence constraint is not binding yet, but the third reform may be implemented at this time point, so the economy jumps from point G to point H, and so on. My task is to find the optimal adjustment scheme, namely, the optimal solid curve such that the representative household's goal function (1) is maximized.

Before I mathematically characterize this dynamic reform problem, which appears to be mechanical, it may be important to highlight its economic relevance. As can be seen from the motivating examples in Section 2, reform and growth (convergence) interact with each other repeatedly. Reform is needed to sustain the catch-up process, which in turn leads to sequentially binding growth bottlenecks as the economy grows. Binding constraints are different at different development stages. These newly-arising bottlenecks then trigger further rounds of reforms. Without catch-up growth, new institutional bottlenecks would not present themselves in the first place. This is precisely the logic behind China's pragmatic approach of gradual reforms. Fig. 1 shows that institutions can be improved successively along with economic growth. Alternatively, δ_0 can be thoroughly improved to the perfect level η in one step (if financially feasible), and then the economy enjoys convergence without the necessity to conduct reforms in the future. Which one is better and what else do we know? These issues are addressed by this model.

Eq. (2) implies that it can be assumed without loss of generality that $g_H = 0$, as I am most interested in convergence (relative performance) of the developing country.[18] Thus, $x(t) \equiv h(t)$, $\forall t$. The interest rate r in the developing country is exogenously determined by the international credit market. I set r equal to ρ. To make the analysis empirically relevant and theoretically concise, I focus on the case when $\mu > r$.[19] Section 4 studies the problem when the international credit market is perfect so that the developing economy can borrow internationally. Optimal reform under an imperfect credit market is studied in Section 5. Section 6 concludes by briefly discussing several possible directions for future research.

[17] It is consistent with the standard result that, in the long-run equilibrium, the developed and developing countries have the same growth rate on the balance growth paths, as in Klenow and Rodriguez-Clare (2005) and Benhabib and Spiegel (2005).

[18] To see this, we can simply define $\hat{\mu} \equiv \mu + g_H$ when $g_H > 0$ with $\hat{\mu}$ reinterpreted as the catching-up speed or relative speed between the two economies. So learning externality still exists when the learning constraint binds, even though convergence stops.

[19] μ is the difference in the growth rates between the two countries during the convergence process. When the two countries are China and the US, μ is clearly larger than the annual interest rate of the risk-free treasury bills in the last 30 years. Theoretically, it is straightforward to analyze the case when $\mu \leq r$ by following exactly the same method, but no additional insights can be obtained.

4. Reform under perfect credit market

When international borrowing is allowed, any optimal (hence beneficial) institutional adjustment by definition must satisfy the budget constraint. The Ramsey government needs to find an optimal adjustment scheme, $\{\delta_i, t_i\}_{i=1}^{\infty}$, and an optimal time path of consumption, $c(t) \geq 0, \forall t$, to maximize the objective function (1) subject to Eqs. (2), (3), with δ_0 and h_0 given, and subject to the following budget constraint:

$$\int_0^{\infty} c(t)e^{-rt}dt \leq \sum_{i=0}^{\infty}\left[\int_{t_i}^{t_{i+1}} h(t)e^{-rt}dt - C(\delta_i, \delta_{i+1})e^{-rt_{i+1}}\right], \tag{4}$$

that is, the total present value of consumption must not exceed the total present value of output (income) net of all the reform costs.[20] t_0 is set equal to 0. The status quo is maintained if the net benefit of the reform is zero.

Given δ_0 and h_0, the social planner's problem can be rewritten as follows:

$$V(\delta_0, h_0) \equiv \max_{\{\delta_i, t_i\}_{i=1}^{\infty}} \sum_{i=0}^{\infty}\left[\int_{t_i}^{t_{i+1}} h(t)e^{-rt}dt - C(\delta_i, \delta_{i+1})e^{-rt_{i+1}}\right], \tag{5}$$

subject to Eqs. (2), (3), and that the associated adjustments must be always affordable:

$$\sum_{i=0}^{\infty}\left[\int_{t_i}^{t_{i+1}} h(t)e^{-rt}dt - C(\delta_i, \delta_{i+1})e^{-rt_{i+1}}\right] \geq 0. \tag{6}$$

The key analytical challenge lies in the fact that the optimization problem is non-stationary in the sense that there exists no fixed point for the value function or the implicit policy function for the associated Bellman equation. This is mainly because of the discontinuity of the catch-up speed before and after learning constraints become binding (see Eq. (2)) and that $\delta(t)$ may change discontinuously for only a finite number of times (to be clear soon). However, this problem can still be analyzed recursively. Let N denote the total number of adjustment opportunities that are available to the planner. I first set N to be a given finite number and examine the corresponding mechanics of this dynamic system. Let V_N denote the value function with a total of N adjustment opportunities. Later, I will set $N = \infty$ and explore the optimal number of adjustment options that are actually needed. Observe that $V(\delta_0, h_0)$ in Eq. (5) must be bounded both from above and from below because $h(t) \leq 1, \forall t$.

4.1. No adjustment opportunity (N = 0)

When $N = 0$, convergence occurs until the convergence constraint becomes binding (at point B shown in Fig. 1), so GDP evolves as follows:

$$h(t) = \begin{cases} h_0 e^{\mu t}, & \text{if } t < \hat{t} \\ h_0 e^{\mu \hat{t}}, & \text{if } t \geq \hat{t} \end{cases},$$

where $\hat{t}$ is the time point when the convergence constraint just binds:

$$\hat{t} = \max\left\{0, \frac{1}{\mu}\ln\frac{\eta}{\delta_0 h_0}\right\}. \tag{7}$$

The corresponding value function with zero adjustment is given by

$$V_0(\delta_0, h_0) = h_0\int_0^{\hat{t}} e^{\mu t}e^{-rt}dt + e^{-r\hat{t}}\int_0^{\infty}\frac{\eta}{\delta_0}e^{-rt}dt,$$

[20] The model is cast as a central planner problem rather than a competitive equilibrium problem for reasons beyond the second welfare theorem and modeling convenience: (1) some important markets may be missing in the less developed economy, hence resource allocation may not fully operate through the market mechanism, and (2) in reality the central governments in many transitional economies have a far greater administrative power than their counterparts in the developed economies, both in terms of shaping and changing the institutions. In reality, in many developing countries such as China or India, the central governments do have and implement very formal and extensive five-year, 10-year or 20-year plans to reform economic institutions.

which, by revoking Eq. (7), yields

$$V_0(\delta_0,h_0)=\begin{cases}\dfrac{\mu h_0}{r(\mu-r)}\left(\dfrac{\eta}{\delta_0 h_0}\right)^{\frac{\mu-r}{\mu}}-\dfrac{h_0}{\mu-r}, & \text{if } \delta_0 h_0<\eta\\ \dfrac{h_0}{r}, & \text{if } \delta_0 h_0\geq\eta\end{cases}. \tag{8}$$

To avoid analytical triviality, the initial income gap is assumed to be sufficiently large that reforms are desirable:

Assumption A0.

$$h_0<\eta/\delta_0. \tag{A0}$$

4.2. One adjustment opportunity (N = 1)

Let t_1 denote the time when the barrier variable is adjusted. The control can be exercised either weakly before or weakly after the convergence constraint binds, so the value function is given by

$$V_1(\delta_0,h_0)=\max\{G_1(\delta_0,h_0),F_1(\delta_0,h_0)\},$$

where

$$G_1(\delta_0,h_0)\equiv\max_{t_1\leq\hat{t},\delta_1\geq\eta}\int_0^{t_1}h_0e^{\mu t}e^{-rt}dt+e^{-rt_1}\left[V_0\left(\delta_1,h_0e^{\mu t_1}\right)-C(\delta_0,\delta_1)\right], \tag{9}$$

and

$$F_1(\delta_0,h_0)\equiv\max_{\hat{t}\leq t_1,\delta_1\geq\eta}\left[\begin{array}{l}\int_0^{\hat{t}}h_0e^{\mu t}e^{-rt}dt+\int_{\hat{t}}^{t_1}\dfrac{\eta}{\delta_0}e^{-rt}dt\\ +e^{-rt_1}\left[V_0\left(\delta_1,\dfrac{\eta}{\delta_0}\right)-C(\delta_0,\delta_1)\right]\end{array}\right] \tag{10}$$

$$=\max_{\hat{t}\leq t_1,\delta_1\geq\eta}\left[\begin{array}{c}V_0(\delta_0,h_0)+\\ +e^{-rt_1}\left[V_0\left(\delta_1,\dfrac{\eta}{\delta_0}\right)-C(\delta_0,\delta_1)-V_0\left(\delta_0,\dfrac{\eta}{\delta_0}\right)\right]\end{array}\right]. \tag{11}$$

The following lemma says that the optimal reform time is weakly after the convergence constraint first becomes binding.

Lemma 1. *$V_1(\delta_0,h_0)=F_1(\delta_0,h_0)$ for any (δ_0,h_0) that satisfies Assumption A0.*

Proof. Refer to Appendix 1. ■

The intuition is straightforward. For any adjustment made strictly before the convergence constraint becomes binding, the net value can be strictly increased if the same size adjustment is made at $\hat{t}$. This is because the gross benefit of any such adjustment is independent of the adjustment time before the convergence constraint binds and the same adjustment cost is paid later. This lemma allows us to focus on the adjustment made only weakly after the learning barrier becomes binding.

Lemma 2. *$t_1^*=\hat{t}$ if $\delta_1^*<\delta_0$ and $t_1^*<\infty$, where $\hat{t}$ is given by Eq. (7).*

Proof. Refer to Appendix 2. ■

Lemma 2 states that the barrier adjustment, if made, must occur when the convergence constraint just binds. The intuition is that any further delay is undesirable because the optimal adjustment size remains the same and the net gain of reform is reaped later, as indicated by the second term in Eq. (11). The optimal adjustment size is obtained from the first order condition. It is an interior solution if and only if the following is true:

$$A\phi r\leq\frac{\eta}{\delta_0}\leq(A\phi r)^{\frac{1}{\phi+\frac{r}{\mu}}}, \tag{12}$$

where the first inequality ensures that the adjustment is downward ($\delta_1 \le \delta_0$) and the second inequality ensures that the new barrier is no smaller than η (that is, $\delta_1 \ge \eta$). For the convenience of exposition, define

$$\widetilde{B}(z) \equiv A\left[\frac{A\phi rz}{\eta}\right]^{\frac{-\phi}{\phi+\frac{r}{\mu}-1}}\left(\frac{\phi\mu}{\mu-r}-1\right)-\frac{\eta\mu}{r(\mu-r)z};$$
$$\hat{B}(z) \equiv \frac{\mu}{r(\mu-r)}\left(\frac{\eta}{z}\right)^{\frac{r}{\mu}}-A\left(\frac{z}{\eta}\right)^{\phi}-\frac{\eta\mu}{r(\mu-r)z}.$$

Proposition 1. *Suppose $N=1$. When Eq. (12) is satisfied and $B<\widetilde{B}(\delta_0)$, an optimal downward barrier adjustment will be made at $\hat{t}$ (given by Eq. (7)) and $\delta_1^*=\theta(\delta_0)\delta_0$, where*

$$\theta(\delta_0) \equiv \left[\frac{A\phi r\delta_0}{\eta}\right]^{\frac{1}{\phi+\frac{r}{\mu}-1}}. \tag{13}$$

So the adjustment size is $\theta(\delta_0)^{-1}$. When $A\phi r \le (A\phi r)^{\frac{1}{\phi+\frac{r}{\mu}}} < \frac{\eta}{\delta_0}$ and $B<\hat{B}(\delta_0)$ both hold, an optimal downward barrier adjustment is made at $\hat{t}$ and $\delta_1^*=\eta$. Otherwise no adjustment will be made. Correspondingly, the value function is given by

$$V_1(\delta_0,h_0)=\begin{cases}\frac{\mu\eta}{r(\mu-r)}\left(\frac{\eta}{\delta_0 h_0}\right)^{\frac{-r}{\mu}}\theta(\delta_0)^{\frac{r}{\mu}-1}\delta_0^{-1}-\frac{h_0}{\mu-r}-\left(\frac{\eta}{\delta_0 h_0}\right)^{\frac{-r}{\mu}}\left(A\theta(\delta_0)^{-\phi}+B\right), & \text{when } \widetilde{B}(\delta_0)>B \text{ and Eq. (12) is satisfied.}\\ \frac{\mu}{r(\mu-r)}(h_0)^{\frac{r}{\mu}}-\frac{h_0}{\mu-r}-\left(\frac{\eta}{\delta_0 h_0}\right)^{\frac{-r}{\mu}}\left(A\left(\frac{\eta}{\delta_0}\right)^{-\phi}+B\right), & \text{when } \hat{B}(\delta_0)>B \text{ and } A\phi r\le(A\phi r)^{\frac{1}{\phi+\frac{r}{\mu}}}<\frac{\eta}{\delta_0}\\ V_0(\delta_0,h_0), & \text{otherwise}\end{cases}. \tag{14}$$

Proof. Refer to Appendix 3. ■

The intuition is easy to understand by checking the option value of having one adjustment opportunity. Suppose the current institutional variable is δ and the convergence constraint is already binding (i.e., $x=\frac{\eta}{\delta}$). Suppose the barrier variable is adjusted from δ to some $\widetilde{\delta}\in[\eta,\delta)$. Let $y\equiv\frac{\delta}{\widetilde{\delta}}$ denote the adjustment size and $\Omega(y,\delta)$ denote the instantaneous net gain by undertaking an adjustment of size y from δ. Thus

$$\Omega(y,\delta)=V_0\left(\widetilde{\delta},\frac{\eta}{\delta}\right)-C\left(\delta,\widetilde{\delta}\right)-V_0\left(\delta,\frac{\eta}{\delta}\right).$$

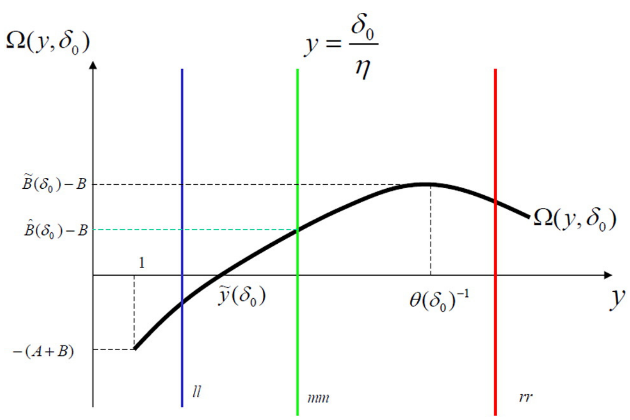

Fig. 2. One adjustment option under perfect credit market. Note: The horizontal axis is reform size y and the vertical axis is $\Omega(y,\delta_0)$, denoting instantaneous net gain of a reform with reform size y from initial barrier δ_0. The vertical line $y=\frac{\delta_0}{\eta}$ is the largest possible adjustment size, which may have three different types of values, corresponding to three different positions: *ll*, *mm*, *rr*, respectively.

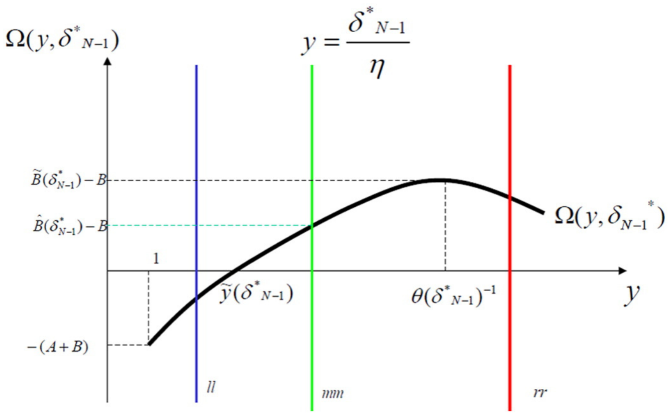

Fig. 3. Last adjustment option under perfect credit market. Note: The horizontal axis is reform size y and the vertical axis is $\Omega(y, \delta^*_{N-1})$, denoting instantaneous net gain of the final (the Nth) reform with reform size y from barrier δ^*_{N-1}. The vertical line $y=\frac{\delta^*_{N-1}}{\eta}$ is the largest possible adjustment size for the final reform, which may have three different types of values, corresponding to three different positions: *ll*, *mm*, *rr*, respectively.

Using Eqs. (3) and (8), we obtain

$$\Omega(y,\delta)\equiv\frac{\mu\eta}{\delta r(\mu-r)}\left[y^{1-\frac{r}{\mu}}-1\right]-\left[Ay^{\phi}+B\right]. \tag{15}$$

An adjustment will be exercised if and only if there exists some adjustment size $\hat{y}\in\left(1,\frac{\delta}{\eta}\right]$ such that the net adjustment gain $\Omega(\hat{y},\delta)>0$. The option value of having one adjustment opportunity is therefore $\max\left\{0,\ \max_{y\in\left(1,\frac{\delta}{\eta}\right]}\Omega(y,\delta)\right\}$. Let $\tilde{y}(\delta)$ denote the smallest positive root of $\Omega(y,\delta)=0$ for any given δ if $\max_{y\in\left(1,\frac{\delta}{\eta}\right]}\Omega(y,\delta)>0$. Observe that $\lim_{y\downarrow 1}\Omega(y,\delta)=-(A+B)<0$ and $\Omega(y,\delta)$ is continuous and strictly increasing in y on the interval $(1,\theta(\delta)^{-1})$. So when $\widetilde{B}(\delta)>B$, the mean value theorem implies that there must exist a unique root of $\Omega(y,\delta)$, denoted as $\tilde{y}(\delta)$.

More intuitively, the optimal reform strategy described in Proposition 1 can be illustrated in Fig. 2.

Notice that $\delta=\delta_0$ at the beginning. An optimal reform size y (horizontal axis) should be chosen to maximize the net instantaneous reform gain $\Omega(y,\delta_0)$ at time $\hat{t}$. Curve $\Omega(y,\delta_0)$ is given by Eq. (15). Recall that $\frac{\delta_0}{\eta}$ is the largest possible adjustment size implied by Eq. (3), so optimal y has to be to the left of the vertical line $y=\frac{\delta_0}{\eta}$ and also larger than 1. In general, the vertical line $y\frac{\delta_0}{\eta}$ may have three possible positions, depending on whether $\frac{\delta_0}{\eta}\geq\theta(\delta_0)^{-1}$ (a position like *rr*), or $\frac{\delta_0}{\eta}\in\left(\widetilde{Y}(\delta),\theta(\delta_0)^{-1}\right]$ (a position like *mm*), or $\frac{\delta_0}{\eta}\in(1,\tilde{y}(\delta)]$ (a position like *ll*). The first inequality in Eq. (12) ensures that the interior adjustment size $\theta(\delta_0)^{-1}$ is greater than one, whereas the second weak inequality ensures that $\theta(\delta_0)^{-1}$ is smaller than $\frac{\delta_0}{\eta}$. That is, vertical line $y=\frac{\delta_0}{\eta}$ is in a position like *rr*. In that case, the optimal adjustment size is $\theta(\delta_0)^{-1}$ and the option value $\Omega(y,\delta_0)$ reaches the maximum $\widetilde{B}(\delta_0)-B$. Note that $B<\widetilde{B}(\delta_0)$ guarantees that the option value of having one adjustment opportunity is strictly positive $\left(\max_{y\in\left(1,\frac{\delta}{\eta}\right]}\Omega(y,\delta_0)>0\right)$. When the second weak inequality in Eq. (12) is violated, there are two possibilities. One is $\hat{B}(\delta_0)>B$, in which case line $y=\frac{\delta_0}{\eta}$ is at a position like *mm* (that is, $\frac{\delta_0}{\eta}>\tilde{y}(\delta_0)$) so the option value of adjustment $\max_{y\in\left(1,\frac{\delta}{\eta}\right]}\Omega(y,\delta_0)=\hat{B}(\delta_0)-B$, which is strictly positive. And the barrier variable is adjusted to η. The other possibility is when $\hat{B}(\delta_0)\leq B$, in which case line $y=\frac{\delta_0}{\eta}$ is at a position like *ll* so the adjustment option is waived because $\max_{y\in\left(1,\frac{\delta}{\eta}\right]}\Omega(y,\delta_0)<0$. For all the remaining circumstances, no adjustment is made either. This completes the geometric illustration for $N=1$, as summarized in Proposition 1.

From the backward induction point of view, the above analysis also applies when the social planner with N adjustment opportunities decides its last adjustment option after using up the first N–1 opportunities. When compared with Fig. 2, all the functional forms and curves remain unchanged except that $\delta=\delta^*_{N-1}$. For example, $\Omega(y,\delta)$ is still given by Eq. (15) except that $\delta=\delta^*_{N-1}$, which is taken as given at that stage. However, for visual clarity, Fig. 3 is still provided here to illustrate the optimal decision for this last option of reform.

Fig. 2 is a special case of Fig. 3 when $N = 1$. Several points are worth mentioning. First, δ_{N-1}^* is taken as given for the decision at the last option, but it is an endogenous choice made when there are two options left, so the whole problem can be solved recursively.[21] Second, if the vertical line $y = \frac{\delta_{N-1}^*}{\eta}$ is in a position like *ll*, then the last option of adjustment is optimally waived and the long-run steady state of the institutional variable is δ_{N-1}^*. If $y = \frac{\delta_{N-1}^*}{\eta}$ is in a position like *mm*, then $\delta_N^* = \eta$ and the developing country will eventually have the same GDP per capita as the developed country. If $y = \frac{\delta_{N-1}^*}{\eta}$ is in a position like *rr*, then the long-run barrier variable is $\delta_N^* = \theta(\delta_{N-1}^*)\delta_{N-1}^*$ and a permanent GDP gap exists between the two countries. This is because the barrier adjustment becomes increasingly costly while the benefit for the same adjustment size decreases as the economy grows. Eventually the GDP gap becomes so small that any further adjustment becomes unattractive.

The conditions in Eq. (14) are complicated. As an alternative, the following lemma gives a useful and easy-to-check necessary condition to exercise the one-shot control.

Lemma 3. *The one-time control will be exercised only if*

$$A + B < \frac{1}{r}\left[\frac{\mu}{r}\right]^{\frac{r}{r-\mu}}, \tag{16}$$

and $\frac{\eta}{\delta_0} \in \left(\underline{\beta}, \overline{\beta}\right)$, *where* $\underline{\beta}$ *and* $\overline{\beta}$ *are the two distinct roots of the following equation:*

$$x^{\frac{r}{\mu}} = x + \frac{(A+B)\ r(\mu - r)}{\mu}.$$

Proof. Refer to Appendix 4. ■

To understand Eq. (16), observe that any adjustment at least costs $A + B$, so it has to be sufficiently small to warrant a reform. Moreover, if $\frac{\eta}{\delta_0} \geq \overline{\beta}$, then δ_0 is sufficiently close to η that the benefit from any further adjustment is too small to warrant further adjustment. If $\frac{\eta}{\delta_0} \leq \underline{\beta}$, then no further one-step adjustment will be made because δ_0 is so high that it requires a large reduction in δ to achieve any given amount of utility improvement, making the cost of the associated adjustment larger than the gain from any one-step adjustment.

4.3. Optimal reform

The value function with N adjustment options, where $1 \leq N < \infty$, is given by

$$V_N(\delta_0, h_0) = \max\{G_N(\delta_0, h_0), F_N(\delta_0, h_0)\},$$

where

$$G_N(\delta_0, h_0) \equiv \max_{t_1 \leq \hat{t}, \delta_1} \int_0^{t_1} h_0 e^{\mu t} e^{-rt} dt + e^{-rt_1}\left[V_{N-1}\left(\delta_1, h_0 e^{\mu t_1}\right) - C(\delta_0, \delta_1)\right];$$
$$F_N(\delta_0, h_0) \equiv \max_{\hat{t} \leq t_1, \delta_1} e^{-rt_1}\left[V_{N-1}\left(\delta_1, \frac{\eta}{\delta_0}\right) - C(\delta_0, \delta_1) - V_0\left(\delta_0, \frac{\eta}{\delta_0}\right)\right] + V_0(\delta_0, h_0).$$

I obtain the following result by using the recursive method:

Proposition 2. *Any institutional adjustment must occur precisely when the convergence constraint becomes binding, that is,*

$$t_i^* = \frac{1}{\mu}\ln\frac{\eta}{\delta_{i-1}^* h_0}, \forall i = 1, 2, \ldots, N. \tag{17}$$

In addition, the developing economy keeps catching up at a constant speed μ until the last convergence constraint binds, after which convergence stops: that is

$$\frac{\dot{h}(t)}{h(t)} = \begin{cases} \mu, & \text{when} \quad t \leq t_N^* \\ 0, & \text{otherewise} \end{cases}.$$

Proof. Refer to Appendix 5. ■

This proposition states that economic convergence is accompanied by a process of cumulative institutional building. The institutional barrier is sequentially reduced in a timely manner to ensure a generically unbinding convergence constraint. In equilibrium

[21] A full characterization with two options ($N = 2$) is provided in Appendix 7.

the GDP dynamics also appear to be solely determined by the human capital accumulation, as argued in the standard endogenous growth literature. However, what this model highlights is the crucial and hidden role played by the cumulative institutional building in sustaining this convergence process. Without the timely relaxations of institutional binding constraints at different development levels, convergence will stop prematurely. This fundamental interaction between institutional reforms and economic growth has been largely ignored in the existing convergence literature.

Recall that the "Washington Consensus" emphasizes that all the reforms should be undertaken in one step so that all the future growth will be free of any binding institutional bottlenecks (Stiglitz, 1998). It is also often argued that gradual and partial reforms may create more distortions, so reforms should be comprehensive and quick (Murphy et al., 1992). By contrast, the model developed here formalizes a rationale for why optimal reforms can be done sequentially along with the convergence. The model's predictions for reform and convergence are quite consistent with the Chinese experience discussed in Section 2 as well as many cross-country real-life episodes of accelerations and reforms (Rodrik, 2005; Sachs & Warner, 1995; Wade, 1990; World Bank, 2005).

Moreover, if a binding constraint can be interpreted as a "crisis" since the constraint can potentially strangle further convergence, then Proposition 2 is also congruent with the "crisis hypothesis" empirically established in the reform literature, which states that the reform is more likely to occur when a "crisis" appears (Alesina et al., 2006; Drazen & Grilli, 1993).

In the model, cumulative reforms are needed to sustain the convergence, but in equilibrium do reforms occur infinite times? To address this issue, I define $N^* \equiv \inf\left\{\arg\max_{N} V_N(\delta_0, h_0)\right\}$, the optimal minimum number of institutional adjustments.

Proposition 3. *There is only a finite number of reforms ($N^* < \infty$).*

Proof. Refer to Appendix 6. ■

To understand the intuition for why the Ramsey government chooses to conduct only a finite number of reforms, first note that the total potential gain of reform is finite. In addition, Eq. (17) in the previous proposition implies that no reform would occur after $\frac{-\ln\ h_0}{\mu}$, which means that each desirable reform must entail a minimum positive cost with the present discounted value strictly larger than $(A+B)e^{\frac{-\ln\ h_0}{\mu}}$, so it does not pay to do an infinite number of reforms. Notice that this is true as long as A and B are not both zero simultaneously. It implies that convergence stops at some finite time point. Methodologically, this proposition also warrants the method of backward induction employed in my characterization.

Suppose $N^* \geq 1$. The original optimization problem (5) can be rewritten as

$$\max_{N,\{\delta_i\}_{i=1}^{N}} V_0(\delta_N, h_0) - \sum_{i=1}^{N} e^{-rt_i}\left[A\left(\frac{\delta_{i-1}}{\delta_i}\right)^{\phi} + B\right] \tag{18}$$

subject to

$$\begin{aligned} &\delta_i < \delta_{i-1} \ \text{ for each } \ i = 1, \ldots, N, \\ &\delta_N \geq \eta; \ \ \delta_0 \ \text{ and } \ h_0 \ \text{ are given,} \end{aligned}$$

where t_i is given by Eq. (17) for any $i = 1, \ldots, N$.

Recall that the optimal adjustment plan automatically satisfies the budge constraint when the international credit market is complete. Substituting Eq. (17) into Eq. (18) and using Eq. (8) yields the following equivalent problem:

$$\max_{N,\{\delta_i\}_{i=1}^{N}} \frac{\mu\eta}{r(\mu-r)}(\delta_N)^{\frac{r}{\mu}-1} - \sum_{i=1}^{N} \delta_{i-1}^{\frac{r}{\mu}}\left[A\left(\frac{\delta_{i-1}}{\delta_i}\right)^{\phi} + B\right]. \tag{19}$$

Observe that N^* and $\{\delta_i^*\}_{i=1}^{N^*}$ are independent of h_0 as long as Assumption A0 is satisfied. This is because, for any given δ_0, no matter what h_0 is, the economy will have the same GDP at time $\hat{t}$. From that point on, the optimization problem is identical and independent of h_0, so the initial institutional barrier δ_0 alone will determine the optimal adjustment scheme. When $A = 0$, Eq. (19) implies that any reform, if initiated ($N^* > 0$), should be undertaken thoroughly once and for all ($N^* = 1$ and $\delta_N^* = \eta$). By revoking Eq. (14), I obtain that $N^* = 1$ if and only if $\hat{B}(\delta_0) > B$, or equivalently, $\frac{\mu}{r(\mu-r)}\left[\left(\frac{\eta}{\delta_0}\right)^{\frac{r}{\mu}} - \frac{\eta}{\delta_0}\right] > B$. Otherwise, no reform occurs. For exposition convenience, let $y_i \equiv \frac{\delta_{i-1}}{\delta_i}$ denote the size of the ith institutional adjustment for any positive integer $i \leq N^*$ and define $\mathcal{N} \equiv \{1, 2, \ldots, N^* - 1\}$.

Proposition 4. *Suppose $A > 0$ and $N^* \geq 2$.*[22] *The reform size changes monotonically over time. More precisely, when $\delta_{N^*}^* > \eta$, the following is true*:

$$\frac{y_{i+1}}{y_i} \quad 1, \forall i \in \mathcal{N}, \ \ iff\, y_j \quad \varpi, \ \ for \ \ some \ \ j \in \mathcal{N}, \tag{20}$$

[22] A full characterization for the case with $N = 2$ is provided in Appendix 7.

where ϖ is uniquely determined by

$$\varpi^{\frac{r}{\mu}}\phi - \frac{B}{A}\frac{r}{\mu\varpi^{\phi}} = \frac{r}{\mu} + \phi. \tag{21}$$

When $\delta^*_{N^*} = \eta$, the adjustment is also strictly monotonic or constant over time.

Proof. Refer to Appendix 8. ■

This proposition states that, whenever multiple reforms are conducted, the magnitudes of the reforms either increase or diminish over time. Based on Eq. (2), the monotonicity of the reform sizes implies that reforms are more frequent when the reform sizes diminish over time because the convergence period supported by each reform becomes shorter and shorter. Likewise, if the reform sizes increase over time, then the frequency of reforms becomes smaller.

Another immediate implication of this proposition is that either the reform sizes are all above ϖ or all below ϖ, the value of which is determined by Eq. (21). Moreover, if a GDP gap exists in the long run $\left(\delta^*_{N^*} > \eta\right)$, then $y_N = \theta^{-1}(\delta_{N-1})$ and $\delta_N = \delta_{N-1} y_N^{-1}$. Based on Proposition 4, it can be shown that the long-run GDP per capita is larger than $A\phi r\varpi^{\phi+\frac{r}{\mu}}$ if and only if the reform sizes are monotonically increasing, and the GDP per capita is smaller than $A\phi r\varpi^{\phi+\frac{r}{\mu}}$ if the reform sizes are monotonically decreasing. The GDP per capita equals $A\phi r\varpi^{\phi+\frac{r}{\mu}}$ in the long run if and only if the reform sizes are constant, in which case

$$\delta_N = \frac{\eta}{A\phi r}\varpi^{-\left(\phi+\frac{r}{\mu}\right)} = \delta_0\varpi^{-N},$$

therefore

$$N^* = \frac{\log\frac{\delta_0 A\phi r}{\eta}}{\log\varpi} + \phi + \frac{r}{\mu}.$$

It, together with Eq. (21), implies that $\frac{\partial N^*}{\partial \delta_0} > 0$, so the higher the initial institutional barrier, the more reforms there will be; $\frac{\partial N^*}{\partial \eta} < 0$, implying that more efficient diffusion and adoption of technology reduces the number of reforms. Moreover, $\frac{\partial N^*}{\partial \phi} > 0$ and $\frac{\partial N^*}{\partial A} > 0$, indicating that the less distorting the reform process (smaller ϕ or A), the fewer steps of reforms are needed. $\frac{\partial N^*}{\partial B} < 0$, so a larger fixed cost leads to fewer reforms. These results are intuitive: when the variable adjustment cost becomes relatively important, it is better to reduce the size of adjustment size (and also make the reforms more frequent). So if the developing economy has a powerful single-party administrative central government (think about China), then it has a relatively small B but a relatively big A (also see Besley and Kudamatsu (2008)). The model implies that the optimal reform for this economy should be more piece-meal. Even within democracies, a proportional representation parliamentary system can be very different from a presidential system. The latter tends to have a smaller B than a parliamentary system and therefore the model predicts that a democracy with a presidential system should adopt a more gradual small-step reform than the countries with a proportional representation system, holding everything else equal (see Persson and Tabellini (2002)).

Dixit (2004) argues that setting up formal institutions (such as legal rules and democratic political systems) requires a large B but a relatively small A, whereas the opposite is true for informal institutions. With this interpretation, the model implies that the optimal reform tends to be quicker when many informal institutions are still on the reform list, especially at the early stage of reform, but the reform gets slower when formal institutions need changing, presumably at the later stage of reform. All these predictions are testable empirically.

5. Reform under imperfect credit market

A perfect international credit market allows us to essentially ignore the budget constraint problem. However, when the international credit market is imperfect in the sense that the developing country cannot borrow in the international market, the country has to rely on its own savings to finance its institutional adjustment. Since the Ramsey government can freely postpone consumption because $\rho = r$, consumption can be always zero before the final reform, just to avoid the binding budget constraint problem as much as possible. That is, $c(s) = 0, \forall s < T^{**}$, where T^{**} denotes the time of the final adjustment. The feasibility constraint (6) can be rewritten as follows

$$\int_0^{\widetilde{t}_{i+1}} h(t)e^{-rt}dt - \sum_{j=0}^{i} C\left(\delta_j, \delta_{j+1}\right)e^{-r\widetilde{t}_{j+1}} \geq 0 \text{ for each } i = 0, 1, 2, \ldots, \tag{22}$$

where $\widetilde{t}_i$ denotes the time point of the i-th adjustment in the imperfect credit market. Let $\tilde{N}$ denote the minimum optimal number of adjustments. Obviously, $\tilde{N} < \infty$ because the same logic in the proof of Proposition 3 remains valid.

The Ramsey government now maximizes the utility function (1) subject to Eqs. (2), (3), with δ_0 and h_0 given, and subject to a sequence of budget constraints given by Eq. (22).

Observe that T^{**}(or equivalently $\widetilde{t}_{\widetilde{N}}$) must be finite, otherwise the net benefit of the last reform is not strictly positive, which contradicts Eq. (22). If the optimal adjustment scheme obtained in the last section (with the perfect international credit market) automatically satisfies Eq. (22), then that scheme and the associated growth dynamics will be also the optimal ones in the imperfect credit market. Otherwise, the constrained optimization must be newly analyzed.

I consider the simplest case, in which there is only one opportunity to reform.[23] The value function becomes

$$\widetilde{V}_1(\delta_0, h_0) = max\left\{\widetilde{G}(\delta_0, h_0), \widetilde{F}(\delta_0, h_0)\right\}, \tag{23}$$

where

$$\widetilde{G}(\delta_0, h_0) \equiv \max_{\widetilde{t}_1 \leq \hat{t}, \delta_1} \int_0^{\widetilde{t}_1} h_0 e^{\mu t} e^{-rt} dt + e^{-r\widetilde{t}_1}\left[V_0\left(\delta_1, h_0 e^{\mu \widetilde{t}_1}\right) - C(\delta_0, \delta_1)\right], \tag{24}$$

subject to

$$\int_0^{\widetilde{t}_1} h_0 e^{\mu t} e^{-rt} dt \geq e^{-r\widetilde{t}_1} C(\delta_0, \delta_1), \tag{25}$$

and

$$\widetilde{F}(\delta_0, h_0) \equiv \max_{\hat{t} \leq \widetilde{t}_1, \delta_1} \int_0^{\hat{t}} h_0 e^{\mu t} e^{-rt} dt + \int_{\hat{t}}^{\widetilde{t}_1} \frac{\eta}{\delta_0} e^{-rt} dt + e^{-r\widetilde{t}_1}\left[V_0\left(\delta_1, \frac{\eta}{\delta_0}\right) - C(\delta_0, \delta_1)\right], \tag{26}$$

subject to

$$\int_0^{\hat{t}} h_0 e^{\mu t} e^{-rt} dt + \int_{\hat{t}}^{\widetilde{t}_1} \frac{\eta}{\delta_0} e^{-rt} dt \geq e^{-r\widetilde{t}_1} C(\delta_0, \delta_1). \tag{27}$$

As before, I will focus on the case when $\eta > x_0\delta_0$.

The same logic in Lemma 1 still applies, so any adjustment $(0 < \widetilde{t}_1 < \infty)$ must be made weakly after the convergence constraint is binding: $\widetilde{V}_1(\delta_0, h_0) = \widetilde{F}(\delta_0, h_0)$. Eq. (26) can be rewritten as

$$\widetilde{F}(\delta_0, h_0) = \max_{\hat{t} \leq \widetilde{t}_1, \delta_1} V_0(\delta_0, h_0) + e^{-r\widetilde{t}_1}\left[V_0\left(\delta_1, \frac{\eta}{\delta_0}\right) - C(\delta_0, \delta_1) - V_0\left(\delta_0, \frac{\eta}{\delta_0}\right)\right]. \tag{28}$$

Proposition 5. *In the imperfect credit market, when Eq. (12) and $B < \widetilde{B}(\delta_0)$ are true, the first-best reform size (given by Eq. (13)) is implemented at time $\hat{t}$ if and only if the following two conditions are true:*

$$\frac{\eta}{(\mu - r)\delta_0} - A\left[\frac{A\phi r \delta_0}{\eta}\right]^{\frac{-\phi}{\phi + \frac{r}{\mu} - 1}} > B, \tag{29}$$

and $h_0 \leq h^*$, where h^* is given by

$$h^* \equiv \left\{\left(\frac{\eta}{\delta_0}\right)^{\frac{-r}{\mu}}\left[\frac{\eta}{\delta_0} - (\mu - r)\left(A\left[\frac{A\phi r \delta_0}{\eta}\right]^{\frac{-\phi}{\phi + \frac{r}{\mu} - 1}} + B\right)\right]\right\}^{\frac{\mu}{\mu - r}}.$$

Proof. Refer to Appendix 9. ■

This proposition says that whether self-financing is enough depends on the initial human capital h_0. When h_0 is sufficiently large, the first-best reform size cannot be sufficiently financed. This appears counter-intuitive as one may think that higher initial endowment would imply a higher financing ability. This paradox can be resolved as follows. Although the optimal size of reform is independent of the initial human capital in the perfect credit market (recall Eq. (13)), the optimal timing of reform does depend on the initial endowment (or GDP). Eq. (7) suggests that the higher the initial human capital, the sooner the convergence constraint becomes binding, so the present discounted cost of the first-best reform size becomes higher. It turns out that this timing effect dominates the initial endowment effect; therefore, the convergence constraint binds before enough saving is accumulated to cover the cost for the first-

[23] Characterization of multiple reforms in the imperfect credit market is much more complicated and hence reserved for future research.

best reform size. This proposition implies that there may exist an advantage of backwardness in economic reforms: an initially poorer country has a stronger financing ability to make a reform because the country enjoys a longer period of convergence before reaching the first growth bottleneck.

Now if $h_0 > h^*$, how does the developing economy modify its plan under the financial constraint? Solving Eqs. (28) and (27) by using the Lagrangian, I obtain that, if an adjustment is made and Eq. (27) binds, the optimal barrier target δ_1 is determined by the following equation:

$$\frac{\frac{\partial V_0(\delta_1,h_0)}{\partial \delta_1}}{V_0(\delta_1,h_0)}=\frac{\frac{\partial\left[C(\delta_0,\delta_1)+V_0\left(\delta_0,\frac{\eta}{\delta_0}\right)\right]}{\partial \delta_1}}{C(\delta_0,\delta_1)+V_0\left(\delta_0,\frac{\eta}{\delta_0}\right)}, \tag{30}$$

which states that the marginal percentage increase in the value due to the reform is equal to the marginal percentage increase in the total opportunity cost, which comprises the direct adjustment cost, $C(\delta_0,\delta_1)$ and the foregone utility level without institutional adjustment, $V_0\left(\delta_0,\frac{\eta}{\delta_0}\right)$. This is mainly because budget constraint (27) is binding. Any beneficial reform satisfies $V_0(\delta_1,h_0)>C(\delta_0,\delta_1)+V_0\left(\delta_0,\frac{\eta}{\delta_0}\right)$, so the optimal δ_1 must satisfy $\frac{\partial V_0(\delta_1,h_0)}{\partial \delta_1}>\frac{\partial C(\delta_0,\delta_1)}{\partial \delta_1}$, confirming that the reform size is smaller: $\delta_1>\delta_0\theta(\delta_0)$. Eq. (30) can be rewritten as

$$M\delta_1^{\frac{r}{\mu}+\phi-1}+H\delta_1^{\frac{r}{\mu}-1}+\frac{A\phi\delta_0^{\phi}h_0}{\mu-r}=0, \tag{31}$$

where

$$M\equiv\left(B+\frac{\eta}{r\delta_0}\right)\frac{\eta}{r}\frac{\eta}{h_0},\ H\equiv A\delta_0^{\phi}\frac{\eta}{r}\left(\frac{\eta}{h_0}\right)^{-\frac{r}{\mu}}\left(1-\frac{\phi\mu}{\mu-r}\right),\ \delta_1\in[\eta,\delta_0).$$

The left hand side of Eq. (31) is strictly increasing in δ_1, so there is at most one solution.

Recall that the option value of having one opportunity to reform is positive when $B<\widetilde{B}(\delta_0)$, so an adjustment must be made because any adjustment size would become feasible in the long run. In other words, the solution to Eq. (31), δ_1^*, must exist and satisfy $\Omega\left(\frac{\delta_0}{\delta_1^*},\delta_0\right)>0$. The optimal adjustment time is determined by the binding budget constraint:

$$\hat{t}_1^*=\frac{1}{r}\ln\frac{C(\delta_0,\delta_1^*)+V_0\left(\delta_0,\frac{\eta}{\delta_0}\right)}{V_0(\delta_0,h_0)}. \tag{32}$$

To summarize, we have:

Proposition 6. *Suppose $\eta/\delta_0>h_0>h^*$, the international credit market is incomplete, and reform can be implemented at most once. Under assumptions (12), (29), (40) and $B<\widetilde{B}(\delta_0)$, a reform is made at $\hat{t}_1^*$ given by Eq. (32) and δ_1^* is uniquely determined by Eq. (31).*

More notations are needed to illustrate this proposition more intuitively. Let $\widetilde{\delta}_1$ denote the largest adjustment target affordable at the first binding time point $\hat{t}$, given by Eq. (7). When the following is true:

$$\frac{h_0}{(\mu-r)}\left[\frac{\eta}{\delta_0h_0}-\left(\frac{\eta}{\delta_0h_0}\right)^{\frac{r}{\mu}}\right]>A+B, \tag{33}$$

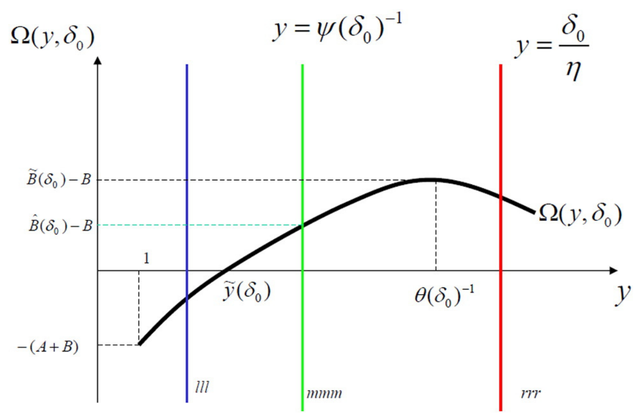

Fig. 4. Optimal reform under imperfect credit market. Note: The horizontal axis is reform size y and the vertical axis is $\Omega(y,\delta_0)$, denoting instantaneous net gain of a reform with reform size y from initial barrier δ_0. The vertical line $y=\frac{\delta_0}{\eta}$ is the largest possible adjustment size and the vertical line $y=\psi(\delta_0)^{-1}$ is the largest affordable reform size, which may have two different types of values, corresponding to two different positions: *lll* and *mmm*, respectively.

the binding budget constraint implies $\widetilde{\delta}_1 = \delta_0\psi(\delta_0)$, where $\psi(\delta_0) \equiv \left[\frac{\frac{h_0}{(\mu-r)}\left[\frac{\eta}{\delta_0 h_0}-\left(\frac{\eta}{\delta_0 h_0}\right)^{\frac{r}{\mu}}\right]-B}{A}\right]^{-\frac{1}{\phi}}$ is the reciprocal of the largest affordable adjustment size at time $\hat{t}$. This proposition can be illustrated by Fig. 4.

The key difference from Fig. 2 is that now the first-best reform in Section 4 may no longer be affordable due to financial constraint. In other words, any reform size y cannot exceed the largest affordable reform size $\psi(\delta_0)^{-1}$. Note that Eq. (33) ensures that $\psi(\delta_0)^{-1} > 1$ (that is, some institution-improving reform is affordable). $h_0 > h^*$ implies that $\psi(\delta_0)^{-1} < \theta(\delta_0)^{-1}$, that is, the most desirable adjustment size $\theta(\delta_0)^{-1}$ is infeasible due to the binding budget constraint. At time $\hat{t}$, the set of the affordable adjustment sizes is $[1, \psi(\delta_0)^{-1}]$. When $\psi(\delta_0)^{-1} < \tilde{y}(\delta_0)$ (that is, vertical line $y = \psi(\delta_0)^{-1}$ is at a position like line *lll*), $\Omega(y, \delta_0) < 0$ for any $y \in [1, \psi(\delta_0)^{-1}]$, so no affordable adjustment is profitable enough to compensate the adjustment cost at $B<\widetilde{B}$. Nevertheless, $B<\widetilde{B}(\delta_0)$ ensures that the option value of the adjustment opportunity is strictly positive, so the one-shot reform must be always made because any adjustment size will become affordable when savings last for a sufficiently long period. Obviously, the reform must occur strictly after $\hat{t}$. If $\psi(\delta_0)^{-1} > \tilde{y}(\delta_0)$ (that is, vertical line $y = \psi(\delta_0)^{-1}$ is at a position like line *mmm*), then a profitable adjustment is affordable at $\hat{t}$. The monotonicity of $\Omega(\cdot, \delta_0)$ on the relevant interval implies that if an adjustment is made at $\hat{t}$, the optimal adjustment size must be $\psi(\delta_0)^{-1}$, the largest feasible adjustment size.

Let $\widetilde{T}_1^*$ denote the time at which the first-best adjustment size Eq. (13) first becomes affordable, then $\widetilde{T}_1^*$ is determined by

$$\int_0^{\hat{t}} h_0 e^{\mu t} e^{-rt} dt + \int_{\hat{t}}^{\widetilde{T}_1^*} \frac{\eta}{\delta_0} e^{-rt} dt = e^{-r\widetilde{T}_1^*} C(\delta_0, \theta(\delta_0)\delta_0). \tag{34}$$

No reform is later than $\widetilde{T}_1^*$ because the first-best adjustment size Eq. (13) is affordable by $\widetilde{T}_1^*$ and any further delay would result in time discounting and hence undesirable. In other words, $\hat{t}_1^* \in \left[\hat{t}, \widetilde{T}_1^*\right]$. In addition, Eq. (32) shows that, when the reform has a larger size (smaller δ_1^*), it occurs later (larger $\hat{t}_1^*$). Notice that Eq. (31) implies

$$\frac{\partial \delta_1^*}{\partial A} > 0, \frac{\partial \delta_1^*}{\partial B} < 0, \frac{\partial \delta_1^*}{\partial \delta_0} > 0, \frac{\partial \delta_1^*}{\partial h_0} > 0.$$

The first two comparative static results are explained before and straightforward. $\frac{\partial \delta_1^*}{\partial \delta_0} > 0$ indicates that there exists institutional persistence: the post-reform institution continues to be inferior if the initial institution is inferior. $\frac{\partial \delta_1^*}{\partial h_0} > 0$ echoes Proposition 5 in terms of the existence of the advantage of backwardness in reforms.

Clearly, $\hat{t}_1^* > \hat{t}$ when $\psi(\delta_0)^{-1} < \tilde{y}(\delta_0)$, which implies that the developing economy stops converging at time $\hat{t}$ and convergence resumes only after $\hat{t}_1^*$. This pattern of punctuated convergence is different from the continuous convergence in the perfect international credit market, or when sufficient foreign aid is available.[24]

6. Concluding remarks

There is compelling cross-country empirical evidence showing that economic accelerations in developing economies often kick-start after a modest policy change or institution reform. It does not have to be a fundamental and cross-the-board reform. It is also observed that sustained convergence of those successful chasers features a process of successive reforms that relax different and sequentially binding growth bottlenecks as the economy grows. Reforms support convergence, which in turn leads to new binding constraints and thus triggers new reforms. It is economic development that turns a previously relaxed constraint into a binding bottleneck. Then a further reform is required to eliminate the barrier to sustain the catch-up growth. China is a case in point. I develop a stylized growth model to formalize this interactive process between convergence and reforms. Using recursive methods, I characterize this technically non-trivial dynamic reform problem faced by an artificial benevolent social planner and I also fully characterize the resulting growth pattern.

In this normative investigation, the predictions and prerequisites of the first-best reform are all explicitly specified and organized in a logically coherent way, which facilitates future explorations. Qualitatively, it seems fruitful to introduce uninsurable uncertainty into the model, which is indispensable if we want to capture the experimental and pragmatic nature of China's reform and growth more deeply (Hausmann et al., 2008; Qian, 2003; Rodrik, 2010) or if macro volatility and risk tolerance are major concerns (Dewatripont & Roland, 1995, Fernandez & Rodrik, 1991). Another promising avenue is to introduce more explicit political economy elements such as conflicting groups, selfish reformers, and hierarchic government (Wei, 1997; Roland, 2000; Acemoglu, 2005; Acemoglu et al., 2005; Li et al., 2012; Xu, 2011: Wang, 2013), or to explicitly discuss both economic and political liberalizations (Caselli & Gennaioli, 2008; Giavazzi & Tabellini, 2005). On the quantitative side, empirical investigations are called for to assess the performance of the current theoretical model or its extensions.

[24] However, Easterly (2005) argues that in reality loans and foreign aid in general do not help structural adjustment and economic growth in most recipient countries.

Appendix 1

Proof of Lemma 1. By contradiction, suppose there exists an optimal adjustment time $t_1^*\in[0,\hat{t})$ and a real adjustment is made so that $\delta_1 \neq \delta_0$. Substituting Eq. (8) into Eq. (9), we can easily prove that for $\forall t_1\in(0,\hat{t}]$,

$$\frac{\partial}{\partial t_1}\left\{\int_0^{t_1} h_0 e^{\mu t} e^{-rt} dt + e^{-rt_1}\left[V_0\left(\delta_1, h_0 e^{\mu t_1}\right) - C(\delta_0,\delta_1)\right]\right\} > 0, \forall \delta_1 \neq \delta_0.$$

Moreover, any adjustment affordable at t_1^* must be affordable at $\hat{t}$. This is a contradiction. If it's optimal not to make any adjustment, $F_1(\delta_0, h_0) = V_0(\delta_0, h_0)$, where $t_1^* = \infty$. Q.E.D.

Appendix 2

Proof of Lemma 2. The previous lemma shows $t_1^* \geq \hat{t}$. When some nontrivial adjustment is made ($\delta_1^* < \delta_0 and T_1^* < \infty$), we must have $V_0\left(\delta_0, \frac{\eta}{\delta_0}\right) < V_0\left(\delta_1^*, \frac{\eta}{\delta_0}\right) - C(\delta_0, \delta_1^*)$. By Lemma 1 and the functional form of V_0 in Eq. (8), we must have

$$\frac{\partial[\text{RHS of } F_1(\delta_0,h_0)]}{\partial t_1} = re^{-rT_1}\left[V_0\left(\delta_0, \frac{\eta}{\delta_0}\right) + C(\delta_0,\delta_1) - V_0\left(\delta_1, \frac{\eta}{\delta_0}\right)\right] \leq 0.$$

Since $t_1^* < \infty$, it must be that $\frac{\partial[\text{RHS of } F_1(\delta_0,h_0)]}{\partial t_1} < 0$ hence $t_1^* = \hat{t}$. Q.E.D.

Appendix 3

Proof of Proposition 1. We have the following two first order conditions with respect to t_1 and δ_1

$$\frac{\partial[\text{RHS of } F_1(\delta_0,h_0)]}{\partial t_1} = re^{-rt_1}\left[V_0\left(\delta_0, \frac{\eta}{\delta_0}\right) + C(\delta_0,\delta_1) - V_0\left(\delta_1, \frac{\eta}{\delta_0}\right)\right] \leq 0$$
$$\frac{\partial[\text{RHS of } F_1(\delta_0,h_0)]}{\partial \delta_1} = 0 \Rightarrow \delta_1^* = \theta(\delta_0)\delta_0 \in [\eta, \delta_0) \text{ guaranteed by A1}.$$

The left inequality of Eq. (12) guarantees that $\delta_1^* < \delta_0$, while the right weak inequality of Eq. (12) makes sure that $\delta_1^* \geq \eta$. The condition $B < \widetilde{B}(\delta_0)$ ensures

$$V_0\left(\delta_0, \frac{\eta}{\delta_0}\right) + C(\delta_0, \delta_1^*) - V_0\left(\delta_1^*, \frac{\eta}{\delta_0}\right) < 0,$$

therefore $t_1^* = \hat{t}$. The second order condition is also satisfied. Under A0, Eq. (12), and $B < \widetilde{B}(\delta_0)$, we have

$$\begin{aligned} V_1(\delta_0, h_0) = {} & \frac{\mu\eta}{r(\mu-r)}\left(\frac{\eta}{\delta_0 h_0}\right)^{\frac{-r}{\mu}} \theta(\delta_0)^{\frac{r}{\mu}-1}\delta_0^{-1} \\ & - \frac{h_0}{\mu-r} - \left(\frac{\eta}{\delta_0 h_0}\right)^{\frac{-r}{\mu}}\left(A\theta(\delta_0)^{-\phi} + B\right), \end{aligned} \tag{35}$$

where $\theta(\delta_0)$ is given by Eq. (13). If $B > \widetilde{B}(\delta_0)$ or if the left inequality in Eq. (12) is violated, then $V_1(\delta_0, h_0) = V_0(\delta_0, h_0)$. If the right weak inequality in Eq. (12) is violated, then there are two possibilities. One is to waive the adjustment option because the adjustment cost dominates even the largest possible gain from an institutional adjustment, in which case we have

$$V_1(\delta_0, h_0) = V_0(\delta_0, h_0) \text{ if } V_0\left(\delta_0, \frac{\eta}{\delta_0}\right) + C(\delta_0, \eta) - V_0\left(\eta, \frac{\eta}{\delta_0}\right) \geq 0.$$

The second possibility is to exercise the adjustment option by fully exhausting the learning potential:

$$\delta_1^* = \eta \text{ and } V_0\left(\delta_0, \frac{\eta}{\delta_0}\right) + C(\delta_0, \eta) - V_0\left(\eta, \frac{\eta}{\delta_0}\right) < 0.$$

The second possibility requires $\widetilde{B}(\delta_0) > B$, where

$$\hat{B}(y) \equiv \frac{\mu}{r(\mu-r)}\left(\frac{\eta}{y}\right)^{\frac{r}{\mu}} - A\left(\frac{y}{\eta}\right)^{\phi} - \frac{\eta\mu}{r(\mu-r)y}.$$

In that case,

$$V_1(\delta_0,h_0)=\frac{\mu}{r(\mu-r)}(h_0)^{\frac{r}{\mu}}-\frac{h_0}{\mu-r}-\left(\frac{\eta}{\delta_0 h_0}\right)^{\frac{-r}{\mu}}\left(A\left(\frac{\eta}{\delta_0}\right)^{-\phi}+B\right).$$

In summary, the value function with one adjustment opportunity is given by

$$V_1(\delta_0,h_0)=\begin{cases}\frac{\mu\eta}{r(\mu-r)}\left(\frac{\eta}{\delta_0 h_0}\right)^{\frac{-r}{\mu}}\theta(\delta_0)^{\frac{r}{\mu}-1}\delta_0^{-1} & \text{when} \quad \widetilde{B}(\delta_0)>B \text{ and } Eq.(12) \text{ is satisfied.}\\ -\frac{h_0}{\mu-r}-\left(\frac{\eta}{\delta_0 h_0}\right)^{\frac{-r}{\mu}}\left(A\theta(\delta_0)^{-\phi}+B\right), & \\ \frac{\mu}{r(\mu-r)}(h_0)^{\frac{r}{\mu}}-\frac{h_0}{\mu-r} & \text{when} \quad \hat{B}(\delta_0)>B \text{ and } A\phi r\le(A\phi r)^{\frac{1}{\phi+\frac{r}{\mu}}}<\frac{\eta}{\delta_0}\\ -\left(\frac{\eta}{\delta_0 h_0}\right)^{\frac{-r}{\mu}}\left(A\left(\frac{\eta}{\delta_0}\right)^{-\phi}+B\right), & \\ V_0(\delta_0,h_0), & \text{otherwise}\end{cases}.$$

Q.E.D.

Appendix 4

Proof of Lemma 3. The one-time control will be exercised non-trivially if and only if

$$V_0\left(\delta_0,\frac{\eta}{\delta_0}\right)<V_0\left(\delta,\frac{\eta}{\delta_0}\right)-C(\delta_0,\delta),$$

so $\delta<\delta_0$ only if

$$V_0\left(\delta_0,\frac{\eta}{\delta_0}\right)<V_0\left(\delta,\frac{\eta}{\delta_0}\right)-(A+B),$$

which implies (recall $\mu>r$)

$$\delta<\left[\delta_0^{\frac{r}{\mu}-1}+\frac{\delta_0^{\frac{r}{\mu}}(A+B)r(\mu-r)}{\mu\eta}\right]^{\frac{1}{\frac{r}{\mu}-1}}.$$

Since $\delta\ge\eta$, we require

$$\eta<\left[\delta_0^{\frac{r}{\mu}-1}+\frac{\delta_0^{\frac{r}{\mu}}(A+B)r(\mu-r)}{\mu\eta}\right]^{\frac{1}{\frac{r}{\mu}-1}},$$

or equivalently,

$$\left(\frac{\eta}{\delta_0}\right)^{\frac{r}{\mu}}>\frac{\eta}{\delta_0}+\frac{(A+B)r(\mu-r)}{\mu},$$

which is possible if and only if Eq. (16) is satisfied and $\frac{\eta}{\delta_0}\in\left(\underline{\beta},\overline{\beta}\right)$. Eq. (16) ensures $0<\underline{\beta}<\left[\frac{\mu}{r}\right]^{\frac{1}{\frac{r}{\mu}-1}}<\overline{\beta}<1$. Q.E.D.

Appendix 5

Proof of Proposition 2.

$$V_N(\delta_0,h_0)=max\{G_N(\delta_0,h_0),F_N(\delta_0,h_0)\},\tag{36}$$

where

$$G_N(\delta_0,h_0)\equiv\max_{t_1\le\hat{t},\delta_1}\int_0^{t_1}h_0e^{\mu t}e^{-rt}dt+e^{-rt_1}\left[V_{N-1}\left(\delta_1,h_0e^{\mu t_1}\right)-C(\delta_0,\delta_1)\right];$$

$$F_N(\delta_0,h_0)\equiv\max_{\hat{t}\le t_1,\delta_1}e^{-rt_1}\left[V_{N-1}\left(\delta_1,\frac{\eta}{\delta_0}\right)-C(\delta_0,\delta_1)-V_0\left(\delta_0,\frac{\eta}{\delta_0}\right)\right]+\frac{h_0\mu}{\mu-r}\left(\frac{\eta}{\delta_0h_0}\right)^{1-\frac{r}{\mu}}-\frac{h_0}{\mu-r}.$$

First observe

$$\begin{aligned} G_N(\delta_0,h_0) \equiv \max_{t_1\le\hat{t},\delta_1} & \int_0^{t_1} h_0 e^{\mu t} e^{-rt} dt + e^{-rt_1} V_{N-1}\left(\delta_1, h_0 e^{\mu t_1}\right) - e^{-rt_1} C(\delta_0,\delta_1) \\ &= \max_{t_1\le\hat{t},\delta_1}\left[V_{N-1}(\delta_1,h_0) - e^{-rt_1}C(\delta_0,\delta_1)\right] \\ &\le \max_{\delta_1}\left[V_{N-1}(\delta_1,h_0) - e^{-r\hat{t}}C(\delta_0,\delta_1)\right] \\ &\le F_N(\delta_0,h_0), \end{aligned}$$

hence $V_N(\delta_0, h_0) = F_N(\delta_0, h_0)$ for any $N \ge 1$. That is, no adjustment will be made before the learning barrier becomes binding. Second, no adjustment will be made strictly after the learning barrier becomes binding. This is because $F_N(\delta, x) > V_{N\text{-}1}(\delta, x)$ if and only if there exists a $\widetilde{\delta} \in [\eta, \delta]$ such that

$$\left[V_{N-1}\left(\widetilde{\delta}, x\right) - C\left(\delta, \widetilde{\delta}\right)\right] - V_{N-1}(\delta, x) > 0. \quad (37)$$

That is, an adjustment will be made if and only if the net benefit from the adjustment exceeds the value without adjustment. Suppose at time t the learning barrier becomes binding (that is, $x = \frac{\eta}{\delta}$), then if $F_N(\delta, x) > V_{N\text{-}1}(\delta, x)$, it's optimal to make the adjustment without any delay because of the time discounting. Note that the left hand side of Eq. (37) is the instantaneous value of net benefit from adjustment, which determines the optimal adjustment $\widetilde{\delta}$ by the first order condition. So the instantaneous value of the net benefit from adjustment is exactly the same for any time weakly after t. Moreover, the adjustment can always be fully financed because Eq. (37) implies the adjustment is profitable. The implied GDP dynamics is obvious. Q.E.D.

Appendix 6

Proof of Proposition 3. According to the previous proposition, there will be no adjustment after $\hat{t} = -\frac{\ln h_0}{\mu}$, the time point when the developing country exactly achieves the same human capital level as the developed country if all the potential benefit of externality can be fully exploited. The total present discounted value of the gross benefit from the whole scheme of institutional adjustment can be no larger than

$$V_0(\eta, h_0) - V_0(\delta_0, h_0) = \frac{\mu}{r(\mu - r)}\left(\frac{1}{h_0}\right)^{\frac{-r}{\mu}} - \frac{\eta}{\delta_0}\frac{\mu}{r(\mu - r)}\left(\frac{\eta}{\delta_0 h_0}\right)^{\frac{-r}{\mu}}.$$

The present discounted cost of each downward adjustment can be no smaller than

$$e^{-r\hat{t}}(A + B).$$

The minimum optimal number of adjustments is therefore no larger than $\frac{V_0(\eta, h_0) - V_0(\delta_0, h_0)}{e^{-r\hat{t}}(A+B)}$. This is also true even when A or B equals zero. Q.E.D.

Appendix 7. Characterization of the problem when $N = 2$

Similar to the previous case, when two adjustment opportunities are available, the value function becomes

$$V_2(\delta_0, h_0) = \max\{G_2(\delta_0, h_0), F_2(\delta_0, h_0)\},$$

where $G_2(\delta_0, h_0)$ is the value function when the first adjustment occurs before $\hat{t}$:

$$G_2(\delta_0, h_0) \equiv \max_{t_1\le\hat{t},\delta_1} \int_0^{t_1} h_0 e^{\mu t} e^{-rt} dt + e^{-rt_1}\left[V_1\left(\delta_1, h_0 e^{\mu t_1}\right) - C(\delta_0, \delta_1)\right],$$

and $F_2(\delta_0, h_0)$ is the value function when the first adjustment occurs after $\hat{t}$:

$$F_2(\delta_0, h_0) \equiv \max_{t_1\le\hat{t},\delta_1}\left[\begin{array}{l} \int_0^{\hat{t}} h_0 e^{\mu_0 t} e^{-rt} dt + \int_{\hat{t}}^{t_1} \frac{\eta}{\delta_0} e^{-rt} dt \\ + e^{-rt_1}\left[V_1\left(\delta_1, \frac{\eta}{\delta_0}\right) - C(\delta_0, \delta_1)\right] \end{array}\right].$$

Note that

$$G_2(\delta_0,h_0) = \max_{t_1\le\hat{t},\delta_1}\left[V_1(\delta_1,h_0)-e^{-rt_1}C(\delta_0,\delta_1)\right]$$
$$\le \max_{\delta_1}\left[V_1(\delta_1,h_0)-e^{-r\hat{t}}C(\delta_0,\delta_1)\right]\le F_2(\delta_0,h_0),$$

therefore $V_2(\delta_0, h_0) = F_2(\delta_0, h_0)$. Suppose two nontrivial adjustments are made. There are two possibilities. First, when Eq. (12) is satisfied, the first order condition with respect to δ_1 yields

$$B\frac{r}{\mu}\delta_1^{\frac{r}{\mu}+\phi} = A\delta_0^{\phi+\frac{r}{\mu}}\phi-k\delta_1^{\frac{r}{\mu}+\phi-\frac{\phi}{\frac{r}{\mu}+\phi-1}}, \tag{38}$$

where $k\equiv\frac{\eta(\phi\mu+r)}{r\phi\mu}\left(\frac{Ar\phi}{\eta}\right)^{\frac{\frac{r}{\mu}-1}{\frac{r}{\mu}+\phi-1}}$. No closed-form solution can be obtained, but it can be shown that the solution exists and is unique if $\frac{r}{\mu}+\phi\ge 2$, which is assumed true. In Fig. A, the upward-sloping curve plots the term on the left hand side of Eq. (38) while the downward-sloping curve corresponds to the right hand side.

Let δ_1^* denote the unique solution to Eq. (38). $\delta_1^* > \eta(Ar\phi)^{-\frac{1}{\frac{r}{\mu}+\phi}}$ must hold, so

$$\eta<\delta_0\left[\frac{A^2r\phi^2}{B\frac{r}{\mu}+\frac{(\phi\mu+r)}{r\phi\mu}(Ar\phi)^{\frac{\left(\frac{r}{\mu}-1\right)\left(\frac{r}{\mu}+\phi\right)+\phi}{\left(\frac{r}{\mu}+\phi-1\right)\left(\frac{r}{\mu}+\phi\right)}}}\right]^{\frac{1}{\frac{r}{\mu}+\phi}}. \tag{39}$$

In addition, $\delta_1^* < \delta_0$ must also hold, or equivalently,

$$A\phi-B\frac{r}{\mu}\le 0,\ \ \text{or}\ \ \eta<\delta_0\left[\frac{r\phi\mu\left(A\phi-B\frac{r}{\mu}\right)}{(\phi\mu+r)(Ar\phi)^{\frac{\frac{r}{\mu}-1}{\frac{r}{\mu}+\phi-1}}}\right]^{\frac{\frac{r}{\mu}+\phi-1}{\phi}}\ \ \text{when}\ \ A\phi-B\frac{r}{\mu}>0. \tag{40}$$

Moreover, $t_1^* = \hat{t}$ if $V_0\left(\delta_0,\frac{\eta}{\delta_0}\right)+C(\delta_0,\delta_1^*)-V_1\left(\delta_1^*,\frac{\eta}{\delta_0}\right)\le 0$, which is equivalent to $\Delta(\delta_0, \delta_1^*) \ge 0$ when both Eqs. (39) and (40) are satisfied, where

$$\Delta(\delta_0,\delta_1^*)\equiv(\delta_1^*)^{\frac{r}{\mu}-\frac{\phi}{\frac{r}{\mu}+\phi-1}}\left(\frac{Ar\phi}{\eta}\right)^{\frac{\frac{r}{\mu}-1}{\frac{r}{\mu}+\phi-1}}\frac{\eta}{r\phi}\left(\frac{\phi\mu}{\mu-r}-1\right)\delta_0^{-\frac{r}{\mu}}$$
$$-\frac{\eta\mu}{r(\mu-r)\delta_0}-B-B\left(\frac{\delta_1^*}{\delta_0}\right)^{\frac{r}{\mu}}-A\delta_0^{\phi}\delta_1^{*-\phi}.$$

We still need to check whether $\widetilde{B}(\delta_1^*)\ge B$. When $\Delta(\delta_0, \delta_1^*) \ge 0$ and $\widetilde{B}(\delta_1^*)\ge B$ are both satisfied, we have $\delta_2^* = \theta(\delta_1^*)\delta_1^*$ and $t_2^* = \frac{1}{\mu}ln\frac{\eta}{\delta_1^*h_0}$. The developing economy grows at speed $(\mu + g_H)$ up to the time point $\frac{1}{\mu}ln\frac{\eta}{\delta_2^*h_0}$, after which the convergence stops and there will be a permanent GDP gap between the two economies $\left(\frac{\eta}{\delta_2^*}<1\right)$.

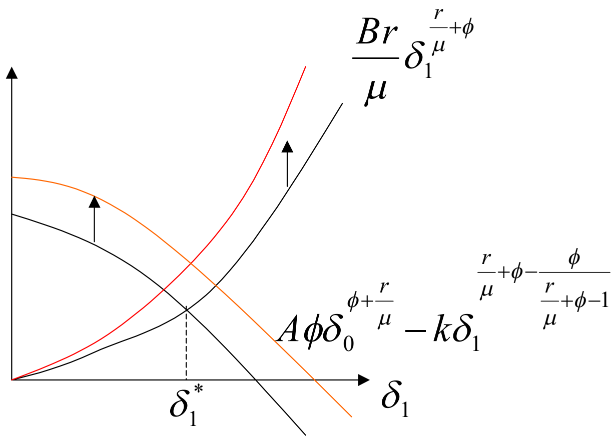

Fig. A. Optimal adjustment size when $N = 2$. Note: The horizontal axis δ_1^* denotes the optimal target level of the barrier variable after the first reform, and the vertical axis is the function value. The upward-sloping curve plots the function value for the left hand side of Eq. (38) while the downward-sloping curve corresponds to that of the right hand side.

Comparative statics analysis shows the following: An increase in B will move δ_1^* leftward (see Fig. A), because the costing–saving motive will make adjustment less frequent but the size for each adjustment larger. In contrast, a higher A results in a higher δ_1^* because the variable adjustment cost parameter A affects the marginal adjustment cost. The higher the initial barrier, the more modest the first target of barrier adjustment.

In addition, we have $\frac{\partial \delta_1^*}{\partial \eta} < 0$, implying that the first adjustment is larger when the relative scale of the economy becomes bigger and $0 \frac{\partial \delta_1^*}{\partial \delta_0} > 0$, meaning the institutional barrier exhibits certain persistence as an initial inferior institution leads to an relatively inferior institution after the first adjustment.

When $\widetilde{B}(\delta_1^*) < B$ or $\Delta(\delta_0, \delta_1^*) < 0$ or any other conditions are not satisfied, the following problem needs to be solved:

$$F_2(\delta_0, h_0) \equiv \max_{\delta_1} \int_0^{\hat{t}} h_0 e^{\mu_0 t} e^{-rt} dt + e^{-r\hat{t}} \left[V_1\left(\delta_1, \frac{\eta}{\delta_0}\right) - C(\delta_0, \delta_1) \right],$$

where

$$V_1\left(\delta_1, \frac{\eta}{\delta_0}\right) = \frac{\mu}{r(\mu - r)} \left(\frac{\eta}{\delta_0}\right)^{\frac{r}{\mu}} - \frac{\eta}{\delta_0(\mu - r)} - \left(\frac{\delta_0}{\delta_1}\right)^{\frac{-r}{\mu}} \left(A\left(\frac{\eta}{\delta_1}\right)^{-\phi} + B\right).$$

The first order condition is

$$-\left(\frac{r}{\mu} + \phi\right) A \eta^{-\phi} \delta_1^{\phi} + \phi A \delta_0^{\phi + \frac{r}{\mu}} \delta_1^{-\phi - \frac{r}{\mu}} = B \frac{r}{\mu}, \tag{41}$$

which implies the existence and uniqueness of the root δ_1^*. So $\frac{\partial \delta_1^*}{\partial \eta} > 0$; $\frac{\partial \delta_1^*}{\partial \delta_0} > 0$; $\frac{\partial \delta_1^*}{\partial A} > 0$; $\frac{\partial \delta_1^*}{\partial B} < 0$. The only difference from the previous case is that $\frac{\partial \delta_1^*}{\partial \eta}$ has a different sign. The following two conditions need verifying:

$$V_1\left(\delta_1^*, \frac{\eta}{\delta_0}\right) \geq C(\delta_0, \delta_1^*) + V_0\left(\delta_0, \frac{\eta}{\delta_0}\right), \tag{42}$$

and $\hat{B}(\delta_1^*) \geq B$. Eq. (41) implies that $\delta_1^* > \eta$ is equivalent to $\eta < \left[\frac{A\phi}{(A+B)\frac{r}{\mu} + A\phi}\right]^{\frac{1}{\frac{r}{\mu}+\phi}} \delta_0$. And to ensure $\delta_2^* = \eta$, we must require $\eta \geq \left[\frac{A^2\phi^2 r}{B\frac{r}{\mu} + A\left(\phi + \frac{r}{\mu}\right)(A\phi r)^{-\frac{\phi}{\frac{r}{\mu}+\phi}}}\right]^{\frac{1}{\frac{r}{\mu}+\phi}} \delta_0$. It also ensures $\delta_2^* < \delta_1^*$. To summarize, we have the following result:

Suppose $N = 2$ and both Assumptions A0 and Eq. (12) are satisfied. [1] $\delta_2^* = \eta$ if and only if $\left[\frac{A^2\phi^2 r}{B\frac{r}{\mu} + A\left(\phi + \frac{r}{\mu}\right)(A\phi r)^{-\frac{\phi}{\frac{r}{\mu}+\phi}}}\right]^{\frac{1}{\frac{r}{\mu}+\phi}} \leq \frac{\eta}{\delta_0} < \left[\frac{A\phi}{(A+B)\frac{r}{\mu} + A\phi}\right]^{\frac{1}{\frac{r}{\mu}+\phi}}$, Eq. (42) is satisfied and $\hat{B}(\delta_1^*) \geq B$, where δ_1^* is uniquely determined in Eq. (41); [2] $\delta_2^* > \eta$ if and only if $\Delta(\delta_0, \delta_1^*) \geq 0$, $\widetilde{B}(\delta_1^*) \geq B$, Eqs. (39) and (40) are all satisfied, where δ_1^* is uniquely determined by Eq. (38) and $\delta_2^* = \theta(\delta_1^*)\delta_1^*$; [3] Otherwise, $V_2(\delta_0, h_0) = V_1(\delta_0, h_0)$ given by Eq. (14).

Appendix 8

Proof of Proposition 4. The first order condition with respect to δ_i is

$$\left(\frac{\delta_i}{\delta_{i+1}}\right)^{\phi} \left[\frac{r}{\mu} + \phi\right] + \frac{B\,r}{A\,\mu} = \left[\frac{\delta_{i-1}}{\delta_i}\right]^{\frac{r}{\mu}+\phi} \phi \quad \text{for} \ \forall i < N^*, \tag{43}$$

which can be rewritten as

$$\left(\frac{y_{i+1}}{y_i}\right)^{\phi} = \frac{y_i^{\frac{r}{\mu}} \phi - \frac{B\ r}{A \mu y_i^{\phi}}}{\frac{r}{\mu} + \phi} \quad \text{for} \ \forall i < N^*,$$

which requires $y_i > \left[\frac{rB}{A\mu\phi}\right]^{\frac{1}{\phi + \frac{r}{\mu}}}$. It also implies

$$\frac{y_{i+1}}{y_i} \gtreqless 1, \forall i \in \mathcal{N}, \ \text{iff} \ y_j \gtreqless \varpi, \ \text{for some} \ j \in \mathcal{N},$$

where ϖ is uniquely determined by

$$\omega^{\frac{r}{\mu}}\phi - \frac{B}{A}\frac{r}{\mu\varpi^{\phi}} = \frac{r}{\mu} + \phi.$$

The first order condition with respect to δ_{N^*} is

$$\begin{aligned} &\left(\frac{Ar\phi}{\eta}\delta_{N-1}^{\frac{r}{\mu}+\phi}\right)^{\frac{1}{\frac{r}{\mu}+\phi-1}} = \delta_N \ \text{if} \ \delta_N > \eta, \\ &\left(\frac{Ar\phi}{\eta}\delta_{N-1}^{\frac{r}{\mu}+\phi}\right)^{\frac{1}{\frac{r}{\mu}+\phi-1}} \leq \delta_N \ \text{if} \ \delta_N = \eta. \end{aligned} \tag{44}$$

To solve the problem completely, we define $\delta^*_{N-2} \equiv \Gamma(\delta^*_{N-1}, \delta^*_N)$ from Eq. (43) when $\delta^*_N > \eta$ Obviously, $\Gamma_1 > 0$ and $\Gamma_2 < 0$. Recursively, we have

$$\begin{aligned} &\delta^*_{N-3} = \Gamma(\delta^*_{N-2}, \delta^*_{N-1}) = \Gamma(\Gamma(\delta^*_{N-1}, \delta^*_N), \delta^*_{N-1}); \\ &\delta^*_{N-4} = \Gamma(\delta^*_{N-3}, \delta^*_{N-2}) = \Gamma(\Gamma(\Gamma(\delta^*_{N-1}, \delta^*_N), \delta^*_{N-1}), \Gamma(\delta^*_{N-1}, \delta^*_N)); \ldots \end{aligned}$$

We ultimately have δ_0 as a function of δ^*_{N-1} and δ^*_N. Together with Eq. (44), both δ^*_{N-1} and δ^*_N, hence everything else, can be pinned down. When $\delta_N = \eta$, we have $\delta^*_{N-2} \equiv \Gamma(\delta^*_{N-1}, \eta)$. Using the same recursive substitution, we can express δ_0 as a function of δ^*_{N-1}, from which δ^*_{N-1} hence δ^*_i can be obtained for $\forall i = 1, 2, \ldots N$.

[1] When $A = 0$, Eq. (19) becomes

$$\max_{N,\{\delta_i\}_{i=1}^{N}} \frac{\mu\eta}{r(\mu - r)}(\delta_N)^{\frac{r}{\mu}-1} - B\sum_{i=1}^{N}\delta_{i-1}^{\frac{r}{\mu}}.$$

Obviously, $N^* = 1$ if any adjustment is made. $\delta^*_1 = \eta$ is the solution to the following problem

$$\max_{\delta_i \geq \eta} \frac{\mu\eta}{r(\mu - r)}(\delta_1)^{\frac{r}{\mu}-1} - B\delta_0^{\frac{r}{\mu}}.$$

[2] When $A \neq 0$, Lemma 3 implies that $\delta_N = \theta(\delta_{N-1})\delta_{N-1}$ when $\delta_N > \eta$. Thus the reform sizes are strictly increasing if and only if $y_N > \varpi$, or equivalently, $\delta_N < \frac{\eta}{A\phi r}\varpi^{-\left(\phi+\frac{r}{\mu}\right)}$. It means that the long run GDP $h = \frac{\eta}{\delta_N} > A\phi r\varpi^{\phi+\frac{r}{\mu}}$.
When $\delta^*_{N^*} = \eta$, and $N^* \geq 2$, then by applying Eq. (41), we have

$$-\left(\frac{r}{\mu} + \phi\right)A\left[\frac{\delta_{N^*-1}}{\eta}\right]^{\phi} + \phi A\left[\frac{\delta_{N^*-2}}{\delta_{N^*-1}}\right]^{\phi+\frac{r}{\mu}} = B\frac{r}{\mu},$$

then equal adjustment size is possible only if

$$\frac{\delta_{N^*-1}}{\eta} = \frac{\delta_{N^*-2}}{\delta_{N^*-1}} = \left[\frac{\left(\frac{r}{\mu} + \phi\right)}{\phi}\right]^{\frac{\mu}{r}},$$

which is still consistent with the optimal size obtained when $\delta^*_{N^*} > \eta$. Q.E.D.

Appendix 9

Proof of Proposition 5. Under assumption (12) and $B < \widetilde{B}(\delta_0)$, the optimal adjustment size given by Eq. (13) can be fully financed by the domestic saving of the developing economy if and only if $Q(h_0) \geq 0$, where

$$Q(z) \equiv \frac{z}{(\mu - r)}\left[\frac{\eta}{\delta_0 z} - \left(\frac{\eta}{\delta_0 z}\right)^{\frac{r}{\mu}}\right] - \left(A\left[\frac{A\phi r\delta_0}{\eta}\right]^{\frac{-\phi}{\phi+\frac{r}{\mu}-1}} + B\right).$$

Obviously, $Q(z) < 0$ for any z when Eq. (29) is violated. In that case, the first-best reform is never feasible. Observe that $Q'(z) < 0$ whenever $z > 0$. There is a unique root, h^*, of the equation $Q(h^*) = 0$. It can be verified that $h^* < \frac{\eta}{\delta_0}$ because of Eq. (29). Thus $Q(h_0) > 0$ iff $h_0 < h^*$.

Appendix 10. Non-degenerate CRRA utility function and proof of the claim in footnote 11

With different re-interpretations and slight modifications, all the important results for GDP growth and optimal institutional reforms derived in Section 4 remain unchanged when we adopt a non-degenerate CRRA utility function under the assumption of perfect international credit market (with exogenous constant interest rate r and constant international price of final good, equal to unity). The following is the formal proof for this claim.

Suppose the utility function (1) in Section 3 is now replaced by the following:

$$\int_0^\infty \frac{c(t)^{1-\sigma}-1}{1-\sigma} e^{-\rho t} dt, \tag{R1}$$

where $\sigma \in [0, \infty)$. We originally focus on the special case with $\sigma = 0$ in the main text. Everything else remains the same for the economic environment. Since the international credit market is perfect, the Ramsey government optimizes reform and consumption in two sequential and separate steps. First, it maximizes the representative household's permanent income (i.e., the total sum of discounted value of income (output)) by choosing optimal reforms and obtains $V(\delta_0,h_0)$. This is precisely the optimization problem in Eq. (5). The solution to this optimal reform problem and the associated output evolution path obtained in Section 4 remain unchanged. Second, given the permanent income $V(\delta_0,h_0)$, the representative consumer maximizes (R1) subject to the following budget constraint:

$$\int_0^\infty c(t) e^{-rt} dt \le V(\delta_0, h_0), \tag{R1.5}$$

which can be equivalently rewritten as

$$\dot{a}(t) = r \cdot a(t) - c(t), \tag{R2}$$

where $a(t)$ denotes the total asset (income) at time t. Due to perfectness of international credit market, we have $a(0) = V(\delta_0, h_0)$, the right hand side of which has already been obtained in the first step. Solving the associated Hamiltonian system, we obtain the following standard Euler equation:

$$\frac{\dot{c}}{c} = \frac{r-\rho}{\sigma}, \tag{R3}$$

which says that the consumption growth rate is constant over time (recall we assume that r is exogenous and time-invariant). Following the standard practice in the pertinent literature, we must impose the following condition to rule out explosive growth:

$$r - \frac{r-\rho}{\sigma} > 0.$$

Combined with (R1.5), we obtain

$$c(0) = \left(r - \frac{r-\rho}{\sigma}\right) V(\delta_0, h_0),$$

and

$$c(t) = c(0) e^{\frac{r-\rho}{\sigma} t}, \forall t \in [0, \infty).$$

In particular, $c(t)$ would be constant over time iff $r = \rho$. Consumption grows when $r > \rho$. In this sense, the optimal institutional reforms only affect the level of consumption via $V(\delta_0,h_0)$, but it cannot affect the consumption growth rate, which is trivially governed by (R3). This is what I meant by saying that my paper focuses on the level effect instead of the growth effect in footnote 8. Observe that, despite the change in the consumption dynamics, the equilibrium output path is still identical to the one in Section 4 because the time path of $h(t)$ only depends on the reform strategies and is independent of consumption decisions. Things would be different if physical capital is used for production. This is part of the reason why I stay with the setting of Lucas (2009) for the sake of analysis simplicity.

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