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The Optimal Transfer of Capital and Embodied Technologies to Developing Countries*

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Abstract:

We study the North-South diffusion of technologies embodied in internationally mobile capital in a framework of intertemporal global welfare maximization. Convergence of the growth rates of technical change in the North and South always occurs in the long-run. However, the degree to which the North-South technology gap can be narrowed depends crucially on the level of the absorptive capacity (human capital, infrastructure, legal framework, etc.) in the South. Performing own innovations in the South narrows the technology gap only in the short-run. An optimal development policy requires more capital to be allocated to the South in earlier stages of development. Allowing for optimal investment into the absorptive capacity, the absorptive capacity rises steadily with the aim to close the technology gap completely. Our results show that an optimal development policy requires FDI to be matched by investment into the absorptive capacity.

Keywords: Technology diffusion, technology transfer, capital mobility, human capital, absorptive capacity

JEL classification: F21, O11, O33, O47

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1 Introduction

Technology transfer to developing countries is currently frequently discussed, not only concerning development policy, but also concerning climate and energy policy. The reason is that applying advanced technologies in developing countries enhances economic development and reduces energy and emission intensities of production at the same time. A global technology fund governed by the World Bank is one way to support an energy efficient economic development of countries that lack in advanced technologies.

According to the World Bank (2008) the level of technological achievement in developing countries has converged to that of high-income countries during the past 15 years. This convergence is mainly accredited to a sustained policy of increased openness to foreign trade, FDI and increased investments in human capital.

A broad strand of the empirical literature examines the effects of international capital flows (FDI) on productivity and growth in recipient countries. (Kokko 1992, Blomström and Kokko 1998, OECD 2002, Keller 2004, Saggi 2002 provide overviews.) Moreover, a number of authors identify a positive effect of human capital in recipient countries on technology diffusion (Benhabib and Spiegel 1994, Crispolti and Marconi 2005, Kneller 2005, Girma 2005, Lai et al. 2006), while others do not identify it (Sjöholm 1997, Xu and Wang 2000). Additionally, some authors find a crucial minimum human capital level which is necessary to achieve technological catching up (Borensztein et al. 1998, Crespo et al. 2004, Benhabib and Spiegel 2005, Ciruelos and Wang 2005, also see OECD 2002). Furthermore, several authors find evidence that technology diffusion increases the larger the technology gap between the recipient and the source country (Griffith et al. 2002, 2004, Girma 2005), while others find weak evidence (Kokko et al. 1996) or do not find such evidence (Benhabib and Spiegel 2005, Girma et al. 2001, Girma and Görg 2005).

Given this empirical background of technology spillovers through capital mobility and the role of human capital, the following questions arise: How should capital be allocated to the North (industrialized countries) and to the South (developing countries) on the optimal time path in order to maximize global welfare? How does this optimal path depend on the human capital endowment of the recipient country and how should human capital be accumulated on the optimal time path? Does convergence of growth rates of the North and the South fail if the human capital level is too low? Finally, how does innovation performed in the South interact with North-South technology diffusion?

Several theoretical approaches describe international technology diffusion related to international investment (Findlay 1978, Krugman 1979, Das 1987, Wang and Blomström 1992). Acemoglu, Aghion and Zilibotti (2003a, 2003b) provide full micro-founded analyses of the role of imitation and innovation in relation to the distance to the technology frontier. Nevertheless, these theories do not directly answer the questions above.

Keller (1996) examines the complementary interaction of trade liberalization and human capital accumulation in developing countries in the context of international technology diffusion. He shows that the growth rates of developing countries are limited by their human capital endowments.

While Keller (1996) deals with trade liberalization, our paper focuses on international capital mobility between North and South. We base our analysis on the classical theories of technological catching up formulated by Nelson and Phelps (1966) and by Findlay (1978). We assume that technologies are embodied in capital transferred from North to South.

According to the Nelson and Phelps theory, technological catching up is faster, the larger the gap between the technology in practice and the technology frontier and the better the human capital endowment. The intuition is as follows: When the technology level of the "learning" country is low, most of the newly arriving technologies are not yet known, and can therefore be adopted in a beneficial way. When the technology level of the "learning" country is high, many of the newly arriving technologies are already known and therefore without an additional benefit.

We transfer the Nelson and Phelps theory to a North-South framework with international capital mobility (compare Benhabib and Spiegel 2005). Technologies are assumed to be embodied in capital. They consequently diffuse from North to South. Furthermore, skills that are necessary to apply the technologies diffuse from North to South through capital transfer as well. Herein, the South needs to be able to adopt the newly arriving technologies and skills. This ability is characterized by the human capital endowment. This ability can be interpreted in a broader sense including all factors that enhance the adoption of new technologies, such as education, infrastructure, telecommunication possibilities, the legal framework (like the protection of intellectual property rights), the business environment (like access to financial markets), security and other factors. In this broader sense, we summarize these factors as the absorptive capacity. A better absorptive capacity enhances the technology diffusion speed for every given technology gap, since it improves the ability to adopt and apply new technologies. In case of exogenous technological progress of the frontier, the technology in practice in the South follows the technology frontier given by the North with the same rate of progress and a constant relative South-North technology ratio.

We study our North-South framework applying intertemporal optimization. It turns out that convergence of growth rates of technical change in the North and the South always occurs. The size of the long run North-South technology gap depends crucially on the level of the absorptive capacity in the South. On the optimal path more capital is allocated to the South at early stages of development of the South, because the capital has a higher social benefit at early stages of development due to faster technology diffusion. The South can catch up to the North in terms of technologies in the short-run by creating own innovations. But the South cannot catch up by creating own innovations in the long-run. Allowing for optimal investment into the absorptive capacity of the South, the absorptive capacity rises steadily, narrowing the technology gap continuously. Therefore, an optimal development policy requires FDI to be matched by investment into the level of the absorptive capacity in the South aiming at full convergence of technology *levels*.

The paper is structured as follows: Section 2 sets up and analyzes four model versions: Section 2.1 examines the basic model with a constant technology frontier analytically and numerically. Section 2.2 examines the basic model with an exogenously growing technology frontier numerically. Section 2.3 analyzes the interaction of capital and technology transfer to the South including innovation performed in the South. Section 2.4 endogenizes human capital accumulation in the South. Section 3 discusses and interprets the results of Section 2. Section 4 concludes.

2 The Model

Consider an economy consisting of an industrialized region (North), which creates advanced technologies and a developing region (South), which adopts technologies created in the North as a technological follower. An is the level of the exogenous technology frontier in the North, and As is the endogenous technology in practice in the South. Both, An and As are levels of total factor productivity. Nelson and Phelps (1966) derive an equation for the long run technological "equilibrium gap" which we solve for the steady state technology share to obtain:[1]

$$\tilde{A} := \frac{As}{An} = \frac{\phi(Hs)}{\phi(Hs) + \lambda} \tag{1}$$

$\phi(\cdot)$ is the speed of technology diffusion and depends solely on Hs, the level of human capital in the South. λ is the growth rate of technological progress in the North. Nelson and Phelps (1966) assume that λ is exogenous. Notice, that the steady state technology share rises with a higher level of human capital but falls with a higher rate of technological progress in the North. The intuition is that a higher educational level eases the adoption of technologies and skills such that the technology diffusion speed is enhanced. A higher rate of technical progress in the North, on the other hand, complicates the South's attempt to follow the North's technical progress.

Our modeling approach introduces elements of Findlay (1978) into the Nelson and Phelps theory. We assume that the speed of technology diffusion does not only depend on the human capital endowment but also on the intensity of internationally mobile capital in the South.

This assumption is based on the idea that internationally mobile capital transferred from the North to the South embodies technologies up to the North's technology level. The arriving technologies are not immediately available in all Southern production processes. They rather need time to diffuse into, and through the Southern economy. Potential channels of this kind of diffusion are product and process imitation, improvements of skills and increased competition between domestic and foreign firms. All factors that determine the ability of the host country to benefit from the transferred technologies represent the so-called absorptive capacity. These factors are for example education, infrastructure, the legal framework, security and other determinants of the business environment. Since we assume human capital to represent the absorptive capacity, we use

[1] In general, we do not show time indices explicitly. n denotes North and s denotes South throughout the paper.

these two terms interchangeably. In line with Nelson and Phelps (1966) we define $\phi(\cdot)$ as the speed of technology diffusion. It depends on Hs, the level of human capital in the South and in our case additionally on ks, the intensity of internationally mobile capital in the South. We assume $\phi_{Hs}(Hs, ks) > 0$, $\phi_{ks}(Hs, ks) > 0$ and $\phi_{Hs,ks}(Hs, ks) > 0$. Hs and ks are complements, because more foreign investment achieves an even larger positive spillover when at the same time the human capital level is higher. This specification is in accordance with the empirical specifications described in the introduction (for instance Borensztein et al. 1998, Benhabib and Spiegel 2005, Girma and Görg 2005).

We differentiate between four kinds of convergence: strong convergence, weak convergence, strong divergence and weak divergence:

Let $A(t) = \frac{As(t)}{An(t)}, As(t) \leq An(t)$ denote the South-North technology ratio at time t. Furthermore, let $\lim_{t\to\infty} A(t) = \tilde{A}$ denote the steady state South-North technology ratio. $\hat{An}$ and $\hat{As}$ are the (steady state) growth rates of the technology levels in the North and in the South.

Definition 1. *$\tilde{A} = 1$, $A(0) < \tilde{A}$ and $\hat{An} = \hat{As}$ is defined as **strong convergence**.*

Strong convergence implies full technological catching up in growth rates and levels.

Definition 2. *$0 < \tilde{A} < 1$, $A(0) < \tilde{A}$ and $\hat{An} = \hat{As}$ is defined as **weak convergence**.*

Weak convergence implies that the South-North technology ratio is higher in the steady state than in the initial situation. In the steady state the South's rate of technical change is equal to the North's rate of technical change. However, a constant relative North-South technology gap remains.

Definition 3. *$0 < \tilde{A} < 1$, $A(0) > \tilde{A}$ and $\hat{An} = \hat{As}$ is defined as **weak divergence**.*

Weak divergence implies that the South-North technology ratio is lower in the steady state than in the initial situation. Again, in the steady state the South's growth rate of technical change is equal to the North's growth rate, and a constant relative technology gap remains in the long-run.

Definition 4. *$\tilde{A} = 0$, $A(0) > \tilde{A}$ and $\hat{An} > \hat{As}$ is defined as **strong divergence**.*

Strong divergence implies that the South-North technology ratio goes to zero in the long-run. This occurs because in the steady state the South's growth rate of technical change is smaller than the North's growth rate.

In the following sections we study the socially optimal allocation of internationally mobile capital in the presence of international technology diffusion. In this context, we focus especially on the role of human capital. For a better understanding of the dynamic interplay between technology diffusion and capital mobility, we first analyze this interplay with the simplifying assumption of a constant technology frontier in the basic model (Model 1). We solve this basic model analytically. Furthermore, we present the numerical results of several extensions to the basic model. These extensions are: exogenous technical change in the North (Model 2), endogenous innovation in the South (Model 3) and finally endogenous human capital accumulation in the South (Model 4).

2.1 Constant Technology Level in the North (Model 1)

Equation (2) denotes the change of the technology level in the South over time. There is a fixed level of internationally mobile capital $\bar{K}$ expressed in (4), which can be allocated to the North (Kn) and to the South (Ks) via capital movements Is. The direction of capital flows Is is defined from North to South, and capital flows are interpreted as FDI. (When capital flows from South to North, Is becomes negative.) Therefore, the stock of mobile capital in the South accumulates according to (3). Ds is the exogenous volume of domestic capital in the South.

$$\dot{As} = \mu Hs \frac{Ks}{Ds}(An - As) \quad (2)$$

$$\dot{Ks} = Is \quad (3)$$

$$\bar{K} = Kn + Ks \quad (4)$$

The foreign capital intensity $ks = \frac{Ks}{Ds}$ is defined as the ratio of the mobile foreign capital stock to the immobile domestic capital stock (see e.g. Findlay 1978, Diao et al. 2005). Domestic capital indicates the size of the economy and is assumed to be constant. A higher foreign capital intensity induces a higher technology spillover when there is more human capital Hs. μ is a constant parameter that determines the "technical" spillover strength and that cannot be influenced by economic policy. The multiplicative specification strictly follows the empirical literature applying interaction terms (e.g. Borensztein et al. 1998, Benhabib and Spiegel 2005, Girma and Görg 2005).

Convex transaction costs of capital movements are given by

$$C(Is) \geq 0, \quad C(0) = 0, \quad C_{Is}(|Is|) > 0, \quad C_{Is}(0) = \gamma_0, \quad C_{IsIs}(Is) \geq 0, \tag{5}$$

Output is produced depending on the technology level Ai and internationally mobile capital input Ki in each region i:

$$Yi(Ai, Ki) \qquad \text{with} \quad i = n, s \tag{6}$$

Utility is drawn from consumption of the produced output Yi:

$$Ui(Yi), \quad Ui_{Yi}(Yi) > 0, \quad Ui_{YiYi}(Yi) < 0, \quad Ui_{Yi}(0) = 0 \quad \text{with} \quad i = n, s \tag{7}$$

The global welfare maximizing social planer solves the following dynamic optimization problem taking into account equations (2)-(7), where we insert $K_n = \bar{K} - K_s$ into $Yn(An, Kn)$:

$$\max_{Is} \int_0^\infty e^{-\rho t} \left(Un(Yn(An, Ks)) + Us(Ys(As, Ks)) - C(Is) \right) dt \tag{8}$$

with ρ being the (social) discount rate. We formulate the current value Hamiltonian (CVH) as:

$$\begin{aligned} CVH &= Un(Yn(An, Ks)) + Us(Ys(As, Ks)) - C(Is)) \\ &+ \lambda_{As} \mu Hs \frac{Ks}{Ds}(An - As) \\ &+ \lambda_{Ks} Is \end{aligned} \tag{9}$$

Applying the maximum principle yields the following first order conditions:

$$
\begin{aligned}
C_{Is} &= \lambda_{Ks} && (10)\\
\dot{\lambda}_{As} - \rho\lambda_{As} &= -Us_{Ys}Ys_{As} + \lambda_{As}\mu Hs\frac{Ks}{Ds} && (11)\\
\dot{\lambda}_{Ks} - \rho\lambda_{Ks} &= -Un_{Yn}Yn_{Ks} - Us_{Ys}Ys_{Ks} - \lambda_{As}\mu Hs\frac{An - As}{Ds} && (12)
\end{aligned}
$$

We need the initial conditions $As(0) = As_0$, $Ks(0) = Ks_0$ and the transversality conditions in order to calculate the optimal time paths:

$$
\lim_{t\to\infty} \lambda_{Ks} \cdot e^{-rt} \geq 0, \quad \lim_{t\to\infty} \lambda_{As} \cdot e^{-rt} \geq 0 \qquad (13)
$$

The static efficiency condition (10) implies that along the optimal path, FDI will be chosen such that the marginal investment costs equal the shadow price of the capital stock in the South. In the next step we study the dynamic properties of the model at hand in closed form. For that purpose we establish a modified hamiltonian dynamic system (MHDS). Using (10) we define Is as increasing in λ_{Ks}. We specify this by $Is = \Gamma(\lambda_{Ks})$, $\Gamma(\gamma_0) = 0$ and $\Gamma_{\lambda_{Ks}} > 0$ derived from equations (5) and (10). As a result we obtain the MHDS:

$$
\begin{aligned}
\dot{As} &= \mu Hs\frac{Ks}{Ds}(An - As) && (14)\\
\dot{Ks} &= \Gamma(\lambda_{Ks}) && (15)\\
\dot{\lambda}_{As} &= \left(\rho + \mu Hs\frac{Ks}{Ds}\right)\lambda_{As} - Us_{Ys}Ys_{As} && (16)\\
\dot{\lambda}_{Ks} &= -Un_{Yn}Yn_{Ks} - Us_{Ys}Ys_{Ks} - \lambda_{As}\mu Hs\frac{An - As}{Ds} + \rho\lambda_{Ks} && (17)
\end{aligned}
$$

We deduct from (14)that the South's technology level will always increase, i.e. $\dot{As} > 0$, since $An \geq As, \forall t$ and all other values are > 0. The shadow price of mobile capital in the South, λ_{Ks}, drives equation (15). Because of the properties of $\Gamma(\lambda_{Ks})$, Ks increases if λ_{Ks} is positive. If in the initial situation the mobile capital endowment of the South is too low compared to the optimal steady state situation, the shadow price of mobile capital will be positive, and capital will be allocated to the South.

We turn to equation (16). Since λ_{As}, the shadow price of the South's technology level, is always > 0, its change over time depends negatively on the marginal social product of the South's technology level ($Us_{Ys}Ys_{As}$) and positively on its own level, weighted by the sum of the (social) discount rate and the spillover strength. Turning to (17), note that an increasing endowment Ks raises, ceteris paribus, the social marginal product of mobile capital in the North ($Un_{Yn}Yn_{Ks}$) and lowers the social marginal product of mobile capital in the South ($Us_{Ys}Ys_{Ks}$). Therefore, $\dot{\lambda}_{Ks}$, the change of the shadow price of capital in the South over time, becomes more negative when there is less mobile capital in the South and when the spillover strength (the second last term in 17) is greater.

We can interpret equations (16) and (17) in the following way: A low technology level and a low capital endowment of the South increase the need of transferring capital and embodied technologies to the South in order to achieve the optimal steady state situation fast. (The convex transaction costs slow down the capital movement.) Moreover, a higher spillover strength increases the benefit of a fast capital transfer to the South. This fast capital transfer in turn reduces λ_{As} and λ_{Ks}. While λ_{As} stays positive, λ_{Ks} becomes negative once capital is transferred back from South to North. In the steady state λ_{Ks} is equal to γ_0, and we do not observe capital transfer anymore. The reason for transferring capital back is the lower technology diffusion strength when the South comes closer to the technology frontier.

A steady state of the dynamic system (14)-(17) requires $\dot{As} = \dot{Ks} = \dot{\lambda}_{As} = \dot{\lambda}_{Ks} = 0$. Solving for the steady state levels of the state and co-state variables we obtain

$$As = An \quad (18)$$

$$\lambda_{Ks} = \gamma_0 \quad (19)$$

$$Us_{Ys}Ys_{As} = \lambda_{As}\left(\rho + \frac{Hs\mu Ks}{Ds}\right) \quad (20)$$

$$Us_{Ys}Ys_{Ks} = -Un_{Yn}Yn_{Ks} \quad (21)$$

Equation (18) states that strong convergence is achieved in the long-run. The reason is obvious. Due to the lack of technical progress in the North ($\hat{An} = 0$), the South will gradually catch up with the North's technology level. The shadow price of foreign capital allocated to the South must be higher than the marginal transaction costs such that a North-South capital movement is beneficial. From equation (19) we can deduct that the shadow price of mobile capital is γ_0 in the steady state. Consequently, since $\Gamma(0) = \gamma_0$

and $C_{Is}(0) = \gamma_0$ according to (5), Is is zero and no further capital re-allocation will take place. In the special case $\gamma_0 = 0$, the shadow price of mobile capital is zero in the steady state, and no capital is transferred anymore.

Furthermore, we read from equation (20) that in the steady state the marginal social product of the technology level in the South will be equal to its shadow price weighted by the sum of the (social) discount rate and the spillover strength, independent of the distance to the technology frontier. Finally, equation (21) tells us that mobile capital will be allocated in order to equalize the social marginal products of capital in the North and South.[2]

We now turn to the dynamic properties of the basic model and show that it is saddle point stable. The Jacobian of the MHDS (14)-(17) is given by:

$$J = \begin{bmatrix} -\frac{Hs\mu Ks}{Ds} & 0 & 0 & 0 \\ 0 & 0 & 0 & \Gamma_{\lambda_{Ks}}(0) \\ -Us_{YsYs}Ys_{As}^2 - Us_{Ys}Ys_{AsAs} & J_1 & \rho + \frac{Hs\mu Ks}{Ds} & 0 \\ J_1 & J_2 & 0 & \rho \end{bmatrix} \tag{22}$$

where

$$J_1 = \frac{Hs\mu\lambda_{As}}{Ds} - Us_{YsYs}Ys_{As}Ys_{Ks} - Us_{Ys}Ys_{AsKs} \tag{23}$$

$$J_2 = -Yn_{Ks}^2 Un_{KsKs} - Un_{Yn}Yn_{KsKs} - Us_{YsYs}Ys_{Ks}^2 - Us_{Ys}Ys_{KsKs} \tag{24}$$

For this system of four linear first order differential equations the four characteristic roots can be obtained by using Dockner (1985):

$$\varrho_{1,2,3,4} = \frac{\varrho}{2} \pm [(\frac{\varrho}{2})^2 - \frac{1}{2}\Omega \pm \frac{1}{2}(\Omega^2 - 4\Delta)^{\frac{1}{2}}]^{\frac{1}{2}} \tag{25}$$

[2]Note that $Ys_{Ks} > 0$ and $Yn_{Ks} < 0$.

where Δ is the determinant of the Jacobian in (22) being:

$$\begin{aligned} \Delta &= -\frac{1}{Ds^2} Hs\mu Ks(Ds\rho + Hs\mu Ks)\Gamma_{\lambda_{Ks}}(0) \\ &\cdot \left(Yn_{Ks}^2 Un_{YnYn} + Un_{Yn} Yn_{Ks} + Us_{YsYs} Ys_{Ks} + Us_{Ys} Ys_{KsKs}\right) > 0 \end{aligned} \tag{26}$$

and

$$\begin{aligned} \Omega &= \Gamma_{\lambda_{Ks}}(0) \\ &\cdot \left(Yn_{Ks}^2 Un_{YnYn} + Un_{Yn} Yn_{KsKs} + Us_{YsYs} Ys_{Ks}^2 + Us_{Ys} Ys_{KsKs}\right) < 0 \end{aligned} \tag{27}$$

Given that $\Delta > 0$ and $\Omega < 0$, the system has saddle point properties.

Next, we assume specific functional forms and analyze the basic model numerically. We assume a Cobb-Douglas production that combines internationally mobile capital Ki with immobile domestic capital Di and immobile domestic labor Li. Ui is the social utility function, and C denotes the costs of FDI activities.[3] The larger ν, the higher the consumers' preference to smooth consumption over time is.

$$Yi = AiKi^{\alpha} Di^{\beta} Li^{1-\alpha-\beta} \qquad \text{with} \quad i = n, s \tag{28}$$

$$Ui = \frac{Yi^{1-\nu} - 1}{1 - \nu} \tag{29}$$

$$C = \gamma_0 |Is| + \gamma_1 Is^2 \tag{30}$$

The parameter values for the simulations can be found in the Appendix. They are based on empirical findings in the literature as described in the Appendix. Figure 1 illustrates the results of the basic model (Model 1).

We observe strong convergence in Figure 1, i.e. A reaches 1, since the technology frontier An is constant. The Southern mobile capital stock Ks also converges to a constant level in the long-run. In the short-run Ks overshoots. The intuition is the following: The social planner equalizes not only the pure marginal products of capital, but also the social benefit of mobile capital allocated to the South via the

[3]For reasons of numerical tractability, we need to set $\gamma_0 = 0$ in equation (30). Note that in the numerical simulations the factor endowments of the North and the South are not equal. Hence, independent of the choice of the transaction cost parameter values, the resulting capital allocation will not be symmetric between North and South. Thus, the choice of γ_0 does not change our results qualitatively.

technology spillover. The spillover benefit is higher the larger the technology gap. Since the technology gap is largest at $t = 0$, transferring capital to the South has a high social benefit resulting in the highest FDI value Is at $t = 0$. The closer the Southern technology level is to the level of the frontier, the lower the spillover strength. Therefore, less mobile capital is allocated to the South in later stages of development, so that Is becomes negative. Furthermore, high values of Ks result in a greater spillover strength. Thus, there is an incentive to temporarily raise the South's mobile capital level above its steady state level in order to accelerate the technological spillover. The simulation confirms that the shadow prices of technologies and capital in the South start at positive values in $t = 0$ and than drop when capital and embodied technologies move to the South as indicated by equations (16) and (17).

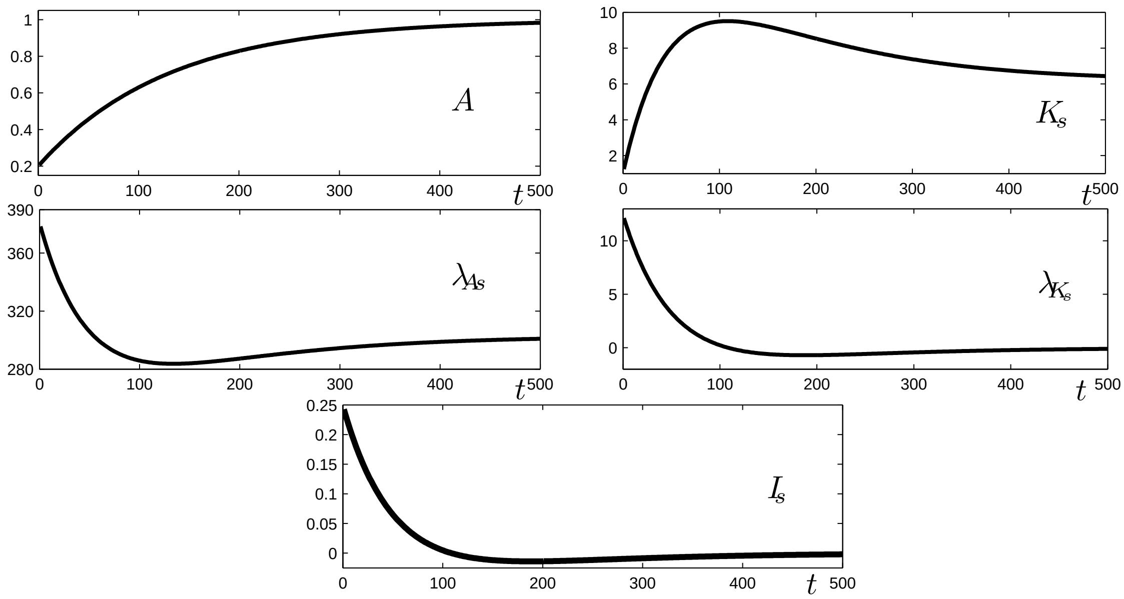

Figure 1: Model 1 - Strong convergence when the Northern technology frontier is constant

2.2 Exogenous Technical Progress in the North (Model 2)

We have primary focused on the optimal allocation of internationally mobile capital in the last section. We have assumed the technology frontier to be constant in the basic model. In the following sections we will present some extensions to the basic model. From now on, we assume the technological frontier to be exogenously increasing. (We simply present the numerical solutions, while the analytical treatment of the extended models would be similar to the previous one.)

We first turn to the case where the technology frontier is no longer constant but increases exponentially. Using equation (8) we formulate the the social planner's objective function as:

$$\max_{Is} \int_0^\infty e^{-\rho t} \left(Un(Yn(An, Ks)) + Us(Ys(As, Ks)) - C(Is) \right) dt \tag{31}$$

subject to

$$\dot{As} = \mu Hs \frac{Ks}{Ds}(An - As) \tag{32}$$

$$\dot{An} = \lambda An \tag{33}$$

$$\dot{Ks} = Is \tag{34}$$

Notice that An is no longer fixed. Hence, strong convergence can only be achieved if As and An grow both with λ and $As = An$. We can write the growth rates of As and An from (32) and (33) as:

$$\hat{As} = \mu Hs \frac{Ks}{Ds} \left(\frac{An}{As} - 1 \right) \tag{35}$$

$$\hat{An} = \lambda \tag{36}$$

From that we can obtain the growth rate of A:

$$\hat{A} = \mu Hs \frac{Ks}{Ds} \left(\frac{1}{A} - 1 \right) - \lambda \tag{37}$$

Since steady state convergence requires $\hat{A}$ to be constant, we can solve equation (37) for the steady state technology South-North technology ratio $\tilde{A}$, which is equation (1) with specific functional forms:

$$\tilde{A} = \frac{\mu Hs \frac{\tilde{Ks}}{Ds}}{\mu Hs \frac{\tilde{Ks}}{Ds} + \lambda} \tag{38}$$

$\tilde{Ks}$ is the mobile capital endowment of the South in the steady state. Notice that setting $\lambda = 0$ we are back in Model 1 with $A = 1$, i.e. strong convergence. For $\lambda > 0$

however, strong convergence will never occur since μ, Hs and Ds are constant and $\tilde{K}s$ has an upper bound at $\bar{K}$. In general, one can say that the smaller the North's rate of technological progress and the larger the spillover strength, the larger will be the steady state technology share A. Also, the larger the human capital endowment Hs, the larger will be the steady state technology share (compare Nelson and Phelps 1966).[4]

2.3 Innovation in the South (Model 3)

We observed in the previous section that the South is able to catch up more if its level of human capital is higher. However, strong convergence is not possible. Own innovation in the South might effectively narrow the the technology gap as suggested in the literature (for example Benhabib and Spiegel 2005). The following model (Model 3) deals with this idea.

In addition to Model 2, we now assume that the South's level of technological change can be increased by innovations created in the South. R&D investment in own innovation in the South is denoted by Ns. θ is the exogenously given success rate of Southern innovation. The higher θ, the larger the technical progress achieved per unit of R&D investment. Using again equation (8) the social planner's welfare maximization problem now reads:

$$\max_{Is,Ns} \int_0^\infty e^{-\rho t} \left(Un(Yn(An, Ks)) + Us(Ys(As, Ks)) - C(Is) - C_2(Ns) \right) dt \tag{39}$$

subject to

$$\dot{As} = \mu Hs \frac{Ks}{Ds}(An - As) + \theta Ns \tag{40}$$

$$\dot{An} = \lambda An = \lambda An(0)e^{\lambda t} \tag{41}$$

$$\dot{Ks} = Is \tag{42}$$

[4]The simulation results will be presented in the next section together with the case of own innovation in the South.

Performing R&D in the South creates convex costs:

$$C_2(Ns) = \gamma_2 Ns^2 \tag{43}$$

The question is, whether the South can permanently increase A, i.e. catch up, in a situation where its absorptive capacity is low by performing own innovation. Again, we solve for the steady state technology ratio $\tilde{A}$:

$$\tilde{A} \quad = \quad \frac{\mu Hs \frac{\tilde{Ks}}{Ds}}{\mu Hs \frac{\tilde{Ks}}{Ds} + \lambda - \frac{\theta Ns Ds}{As}} \tag{44}$$

This equation differs from equation (38) with respect to the term $-\frac{\theta Ns Ds}{As}$ in the denominator. Since λ, Ds and θ are constant, the South's steady state R&D investment level Ns must grow at the same rate as $\hat{As} = \lambda$ (given the case of convergence of growth rates), in order to achieve strong convergence. This is probably not possible due to the lower innovative capability of developing countries compared with industrialized countries. Since we assume increasing marginal investment costs, raising Southern innovation extraordinarily would cause too high costs.

Both, Model 2 and Model 3 have been simulated and the results are plotted in Figure 2 below. For Model 2 we use two scenarios, (i) where the level of the absorptive capacity in the South, Hs, is low and (ii) where Hs is high. For Model 3 (iii) we use the low level of Hs.

The dotted line (i) in Figure 2 shows the situation where the technology ratio A widens compared with the initial ratio, because the Southern absorptive capacity is too low ($Hs = 1$). Still, in the steady state the South grows with the same rate $\hat{As}$ as the North (weak divergence). In contrast to the situation of strong divergence, the global social planner does not allow all capital to flee from the South, because this would pull down consumption and technology diffusion even more. But this cannot be welfare optimal, summing up the welfare of the North and the South. There will rather be an equilibrium situation, where the technology gap has become larger, but the growth rate of the South has reached the growth rate of the North (weak convergence).

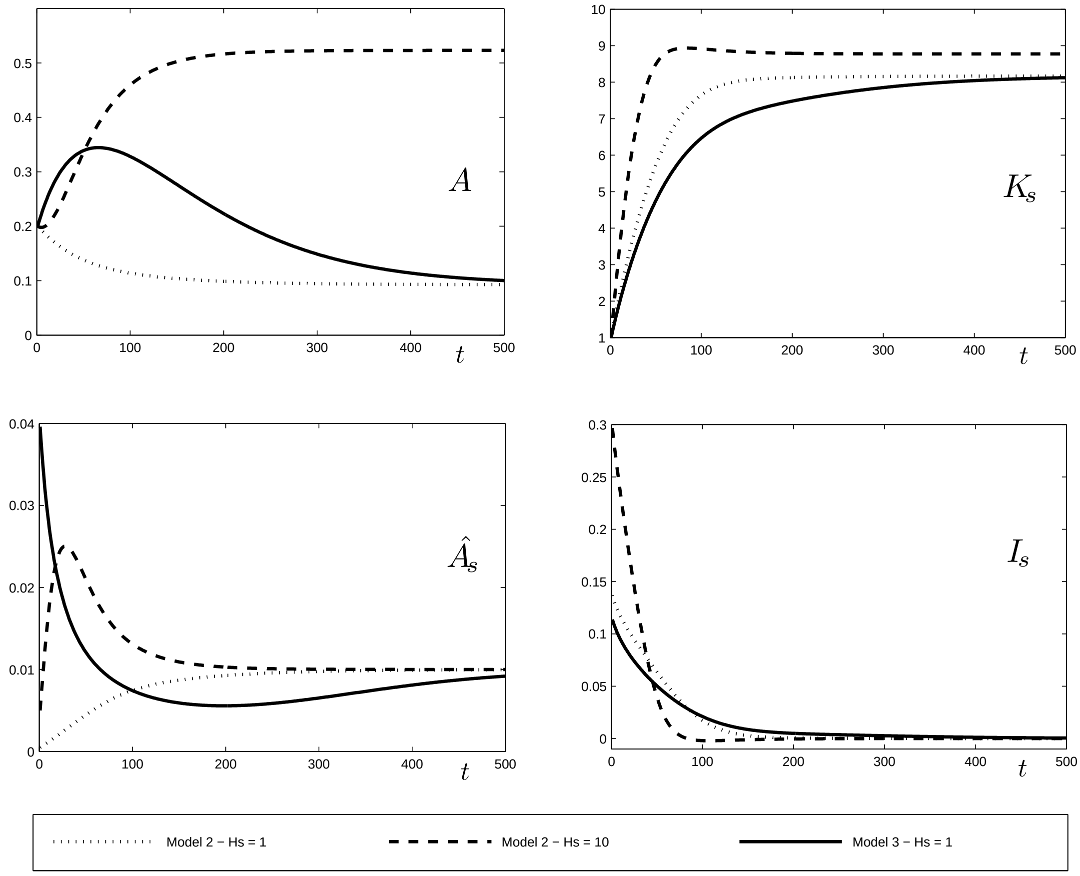

Figure 2: (i) Model 2 - $Hs = 1$ - Weak divergence when the human capital level is insufficient, (ii) Model 2 - $Hs = 10$ - Weak convergence if it is sufficient, (iii) Model 3 - $Hs = 1$ - The temporal effect of Southern innovation

In scenario (ii) on the other hand, the absorptive capacity is sufficiently high (i.e. $Hs = 10$), such that the initial technology gap becomes smaller. This means the South can catch up to a certain extent (weak convergence). The figure illustrates that the diffusion speed, represented by the rate of technical progress $\hat{A}s$ does not reach its maximum when the distance to the technology frontier is largest, i.e. A is smallest, but at a medium distance to frontier. The intuition is as follows: Far away from the technology frontier, the technology diffusion speed is highest, as implied by Nelson and Phelps (1966). On the other hand, far away from the technology frontier, the mobile foreign capital intensity in the South is still low. Consequently, the diffusion of technologies embodied in foreign capital is weak. The maximum of both effects in combination is reached at a medium distance to frontier. The resulting A curve shows an s-shape that is typical for technology diffusion processes.

When simulating Model 3, Southern innovation indeed increases A in the short-run. At the same time less foreign capital flows to the South compared to Model 2. This means, given the current parameter settings, it is more efficient to enhance the Southern output by own innovation than solely transferring capital and embodied technologies to the South. The choice between transferring capital with embodied technologies to the South and performing innovation directly in the South depends on the related costs. These costs are captured qualitatively in the model, but hard to determine quantitatively. Over the long-run the technology gap widens again, since the rate of technical progress in the South is lower than in the North, and Southern "imitation" and innovation act as substitutes, not as complements that could jointly push the South on a higher growth path.

Therefore, the dynamic optimization framework can explain what we observe in reality as reported by the World Bank (2008): Some countries catch up in terms of technologies, while others fall behind. This means, even an optimal allocation of capital across North and South and the resulting diffusion of technologies does not guarantee that the technology gap narrows or is closed completely in the long-run. It is still necessary to increase the Southern human capital endowment in order to come closer to the frontier. This can also explain the diverse results of the econometric literature.

In this context, improving the human capital endowment, infrastructure etc. will improve both, the absorption of foreign technologies as well as the capability for creating own innovations.

2.4 Human Capital Accumulation in the South (Model 4)

So far, we have examined the convergence behavior depending on a given human capital endowment (more general absorptive capacity) Hs. Now we allow the social planner to accumulate Hs optimally over time. Investment in human capital is denoted by Fs and creates convex costs:

$$C_3(Fs) = \gamma_3 Fs^2 \tag{45}$$

Human capital depreciates at the rate η. Again we formulate the social planner's objective as:

$$\max_{Is,Fs} \int_0^{\infty} e^{-\rho t} \left(Un(Yn(An,Ks)) + Us(Ys(As,Ks)) - C(Is) - C_3(Fs) \right) dt \qquad (46)$$

subject to

$$\dot{As} = As\mu Hs \frac{Ks}{Ds}(An - As) \qquad (47)$$

$$\dot{An} = \lambda An = \lambda An(0)e^{\lambda t} \qquad (48)$$

$$\dot{Ks} = Is \qquad (49)$$

$$\dot{Hs} = Fs - \eta Hs \qquad (50)$$

We recall equation (38) for the steady state technology share $\tilde{A}$. The crucial difference to Model 2 is that the level of human capital in the South can be continuously increased, which causes the the steady state technology ratio to increase as well. Figure 3 displays the simulation results for Model 4.

In Model 4 the social planner prevents the South from falling behind by investment into human capital (the absorptive capacity). According to Figure 3, a strong initial increase in the rate of human capital investment is followed by continuous growth in the human capital endowment as well as in the human capital investment rate. The latter is necessary to compensate the depreciation of human capital and to raise technology diffusion additionally.

The narrowing and finally, the closure of the technology gap is the result of a constantly growing human capital endowment. The optimal path of A shows an s-shape, which is typical for technology diffusion processes, since initially the level of human capital is increased very sharply and the foreign capital stock needs to be built up first. Thereafter, capital transfer and human capital accumulation slow down when coming closer to the steady state. Accordingly, the long term aim of development policy is to achieve full convergence of the Southern technology *level* with the Northern level, i.e. strong convergence.[5]

[5]Note that the upper left graph in Figure 4 is the same representation as the one below, but with a smaller time frame that possibly covers a couple of decades in reality. The other graphs in Figure 4 cover a very long time frame which is beyond the scope of current economic policy. However, the graphs

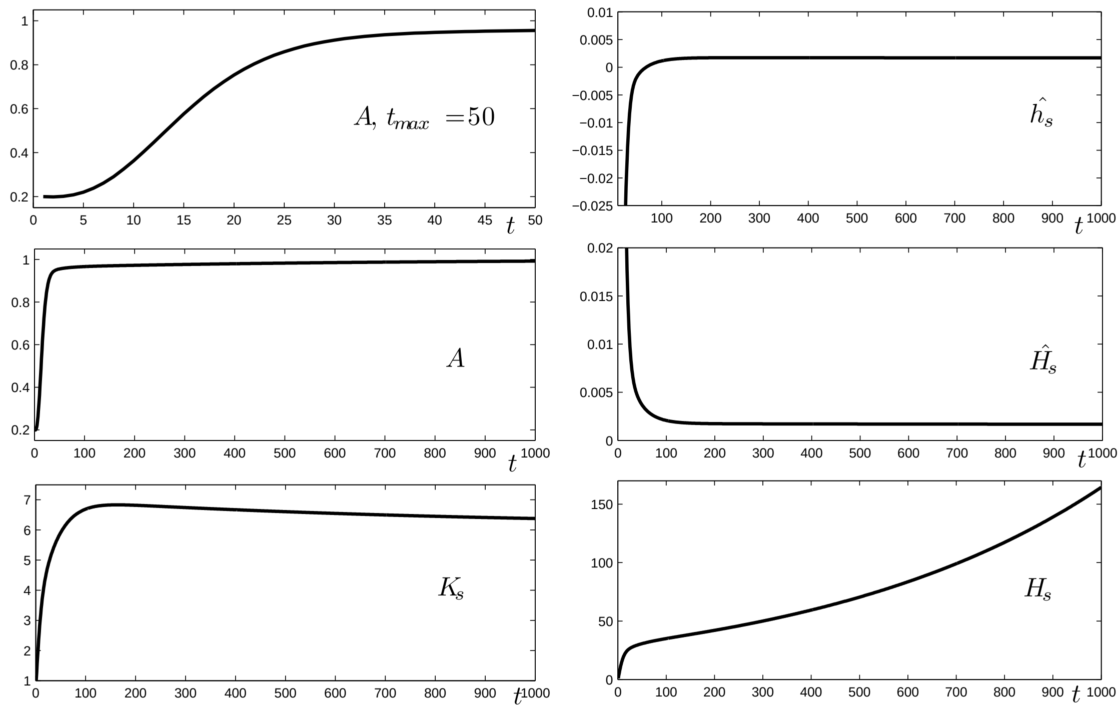

Figure 3: Model 4 - Strong convergence in the long-run driven by human capital accumulation

The two graphs in the middle show an opposite behavior of the South-North technology ratio A and of the rate of human capital accumulation $\hat{H}s$.[6] Hence, investment into the Southern absorptive capacity is especially important when the Southern technology level is still low in order to accelerate catching up. We observe again in the lower left graph that more mobile capital is allocated to the South in earlier stages of development, while mobile capital is gradually drawn back to the North afterwards. The reason is that technology diffusion becomes weaker when the South approaches the technology frontier.

3 Discussion

The outcomes of the different examinations of our model are in accordance with the empirical evidence described in the introduction. The South is able to catch up in terms

show us whether a constant steady state situation will be reached and how it will look like.

[6] $\hat{hs}$ denotes the growth rate of Fs, i.e. of investment into human capital in the South.

of technologies (weak convergence[7]) if the absorptive capacity is sufficiently high. The South falls further behind (weak divergence[8]) if it is not. Convergence in technology levels (strong convergence[9]) occurs when the level of the technology frontier remains constant over time. Allowing for investment into the absorptive capacity, global welfare maximization also aims at strong convergence as a long-run goal. Divergence of the technology growth rates of the North and the South (strong divergence[10]) does not occur in our framework. The reason is that the social planner who maximizes global welfare does not allow Southern consumption to vanish due to a complete lack of mobile capital and new technologies. Southern consumption dropping to zero would not be welfare optimal.

Suppose that in the initial situation the (social) marginal product of capital is higher in the South than in the North. As a consequence, capital is transferred from North to South. The transaction speed is finite due to transaction costs. The capital flow starts at a high level and then decreases, the more equal the social marginal products of the North and the South become. Under the assumption that the return on investment in the South is transferred back to the North, the capital transfer makes both North and South better off. The North gains a higher return on investment due to the higher marginal product of capital in the South than in the North. The South benefits from the output increase due to the presence of foreign capital and from the technology diffusion through foreign capital.

Moreover, the social planner takes the additional social marginal benefit of capital transfer due to the induced technology diffusion into account. Far away from the technology frontier the social marginal benefit is higher than close to the frontier, since technology diffusion is stronger the farther the distance to frontier. As a consequence, the amount of internationally mobile capital allocated to the South reaches a maximum at a certain distance to frontier. It declines thereafter, when the South catches up to the

[7]Weak convergence means catching up until a certain South-North technology ratio is reached and the rates of technical progress in the North and the South are equal. For the definitions of convergence and divergence types see the beginning of section 2.

[8]Weak divergence means falling behind until a certain South-North technology ratio is reached and the rates of technical progress in the North and the South are equal.

[9]Strong convergence means convergence of the technology rates and the levels in the North and the South.

[10]Strong divergence means that the Southern rate of technical progress is lower than the Northern rate of technical progress so that the South falls completely behind in terms of technologies and foreign capital allocation.

technology frontier, because the social marginal benefit of mobile capital in the South decreases. In case of technological catching up the technology accumulation process is s-shaped which is typical for technology diffusion processes.

Therefore, our study confirms that technology diffusion is strongest at a medium distance to the technology frontier (as discussed by Benhabib and Spiegel 2005). Different to the literature so far, this is not an artificial assumption, but results from the introduction of international capital mobility in our study. The intuition is that being far away from the frontier, there is typically also a lack of foreign capital, so that the technology diffusion speed is low. The diffusion speed increases when additional capital flows in and decreases when coming closer to the technology frontier, since there are less technologies left that can be adopted. These two opposite effects yield the maximum diffusion speed at a medium distance to the technology frontier.

The capital endowment in the South never goes to zero, since this would drive production and therefore utility in the South to zero. Consequently, there is no growth trap, where the South completely falls behind the North in terms of the technology level and the mobile capital endowment. Convergence of growth rates of the North and the South always occurs. However, the technology gap widens, if the absorptive capacity (human capital endowment) of the South is too low.

There is a trade-off between transferring capital with embodied technologies to the South and performing own R&D activities in the South. This trade-off depends on the costs of international technology transfer and of own innovation. Own innovation in the South narrows the technology gap in the short-run, but it cannot prevent the South falling behind in terms of technology in the long-run. The reason is that the innovative capability of the South is lower than the innovative capability of the North. The further technological progress in the North proceeds, the more difficult, or in other words more costly, it becomes for the South to follow the North via own innovation, if the technology diffusion mechanism does not work sufficiently. The latter occurs when the absorptive capacity of the South is too low.

Instead of endogenous innovation in the South, we study endogenous investment in human capital (the absorptive capacity) in the next step. A main contribution of our paper is to show that starting at a low human capital endowment, the global social planner first strongly invests in the absorptive capacity. In the long-run the social planner permanently invests in human capital with a constant investment rate such that the North-South technology gap narrows steadily aiming at strong convergence.

However, our model neglects all other channels of international technology diffusion, such as patents, trade and migration as well as domestic capital accumulation and endogenous technical progress. It cannot capture other determinants of capital mobility (FDI) besides returns on capital, either. We use standard functional forms. Further research could investigate CES functions instead of Cobb-Douglas functions and non-linear influences of the absorptive capacity and the distance to frontier on technology diffusion. The simulation results would also change quantitatively when choosing other parameter values. Nevertheless, we believe that the choice of parameter values leads to qualitatively robust results, since the values are derived from empirical facts (see Appendix, Table 1 and the explanations for the choice of parameter values.)

Moreover, the utilities in the North and the South could be weighted in the social planner's objective function. This would alter the allocation of mobile capital. If the social planner gives less weight to the South, it will become more likely that the South falls behind in terms of technologies. Another aspect neglected by the the model setup is that improvements in education, infrastructure etc. probably enhance both, technology diffusion and own innovation. In that respect technology diffusion and innovation have a more complementary character.

4 Conclusion

Our examinations confirm the importance of investing into the absorptive capacity in developing countries in order to narrow the North-South technology gap via capital based technology diffusion. Herein, the absorptive capacity depends on education, infrastructure, telecommunication possibilities, the legal framework (like the protection of intellectual property rights), the business environment (like access to financial markets), security and other factors. If countries lack in these respects, the international technology gap may increase and remain large in the long-run.

A main result of our study is that economies relying on capital and technology inflows need to improve their absorptive capacity the further they develop along the optimal time path. Since many developing countries are not able to carry out such investment into the absorptive capacity by themselves, foreign aid for developing countries by industrialized countries is required. Thus, foreign aid directed to education, infrastructure etc. needs to rise continuously along the optimal time path with the long-run aim to close the North-South technology gap completely.

It turns out that own innovation in developing countries narrows the technology gap in the short-run, but it cannot prevent the developing countries falling behind in terms of technologies in the long-run. This outcome is in accordance with Acemoglu et al. (2003a and 2003b), who show that innovation is no appropriate option for technological followers far away from the technology frontier. Hence, one cannot expect developing countries to catch up in terms of technologies by creating own innovations without technological assistance by the industrialized countries. This results rather confirms the importance of supporting international technology diffusion to developing countries.

Moreover, capital transfer to developing countries has a higher social benefit due to the diffusion of embodied technologies, the larger the North-South technology gap. This leads to an intuitive main result of our examination. More capital is allocated to developing countries at early stages of development along the optimal time path. When economic development proceeds, some capital is withdrawn, since the social benefit of the capital due to technology diffusion is smaller being closer to the technology frontier. Economic policy can control the capital allocation via taxes and subsidies on capital and international capital transfer and other regulations. Furthermore, development policy can directly transfer capital with embodied technologies to developing countries in form of project based (technical) aid. Our analysis implies for development policy that capital transfer (or expressed in a more general way, financial support) should be linked to the current technological state of the recipient country. Developing countries that are far away from the technology frontier require more investment (support), while the investment should be reduced when the developing countries come closer to the frontier.

Further research could investigate these relationships in a more complex computable general equilibrium model using real country specific data.

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6 Appendix - Parameter Values

Parameter	Value	Parameter	Value
$Ks(0)$	1	$\bar{K}$	10
$As(0)$	.2	An	1
Ls	40	Ln	10
Ds	20	Dn	20
Hs	1 (10)	μ	.0025
α	.08	β	.26
ν	0.01	ρ	.01
γ_1	50	λ	.01
γ_2	100	θ	.05
γ_3	50	η	.01

Table 1: Parameter Values for Models 1 to 4

The parameter values for the simulations reported in Table 1 are based on empirical facts. Since the accumulation of capital, human capital and technological knowledge and the resulting economic convergence are long-term processes, the simulations cover a number of decades.

If two regions produce the same goods with the same constant returns to scale production function with capital and labor as inputs, differences in income per capita represent differences in capital per capita (Alfaro et al. 2005). According to Lucas (1990) the marginal product of capital in India should theoretically be about 58 times higher than the marginal product of capital in the U.S. Such a large international difference in returns to capital investment would lead to an immediate capital reallocation. Lucas asks why this simple calculation is obviously misleading. The literature names differences in the fundamentals of the economies and capital market imperfections as the main reasons (Alfaro et al. 2005). "While gross returns on investment can be very high in Africa, the effect is more than counterbalanced by high taxes and a significant risk of capital losses" (OECD 2002). Consequently, FDI as well as local private investment are very low relative to GDP in Africa, despite the large differences in capital per capita. Caselli and Feyrer (2007) find that the marginal product of capital in developing countries is up to six times and on average more than twice as large as the marginal product in industrialized countries. But once they adjust for price differences between capital and consumption goods and use the share of reproducible capital instead of all capital, the large differences in marginal products of capital vanish, and the rich countries have on average higher marginal products than the poor countries. However, our stylized model cannot capture other determinants of capital movements besides the pure marginal product of capital.

Instead of assuming extremely high differences in marginal products of capital, we follow Caselli and Feyrer (2007) by assuming an initial productivity level ratio between North and South of $\frac{1}{5}$. The initial ratio of foreign capital in the South to all capital (immobile domestic plus mobile capital) in the South is chosen $\frac{1}{21}$. Allocating all mobile capital to the South yields a foreign capital ratio of $\frac{1}{3}$ as an upper bound. In Figure 2 the initial capital inflow to the South is between 0.1 and 0.3. This yields ratios of capital inflows to all capital in the South of about 1%. Both ratios appear realistic (compare for instance World Bank 2007). The income share of labor is set to 0.66 and that of capital to 0.34 in accordance with common evidence. The latter share is split into 0.8 for foreign and 0.26 for domestic capital, assuming that the income share of domestic capital is higher than the income share of foreign capital.

Concerning the rate of technical progress, Färe et al. (1994) find annual growth rates of total factor productivity in industrialized countries of about 1%, which we choose for the rate of progress of the technology frontier in our model. Moreover, R&D expenditures as a fraction of GDP are on average about 2% in the EU-15 up to 4% in Sweden and only around 0.5% in the poorer European regions with low per capita incomes (Eurostat 2008). These expenditures give an idea about realistic levels of own innovation in the follower country. They clearly show that developing countries are far away from being as innovative as the industrialized countries, which is an important assumption in our analyses. We adjust the cost parameter of innovation in the South accordingly.

Another crucial factor in the model is educational attainment as an indicator for the human capital endowment and hence for the absorptive capacity. Barro and Lee (2001) report the average number of years of schooling of people in the age of 25 years and older. While the number of years of schooling in 1960 was on average 1.79 in developing countries, 7.17 in transitional economies and 6.97 in advanced economies, the numbers rose to 4.89 in developing countries, 9.95 in transitional economies and 9.80 in advanced economies until 2000. The lower right graph in Figure 4 illustrates that human capital improvements within a time frame of 50 model periods are roughly in accordance with the empirical findings. The substantial rise in human capital over the whole time frame shown in the lower right graph rather represents a very long time horizon of many decades or even centuries. However, running the model over a very long time horizon shows us whether a constant steady state situation is reached and how it looks like.