

# Quantifying Optimal Growth Policy\*

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## Abstract

How does the optimal growth policy in advanced economies look like? This paper aims at starting the discussion on this research question within a comprehensive endogenous growth model. The analysis captures important elements of the tax-transfer system and accounts for transitional dynamics. Currently, for calculating corporate taxable income US firms are allowed to deduct approximately all of their capital and R&D costs from sales revenue. Our analysis suggests that this policy leads to severe underinvestment in both R&D and physical capital. We find that firms should be allowed to deduct between 2-2.5 times their R&D costs and about 1.5-1.7 times their capital costs. Implementing the optimal policy mix is likely to entail huge welfare gains.

**Key words:** Economic growth; Endogenous technical change; Optimal growth policy; Tax-transfer system; Transitional dynamics.

**JEL classification:** H20, O30, O40.

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# 1 Introduction

How does the optimal growth policy in advanced economies look like? We believe that this is an exceptionally important research question. One must acknowledge that, after three decades of Endogenous Growth Theory, we still do not have a sound understanding about the implied optimal growth policy. The papers' main contribution is to start the discussion on this research question, as seriously and carefully as possible. The topic on optimal growth policy in advanced economies appears heavily underresearched. This becomes evident by noting that there is no paper in top journals during the time period 1980 - 2011 that has dealt with *optimal growth policy* in industrialized economies.<sup>1</sup> In contrast, there are, for instance, 450 papers on optimal monetary policy in top journals during 1980 - 2011. The paper at hand is intended to represent a first contribution to correct for this mismatch. Our results strongly suggest that there is a substantial welfare gain from implementing of the first best policy programme.

There is common sense among economists that private firms in advanced economies conduct too little R&D. This conviction can be substantiated by noting that the social rate of return to business enterprise R&D is far above the private rate of return. The empirical productivity literature has identified social rates of return to R&D between 70 percent and more than 100 percent (e.g. Scherer, 1982; Griliches and Lichtenberg, 1984). Jones and Williams (1998) argue that, due to methodical shortcomings, these estimates should indeed be viewed as lower bounds. Hall (1996) reports that estimates of the private rate of return to R&D cluster around 10 percent to 15 percent. It is also widely believed that this R&D underinvestment bias is likely to cause a substantial welfare loss. Moreover, there is strong evidence showing that fiscal incentives are effective in increasing the economy-wide R&D intensity (e.g. Bloom, Griffith and van Reenen, 2002). The important policy question then reads as follows: What is the level of fiscal intervention which is required to remove the R&D underinvestment gap?

To answer this question, it is necessary to take both the general equilibrium di-

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<sup>1</sup>The set of 'top journals' is interpreted as TOP-10 journals according to Engemann and Wall (2009, Table 4) plus the respective leading field journal.

mension and the intertemporal dimension associated with R&D into account. Hence, endogenous growth theory provides a natural analytical framework for studies that aim at advising policy makers about the design of welfare-maximizing growth policy. However, any such analysis faces the problem to meet a balance between maintaining analytical tractability and avoiding that the model is too stylized to base policy recommendations upon it. It is true that any specific policy advise (like the calculation of the optimal R&D subsidy rate) requires numerical evaluations at some stage of the analysis. Nevertheless, we want to limit ourselves to models where the steady state can be derived analytically for at least two reasons. First, analytical solutions are generally useful in understanding the mechanics of a model such that numerical results can then be used mainly for quantification purposes. Second, analytical steady state results are salient to match endogenous variables to observables when calibrating the model. Using the steady state as an anchor for calibration appears as a reasonable strategy in the case of the US economy. This allows us to limit the degree of freedom in the numerical analysis substantially.

This paper employs a comprehensive endogenous growth framework to evaluate reforms of US growth policy and to derive the optimal policy mix. We allow for investment in physical capital, human capital and R&D, thereby accounting for the three major engines of economic growth.<sup>2</sup> We also account for distortions from taxation. Despite the complexity of the model, well interpretable closed-form solutions for the steady state are obtained.

We think that any serious and careful study on optimal growth policy in advanced economies should at least meet the following two requirements. (i) Important elements of the income tax system must be captured when calculating optimal Pigouvian corrections for distortions of growth-relevant investment incentives. Taxes on labor income,

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<sup>2</sup>Previous growth models which encompass three growth engines focus on other aspects than our study. Funke and Strulik (2000) argue that economic development can be represented as a sequence of growth stages, where every stage is characterized by one of the growth engines as dominant growth driver. Jones (2002) shows that the average growth rate of US output per working hour (1953-1993) has a large transitional dynamics component, due to rising educational attainment over time and an increasing share of labor devoted to R&D. Papageorgiou and Perez-Sebastian (2006) replicate several empirical regularities of economic development in Japan and South Korea during the Post-WWII period.

bond yields, capital gains and corporate income may be levied for other (e.g. redistributive) purposes than stimulating economic growth. However, like externalities and market power, they may directly distort investment decisions. Failing to account for income taxation thus potentially gives rise to misleading growth policy recommendations. Another reason to take the public finance side seriously when calculating quantitative policy recommendations results from the requirement of a careful calibration strategy. Setting model parameters such that endogenous variables match observables requires to take public policy into account since endogenous variables may depend on public policy. (ii) Transitional dynamics should be taken into account in the numerical evaluation of growth policy reforms. This requires to calculate the entire transition path in response to policy shocks. It is well-known that, in growth models with decreasing marginal productivity of capital, it may take a long time (possibly more than hundred years) after some shock until per capita income adjusts to anywhere near the new steady state. It is thus salient to compute the policy mix which maximizes the intertemporal welfare gain from a policy reform and not just focus on maximization of steady state welfare. Moreover, the underlying R&D-based growth model represents a non-linear, highly dimensional, saddle-point stable, differential-algebraic system. For plausible calibrations, the stable eigenvalues differ substantially in magnitude; hence, the dynamic system belongs to the class of stiff differential equations. Simulating such a dynamic model is all but trivial.<sup>3</sup> We employ a recent procedure, called relaxation algorithm (Trimborn, Koch and Steger, 2008), which can deal with these conceptual difficulties.

Our study produces three main results. (i) Despite multiple (four) distortions in the market economy plus various forms of distortionary income taxation, the first best allocation can be supported by an appropriate set of three subsidy rates (subsidies on physical capital investment, R&D investment, and education). This finding is remarkable in two respects: First, a small number (relative to the number of distortions) of

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<sup>3</sup>The growth literature has used the techniques of linearization, time elimination, or backward integration. Linearization delivers bad approximations if the deviation from the steady state is large, time elimination does not work if there are non-monotonic adjustments, and backward integration fails in case of stiff differential equations.

policy instruments is accordingly sufficient to restore the first best solution. Second, the suggested policy instruments do already exist in real-world economies. (ii) The current R&D subsidization in the US leads to dramatic underinvestment in R&D. Innovating firms should be allowed to deduct more than twice their R&D costs from sales revenue for calculating taxable corporate income, rather than just 1.1 times their R&D costs under the current policy. The US stimulus for investment in physical capital is also suboptimally low. The investment rate is biased downwards due to both price setting power of firms and capital income taxation. Firms should be allowed to deduct about 1.5 times their capital costs from sales revenue, rather than full deduction of their capital costs under the current policy. Investment in human capital should also be subsidized, roughly to the extent labor income is taxed. The optimal policy mix is remarkably robust to parameter changes. (iii) A policy reform targeted to all three growth engines simultaneously may entail huge welfare gains. An appropriate policy reform could achieve an intertemporal welfare gain which is equivalent to a permanent doubling of per capita consumption.

Our paper is closely related to the literature which studies the R&D underinvestment problem in a steady state. Our analysis suggests that R&D underinvestment is more severe than previously found. Our main point of reference is the innovative study by Jones and Williams (2000). Like we do, they employ a horizontal innovation model without strong scale effects à la Jones (1995). Other contributions in this direction are Steger (2005) and Strulik (2007) who find an even smaller degree of underinvestment in R&D than Jones and Williams (2000). Similar to our steady state analysis, however, Steger (2005) finds that the market economy quite heavily underinvests in physical capital accumulation.<sup>4</sup> Also related to our paper are studies which derive the long run optimal R&D subsidy in an endogenous growth framework. Sener (2008) studies an endogenous growth model without scale effects where the steady state growth rate depends on the R&D subsidy. The optimal steady state R&D subsidy is deter-

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<sup>4</sup>Chu (2009) also finds underinvestment in R&D and physical capital. He proposes to increase patent breadth and optimize the profit sharing rule between current and former inventors to increase welfare. However, he shows that these policy measures do not lead to the first best allocation.

mined numerically. More recently, Nuño (2011) analyzes optimal long run investment subsidies in a Schumpeterian growth model with business cycles.<sup>5</sup>

There are two major differences of our analysis to these contributions. (i) The paper at hand investigates the optimal policy recommendations implied by standard R&D-based growth models by accounting for distortionary income taxation. It suggests how to correct for underinvestment in the various growth channels by introducing policy instruments targeted to the market failures captured in the model and calculating the optimal growth policy mix. (ii) We are able to solve numerically also for the transition path. This allows us to evaluate policy reforms and compute welfare-maximizing values of policy instruments not only from a steady state perspective but also from a dynamic one.

The plan of the paper is as follows. Section 2 describes the underlying model. Section 3 derives the steady state solution for the market economy and for the social planning optimum. The calibration strategy is outlined in Section 4, while the optimal long run policy mix is presented in Section 5. The dynamic evaluation of policy reforms is discussed in Section 6. The main conclusions are summarized in Section 7. Technical details have been relegated to an appendix.

## 2 The Model

Consider the following continuous-time model with three engines of economic growth: horizontal innovations, physical capital accumulation and human capital formation. There is a homogenous final output good with price normalized to unity. Final output is produced under perfect competition according to

$$Y = \left( \int_0^A (x_i)^{\frac{\beta-1}{\beta}} di \right)^{\frac{\alpha\beta}{\beta-1}} (H^Y)^{1-\alpha}, \quad (1)$$

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<sup>5</sup>Nuño (2011) investigates the costs of business cycles under different R&D subsidization regimes. While this is an important and interesting topic, the addressed research question is completely different compared to ours.

$0 < \alpha < 1$ ,  $\beta > 1$ , where  $H^Y$  is human capital (efficiency units of labor) in the manufacturing sector,  $A$  is the mass (“number”) of intermediate goods and  $x_i$  denotes the quantity of intermediate good  $i$ . (Time index  $t$  is omitted whenever this does not lead to confusion.) The number of varieties,  $A$ , expands through horizontal innovations, protected with (potentially) infinite patent length. As usual,  $A$  is interpreted as the economy’s stock of knowledge.  $A_0 > 0$  is given. The labor market is perfect.

In each sector  $i$  there is one firm – the innovator or the buyer of a blueprint for an intermediate good – which has access to a one-to-one technology: one unit of foregone consumption (capital) can be transformed into one unit of output. Capital depreciates at rate  $\delta_K \geq 0$ . Capital supply in the initial period,  $K_0$ , is given. The capital market is perfect.

Moreover, in each sector  $i$  there is a competitive fringe which can produce a perfect substitute for good  $i$  (without violating patent rights) but is less productive in manufacturing the good (see, e.g., Aghion and Howitt, 2005): one unit of output requires  $\kappa$  units of capital;  $1 < \kappa \leq \frac{\beta}{\beta-1}$ .

There is free entry into the R&D sector. Suppose that in each point of time,  $(1 + \psi)\dot{A}$  patents are generated. As in Jones and Williams (2000),  $\psi\dot{A}$  of these patents replace existing patents, such that there will be “business stealing”. Thus, in each point of time, the probability of an existing innovator to be replaced is equal to the fraction of firms driven out of business,  $\psi\dot{A}/A$ ; the expected effective patent life is therefore limited to the inverse of this probability. Ideas for new intermediate goods are generated according to

$$(1 + \psi)\dot{A} = \tilde{\nu}A^\phi H^A, \text{ with } \tilde{\nu} \equiv \nu (H^A)^{-\theta}, \quad (2)$$

where  $H^A$  is the human capital level in the R&D sector,  $\nu > 0$ ,  $\phi < 1$ ,  $0 \leq \theta < 1$ ,  $\psi \geq 0$ .  $\tilde{\nu}$  is taken as given in the decision of R&D firms; that is, R&D firms perceive a constant returns to scale R&D technology, although the social return to higher R&D input is decreasing whenever  $\theta > 0$ . The wedge between private and social return may arise because firms do not take into account that rivals may work on the same idea such

that, from a social point of view, some of the R&D input is duplicated (“duplication externality”). Parameter  $\theta$  captures the extent of this externality.  $\phi > 0$  gives the strength of the standard intertemporal knowledge spill-over (or standing on shoulders effect).

There is an infinitely-living, representative dynasty with initial per capita wealth,  $a_0 > 0$ . Household size,  $N$ , grows with constant exponential rate,  $n \geq 0$ .  $N_0$  is given and normalized to unity. Preferences are represented by the standard utility function

$$U = \int_0^{\infty} \frac{c^{1-\sigma} - 1}{1-\sigma} e^{-(\rho-n)t} dt, \quad (3)$$

$\sigma > 0$ , where  $c$  is consumption per capita. Households take factor prices as given.

The process of skill accumulation depends on the amount of human capital an individual invests (e.g., paying teachers) in education,  $h^H$ . Moreover, it is characterized by human capital transmission within the representative dynasty.<sup>6</sup> We also assume that human capital depreciates over time at rate  $\delta_H > 0$ . Formally, suppose that the human capital level per capita,  $h$ , evolves according to

$$\dot{h} = \xi (h^H)^\gamma h^\eta - \delta_H h, \quad (4)$$

$\gamma, \eta, \xi > 0$ ,  $\gamma + \eta < 1$ .  $\gamma < 1$  captures decreasing returns to teaching input. Parameter  $\eta$  is associated with human capital transmission within the dynasty over time.  $\gamma + \eta < 1$  (thus,  $\eta < 1$ ) implies that, on a balanced growth path,  $h$  assumes a stationary long-run value.<sup>7</sup> According to (4),  $\dot{h}/h = 0$  implies that

$$h = \left( \frac{\xi}{\delta_H} \right)^{\frac{1}{1-\gamma-\eta}} (h^H)^{\frac{\gamma}{1-\gamma-\eta}}, \quad (5)$$

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<sup>6</sup>There is overwhelming evidence for the hypothesis that the education of parents affects the human capital level of children, even when controlling for family income. For recent studies, also providing an overview of the previous literature, see Plug and Vijverberg (2003) as well as Black, Devereux and Salvanes (2005).

<sup>7</sup>We abstract from human capital externalities in education of the kind formulated by Lucas (1988). In fact, there seems to be little evidence in favor of such externalities (see, e.g., Acemoglu and Angrist, 2000).

where  $\mathfrak{h}^H \equiv h^H/h$  is the fraction of human capital devoted to the education sector.

The government possesses a variety of policy instruments which potentially affect the three engines of growth. At the household level it may subsidize education at rate  $s_H$  per unit of educational input. At the firm level, we assume that there is corporate income taxation. The corporate tax rate is identical across sectors and denoted by  $\tau_c$ . Intermediate good firms may deduct at least part of their capital costs (for instance, via depreciation allowances or an investment tax credit), at rate  $1 + s_d$ . If  $s_d = 0$ , capital costs are fully deductible from sales revenue; if  $s_d < (>)0$ , they are less than (more than) fully deductible. Similarly, the R&D sector may deduct  $1 + s_R$  of their R&D spending from sales revenue. Households are taxed in various ways. There is a tax on wage income at rate  $\tau_w$ , a tax on income from bond holdings at rate  $\tau_r$ , and a capital gains tax paid on increases in share prices. To be able to calibrate all the tax instruments at observed levels, we also allow for redistribution via a lump sum transfer to households.<sup>8</sup> The government balances the budget in each point of time.

Let  $w$  and  $r$  denote the wage rate per unit of human capital and the interest rate, respectively. Moreover, denote by  $T$  the transfer per capita, which equals the sum of tax revenue minus subsidies, both divided by  $N$ . Financial wealth per individual,  $a$ , accumulates according to

$$\dot{a} = [(1 - \tau_r)r - n]a + (1 - \tau_w)wh - (1 - s_H)wh^H - c + T. \quad (6)$$

It turns out that, for the transversality conditions of both the household optimization problem and the social planner problem to hold and the value of the utility stream,  $U$ , to be finite, we have to restrict the parameter space such that

$$\rho - n + (\sigma - 1)g > 0 \text{ with } g \equiv \frac{\alpha(1 - \theta)n}{(1 - \alpha)(\beta - 1)(1 - \phi)}. \quad (\text{A1})$$

As will become apparent,  $g$  is the economy's long run growth rate both in decentralized

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<sup>8</sup>There may well be heterogeneity of individuals, despite the assumption that there exists a representative consumer; consistent with the homothetic utility function (3). See Mas-Colell, Whinston and Green (1995) for a discussion.

equilibrium and in social planning optimum. We maintain assumption A1 throughout.

### 3 Steady State Analysis

The long run, decentralized equilibrium is compared to the social planning optimum. We also conduct a comparative-static analysis of the impact of changes of tax parameters on the equilibrium allocation of human capital.

#### 3.1 Market Equilibrium

We start with intermediate goods producers. Denote by  $R \equiv r + \delta_K$  the user cost of capital for an intermediate good firm (before taxation). As one unit of capital is required for one unit of output and firms are eligible to deduct capital costs at subsidy rate  $s_d$  from pre-tax profits to obtain the corporate tax base, producer  $i$  has profits

$$\pi_i = p_i x_i - R x_i - \tau_c [p_i x_i - (1 + s_d) R x_i] \quad (7)$$

$$= (1 - \tau_c) [p_i - (1 - s_K) R] x_i, \quad (8)$$

where  $p_i$  is the price of good  $i$  and we defined  $s_K \equiv \frac{\tau_c s_d}{1 - \tau_c}$  for the latter equation.

According to (1), the demand function for intermediate good  $i$  reads

$$x_i = \frac{\alpha Y (p_i)^{-\beta}}{P^{1-\beta}}, \quad (9)$$

where

$$P \equiv \left( \int_0^A (p_i)^{1-\beta} di \right)^{\frac{1}{1-\beta}} \quad (10)$$

is a price index. Profit maximization implies that the optimal price of each firm  $i$  is given by

$$p_i = p = \kappa (1 - s_K) R. \quad (11)$$

To see this, note that a firm which owns a blueprint perceives the price elasticity of

demand as being  $-\beta$  (taking aggregates  $Y$  and  $P$  as given). Thus, it would choose a mark-up factor which is equal to  $\frac{\beta}{\beta-1}$  if it were not facing a competitive fringe. Moreover, the competitive fringe would make losses at a price lower than  $\kappa(1-s_K)R$ . Thus, as  $\kappa \leq \frac{\beta}{\beta-1}$ , each firm  $i$  sets the maximal price allowing it to remain monopolist. According to (9) - (11), resulting output is given by

$$x_i = x = \frac{\alpha Y}{A\kappa(1-s_K)R}. \quad (12)$$

Substituting (12) into (1) and solving for  $Y$  implies

$$y \equiv \frac{Y}{N} = A^{\frac{\alpha}{(1-\alpha)(\beta-1)}} \left( \frac{\alpha}{\kappa(1-s_K)R} \right)^{\frac{1}{1-\alpha}} h^Y \quad (13)$$

for per capita income, where  $h^Y \equiv H^Y/N$ . Thus, the total amount of physical capital,  $K = \int_0^A x_i di = Ax$ , divided by population size, is given by

$$k \equiv \frac{K}{N} = A^{\frac{\alpha}{(1-\alpha)(\beta-1)}} \left( \frac{\alpha}{\kappa(1-s_K)R} \right)^{\frac{1}{1-\alpha}} h^Y. \quad (14)$$

Expressions (13) and (14) suggest that, if the interest rate  $r$  is stationary in the long run, the capital stock per capita and per capita income grow at the same rate along a balanced growth path.

Let  $P^A$  denote the present discounted value of the (after-tax) profit stream generated by an innovation. Thus,  $P^A$  is the price an intermediate good producer pays to the R&D sector for a new blueprint as well as the stock market evaluation of an intermediate good firm. In equilibrium, arbitrage possibilities in the capital market are absent. The dividends paid out by an intermediate good firm (being identical for all  $i$  due to symmetry, i.e.,  $\pi_i = \pi$ ),  $\pi/P^A$ , plus the growth rate of  $P^A$  after capital gains are taxed,  $(1-\tau_g)\dot{P}^A/P^A$ , must be equal to the sum of the after-tax interest rate,  $(1-\tau_r)r$ , and the probability that an existing innovator is driven out of business,

$\psi\dot{A}/A$ .<sup>9</sup> The no arbitrage condition for the capital market therefore reads

$$(1 - \tau_g) \frac{\dot{P}^A}{P^A} + \frac{\pi}{P^A} = (1 - \tau_r)r + \frac{\psi\dot{A}}{A}. \quad (15)$$

In the R&D sector, where firms are eligible to deduct R&D costs at subsidy rate  $s_R$  from pre-tax profits to obtain the corporate tax base, a representative firm maximizes

$$\Pi = P^A(1 + \psi)\dot{A} - wH^A - \tau_c \left[ P^A(1 + \psi)\dot{A} - (1 + s_R)wH^A \right] \quad (16)$$

$$= (1 - \tau_c) \left[ P^A\tilde{\nu}A^\phi H^A - (1 - s_A)wH^A \right], \quad (17)$$

taking  $A$  and  $\tilde{\nu}$  as given, where we defined  $s_A \equiv \frac{s_R\tau_c}{1-\tau_c}$  and used (2) for the latter equation. Rates  $s_A$  and  $s_K$  are referred to as behaviorally relevant subsidies of R&D costs and capital costs, respectively.

The household's problem is to solve

$$\max_{\{c_t, h_t^H\}} U \quad \text{s.t. (4), (6), } h_t \geq 0, \quad \lim_{t \rightarrow \infty} a_t \exp \left( - \int_0^t [(1 - \tau_r)r_s - n] ds \right) \geq 0. \quad (18)$$

The household chooses the optimal consumption path, where savings are supplied to the financial market, and the optimal (path of) education investment.

**Definition.** A market equilibrium in this economy consists of time paths for the quantities  $\{h_t^A, h_t^Y, h_t^H, c_t, \{x_{it}\}_{i=0}^A, a_t, Y_t, K_t, A_t, T_t\}_{t=0}^\infty$  and prices  $\{P_t^A, \{p_{it}\}_{i=0}^A, w_t, r_t\}_{t=0}^\infty$  such that

1. final goods producers, intermediate goods producers and R&D firms maximize profits,

2. households maximize intertemporal welfare,

3. the capital resource constraint  $\int_0^A x_{it} di = K$  holds,

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<sup>9</sup>Note that the after-tax income from asset holding of a household is  $(1 - \tau_r)rK/N + (1 - \tau_g)\dot{P}^AA/N + \pi A/N - P^A\psi\dot{A}/N$ . Under (15) and since  $Na = K + P^AA$ , this equals  $(1 - \tau_r)ra$ , as reflected in the budget constraint (6) of a household.

4. the capital market equilibrium condition, equ. (15), holds,
5. the labor market clears (i.e.  $h^A + h^Y + h^H = h$ ), the intermediate goods markets clear, and the financial market clears (i.e.  $aN = K + P^A A$ ),<sup>10</sup>
6. the government runs a balanced budget, i.e. the transfer per capita  $T$  equals total tax revenues minus total subsidies, both divided by  $N$ .

In the proof of the first proposition we derive the full dynamical system (employed in the numerical analysis of Section 6), which describes, given initial conditions  $A_0$ ,  $h_0$ ,  $N_0$  and  $K_0$ , the dynamic evolution of the economy as well as the steady state equilibrium. The following holds in a steady state:

**Proposition 1.** (Long run market equilibrium) *There exists a unique balanced growth equilibrium, which is characterized as follows.*

(i) *The number of ideas grows with rate*

$$\frac{\dot{A}}{A} = \frac{(1 - \theta)n}{1 - \phi} \equiv g_A. \quad (19)$$

(ii) *Equity wealth per capita ( $q \equiv P^A A/N$ ), the wage rate ( $w$ ), income per capita ( $y$ ), consumption per capita ( $c$ ), financial wealth per capita ( $a$ ), and the physical capital stock per capita ( $k$ ) grow with rate*

$$g = \frac{\alpha g_A}{(1 - \alpha)(\beta - 1)}. \quad (20)$$

(iii) *The human capital level per capita ( $h$ ) is stationary and we have*

$$\frac{h^H}{h} = \frac{1 - \tau_w}{1 - s_H} \frac{\gamma \delta_H}{\rho - n + g(\sigma - 1) + \delta_H(1 - \eta)} \equiv \mathfrak{h}^{H*}, \quad (21)$$

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<sup>10</sup>According to Walras' law, the final goods market then clears as well.

and, defining  $h^A \equiv H^A/N$ ,

$$\frac{h^A}{h} = \frac{1 - \mathfrak{h}^{H^*}}{\frac{1-s_A}{1-\tau_c}\Lambda(\tau_g) + 1} \equiv \mathfrak{h}^{A^*} \text{ with} \quad (22)$$

$$\Lambda(\tau_g) \equiv \frac{\sigma g + \rho + \psi g_A - (n + g - g_A)(1 - \tau_g)}{(1 - 1/\kappa)(\beta - 1)(1 + \psi)g}. \quad (23)$$

(iv) The savings and investment rate,  $sav \equiv 1 - c/y$ , is given by

$$sav = \frac{\alpha(n + g + \delta_K)}{(1 - s_K)\kappa \left( \frac{\sigma g + \rho}{1 - \tau_r} + \delta_K \right)} \equiv sav^*. \quad (24)$$

**Proof.** See Appendix. ■

Like in Jones (1995), the growth rate of per capita income along a balanced growth path is independent of economic policy (in contrast to the level of income). This is an attractive feature for our numerical analysis. It allows us to attribute growth effects of policy shocks (starting from balanced growth equilibrium) entirely to the transitional dynamics. Proposition 1 also implies that life-time utility (3) is finite if and only if assumption (A1) holds.

Moreover, Proposition 1 shows that the three policy instruments which are targeted to the three engines of growth in the model affect only the respective engine it is designed for in the long run. For instance, subsidizing physical capital does neither affect the level nor the allocation of human capital in long run equilibrium. But an increase in the behaviorally relevant capital cost subsidy,  $s_K$ , raises the long run savings rate and investment share,  $sav^*$ . Similarly, an increase in the education subsidy rate,  $s_H$ , raises the long run fraction of human capital devoted to education,  $\mathfrak{h}^{H^*}$ , and therefore also raises the long run level of human capital per capita, according to (5). A change in  $s_H$  has no effect, however, on the long run fraction of human capital devoted to R&D,  $\mathfrak{h}^{A^*}$ , or on the investment rate,  $sav^*$ . Analogously, an increase in the behaviorally relevant R&D subsidy,  $s_A$ , stimulates R&D activity of firms (i.e.,  $\mathfrak{h}^{A^*}$  increases) but does not affect incentives to invest in education or physical capital in long run equilibrium.

Furthermore, we find that taxing wages gives a disincentive to invest in education,

i.e., an increase in  $\tau_w$  lowers  $\mathfrak{h}^{H*}$ . Similarly, an increase in the corporate tax rate (entering arbitrage condition (15) via instantaneous profits of intermediate good firms,  $\pi$ ) gives a disincentive to invest in R&D; consequently,  $\mathfrak{h}^{A*}$  is decreasing in  $\tau_c$ , all other things equal. Moreover, an increase in the rate at which capital gains are taxed,  $\tau_g$ , lowers R&D incentives, leading to a decline in  $\mathfrak{h}^{A*}$ , if  $n + g > g_A$  (which turns out to hold with our calibration outlined in Section 4). Finally, the long run savings rate,  $sav^*$ , is decreasing in the capital income tax rate,  $\tau_r$ .

### 3.2 Social Planning Optimum

A social planner chooses a symmetric capital allocation across intermediate firms, i.e.,  $x_i = K/A$  for all  $i$ . Noting the output technology (1), per capita output ( $y = Y/N$ ) may be expressed as:

$$y = A^{\frac{\alpha}{\beta-1}} k^\alpha (h^Y)^{1-\alpha}. \quad (25)$$

Thus, the capital stock per capita ( $k = K/N$ ) evolves according to

$$\dot{k} = A^{\frac{\alpha}{\beta-1}} k^\alpha (h^Y)^{1-\alpha} - (\delta_K + n)k - c. \quad (26)$$

Also note that the social planner takes R&D externalities into account. Using (2), he observes the knowledge accumulation condition

$$\dot{A} = \frac{\nu}{1+\psi} A^\phi (Nh^A)^{1-\theta}. \quad (27)$$

The social planner's problem thus is to solve

$$\max U \quad \text{s.t.} \quad (4), (26), (27), h^A = h - h^Y - h^H, \quad (28)$$

and non-negativity constraints, where  $c$ ,  $h^A$ ,  $h^H$ ,  $h^Y$  are control variables and  $h$ ,  $k$ ,  $A$  are state variables.

**Proposition 2.** (Long run social optimum) *There exists an interior, unique long-*

run solution of the social planner problem (28) which is characterized as follows:

(i) As in decentralized long run equilibrium, the growth rate of  $A$  is given by  $g_A$  (see (19)) and the growth rates of  $c, k, y$  are given by  $g$  (see (20)).

(ii) The fraction of human capital devoted to education and R&D are given by

$$\frac{h^H}{h} = \frac{\gamma\delta_H}{\rho - n + g(\sigma - 1) + \delta_H(1 - \eta)} \equiv \mathfrak{h}_{opt}^H, \quad (29)$$

$$\frac{h^A}{h} = \frac{1 - \mathfrak{h}_{opt}^H}{\Gamma + 1} \equiv \mathfrak{h}_{opt}^A \text{ with } \Gamma \equiv \frac{\rho + g\sigma - \theta n - g}{(1 - \theta)g}. \quad (30)$$

(ii) The savings and investment rate reads as follows

$$sav = \frac{\alpha(n + g + \delta_K)}{\sigma g + \rho + \delta_K} \equiv sav_{opt}. \quad (31)$$

**Proof.** See Appendix. ■

As for the decentralized equilibrium, the productivity of R&D and education, parameterized by  $\nu$  and  $\xi$ , respectively, do neither affect the allocation and level of human capital nor the investment rate in the long run social optimum. Unlike in steady state market equilibrium, also parameter  $\psi$ , which captures the strength of the business stealing effect, and the mark-up factor  $\kappa$  do not affect the optimal resource allocation.

Like in Jones and Williams (2000), there are four R&D externalities. The duplication externality ( $\theta > 0$ ) promotes overinvestment in R&D, whereas a standing on shoulders effect ( $\phi > 0$ ) promotes underinvestment. The business stealing effect ( $\psi > 0$ ) gives rise to two counteracting effects on the human capital allocation in the market economy, relative to the unaffected social optimum. On the one hand, existing intermediate good firms are at risk of being replaced by future innovators. An increase in  $\psi$  thus lowers the value of patents ( $P^A$ ) by raising the effective discount rate (right-hand side of (15)) and therefore depresses the long run equilibrium fraction of human capital devoted to R&D,  $h^A/h$ . On the other hand, an innovator obtains a rent from an innovation even when he does not contribute to the knowledge stock of the economy,  $A$ . To achieve the same increase in  $A$ , more R&D labor is required if  $\psi$  increases, which

tends to raise the equilibrium value of  $h^A/h$ . If and only if the latter effect dominates, the fraction of human capital devoted to R&D in decentralized equilibrium increases in  $\psi$ . In this case,  $\psi > 0$  promotes overinvestment. According to (22),  $\mathfrak{h}^{A*}$  is increasing in  $\psi$ , for instance, if the capital gains tax rate ( $\tau_g$ ) is zero or small. Finally, innovators may not be able to appropriate the full economic surplus from raising the knowledge stock of the economy. To see this, note from (8), (11) and (12) that instantaneous profit of an intermediate goods firm  $i$  reads  $\pi_i = \alpha(1 - \tau_c)\frac{\kappa-1}{\kappa}\frac{Y}{A}$ , whereas  $\frac{\partial Y}{\partial A} = \frac{\alpha}{\beta-1}\frac{Y}{A}$  holds, according to (25). If and only if  $(1 - \tau_c)(1 - \frac{1}{\kappa}) < \frac{1}{\beta-1}$ , there is a “surplus appropriability problem” which promotes underinvestment. (If  $(1 - \tau_c)(1 - \frac{1}{\kappa}) > \frac{1}{\beta-1}$ , there is a force towards overinvestment.) Thus, depending on parameter values, there may be over- or underinvestment in R&D. This leaves a critical role for the calibration strategy to obtain useful numerical results on the optimal resource allocation and policy mix.

Comparing (21) and (29), we find that in the case where the tax rate on wage income equals the effective education subsidy rate ( $\tau_w = s_H$ ), both the long run fraction of human capital devoted to education and, according to (5), the long run level of human capital are socially optimal. That is, the distortion stemming from wage taxation can be exactly offset by an education subsidy. Generally, we find that  $\mathfrak{h}^{H*} < (=, >)\mathfrak{h}_{opt}^H$  if  $s_H < (=, >)\tau_w$ . Finally, in absence of a capital cost subsidy ( $s_d = s_K = 0$ ), the savings rate will be too low whenever  $\tau_r \geq 0$ , i.e.,  $sav^* < sav_{opt}$ , according to (24) and (31).

We next characterize the optimal policy mix in the long run.

**Proposition 3.** (Optimal long run policy mix) *There exists a policy mix  $(s_H^{opt}, s_A^{opt}, s_K^{opt})$  which for any feasible values of tax parameters  $(\tau_w, \tau_c, \tau_g, \tau_r)$  implements the long-run social planning optimum. It is characterized as follows:*

$$s_H = \tau_w, \tag{32}$$

$$s_A = 1 - \frac{(1 - \tau_c)\Gamma}{\Lambda(\tau_g)} \equiv s_A^{opt}, \text{ i.e. } s_R = \frac{1 - \tau_c}{\tau_c}s_A^{opt} \equiv s_R^{opt}, \tag{33}$$

$$s_K = 1 - \frac{\sigma g + \rho + \delta_K}{\kappa \left( \frac{\sigma g + \rho}{1 - \tau_r} + \delta_K \right)} \equiv s_K^{opt}, \text{ i.e. } s_d = \frac{1 - \tau_c}{\tau_c}s_K^{opt} \equiv s_d^{opt}. \tag{34}$$

**Proof.** Set  $\mathfrak{h}^{H*} = \mathfrak{h}_{opt}^H$ ,  $\mathfrak{h}^{A*} = \mathfrak{h}_{opt}^A$  and  $sav^* = sav_{opt}$  to derive (32), (33) and (34), respectively, by using the expressions in Proposition 1 and 2. ■

How subsidies on R&D and capital costs depend on tax parameters follows from the tax distortions discussed after Proposition 1. Moreover, note that a higher mark up factor  $\kappa$  drives a bigger wedge between the equilibrium investment rate and the socially optimal investment rate, provided that capital income is not subsidized ( $\tau_r \geq 0$ ). Thus, an increase in price setting power calls for a higher subsidy on capital costs.

It is remarkable that, according to Proposition 3, the first-best allocation in the steady state can be restored, despite numerous distortions from goods market imperfection, externalities and income taxation, with a very limited number of tax/subsidy instruments (one targeted to each engine of growth).<sup>11</sup>

## 4 Calibration

A calibration strategy is proposed which attempts to match observable endogenous variables for the US. We assume that the observed values correspond to the steady state in the model under the status quo policy.

### 4.1 Policy Parameters

In the US, the statutory tax rate on dividend income and corporate income coincide. We thus set  $\tau_r = \tau_c = 0.395$ , as published by the OECD tax database (federal and sub-central government taxes combined). Using the same source, the labor income tax,  $\tau_w$ , is set equal to the total tax wedge (wage income tax rate including all social security contributions and from all levels of governments combined) which applies to average wage income. It is given by  $\tau_w = 0.3$ . The behaviorally relevant R&D subsidy rate,  $s_A$ , is (for the year 2007) taken from OECD (2007a, p.73),  $s_A = 0.066$ ,<sup>12</sup> in turn

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<sup>11</sup>Independent research by Nuño (2011) has led to a similar result. He shows that the first-best, long-run allocation can be supported by an appropriate investment subsidy and R&D subsidy.

<sup>12</sup>The OECD reports a R&D subsidy rate  $RDS = 1 - Bindex$ , where the so-called B-index is given by  $Bindex = \frac{1-\Xi}{1-\tau_c}$ , with  $\tau_c$  being the statutory corporate income tax rate and  $\Xi$  the net present

implying  $s_R = 0.1$ .

Devereux, Griffith and Klemm (2002, p. 459) report for the US a rate of depreciation allowances for capital investments of almost 80 percent. This would suggest that  $s_d$  is somewhat above  $-0.2$  and thus  $s_K < 0$ . However, as the authors point out, the definition of corporate income tax base is very complex and there are other possibilities than depreciation allowances to deduct capital costs, which they cannot provide data on. We take into account further allowances by assuming that, initially,  $s_d = s_K = 0$  (i.e. full deduction of capital costs).

As a result of the ‘Jobs and Growth Tax Relief Reconciliation Act’ of 2003, long-term capital gains are taxed at 15 percent if income is above some threshold. Otherwise, until 2008 it was 5 percent and until 2010 it is 0 percent. Before 2003 it was 20 percent. We calibrate  $\tau_g$  to 12 percent throughout. Fortunately, our results are strongly robust with respect to changes in  $\tau_g$  (to save space the sensitivity analysis is not displayed).

Finally, we need to calibrate the education subsidy rate ( $s_H$ ), which is most difficult. For instance, we observe the fraction of public education expenditure in total expenditure. In the year 2004, the average was 68.4 percent in the US (OECD, 2007b, Tab. B3.1, p. 219); among the public spending, 20.7 percent was on student loans, scholarships and other household grants (rather than direct public spending on institutions). To complicate things further, a substantial fraction of total household spending on education is unobservable, like private teachers at home, time costs of parents etc. (neither counted as education expenditure in databases nor subsidized). It is thus difficult to come up with a well-founded estimate. We assume that the education subsidy is set such that the long run fraction of human capital devoted to education,  $h^{H*}$ , and the long run level of human capital are socially optimal, given the distortion introduced by wage taxation,  $s_H = \tau_w (= 0.3)$ . That is, we focus on distortions of R&D investment and physical capital investment in our numerical analysis. Table 1 summarizes the underlying set of policy parameters.

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discounted value of depreciation allowances, tax credits and special allowances on R&D assets. In the context of our model,  $\Xi = \tau_c(1 + s_R)$ . Thus,  $RDS = \frac{\tau_c s_R}{1 - \tau_c} = s_A$ .

Policy parameters	Value	Source
$\tau_r$	0.395	OECD Tax Database (2008)
$\tau_c$	0.395	OECD Tax Database (2008)
$\tau_w$	0.30	OECD Tax Database (2008)
$\tau_g$	0.12	cf. discussion in text
$s_A$	0.066	OECD (2007a); cf. discussion in text
$s_R$	0.101	implied
$s_K$	0	Devereux et al. (2002); cf. discussion in text
$s_d$	0	implied
$s_H$	0.3	cf. discussion in text

Table 1: Policy parameters.

## 4.2 Other Parameters

Other parameters are calibrated as follows. First,  $n$  is set to the average population growth rate for the period 1990-2004. Taking data from the Penn World Tables (PWT) 6.2 (Heston, Summers and Baten, 2006), we find  $n = 0.01$ . For the same period, and again from PWT 6.2, the average growth rate of per capita income is 2.1 percent. We calibrate  $g$  to match this growth rate (thereby averaging out business cycle phenomena).

We use measures for the investment rate ( $sav$ ) and the capital-output ratio to calibrate the depreciation rate of physical capital,  $\delta_K$ , as follows. The investment rate is given by  $sav = (\dot{K} + \delta_K K)/Y = (\dot{K}/K + \delta_K)k/y$ . Using  $\dot{K}/K = n + g$  and solving for  $\delta_K$  yields

$$\delta_K = \frac{sav}{k/y} - n - g. \quad (35)$$

Averaging over the period 1990-2004,  $sav$  is equal to about 21 percent, according to PWT 6.2. For the capital-output ratio, we take averages over the period 2002-2007 calculated from data of the US Bureau of Economic Analysis. The capital stock is taken to be total fixed assets (private and public structures, equipment and software). At current prices, this gives us  $k/y = 3$ . From (35), the evidence then suggests that  $\delta_K$  is about 4 percent, which is a standard value in the literature. In the literature, the

depreciation rate of human capital is typically set slightly lower than  $\delta_K$ . We choose  $\delta_H = 0.03$ . This is in the range of the estimated value in Heckman (1976), who finds that  $\delta_H$  is between 0.7 and 4.7 percent. For the steady state analysis in Section 5, we do not need to know  $\delta_H$ , as will become apparent.

Moreover, we match the steady state interest rate to 7 percent, which coincides with the real long-run stock market return estimated by Mehra and Prescott (1985).<sup>13</sup> In our framework, the standard Keynes-Ramsey rule,

$$\frac{\dot{c}}{c} = \frac{(1 - \tau_r)r - \rho}{\sigma}, \quad (36)$$

holds (see the proof of Proposition 1). In steady state,  $\dot{c}/c = g$ , according to Proposition 1. Thus, preference parameters  $(\sigma, \rho)$  fulfill:<sup>14</sup>

$$\sigma g + \rho = (1 - \tau_r)r. \quad (37)$$

For  $g = 0.021$ ,  $r = 0.07$ ,  $\tau_r = 0.395$  and a typical value for the time preference rate of  $\rho = 0.02$ , we find  $\sigma = 1.08$ . For the steady state analysis in Section 5, we do not need to set the values for  $\rho$  and  $\sigma$  separately but only their combination on the left-hand side of (37), which equals the (after-tax) long run interest rate,  $(1 - \tau_r)r (= 0.042)$ . When the transitional dynamics are fully taken into account in Section 6, we set  $\rho = 0.02$  and  $\sigma = 1.08$ .

Production technology parameters  $\alpha$  and  $\beta$  are potentially critical since they determine the elasticity of output with respect to the state of knowledge,  $A$ . To see this, use  $x_i = K/A$  for all  $i$  and  $H^Y = Nh^Y$  in (1) to find

$$Y = BK^\alpha N^{1-\alpha} \text{ with } B \equiv A^{\frac{\alpha}{\beta-1}} (h^Y)^{1-\alpha}. \quad (38)$$

We employ a relationship between  $\alpha$  and  $\beta$  which can be recovered from estimates of

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<sup>13</sup>Jones and Williams (2000) argue that this rate of return is more appropriate for calibration of growth models than the risk-free rate of government bonds.

<sup>14</sup>Rewriting assumption (A1) by using (37) implies that  $(1 - \tau_r)r > n + g$ , i.e., the after-tax interest rate must exceed the long-run growth rate of aggregate income.

the output elasticity with respect to the R&D capital stock. Using (38), this elasticity is equal to  $\frac{\partial Y}{\partial A} \frac{A}{Y} = \frac{\alpha}{\beta-1} \equiv \varphi$ . Thus,

$$\beta = 1 + \frac{\alpha}{\varphi}. \quad (39)$$

We can write  $\log B = \Upsilon + \varphi \log A$ , where  $\Upsilon \equiv (1 - \alpha) \log h^Y$ , according to (38). Regressing  $\log B$  (by using that the total factor productivity is given by  $B = YK^{-\alpha}N^{\alpha-1}$ ) on a measure of knowledge capital ( $\log A$ ), Coe and Helpman (1995) obtain  $\varphi = 0.23$ , which is the value we use.

The steady state fraction of intermediate good firms driven out of the market each instant is  $\psi g_A$ . Its inverse is equal to the effective patent life,  $EPL$ . Thus, we have

$$\psi = \frac{1}{EPL} \frac{1}{g_A}, \quad (40)$$

where

$$g_A = \frac{(1 - \alpha)(\beta - 1)g}{\alpha}, \quad (41)$$

according to (20). We follow Jones and Williams (2000) in assuming an effective patent life of 10 years ( $EPL = 10$ ).

Moreover, using (13) and (14) together with  $R = r + \delta_K$ , we find the following relationship between  $\alpha$  and mark-up factor  $\kappa$ :

$$\kappa = \frac{\alpha}{(1 - s_K)(r + \delta_K) \frac{k}{y}}. \quad (42)$$

A key parameter is  $\alpha$ , which according to (39)-(42) determines  $\beta$ ,  $\psi$ ,  $g_A$  and  $\kappa$ , for given calibrated values of  $\varphi$ ,  $EPL$ ,  $g$ ,  $s_K$ ,  $r$ ,  $\delta_K$ ,  $k/y$ . In the literature, the value of  $\alpha$  is typically motivated by using the labor share in total income. However, due to the existence of R&D workers and teachers in the model,  $\alpha$  is related to the fraction of income which accrues to production workers only (rather than to the entire labor share): we have  $wh^Y/y = 1 - \alpha$ . Moreover, as pointed out by Krueger (1999), among others, there is little consensus on how to measure the total labor share as fraction of GDP. In

our context, the labor share is  $wh/y$ . When two thirds of business proprietor's income is added to labor income, Krueger (1999) shows that the US labor share fluctuates over time between 75 and 80 percent. Otherwise the labor share would be significantly lower. For instance, the OECD reports a labor share around 65 percent for the US. Due to the uncertainty about the labor share, we propose a different route than typically taken in the literature. Our calibration strategy is to determine the human capital income share endogenously, together with the salient parameter  $\alpha$ . This is done as follows. Defining  $\omega \equiv wh/y$ ,  $\omega^H \equiv wh^H/y$  and  $\omega^A \equiv wh^A/y$ , we obtain from  $h^Y + h^A + h^H = h$  and  $wh^Y/y = 1 - \alpha$  that

$$\omega = 1 + \omega^H + \omega^A - \alpha. \quad (43)$$

By definition, we have  $h^A/h = \omega^A/\omega$  and  $h^H/h = \omega^H/\omega$ . Substituting both  $\mathfrak{h}^{A*} = \omega^A/\omega$  and  $\mathfrak{h}^{H*} = \omega^H/\omega$  into expression (22) for the long run equilibrium fraction of human capital devoted to R&D, and then using (43), we find

$$\frac{1 - s_A}{1 - \tau_c} \Lambda(\tau_g) \omega^A = 1 - \alpha. \quad (44)$$

Given  $\omega^A$  and taking into account relationships (37), (39), (40), (41) and (42) to find  $\Lambda(\tau_g)$  as defined in (23),  $\alpha$  is implied by (44). Note that  $\omega^A$  is the R&D intensity in the economy. For the period 1990-2006 we find that the average R&D costs of business enterprises (BERD) as fraction of GDP is 1.9 percent (OECD, 2008a). When we use gross R&D investment intensity (GERD), the figure would be higher (about 2.6 percent). As most but not all R&D costs are labor costs, this suggests to calibrate  $\omega^A = 0.02$ . However, one may argue that not all R&D activity in the sense of the model is captured by typical R&D intensity measures. According to OECD (2008b, Tab. 1.1), total investment in intangible assets in the US as a fraction of GDP was almost 12 percent for the period 1998-2000. However, 5 percent of GDP was spent to develop intangible assets like brand equity, firm-specific human capital and the organizational firm structure, which are not R&D activities in the sense of our model. We therefore consider  $\omega^A = 0.07$  as an alternative scenario to the case of  $\omega^A = 0.02$  in

our numerical analysis.

Note that we do not need to know the fraction of human capital used in education,  $\omega^H$ , to calibrate  $\alpha$ . Moreover, all parameters which are needed to find  $\alpha$  can be led back to observables. With  $n = 0.01$ ,  $g = 0.021$ ,  $r = 0.07$ ,  $k/y = 3$ ,  $sav = 0.213$  (thus,  $\delta_K = 0.04$ ),  $EPL = 10$ ,  $\tau_r = \tau_c = 0.395$ ,  $\tau_w = 0.3$ ,  $\tau_g = 0.12$ , we find for the case where the R&D intensity is  $\omega^A = 0.02$  that  $\alpha = 0.36$ . In turn, this value of  $\alpha$  implies  $\beta = 2.58$ ,  $\psi = 1.74$ ,  $g_A = 0.06$  and  $\kappa = 1.1$ . If the R&D intensity is set to  $\omega^A = 0.07$ , we obtain  $\alpha = 0.44$ ,  $\beta = 2.93$ ,  $\psi = 2$ ,  $g_A = 0.05$  and  $\kappa = 1.35$ . Interestingly, both values for mark-up factor  $\kappa$  are in the range (between 1.05 and 1.4) which has been estimated by Norrbin (1993).

To calculate the long run equilibrium allocation of human capital, characterized by  $\mathfrak{h}^{A*} = \omega^A/\omega$  and  $\mathfrak{h}^{H*} = \omega^H/\omega$ , we next need to find the human capital income share,  $\omega$ , by calibrating  $\omega^H$  and using (43). To calibrate  $\omega^H$ , we add expenditure from public and private sources over all education levels. This gives us an average value of 7 percent for the time period 1990-2003 (OECD, 2007b, Tab. B2.1, p. 205).<sup>15</sup> As not all education expenditure is on salary of teaching personnel, we use  $\omega^H = 0.05$ . For  $\omega^A = 0.02$ , we then find  $\omega = 0.71$  and therefore  $\mathfrak{h}^{H*} = \mathfrak{h}_{opt}^H = \frac{5}{71} = 0.071$  and  $\mathfrak{h}^{A*} = \frac{2}{71} = 0.028$ .<sup>16</sup> For  $\omega^A = 0.07$ , we obtain  $\omega = 0.68$ ,  $\mathfrak{h}^{H*} = \mathfrak{h}_{opt}^H = 0.074$  and  $\mathfrak{h}^{A*} = 0.104$ .

Parameters  $\rho$ ,  $\sigma$ ,  $\gamma$ ,  $\eta$ ,  $\phi$ ,  $\delta_H$ ,  $\nu$ ,  $\xi$  do not have to be known for the steady state analysis in Section 5. Scale parameters  $\nu$  and  $\xi$  in the technology of accumulating knowledge and human capital, respectively, do not enter the long run values for the allocation variables derived in Proposition 1 (decentralized equilibrium) and Proposi-

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<sup>15</sup>Although there is no publicly provided education in our model, it is more appropriate to take such expenditure into account, in addition to private education spending. An underlying assumption which justifies that choice is that credit constraints are negligible for advanced economies, such that publicly provided education and private education are almost perfect substitutes. In fact, recent studies find no evidence for the relevance of educational borrowing constraints in the US (see, e.g., Cameron and Taber, 2004, and the references therein).

<sup>16</sup>We shall note that  $h^A/h$  does not necessarily correspond to the fraction of workers in R&D and thus cannot be readily observed even under the assumption that the economy is in steady state. Although there is a representative agent, there may well be heterogeneity, such that not all individuals possess the same level of human capital. Thus, an implied  $h^A/h$  which exceeds the fraction of R&D workers (equal to about 1 percent) is consistent with the fact that the average R&D worker has a higher level of human capital than the average worker in the labor force.

tion 2 (social optimum). They also do not affect the allocation variables of interest in the transitional dynamics and can thus be set arbitrarily.<sup>17</sup>

In contrast, the duplication externality parameter  $\theta$  and the standing on shoulder parameter  $\phi$  play an important role.  $\theta$  and  $\phi$  can, however, not be set independently. Given  $g$ ,  $n$ ,  $\alpha$ ,  $\beta$  and  $\theta$ , we obtain  $\phi$  from (19) and (20):

$$\phi = 1 - \frac{\alpha n(1 - \theta)}{(1 - \alpha)(\beta - 1)g}. \quad (45)$$

Finally, also parameters  $\gamma$  and  $\eta$  are not independent from each other when assuming that the economy initially is in steady state. According to (21), given  $\rho + \sigma g = (1 - \tau_r)r$ ,  $g$ ,  $n$ ,  $\delta_H$ ,  $s_H = \tau_w$  and  $h^H/h = \mathfrak{h}^{H*}$ , we obtain the relationship

$$\gamma = \frac{(1 - \tau_r)r - n - g + \delta_H(1 - \eta)}{\delta_H} \mathfrak{h}^{H*}. \quad (46)$$

In Section 6 we consider  $\eta \in \{0.15, 0.3\}$  and obtain  $\gamma$  by using (46). It turns out that results are basically insensitive to variations in  $\eta$  (and  $\gamma$ ). Table 2 provides an overview of the underlying steady state values of endogenous variables, the parameters which were set by the authors, and the implied parameter values.

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<sup>17</sup>We can show numerically that  $\nu$  and  $\xi$  do not affect the eigenvalues of the dynamical system.

Endogenous variables	Value	Source
$sav$	0.21	Heston et al. (2006)
$k/y$	3	US Bureau of Economic Analysis
$r$	0.07	Mehra and Prescott (1985)
$g$	0.021	Heston et al. (2006)
$\omega^A \equiv \frac{wh^A}{y}$	0.02 (0.07)	OECD (2008a); cf. discussion in text
$\omega^H \equiv \frac{wh^H}{y}$	0.05	OECD (2007b); cf. discussion in text
Parameters set by authors	Value	Source
$\rho$	0.02	cf. discussion in text
$\varphi$	0.23	Coe and Helpman (1995)
$\delta_H$	0.03	cf. discussion in the text
$n$	0.01	Heston et al. (2006)
$EPL$	10	Jones and Williams (2000)
$\eta$	{0.15,0.3}	cf. discussion in text
$\theta$	{0,0.25,0.5,0.75,0.9,0.95,0.99}	cf. discussion in text
Implied parameters	Value for $\omega^A = 0.02$ (value for $\omega^A = 0.07$ )	
$\delta_K$	0.04 (0.04)	implied by $sav, k/y, n, g$
$\sigma$	1.08 (1.08)	implied by $g, \tau_r, r, \rho$
$\alpha$	0.36 (0.44)	implied by $EPL, g, r, \delta_K, k/y, \varphi$
$\beta$	2.58 (2.93)	"
$\psi$	1.74 (2.00)	"
$\kappa$	1.1 (1.35)	"
$\phi$	0.91 (0.89)	for $\theta = 0.5$ , implied by equ. (45)
$\gamma$	0.087 (0.090)	for $\eta = 0.15$ , implied by equ. (46)

Table 2: Endogenous variables (steady state), parameters set by authors, and implied parameters.

## 5 Optimal Long Run Policy Mix

Before analyzing the optimal policy programme that maximizes intertemporal welfare by calculating the entire transition path in response to a policy reform, we compare the long run social optimum to the decentralized steady state equilibrium, under existing US tax policy. This also allows us to compare the results with the previous literature, which exclusively focussed on a long run analysis (e.g., Jones and Williams, 2000; Steger, 2005; Strulik, 2007). Importantly, we also derive the optimal subsidy rates targeted to R&D and capital costs, by employing Proposition 3. Regarding human capital, recall that  $s_H = \tau_w$  is optimal.

### 5.1 R&D Investment

We start with R&D investment, for different values of the degree of duplication externality  $\theta$ .

$\theta$	$\mathfrak{h}_{opt}^A$ (in %)	$\mathfrak{h}^{A*}$ (in %)	$\mathfrak{h}_{opt}^A/\mathfrak{h}^{A*}$	$s_A^{opt}$	$s_R^{opt}$
0	45.4	2.8	16.1	0.97	1.48
0.25	41.7	2.8	14.8	0.96	1.48
0.5	35.9	2.8	12.7	0.95	1.46
0.75	25.3	2.8	8.9	0.92	1.41
0.9	13.4	2.8	4.7	0.83	1.27
0.95	7.5	2.8	2.7	0.67	1.02
0.99	1.7	2.8	0.6	-0.61	-0.93

(a) Parameters matched to R&D intensity of 2 % (i.e.  $\omega^A = 0.02$ ).

$\theta$	$\mathfrak{h}_{opt}^A$ (in %)	$\mathfrak{h}^{A*}$ (in %)	$\mathfrak{h}_{opt}^A/\mathfrak{h}^{A*}$	$s_A^{opt}$	$s_R^{opt}$
0	45.3	10.4	4.4	0.88	1.34
0.25	41.6	10.4	4.0	0.86	1.31
0.5	35.8	10.4	3.5	0.81	1.25
0.75	25.2	10.4	2.4	0.69	1.05
0.9	13.3	10.4	1.3	0.30	0.46
0.95	7.5	10.4	0.7	-0.34	-0.52
0.99	1.7	10.4	0.2	-5.45	-8.35

(b) Parameters matched to R&D intensity of 7 % (i.e.  $\omega^A = 0.07$ ).

Table 3: Long run fraction of human capital in R&D (social optimum and decentralized) and optimal R&D policy.

Notice: Underlying set of parameters as in Tables 1&2. Results are independent of  $\rho$ ,  $\sigma$ ,  $\gamma$ ,  $\eta$ ,  $\delta_H$ ;  $\phi$  is implied by equ. (45).

According to panel (a) of Tab. 3, which is based on an R&D intensity of 2 percent in long run market equilibrium, there is dramatic underinvestment in R&D in the case where the duplication externality is not very high. We find that for  $\theta \leq 0.9$ , the long run socially optimal human capital fraction  $\mathfrak{h}_{opt}^A$  is in the wide range of about 5 – 16 times higher than the market equilibrium fraction  $\mathfrak{h}^{A*}$ . What we would like to know, however, is how to improve the allocation of labor and to what extent which kind of tax policy should be used. Interestingly, due to the effectiveness of R&D subsidies for the equilibrium fraction  $\mathfrak{h}^{A*}$ , the necessary R&D policy to restore the social optimum does not so much depend on  $\theta$ , if  $\theta \leq 0.9$ . Our results suggest that the R&D sector should be able to deduct from pre-tax profits to obtain the corporate income tax base about 1.27 – 1.48 the amount invested in R&D. Thus, as pre-tax profits in the sense of the model are already net of R&D costs, this suggests that firms should be allowed to deduct up to 2.5 times their R&D costs from sales revenue to obtain the tax base. The current R&D subsidy policy in the US thus seems insufficient. Only if  $\theta$  is very high, about 0.98 or higher, there is overinvestment in R&D such that current R&D subsidies

should be cut. Such a large degree of the duplication externality does not seem to be realistic, however.

Panel (b) shows that when we assume an R&D intensity of 7 percent, the R&D underinvestment problem is less dramatic, but still substantial. For  $\theta \leq 0.9$  there should be 1.3 – 4.4 times higher human capital investment in R&D. Interestingly and importantly for a robust policy implication, the optimal R&D subsidy is not that different to the previous case. For  $\theta \leq 0.75$ , firms should be able to deduct 1.05 – 1.34 times the amount of R&D costs from pre-tax profits.

In addition to varying  $\theta$  and  $\omega^A$  we now discuss briefly the sensitivity of our main result in response to plausible changes in  $r$ ,  $\varphi$ , and  $EPL$ . One may indeed argue that  $r = 0.07$  is too high. However, if the steady state interest rate is set to a smaller number, the observation of massive underinvestment in R&D and substantial welfare gains in response to an increase in R&D subsidies would even be reinforced. To see this, notice that  $\rho$  and  $\sigma$  are positively related, via (37), to the after-tax interest rate,  $(1 - \tau_r)r$ . Setting  $r$  to a lower value, given  $g$ , means that individuals are assumed to be more patient. Moreover, according to (30) in Proposition 2, the optimal fraction of human capital in R&D,  $h_{opt}^A$ , is decreasing in both preference parameters,  $\rho$  and  $\sigma$ . That is, if individuals are more patient, the social planner devotes more resources to R&D. Hence, a lower value for  $r$  implies a larger R&D underinvestment gap in the market economy. Moreover, there may also be concerns with regard to  $\varphi = 0.23$ . Given  $\frac{\partial Y}{\partial A} \frac{A}{Y} = \varphi$  and  $\frac{A}{Y} = 0.26$  (Griliches, 1992),  $\varphi = 0.23$  implies a social rate of return to R&D of about 100 percent. One may argue that the social rate of return of 70 percent is also in line with empirical evidence and hence  $\varphi = 0.18$ . However, the extent of the R&D underinvestment bias is largely insensitive with regard to lowering  $\varphi$ ; the reason is that the calibration strategy implies an inverse relation between  $\alpha$  and  $\beta$ . Similarly, we have also set  $EPL = 5$  and  $EPL = 20$ , instead of  $EPL = 10$ . Again, the results (not displayed to save space) turn out to be largely insensitive.

In sum, our analysis suggests that US firms should be allowed to deduct up not less than twice their R&D costs from sales revenue for calculating taxable corporate

income.

## 5.2 Physical Capital Investment

For an R&D intensity of 2 percent (see Tab. 2, especially the lower part, for the implied calibration), we find that the US economy underinvests in physical capital. Employing Proposition 2, the optimal long run investment rate,  $sav_{opt}$ , is equal to 31.3 percent, whereas in market equilibrium the investment as a fraction of GDP,  $sav^*$ , is 21.3 percent (used for the calibration of capital depreciation rate  $\delta_K$  in (35)). According to Proposition 3, this means that US firms should be allowed to deduct about one and a half of their capital costs from sales revenue (i.e.  $s_d^{opt} = 0.49$ ) rather than being allowed to deduct their capital costs by 100 percent (i.e.  $s_d = 0$ ) for calculating corporate income. For an R&D intensity of 7 percent (see Tab. 2, especially the lower part, for the implied calibration), the gap between the decentralized and the socially optimal investment rate is even larger ( $sav^* = 0.213$ ,  $sav_{opt} = 0.38$ ,  $s_d^{opt} = 0.68$ ).

## 5.3 Comparison to the Literature

Previous analyses suggest that the R&D underinvestment problem is considerably less dramatic than implied by our study. There are two main differences between our analysis and the literature. First, we explicitly capture tax/subsidy policy and calibrate the economy accordingly. Second, our calibration strategy does not use some empirical measure of the labor share (or human capital income share) to calibrate the output elasticity of labor/human capital,  $1 - \alpha$ . Our baseline calibration rather uses evidence on the R&D intensity to calibrate  $\alpha$  for the long run, in turn determining the human capital income share,  $\omega$ , endogenously.

We will now demonstrate, exemplarily, that if we followed the strategy of the important and prominent contribution of Jones and Williams (2000), we obtain results which are similar to theirs. First, one can show how abstracting from the tax system leads to a downward bias of the extent of R&D underinvestment. According to (30) in Proposition 2, the optimal fraction of human capital in R&D,  $h_{opt}^A$ , is decreasing

in both preference parameters,  $\rho$  and  $\sigma$ . That is, if individuals are less patient, the social planner devotes less resources to R&D. According to (37),  $\rho$  and  $\sigma$  are positively related – by the Keynes-Ramsey rule – to the after-tax interest rate,  $(1 - \tau_r)r$ . Setting the tax rate on capital income,  $\tau_r$ , to zero rather than to its actual value means that individuals are assumed to be less patient. This brings the socially optimal R&D resources closer to the market equilibrium. Moreover, as discussed after Proposition 1, both corporate income taxation and the capital gains tax distort R&D incentives. R&D subsidies have to account for these distortions. To see the effects numerically, suppose again  $n = 0.01$ ,  $g = 0.021$ ,  $r = 0.07$ ,  $k/y = 3$ ,  $\delta_K = 0.04$ ,  $EPL = 10$ ,  $\omega^H = 0.05$  and recalibrate the model by assuming that there are no taxes and subsidies. For an R&D intensity  $\omega^A = 0.02$ , we then obtain  $\alpha = 0.36$  and, accordingly,  $\omega = 1.07 - \alpha = 0.71$  for the labor share (recall  $\omega^H = 0.05$ ). Thus, the equilibrium fraction of human capital in R&D,  $\mathfrak{h}^{A*}$ , is again about 2.8 percent ( $= \frac{2}{71}$ ); moreover,  $\mathfrak{h}^{H*} = \mathfrak{h}_{opt}^H = 0.07$  ( $= \frac{5}{71}$ ). However, the optimal R&D effort,  $\mathfrak{h}_{opt}^A$ , is now given by 28 percent for  $\theta = 0$ , by 18 percent for  $\theta = 0.5$ , and by 10.3 percent for  $\theta = 0.75$ . Thus, the relative gap to the market equilibrium shrinks considerably compared to the case with taxes and subsidies shown in Tab. 3 (a); for instance, if  $\theta = 0.75$ ,  $\mathfrak{h}_{opt}^A/\mathfrak{h}^{A*}$  is now equal to 3.7 instead of 8.9.

If, in addition to abstracting from taxes and subsidies, we assume  $\omega^A = 0.07$  instead of  $\omega^A = 0.02$  (calibration as for Tab 3 (b)), then  $\alpha$  becomes 0.42 and the implied labor share,  $\omega = 1.12 - \alpha$ , is 70 percent, i.e., almost equal to the labor share in the case where  $\omega^A = 0.02$ . Consequently, we obtain very similar values for  $\mathfrak{h}_{opt}^H$  and therefore for  $\mathfrak{h}_{opt}^A$  as in the case where the R&D subsidy is 2 percent. However, now  $\mathfrak{h}^{A*} = \frac{7}{70}$ , i.e., 10 percent of human capital is allocated to R&D in market equilibrium. This means that  $\mathfrak{h}_{opt}^A/\mathfrak{h}^{A*}$  is equal to 2.8 for  $\theta = 0$ , to 1.8 for  $\theta = 0.5$ , and to 1.03 for  $\theta = 0.75$ ; that is, for  $\theta = 0.75$  the long run equilibrium R&D intensity is about socially optimal. Interestingly, these figures almost match the results of Jones and Williams (2000) who also assume an interest rate of 7 percent and an effective patent life of 10 years in their baseline calibration. In fact, they set the output elasticity of labor such that

the R&D intensity is about 7 percent and abstract from taxes or subsidies – the case just examined. As a result, for the same extent of the duplication externality which corresponds to  $\theta = 0$ ,  $\theta = 0.5$  and  $\theta = 0.75$ , they obtain an R&D investment in social optimum relative to the equilibrium investment of 2.2, 1.7 and unity, respectively. This demonstrates that the different results of our study, shown in Tab. 3, stem from the public finance side in the model, which is supposed to capture the key elements of the US tax-transfer system.

Regarding investment in physical capital, Steger (2005) finds a similar extent of underinvestment problem like we do. He employs a general, semi-endogenous R&D-based growth model to investigate the allocative bias in the R&D share and the saving rate along the balanced growth path. The main finding is that the market economy slightly underinvests in R&D but heavily underinvests in physical capital accumulation. For his baseline calibration, the optimal investment rate along a balanced growth path should be about 15 percentage points higher than the steady state equilibrium rate. This figure is largely robust to parameter variations. Our analysis suggests a gap of 10-17 percentage points.

## 6 Dynamic Policy Evaluation

The analysis in the previous Section has ignored transitional dynamics. However, there may be very slow adjustment to the new steady state in response to policy shocks. We now examine which policy reform maximizes the intertemporal welfare gain, starting from an initial balanced growth path. The resulting change in intertemporal welfare ( $U$ ) is measured by the consumption-equivalent change in intertemporal welfare, denoted by  $\Theta$  (see appendix for details). The transitional dynamics are simulated by applying the relaxation algorithm (Trimborn et al., 2008).<sup>18</sup> For tractability reasons we restrict the attention to the case where subsidy rates are time-invariant.<sup>19</sup> That is, we start

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<sup>18</sup>Details of the numerical evaluations presented in this section are discussed in supplementary material available on request.

<sup>19</sup>The optimal subsidies may be time variant. However, Grossmann et al. (2010) have shown that the welfare loss from setting the R&D subsidy to its optimal long run level is negligible compared to

from an initial steady state under the status quo policy and calculate the time path of consumption in response to a one-time change in the subsidy rates. The policy mix which maximizes the welfare gain is denoted by  $(\bar{s}_R^{opt}, \bar{s}_d^{opt}, \bar{s}_H^{opt})$ .

The results are presented in Tab. 4. We find that the dynamically optimal subsidy rates, when restricted to be time-invariant, are not much different from those suggested by the steady state analysis  $(s_R^{opt}, s_d^{opt}, s_H^{opt})$ . Both  $\bar{s}_R^{opt}$  and  $\bar{s}_d^{opt}$  are slightly higher than optimal long run values  $s_R^{opt}$  and  $s_d^{opt}$ , respectively. Deviation of  $\bar{s}_H^{opt}$  from the optimal long run education subsidy ( $s_H^{opt} = 0.3$ ) is overall negligible and does not seem to follow a pattern. Also note that the results do not critically depend on  $\eta$  (and thus not on  $\gamma$ ). Like in the steady state analysis, the only important parameter we could not satisfactorily calibrate is the extent of the duplication externality  $\theta$ . Fortunately, the optimal policy mix does not critically depend on  $\theta$  for intermediate values of this parameter. Thus, we can safely conclude that the underinvestment problem is severe for R&D and substantial for physical capital. The policy implications outlined in Section 5 roughly apply.

$\theta$	$\eta$	$\phi$	$\gamma$	$s_R^{opt}$	$\bar{s}_R^{opt}$	$s_d^{opt}$	$\bar{s}_d^{opt}$	$s_H^{opt}$	$\bar{s}_H^{opt}$	$\Theta$
0.5	0.15	0.91	0.09	1.46	1.49	0.49	0.54	0.3	0.27	4.16
0.5	0.3	0.91	0.08	1.46	1.49	0.49	0.54	0.3	0.31	4.16
0.75	0.15	0.95	0.09	1.41	1.44	0.49	0.52	0.3	0.30	0.98
0.75	0.3	0.95	0.08	1.41	1.44	0.49	0.52	0.3	0.32	0.98

(a) Parameters matched to R&D intensity of 2 % (i.e.  $\omega^A = 0.02$ ).<sup>20</sup>

the case where the time varying, first-best subsidy rates are implemented.

<sup>20</sup>For  $\omega^A = 0.02$  and  $\theta = 0.25$  the algorithm does not converge. The gap between the decentralized allocation and the socially optimal solution and, hence, the implied optimal policy change is so large that a numerical solution cannot be found in this case. This indicates that the implied  $\bar{s}_d^{opt}$  and  $\Theta$  are even larger compared to the case  $\omega^A = 0.02$  and  $\theta = 0.5$ .

$\theta$	$\eta$	$\phi$	$\gamma$	$s_R^{opt}$	$\bar{s}_R^{opt}$	$s_d^{opt}$	$\bar{s}_d^{opt}$	$s_H^{opt}$	$\bar{s}_H^{opt}$	$\Theta$
0.25	0.15	0.84	0.09	1.31	1.37	0.68	0.71	0.3	0.30	1.62
0.25	0.3	0.84	0.08	1.31	1.37	0.68	0.71	0.3	0.28	1.62
0.5	0.15	0.90	0.09	1.25	1.31	0.68	0.71	0.3	0.31	0.86
0.5	0.3	0.90	0.08	1.25	1.31	0.68	0.71	0.3	0.30	0.86
0.75	0.15	0.95	0.09	1.05	1.10	0.68	0.70	0.3	0.33	0.32
0.75	0.3	0.95	0.08	1.05	1.10	0.68	0.70	0.3	0.27	0.32

(b) Parameters matched to R&D intensity of 7 % (i.e.  $\omega^A = 0.07$ ).

Table 4: Optimal growth policy mix and welfare gain,  $\Theta$ .

The potential welfare gains when implementing the optimal growth policy mix are remarkable. For instance, for  $\theta = 0.5$ , the intertemporal welfare gain is equivalent to a permanent annual increase in the consumption level per capita,  $\Theta$ , of about 86 percent if we start out with an R&D intensity of  $\omega^A = 0.07$ ; it even equals 416 percent for the case  $\omega^A = 0.02$ . Unlike the optimal policy mix, the welfare gain from implementing an appropriate policy reform critically depends on both  $\theta$  and  $\omega^A$ . As discussed in Section 4, it may make more sense to view R&D activity in a broader way as measured by the officially reported R&D intensity. Therefore, we prefer the case  $\omega^A = 0.07$  to the case  $\omega^A = 0.02$ . This suggests that for an intermediate value of  $\theta \approx 0.5$ , the welfare gain from an appropriate policy reform is roughly equivalent to a permanent doubling of per capita consumption.

## 7 Conclusion

This paper has employed a comprehensive endogenous growth model to derive the optimal growth policy mix. Our analysis represents a first step to examine the growth policy implications of distortions resulting from income taxation, R&D externalities, and product market imperfections. It is consciously based on well-understood and widely-used ingredients in endogenous growth theory. The analysis has accounted for the US tax system as well as transitional dynamics in response to policy shocks. The

results suggest that the current policy leads to severe underinvestment in both R&D and physical capital. We find that firms should be allowed to deduct between 2-2.5 times their R&D costs and about 1.5-1.7 times their capital costs from sales revenue for calculating taxable corporate income. The results on the optimal policy mix are not sensitive to reasonable changes in the calibration. A policy reform targeted to all three growth engines simultaneously may entail an intertemporal welfare gain which is equivalent to a permanent doubling of per capita consumption.

Should we take these results at face value? One may object that the welfare gain is too large to appear plausible. We basically agree on this point in the sense that one should be sceptical at this stage of the research process. Our reading of the results is that there is strong indication for the welfare significance of the quest for the optimal growth policy. Therefore, we believe that there should be more research on this important topic.

Future studies should focus on the following issues. (i) The quantitative optimal growth policy and the resulting welfare implications may, of course, be sensitive with respect to the underlying theoretical model. One should therefore investigate whether the results are robust with respect to changes in the underlying analytical framework (e.g., Schumpeterian rather than horizontal R&D based growth models). (ii) Whereas standard growth theory assumes that human capital is general and thus can be reallocated between R&D and production sectors without frictions, future research should study the implications of imperfect intersectoral labor mobility for optimal growth policy.<sup>21</sup> (iii) Rather than considering Pigouvian subsidies one could also investigate the implications of a Ramsey-type second-best tax problem. That is: how does the optimal growth policy look like when a pre-determined government revenue requirement has to be met? (iv) Finally, it seems indicated to incorporate potential risks associated with innovations in an analysis of dynamically optimal growth policy.<sup>22</sup>

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<sup>21</sup>Grossmann (2007) investigates an endogenous growth model in which workers choose their type of education (production vs. R&D skills) ex ante and are immobile across occupations.

<sup>22</sup>See Jones (2011) for a first analytical framework in this direction.

## 8 Appendix

### 8.1 Proof of Proposition 1

The current-value Hamiltonian which corresponds to the household optimization problem (18) is given by

$$\mathcal{H} = \frac{c^{1-\sigma} - 1}{1-\sigma} + \mu [\xi (h^H)^\gamma h^\eta - \delta_H h] + \lambda [(1-\tau_r)r - n]a + (1-\tau_w)wh - (1-s_H)wh^H - c + T, \quad (47)$$

where  $\lambda$  and  $\mu$  are multipliers (co-state variables) associated with constraints (4) and (6), respectively. Necessary optimality conditions are  $\partial\mathcal{H}/\partial c = \partial\mathcal{H}/\partial h^H = 0$  (control variables),  $\dot{\mu} = (\rho - n)\mu - \partial\mathcal{H}/\partial h$ ,  $\dot{\lambda} = (\rho - n)\lambda - \partial\mathcal{H}/\partial a$  (state variables), and the corresponding transversality conditions. Thus,

$$\lambda = c^{-\sigma} \quad (48)$$

$$\mu\xi\gamma(h^H)^{\gamma-1}h^\eta = \lambda(1-s_H)w, \quad (49)$$

$$\frac{\dot{\mu}}{\mu} = \rho - n - \xi (h^H)^\gamma \eta h^{\eta-1} + \delta_H - \frac{\lambda}{\mu}w(1-\tau_w), \quad (50)$$

$$\frac{\dot{\lambda}}{\lambda} = \rho - (1-\tau_r)r, \quad (51)$$

$$\lim_{t \rightarrow \infty} \mu_t e^{-(\rho-n)t} h_t = 0, \quad (52)$$

$$\lim_{t \rightarrow \infty} \lambda_t e^{-(\rho-n)t} a_t = 0. \quad (53)$$

Differentiating (48) with respect to time and using (51), we obtain the Euler equation

$$\frac{\dot{c}}{c} = \frac{(1-\tau_r)r - \rho}{\sigma}. \quad (54)$$

Now, define  $\tilde{z} \equiv zA^{-\frac{\alpha}{(1-\alpha)(\beta-1)}}$  for  $z \in \{w, c, a, T\}$ ; we will show that the adjusted values

( $\tilde{z}$ ) of these variables are stationary in the long run. From (54),

$$\frac{\dot{\tilde{c}}}{\tilde{c}} = \frac{(1 - \tau_r)r - \rho}{\sigma} - \frac{\alpha}{(1 - \alpha)(\beta - 1)} \frac{\dot{A}}{A}. \quad (55)$$

Differentiating (49) with respect to time and making use of (4), (49), (50) and (51) we obtain:

$$\frac{\dot{h}^H}{h^H} = \frac{1}{1 - \gamma} \left[ (1 - \tau_r)r - n + (1 - \eta)\delta_H - \frac{1 - \tau_w}{1 - s_H} \frac{\xi\gamma h^\eta}{(h^H)^{1-\gamma}} - \frac{\dot{w}}{w} \right]. \quad (56)$$

Moreover, with  $H^A = Nh^A$ , (2), (4), (6) can be written as

$$\frac{\dot{A}}{A} = \frac{\nu}{1 + \psi} A^{\phi-1} (Nh^A)^{1-\theta}, \quad (57)$$

$$\frac{\dot{h}}{h} = \xi(h^H)^\gamma h^{\eta-1} - \delta_H, \quad (58)$$

$$\frac{\dot{\tilde{a}}}{\tilde{a}} = (1 - \tau_r)r - n + (1 - \tau_w) \frac{\tilde{w}h}{\tilde{a}} - (1 - s_H) \frac{\tilde{w}h^H}{\tilde{a}} - \frac{\tilde{c}}{\tilde{a}} - \frac{\alpha}{(1 - \alpha)(\beta - 1)} \frac{\dot{A}}{A} + \frac{\dot{T}}{\tilde{a}}. \quad (59)$$

Next, substitute (11) and (12) into (8) and use both (13) and  $R = r + \delta_K$  to obtain the following expression for the profit of each intermediate goods producer  $i$ :

$$\pi_i = \pi = A^{\frac{\alpha}{(1-\alpha)(\beta-1)-1}} (1 - \tau_c)(\kappa - 1) \left( \frac{\alpha}{\kappa} \right)^{\frac{1}{1-\alpha}} [(1 - s_K)(r + \delta_K)]^{-\frac{\alpha}{1-\alpha}} H^Y. \quad (60)$$

Now define  $\tilde{q} \equiv P^A A^{1 - \frac{\alpha}{(1-\alpha)(\beta-1)}} / N$  and differentiate  $\tilde{q}$  with respect to time; then use the resulting expression as well as (60) to rewrite (15) as

$$\frac{\dot{\tilde{q}}}{\tilde{q}} = \left( 1 - \frac{\alpha}{(1 - \alpha)(\beta - 1)} \right) \frac{\dot{A}}{A} - n + \frac{1}{1 - \tau_g} \times \left( \frac{(1 - \tau_r)r + \psi \frac{\dot{A}}{A} - \frac{(1 - \tau_c)(\kappa - 1) \left( \frac{\alpha}{\kappa} \right)^{\frac{1}{1-\alpha}} [(1 - s_K)(r + \delta_K)]^{-\frac{\alpha}{1-\alpha}} h^Y}{\tilde{q}}}{\tilde{q}} \right) \quad (61)$$

The capital market clearing condition reads  $Na = K + P^A A$ ; it implies, by using

(14) and  $R = r + \delta_K$  (as well as the definitions of  $\tilde{a}$  and  $\tilde{q}$ ), that

$$\tilde{a} = \left( \frac{\alpha}{\kappa(1-s_K)(r+\delta_K)} \right)^{\frac{1}{1-\alpha}} h^Y + \tilde{q}. \quad (62)$$

The wage rate equals the marginal product of human capital in the final goods sector, i.e.,  $w = (1-\alpha)Y/H^Y$ . Using (13) we obtain

$$\tilde{w} = (1-\alpha) \left( \frac{\alpha}{\kappa(1-s_K)(r+\delta_K)} \right)^{\frac{\alpha}{1-\alpha}}. \quad (63)$$

Moreover, in equilibrium,  $\Pi = 0$  holds. This leads to

$$w = \frac{P^A \tilde{v} A^\phi}{1-s_A}, \quad (64)$$

according to (17). Combining (64) with (2) and using both  $\tilde{q} = P^A A^{1-\frac{\alpha}{(1-\alpha)(\beta-1)}}/N$  and  $\tilde{w} = A^{-\frac{\alpha}{(1-\alpha)(\beta-1)}} w$ , we can write

$$h^A = \frac{\tilde{q}(1+\psi)\frac{\dot{A}}{A}}{(1-s_A)\tilde{w}}. \quad (65)$$

We next derive steady state values. In steady state, the growth rate of  $A$  must be equal to zero. Differentiating the right-hand side of (57) with respect to time and setting the resulting term to zero leads to  $\dot{A}/A = g_A$  as given by (19), provided that  $\dot{h}^A = 0$ . In the following we show that  $\dot{h}^A = 0$  indeed holds if  $\dot{A}/A = g_A$ ; we therefore set  $\dot{A}/A = g_A$  to derive the following (candidates of) steady state values. Setting  $\dot{c} = 0$  in (55) and using  $g = \frac{\alpha g_A}{(1-\alpha)(\beta-1)}$ , we find

$$r = \frac{\sigma g + \rho}{1-\tau_r}. \quad (66)$$

Note that substituting (66) into (63) also gives us a stationary value for  $\tilde{w}$  in terms of exogenous parameters only. According to (58) and  $\dot{h} = 0$ , we obtain

$$h = \left( \frac{\xi}{\delta_H} \right)^{\frac{1}{1-\eta}} (h^H)^{\frac{\gamma}{1-\eta}}. \quad (67)$$

Setting  $\dot{h}^H = 0$  in (56) (which holds in steady state, as will become apparent) and employing both  $\dot{w}/w = g$  and (66) implies<sup>23</sup>

$$h^H = \left( \frac{1 - \tau_w}{1 - s_H} \frac{\gamma}{(\sigma - 1)g + \rho - n + (1 - \eta)\delta_H} \right)^{\frac{1-\eta}{1-\gamma-\eta}} \left( \frac{\xi}{(\delta_H)^\eta} \right)^{\frac{1}{1-\gamma-\eta}}. \quad (68)$$

Combining (67) and (68) gives us expression (21) for the equilibrium fraction of human capital devoted to education.

Using  $\dot{A}/A = g_A$  in (65), we furthermore obtain

$$h^A = \frac{(1 + \psi)g_A \tilde{q}}{(1 - s_A)\tilde{w}} \quad (69)$$

To find the steady state values for  $h^Y$  and  $\tilde{q}$ , first substitute (69) into labor market clearing condition  $h^Y = h - h^H - h^A$ , which gives us

$$h^Y = h - h^H - \frac{(1 + \psi)g_A \tilde{q}}{(1 - s_A)\tilde{w}}. \quad (70)$$

Also set  $\dot{\tilde{q}} = 0$  in (61) and use  $\dot{A}/A = g_A$  to find  $\tilde{q} = \Omega h^Y$  with

$$\Omega \equiv \frac{(1 - \tau_c)(\kappa - 1) \left(\frac{\alpha}{\kappa}\right)^{\frac{1}{1-\alpha}}}{[(1 - \tau_r)r + \psi g_A - (n + g - g_A)(1 - \tau_g)] [(1 - s_K)(r + \delta_K)]^{\frac{\alpha}{1-\alpha}}}. \quad (71)$$

Substituting  $\tilde{q} = \Omega h^Y$  into (70) and solving for  $h^Y$  yields

$$h^Y = \frac{h - h^H}{1 + \frac{(1 + \psi)g_A \Omega}{(1 - s_A)\tilde{w}}} \quad (72)$$

and thus

$$\tilde{q} = \frac{\Omega(h - h^H)}{1 + \frac{g_A \Omega}{(1 - s_A)\tilde{w}}}. \quad (73)$$

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<sup>23</sup>That the wage rate grows with rate  $g$  in steady state follows from  $w = \tilde{w}A^{-\frac{\alpha}{(1-\alpha)(\beta-1)}}$  and  $\dot{\tilde{w}} = 0$ .

Substituting (73) into (69) yields

$$h^A = \frac{h - h^H}{\frac{(1-s_A)\tilde{w}}{\Omega(1+\psi)g_A} + 1}. \quad (74)$$

Dividing by both sides of (74) by  $h$ , substituting into it both expressions (63) for  $\tilde{w}$  and (71) for  $\Omega$  as well as using  $(1 - \tau_r)r = \sigma g + \rho$  from (66) gives us expression (22) for the steady state fraction of human capital devoted to R&D.

Equations (67), (72), (73) and (74) give us explicit expressions for  $h$ ,  $h^Y$ ,  $\tilde{q}$  and  $h^A$ , respectively, noting that  $h^H$  is explicitly given by (68) and  $\tilde{w}$  by (63), using (66) for the latter. Setting next  $\dot{\tilde{a}} = 0$  in (59) and using (66),  $\dot{A}/A = g_A$  as well as  $g = \frac{\alpha g_A}{(1-\alpha)(\beta-1)}$  yields

$$\tilde{c} = [(\sigma - 1)g + \rho - n]\tilde{a} + (1 - \tau_w)\tilde{w}h - (1 - s_H)\tilde{w}h^H + \tilde{T}. \quad (75)$$

We also need to show that the adjusted lump-sum transfer per capita,  $\tilde{T}$ , is stationary in the long run when  $r$ ,  $h$ ,  $h^A$ ,  $h^Y$ ,  $h^H$ ,  $\tilde{w}$ ,  $\tilde{c}$ ,  $\tilde{a}$ ,  $\tilde{q}$  are stationary. Under a balanced government budget it must hold that the sum of education subsidy payments ( $s_H w N h^H$ ) and lump-sum transfer payments ( $TN$ ) is equal to the sum of revenue from labor income taxation ( $\tau_w w N h$ ), taxation of capital income from asset holding ( $\tau_r r K$ ), taxation of capital gains ( $\tau_g \dot{P}^A A$ ), and corporate income taxation of intermediate good firms after depreciation allowances ( $\int_0^A \tau_c (p_i x_i - R x_i - s_d R x_i) di$ ), and of R&D firms after R&D subsidy ( $\tau_c (P^A \dot{A} - w H^A - s_R w H^A)$ ). Hence, using  $p_i = \kappa(1 - s_K)R$  for all  $i$ ,  $K = \int_0^A x_i di$ ,  $R = r + \delta_K$  as well as expressions (15) and (60), we have

$$\begin{aligned} \tilde{T} = & \tau_w \tilde{w} h + \tau_r r \tilde{k} + \tau_c [\kappa(1 - s_K) - (1 + s_d)] (r + \delta_K) \tilde{k} + \frac{\tau_g}{1 - \tau_g} \times \\ & \left( \left[ (1 - \tau_r)r + \psi \frac{\dot{A}}{A} \right] \tilde{q} - (1 - \tau_c)(\kappa - 1) \left( \frac{\alpha}{\kappa} \right)^{\frac{1}{1-\alpha}} [(1 - s_K)(r + \delta_K)]^{-\frac{\alpha}{1-\alpha}} h^Y \right) \\ & \tau_c \left[ \tilde{q}(1 + \psi) \frac{\dot{A}}{A} - (1 + s_R)\tilde{w}h^A \right] - s_H \tilde{w}h^H, \end{aligned} \quad (76)$$

where  $\tilde{k} \equiv A^{-\frac{\alpha}{(1-\alpha)(\beta-1)}} k$ . According to (14),  $\tilde{k}$  is stationary in the long run if  $h^Y$  is; thus, provided that  $\dot{A}/A = g_A$  as claimed,  $\tilde{T}$  is stationary. We also see that, in steady

state both per capita capital stock  $k$  and, according to (13), per capita income grow with rate  $g$  as given by (20).

The investment share is given by  $sav = (\dot{K} + \delta_K K)/Y = (\dot{K}/K + \delta_K)k/y$ . Using  $\dot{K}/K = n + g$  together with expressions (14) and (13) for  $k$  and  $y$ , respectively, we obtain

$$sav = \frac{\alpha(n + g + \delta_K)}{\kappa(1 - s_K)R}. \quad (77)$$

Using  $R = r + \delta_K$  and expression (66) for  $r$  confirms (24).

Finally, it remains to be shown that the transversality conditions (52) and (53) hold under assumption (A1). Differentiating (49) with respect to time and using  $\dot{h} = \dot{h}^H = 0$  as well as  $\dot{w}/w = g$  implies that, along a balanced growth path,  $\dot{\mu}/\mu = \dot{\lambda}/\lambda + g$ . From (51) and (66) we find  $\dot{\lambda}/\lambda = -\sigma g$  and thus  $\dot{\mu}/\mu = (1 - \sigma)g$ . As  $h$  becomes stationary, (52) holds if  $\lim_{t \rightarrow \infty} e^{[(1-\sigma)g+n-\rho]t} = 0$ , or  $\rho > (1 - \sigma)g + n$ . Using the expression for  $g$  in (20) shows that the latter condition is equivalent to (A1). Similarly, using  $\dot{\lambda}/\lambda = -\sigma g$  and the fact that  $a$  grows with rate  $g$  in the long run, we find that also (53) holds if  $\rho > (1 - \sigma)g + n$ . This concludes the proof. ■

## 8.2 Proof of Proposition 2

The current-value Hamiltonian which corresponds to the social planning problem (28) is given by

$$\begin{aligned} \mathcal{H} = & \frac{c^{1-\sigma} - 1}{1 - \sigma} + \lambda_k \underbrace{\left( A^{\frac{\alpha}{\beta-1}} k^\alpha (h^Y)^{1-\alpha} \right)}_{=y} - (\delta_K + n)k - c) + \\ & \lambda_h [\xi (h^H)^\gamma h^\eta - \delta_H h] + \lambda_A \bar{\nu} A^\phi N^{1-\theta} \underbrace{\left( h - h^Y - h^H \right)}_{=h^A}^{=\dot{A}}, \end{aligned} \quad (78)$$

$\bar{\nu} \equiv \frac{\nu}{1+\psi}$ , where  $\lambda_k$ ,  $\lambda_h$  and  $\lambda_A$  are co-state variables associated with constraints (26), (4) and (27), respectively. Necessary optimality conditions are  $\partial \mathcal{H}/\partial c = \partial \mathcal{H}/\partial h^H = \partial \mathcal{H}/\partial h^Y = 0$  (control variables),  $\dot{\lambda}_z = (\rho - n)\lambda_z - \partial \mathcal{H}/\partial z$  for  $z \in \{k, h, A\}$  (state

variables), and the corresponding transversality conditions. Thus,

$$\lambda_k = c^{-\sigma} \quad (79)$$

$$\lambda_h \xi \gamma (h^H)^{\gamma-1} h^\eta = \lambda_A (1 - \theta) \bar{\nu} A^\phi N^{1-\theta} (h^A)^{-\theta}, \quad (80)$$

$$\lambda_k (1 - \alpha) A^{\frac{\alpha}{\beta-1}} k^\alpha (h^Y)^{-\alpha} = \lambda_A (1 - \theta) \underbrace{\bar{\nu} A^\phi N^{1-\theta} (h^A)^{-\theta}}_{=\dot{A}/h^A}, \quad (81)$$

$$\frac{\dot{\lambda}_k}{\lambda_k} = \rho - \frac{\alpha y}{k} + \delta_K, \quad (82)$$

$$\frac{\dot{\lambda}_h}{\lambda_h} = \rho - n - \xi (h^H)^\gamma \eta h^{\eta-1} + \delta_H - \frac{\lambda_A}{\lambda_h} (1 - \theta) \bar{\nu} A^\phi N^{1-\theta} (h^A)^{-\theta}, \quad (83)$$

$$\frac{\dot{\lambda}_A}{\lambda_A} = \rho - n - \frac{\lambda_k}{\lambda_A} \frac{\alpha}{\beta-1} A^{\frac{\alpha}{\beta-1}-1} k^\alpha (h^Y)^{1-\alpha} - \phi \frac{\dot{A}}{A} \quad (84)$$

$$\lim_{t \rightarrow \infty} \lambda_{z,t} e^{-(\rho-n)t} z_t = 0, \quad z \in \{k, h, A\}. \quad (85)$$

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

We exclusively focus on the long run. In steady state, with  $h^A$  being stationary,  $A$  must grow with rate  $g_A$ . Moreover,  $y$ ,  $k$ , and  $c$  must grow at the same rate  $g$ , if  $h^Y$  is stationary. Differentiating (79) with respect to time, we obtain

$$\frac{\dot{\lambda}_k}{\lambda_k} = -\sigma \frac{\dot{c}}{c} = -\sigma g, \quad (86)$$

where we used  $\dot{c}/c = g$  for the latter equation. Combining (86) with (82) implies a capital output ratio

$$\frac{k}{y} = \frac{\alpha}{\rho + \delta_K + \sigma g}. \quad (87)$$

Next, differentiate (80) with respect to time to find that in steady state, under a stationary allocation of human capital,

$$\frac{\dot{\lambda}_h}{\lambda_h} = \frac{\dot{\lambda}_A}{\lambda_A} + g_A \quad (88)$$

holds, where we used  $\dot{A}/A = g_A$ ,  $\dot{N}/N = n$  and the fact that  $(1 - \theta)n = (1 - \phi)g_A$ , according to (19). Making use of the same properties, differentiating (81) with respect to time leads to

$$\frac{\dot{\lambda}_k}{\lambda_k} + \left( \frac{\alpha}{\beta - 1} - 1 \right) g_A + \alpha g = \frac{\dot{\lambda}_A}{\lambda_A}. \quad (89)$$

Using (86) and the definition of  $g$  in (20), we can rewrite (89) to

$$\frac{\dot{\lambda}_A}{\lambda_A} = (1 - \sigma)g - g_A \quad (90)$$

and thus, according to (88),

$$\frac{\dot{\lambda}_h}{\lambda_h} = (1 - \sigma)g. \quad (91)$$

Moreover, substituting the right-hand side of (80) into (83) as well as using both (91) and the fact that  $\xi (h^H)^\gamma h^\eta = \delta_H h$  when  $\dot{h} = 0$ , eventually confirms the expression for  $h^H/h$  in (29).

Next, rewrite (81) to

$$\frac{\lambda_k}{\lambda_A} = \frac{(1 - \theta) \frac{\dot{A}}{A} \frac{h^Y}{h^A}}{(1 - \alpha) A^{\frac{\alpha}{\beta - 1} - 1} k^\alpha (h^Y)^{1 - \alpha}}. \quad (92)$$

Substituting (92) into (84) and using  $\dot{A}/A = g_A$  together with the definition of  $g$  in (20) leads to

$$\frac{\dot{\lambda}_A}{\lambda_A} = \rho - n - (1 - \theta)g \frac{h^Y}{h^A} - \phi g_A. \quad (93)$$

Combining (93) with (90) and using the fact that  $(1 - \phi)g_A = (1 - \theta)n$  leads to

$$\frac{h^Y}{h^A} = \frac{\rho - \theta n + g(\sigma - 1)}{(1 - \theta)g} = \Gamma. \quad (94)$$

Using  $h^Y = h - h^A - h^H$  then confirms the expression for  $h^A/h$  in (30).

To confirm the socially optimal savings and investment rate ( $sav = 1 - c/y$ ) as well, note from (26) that

$$sav = \left( \frac{\dot{k}}{k} + \delta_K + n \right) \frac{k}{y}. \quad (95)$$

Using  $\dot{k}/k = g$  and expression (87) for  $k/y$  confirms (31).

Finally, it is easy to see from (86), (91) and (90) that, under assumption (A1), transversality conditions (85) hold for  $k$ ,  $h$  and  $A$ , respectively (using  $\dot{k}/k = g$ ,  $\dot{h} = 0$  and  $\dot{A}/A = g_A$ ). This concludes the proof. ■

### 8.3 Consumption-equivalent change in intertemporal welfare - derivation of $\Theta$

First, adjust per capita consumption to  $\tilde{c} \equiv cA^{-\frac{\alpha}{(1-\alpha)(\beta-1)}}$ , which is stationary in the long run (Proposition 1). Moreover, denote the change in life-time utility by  $\Delta U$  and the (hypothetical) permanent change in adjusted steady per capita consumption by  $\Delta\tilde{c}$ . Initially, there is an adjusted steady consumption stream  $\tilde{c}_0$ , as we start from an initial balanced growth path. Then we have

$$\Delta U = \int_0^\infty \frac{((\tilde{c}_0 + \Delta\tilde{c})e^{gt})^{1-\sigma} - 1}{1-\sigma} e^{-(\rho-n)t} dt - \int_0^\infty \frac{(\tilde{c}_0 e^{gt})^{1-\sigma} - 1}{1-\sigma} e^{-(\rho-n)t} dt \quad (96)$$

which we can solve to find

$$\Theta \equiv \frac{\Delta\tilde{c}}{\tilde{c}_0} = \frac{(\tilde{c}_0^{1-\sigma} + \Delta U(\sigma-1)(g(1-\sigma) + n - \rho))^{\frac{1}{1-\sigma}}}{\tilde{c}_0} - 1. \quad (97)$$

We numerically find  $\tilde{c}_0$  under the status quo policy and obtain the change in welfare  $\Delta U$  which results from a policy reform. In turn, we get  $\Theta = \Delta\tilde{c}/\tilde{c}_0$  from (97).

## Supplementary Material (not intended for publication)

This supplement provides details of numerical evaluations in Section 6.

**Consistency checks and the goods market clearing condition:** To rule out errors from typos in the program code or due to software limitations, we took caution as follows. First, we implemented the model in two different software packages, Mathematica and Matlab, by two different authors separately. Second, we checked numerically whether the goods market clears (which must hold true due to Walras’

law). We now show that the goods market clearing condition  $Y = C + I$ , where  $I \equiv \dot{K} + \delta_K K$  is total investment and  $C \equiv Nc$  is total consumption spending, is fulfilled. That is,  $\dot{K} = Y - C - \delta_K K$ . This condition is not used in the program codes and therefore can be used as a test of correct implementation.

The following relationships will be used to show that  $Y = C + I$ .

- The no-arbitrage condition (15) implies

$$(1 - \tau_r)rP_A - \dot{P}^A = \pi - \tau_g\dot{P}^A - \psi P^A \frac{\dot{A}}{A}. \quad (98)$$

- Tax revenue in intermediate goods sector: From profit function of an intermediate good producer  $i$ ,

$$\pi_i = \pi = p_i x_i - R x_i - \tau_c(p_i x_i - R x_i - s_d R x_i),$$

we obtain

$$\begin{aligned} & \int_0^A \tau_c(p_i x_i - R x_i - s_d R x_i) di \\ &= \int_0^A (p_i x_i - R x_i - \pi_i) di \\ &= [\kappa(1 - s_K) - 1] RK - \pi A. \end{aligned} \quad (99)$$

To derive the latter equation we used the facts that  $p_i = \kappa(1 - s_K)R$  for all  $i$  and  $K = \int_0^A x_i di$ .

- Tax revenue from R&D firms: From the expression for profits of the representative R&D firm,

$$\Pi = P^A(1 + \psi)\dot{A} - wH^A - \tau_c \left( P^A(1 + \psi)\dot{A} - wH^A - s_R wH^A \right),$$

and the fact that  $\Pi = 0$  in equilibrium, we have

$$\tau_c \left( P^A(1 + \psi)\dot{A} - wH^A - s_R wH^A \right) = P^A(1 + \psi)\dot{A} - wH^A. \quad (100)$$

- From the asset accumulation equation (6) of households:

$$N\dot{a} = [(1 - \tau_r)r - n] Na + (1 - \tau_w)wNh - (1 - s_H)Nwh^H - Nc + NT. \quad (101)$$

Now we proceed in several steps:

- Step 1: Given the linear-homogenous production function (1) and due to perfect competition we know that profits are zero in the final goods sector. Thus,

$$Y = \int_0^A p_i x_i di + wH^Y.$$

Using  $p_i = \kappa(1 - s_K)R$ ,  $K = \int_0^A x_i di$  and  $H^Y = N(h - h^A - h^H)$ , we obtain

$$Y = \kappa(1 - s_K)RK + wN(h - h^A - h^H)$$

and thus

$$Y - wNh - RK + wNh^H = [\kappa(1 - s_K) - 1] RK - wH^A. \quad (102)$$

- Step 2: Under a balanced government budget, the aggregate lump-sum transfer

to households is

$$\begin{aligned}
NT &= \tau_w wNh + \tau_r rK + \tau_g \dot{P}^A A - s_H Nwh^H + \\
&\quad \int_0^A \tau_c (p_i x_i - Rx_i - s_d Rx_i) di + \\
&\quad \tau_c \left( P^A (1 + \psi) \dot{A} - wH^A - s_R wH^A \right) \\
&= \tau_w wNh + \tau_r rK + \tau_g \dot{P}^A A - s_H Nwh^H + \\
&\quad [\kappa(1 - s_K) - 1] RK - \pi A + P^A (1 + \psi) \dot{A} - wH^A, \quad (103)
\end{aligned}$$

where we used (99) and (100) for the latter equation. Using (102), we can rewrite (103) as

$$\begin{aligned}
NT &= \tau_w wNh + \tau_r rK + \tau_g \dot{P}^A A - s_H Nwh^H + \\
&\quad Y - wNh - RK + wNh^H - \pi A + P^A (1 + \psi) \dot{A},
\end{aligned}$$

or, equivalently,

$$\begin{aligned}
Y &= (1 - \tau_w)wNh + RK + \pi A - P^A (1 + \psi) \dot{A} + \\
&\quad NT - \tau_r rK - \tau_g \dot{P}^A A - (1 - s_H)Nwh^H. \quad (104)
\end{aligned}$$

This gives us an expression for GDP from the distribution side.

- Step 3: Total assets of households are given by  $Na = K + P^A A$ . Differentiating with respect to time yields:

$$\dot{N}a + N\dot{a} = \dot{K} + \dot{P}^A A + P^A \dot{A}.$$

Using  $\dot{N} = nN$  we can write

$$N\dot{a} = \dot{K} + \dot{P}^A A + P^A \dot{A} - nNa. \quad (105)$$

Combining (105) with asset accumulation equation (101) we find

$$\begin{aligned} & \dot{K} + \dot{P}^A A + P^A \dot{A} - nNa \\ = & [(1 - \tau_r)r - n] Na + (1 - \tau_w)wNh - (1 - s_H)Nwh^H - Nc + NT. \end{aligned}$$

Using  $Na = K + P^A A$  and rearranging terms we obtain

$$\begin{aligned} \dot{K} = & (1 - \tau_r)rK + (1 - \tau_w)wNh - (1 - s_H)Nwh^H - Nc + NT + \\ & \left[ (1 - \tau_r)rP^A - \dot{P}^A \right] A - P^A \dot{A}. \end{aligned}$$

Using (98) and  $r = R - \delta_K$  this leads to

$$\begin{aligned} \dot{K} = & RK - \delta_K K - \tau_r rK + (1 - \tau_w)wNh - (1 - s_H)Nwh^H + \\ & \pi A - \tau_g \dot{P}^A A - P^A(1 + \psi)\dot{A} - Nc + NT. \end{aligned}$$

Finally, using expression (104) for  $Y$  confirms the goods market clearing condition

$$\dot{K} = Y - Nc - \delta_K K,$$

or,

$$Y = C + I,$$

where  $I \equiv \dot{K} + \delta_K K$  is aggregate gross investment and  $C \equiv Nc$  is total consumption. *Q.E.D.*

**Dynamical system:** The following equations are employed for numerical simulations in Section 6.1.

$$\frac{\dot{c}}{c} = \frac{(1 - \tau_r)r - \rho}{\sigma}. \quad (106)$$

$$\mu\xi\gamma(h^H)^{\gamma-1}h^\eta = c^{-\sigma}(1 - s_H)w, \quad (107)$$

$$\frac{\dot{\mu}}{\mu} = \rho - n - \xi (h^H)^\gamma \eta h^{\eta-1} + \delta_H - \frac{c^{-\sigma}}{\mu} w(1 - \tau_w), \quad (108)$$

$$\frac{\dot{P}^A}{P^A} = \frac{1}{1 - \tau_g} \left( (1 - \tau_r)r + \frac{\psi\nu}{1 + \psi} A^{\phi-1} (Nh^A)^{1-\theta} - \frac{(1 - \tau_c)(\kappa - 1) \left(\frac{\alpha}{\kappa}\right)^{\frac{1}{1-\alpha}} [(1 - s_K)(r + \delta_K)]^{-\frac{\alpha}{1-\alpha}} Nh^Y}{P^A A^{1 - \frac{\alpha}{(1-\alpha)(\beta-1)}}} \right), \quad (109)$$

$$\frac{\dot{A}}{A} = \frac{\nu}{1 + \psi} A^{\phi-1} (Nh^A)^{1-\theta}, \quad (110)$$

$$\frac{\dot{h}}{h} = \xi (h^H)^\gamma h^{\eta-1} - \delta_H, \quad (111)$$

$$\frac{\dot{N}}{N} = n, \quad (112)$$

$$\dot{a} = [(1 - \tau_r)r - n]a + (1 - \tau_w)wh - (1 - s_H)wh^H - c + T, \quad (113)$$

$$\begin{aligned} T = & \tau_w wh + \tau_r rk + \tau_c [\kappa(1 - s_K) - (1 + s_d)](r + \delta_K)k + \\ & \frac{\tau_g}{1 - \tau_g} \left( (1 - \tau_r)r P^A \frac{A}{N} + \frac{P^A}{N} \frac{\psi\nu}{1 + \psi} A^\phi (Nh^A)^{1-\theta} - \right. \\ & \left. A^{\frac{\alpha}{(1-\alpha)(\beta-1)}} (1 - \tau_c)(\kappa - 1) \left(\frac{\alpha}{\kappa}\right)^{\frac{1}{1-\alpha}} [(1 - s_K)(r + \delta_K)]^{-\frac{\alpha}{1-\alpha}} h^Y \right) + \\ & \tau_c \left[ P^A \nu A^\phi N^{-\theta} (h^A)^{1-\theta} - (1 + s_R)wh^A \right] - s_H wh^H, \end{aligned} \quad (114)$$

$$k = A^{\frac{\alpha}{(1-\alpha)(\beta-1)}} \left( \frac{\alpha}{\kappa [(1 - s_K)(r + \delta_K)]} \right)^{\frac{1}{1-\alpha}} h^Y, \quad (115)$$

$$a = k + \frac{P^A A}{N}, \quad (116)$$

$$w = A^{\frac{\alpha}{(1-\alpha)(\beta-1)}} (1 - \alpha) \left( \frac{\alpha}{\kappa(1 - s_K)(r + \delta_K)} \right)^{\frac{\alpha}{1-\alpha}}. \quad (117)$$

$$h^A = \frac{1}{N} \left( \frac{P^A \nu A^\phi}{(1 - s_A)w} \right)^{\frac{1}{\theta}}. \quad (118)$$

$$h^A + h^H + h^Y = h. \quad (119)$$

Initial conditions are:  $a_0, K_0, A_0, N_0, h_0$ .

We obtain the following (initial) steady state values:

$$r = \frac{\sigma g + \rho}{1 - \tau_r}, \quad (120)$$

$$w = A^{\frac{\alpha}{(1-\alpha)(\beta-1)}} (1 - \alpha) \left( \frac{\alpha}{\kappa(1 - s_K)(r + \delta_K)} \right)^{\frac{\alpha}{1-\alpha}}, \quad (121)$$

$$h^H = \left( \frac{1 - \tau_w}{1 - s_H} \frac{\gamma}{(\sigma - 1)g + \rho - n + (1 - \eta)\delta_H} \right)^{\frac{1-\eta}{1-\gamma-\eta}} \left( \frac{\xi}{(\delta_H)^\eta} \right)^{\frac{1}{1-\gamma-\eta}}, \quad (122)$$

$$h = \left( \frac{\xi}{\delta_H} \right)^{\frac{1}{1-\eta}} (h^H)^{\frac{\gamma}{1-\eta}}, \quad (123)$$

$$\Omega = \frac{(1 - \tau_c)(\kappa - 1) \left( \frac{\alpha}{\kappa} \right)^{\frac{1}{1-\alpha}}}{[(1 - \tau_r)r + \psi g_A - (n + g - g_A)(1 - \tau_g)] [(1 - s_K)(r + \delta_K)]^{\frac{\alpha}{1-\alpha}}}. \quad (124)$$

$$h^A = \frac{(1 + \psi)g_A \Omega (h - h^H)}{(1 - s_A) w A^{\frac{\alpha}{(1-\alpha)(\beta-1)}} + (1 + \psi)g_A \Omega}, \quad (125)$$

$$h^Y = \frac{h - h^H}{1 + A^{\frac{\alpha}{(1-\alpha)(\beta-1)}} \frac{(1+\psi)g_A \Omega}{(1-s_A)w}}, \quad (126)$$

$$P^A = \frac{N A^{\frac{\alpha}{(1-\alpha)(\beta-1)-1}} \Omega (h - h^H)}{1 + A^{\frac{\alpha}{(1-\alpha)(\beta-1)}} \frac{(1+\psi)g_A \Omega}{(1-s_A)w}}, \quad (127)$$

$$c = [(\sigma - 1)g + \rho - n]a + (1 - \tau_w)wh - (1 - s_H)wh^H + T, \quad (128)$$

$$T = \tau_w wh + \tau_r r k + \tau_c [\kappa(1 - s_K) - (1 + s_d)](r + \delta_K)k + \frac{\tau_g}{1 - \tau_g} \left( [(1 - \tau_r)r + \psi g_A] P^A \frac{A}{N} - \right. \quad (129)$$

$$\left. A^{\frac{\alpha}{(1-\alpha)(\beta-1)}} (1 - \tau_c)(\kappa - 1) \left( \frac{\alpha}{\kappa} \right)^{\frac{1}{1-\alpha}} [(1 - s_K)(r + \delta_K)]^{-\frac{\alpha}{1-\alpha}} h^Y \right) + \tau_c \left[ P^A (1 + \psi)g_A \frac{A}{N} - (1 + s_R)wh^A \right] - s_H wh^H, \quad (130)$$

$$k = A^{\frac{\alpha}{(1-\alpha)(\beta-1)}} \left( \frac{\alpha}{\kappa [(1 - s_K)(r + \delta_K)]} \right)^{\frac{1}{1-\alpha}} h^Y, \quad (131)$$

$$a = k + \frac{P^A A}{N}. \quad (132)$$

(Also recall that  $g_A = \frac{(1-\theta)n}{1-\phi}$  and  $g = \frac{\alpha g_A}{(1-\alpha)(\beta-1)}$ .)

**Numerical procedure for the optimal dynamic policy mix:** As a reference point of our analysis in Section 6.2, we compute the transition path from the initial steady state to the steady state, implied by the parameters  $(s_R^{opt}, s_d^{opt}, s_H^{opt})$ , which maximize steady state consumption. Obviously, this transition path does not yield the maximum welfare for time-invariant policies. Then, a search algorithm is applied to find a set of parameters, which induces a transition path yielding a higher level of welfare. This transition path starts at the initial steady state and terminates at the steady state implied by the set of test parameters. We then vary one parameter at a time and calculate the implied transition as well as the associated welfare. If this welfare is higher, the reference set of policy parameters is updated accordingly. The procedure is terminated when no further significant improvements in welfare can be achieved.

The parameters are varied stochastically. A deterministic search grid would either lead to a high computational demand (in case of a “fine grid”), or a low accuracy (in case of a “rough grid”). By varying the policy parameters stochastically, the algorithm uses small and large steps to improve welfare.

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