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Socially optimal North–South capital transfer and technology diffusion

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We study North–South capital transfer and the diffusion of embodied technologies within a framework of intertemporal global welfare maximization. We show saddle path stability and characterize the steady state. We then examine the transition path by running numerical experiments based on realistic data. As a result, technology diffusion will succeed if the absorptive capacity is sufficient which requires sufficient investment. While a large share of capital is allocated to the South in early periods, this share declines in later periods when the South has caught up in terms of technologies.

Keywords: technology diffusion; technology transfer; capital mobility; human capital; absorptive capacity; optimal control

JEL Classifications: F21; O11; O33; O47

1. Introduction

The question why certain economies are able to catch up in terms of technologies, per capacity income and consumption while others are not is one of the most crucial questions in economics. 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, foreign direct investment (FDI) and increased investments in human capital. More specifically, the World Bank (2006) assesses 'The Development Potential of Surging Capital Flows'. This report emphasizes that the development potential is restricted to middle-income countries while many low-income countries do not get access to foreign capital.[1] Our analysis of a social planner framework with intertemporal

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optimization will theoretically describe these empirical facts. It will confirm that a sufficient absorptive capacity including human capital is essential for a successful North–South technology diffusion. It will turn out that a rapid North–South transfer of capital that embodies advanced technologies is followed by a steady decrease in the share of such capital allocated to the South. A precondition is, however, investment in the absorptive capacity (human capital) in the South.

Moreover, 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; Saggi 2002; Keller 2004 provide overviews.) 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; Girma 2005; Kneller 2005; Lai et al. 2006) while others do not identify it (Sjöholm 1999, 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, Redding and Simpson 2002, 2004; Girma 2005) while others find weak evidence (Kokko, Tansini and Zejan 1996) or do not find such evidence (Girma, Greenaway and Wakelin 2001, Benhabib and Spiegel 2005, Girma and Görg 2007). We refer to the mixed results of this literature strand by running experiments where technology diffusion associated with capital mobility (representing FDI) can succeed or fail depending on the absorptive capacity (human capital).

A number of theoretical approaches describe international technology diffusion related to international investment (Findlay 1978; Krugman 1979; Das 1987; Wang and Blomström 1992; Benhabib and Spiegel 2005). 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. 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. Hübler (2011a) shows the possibility of a poverty trap via the interaction of international capital mobility and technology diffusion if the absorptive capacity is too low. While Hübler (2011a) examines a market solution, we will examine the socially optimal solution. Following the literature, we assume that technologies are embodied in capital transferred from North to South and that technology diffusion is stronger, the larger the South–North technology gap.

Technology transfer to developing countries is currently not only discussed with regard to development policy but often with regard to climate and energy policy. Technology transfer was a main issue at the 2007 Bali conference, 2009 Copenhagen conference and the 2010 Cancún on climate policies. Applying advanced technologies in developing countries enhances economic development and reduces energy and emissions intensities of production at the same time. Herein, the interaction of climate policy and development policy receives increasing attention (for example, World Bank 2010). In this context, the developing countries call for financial and technological assistance from the industrialized countries: First, because the industrialized countries have been the main emitters of greenhouse gases so far while the developing countries will probably suffer most from climate change. Second, because advanced technologies with the potential of enhancing economic growth and reducing greenhouse gas emissions are mainly available in the industrialized countries while many developing countries lack in advanced technologies. The challenge is therefore to foster and finance North–South technology transfer. Herein, a global technology fund is one possibility. The investment of carbon tax revenues in emissions saving technologies is another possibility. Additional emissions permits for developing countries within a global cap and trade regime are another possibility to foster technology transfer if the revenues from selling permits are invested in efficient technologies.

Therefore, it is not surprising that numerical models for (climate) policy analysis take up this issue. Sometimes technology diffusion across regions is modeled with the help of a global knowledge stock (for instance Buonanno, Carraro, and Galeotti 2003). There are also a few CGE models in the field of development economics that take technology spillovers via FDI and trade into account (van Meijl and van Tongeren 1999, Diao, Rattsø and Stokke 2005, 2006). In the field of climate policy modeling, Hübler (2011b) models technology diffusion to China via FDI inflows and imports distinguishing vertical (across sectors within the production chain) and horizontal spillovers (within sectors). Bosetti et al. (2008) model international technology spillovers in an endogenous growth model (WITCH). They combine the ingredients distance to technology frontier, knowledge pool and absorptive capacity. Leimbach and Edenhofer (2007) and Leimbach and Eisenack (2009) present algorithms similar to Negishi (1972) that can solve trade-induced technology spillovers in growth models. Leimbach and Baumstark (2010) implement inter-regional technology diffusion coupled to bilateral trade in an endogenous growth model. In this literature strand, the theoretical foundations with respect to saddle path stability, steady state characteristics and the transition path to the steady state appear as an open research question which we will address in our analysis.

The paper is structured as follows: Section 2 sets up the model. Section 3 deals with saddle path stability, and Section 4 characterizes the steady state.

Section 5 deals with the transition to the steady state by running three experiments. Section 6 discusses the analysis critically, and Section 7 concludes.

2. The model

We examine an intertemporal optimization problem covering two world regions, North n and South s, where $r = \{n, s\}$ throughout the analysis. The objective is global welfare, that is the sum of Northern and Southern utility U^r, accumulated and discounted over time. Herein, our social planner scenario can be interpreted as an ideal benchmark for international economic policy, in particular for international organizations such as UN, OECD and WTO.

$$\max_{\{I^{K^r}, I^{H^r}, I^{D^{ns}}\}} \int_0^{\infty} e^{-\rho t} \sum^{r} U^r(C^r, L^r)dt \tag{1}$$

where ρ is the time discount rate. Time indices are suppressed throughout the analysis. Furthermore, in mathematical equations only round parentheses indicate a function f of (.) in contrast to other forms of parentheses.

Total regional utility U^r increases in per capita consumption C^r/L^r and in the regional population L^r. This results in a maximization of the sum of all per capita incomes. Herein, U^r is a concave, increasing function of C^r/L^r, and C^r is the part of production Y^r that is not invested.

$$C^n = Y^n - I^{K^n} - R(I^{H^n}) - S(I^{D^{ns}}) \tag{2}$$

$$C^s = Y^s - I^{K^s} - R(I^{H^s}) \tag{3}$$

We distinguish investment in region-specific capital I^{K^r} following the standard Ramsey approach, and investment in the absorptive capacity (including human capital as a main determinant) of the South, denoted by I^{H^r}. Absorptive capacity denotes the ability to absorb newly arriving foreign technologies. Herein, the improvement of the absorptive capacity of the South can be financed by the South on its own or by the North (in form of private and public investment or foreign aid). Herein, investment costs R increase in I^{H^r} in a convex form. The underlying assumption is that the generation of human capital via education expenditures is a costly long-run process that can only be accelerated under rising costs limited by a lack of teaching personnel and buildings.

While capital K^r is in general immobile across regions, a certain exogenously given volume of Northern capital D is mobile across regions so that $D = D^n + D^s$. Herein, total D may increase over time. North–South transfer of capital D, denoted by $I^{D^{ns}}$, creates transaction costs S borne by the North. (One can imagine that Northern investors bear the transaction costs and at the same time receive a return on investment in the South.) Transaction costs may rise in a convex form which implies that there are capacity restrictions and time consuming processes that can only be accelerated under rising costs. Initially, D is located in the North, and hence can be transferred to the South. D is supposed to embody advanced technologies so that it is associated with inter-regional technology diffusion. Hence, we may call D "high-tech" capital.

This leads to the following equations of motion for investment, where all capital stocks are supposed to depreciate at the rate δ:[2]

$$\dot{K}^r = I^{K^r} - \delta K^r \tag{4}$$

$$\dot{H}^s = I^{H^n} + I^{H^s} - \delta H^s \tag{5}$$

$$\dot{D}^s = I^{D^{ns}} = -\dot{D}^n \tag{6}$$

Output Y^r is produced using the production factors technological knowledge A^r (total factor productivity modeled as a knowledge stock), capital K^r, "high-tech" capital D^r and labor L^r:

$$Y^r = Y^r(A^r, K^r, D^r, L^r) \tag{7}$$

Y^r is concave and increasing in K^r, D^r and L^r. Labor supply is exogenously given and grows over time at a certain rate ω^r. K^r and D^r evolve as described above. Y^r is proportional to A^r. Therein, the Northern knowledge stock A^n is constant and grows exogenously at a rate λ. The Southern knowledge stock A^s accumulates endogenously via inter-regional technology (knowledge) diffusion:

$$\dot{A}^s = T^s(H^s, D^s, A^n - A^s) \tag{8}$$

Southern technical progress T^s is concave and increasing in H^s and D^s. The underlying assumption is that advanced Northern knowledge is embodied in mobile Northern capital D. This knowledge diffuses through the Southern economy via product and process imitation and other adoption and learning processes. T^s increases in convex form in the South–North technology gap $A^n - A^s$. The underlying assumption is that the closer A^s comes to the technology frontier given by A^n, the slower becomes technology diffusion. The underlying intuition is that a lot of knowledge is left for adoption far away from the technology frontier while less knowledge is left for adoption closer to the technology frontier. Technical progress will become zero if at least one of the arguments of T^s becomes zero.

We assume initial values $K^r(0)$, $H^r(0)$, $D^r(0)$ and $A^r(0)$ for the stock variables. Moreover, we require transversality conditions (compare Acemoglu 2009, chapter 7): $\lim_{t\to\infty}[\mu^{K^r} K^r e^{-\rho t}] = 0$, $\lim_{t\to\infty}[\mu^D D^s e^{-\rho t}] = 0$,

$\lim_{t\to\infty}[\mu^H H^s e^{-\rho t}] = 0$, $\lim_{t\to\infty}[\mu^A A^s e^{-\rho t}] = 0$, where μ denotes costate variables.

3. Saddle path stability

In order to examine the basic dynamic properties of the model, especially saddle path stability, we make the following simplifying assumptions:

> Assumption (1): The growth rates of A^n and of L^r are zero, and total D is constant, but still mobile across regions.
> Assumption (2): The capital stocks K^r and the human capital stock H^s are fixed, neglecting depreciation and investment.

These assumptions lead to the following simplified model with two stock variables, high-tech capital D^s and technology A^s, and one control variable, North–South transfer of high-tech capital $I^{D^{ns}}$:

$$\max_{\{I^{D^{ns}}\}} \int_0^\infty e^{-\rho t} \sum^r U^r(C^r)dt \tag{9}$$

with respect to

$$C^n = Y^n(A^n, D - D^s) - S\big(I^{D^{ns}}\big) \tag{10}$$

$$C^s = Y^s(A^s, D^s) \tag{11}$$

$$Y^r = Y^r(A^r, D^r) \tag{12}$$

$$\dot{D}^s = I^{D^{ns}} = -\dot{D}^n \tag{13}$$

$$\dot{A}^s = T^s(D^s, A^n - A^s) \tag{14}$$

The associated Current Value Hamiltonian reads:

$$\begin{aligned} \aleph = {} & U^n(Y^n(A^n, D - D^s) - S(I^{D^{ns}})) + U^s(Y^s(A^s, D^s)) \\ & + \mu^D I^{D^{ns}} + \mu^A T^s(D^s, A^n - A^s) \end{aligned} \tag{15}$$

The first-order conditions $\frac{\partial\aleph}{\partial I^{D^{ns}}} = 0$, $\frac{\partial\aleph}{\partial D^s} = \rho\mu^D - \dot{\mu}^D$ and $\frac{\partial\aleph}{\partial A^s} = \rho\mu^A - \dot{\mu}^A$ yield the following Modified Hamiltonian System:

$$\dot{A}^s = T^s(D^s, A^n - A^s) \tag{16}$$

$$\dot{D}^s = [S_{I^{D^{ns}}}]^{\text{inverse}}\left(\frac{\mu^D}{U^s_{C^s}}\right) \tag{17}$$

$$\dot{\mu}^{A} = \left[\rho - T^{s}_{A^{s}}\right]\mu^{A} - U^{s}_{C^{s}} Y^{s}_{A^{s}}(A^{s}, D^{s}) \tag{18}$$

$$\begin{aligned}\dot{\mu}^{D} = {} & \mu^{D}\rho - \mu^{A} T^{s}_{D^{s}}(D^{s}, A^{n} - A^{s}) + U^{n}_{C^{n}} Y^{n}_{D^{s}}(A^{n}, D - D^{s}) \\ & - U^{s}_{C^{s}} Y^{s}_{D^{s}}(A^{s}, D^{s})\end{aligned} \tag{19}$$

We can then derive the following Jacobian matrix:

$$\Im = \begin{bmatrix} T^{s}_{A^{s}} & T^{s}_{D^{s}} & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{U^{s}_{C^{s}}}\left[S_{I^{D^{ns}}}\right]^{\text{inverse}}_{(.)} \\ \imath_{31} & \imath_{32} & \rho - T^{s}_{A^{s}} & 0 \\ \imath_{41} & \imath_{42} & -T^{s}_{D^{s}} & \rho \end{bmatrix} \tag{20}$$

where

$$\imath_{31} = -\mu^{A} T^{s}_{A^{s}A^{s}} - U^{s}_{C^{s}C^{s}}\left[Y^{s}_{A^{s}}\right]^{2} - U^{s}_{C^{s}} Y^{s}_{A^{s}A^{s}} \tag{21}$$

$$\imath_{32} = -\mu^{A} T^{s}_{A^{s}D^{s}} - U^{s}_{C^{s}C^{s}} Y^{s}_{A^{s}} Y^{s}_{D^{s}} - U^{s}_{C^{s}} Y^{s}_{A^{s}D^{s}} = \imath_{41} \tag{22}$$

$$\begin{aligned}\imath_{42} = {} & -\mu^{A} T^{s}_{D^{s}D^{s}} + U^{n}_{C^{n}C^{n}}\left[Y^{n}_{D^{s}}\right]^{2} + U^{n}_{C^{n}} Y^{n}_{D^{s}D^{s}} \\ & - U^{s}_{C^{s}C^{s}}\left[Y^{s}_{D^{s}}\right]^{2} - U^{s}_{C^{s}} Y^{s}_{D^{s}D^{s}}\end{aligned} \tag{23}$$

According to Dockner (1985), saddle path stability requires $\Re < 0$ and $0 < |\Im| \leq \left[\frac{\Re}{2}\right]^{2}$. This means in our case:

$$\begin{aligned}\Re &= \begin{vmatrix} T^{s}_{A^{s}} & 0 \\ \imath_{31} & \rho - T^{s}_{A^{s}} \end{vmatrix} + \begin{vmatrix} 0 & \frac{1}{U^{s}_{C^{s}}}\left[S_{I^{D^{ns}}}\right]^{\text{inverse}}_{(.)} \\ \imath_{42} & \rho \end{vmatrix} + 2\begin{vmatrix} T^{s}_{D^{s}} & 0 \\ \imath_{32} & 0 \end{vmatrix} \\ &= \left[\rho - T^{s}_{A^{s}}\right] T^{s}_{A^{s}} - \frac{1}{U^{s}_{C^{s}}}\left[S_{I^{D^{ns}}}\right]^{\text{inverse}}_{(.)}\imath_{42} < 0\end{aligned} \tag{24}$$

$$0 < |\Im| = -\left[\rho - T^{s}_{A^{s}}\right] T^{s}_{A^{s}} \frac{1}{U^{s}_{C^{s}}}\left[S_{I^{D^{ns}}}\right]^{\text{inverse}}_{(.)}\imath_{42} \leq \left[\frac{\Re}{2}\right]^{2} \tag{25}$$

These conditions are in general fulfilled according to the following argumentation:

> Equation (23): The marginal product of *D* is higher in the South than in the North due to a scarcity of high-tech capital *D* in the South. As a consequence, *D* is transferred from North to South which is the case that we examine. Since *U* is concave and increasing in *D*, the second

derivative of U with respect to D is negative and has a higher magnitude in the South than in the North.[3] Furthermore, the second derivative of T^s with respect to D^s is negative when T^s is concave and increasing in D^s. μ^A is supposed to be positive since a higher Southern technology level raises the objective value. Therefore, the whole expression of i_{42} is positive.

Equation (24): $T^s_{A^s}$ is negative because a higher technology level in the South ceteris paribus narrows the technology gap and hence reduces technology diffusion. $U^s_{C^s}$ is positive since utility increases in consumption. $[S_{I^{D^{ns}}}]^{\text{inverse}}_{(\cdot)}$ is also positive according to the following argumentation: Transaction costs S increase in the transferred volume $I^{D^{ns}}$. Therefore, the derivative $S_{I_{D^{ns}}}$ is positive and also its inverse. When we assume convex transaction costs, the second derivative $[S_{I^{D^{ns}}}]^{\text{inverse}}_{(\cdot)}$ is still positive. Recalling that i_{42} is positive, the total expression is smaller than zero so that equation (24) is indeed fulfilled.

Equation (25): By the same argumentation as above, the total expression is indeed larger than zero. Moreover, the right hand side of the inequality in equation (25) obviously has the form $-xy \leq \left[\frac{x-y}{2}\right]^2$ where $x = \left[\rho - T^s_{A^s}\right] T^s_{A^s}$ and $y = \frac{1}{U^s_{C^s}} [S_{I^{D^{ns}}}]^{\text{inverse}}_{(\cdot)} \imath_{42}$. This can be equivalently transformed into $0 \leq [x + y]^2$ which is obviously fulfilled.

To conclude, this section has shown that based on our stylized theoretical framework, inter-regional capital transfer and technology diffusion lead to a stable steady state following a specific saddle path.

4. Steady state characteristics

In this section, we relax Assumption (2), that is, capital K and human capital H are accumulated until a steady state is reached while we still hold the exogenous drivers of the dynamics as well as D constant (Assumption 1). Thus, all time derivatives will be zero in the steady state. Therefore, we directly gain from equations (4) and (5):

$$\frac{I^{K^r}}{K^r} = \frac{I^{H^n} + I^{H^s}}{H^s} = \delta \tag{26}$$

This means, we find constant investment ratios. Neglecting exogenous dynamic drivers, this implies constant steady state values of capital stocks and investment in absolute terms. Furthermore, equation (8) will yield a steady state situation where A^s equals A^n, that is full technological catching up, since A^n is assumed to be constant. This means, technical progress will cease in the South. Moreover, we can characterize the socially optimal allocation of D across the regions and the socially optimal volumes of capital K^r and of the absorptive capacity H^s by setting up the Current Value Hamiltonian and by evaluating the consecutive first-order conditions:

$$\begin{aligned}\aleph' = {} & U^n(Y^n(A^n, K^n, D^n, L^n) - I^{K^n} - R(I^{H^n}) - S(I^{D^{ns}})) \\ & + U^s(Y^s(A^s, K^s, D^s, L^s) - I^{K^s} - R(I^{H^s})) \\ & + \mu^{K^n}[I^{K^n} - \delta K^n] + \mu^H[I^{H^n} + I^{H^s} - \delta H^s] + \mu^D I^{D^{ns}} \\ & + \mu^{K^s}[I^{K^s} - \delta K^s] + \mu^A T^s(H^s, D^s, A^n - A^s)\end{aligned} \tag{27}$$

The first-order conditions $\frac{\partial \aleph'}{\partial I^{K^r}} = \frac{\partial \aleph'}{\partial I^{H^r}} = \frac{\partial \aleph'}{\partial I^{D^{ns}}} = 0$, $\frac{\partial \aleph'}{\partial K^r} = \rho \mu^{K^r} - \dot{\mu}^{K^r}$, $\frac{\partial \aleph'}{\partial H^s} = \rho \mu^H - \dot{\mu}^H$, $\frac{\partial \aleph'}{\partial D^s} = \rho \mu^D - \dot{\mu}^D$ and $\frac{\partial \aleph'}{\partial A^s} = \rho \mu^A - \dot{\mu}^A$ yield the following optimality conditions where the left-hand side always represents marginal benefits and the right-hand side marginal costs:

$$Y^n_{K^n} = Y^s_{K^s} = \rho + \delta \tag{28}$$

Equation (28) is the standard condition stating that the marginal product of capital matches the time discount rate (that can be equal to the interest rate) plus depreciation.

$$U^s_{C^s} Y^s_{A^s} T^s_{H^s} = [\rho + \delta]\left[\rho - T^s_{A^s}\right] U^r_{C^r} R_{I^{H^r}} \tag{29}$$

According to this equation, raising H^s, the absorptive capacity of the South, will be more beneficial if its marginal benefit for technology diffusion is higher, if the marginal product with respect to technology in production is higher and if the Southern marginal utility is higher. At the same time, investment in H^s creates costs for the investing region r. These costs will be higher if the marginal utility of region r is higher and if the marginal investment costs are higher. Moreover, a higher discount rate and a higher depreciation rate reduce the future value of the investment and thus raise costs. Finally, a higher magnitude (that means a lower value) of $T^s_{A^s}$, which is by assumption negative, implies a stronger reduction in future technology diffusion due to current technology diffusion. Thus, a higher of $T^s_{A^s}$ creates higher costs. While this condition characterizes the optimal volume of H^s, the following condition characterizes the optimal volume of high-tech capital allocated to the South, denoted by D^s:

$$U^s_{C^s} Y^s_{D^s} + \frac{U^s_{C^s} Y^s_{A^s} T^s_{D^s}}{\rho - T^s_{A^s}} = U^n_{C^n} Y^s_{D^n} + U^n_{C^n} S_{I^{D^{ns}}} \rho \tag{30}$$

While the use of D in the South creates benefits for the South represented by the left-hand side of the equation, it creates costs for the North, represented by the right-hand side. The South gains a direct benefit from D^s through increased output. This benefit increases in the marginal product of D and in marginal utility. In the same way, D^s creates costs for the North. Additionally, D^s creates a social marginal benefit for the South via increased technology diffusion. This benefit will be higher if D's marginal benefit with respect to technology diffusion is higher, if the marginal product with respect to technology in production is higher and if the Southern marginal utility is higher. Again, a higher discount rate and a higher $T^s_{A^s}$ reduce the future value of increasing technology diffusion. On the cost side, inter-regional capital transfer creates costs that rise in the Northern marginal utility, in marginal transaction costs and in the discount rate. A larger share of D will therefore be allocated to the South if the technology spillover is stronger and transaction costs are lower. Therein, a strong spillover requires a high absorptive capacity.

To conclude, this section has explained the socially optimal distribution of high-tech capital to North and South and the socially optimal level of the absorptive capacity. In order to raise South–North technology diffusion, high-tech capital and 'human capital' (absorptive capacity) need to rise simultaneously. It is therefore neither sufficient nor efficient to transfer high-tech capital to the South if the local preconditions for absorbing the embodied technologies are not existing.

5. Transition path simulations

In this section, we additionally relax Assumption (1) which implies that we include exogenous technical progress (in the North) and population growth (in the South) as dynamic drivers. High-tech capital D is assumed to be a certain fraction σ of all kinds of capital originating from the North, summarized as K^n. Therefore, D is neither a strictly exogenous nor a separate endogenous variable. The model runs under the optimization software GAMS[4] (dynamic non-linear programming). The model is numerically calibrated to the GTAP 7 (2004) data[5] for the benchmark year 2004 and to data from Phoenix in Hilderink and Lucas (2008). The time frame under scrutiny is 2004–2100. (The model is run further so that no end effects occur within this time frame.) The North encompasses all OECD countries[6] while the South encompasses the rest of the world. Furthermore, we need to make plausible assumptions on cost parameters and other parameters. Variables are listed in Table A1, all parameter values are reported in Table A2. In particular, we assume the following functional forms:

Total utility of a region is derived from per capita utility times population (Leimbach et al. 2010):

$$U^r = L^r ln\left(\frac{C^r}{L^r}\right) \tag{31}$$

Production is of Cobb–Douglas type. K and D are substitutes in production.

$$Y^r = A^r\{[K^r]^\alpha + [D^r]^\alpha\}[L^r]^{1-\alpha} \tag{32}$$

Technology diffusion increases in H^s and D^s and in the South–North technology gap (compare Nelson and Phelps 1966). θ is a constant governing the strength of technology diffusion. A^n grows at the rate λ.

$$\dot{A}^s = T^s = [A^n - A^s][H^s]^\beta[D^s]^\beta\theta \tag{33}$$

Since we assume technical progress in the North at a rate λ, we will find a steady state with a constant South–North technology ratio (following Nelson and Phelps 1966). To see this, we divide the last equation by A^s and set it equal to $\dot{A}^n/A^n = \lambda$ to obtain:

$$\frac{A^s}{A^n} = \left[1 + \frac{\lambda}{[H^s]^\beta[D^s]^\beta\theta}\right]^{-1} \tag{34}$$

This South–North technology ratio increases in the Southern absorptive capacity and in high-tech capital (up to a limit of one which implies full technological convergence) and decreases in the rate of technical progress in the North. Intuitively, a better absorptive capacity and more foreign high-tech capital ease technology diffusion while a faster pace of technical progress of the technology frontier makes it more difficult to follow and to catch up.

Finally, we assume quadratic cost functions for investment in human capital (absorptive capacity) and for inter-regional high-tech capital transfer:

$$R = I^{H^r} + \tau^R\left[I^{H^r}\right]^2 \tag{35}$$

$$S = I^{D^{ns}} + \tau^S\left[I^{D^{ns}}\right]^2 \tag{36}$$

The quadratic cost terms add to the usual investment terms I^{H^r} and $I^{D^{ns}}$ that convert output into (human) capital in a 1:1 fashion (as in the case of normal capital K in the Ramsey model).

In the following, we will run three policy experiments:

- In experiment $-H-D$, human capital (absorptive capacity) and foreign high-tech capital in the South are fixed at their low initial levels. As a consequence, investment in human capital only matches depreciation, and D^n grows while D^s does not grow.
- In experiment $-H+D$, human capital (absorptive capacity) stays fixed at its low initial level while high-tech capital is endogenously allocated across regions.

- In experiment $+H+D$, both, human capital and high-tech capital, are endogenous so that the North and the South can invest in the South's human capital stock.

Figures 1, 2–3 show and explain the simulation results. In each figure, from top to bottom the first graph sketches technology and income (production) growth rates for each region and each point of time. The second graph sketches the South–North technology ratio and the share of Southern high-tech capital in all high-tech capital at each point of time. The third graph sketches per capita income and per capita consumption.

In experiments $-H-D$ (Figure 1) and $-H+D$ (Figure 2), the South stagnates in terms of technology, per capita production (income) and per capita consumption.

In experiment $+H+D$ (Figure 3), human capital (absorptive capacity) improves over time via human capital investment by the North and the South. Herein, the human capital investment ratio I^{H^r}/Y^r decreases from around 3% in 2004 to 0.1% in 2100 for each region. Interestingly, I^{H^r}

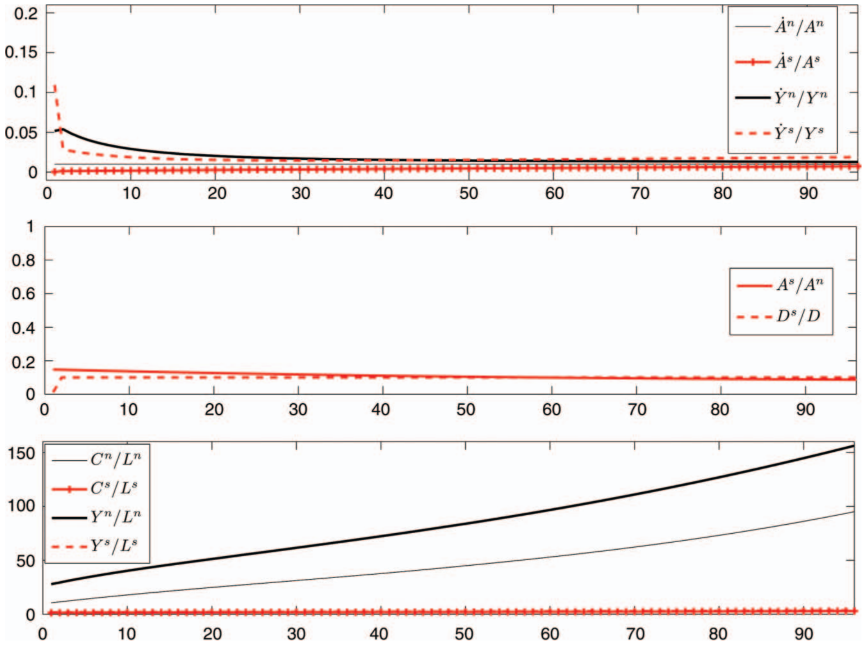

Figure 1. Experiment $-H-D$. Human capital (absorptive capacity) in the South and high-tech capital transfer to the South are both hindered so that the South stagnates in terms of technology, per capita income and per capita consumption (measured in thousands of 2004-$ per person).

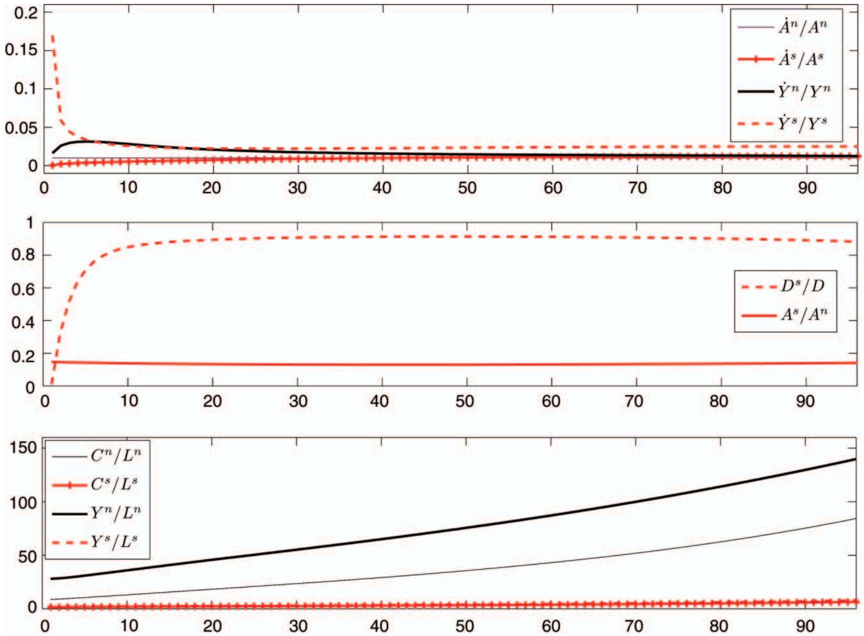

Figure 2. Experiment $-H{+}D$. High-tech capital can be transferred to the South so that indeed most of the high-tech capital is transferred. Nevertheless, technology diffusion fails because human capital (absorptive capacity) is still hindered so that the South still stagnates.

steadily rises in absolute terms in the South while it steadily decreases in absolute terms in the North. This means, due to technical progress and economic growth, the South is more and more able to "care for its own". As a result of combining investment in human capital with high-tech capital transfer, South–North technology diffusion succeeds. Interestingly, almost all high-tech capital is transferred to the South within the first decade while the high-tech capital share of the South is steadily reduced thereafter. The reason is the lower social benefit of high-tech capital in the South with respect to technology diffusion when the South has already caught up in terms of technologies. Obviously, the South almost reaches the technology level of the North while a certain technology gap remains as predicted by theory. In contrast to experiments $-H-D$ and $-H{+}D$, Southern per capita consumption almost reaches the Northern one. Investments in physical and human capital drive a substantial wedge between production (income) and consumption in both regions.

To conclude, the simulations show that *both*, North–South mobility of high-tech capital and investment in human capital (absorptive capacity) of the South are necessary to enable successful technology diffusion.

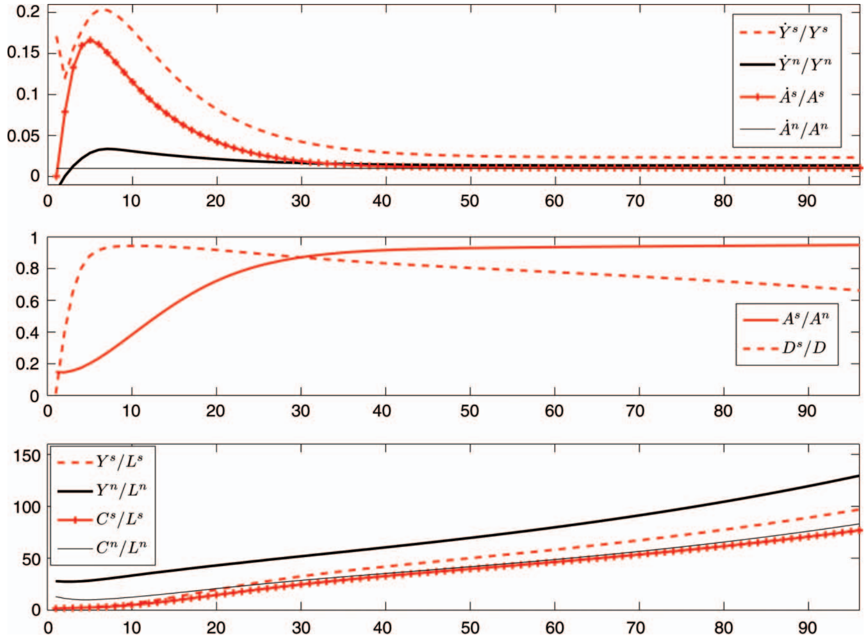

Figure 3. Experiment $+H+D$. Human capital (absorptive capacity) of the South improves over time via human capital investment by the North and the South. As a result of combining investment in human capital with high-tech capital transfer, South–North technology diffusion succeeds.

While high-tech capital gains a high additional social benefit via the transfer of advanced technologies in early periods, it gains a lower additional benefit in later periods when the South has caught up in terms of technologies. As a consequence, high-tech capital is steadily withdrawn from the South along the socially optimal time path. Successful technology diffusion substantially raises Southern per capita income and consumption as well as total Southern utility compared with a situation of economic stagnation where technology diffusion fails.

6. Discussion and caveats

Our model is stylized and theoretical. The model assumes a global social planner who maximizes the sum of the utilities of the North and the South. Therein, it sketches a socially optimal benchmark and does not create the most likely path of future development. The social planner scenario can be seen as an ideal benchmark for international economic policy in the fields of international investment, trade and economic development, in particular for international organizations such as UN, OECD and WTO. Notably, our numerical analysis uses real economic data for the benchmark year 2004, and we run different numerical experiments. Herein, the experiments where investment in human capital (absorptive capacity) or in both, human capital and high-tech capital, is hindered, result in economic stagnation of the South. This outcome appears to be a good representation of the current situation of many developing countries for example in Sub-Saharan Africa. However, our regional aggregation is very crude so that conclusions for specific countries are not appropriate.

Moreover, our model neglects all other channels of international technology diffusion such as patents, trade in particular commodities and migration. It cannot capture other determinants of capital mobility (FDI) besides returns on capital such as political stability or property rights, either, which would go beyond the scope of standard economic models. Furthermore, the model strictly distinguishes between investment in human capital (absorptive capacity) associated with technology diffusion and investment in physical capital used in production in order to disentangle their effects. In reality, both kinds of investment are complementary and interact.

Finally, the numerical solution is bound to specific functional forms of production and technology diffusion. Further research could examine alternative functional forms, especially for the mechanism of technology diffusion. Moreover, a multi-region, multi-sector analysis could generate more detailed and more realistic results. An integrated assessment model that includes carbon emissions and the climate system could assess the interaction of technology diffusion with climate change.

7. Conclusion

The first contribution of the article is to verify the dynamic properties of North–South technology diffusion interacting with North–South capital transfer. It shows saddle path stability and characterizes the determinants of the steady state. This is especially important with respect to modeling international technology diffusion associated with FDI and trade in current (climate) policy assessment models.

The second contribution is to run numerical simulation experiments using the GTAP 7 data. The simulations yield a situation of economic stagnation if the absorptive capacity of the South is not sufficient to enable technology diffusion. In this situation, 'high-tech' capital that embodies advanced technologies may be transferred from North to South to a large extent but with a small effect on technological catching up. When investment in the absorptive capacity is allowed, rapid North–South capital transfer will enable technological catching up. Interestingly, the share of 'high-tech' capital in the South will steadily be reduced thereafter. The reason is that the South has already caught up in terms of technologies so that the additional social benefit of 'high-tech' capital has declined. This emphasizes that in the socially optimal case investment in education and infrastructure and improvements in the political and legal system and other factors that improve the absorptive capacity are crucial preconditions for successful technology diffusion. The absorptive capacity needs to be improved substantially and immediately along the optimal path. Thereafter it needs to be improved steadily or at last maintained so that technology diffusion does not cease. Capital transfer, possibly in form of FDI, loans, guarantees and foreign aid, is partly an intermediate measure to take the South onto a convergent growth path. In the future, the South will be able to 'stand more and more on its own feet'.

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Notes

1. According to Lucas (1990) the marginal product of capital in India is theoretically about 58 times higher than the marginal product of capital in the USA. The resulting large international difference in returns to capital investment is expected to lead to an immediate capital flow from the USA to India. Lucas asks why this simple calculation is obviously misleading. To answer this question, the literature names differences in the fundamentals of economies and capital market imperfections as main reasons (Alfaro et al. 2005).
2. We assume equal depreciation rates of physical and human capital. Moreover, we assume equal depreciation rates for North and South. These rates differ in general in reality. It is nevertheless difficult to make an econometrically clear decision: In a one-sector growth model capital includes various forms of capital, and the composition of capital differs across regions. Additionally, in our model human capital is interpreted in a broader sense such that it includes various factors that foster the diffusion and the absorption of knowledge. Therefore, we assume equal depreciation rates for mathematical convenience and clarity and because of a lack of precisely applicable data. It is of course open to the reader to suppose different indices of δ for K, H and D as well as for n and s.
3. This can be seen by choosing a typical utility and production function and sketching their graphs.
4. http://www.gams.com/. The model is written in discrete time form and solved by maximizing the objective given the model constraints.
5. https://www.gtap.agecon.purdue.edu/
6. The 33 member countries of OECD in 2010 are: Australia, Austria, Belgium, Canada, Chile, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Japan, Korea, Luxembourg, Mexico, the Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, United Kingdom, United States.

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Appendix

Table A1. Variables.

Variable	Explanation
$t = [1, \infty[$	Time (horizon under scrutiny: 2004–2100)
$r = \{n, s\}$	Region (North, South)
$U^r(t)$	Utility
$Y^r(t)$	Production (income)
$A^r(t)$	Stock of technological knowledge
$K^r(t)$	Capital stock
$D^r(t)$	High-tech capital stock
$H^s(t)$	Human capital stock (absorptive capacity)
$I^{K^r}(t)$	Investment in capital
$I^{D^{ns}}(t)$	North–South high-tech capital transfer
$I^{H^r}(t)$	Investment in human capital
$R(t)$	Costs of human capital investment
$\mathrm{S}(t)$	Costs of high-tech capital transfer

Table A2. Parameters (initial values for $t = 0 \leftrightarrow$ year 2004 and constants).

Parameter	Explanation	Value [unit] (source)
$Y^n(0)$	Production (GDP) North	33.144 [trill. US-$] (GTAP 7)
$Y^s(0)$	Production (GDP) South	7.826 [trill. US-$] (GTAP 7)
$A^n(0)$	Knowledge stock North	12.242 (Solow residual)
$A^s(0)$	Knowledge stock South	1.804 (Solow residual)
$K^n(0)$	Capital stock North	91.062 [trill. US-$] (GTAP 7)
$K^s(0)$	Capital stock South	20.005 [trill. US-$] (GTAP 7)
$D^s(0)$	High-tech capital stock South	0.01 [trill. US-$]
$H^s(0)$	Human capital stock South	0.001
$L^n(0)$	Labor force North	0.436 [bill. US-$] (Phoenix)
$L^s(0)$	Labor force North	2.097 [bill. US-$] (Phoenix)
α	Exponent of K^r and D^r in production	0.3
β	Exponent of H^s and D^s in tech diffusion	0.5
δ	Depreciation rate of K^r and H^s	0.05 [per period]
λ	Rate of technical progress in North	0.01 [per period]
ρ	Time discount rate	0.02 [per period]
σ	Share of capital D in K^n	0.001
τ^R	Human capital investment cost parameter	10
τ^S	High-tech capital transaction cost parameter	100
θ	Strength of technology diffusion	0.02
ω^n	Population growth rate North	0 [per period] (Phoenix)
ω^s	Population growth rate South	0.009 [per period] (Phoenix)