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Optimal Growth Policy: the Role of Skill Heterogeneity

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Optimal Growth Policy: the Role of Skill Heterogeneity
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Abstract
A simple semi-endogenous growth model is employed to show that optimal subsidization of both R&D and capital costs is independent of the distribution of R&D skills in the workforce. This holds despite the empirically supported fact that a higher R&D subsidy rate raises wages of R&D workers.

Key words: Optimal growth policy; R&D skills; R&D subsidy; Semi-endogenous growth, Heterogeneity.
JEL classification: O30; O40; H20.
1 Introduction

Empirical evidence suggests that the social return to R&D significantly exceeds the private return (e.g. Grilichis and Lichtenberg, 1984; Jones and Williams, 1998). Likewise, calibrated R&D-based growth models find a substantial R&D underinvestment gap (e.g. Jones and Williams, 2000). These results seem to call for large R&D subsidies (Grossmann, Steger and Trimborn, 2010a,b).

However, a frequent critique of raising R&D subsidies is that R&D skills are in limited supply and those with high R&D skills may already be allocated to R&D occupations. It has been argued that, therefore, stimulating demand for R&D workers primarily raises wages of R&D personnel rather than fostering innovation. In fact, Goolsbee (1998) shows that remuneration of R&D workers is positively affected by public policies to support R&D. It therefore seems that the distribution of R&D skills affects the optimal R&D policy: more limited R&D skills should imply lower optimal R&D subsidies.

We introduce R&D skill heterogeneity in a standard semi-endogenous growth model à la Jones (1995) and show analytically that, surprisingly, the optimal R&D policy is in fact independent of the distribution of R&D skills. The wedge between R&D investment in market equilibrium and social planning optimum is solely driven by positive R&D externalities. This holds despite a positive relationship between R&D subsidies and wages of R&D workers. Moreover, the optimal capital subsidy is also independent of the skill distribution.

2 The Model

Time is continuous and indexed by $t$. The time index is omitted whenever this does not lead to confusion. Homogenous final output is produced according to

$$Y = (L^Y)^{1-\alpha} \int_0^A x(i)^{\alpha} \, di,$$  \hspace{1cm} (1)
$0 < \alpha < 1$, where $L^Y$ denotes labor in manufacturing, $A$ the “number” of intermediate goods and $x(i)$ the quantity of intermediate good $i$. The final goods sector is perfectly competitive and the output price is normalized to unity.

There is perfect competition in the R&D sector. The number of ideas evolves according to

$$\dot{A} = \nu A^\phi L^A, \quad (2)$$

where $L^A$ is R&D labor input (in efficiency units), $\nu > 0$, $\phi < 1$. The price mark-up charged by each firm cannot exceed $\kappa \in (1, 1/\alpha]$, due to the existence of a competitive fringe (e.g. Aghion and Howitt, 2005). Parameter $\kappa$ captures the degree of imperfection of goods market competition. The capital stock, $K = \int_0^A x(i)di$, depreciates at rate $\delta \geq 0$. Both the capital and labor market are perfect. Initial levels of state variables, $K_0$ and $A_0$, are given.

There is mass one of identical households indexed by $j \in [0, 1]$. The size of each household grows with constant exponential rate, $n \geq 0$. Normalizing $N_0 = 1$, household size and population size at time $t$ are both equal to $N_t = e^{nt}$. In contrast to standard R&D-based growth models, we allow for R&D skill heterogeneity. Each household $j$ inelastically supplies either one unit of labor to the final goods sector or $h(j)$ efficiency units to the R&D sector. R&D skills are the same within each household. The probability density function of $h$ is denoted by $f(h)$, which is continuous with support $[\underline{h}, \bar{h}]$, $0 \leq \underline{h} < \bar{h}$. In equilibrium, the workers with the highest R&D skills are allocated to the R&D sector. That is, there will be a threshold skill level $\tilde{h}$ at which workers are indifferent in which sector to work. R&D workers with $h > \tilde{h}$ will earn a wage premium compared to workers in final good production. The amount of efficiency units of R&D labor is given by $L^A = N \int_{\underline{h}}^{\bar{h}} h f(h) dh$. Consequently, the ratio of efficiency units to the size of the overall workforce $l^A \equiv \frac{L^A}{N}$ is

$$l^A = \int_{\underline{h}}^{\bar{h}} h f(h) dh. \quad (3)$$
The labor resource constraint reads \( L^Y + N^A = N \), where \( N^A \equiv N \int_{\tilde{h}}^{h} f(h)dh \) is the number of workers allocated to R&D.

The government may subsidize both R&D costs (R&D sector) and capital costs (intermediate goods sector), at time-invariant rates \( s_A \) and \( s_K \). Subsidies are financed by a lump-sum tax \( (T) \) on households and the government budget is balanced each period.

Preferences of household \( j \in [0, 1] \) are given by

\[
U(j) = \int_{0}^{\infty} \left( \frac{(c_t(j))^{1-\sigma}}{1-\sigma} - 1 \right) e^{-(\rho-n)t} dt,
\]

\( \sigma > 0 \), where \( c(j) \) is consumption per member of household \( j \). Households take factor prices as given. Let \( w^A \) and \( w^Y \) denote wage rates per efficiency unit of R&D labor and for a worker in final production. Moreover, let \( I(j) \) be the wage income of a member of household \( j \). We will have

\[
I(j) = \begin{cases} 
    w^A h(j) & \text{if } h(j) \geq \tilde{h}, \\
    w^Y & \text{otherwise}.
\end{cases}
\]

Financial wealth of individual \( j \), \( a(j) \), accumulates according to

\[
\dot{a}(j) = (r-n)a(j) + I(j) - c(j) - T,
\]

where \( r \) denotes the interest rate and \( a_0(j) > 0 \). For the transversality conditions to hold and the value of utility streams to be finite, we impose

\[
\rho - n + (\sigma - 1)g > 0 \text{ with } g \equiv \frac{n}{1 - \phi}.
\]

(A1)

3 Analysis

We first analyze the decentralized equilibrium and then the social planner solution. This allows us to derive the optimal growth policy mix.
3.1 Market Equilibrium

As one unit of capital is required for one unit of output and capital costs are subsidized according to $s_K$, producer $i$ has profits

$$\pi(i) = [p(i) - (1 - s_K)(r + \delta)] x(i),$$  \hspace{1cm} (7)

where $p(i)$ is the price of good $x(i)$. Given that the mark-up is constrained by $\kappa \in (1, 1/\alpha]$, the optimal supply price of each firm $i$ reads (see Grossmann et al., 2010b)

$$p(i) = \kappa(1 - s_K)(r + \delta).$$  \hspace{1cm} (8)

According to (1), the inverse demand function for intermediate good $i$ is given by $p(i) = \alpha(L^Y/x(i))^{1-\alpha}$. Combining this inverse demand function with (8) and solving for $x(i)$ we obtain

$$x(i) = x = \left( \frac{\alpha}{\kappa(1 - s_K)(r + \delta)} \right)^{\frac{1}{1-\alpha}} L^Y. \hspace{1cm} (9)$$

Using (9) in (7), we see that $\pi(i) = \pi \forall i$. Using (1) for aggregate income and $K = Ax$ for the capital stock, (9) also implies

$$Y = A \left( \frac{\alpha}{\kappa(1 - s_K)(r + \delta)} \right)^{\frac{\alpha}{1-\alpha}} L^Y, \hspace{1cm} (10)$$

$$\frac{K}{Y} = \frac{\alpha}{\kappa(1 - s_K)(r + \delta)}. \hspace{1cm} (11)$$

For a given interest rate (which is policy-independent in the long run), an increase in $s_K$ raises capital-output ratio $K/Y$, whereas a higher mark-up ($\kappa$) reduces it.

Let $P^A$ denote the value of an intermediate good firm. The usual capital market equilibrium condition reads

$$\frac{\dot{P}^A}{P^A} + \frac{\pi}{P^A} = r. \hspace{1cm} (12)$$
The representative R&D firm maximizes profits as given by

$$\Pi \equiv P^A \rho^A L^A - (1 - s_A)w^A L^A. \quad (13)$$

**Definition 1.** A market equilibrium consists of time paths for the quantities \( \{L^A_t, L^Y_t, \{c_t(j), a_t(j)\}_{j \in [0,1]}, \{x_t(i)\}_{i \in [0,A_t]}, Y_t, K_t, A_t\}_{t=0}^{\infty} \), threshold skill level \( \{\tilde{h}_t\}_{t=0}^{\infty} \), lump-sum tax \( \{T_t\}_{t=0}^{\infty} \) and prices \( \{P^A_t, \{p_t(i)\}_{i \in [0,A_t]}, w^A_t, w^Y_t, r_t\}_{t=0}^{\infty} \) such that final goods producers, intermediate goods producers and R&D firms maximize profits, each household \( j \) chooses the consumption path to maximize (4) s.t. (6) and supplies labor to the R&D sector if and only if \( w^A h(j) \geq w^Y \) (i.e. \( \tilde{h} = \frac{w^Y}{w^A} \)), the capital resource constraint \( \int_0^A x(i)di = K \) holds, the labor market clears,

$$l^Y \equiv \frac{L^Y}{N} = 1 - \int_{\tilde{h}}^{\hat{h}} f(h)dh, \quad (14)$$

the capital market equilibrium condition (12) holds, the goods markets clear, the financial market clears (i.e. \( \int_0^N a(j)dj = K + P^A A_t \)), and the lump-sum tax \( T \) balances the government budget each period.

Let us denote values of stationary variables in balanced growth equilibrium (BGE) with superscript \( (*) \). Proofs are relegated to an online-appendix.

**Proposition 1.** There exists a unique BGE such that:

(i) The number of ideas \( A \) grows at rate \( g = \frac{n}{1 - \rho} \). Consumption and asset levels, \( c(j), a(j) \), also grow at rate \( g \ \forall j \). Aggregate final output, \( Y \), and the capital stock, \( K \), grow at rate \( g + n \). The value of an innovation, \( P^A \), grows at rate \( n \).

(ii) There is a unique stationary long-run threshold skill level, \( \tilde{h}^* \), which determines if a worker \( j \) is allocated to final goods production (for \( h(j) < \tilde{h} \)) or R&D (for \( h(j) \geq \tilde{h} \)); \( \tilde{h}^* \) is decreasing in the R&D subsidy rate, \( s_A \), and independent of the capital subsidy rate, \( s_K \).

Proposition 1 suggests that subsidizing physical capital does not affect the long run...
allocation of labor, whereas an increase in the R&D subsidy rate stimulates the R&D activity of firms (i.e., \( l^{A*} \) increases and \( l^{Y*} \) decreases).

An important variable in the innovation literature is the fraction of workers allocated to R&D, \( d \equiv \int_{\tilde{h}}^{h} f(h) \, dh \).

**Corollary 1.** The long run fraction of labor allocated to R&D, \( d^* \), is (i) increasing in the R&D subsidy rate, \( s_A \), and (ii) not systematically affected by the distribution of R&D skills.

Part (i) is straightforward since threshold level \( \tilde{h}^* \) in BGE is decreasing in \( s_A \). The intuition for part (ii) is discussed below.

### 4 Social Planning Optimum and Optimal Policy

The social planner chooses a symmetric capital allocation across intermediate goods production sites, i.e., \( x(i) = K/A \forall i \). From (1) one then gets \( Y = K^\alpha(AY)^{1-\alpha} \). The aggregate capital stock evolves according to \( \dot{K} = Y - Nc - \delta K \), where \( c \) denotes per capita consumption. Hence, in per capita terms we have

\[
\dot{k} = k^\alpha(Al^Y)^{1-\alpha} - c - (\delta + n)k. \tag{15}
\]

As preferences are homothetic, there exists a representative consumer (Mas-Colell, Whinston and Green, 1995). The social planner’s problem thus reads

\[
\max_{\{c_t\}} \int_0^\infty (c_t)^{1-\sigma} - 1 - (\rho - n)\, dt \quad \text{s.t. (2), (3), (14), (15),}
\]

and non-negativity constraints. \( c, \tilde{h} \) are control variables and \( k, A \) are state variables. We focus on the BGE when comparing the first best solution with the market outcome.

**Proposition 2.** In the long-run social planning optimum:

(i) The number of ideas \( A \) and per capita consumption \( c \) grow at rate \( g \), whereas \( Y \) and \( K \) both grow at rate \( g + n \).
(ii) There exists a unique socially optimal long-run threshold skill level, $\bar{h}_{\text{opt}}$, which is stationary. For $s_A = 0$ (no R&D subsidy) and $\phi \geq 0$, we have $\bar{h}_{\text{opt}} < h^*$, i.e., there is R&D underinvestment.

**Proposition 3.** The socially optimal, long-run R&D and capital cost subsidy rates are

$$s_{K}^{\text{opt}} = 1 - \frac{1}{\kappa}, \quad (17)$$

$$s_{A}^{\text{opt}} = 1 - \frac{1 - 1/\kappa}{1/\alpha - 1/\sigma g + \rho} \left( \sigma - 1 \right) g + \rho - n, \quad (18)$$

which are independent of the distribution of R&D skills.

There are two sources of inefficiency of R&D investments. First, if $\phi > 0$, there is a standing on shoulders effect, not taken into account by R&D firms, which promotes underinvestment. Second, innovators can only appropriate part of the economic surplus from raising the knowledge stock. To see this, first note that $x(i) = K_A = \frac{K Y}{Y A}$, $\forall i$. Substituting this into (7) and using (8) and (11) reveals that $\pi = \alpha(1 - \frac{1}{\kappa}) \frac{Y}{A}$. According to (10), $\frac{\partial Y}{\partial A} = \frac{Y}{A}$. Since $\alpha(1 - \frac{1}{\kappa}) < 1$, the profit of an innovator $\pi$ is lower than the contribution of an additional idea to output, $\frac{\partial Y}{\partial A}$. This "surplus appropriability problem" promotes underinvestment. Overall, decentralized R&D investment is suboptimally low, calling for $s_A > 0$, whenever $\phi \geq 0$.

Due to monopolistic competition, intermediate goods supply and therefore the demand for capital are inefficiently low as well. This implies suboptimally slow capital accumulation, which calls for a subsidy on capital costs.

The novel result is that both the R&D underinvestment gap and optimal growth policy are independent of the distribution of R&D skills. When raising demand for R&D workers by subsidizing R&D costs, more R&D workers enter R&D occupations. This is socially desirable although the additional R&D workers possess lower skills than the ones already active. All that matters for the R&D underinvestment gap are the market imperfections which bias the demand for R&D skills. The main assumptions which drive our "independence result" is the possibility of firms to discriminate wage payments according to skill and that all workers possess positive R&D skills in the
relevant upper end of the distribution of R&D skills. Less skilled R&D workers earn lower income than higher skilled ones. Thus, even if the additional R&D workers, which are employed after an increase in R&D subsidization, are of lower skill, the decision of firms to hire them is not affected by the skill distribution. The possibility of wage discrimination is also the reason why the distribution of skills does not systematically affect the allocation of labor (part (ii) of Corollary 1).

Our results are consistent with the finding of Goolsbee (1998) that R&D workers gain from higher R&D subsidies. To see this, note from \( \hat{h} = \frac{w^Y}{w^A} \) (Definition 1) that long-run wage income of a R&D worker \( j \) with skill \( h(j) \geq \hat{h}^* \), relative to a production worker, is equal to the ratio of his skill to the one of the marginal entrant into a R&D occupation:

\[
\frac{w^A h(j)}{w^Y} = \frac{h(j)}{\hat{h}^*}.
\]

According to part (i) of Proposition 1, even in the long run an increase in R&D subsidy rate \( s^A \), by reducing threshold skill level \( \hat{h}^* \), benefits those who would be R&D workers also without the subsidy. However, this does not mean that R&D subsidization is problematic. To the contrary, it is a possibility to lure additional workers into R&D occupations, which is socially desirable.

References


Online-Appendix

Proof of Proposition 1: The current-value Hamiltonian which corresponds to the intertemporal optimization problem of household $j$ is given by

$$
H(j) = \frac{c(j)^{1-\sigma} - 1}{1 - \sigma} + \lambda(j) [(r - n)a(j) + I(j) - c(j) - T],
$$

(20)

where $\lambda(j)$ is the co-state-variable associated with constraint (6). Necessary optimality conditions are $\frac{\partial H(j)}{\partial c(j)} = 0$, $\frac{\dot{\lambda}(j)}{\lambda(j)} = (\rho - n)\lambda(j) - \frac{\partial H(j)}{\partial a(j)}$, and the corresponding transversality condition. Thus,

$$
\dot{\lambda}(j) = \frac{\lambda(j)}{c(j)} = -\sigma \frac{\dot{c}(j)}{c(j)},
$$

(21)

$$
\dot{\lambda}(j) = \rho - r,
$$

(22)

$$
\lim_{t \to \infty} \lambda_t e^{-(\rho - n)t}a_t(j) = 0.
$$

(23)

Combining (21) with (22), we obtain the standard Euler equation

$$
\frac{\dot{c}(j)}{c(j)} = \frac{r - \rho}{\sigma}
$$

(24)

Next, substitute (8) and (9) into (7) to obtain the following expression for the profit of each intermediate goods producer $i$:

$$
\pi(i) = \pi = (\kappa - 1) \left( \frac{\alpha}{\kappa} \right)^{\frac{1}{\alpha}} \left[ \left( 1 - s_K \right) (r + \delta) \right]^{\frac{-\alpha}{\alpha}} L^Y.
$$

(25)

Since final goods producers take the wage rate $w^Y$ as given, it is equal to its marginal productivity of labor, $w^Y = (1-\alpha)Y/L^Y$. Also recall from Definition 1 that $w^Y = w^A\tilde{h}$. 

10
Thus,

\[ w^A = \frac{(1 - \alpha)Y}{\tilde{h}L^Y} = \frac{(1 - \alpha)A}{\tilde{h}} \left( \frac{\alpha}{\kappa(1 - s_K)(r + \delta)} \right)^{\frac{\alpha}{1 - \alpha}}, \tag{26} \]

where (27) follows by using (10). Moreover, the profit-maximizing choice of the R&D sector implies \( \Pi = 0 \); thus, \( P^A \nu A^\phi = (1 - s_A)w^A \), according to (13). Substituting (26) into the latter equation implies

\[ P^A = \frac{(1 - s_A)(1 - \alpha)}{\nu A^{\phi-1} \tilde{h}} \left( \frac{\alpha}{\kappa(1 - s_K)(r + \delta)} \right)^{\frac{n}{1 - \alpha}}, \tag{28} \]

We derive the steady state by assuming that part (i) of Proposition 1 holds and show that the implications of this assumption are consistent with the assumption. For later use, setting \( \dot{c}(j)/c(j) = g \) in (24) implies that the long run interest rate reads

\[ r^* = \sigma g + \rho. \tag{29} \]

Substituting (25) into (12) and setting \( \dot{P}^A/P^A = n \) implies that

\[ n + \frac{(\kappa - 1) \left( \frac{\alpha}{\kappa} \right)^{\frac{1}{1 - \alpha}} L^Y}{\left[ (1 - s_K)(r + \delta) \right]^{\frac{n}{1 - \alpha}} P^A} = r. \tag{30} \]

From (2), we find \( \dot{A}/A = \nu A^{\phi-1} L^A \). From this it becomes clear that setting \( \dot{A}/A = g \) is consistent with \( L^A \) growing at rate \( n \). Thus, in steady state,

\[ \nu A^{\phi-1} = \frac{g}{N^A}. \tag{31} \]

Using (31) in (28) and substituting the resulting expression as well as (29) in (30) implies that

\[ \frac{1 - \frac{1}{\kappa}}{\frac{1}{\alpha} - 1} \left( \frac{g \tilde{h}L^Y}{(1 - s_A)l^A} \right) = \sigma g + \rho - n. \tag{32} \]
According to (3) and (14), we obtain

$$\frac{l^Y}{l^A} = 1 - \frac{\int h^f (h) dh}{\int h^h h f(h) dh}.$$

(33)

Substituting (33) into (32) leads to

$$\Gamma(\tilde{h}) \equiv \left( 1 - \frac{\int h^h f(h) dh}{\int h^h h f(h) dh} \right) \tilde{h} = \left( 1 - s_A \right) \frac{1 - \frac{1}{\kappa} \sigma g + \rho - n}{g} \equiv \Omega(s_A).$$

(34)

As \( \Gamma'(\tilde{h}) > 0 \), the solution of (34) for \( \tilde{h}^* \) is unique. Moreover, noting that \( \Omega'(s_A) < 0 \) and the fact that \( s_K \) does not enter (34) confirms comparative-static results in part (ii) of Proposition 1.

That \( Y \) and \( K \) growth with rate \( n + g \) in the long run follows from (10) and (11). Finally, we show that the transversality condition (23) holds under assumption (A1). First, use (21) and \( \dot{c}(j)/c(j) = g \) to find that \( \dot{\lambda}(j)/\lambda(j) = -\sigma g \). It remains to be shown that \( a(j) \) grows with rate \( g \) in the long run. Rewriting (6) to

$$\dot{a}(j)/a(j) = r - n + \frac{I(j)}{a(j)} - \frac{c(j)}{a(j)} - \frac{T}{a(j)},$$

(35)

reveals that \( \dot{a}(j)/a(j) = g \) indeed holds in steady state, if both the lump-sum tax per household \( (T) \) and income level \( I(j) \) grow at rate \( g \). Recalling from (29) that the long run interest rate \( r \) is time-invariant, we see from (27) that wages rates \( w^A \) and \( w^Y = w^A \tilde{h} \), and therefore all income levels, grow in steady state at the same rate as \( A \) (namely at rate \( g \)). Moreover, defining \( k \equiv K/N \), the lump-sum tax reads

$$T = s_K (r + \delta) k + s_A w^A l^A.$$

(36)

Use (36) together with the facts that \( w^A \) and \( k \) grow at rate \( g \) in the long run to see that \( \dot{T}/T = g \) holds in steady state. This concludes the proof.

**Proof of Corollary 1:** Part (i) is an immediate implication of the result that \( \tilde{h}^* \) is decreasing in \( s_A \) (part (ii) of Proposition 1). To illustrate part (ii), suppose that the
distribution of R&D skills is uniform, i.e., $f(h) = (\bar{h} - h)^{-1}$. Thus, (34) becomes

$$\frac{(\bar{h} - h)\bar{h}}{h^2 - \bar{h}^2} = \Omega(s_A).$$

(37)

Rewriting (37) reveals that there is only one positive root for the steady state value of threshold skill level $\tilde{h}$, which is given by

$$\tilde{h}^* = \frac{h}{2(1 + \Omega)} \left(1 + \sqrt{1 + 4\Omega(s_A) [1 + \Omega(s_A)] \left(\frac{\tilde{h}}{\bar{h}}\right)^2}\right).$$

(38)

Hence, the fraction of labor in BGE allocated to R&D, $d^* \equiv \int_{h^*}^{\bar{h}} f(h)dh$, reads

$$d^* = \frac{\bar{h} - \tilde{h}^*}{\bar{h} - h} = \frac{\frac{h}{2(1 + \Omega)} \left(1 + \sqrt{1 + 4\Omega(s_A) [1 + \Omega(s_A)] \left(\frac{\tilde{h}}{\bar{h}}\right)^2}\right)}{\frac{h}{2} - 1}.$$  

(39)

This reveals that, for a uniform skill distribution, $d^*$ can be written as function of $\bar{h}/h$. However, the relationship is ambiguous. ■

**Proof of Proposition 2:** The current-value Hamiltonian which corresponds to the social planning problem (16) is given by

$$\mathcal{H} = \frac{c^{1-\sigma} - 1}{1 - \sigma} + \lambda_k[A^{1-\alpha} k^{\alpha} \left(1 - \int_{\tilde{h}}^{\bar{h}} f(h)dh\right) - (\delta + n)k - c] + \lambda_A A^\varphi N \int_{\tilde{h}}^{h} h f(h)dh,$$

(40)

where $\lambda_k$ and $\lambda_A$ are co-state variables associated with constraints (15) and (2), respectively. Necessary optimality conditions are $\partial\mathcal{H}/\partial c = \partial\mathcal{H}/\partial \tilde{h} = 0$ (control variables), $\dot{\lambda}_z = (\rho - n)\lambda_z - \partial\mathcal{H}/\partial z$ for $z \in \{k, A\}$ (state variables), and the corresponding transversality conditions. Thus,

$$\lambda_k = c^{-\sigma}, \text{i.e.,} \quad \frac{\dot{\lambda}_k}{\lambda_k} = -\frac{\check{c}}{\bar{c}}.$$  

(41)
\[(1 - \alpha)\left(\frac{k}{A t^Y}\right)^\alpha = \frac{\lambda_A}{\lambda_k} \nu A^{\phi - 1} N \tilde{h}_t,\]  
\[\hat{\lambda}_k = \rho - \alpha \left(\frac{A t^Y}{k}\right)^{1-\alpha} + \delta,\]  
\[\frac{\hat{\lambda}_A}{\lambda_A} = \rho - n - \frac{\lambda_k}{\lambda_A} (1 - \alpha) \left(\frac{k}{A}\right)^\alpha \left(\frac{l^Y}{l^A}\right)^{1-\alpha} - \phi \frac{\dot{A}}{A},\]  
\[\lim_{t \to \infty} \lambda_{z,t} e^{-(\rho - n)t_{z,t}} = 0, \quad z \in \{k, A\} \].

(\lambda_{z,t} denotes the co-state variable associated with state variable z at time t.)

Solving (42) for \(\lambda_k/\lambda_A\) and using (31) implies
\[\frac{\lambda_k}{\lambda_A} = \frac{g \tilde{h}_t}{(1 - \alpha) l^A \left(\frac{k}{A}\right)^\alpha}.\]  
(46)

Suppose that A and k grow at rate n in the long run, whereas \(\tilde{h}\) and thus also \(l^Y\) and \(l^A\) are stationary. These properties are easily confirmed, as are transversality conditions.

From (46), we then find \(\hat{\lambda}_k/\lambda_k = \hat{\lambda}_A/\lambda_A\). Moreover, using \(\dot{c}/c = g\) in (41) implies that
\[\frac{\hat{\lambda}_k}{\lambda_k} = \frac{\hat{\lambda}_A}{\lambda_A} = -\sigma g.\]  
(47)

Using \(\hat{\lambda}_A/\lambda_A = -\sigma g, \hat{A}/A = g = \frac{n}{1-\phi}\) and (46) in (44), we obtain
\[\frac{\dot{\tilde{h}}}{l^A} = \frac{\rho + (\sigma - 1)g}{g}.\]  
(48)

Using (33) and the definition of function \(\Gamma(\cdot)\), we find that the optimal threshold skill level, \(\tilde{h}_{opt}\), is uniquely given by
\[\Gamma(\tilde{h}_{opt}) = \frac{\rho + (\sigma - 1)g}{g}.\]  
(49)

Recall that \(\Gamma' > 0\). Thus, according to (34) and (49), for \(s_A = 0\) we find that
$\tilde{h}^* > \tilde{h}_{\text{opt}}$ if and only if

$$\frac{1}{\alpha - 1} (\sigma g + \rho - n) > \rho + (\sigma - 1)g.$$ 

Since $1 < \kappa < 1/\alpha$, we have $1/\alpha - 1 > 1 - 1/\kappa$. Moreover, using $g = \frac{n}{1-\sigma}$, we find that $\sigma g + \rho - n \geq \rho + (\sigma - 1)g$ holds if and only if $\phi \geq 0$. This confirms that $\tilde{h}^* > \tilde{h}_{\text{opt}}$ if $s_A = 0$ and $\phi \geq 0$. Finally, use (10) and (11) to see that $Y$ and $K$ growth with rate $n + g$ in the long run. This concludes the proof. ■

**Proof of Proposition 3:** First, substitute (29) into (11) to see that the capital-output ratio in decentralized BGE is given by

$$\left( \frac{K}{Y} \right)^* = \frac{\alpha}{\kappa(1-s_K)(\sigma g + \rho + \delta)}.$$  \hfill (50)

Second, substitute $\dot{\lambda}_K/\lambda_K = -\sigma g$ from (47) into (43) to find

$$\alpha \left( \frac{A_{1} Y}{k} \right)^{1-\alpha} = \sigma g + \rho + \delta.$$  \hfill (51)

Since $(A_{1} Y/k)^{1-\alpha} = Y/K$, the socially optimal capital-output ratio is given by

$$\left( \frac{K}{Y} \right)_{\text{opt}} = \frac{\alpha}{\sigma g + \rho + \delta}.$$  \hfill (52)

The optimal capital subsidy, $s_{K}^{\text{opt}}$, follows from setting $(K/Y)^* = (K/Y)_{\text{opt}}$. To find the optimal R&D subsidy, $s_{A}^{\text{opt}}$, set the right-hand sides of (34) and (49) equal to each other. ■
<table>
<thead>
<tr>
<th>Nr.</th>
<th>Autor/In</th>
<th>Titel</th>
<th>Jahr</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Wolfgang Bernhardt</td>
<td>Stock Options wegen oder gegen Shareholder Value? Vergütungsmodelle für Vorstände und Führungskräfte</td>
<td>04/1998</td>
</tr>
<tr>
<td>2</td>
<td>Thomas Lenk / Volkmar Teichmann</td>
<td>Bei der Reform der Finanzverfassung die neuen Bundesländer nicht vergessen!</td>
<td>10/1998</td>
</tr>
<tr>
<td>4</td>
<td>Kristin Wellner</td>
<td>Möglichkeiten und Grenzen kooperativer Standortgestaltung zur Revitalisierung von Innenstädten</td>
<td>12/1998</td>
</tr>
<tr>
<td>5</td>
<td>Gerhardt Wolff</td>
<td>Brauchen wir eine weitere Internationalisierung der Betriebswirtschaftsfahre?</td>
<td>01/1999</td>
</tr>
<tr>
<td>6</td>
<td>Thomas Lenk / Friedrich Schneider</td>
<td>Zurück zu mehr Föderalismus: Ein Vorschlag zur Neugestaltung des Finanzausgleichs in der Bundesrepublik Deutschland unter besonderer Berücksichtigung der neuen Bundesländer</td>
<td>12/1998</td>
</tr>
<tr>
<td>7</td>
<td>Thomas Lenk</td>
<td>Kooperativer Föderalismus – Wettbewerbsorientierter Föderalismus</td>
<td>03/1999</td>
</tr>
<tr>
<td>8</td>
<td>Thomas Lenk / Andreas Matthes</td>
<td>EU – Osterweiterung – Finanzierbar?</td>
<td>03/1999</td>
</tr>
<tr>
<td>9</td>
<td>Thomas Lenk / Volkmar Teichmann</td>
<td>Die fiskalischen Wirkungen verschiedener Forderungen zur Neugestaltung des Länderfinanzausgleichs in der Bundesrepublik Deutschland: Eine empirische Analyse unter Einbeziehung der Normenkontrollkriterie der Länder Baden-Württemberg, Bayern und Hessen sowie der Stellungnahmen verschiedener Bundesländer</td>
<td>09/1999</td>
</tr>
<tr>
<td>10</td>
<td>Kai-Uwe Graw</td>
<td>Gedanken zur Entwicklung der Strukturen im Bereich der Wasserversorgung unter besonderer Berücksichtigung kleiner und mittlerer Unternehmen</td>
<td>10/1999</td>
</tr>
<tr>
<td>11</td>
<td>Adolf Wagner</td>
<td>Materialien zur Konjunkturforschung</td>
<td>12/1999</td>
</tr>
<tr>
<td>12</td>
<td>Anja Birke</td>
<td>Die Übertragung westdeutscher Institutionen auf die ostdeutsche Wirklichkeit – ein erfolgversprechendes Zusammenspiel oder Aufdeckung systematischer Mängel? Ein empirischer Bericht für den kommunalen Finanzausgleich am Beispiel Sachsen</td>
<td>02/2000</td>
</tr>
<tr>
<td>14</td>
<td>Wolfgang Bernhardt</td>
<td>Unternehmensführung (Corporate Governance) und Hauptversammlung</td>
<td>04/2000</td>
</tr>
<tr>
<td>15</td>
<td>Adolf Wagner</td>
<td>Materialien zur Wachstumsforschung</td>
<td>03/2000</td>
</tr>
<tr>
<td>16</td>
<td>Thomas Lenk / Anja Birke</td>
<td>Determinanten des kommunalen Gebührenaufkommens unter besonderer Berücksichtigung der neuen Bundesländer</td>
<td>04/2000</td>
</tr>
<tr>
<td>17</td>
<td>Thomas Lenk</td>
<td>Finanzwirtschaftliche Auswirkungen des Bundesverfassungsgerichtsurteils zum Länderfinanzausgleich vom 11.11.1999</td>
<td>04/2000</td>
</tr>
<tr>
<td>18</td>
<td>Dirk Böbel</td>
<td>Continuous linear utility for preferences on convex sets in normal real vector spaces</td>
<td>02/2000</td>
</tr>
<tr>
<td>19</td>
<td>Stefan Dierkes / Stephanie Hanrauti</td>
<td>Steuerung dezentraler Investitionsentscheidungen bei nutzungsabhängigem und nutzungsunabhängigem Verschluß des Anlagenvermögens</td>
<td>06/2000</td>
</tr>
<tr>
<td>20</td>
<td>Thomas Lenk / Andreas Matthes / Olaf Hirschelaid</td>
<td>Zur Trennung von Bundes- und Landeskompetenzen in der Finanzverfassung Deutschlands</td>
<td>07/2000</td>
</tr>
<tr>
<td>21</td>
<td>Stefan Dierkes</td>
<td>Marktwerte, Kapitalkosten und Betafaktoren bei wertabhängiger Finanzierung</td>
<td>10/2000</td>
</tr>
<tr>
<td>22</td>
<td>Thomas Lenk</td>
<td>Intergovernmental Fiscal Relationships in Germany: Requirement for New Regulations?</td>
<td>03/2001</td>
</tr>
<tr>
<td>23</td>
<td>Wolfgang Bernhardt</td>
<td>Stock Options – Aktuelle Fragen: Besteuerung, Bewertung, Offenlegung</td>
<td>03/2001</td>
</tr>
<tr>
<td>Nr. 24</td>
<td>Thomas Lenk</td>
<td>Die „kleine Reform“ des Länderfinanzausgleichs als Nukleus für die „große Finanzverfassungs-reform“? 10/2001</td>
<td></td>
</tr>
<tr>
<td>Nr. 27</td>
<td>Sören Bär</td>
<td>Grundzüge eines Tourismusmarketing, untersucht für den Südosten Leipzig 05/2002</td>
<td></td>
</tr>
<tr>
<td>Nr. 28</td>
<td>Wolfgang Bernhardt</td>
<td>Der Deutsche Corporate Governance Kodex: Zuwahl (comply) oder Abwahl (explain)? 06/2002</td>
<td></td>
</tr>
<tr>
<td>Nr. 29</td>
<td>Adolf Wagner</td>
<td>Konjunkturtheorie, Globalisierung und Evolutionsökonomik 08/2002</td>
<td></td>
</tr>
<tr>
<td>Nr. 30</td>
<td>Adolf Wagner</td>
<td>Zur Profilbildung der Universitäten 08/2002</td>
<td></td>
</tr>
<tr>
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<td>Thomas Lenk / Anja Birke</td>
<td>The Measurement of Expenditure Needs in the Fiscal Equalization at the Local Level Empirical Evidence from German Municipalities 10/2002</td>
<td></td>
</tr>
<tr>
<td>Nr. 33</td>
<td>Wolfgang Bernhardt</td>
<td>Die Lust am Fliegen Eine Parabel auf viel Corporate Governance und wenig Unternehmenvorführung 11/2002</td>
<td></td>
</tr>
<tr>
<td>Nr. 35</td>
<td>Uwe Haubold / Michael Nowak</td>
<td>Risikoanalyse für Langfristinvestments Eine simulationsbasierte Studie 12/2002</td>
<td></td>
</tr>
<tr>
<td>Nr. 36</td>
<td>Thomas Lenk</td>
<td>Die Neuregelung des bundesstaatlichen Finanzausgleichs auf Basis der Steuerschätzung Mai 2002 und einer aktualisierten Bevölkerungsstatistik 12/2002</td>
<td></td>
</tr>
<tr>
<td>Nr. 37</td>
<td>Uwe Haubold / Michael Nowak</td>
<td>Auswirkungen der Renditeverteilungsspannungen auf Anlageentscheidungen Eine simulationsbasierte Studie 02/2003</td>
<td></td>
</tr>
<tr>
<td>Nr. 38</td>
<td>Wolfgang Bernhard</td>
<td>Corporate Governance Konex für den Mittelstand? 06/2003</td>
<td></td>
</tr>
<tr>
<td>Nr. 39</td>
<td>Hermut Kormann</td>
<td>Familienunternehmen: Grundfragen mit finanzwirtschaftlichem Bezug 10/2003</td>
<td></td>
</tr>
<tr>
<td>Nr. 40</td>
<td>Matthias Folk</td>
<td>Launhardtische Trichter 11/2003</td>
<td></td>
</tr>
<tr>
<td>Nr. 41</td>
<td>Wolfgang Bernhardt</td>
<td>Corporate Governance statt Unternehmensführung 11/2003</td>
<td></td>
</tr>
<tr>
<td>Nr. 42</td>
<td>Thomas Lenk / Karolina Kaiser</td>
<td>Das Prämienmodell im Länderfinanzausgleich – Anreiz- und Verteilungswirkungen 11/2003</td>
<td></td>
</tr>
<tr>
<td>Nr. 43</td>
<td>Sabine Klinger</td>
<td>Die Volkswirtschaftliche Gesamtrechnung des Haushaltsektors in einer Matrix 03/2004</td>
<td></td>
</tr>
<tr>
<td>Nr. 44</td>
<td>Thomas Lenk / Heide Köpping</td>
<td>Strategien zur Armutsbekämpfung und -vermeidung in Ostdeutschland: 05/2004</td>
<td></td>
</tr>
<tr>
<td>Nr. 45</td>
<td>Wolfgang Bernhardt</td>
<td>Sommermachtfantasien Corporate Governance im Land der Träume. 07/2004</td>
<td></td>
</tr>
<tr>
<td>Nr. 46</td>
<td>Thomas Lenk / Karolina Kaiser</td>
<td>The Premium Model in the German Fiscal Equalization System 12/2004</td>
<td></td>
</tr>
<tr>
<td>Nr. 47</td>
<td>Thomas Lenk / Christine Falken</td>
<td>Komplicative Analyse ausgewählter Indikatoren des Kommunalwirtschaftlichen Gesamtergebnisses 05/2005</td>
<td></td>
</tr>
<tr>
<td>Nr. 48</td>
<td>Michael Nowak / Stephan Barth</td>
<td>Immobilienanlagen im Portfolio institutioneller Investoren am Beispiel von Versicherungsunternehmen Auswirkungen auf die Risikosituation 08/2005</td>
<td></td>
</tr>
</tbody>
</table>
Nr. 49  Wolfgang Bernhardt  Familiengesellschaften – Quo Vadis?
Vorsicht vor zu viel „Professionalisierung“ und Ver-Fremdung
11/2005

Nr. 50  Christian Milow  Der Griff des Staates nach dem Währungsgold
12/2005

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03/2006

08/2006

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08/2006

Nr. 54  Hermut Kormann  Gibt es so etwas wie typisch mittelständige Strategien?
11/2006

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Zwischen Juristentag und Biedenkopf-Kommission
11/2006

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A Multivariate Perspective on Indicators of Ifo, OECD, and ZEW
01/2007

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12/2006

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01/2007

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Zur Informationsfunktion des alten und neuen Rechnungswesens der Kommunen
Teil I: Einführende und Erläuternde Betrachtungen zum Systemwechsel im kommunalen Rechnungswesen
01/2007

Nr. 60  Christine Falken / Mario Schmidt  Kameratoristik versus Doppik
Zur Informationsfunktion des alten und neuen Rechnungswesens der Kommunen
Teil II: Bewertung der Informationsfunktion im Vergleich
01/2007

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Innovative Finanzierungen im Zeitalter Der Medici. Wurzeln der modernen Finanzmärkte
03/2007

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Konjunkturelle, sektorale und regionale Bestimmungsgründe der Entwicklung der Bruttwertschöpfung
1992 bis 2006
07/2007

Nr. 63  Adolf Wagner  Regionalökonomik:
Konvergierende oder divergierende Regionalentwicklungen
08/2007

Nr. 64  Ulrich Heilemann / Jens Ulrich  Good bye, Professor Phillips?
Zum Wandel der Tariflohndeterminanten in der Bundesrepublik 1952 – 2004
08/2007

Nr. 65  Gunther Schnabl / Franziska Schobert  Monetary Policy Operations of Debtor Central Banks in MENA Countries
10/2007

Nr. 66  Andreas Schaller / Simone Valente  Habit Formation, Dynastic Altruism, and Population Dynamics
11/2007

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Eine Erfolgsgeschichte?
01/2008

Nr. 68  Ulrich Heilemann / Jens Ulrich  Viel Um oder wenig? Zur Empirie von Lohnformeln in der Bundesrepublik
01/2008

Nr. 69  Christian Groth / Karl-Josef Koch / Thomas M. Steger  When economic growth is less than exponential
02/2008

Nr. 70  Andreas Bohne / Linda Kochmann  Ökonomische Umweltbewertung und endogene Entwicklung peripherer Regionen
Synthese einer Methodik und einer Theorie
02/2008

Nr. 71  Andreas Bohne / Linda Kochmann / Jan Slavík / Lenka Slavíková  Deutsch-tschechische Bibliographie
Studien der kontingenten Bewertung in Mittel- und Osteuropa
06/2008
<table>
<thead>
<tr>
<th>Nr.</th>
<th>Author(s)</th>
<th>Title</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>72</td>
<td>Paul Lehmann / Christoph Schröter-Schlaack</td>
<td>Regulating Land Development with Tradable Permits: What Can We Learn from Air Pollution Control?</td>
<td>08/2008</td>
</tr>
<tr>
<td>73</td>
<td>Ronald McKinnon / Gunther Schnabl</td>
<td>China’s Exchange Rate Impasse and the Weak U.S. Dollar</td>
<td>10/2008</td>
</tr>
<tr>
<td>74</td>
<td>Wolfgang Bernhardt</td>
<td>Manovergezügungen in der Finanz- und Wirtschaftskrise Rückkehr zu (guter) Ordnung, (klugem) Maß und (vernünftigem) Ziel</td>
<td>12/2008</td>
</tr>
<tr>
<td>76</td>
<td>Gunther Schnabl / Stephan Freitag</td>
<td>An Asymmetry Matrix in Global Current Accounts</td>
<td>01/2009</td>
</tr>
<tr>
<td>77</td>
<td>Christina Ziegler</td>
<td>Testing Predictive Ability of Business Cycle Indicators for the Euro Area</td>
<td>01/2009</td>
</tr>
<tr>
<td>78</td>
<td>Thomas Lenk / Oliver Rattmann / Florian F. Woste</td>
<td>Public Corporate Governance in Public Enterprises: Transparency in the Face of Divergent Positions of Interest</td>
<td>02/2009</td>
</tr>
<tr>
<td>79</td>
<td>Thomas Steger / Lucas Bretschger</td>
<td>Globalization, the Volatility of Intermediate Goods Prices, and Economic Growth</td>
<td>02/2009</td>
</tr>
<tr>
<td>80</td>
<td>Marcela Munoz Escobar / Robert Holländer</td>
<td>Institutional Sustainability of Payment for Watershed Ecosystem Services: Enabling conditions of institutional arrangement in watersheds</td>
<td>04/2009</td>
</tr>
<tr>
<td>81</td>
<td>Robert Holländer / Wu Chunyou / DUAN Ning</td>
<td>Sustainable Development of Industrial Parks</td>
<td>07/2009</td>
</tr>
<tr>
<td>82</td>
<td>Georg Quaas</td>
<td>Realgrößen und Preisindizes im alten und im neuen VGR-System</td>
<td>10/2009</td>
</tr>
<tr>
<td>84</td>
<td>Gunther Schnabl / Andreas Hoffmann</td>
<td>The Theory of Optimum Currency Areas and Growth in Emerging Markets</td>
<td>03/2010</td>
</tr>
<tr>
<td>85</td>
<td>Georg Quaas</td>
<td>Does the macroeconomic policy of the global economy’s leader cause the worldwide asymmetry in current accounts?</td>
<td>03/2010</td>
</tr>
<tr>
<td>86</td>
<td>Volker Grossmann / Thomas M. Steger / Timo Trimborn</td>
<td>Quantifying Optimal Growth Policy</td>
<td>06/2010</td>
</tr>
<tr>
<td>87</td>
<td>Wolfgang Bernhardt</td>
<td>Corporate Governance Kodex für Familienunternehmen? Eine Widerrede</td>
<td>06/2010</td>
</tr>
<tr>
<td>88</td>
<td>Philipp Mandel / Bernd Süssmuth</td>
<td>A ReExamination of the Role of Gender in Determining Digital Piracy Behavior</td>
<td>07/2010</td>
</tr>
<tr>
<td>89</td>
<td>Philipp Mandel / Bernd Süssmuth</td>
<td>Size Matters. The Relevance and Hickian Surplus of Agreeable College Class Size</td>
<td>07/2010</td>
</tr>
<tr>
<td>90</td>
<td>Thomas Kohstall / Bernd Süssmuth</td>
<td>Cyclic Dynamics of Prevention Spending and Occupational Injuries in Germany: 1886-2009</td>
<td>07/2010</td>
</tr>
<tr>
<td>91</td>
<td>Martina Padmanabhan</td>
<td>Gender and Institutional Analysis. A Feminist Approach to Economic and Social Norms</td>
<td>08/2010</td>
</tr>
<tr>
<td>92</td>
<td>Gunther Schnabl / Ansgar Balke</td>
<td>Finanzkrise, globale Liquidität und makroökonomischer Exit</td>
<td>09/2010</td>
</tr>
<tr>
<td>93</td>
<td>Ullrich Heilemann / Roland Schulr / Heinz Josef Münch</td>
<td>A &quot;perfect storm&quot;? The present crisis and German crisis patterns</td>
<td>12/2010</td>
</tr>
<tr>
<td>94</td>
<td>Gunther Schnabl / Holger Zemanek</td>
<td>Die Deutsche Wiedervereinigung und die europäische Schuldenkrise im Lichte der Theorie optimaler Währungsräume</td>
<td>06/2011</td>
</tr>
<tr>
<td>95</td>
<td>Andreas Hoffmann / Gunther Schnabl</td>
<td>Symmetrische Regeln und asymmetrisches Handeln in der Geld- und Finanzpolitik</td>
<td>07/2011</td>
</tr>
<tr>
<td>96</td>
<td>Andreas Schöfer / Mark T. Schneider</td>
<td>Endogenous Enforcement of Intellectual Property, North-South Trade, and Growth</td>
<td>08/2011</td>
</tr>
<tr>
<td>97</td>
<td>Volker Grossmann / Thomas M. Steger / Timo Trimborn</td>
<td>Dynamically Optimal R&amp;D Subsidization</td>
<td>08/2011</td>
</tr>
<tr>
<td>Nr.</td>
<td>Author(s)</td>
<td>Title</td>
<td>Date</td>
</tr>
<tr>
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<td>-------</td>
<td>------</td>
</tr>
<tr>
<td>98</td>
<td>Erik Gawel</td>
<td>Political drivers of and barriers to Public-Private Partnerships: The role of political involvement</td>
<td>09/2011</td>
</tr>
<tr>
<td>99</td>
<td>André Casajus</td>
<td>Collusion, symmetry, and the Banzhaf value</td>
<td>09/2011</td>
</tr>
<tr>
<td>100</td>
<td>Frank Hüttner / Marco Sunder</td>
<td>Decomposing $R^2$ with the Owen value</td>
<td>10/2011</td>
</tr>
<tr>
<td>101</td>
<td>Volker Grossmann / Thomas M. Steger / Timo Trimborn</td>
<td>The Macroeconomics of TANSTAAFL</td>
<td>11/2011</td>
</tr>
<tr>
<td>102</td>
<td>Andreas Hoffmann</td>
<td>Determinants of carry trades in Central and Eastern Europe</td>
<td>11/2011</td>
</tr>
<tr>
<td>103</td>
<td>Andreas Hoffmann</td>
<td>Did the Fed and ECB react asymmetrically with respect to asset market developments?</td>
<td>01/2012</td>
</tr>
<tr>
<td>104</td>
<td>Christina Ziegler</td>
<td>Monetary Policy under Alternative Exchange Rate Regimes in Central and Eastern Europe</td>
<td>02/2012</td>
</tr>
<tr>
<td>105</td>
<td>José Abad / Axel Löffler / Gunther Schnabl / Holger Zemanek</td>
<td>Fiscal Divergence, Current Account and TARGET2 Imbalances in the EMU</td>
<td>03/2012</td>
</tr>
<tr>
<td>106</td>
<td>Georg Quaas / Robert Köster</td>
<td>Ein Modell für die Wirtschaftszweige der deutschen Volkswirtschaft: Das &quot;MOGBOT&quot; (Model of Germany’s Branches of Trade)</td>
<td>03/2012</td>
</tr>
<tr>
<td>107</td>
<td>Andreas Schäfer / Thomas Steger</td>
<td>Journey into the Unknown?: Economic Consequences of Factor Market Integration under Increasing Returns to Scale</td>
<td>04/2012</td>
</tr>
<tr>
<td>108</td>
<td>Andreas Hoffmann / Björn Urbansky</td>
<td>Order, Displacements and Recurring Financial Crises</td>
<td>06/2012</td>
</tr>
<tr>
<td>109</td>
<td>Finn Marten Körner / Holger Zemanek</td>
<td>On the Brink? Intra-euro area imbalances and the sustainability of foreign debt</td>
<td>07/2012</td>
</tr>
<tr>
<td>110</td>
<td>André Casajus / Frank Hüttner</td>
<td>Nullifying vs. dummifying players or nullified vs. dummified players: The difference between the equal division value and the equal surplus division value</td>
<td>07/2012</td>
</tr>
<tr>
<td>111</td>
<td>André Casajus</td>
<td>Solidarity and fair taxation in TU games</td>
<td>07/2012</td>
</tr>
<tr>
<td>112</td>
<td>Georg Quaas</td>
<td>Ein Nelson-Winter-Modell der deutschen Volkswirtschaft</td>
<td>08/2012</td>
</tr>
<tr>
<td>113</td>
<td>André Casajus / Frank Hüttner</td>
<td>Null players, solidity, and the egalitarian Shapley values</td>
<td>08/2012</td>
</tr>
<tr>
<td>114</td>
<td>André Casajus</td>
<td>The Shapley value without efficiency and additivity</td>
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</tr>
<tr>
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<td>Erik Gawel</td>
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<td>02/2013</td>
</tr>
<tr>
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<td>Volker Grossmann / Andreas Schäfer / Thomas M. Steger</td>
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<td>02/2013</td>
</tr>
<tr>
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<td>Volker Grossmann / Thomas M. Steger</td>
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<td>02/2012 (Eingang im Dekanat 03/2013)</td>
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