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Government Demand Composition and Innovative Behavior in Industries

Viktor Slavtchev* and Simon Wiederhold+

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Abstract:
This paper investigates industry-level effects of government purchasing behavior. First, we construct an endogenous growth model. We find that by varying the composition of its purchases the government can induce a reallocation of private resources to stimulate R&D and, with it, the rates of technological change and economic growth. We test the model's predictions empirically for the U.S. using a unique dataset that matches industry-level government purchases for the period 1999-2007 to business R&D. Our results indicate that federal procurement spending indeed stimulates company R&D activities.

JEL classification: E62, H54, H57, O31, O32, O41

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* Friedrich Schiller University Jena, Chair of "Business Dynamics, Innovation and Economic Change" and GK-EIC – The Economics of Innovative Change, Carl-Zeiss-Str. 3, D-07743 Jena, Germany, Tel.: +49 3641 943 223, Fax: +49 3641 943 232, E-Mail: viktor.slavtchev@uni-jena.de.

+ Friedrich Schiller University Jena, GK-EIC – The Economics of Innovative Change, Carl-Zeiss-Str. 3, D-07743 Jena, Germany, Tel.: +49 3641 943 263, Fax: +49 3641 943 202, E-Mail: simon.wiederhold@uni-jena.de.

1. Introduction

This paper studies industry-level effects of government purchasing behavior both from a theoretical and from an empirical perspective. In order to shed light on the transition mechanism for government procurement[1] on innovative behavior in industries, we construct a Schumpeterian growth model that accounts for industry heterogeneity in terms of innovation potential. Long-run growth results from quality-improving innovation and is, in particular, driven by the technological composition of government demand. As innovation has been acknowledged to be a key determinant of long-run growth, the link between public demand and innovation is also relevant for economic growth. Our main theoretical result is that, when government purchases are relatively in favor of industries with an above-average potential to innovate, the rate of technological change is stimulated. The mechanism is as follows: a change in the technological composition of public demand spending, privileging industries with potentially higher quality jumps than the average, causes an increase in the expected profits of firms populating these industries. This happens because higher innovation size implies higher markups over marginal cost and, thus, higher reward for successful innovation activities. Innovations are stimulated because firms direct relatively more resources to R&D, which induces a higher demand for R&D labor. The consequence of this increase in the relative size of the R&D sector is an acceleration of technological change, which unfolds a temporarily higher economic growth.

Having theoretically identified the transmission mechanism for government demand spending on innovative behavior at the industry level, we analyze the empirical plausibility of the model's predictions. To the best of our knowledge, this is the first attempt to empirically investigate the inter-industrial composition as opposed to the pure size of government demand expenditure. We construct a panel consisting of annual industry-level observations on company R&D expenditure and R&D employment, total sales, and government sales (i.e., government procurement). Data on company-sponsored R&D expenditure, R&D employment as well as on total sales are taken from the National Science Foundation (NSF). Data on sales to the federal government (more precisely, on the net value of obligations to the firm under federal contract actions) are provided by the U.S. General Services Administration (GSA). Our final dataset covers 25 U.S. industries in the period 1999-2007.

[1] The term "procurement" refers "*to the function of purchasing goods or services from an outside body*" (Arrowsmith 2005, p. 1). If the state is the awarding authority for a procurement contract, "public procurement" takes place. "Public procurement" and "public demand" are treated as being synonymous throughout this paper.

In our empirical analysis, we find support for our model's main implication, namely that a shift in the composition of federal purchases of goods and services toward industries with a relatively high innovation potential (proxied by R&D intensity) stimulates private R&D. This holds for both R&D expenditure and R&D employment. Moreover, when distinguishing between federal contracts for products and services with and without a pronounced R&D component ("R&D procurement" versus "non-R&D procurement"), we show that the positive effect of total procurement on private R&D activities in R&D intensive industries primarily stems from non-R&D procurement. In most empirical specifications, R&D procurement becomes insignificant once we control for non-R&D government purchases. This finding is in line with the theoretical model, which suggests that the main driver of government procurement to affect private R&D is through an increase in the market size. Since the average value of R&D procurement is only about 10 percent of the value of non-R&D procurement, the model predicts a market-size effect for non-R&D procurement considerably stronger than for R&D procurement. Another concern in the empirical estimation is reverse causality; if the government chose its contractors due to their past performance in R&D, we would overestimate the stimulating effect of government procurement on private R&D. In order to tackle the problem of reverse causality, we use the Anderson-Hsiao (1982) Instrumental Variable (IV) estimator. The results are very similar to those obtained in the fixed-effects set-up, suggesting that any reverse causality bias is negligible.

The remainder of the paper is organized as follows. Section 2 provides a brief review of the literature on the innovation-effects of public demand. Section 3 introduces the basic model. We characterize the balanced-growth equilibrium and examine the dynamic response of the economy to a permanent change in the technological composition of government purchases. In the empirical part of the paper, we test the model's main implication, suggesting that reshuffling public demand spending toward industries with relatively higher innovation potential stimulates firms' R&D activities. In section 4 we describe the data and the definition of variables. In section 5 we discuss our findings. Section 6 concludes.

2. The Innovation Impacts of Public Demand – Previous Literature

The paper suggests that the composition of government demand expenditure is an important determinant of firms' innovation activities, thereby contributing to the literature on the role of the demand side for innovation. Research in this field highlights a formidable array of possible explanations for the rate and the direction of technological change being sensible to demand conditions, which can be aggregated to two main grounds. On the one hand, demand "steers" firms to address certain problems (Rosenberg, 1969). Sophisticated users who are well aware of their needs and able to communicate them to the producers enable interaction between firms and users, leading to a decrease of uncertainty in the innovation process (von Hippel, 1982, 1986; Lundvall, 1988; Guerzoni, 2007). On the other hand, the size of the payoff to successful investment in innovation activities determines their attractiveness for firms. In the words of the U.S. sociologist Seabury C. Gilfillan (1935, pp. 58f.): "*Increasing population and/or industry stimulate invention, because they increase the absolute need for a device, and the number of potential finders, while the cost of finding remain the same. There are more mouths to eat the innovation, so to speak, and more eyes to find it*." Schmookler (1962, 1966) uses patent data to show that inventive activity tended to lag behind the peaks and valleys of output of a commodity. From this observation it can be inferred that market demand forces influence shifts in the allocation of resources to inventive activity. Schmookler (1966, p. 206) concludes concisely: "*[…] invention is largely an economic activity which, like other economic activities, is pursued for gain.*"[2] More recently, Gilfillan's and Schmookler's findings have been further explored by Acemoglu & Linn (2004) in their study on the emergence of new drugs. The authors find that a one percent increase in potential market size for a drug category leads to a four to 7.5 percent increase in the number of new drugs in that category entering the U.S. market. Thereby only a handful of the 1,400 new drugs approved over the last forty years have targeted so-called "tropical" diseases like malaria or tuberculosis, although these diseases are responsible for the death of millions of people every year.

Following the widespread recognition of the role of demand in affecting both the rate and direction of innovation, a stream of literature has emerged that focuses on *public* demand. An early study in this context was Project "HINDSIGHT," conducted on behalf of the U.S. Department of Defense (Sherwin & Isenson, 1967; Rothwell & Zegveld, 1982). A review of the development of 710 military innovations led to the key finding that nearly 95 percent of the innovations were motivated by a recognized defense need. Ruttan (2006) and Mowery (2008) go as far as to suggest that most of the general purpose technologies developed in the U.S. in the 20th century either would not have emerged without the impetus from government demand, or only with a considerable delay. Fridlund (2000) and Berggren & Laestadius (2003) attribute the observed major impact of the public sector in Scandinavian countries on

[2] Schmookler's findings are sometimes interpreted as supporting the statement that the primary stimulus for innovation comes from demand on the marketplace rather than being a result of major breakthroughs in science (e.g. Gilpin, 1975; Acemoglu & Linn, 2004). However, as Schmookler's work deals with inventions, not with commercially successful innovations, this extension is illegitimate (see also Mowery & Rosenberg, 1979, pp. 138f.).

the development of Nordic telecommunication to so-called “development pairs”[3] defined as a long-term relation between industry and customers from the public sphere.[4] Moreover, Scandinavian governments often set challenging novelty requirements and insisted on the development of technical advances while the respective private counterpart hesitated. Complementing these case study results, quantitative studies at the firm level of the influence of public demand on innovation typically support the conjecture that the size of public markets can provide an enormous stimulus to innovation (Lichtenberg, 1987 and 1988; Aschhoff & Sofka, 2009). However, existing evidence concerning the influence of the government as a market on private R&D and innovation behavior is limited and fragmentary. We are not aware of any previous econometric studies investigating the inter-industrial composition as opposed to the pure value of government demand expenditure. However, as will be shown below government procurement is not uniformly distributed across industries, and there might be pronounced industry-level differences in the impact of procurement on companies’ innovative behavior.

In general, several factors can be identified why government demand might be critical for innovation. First, the total magnitude of government purchasing is considerable. In the U.S., the average size of public procurement markets amounted to around $520 billion in 2008, which is equivalent to about 3.6 percent of U.S. GDP. The European Union experienced a particularly pronounced growth of procurement volume since 1995. EUROSTAT data indicates that EU-15 procurement expenditure as a percentage of GDP more than doubled in the period 1995-2006, increasing from 1.41 percent to 3.15 percent. Although this figure is already non-negligible, it can be expected that the magnitude of public demand expenditure is significantly higher in reality. EUROSTAT data reflects government procurement subject to the obligations established by EU directives, which is only a fraction of total public procurement markets (EU, 2004).[5]

Second, regarding the role of government demand, one line of argumentation rests on the importance of the inter-industrial composition of public purchases. Government demand is likely to affect decision making within supplier firms, particularly with respect to investment in R&D, since in a number of industries the public sector is the first user of innovations, patents, and products (Dalpé et al., 1992). In general, public demand frequently constitutes a

[3] Development pairs are one form of an innovation network, which is usually regarded to be conducive to user-producer interaction and interactive learning (Lundvall, 1988; Powell & Grodal, 2004).
[4] Eliasson (2010) discusses thoroughly the case of Ericsson as being a major beneficiary from positive spillovers of government procurement in the Swedish aircraft industry. Moreover, for the whole Swedish economy during the period from 1982 through 2007, Eliasson estimates the economic value of spillovers from Swedish aircraft procurement to be at least 2.6 times as high as the original development investment.
[5] In general, estimates of the importance of public procurement for OECD economies vary depending on the methodology used for their calculation and on the definition of procurement employed (Audet, 2002).

large fraction of total demand in industries of significant technological content, such as environmental protection and medical equipment (Edquist & Hommen, 2000; Edler & Georghiou, 2007). In some industries, however, government purchases comprise a relatively small portion of overall demand (Ramey & Shapiro, 1998; Marron, 2003). The above figures on the quantitative relevance of public procurement become even more impressive when it is taken into account that government purchases are often concentrated in few specific markets.

Third, another viewpoint comes into play that addresses the interrelation between the demand and supply side. In various cases, the government acted as a demanding customer that was both willing and able to interact with supplier firms. It did not restrict its activity to the passive role of providing market incentives but actively showed inventors a beneficial path to pursue in their research efforts.

In essence, various studies that argue empirically suggest a significant impact of public demand spending on private innovation activities. However, of the several factors that drive this result we focus on government procurement as being part of the economic conditions affecting the profitability of innovations. Specifically, we develop an innovation-driven Schumpeterian growth model that allows us to investigate how the inter-industrial composition of public demand influences industry-level innovative behavior and, with it, the pace of both technological change and economic growth.

3. The Model

Our model is primarily inspired by Cozzi & Impullitti (2010). We maintain the basic ingredient of Cozzi and Impullitti's model, namely that the economy is populated by a continuum of heterogeneous industries. This allows us to account for the observable fact that government demand is not uniformly distributed across industries. In one crucial aspect we deviate from Cozzi and Impulliti, namely by imposing a specific assumption on how industries differ in terms of their innovation capacity. In this we draw upon the recent contribution by Minniti et al. (2008) who model the size of innovation as being Pareto distributed. This extension allows a more rigorous analytical treatment of the model compared to Cozzi and Impullitti. We can explicitly solve for the balanced-growth path (hereafter BGP) of the economy and for the transitional dynamics that lead to the BGP. In addition, we are able to make a normative statement on the optimality of the BGP in the decentralized economy and show

how the government can ensure social optimum by adjusting the allocation of its demand expenditure across industries.[6]

3.1 Description of the Model Economy

The economy in the model is closed and consists of two sectors – a final goods (or manufacturing) sector and a research sector where firms seek for innovations. To avoid unnecessary complications and highlight the basic forces at work, labor is the only input factor used in both sectors and is not further differentiated. Labor supply decisions are treated as being exogenous.

As is standard in the Schumpeterian growth literature, there is a continuum of industries in the unit interval indexed by $\omega \in [0,1]$ in the economy under consideration. Each industry produces exactly one consumption good (or product line). The outputs of the various industries substitute only imperfectly for each other. As expansion of variety is not the focus of our model, the set of commodities is fixed in the progress of time. Vertical innovations improve the quality of the respective consumption good. Let the discrete variable $j \in \{0,1,2,...\}$ denote the quality level. Each innovation in industry ω leads to a jump in quality of the product in question from j to $j+1$. The quality increments, denoted by λ, happen independently of each other – an improvement in one industry does not induce an improvement in any other industry. This idea can be illustrated by the metaphor of a quality ladder.

Following the specification introduced by Grossman & Helpman (1991a and 1991b), in a given point in time a good ω possesses a quality level of λ^j if j quality jumps of size λ have happened so far. At time $t=0$, the state-of-the-art quality product in each industry is $j=0$; that is, one firm in each industry knows how to produce a $j=0$ quality product, and no firm knows how to produce any higher quality product. Further, in $t=0$ the quality of each good equals unity, i.e., $\lambda^0 = 1$. Over time, state-of-the art quality follows a progression up a quality ladder. Each step up the ladder, however, requires intentional R&D efforts by firms.

In previous Schumpeterian growth models (Grossman & Helpman, 1991a and 1991b; Aghion & Howitt, 1992; Segerstrom, 1998; Li, 2001 and 2003), different industries were usually treated as being structurally identical so that the economy could be regarded as if it consisted of only a single industry. Therefore, these approaches are only suitable when

[6] The derivation of the social optimum is available from the authors upon request.

growth is analyzed on the macro level but cannot account for industry-specific effects of demand pull and technology push in the multitude of existing industries.[7]

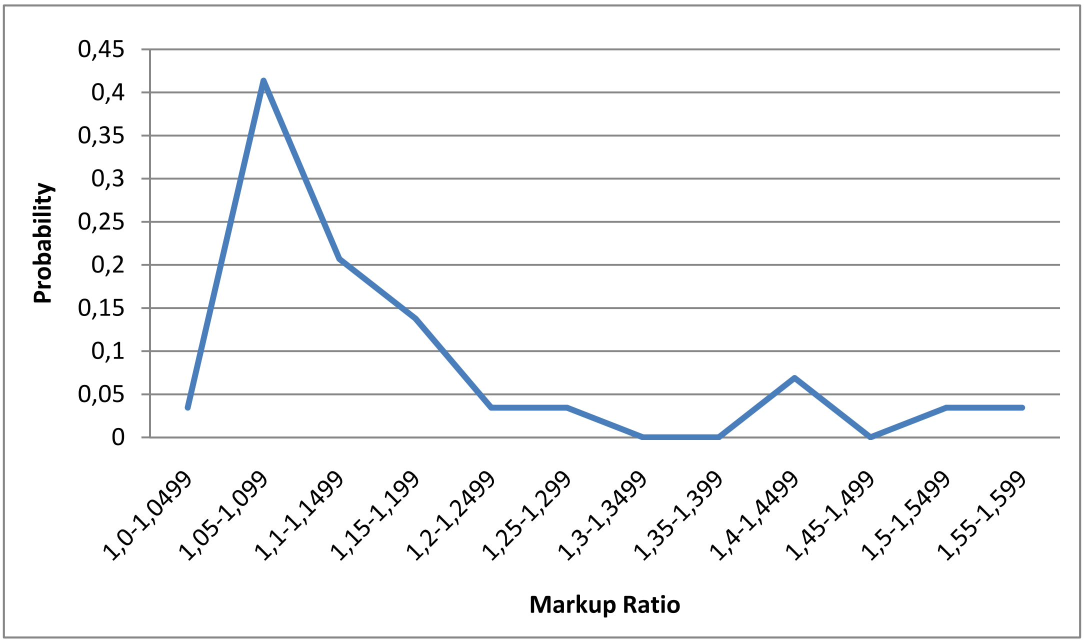
In order to overcome the symmetric treatment of industries, we assume the size of the quality jump after a successful innovation as being uncertain and industry-specific. In line with the recent work by Minniti et al. (2008), the realization of each R&D race is drawn independently from a Pareto distribution. Modeling uncertainty associated with the size of the quality jump to obey a Pareto distribution is supported by the patent literature. Scherer (1965) analyzes patent activities of the 500 largest firms in the U.S. and finds that the distribution of U.S. patent values (measured by profit returns) is highly skewed toward the low-value side, and heavy tailed to the high-value side. This evidence fits to the generic properties of a Pareto distribution quite well. Successive empirical work on patent values and citations often found the Pareto distribution as being accurate in describing the data. Harhoff et al. (2005), for instance, ask patent holders in Germany and in the U.S. to estimate the value of their inventions. The distribution of values yielded by this survey is strikingly close to the Pareto distribution for a wide range of patent values.[8]

The rationale to utilize the Pareto distribution for capturing heterogeneity on the industry level in a Schumpeterian growth model lies in the fact that this stream of models rests on the assumption that for each successful innovation a patent is granted. Moreover, the size of the quality jump associated with a successfully innovating firm affects its profitability for the innovator. For these reasons, empirical results indicating that patent values often follow a Pareto distribution are well suited to be applied to our model economy.

Even more support for Pareto distributed innovation size can be derived from the empirical literature on markups of product prices over marginal cost. Schumpeterian growth models share the feature that quality jumps are understood as an indicator of monopoly power in an industry. More precisely, the quality jump is usually modeled as being equal to the markup of goods prices over marginal cost that a quality leader can charge. Oliveira Martins et al. (1996) estimate markups for 2-digit U.S. manufacturing industries for the period 1970-92. In Figure 1, we plot a stylized probability density function of their data.

[7] The industrial organization literature presents overwhelming empirical evidence that the innovative behavior of firms varies across industries (Stadler, 1999). Geroski (1998) finds a considerable amount of heterogeneity on the firm level that does not disappear over time.

[8] Within a slightly different methodological framework, Kortum (1997) and Jones (2005) model the realization of new ideas (interpreted as productivity levels and production techniques, respectively) as being Pareto distributed.



Source: Own illustration, using data by Oliveira Martins et al. (1996, p. 30)

Figure 1: Stylized probability density function of U.S. markup ratios

It is apparent that the distribution of markups is right-skewed; the mass of the distribution is below the average economy-wide markup (equal to 1.17). In fact, only one third of the industries turn out to have a markup above the mean.

3.2 Consumers

Each household is modeled as a dynastic family whose size grows over time at an exogenous rate n which also equals the rate of population growth. Each household member inelastically supplies labor services in exchange for wages. We normalize the total number of individuals at time $t=0$ to unity, by appropriate choice of unit. Thus, the population of workers at time t equals $L(t)=e^{nt}$. Intertemporal preferences of the representative household are given by:[9]

$$U=\int_0^\infty e^{nt}e^{-\rho t}\log u(t)dt\,, \tag{1}$$

where $\rho>0$ denotes the rate of time preference, and $\log u(t)$ represents the flow of utility per household member at time t. Notice that the assumption $(\rho-n)>0$ is needed to ensure convergence of the utility integral. Any individual's instantaneous utility is represented by:

[9] Our infinite-horizon representative agent framework can be justified by referring to Barro (1974). However, Kirman (1992) points out some critical aggregation issues involved here.

$$\log u(t) = \int_0^1 \log\left[\sum_{j=0}^{j^{\max}(\omega,t)} \lambda^j(\omega,t)\, d(j,\omega,t)\right] d\omega . \quad (2)$$

Equation (2) describes Cobb-Douglas consumer preferences, where $d(j,\omega,t)$ is the consumption of quality j in product line ω at time t. The utility derived by an individual from consumption is therefore determined by the quality-weighted amount of consumption, integrated (because we have a continuum of industries) over all industries $\omega \in [0,1]$. This formulation of instantaneous utility implies that a consumer enjoys one unit of good ω that was improved j times as much as she would enjoy $\lambda(\omega,t)^j$ units of the good if it had never been improved, with $\lambda(\omega,t) > 1$.

The static utility function (2) contains the sum $\sum_{j=0}^{j^{\max}(\omega,t)} \lambda(\omega,t)^j\, d(j,\omega,t)$. It follows that, hypothetically, all existing quality levels ($j = 0,1,2...,j^{\max}$) of each product line could be consumed at a given point in time. However, we show later that in each product line only the good with the lowest quality-adjusted price will face demand.

The representative household maximizes lifetime utility (1) subject to the following intertemporal budget constraint:

$$B(0) + \int_0^\infty w(s) e^{-\int_0^t [r(\tau)-n]d\tau} ds - \int_0^\infty e^{-\int_0^t [r(\tau)-n]d\tau} T(s) ds = \int_0^\infty e^{-\int_0^t [r(\tau)-n]d\tau} c(s) ds , \quad (3)$$

where $B(0)$ is the ex ante endowment of asset holdings of the representative household, $w(t)$ is the wage rate earned by each individual, $T(t)$ is a per capita lump-sum tax and $c(t)$ is the flow of individual consumer expenditure. Consumer spending is given by:

$$c(t) = \int_0^1 \left[\sum_{j=0}^{j^{\max}(\omega,t)} p(j,\omega,t) d(j,\omega,t)\right] d\omega ,$$

where $p(j,\omega,t)$ is the price of product ω with quality j at time t.

The household maximization problem is solved in three stages: first, the allocation of expenditure at any given point in time for each product across available quality levels; second, the allocation of expenditure on the different product lines ω; and, third, the time path of expenditure such that intertemporal utility reaches a maximum.

It can be easily shown that an individual is indifferent between quality vintage j and $j-1$ if $p(j,\omega)/p(j-1,\omega) = \lambda(\omega)$. If the quality leader in industry ω charges a price marginally below $\lambda(\omega)$, the next best quality faces no demand. The elasticity of substitution between goods of different quality vintages within the same industry is infinite. To break ties, we make the assumption that if a household member is indifferent between two quality vintages, she will buy the higher quality product.

From the formulation of the consumption index in (2) it follows that goods of different vintages in each industry are perceived as perfect substitutes, once the quality adjustment is made. As already noted, products of different industries enter utility symmetrically, and the elasticity of substitution between every pair of industries equals minus one. This yields the static demand functions:

$$d(j,\omega,t)=\begin{cases}\dfrac{c(t)}{p(j,\omega,t)} & j=j^{max}(\omega,t)\\ 0 & \text{otherwise}\end{cases} \tag{4}$$

The dynamic optimization problem, i.e., the allocation of lifetime expenditure over time, consists of maximizing discounted utility (1) subject to (2), (3), and (4). The solution of the optimal control problem obeys the Keynes-Ramsey rule:

$$\frac{\dot{c}(t)}{c(t)}=r(t)-\rho\,. \tag{5}$$

This intertemporal optimization condition implies that a constant consumption expenditure path is optimal when the market interest rate is equal to ρ. A rate above ρ induces consumers to increase savings "today" and spend more "tomorrow," resulting in a rise of consumption over time.

Since preferences are homothetic, aggregate demand at time t in industry ω, denoted by $D(j,\omega,t)$, is given by $D(j,\omega,t)=d(j,\omega,t)L(t)$.

3.3 Product Markets

The constant returns to scale production function $Y=L_Y$ holds for *any* quality level in industry ω. The firms within each industry compete over prices. Only a single firm possesses the technology to produce the highest quality product, while its product has a quality advantage of λ over the next best quality in the industry. The optimal strategy for the quality leader is to set the *limit price* $p_L(\omega,t)$, preventing any other firm in the industry from offering its product without losses (Grossman & Helpman, 1991a and 1991b; Segerstrom, 1998).[10] The

[10] Note that Li (2001, 2003) as well as Minniti et al. (2008) develop quality-ladder models in which the producer of the state-of-the-art quality can charge the unconstrained monopoly price. Whether or not she can do that and still leaves no positive profit to producers of previous vintages depends on the size of the quality jump and the degree of substitutability of different vintages. Aghion & Howitt (1998, chap. 2) label as "drastic innovation" the

quality leader will set a quality-adjusted price below the unit costs of its nearest competitor, while that competitor will come up with a price equal to its own marginal cost. Hence the highest price the quality leader can set to capture the entire industry market is its lead over the next best quality follower, implying $p_L(\omega,t) = \lambda(\omega,t)w = \lambda(\omega,t)$.[11] There is no incentive for the quality leader to set a price above the limit price because if she did, she would lose all of its customers.

We now introduce government demand (i.e., government procurement spending) into the model. Per capita public demand spending in industry ω at time t is denoted by $G(\omega,t) \geq 0$, for all $\omega \in [0,1]$ and $t \geq 0$. Because we wish to isolate wealth effects from the distortionary effects of taxation, we assume that the government uses lump-sum tax revenues to finance its procurement expenditure. We further assume that the government balances its budget at any time. To avoid unnecessary complications, we abstract from modeling any effects of public demand expenditure on individual utility or on marginal productivity of private input factors in manufacturing or research.

Since static consumer demand (4) is unit elastic and the quality leader charges a price of $\lambda(\omega,t)$ both for private consumers and the government, the quantity of a state-of-the-art quality product in each industry ω sold to private consumers equals $L(t)c(t)/\lambda(\omega,t)$, while public demand for products at the quality frontier in each industry ω is equal to $L(t)G(\omega,t)/\lambda(\omega,t)$. Given that marginal production cost are unity (recall that labor is the numeraire), the quality leader in each industry ω earns a profit flow of:

$$\pi(\omega,t) = \left\{ \left[\lambda(\omega,t) - 1\right] \frac{c(t)L(t)}{\lambda(\omega,t)} + \left[\lambda(\omega,t) - 1\right] \frac{L(t)G(\omega,t)}{\lambda(\omega,t)} \right\}. \tag{6}$$

In equation (6), $\left[\lambda(\omega,t) - 1\right]$ is to be interpreted as the markup factor over marginal cost. Thus, the parameter $\lambda(\omega,t)$ describes the degree of monopoly power.

3.4 R&D Races

Free entry into each R&D race prevails so that firms may target their research effort at any industry. Labor is the only input used in R&D and can be freely allocated between manufacturing and research. The frictionless nature of the labor market implies that workers earn

case when the monopoly price can be set and the producers of the next best qualities are still squeezed out of the market as well as the case when the limit price is set as “non-drastic innovation”.

[11] Limit pricing obviously leads to tension between static and dynamic optimality (static optimality requires marginal cost pricing). But without positive profits innovation would cease, and so would growth.

the same wage in R&D as in manufacturing, $w=1$. Firms conduct R&D activities in industries in which they are not the current quality leader. This excludes the case in which a firm producing the current state-of-the-art quality in industry ω accumulates patents in that industry.[12] The aim of each firm's R&D efforts is a superior quality and to monopolize the market by achieving a patent (with infinite patent length). All firms have access to the same R&D technology. In industry ω at time *t*, a firm engaged in R&D that employs $l_i(\omega,t)$ units of labor faces a Poisson arrival rate of innovation, $I_i\left(\omega,t\right)$, equal to:

$$I_i(\omega,t)=\frac{Al_i(\omega,t)}{X(\omega,t)}, \tag{7}$$

where $A>0$ is a given technology parameter, and $X(\omega,t)>0$ is a function that captures the difficulty of conducting R&D, taken as given by each R&D firm. The "innovation production function" as specified in (7) takes into account the stochastic in the R&D process. For firm *i* in industry ω, lagging behind the state-of-the-art quality at time *t*, $I_i(\omega,t)dt$ indicates the probability to win the R&D race and become the next quality leader within the time interval $[t,t+dt]$. In (7), the time interval dt approaches zero. Hence $I_i(\omega,t)$ is to be interpreted as the instantaneous probability of firm *i* being successful in finding the next higher quality product per unit of time.

We can conveniently aggregate across firms to obtain the industry-wide arrival rate of innovation by assuming that the probability of winning an R&D race is independent across firms, across industries, and over time. It follows that (7) holds for each firm at any time irrespective of the workforce employed intra- or inter-industrially. The industry-wide arrival rate of innovation reads:

$$I\left(\omega,t\right)=\frac{AL_I\left(\omega,t\right)}{X\left(\omega,t\right)} \tag{8}$$

where $L_I(\omega,t)=\sum_i l_{I,i}(\omega,t)$ denotes the industry-wide R&D labor employment, and $I(\omega,t)=\sum_i I_i(\omega,t)$ is the cumulated arrival rate of innovation of all firms in industry ω at time *t*.

[12] The effect that monopolists may systematically have less incentive to innovate than potential rivals, eventually ceding technological leadership, was first described by Arrow (1962) and is a common feature in the literature of Industrial Organization (Fudenberg et al., 1983; Fudenberg & Tirole, 1985) as well as of R&D-driven endogenous growth models. The occurrence of this effect can be explained as follows. A two-step quality advantage of the monopolist comes along with smaller profits than the gain of a one-step quality improvement in another industry. Therefore, the monopolist will direct all R&D resources to other industries to become the market leader there. As it is the dominant strategy for quality leaders not to invest in further improving their technology, the monopoly will only remain as long as no better technology is found in the R&D sector.

The empirically uncomfortable "scale effect" property[13] of early R&D-driven endogenous growth models (Romer, 1990; Grossman & Helpman, 1991a and 1991b; Aghion & Howitt, 1992) is removed by assuming that R&D difficulty grows in each industry at a rate proportional to the arrival of innovation (Segerstrom, 1998):

$$\frac{\dot{X}(\omega,t)}{X(\omega,t)} = \mu I(\omega,t), \tag{9}$$

where $\mu > 0$ is exogenously given and $X(\omega,0) = X_0$ for all ω. An ever increasing R&D difficulty, as formalized in equation (9), reflects the idea of rational behavior of R&D firms (Li, 2003). During each R&D race, firms may choose between an infinite array of research projects with varying degree of R&D difficulty, $X(\omega,t)$. While the most promising research projects are tried first, these may fail, making firms switch to less promising projects with a higher degree of R&D difficulty. With this in mind, innovating becomes more difficult over time and technological opportunities vanish because of a series of research failures.

This idea of "fishing out" of innovations, which causes a fall in relative productivity of R&D inputs, is consistent with empirical observations. Because Schumpeterian growth models are characterized by the assumption that a steady part of innovations (in fact 100 percent) is patented, patent statistics can be a natural judge of these models. In the second half of the 20th century, patents granted in the U.S. to residents showed a certain degree of stability, fluctuating around 40,000-50,000 per year, while the number of researchers increased greatly. This implies a sharp decrease in patent-to-researcher ratio (Kortum, 1997). Segerstrom (2000, Table 1) finds a comparable development of the patent-to-researcher ratio for a number of highly developed countries such as the U.S., France, Japan, Sweden, and Great Britain.[14]

Once a firm becomes successful in finding an innovation, the size of that innovation is drawn from a Pareto distribution with shape parameter $1/\kappa$ and a scale parameter equal to one.[15] The probability density function of a Pareto distribution with these properties reads:

$$g(\lambda) = \frac{1}{\kappa}\lambda^{-\frac{1+\kappa}{\kappa}}, \quad \lambda \in [1,\infty), \tag{10}$$

where $\kappa \in (0,1)$ is a parameter that measures the degree of dispersion or heterogeneity of the Pareto distribution. The higher κ, the fatter the upper tail of the distribution of quality incre-

[13] "Scale effect" here means a positive relationship between the long-run growth rate of the economy and the population size. Its underlying intuition has been nicely described by Jones (2004, p. 14): "*A larger population means more Mozarts and Newtons, and more Wright brothers, Sam Waltons, and William Shockleys.*" Empirical studies, however, typically reject such population size level effects (see especially Jones, 1995a).

[14] Benjamin F. Jones (2005) sheds some light on the consequences of an ever rising R&D difficulty for the organization of innovation activity. The author analyzes U.S. patent data and presents evidence on inventors striving for narrower, more specialized expertise and showing a greater reliance on teamwork.

[15] We here adopt the specification used in Minniti et al. (2008).

ments. The median of the Pareto distribution equals 2^{κ} and the mean is given by $1/(1-\kappa)$. Both median and mean increase in κ, while the mean is always larger than the median.

For analytical tractability, and to make the analysis of transitional dynamics less tedious, we assume that the initial distribution of λ values is given by $g(\lambda)$ at $t=0$. Then, as the R&D dynamics start off and successfully innovating firms draw new values of λ, the distribution of λ values does not change over time. Notice further that $X(\omega,t)=X_0$ for all ω means $I(\omega,0)=I_0$ (constant) for all ω. Hence a symmetric equilibrium path must exist along which $I(\omega,t)=I(t)$ and $X(\omega,t)=X(t)$ for all ω. As Grossman & Helpman (1991a and 1991b), Segerstrom (1998), Li (2003) and Minniti et al. (2008), we focus on this symmetric equilibrium.

We are now in the position to derive the optimal amount of labor $l_i(\omega,t)$ that each firm *i* employs in R&D. Let $\upsilon^e(\omega,t)$ be the expected discounted reward for R&D successes in industry ω at time *t*. By hiring $l_i(\omega,t)$ units of labor in R&D for a time interval dt, firm *i* expects to realize $\upsilon^e(\omega,t)$ with probability $I_i(\omega,t)$. The optimization problem to be solved by firm *i* at each point in time can then be written as:

$$\max_{l_i} \upsilon^e(\omega,t)\frac{Al_i(\omega,t)}{X(t)}-l_i(\omega,t).$$

Profit maximization yields the first order condition for an interior solution:

$$\upsilon^e(\omega,t)=\frac{X(\omega,t)}{A}. \tag{11}$$

The RHS of (11) is equivalent to the marginal effective cost of innovating. Equation (11) implies that the expected reward for a successful innovation, $\upsilon^e(\omega,t)$, has to increase when R&D difficulty grows in order to provide sufficient incentives for firms to participate in an R&D race. Only if (11) holds for all ω, can a symmetric equilibrium exist, where the innovation rate $I(t)$ is positive, finite, and the same across all industries. In the next section, we determine the expected value of the uncertain profit stream of finding a product of superior quality, $\upsilon^e(\omega,t)$.

3.5 *Stock Market and Specification of Public Demand*

Firms that participate in an R&D race issue securities on a perfect financial market.[16] R&D-performing firms are thus financed by consumers' savings channeled to them through the stock market. Thus, consumers are allowed to choose the R&D sectors where to employ their savings by buying securities. The claims pay nothing in the event that research efforts fail, but entitle the claimants to the income stream associated with quality (and industry) leadership if the efforts succeed.[17] In addition to the (risky) investment in R&D-performing firms, consumers can also buy a risk-free bond with the rate of return $r(t)$. The interest rate $r(t)$ adjusts to clear the capital market at each moment in time. The absence of profitable arbitrage opportunities makes the expected rate of return on securities issued by R&D firms equal to the risk-free rate of return $r(t)$. The no arbitrage condition for the stock market is then given by (Blanchard & Fischer, 1989, p. 215):

$$\frac{\pi^e(\omega,t)}{\upsilon^e(\omega,t)}dt+\frac{\dot{\upsilon}^e(\omega,t)}{\upsilon^e(\omega,t)}(1-I(t)dt)dt-I(t)dt=r(t)dt\,, \tag{12}$$

where $\pi^e(\omega,t)$ denotes the expected profits earned by a successful innovator.

The first term on the LHS of (12) describes the accrued dividend paid to the consumers during time interval dt. The second term shows possible capital gains of a firm's share. However, the value of the quality leader will only appreciate if the respective quality leader is able to maintain her position – this happens with a probability $1-I(t)dt$. The third term represents the capital loss shareholders will suffer in case a better quality is found during the time interval dt. Because a producer of the latest quality vintage who loses her leadership due to a new innovation is immediately squeezed out of the market – causing her stock value to shrink to zero instantly – shareholders lose everything in this case. The third term is thus equal to the probability of the arrival of an innovation per unit of time, $I(t)dt$. The RHS of (12) describes the alternative investment in a safe bond.

Dividing (12) by dt and calculating the limit $dt\to 0$ yields:

$$\frac{\pi^e(\omega,t)}{\upsilon^e(\omega,t)}+\frac{\dot{\upsilon}^e(\omega,t)}{\upsilon^e(\omega,t)}=r(t)+I(t)\,. \tag{13}$$

[16] In other words, all moral hazard and adverse selection problems which – as empirical observations imply – exist mainly for young firms when they attempt to raise capital funds for risky R&D investments, are completely neglected. The integration of imperfect capital markets is a primary aim of newer models of endogenous growth (e.g., King & Levine, 1993; Aghion & Howitt, 2005).

[17] As there is no physical capital in the economy, shares of R&D-performing firms are the only existing commercial paper.

In the stock market equilibrium, the expected dividend rate plus the expected rate of capital gains is equal to the rate of return of the risk-free security plus a risk premium. An expression for $\dot{\upsilon}^e(\omega,t)/\upsilon^e(\omega,t)$ can be obtained by using (11), and the dividend rate becomes:

$$\frac{\pi^e(\omega,t)}{\upsilon^e(\omega,t)} = r(t) + I(t) - \frac{\dot{X}(t)}{X(t)}.$$

Before we can derive an expression for the expected profits of a firm winning an R&D race, $\pi^e(\omega,t)$, we have to be more concrete on how the government allocates its demand expenditure among the various industries in our model economy.

Once a firm wins an R&D race in industry ω, the government observes the realized quality jump and then decides how much to purchase from the new quality leader. Specifically, we model public demand spending as a linear combination of two rules. On the one extreme, there is a perfectly symmetric rule in which each industry in the economy faces the same government demand. On the other extreme, there is a rule that allocates public spending in proportion to the quality jump that occurs in a particular industry; the higher the quality jump in industry ω, the more the successful innovator in this industry benefits from public demand. Formalizing this idea yields the following public demand rule:

$$G(\omega,t) = (1-\gamma)\bar{G} + \gamma\left(\bar{G} + \varepsilon\right),\ 0 \le \gamma \le 1 \tag{14}$$

where $\bar{G} \equiv \int_0^1 G(\omega)d\omega$, $\varepsilon \equiv \begin{cases} -\varepsilon_1 & \text{for } \lambda(\omega,t) < \dfrac{1}{1-\kappa} \\ \varepsilon_2 & \text{for } \lambda(\omega,t) \ge \dfrac{1}{1-\kappa} \end{cases}$ as well as $0 < \varepsilon_1 < \bar{G}$ and $0 < \varepsilon_2 < \bar{G}$.

The demand policy rule (14) necessitates some further remarks. In (14), $\bar{G}$ denotes the average per capita public procurement, i.e., the value of public demand spending a quality leader in each industry ω would receive if the government spread its expenditure $G(\omega)$ evenly across all industries. However, treating all industries equally is not the only option for the government to spend its financial resources in our model. Any increase in the fiscal policy parameter γ will lead to a public demand policy that more heavily promotes industries with above-average quality jumps.[18] This second part of (14) can be nicely interpreted if, just for illustrative purposes, we assume $\gamma = 1$. This would mean that if the quality increment coming along with an innovation in industry ω is smaller than the average economy-wide quality increment, public purchases in this industry are lower than they would have been if the government had distributed its expenditure symmetrically over all industries. On the other hand,

[18] This becomes even more obvious when one observes that (14) can be rewritten as $G(\omega,t) = \bar{G} + \gamma\varepsilon$.

if an innovator in industry ω drew a value of λ above the average quality jump, she would benefit more from public spending than under the perfectly symmetric demand policy rule.

It is worth stressing that (14) imposes a "bang-bang solution" on public demand expenditure.[19] For each $\gamma > 0$, once an industry experiences a quality jump above (below) economy-wide average, the government abruptly spends more (less) in this industry, irrespective of how far beyond the average this industry finds itself after the quality jump. It is easy to show that the strictly positive values ε_1 and ε_2, which indicate how much government spending in "low-jump" respectively "high-jump" industries deviates from average spending, cannot be chosen independently.[20]

As stated above, the distribution of λ values does not change over time. Thus, although there is uncertainty at the industry level concerning the size of the quality jump that occurs after an innovation arrives, there is always the same share of industries with quality increments above respectively below average at the macro level. Moreover, we make the simplifying assumption that average per capita public demand expenditure, $\bar{G}$, is fixed in the progress of time.

After solving for the expected profits of a firm winning an R&D race by taking into account (14)[21] we obtain an expression for $\upsilon^e(\omega, t)$:

$$\upsilon^e(\omega, t) = \frac{\frac{\kappa}{1+\kappa} L(t)\left(c(t) + \bar{G} + \gamma\Gamma\right)}{r(t) + I(t) - \frac{\dot{X}(t)}{X(t)}}, \tag{15}$$

where $\Gamma \equiv \varepsilon_2 \left\{ 1 \big/ \left[1 - (1-\kappa)^{1/\kappa} \right] - 1 \right\}$ is a strictly positive value. In (15), an innovator's profits are discounted using the risk-free rate of return $r(t)$ and the instantaneous probability that the firm loses its leadership position, $I(t)$, adjusted by the increase in R&D difficulty over time, $\dot{X}(t)/X(t)$. Here the effect of "creative destruction" is revealed: the more research (is expected to) occur in an industry, the shorter, *ceteris paribus*, the expected duration of the monopoly profits and the smaller the incentive to innovate.

We now define a new endogenous variable that serves as a measure of relative (i.e., population-adjusted) R&D difficulty: $x(t) \equiv X(t)/L(t)$. We can then express (15) as:

[19] Bang-bang solution is a term used in optimal control theory. If the optimal control switches from one extreme to the other at certain times (i.e., is never strictly in between the bounds) then that control is referred to as a bang-bang solution.
[20] See App. A for a formal derivation of the parameter restriction.
[21] The mathematical details are relegated to App. B.

$$\upsilon^{e}\left(\omega,t\right)=\frac{\frac{\kappa}{1+\kappa}L(t)\left(c(t)+\bar{G}+\gamma\Gamma\right)}{r(t)+I(t)-\frac{\dot{x}(t)}{x(t)}-n}. \tag{16}$$

By subtracting the rate of population growth, *n*, in the denominator of (16), we also take into account that aggregate consumer markets, and thus profits earned by a successful innovator, increase over time. Notice that (16) also holds outside the balanced-growth equilibrium derived below.

Combing equations (11) and (16) and recalling that $x(t)\equiv X(t)/L(t)$ gives us the following *R&D equilibrium condition*:

$$\frac{x(t)}{A}=\frac{\frac{\kappa}{1+\kappa}\left(c(t)+\bar{G}+\gamma\Gamma\right)}{r(t)+I(t)-\frac{\dot{x}(t)}{x(t)}-n}. \tag{17}$$

Profit maximization of R&D firms imposes that in the research equilibrium the marginal revenue product of an innovation [RHS of (17)] must equal its marginal cost [LHS of (17)] at each point in time.

3.6 Labor Market

Labor demand in manufacturing equals aggregate demand from both private and public consumers (recall that the production function in manufacturing reads $Y=L_Y$ and that we assume market clearing). Total employment in manufacturing is then given by:

$$L_Y(t)=\int_0^1\left\{\frac{c(t)L(t)}{\lambda\left(\omega,t\right)}+\frac{G\left(\omega\right)L(t)}{\lambda\left(\omega,t\right)}\right\}d\omega$$

$$=\int_0^1 L(t)\left\{c(t)\int_1^\infty\lambda^{-1}g\left(\lambda\right)d\lambda+\int_1^\infty G\left(\omega\right)\lambda^{-1}g\left(\lambda\right)d\lambda\right\}d\omega .$$

Using the Pareto density function given in (10) as well as the public demand rule as specified in (14) and (A.3), total employment necessary to satisfy private and public consumers' demand for the consumption good can be calculated as:

$$L_Y(t)=L(t)\frac{c(t)+\bar{G}-\gamma\kappa\Gamma}{1+\kappa}.$$

An equation for R&D labor can be derived from solving (8) for the R&D input of a firm in industry ω, then aggregating over the continuum of industries $\omega\in[0,1]$, while taking into account that we assume symmetric behavior, where the industry-level innovation rate $I(\omega,t)$ is the same across industries at each point in time. We obtain:

$$L_I(t) = \frac{I(t)X(t)}{A}.$$

Labor-market clearing implies that $L(t) = L_Y(t) + L_I(t)$ is always fulfilled, which, when slightly rewritten, gives the *resource constraint* of the economy:

$$1 = \frac{c(t) + \bar{G} - \gamma\kappa\Gamma}{1+\kappa} + \frac{I(t)x(t)}{A}. \tag{18}$$

The labor market equilibrium in (18) holds for all *t* outside the BGP by assumption that factor markets clear instantaneously. Equation (18) completes the description of the model.

3.7 Balanced-Growth Equilibrium

We now solve for the BGP of the model, where all endogenous variables grow at a constant (although not necessarily at the same) rate and research intensity $I(t)$ is common across industries. According to (8), constant growth rate of R&D difficulty *X* constrains *I* to be constant over time. For that reason, $\dot{x}/x = \dot{c}/c = 0$ is implied by (18). Then, $r(t) = \rho$ prevails by (5), meaning that the market interest rate must be equal to the rate of time preference in the BGP. Equations (9), (17), and (18) represent a system of three equations in three unknowns x, c, and I. Solving this system of equations allows us to uniquely determine balanced-growth equilibrium values for all endogenous variables.

We first derive an expression for the equilibrium research intensity. Taking the logarithm of the RHS of (8) and differentiating with respect to time yields, using (9):

$$I^* = \frac{n}{\mu}. \tag{19}$$

According to equation (19), the balanced-growth value of the research intensity is completely pinned down by the population growth rate, *n*, and the parameter governing the R&D difficulty, μ.

Having determined the equilibrium value of *I*, we are now in the position to solve for the balanced-growth values of x and c. Given that $I^* = n/\mu$ and $r = \rho$ in the balanced-growth equilibrium, R&D equilibrium condition (17) can be written as:

$$\frac{x(t)}{A} = \frac{\frac{\kappa}{1+\kappa}\left(c(t) + \bar{G} + \gamma\Gamma\right)}{\rho + n\left(\frac{1}{\mu} - 1\right)}. \tag{20}$$

Equation (20) defines a negative linear relationship between per capita private consumption expenditure, c, and relative R&D difficulty, x. The resource constraint (18) becomes:

$$1 = \frac{c(t) + \bar{G} - \gamma\kappa\Gamma}{1+\kappa} + \frac{n}{\eta A} x(t), \tag{21}$$

defining a positive linear relationship between per capita private consumption expenditure, c, and relative R&D difficulty, x. Equation (20) is an upward sloping line in (c, x) space, while (21) is a downward sloping linear function in (c, x) space. Necessary and sufficient condition for both lines to have a unique and positive intersection is given by $\bar{G} < 1$. Solving the system of linear equations in (20) and (21) by applying Cramer's rule uniquely determines the balanced-growth equilibrium values of x and c as:

$$x^* = \frac{A\kappa\mu\left(1+\gamma\Gamma\right)}{n\left(1+\kappa-\mu\right)+\mu\rho}, \tag{22}$$

$$c^* = \frac{\mu\rho\left(1+\kappa+\gamma\kappa\Gamma-\bar{G}\right) - n\left[\bar{G}\left(1+\kappa-\mu\right)+\left(1+\kappa\right)\left(\mu-1\right)+\gamma\kappa\mu\Gamma\right]}{n\left(1+\kappa-\mu\right)+\mu\rho}. \tag{23}$$

Along a BGP, the fraction of the labor force devoted to R&D can be determined as follows. From (8), the R&D labor share reads $nx/(\eta A)$. Substituting into this expression using (22) yields:

$$\left(\frac{L_I}{L}\right)^* = \frac{\kappa n\left(1+\gamma\Gamma\right)}{n\left(1+\kappa-\mu\right)+\mu\rho}. \tag{24}$$

We are now in the position to analyze the long-run effects of a change in the parameters governing public demand expenditure. By differentiating (22) with respect to the appropriate parameter, it is readily established that relative R&D difficulty in balanced-growth equilibrium, x^*, is an increasing function of γ unaffected by changes of $\bar{G}$. In the same vein, the equilibrium value of average per capita private consumption expenditure, c^*, increases in γ but falls in $\bar{G}$. The latter simply reflects the fact that as the government increases its (average) demand spending, it takes away resources from the private sector, thereby reducing private consumption one-for-one.[22] The balanced-growth equilibrium share of R&D employment in (24) is an increasing function of γ and does not depend on $\bar{G}$. Notice further that the balanced-growth values of x, c, and L_I/L are all positively affected by an increase in κ. The larger the expected size of innovations, the higher the values of the endogenous variables along the BGP.

[22] This result of complete crowding-out is a consequence of our assumption that goods purchased by the government neither affect households' utility nor firms' production processes.

Finally, we calculate the balanced-growth rate of the economy. Because we refrain from capital accumulation the concept of growth in the model relates to growth in each individual's utility. This property is shared by all Schumpeterian growth models in which firms' R&D efforts are directed toward increasing the product quality, and per capita consumption does not change in equilibrium. However, even if the same amount of goods is consumed per person, individual utility in (2) augments if R&D turns out to be successful. To obtain an explicit expression for the utility growth rate, we substitute for consumer demand in (2) by using (4):

$$\log u(t) = \int_0^1 \log\left[\frac{c(t)}{\lambda(\omega,t)}\right] d\omega + \int_0^1 j^{\max}(\omega,t)\log\left[\lambda(\omega,t)\right] d\omega\,, \tag{25}$$

where $\int_0^1 j^{\max}(\omega,t)d\omega$ is a measure for the number of quality improvements aggregated over all industries $\omega \in [0,1]$. The index $j^{\max}$ increases when firms are successful in innovating and firms engage in innovative R&D in all industries throughout time in any steady-state equilibrium. In each industry ω, the (Poisson distributed) probability of exactly m improvements within a time interval of length τ can be calculated as:

$$f(m,\tau) = (I\tau)^m e^{-I\tau} / m!,$$

where $f(m,\tau)$ represents the measure of products that are improved exactly m times in an interval of length τ. Following Davidson & Segerstrom (1998, p. 562), $\int_0^1 j^{\max}(\omega,t)d\omega$ then equals tI. Taking this and (19) into account, differentiating (25) with respect to time yields the following balanced-growth rate of per capita utility:[23]

$$\frac{\dot{u}(t)}{u(t)} \equiv g^* = \frac{n}{\mu}\kappa\,. \tag{26}$$

We summarize the balanced-growth properties of our model economy by establishing the following proposition:

Proposition 1. *Existence and uniqueness of BGP*

If $\bar{G} < 1$, *a unique balanced-growth equilibrium always exists, where per capita private consumer expenditure, c, relative R&D difficulty, x, innovation rate in each industry, I, share of*

[23] Notice that the first integral on the RHS of (25) is constant along the BGP. We further exploit the fact that quality jumps follow a Pareto distribution, so $\int_0^1 \log\left[\lambda(\omega,t)\right]d\omega = \kappa$ [using (10)].

R&D workers in employment, L_I / L, and the rate of per capita utility growth, g, are all constant and given by (19), (22), (23), (24), and (26), respectively.[24]

Having derived the steady state of the model, in the next section we will analyze how the endogenous variables in the model are affected by a change in public demand policy on the convergence path to the long-run equilibrium.

3.8 The Dynamic Effects of a Change in the Composition of Public Demand Spending

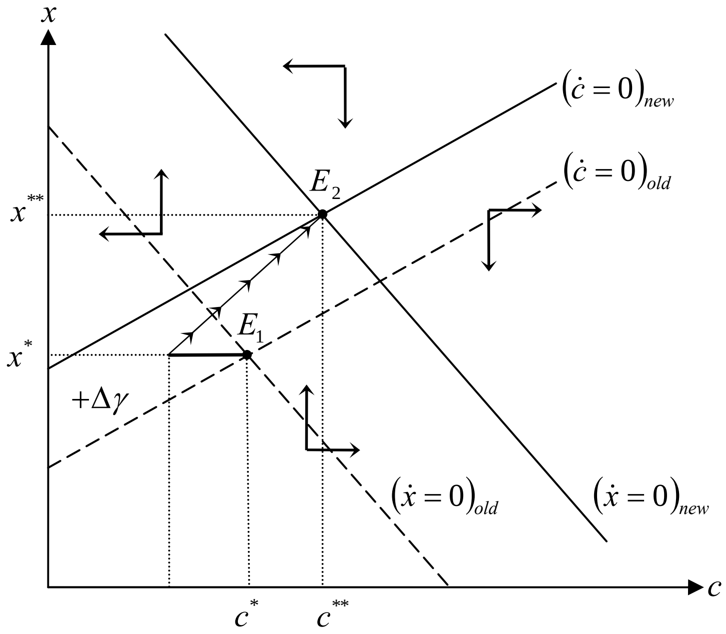
The main result of the model is derived in this section. We here study how a reshuffling of public demand spending in favor of industries with an above-average quality jump, that is, an increase in γ, affects the steady-state properties of our model as well as the transition toward the new balanced-growth equilibrium.[25]

Assume that, initially, the economy rests in the balanced-growth equilibrium $\left(c^*, x^*\right)$, denoted by E_1. Assume further that a permanent and unanticipated increase occurs in γ. This causes the $\left(\dot{x} = 0\right)$ isocline to shift rightward and the $\left(\dot{c} = 0\right)$ isocline to shift upward, as is illustrated in Figure 2.[26]

[24] It can be shown that the dynamical system, given by (22) and (23), is either locally saddle-path stable or locally indeterminate, but never instable. Details on the local stability analysis are available from the authors upon request.

[25] We restrict our attention to the case of saddle-path stability of the BGP.

[26] Depending on the parameter values, the $\left(\dot{c} = 0\right)$ isocline can be either upward sloping or downward sloping. We here focus on the case of an upward sloping $\left(\dot{c} = 0\right)$ demarcation curve. All qualitative results remain the same for the $\left(\dot{c} = 0\right)$ demarcation curve being downward sloping.



Source: Own illustration

Figure 2: Dynamic effects of an increase in γ

To identify the short-run effects of a change in γ, observe first that according to (24) the equilibrium R&D labor depends on γ in a positive manner. Interpreted economically, an increase in γ raises aggregate expected profits from winning an R&D race instantly [see (B.4)]. Firms respond by investing more heavily in R&D. Thus, a rise in γ stimulates R&D, leading immediately to a decrease in per capita private consumption, c, because the additional labor force needed in R&D has to be withdrawn from the manufacturing sector.

In the medium run, relative R&D difficulty, x, experiences an upward movement caused by the temporarily rising innovation intensity, I (due to the additional workforce employed in R&D). By the same token, per capita private consumption, c, increases over time. This can be seen from the equation for the interest rate, which, using (17), reads:

$$r(t)=\frac{A\left[\bar{G}\kappa+c(t)(\kappa-\mu)+\mu\left(1+\kappa-\bar{G}\right)+(1+\mu)\gamma\kappa\Gamma\right]}{(1+\kappa)x(t)}-I(t). \tag{27}$$

The increase in γ leads to a temporary upward shift of $r(t)$ above its steady-state level $r^*=\rho$. When we argue with the Keynes-Ramsey rule in (5), this implies $\dot{c}(t)/c(t)>0$. The intuition behind the increase in the interest rate relates to the stock market where households can channel their savings. The stock market valuation of a new quality leader increases due to the higher expected monopoly profits earned by a successful innovator. Efficiency on financial markets requires that the expected rate of return from holding a stock of a quality leader be equal to the riskless market interest rate that can be obtained through complete diversification. However, as x appears in the denominator in (27), the increase in x will eventually bring r back to its balanced-growth level. An increase in x implies a fall in profitability of R&D projects. Firms that want to engage in R&D are thus less willing to pay high rates of return for the households' savings.

In the long run, c and x reach their new balanced-growth values $c = c^{**}$ and $x = x^{**}$. In the new dynamic equilibrium, denoted by E_2 in Figure 2, both c and x have increased compared to the situation before the policy change occurred. It is noteworthy that the upward movement of per capita private consumption in the new steady state is to be attributed to the assumption that the distribution of quality increments in the economy is Pareto. Due to its right-skewness, the median of the Pareto distribution is always smaller than its mean. Hence the mass of the distribution is on the low-value side. With reference to the model economy, this means that there are more industries with quality jumps below rather than above the mean. It is straightforward to conclude that the higher the value of γ, the lower is the absolute size of public demand. The tax base needed to finance government demand shrinks accordingly, leaving private households more resources to be spent for consumption.

Observe that for $x(t)$ to rise over time in the transition to the new steady state, (9) implies that the innovation rate in each industry, $I(t)$, temporarily exceeds its balanced-growth value, $I^* \left(= n/\mu\right)$. Thus, a permanent redistribution of public spending that privileges industries with a quality jump higher than the economy-wide average generates a temporarily faster rate of technological change. The reason why an increase in γ contributes to a temporary acceleration of technological change may be labeled *R&D incentive* effect. A change in the technological composition of public procurement expenditure, privileging more promising industries (with respect to the quality increments), causes aggregate expected monopoly profits to increase. This happens because higher quality jumps imply higher markups over marginal cost and, thus, higher reward for successful innovation activities [see (B.4) and (16)]. Innovations are stimulated because firms direct relatively more resources to R&D, which induces a higher demand for R&D labor. The consequence of this increase in the relative size of the R&D sector is an acceleration of technological change, and, according to (26), a faster rate of economic growth. Accelerated growth eventually comes to a halt because innovating becomes progressively more difficult over time. Thus, (demand) policy changes have only temporary effects on growth. Such being the case, our model belongs to the class of so-called semi-endogenous growth models.[27]

Proposition 2 recapitulates the dynamic effects of an increase in γ.

Proposition 2. *Dynamic effects of an increase in* γ

A permanent increase in γ*, the parameter that governs the allocation of public procurement spending,*

(i) permanently increases per capita private consumer expenditure (c),

(ii) permanently increases relative R&D difficulty (x),

(iii) permanently increases share of R&D workers in employment (L_I / L*),*

(iv) temporarily increases the rate of technological change (I),

(v) temporarily increases the rate of utility growth (g), and

(vi) has no effect on long-run utility growth.

The theoretical investigation of industry-level effects of government purchases laid out a potential mechanism through which public demand spending might affect innovative behavior in industries, and, with it, the rates of technological change and economic growth. According to the model, it is the composition, as opposed to the size, of aggregate demand that influences private R&D outlays. Consequently, by varying the inter-industrial composition of its purchases in favor of industries with above-average innovative potential, the government holds a leverage to induce private R&D spending, with potentially positive effects on technological change and economic growth.[28] Below we analyze the empirical plausibility of the

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[27] This stratum of literature originated from the seminal paper by Jones (1995b). See Jones (1999) for an illuminating essay on the differences between semi-endogenous and fully-endogenous growth models.

[28] However, two main caveats of the model should be noted. First, due to our assumption of full employment of labor in every instant of time, we neglect search unemployment that may come along with the reallocation of labor force from one sector to another (Aghion & Howitt, 1994). In a more realistic model setup, the welfare gain resulting from a public demand policy relatively in favor of industries with above-average innovation size should be offset against the social costs entailed by such asymmetric policy intervention. Second, in the real world it may be tolerably difficult for public authorities to identify and also to pick "winning industries" (Giordani & Zamparelli, 2008). On the one hand, the assumption that the government has the ability to recognize winners is not highly unrealistic provided that the distribution of quality increments is indeed time invariant and equivalent to the distribution of industrial markups. Hall (1988), Roeger (1995), and Oliveira Martins et al. (1996) present empirical estimates of industrial markups for U.S. manufacturing industries, providing the government with an indication as to the industries where public demand expenditure should be directed from the model's viewpoint. On the other hand, willingness to pick winners may be threatened by the presence of lobbies capable of influencing policy makers' decisions in their favor and by purchasing conservatism of public authorities. To substantiate the latter, a recent survey of the U.K. environmental sector shows that 66 percent of the interviewed companies regarded the procurement process as harmful for their innovativeness as tender specifica-

model's predictions using disaggregated U.S. procurement data at the level of industry. Such detailed quantitative assessment of the compositional effects of government purchases, guided by a theoretical model, is novel in the literature. In the next section we provide a description of the data sources and procedures we use to develop a database suitable for testing the theoretical model's main implications.

4. Data and Variable Construction

4.1 Industry-Specific Government Purchases

Our main source of constructing government purchasing expenditure by industry is federal procurement data collected and provided by the U.S. General Services Administration (GAO). Hence, unlike previous literature, we do not rely upon Input-Output (IO) accounts (Nekarda & Ramey, 2010), which are available for a few points in time only and provide just an indirect and rather crude measure of government procurement by industry. Federal agencies are required by the Federal Acquisition Regulation (FAR) to report procurement data directly to the so-called Federal Procurement Data System – Next Generation (FPDS-NG). The system serves as the central repository of statistical information on federal contracting, containing detailed information on contract actions of more than $2,500. With respect to each procurement carried out above this micropurchase threshold, a wide array of information is provided by FPDS-NG, including, inter alia, the dates of the contract award and the completion of the contract, the number of dollars obligated or deobligated by the contract action, the industry the procured product or service can be assigned to, and whether or not the contract is for R&D. Along these lines, detailed federal purchasing data are available since 1978. Up to 2009, the database contains records of more than 32 million contract actions.[29]

During the import into the database via some custom Python based scripts the raw data was normalized according to the data structure specifications of FPDS-NG. Moreover, some data corrections have been performed on the dataset due to some changes in the North American Industry Classification System (NAICS) and Federal Product Service Codes (PSC). These

tions locked suppliers into traditional technologies (DTI, 2006). In general, public sector employees seem to exhibit a substantial degree of risk aversion (Buurman et al., 2009).

[29] Due to the existence of different government levels in the U.S., the public sector cannot be considered as one single purchaser in general. Ideally, we would need public purchases broken down by government level to fully capture the innovation impacts of public procurement. However, there are no data available on sub-central U.S. procurement on a sufficiently detailed level. However, a recent OECD study estimates that the volume of state and local procurement in the U.S. is almost twice as high as the volume of federal procurement (OECD, 2002). In that sense our results can be interpreted as a very conservative estimate of the effects of U.S. government procurement.

changes were also necessary because some departments have apparently used an old classification with obsolete codes years after the new classifications have been introduced. But no further changes were made on the raw data. The deflator used for the conversion of current to constant contract value (base year 2000) was the Government Consumption Expenditure and Gross Investment Index (GCEGII).[30]

The aggregation of contract-by-contract data on the industry level was complicated by the fact that prior to 2001 only a small fraction of contracts were NAICS-classified. However, we exploited that for each contract a so-called Product and Service Code (PSC) is provided that must correlate to the NAICS code (FPDS, 2008). Basing on contract data with both PSC and NAICS codes for the years 2001 to 2010 we developed a PSC-NAICS concordance. We classify procurement expenditure according to the date the contract between the U.S. federal government and the respective contractor was signed.[31]

The steps described above have been exercised for both R&D procurement contracts (if the first character of PSC was an "A") and for the total of procurement contracts. R&D procurement occurs when the government requests completely new products, processes, or systems. Unlike contracts for supplies and services, most R&D contracts are directed toward objectives for which the work or methods cannot be precisely described in advance. R&D procurement vis-à-vis R&D grants are used only when the principal purpose is the acquisition of supplies or services for the direct benefit or use of the federal Government (FAR, 2005, part 35).

R&D procurement can be hypothesized to exert a direct influence on firms' R&D decisions since the government's intention is to procure innovative goods and services. In the same vein, "regular" (i.e., non-R&D) procurement might influence firms' (R&D) behavior indirectly, e.g. through impacts on competition and especially market size (Cabral et al., 2006). However, it is important to observe that regular procurement may have a direct effect on private R&D also, since it can contain an R&D component. The value of federal contract actions for R&D in FPDS-NG represents only firms' prime R&D contracts. FPDS-NG data do not reflect R&D portions of other procurement contract obligations. In that sense, we do not claim that variable "R&D procurement" covers all industrial R&D funded by the U.S.

[30] We prefer GCEGII over the Consumer Price Index (CPI) since the "market basket of goods" purchased by the federal government is significantly different from the purchases of the typical household.

[31] Since contracts often last for several years and it is theoretically ambiguous when exactly an effect on firms can be expected, an alternative to a date-signed based classification is to distribute equally the total monetary value of a contract over the contract period, given that the date of signature of a contract and its completion date are in different years. If that alternative classification of the procurement variables is used, none of the main results mentioned below change.

federal government, since the latter contains as well R&D subcontracting, grants, and R&E tax credits (Lichtenberg, 1990).

4.2 *Private R&D Activity: Expenditure and Employment*

Our data on private R&D activity stem from the U.S. Survey of Industrial R&D (SIRD), administered by the National Science Foundation (NSF). Providing estimates of R&D expenditure and R&D employment for all domestically performed R&D in companies with five or more employees, the SIRD is the most comprehensive data available on U.S. firms' R&D and also serves as the basis for the government's official estimates of industrial R&D (Lichtenberg, 1990). In principle, the SIRD data cover 38 industries on the 3-digit and 4-digit NAICS level for the years 1999-2007. However, the industry classification methodology used in the survey made an adjustment necessary. The SIRD assigns all of a company's R&D to a single industry based on the activity that accounted for the highest percentage of the company's payroll across its establishments. An artifact of this classification methodology was that a large part of the growth in R&D before 2004 was erroneously attributed to the wholesale trade industry. In fact, this R&D was mostly performed in pharmaceutical and computer manufacturing companies, but due to the growth in the payrolls related to selling and distribution activities, the automated algorithm assigned this R&D to wholesale trade. Since 2004, the NSF thus releases a revised industry classification that reassigns the part of wholesale trade industry's R&D, drawing upon expert review and information available from public sources such as financial reports and company website (NSF, 2007). The reclassification resulted in a doubling of estimated R&D outlays for the pharmaceutical industry (NAICS 3254) and the computer industry (NAICS 3341, 3342, 3344, 3345) in 2004. Also, the industries computer systems design and related services (NAICS 5415) and scientific R&D services (NAICS 5417) experienced a rapid exogenous change due to the reclassification.[32] After dropping these industries from the sample and deflating the industry-wise current-dollar R&D investment series by GDP implicit price deflators provided by the U.S. Bureau of Economic Analysis[33], our real R&D investment dataset embraces 25 industries for the period 1999-2007.[34]

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[32] Other industries were also affected, but to a significantly smaller amount. We decided to include in our sample all industries which experienced not more than a 10 percent shift in its R&D expenditure due to the reclassification.

[33] Ideally, we would want a price deflator that allows for taking into account productivity gains in the production of the R&D output. Reliable output-based R&D deflators are currently not available. Since we cannot draw upon any measure of a price index for the output of R&D processes, a possible alternative is to use a deflator for the goods that embody R&D. Lacking reliable information on the beneficiaries of R&D performed in an industry

In order to test our model's predictions, we need to classify industries according to their innovation potential. Matching closest the assumptions in the model would be an industry classification according to the average quality jump, or average markup of price over marginal cost. Unfortunately, there is no study available providing an estimate of markups at the level of 3-digit or 4-digit industries in the U.S. We thus use R&D intensity of industries as a proxy for innovation potential. Under the assumption that firms channel their R&D investment to the industries with the most promising R&D projects, an industry's R&D intensity might indeed be a reliable indicator for its innovation potential. Six industries in our sample are classified as "R&D intensive," namely basic chemicals (NAICS 3251), resin, synthetic rubber, fibers, and filament (NAICS 3252), motor vehicles, trailers, and parts (NAICS 3361-63), aerospace products and parts (NAICS 3364), other transportation equipment (NAICS other 3365-66, 3369), and software (NAICS 5112).[35] These industries make up between 52 and 60 percent of total R&D in our sample and have an average R&D intensity (defined as R&D expenditure over sales) about twice as high as the non-R&D intensive industries (5.51 vs. 2.27 percent).

Supplementing our data on real R&D investment by industry we use R&D employment as a second R&D performance measure. The impact of public purchasing behavior on R&D employment might significantly differ from its effect on firms' R&D outlays. On the one hand, as observed e.g. by Lichtenberg (1984) and Griliches (1998), "good" deflators of R&D expenditure at the level of industry are missing. The price index we are using to deflate R&D reflects price changes in the consumers' basket of commodities. We thus fail to capture changes in the productivity of R&D expenditure, caused by various technological and scientific breakthroughs. On the other hand, Goolsbee (1998) stresses that government subsidy programs to increase company R&D mainly benefit scientists' and engineers' incomes. The effect on the amount of "real" R&D activity, e.g. measured by working hours or newly-employed R&D personnel, is often negligible. Goolsbee concludes that simple evaluation studies regressing private R&D expenditure on aggregate R&D subsidies might overstate the impact of government R&D spending on "real" private R&D effort by as much as 30-50 per-

(we cannot distinguish between R&D performed and R&D paid for by companies), we translate nominal into real R&D spending with the help of a price index associated with the economy as a whole (GDP deflator).

[34] Notice that on purpose we do not deflate R&D procurement by the same price index as company-sponsored R&D. Deflating both company and federal R&D by the same deflator may induce a spurious positive correlation between these two variables.

[35] In our choice of R&D intensive industries, we follow the classification provided by the Bureau of Economic Analysis in its R&D Satellite Account (http://www.bea.gov/national/rd.htm).

cent.[36] Therefore, looking at the effect of government demand spending on private R&D outlays is only one side of the coin. Complementing this with the analysis of direct, albeit partial, quantity indices of R&D input, such as employment of scientists and engineers, gives us the opportunity to check whether government procurement increases merely private R&D costs by bidding up wages of R&D personnel without having an impact on "real" R&D effort.

For data on R&D employment we again draw upon the SIRD.[37] Due to disclosure limitations, the series on company-sponsored R&D employment has a non-negligible share of missing values. The severity of this problem varies from year to year as the sample size of the underlying survey varies, but generally declines over time. Since our panel is already relatively short, we decided to use total business R&D employment figures (company sponsored plus federally sponsored) in our analysis, which shows considerable less missing values. We have required each industry to have at least 5 time observations to enter the analysis, as to make sure that any change in parameter estimates can be traced back to a change in estimation method, and not to a change in the sample. Fortunately, we are able to observe the same 25 industries as in the R&D expenditure data. In our six R&D intensive industries between 47 and 52 percent of the total sample's R&D personnel is employed. In order to make sure that the data underreporting is not systematically related to any of the variables in the analysis, we have estimated regressions based on a balanced panel of 11 industries. The results from these estimations were quite similar to those reported below.

4.3 Sales

Total sales of a firm in any industry can be seen as the sum of its sales to each of its customers. We measure sales to the government by the value of federal prime contract actions (obligations) by industry and year. Sales to other customers ("private sales") are obtained as follows. The SIRD survey provides estimates of net sales or operating revenue for businesses performing R&D ("total sales"), defined as the dollar value for goods sold or services rendered by companies to customers outside the company, including the federal government, less such items as returns, allowances, freight charges, and excise taxes. Private sales are defined as total sales minus the value of contract actions. We use industry-wise gross output price deflators from BEA's Industry Economic Accounts to convert current to constant dollars.

[36] Wolff&Reinthaler (2008) find in a panel of OECD countries that due to a rise in the R&D subsidy rate private R&D expenditure increase by at least 20 percent more than R&D employment.

[37] Similar to Goolsbee (1998) we would also like to use an average R&D worker's working time as R&D input variable. This would require using household data from the Current Population Survey (CPS). However, the CPS is not stratified over industries, which prevents us from using it in the current analysis.

Relative to the full sample, the share in total sales of our six R&D intensive industries is around 30 – 41 percent, whereas the share in government sales is 10 – 14 percent.[38]

Total annual government sales for the 25 industries we observe range in value between 66 billion and 116 billion. On average, the share of government sales in total sales is about 10 percent in the industries we classify as non-R&D intensive and 1.3 percent in R&D intensive industries.[39] In the total sample, the average ratio of government sales over total sales amounts to 8 percent, approximately.

5. Empirical Strategy and Results

In order to empirically assess the industry-level impact of public procurement on R&D activities, we estimate the following equation:

$$y_{it} = \alpha + \beta_1 * PROC_{it} + \beta_2 * X_{it} + \mu_i + \lambda_t + u_{it}\,, \tag{28}$$

where y_{it} is the outcome (either private R&D expenditure or R&D employment) of industry i at time t, $PROC_{it}$ is a vector of procurement variables, X_{it} is a set of further control variables, μ_i and λ_t are industry and time fixed effects, respectively, and u_{it} is an i.i.d. error term.

In the empirical analysis, we attempt to test the theoretical model's main prediction, namely that the change in the composition of government purchases in favor of R&D intensive industries stimulates company R&D. To be able to do so, we treat procurement in R&D intensive and in non-R&D intensive industries separately, by interacting procurement with a dummy for R&D intensive industries. Moreover, the data available to us allow estimating the impact not only of total procurement but also to distinguish between R&D and non-R&D procurement. Several authors having examined the government influence on private R&D and innovative behavior stress that, because the government often plays both the role of R&D sponsor and that of important customer, the independent effect of each role on private R&D

[38] For reasons of confidentiality, 1 percent of the data points on company-sponsored R&D expenditure and on total sales are not reported in the SIRD data. We imputed those values. We also imputed 33 missing values in our R&D employment sample. However, using the data without imputed values does not change any of our results.

[39] The most "government-oriented" industries (share of government sales in total sales of above 10 percent) are wood products (NAICS 321), furniture and related products (NAICS 337), newspaper, periodical, book, and directory (NAICS 5111), as well as health care services (NAICS 621-23).

behavior needs to be identified (Nelson, 1982; Lichtenberg, 1987 and 1988).[40] Although the theoretical model does not explicitly distinguish between R&D and non-R&D procurement, non-R&D contracting matches more closely the government sales variable in the model. Rather than direct contracting (funding) for R&D, it is the (expected) government market that drives the decisions of the firms in our model economy.

There are a number of conceptual and econometric issues that must be handled in our analysis. First, there is a potential autocorrelation of error terms within industries. For that reason we formulate all variables of our empirical model (28) in first differences (FD). Like time demeaning ("within transformation"), first differences allows to get rid of the fixed effect μ_i, but is superior to the former approach when dealing with autocorrelation. Another reason using the FD estimator is that the theoretical model outlined in chapter 3 predicts effects of changes on changes.

Second, an identifying assumption in the FD estimator is that treatment selection (i.e., the selection of which industry receives public procurement contracts) is random (uncorrelated with the error term). In reality, however, selection might be dependent on past outcomes. In the context of our study we would get upward-biased coefficients if industries with high levels of current R&D are more likely to face an increase in procurement.[41] One way to test whether or not such reverse causality exists in our data is to replace contemporaneous (R&D) procurement with lagged (R&D) procurement. The latter should not be affected by current R&D spending. If very similar results are obtained, this suggests that such bias is negligible.[42] But the inclusion of lagged regressors is not a remedy for the problem of reverse causality in case R&D expenditure are persistent over time. Since this is the case in our data, an IV approach is more appropriate to control for reverse causality than simply including lagged re-

[40] Using data on federal consumption from the national income accounts ("non-R&D procurement") as well as data on federal funds for R&D reported by the National Science Foundation in its SIRD survey ("R&D procurement") for the whole U.S. in the period 1956-1983, Lichtenberg (1987) demonstrates that the positive effect of federal funds for R&D on firm R&D vanishes once he controls for other government consumption. The latter, however, is found to have a significantly positive effect on company R&D.

[41] One could argue that this reverse causality is less severe if most variations in federal purchases are due to military spending. Arguably, military spending is mostly driven by geopolitical events and is for the most part exogenous to the current state of the economy (Nekarda & Ramey, 2010). In the period between 1999 and 2007, between 63 percent and 73 percent of total procurement in the U.S. has been conducted by the Department of Defense. Procurement in this department is likely to possess a military application. Moreover, it is also obvious from the data that total procurement mainly varies with military procurement. However, if the distribution of military procurement across industries is related to specific industry characteristics, a reverse causality bias is still a possibility.

[42] Another reason to take into account lagged values is that one might reasonably hypothesize that company financing responds with a certain lag to changes in public contract expenditure. We investigate this possibility by re-estimating the econometric model reported above with once-lagged and twice-lagged values of the federal procurement variables included.

gressors. We use as instrument the lagged level of the endogenous variable in a panel data model set up in differences (Anderson-Hsiao).

Third, Lichtenberg (1987, 1988) provides evidence for "signaling" effect of public procurement. That is, prospective federal contractors signal their ability to perform R&D and related contracts by producing elaborate technical proposals[43], which entails utilization of R&D personnel and facilities. The idea behind is that firms spend significant amounts on R&D before a government contract is made formal, to be in a position to compete effectively when the contract is actually made public. Consequently, we also test the impact of future procurement on current private R&D.

Table 1 contains the results of the estimation of the contemporaneous effect of procurement on both business R&D expenditure and R&D employment.[44] We find evidence for a positive effect of total procurement on private R&D expenditure, while there is no effect of procurement on R&D employment (models 1 and 6). When looking at R&D intensive and non-R&D intensive industries separately, we find that the positive effect of total procurement on company R&D activities stems from procurement in R&D intensive industries alone; the interaction term between procurement and R&D intensive industries is positive and statistically significant for both R&D expenditure and R&D employment (models 2 and 7). This provides support for our theoretical model; a reshuffling of public purchases toward industries with a comparatively high R&D intensity seems to stimulate private R&D. The difference between the coefficients of procurement in non-R&D intensive and in R&D intensive industries is highly significant ($F_{1,189} = 4.26$, P-value$=0.04$ for R&D expenditure and $F_{1,189} = 4.76$, P-value$=0.03$ for R&D employment). Our estimation results imply that a $1 increase in government sales in R&D intensive industries is associated with a more than 78-cent increase in firm-financed R&D expenditure. Moreover, a $1 million increase in government procurement in R&D intensive industries relates to an additional employment of about 5-6 workers in R&D. We find comparable patterns when distinguishing R&D procurement and non-R&D procurement in the two types of industries. Both R&D procurement (models 3 and 8) and non-R&D procurement (models 4 and 9) have a significant and positive effect on company R&D in R&D intensive industries, while we find both types of procurement to be insignifi-

[43] Lichtenberg (1988) and Kelman (1990) report that potential vendors' written proposals can be several tens of thousands pages in length and can cost the bidder more than a million dollars to produce. Lichtenberg (1986) describes an unpublished study by Allen who carefully investigates firms' proposal efforts related to 14 small (in the order of $30,000 to $50,000) R&D contracts. Allen finds that the total cost of all firm proposal efforts in each competition were often non-negligible, ranging between 3 percent and 150 percent of the direct cost of the contract awarded.

[44] Notice that in all tables below the coefficients express the marginal responses of private R&D to changes in the volume of federal purchases.

cant in non-R&D intensive industries. In other words, as far as non-R&D intensive industries are concerned, neither type of government contracting is able to induce company R&D funding. In R&D intensive industries, however, both R&D and non-R&D procurement are associated with an increase in firm R&D. Judging from the size of the coefficients, this stimulating effect of government procurement seems to be more substantial in the case of R&D contracts. In the last step of the analysis, we further disaggregate procurement into its R&D and non-R&D components in both R&D intensive and non-R&D intensive industries. Again, in non-R&D intensive industries neither type of procurement exerts an influence on private R&D. When looking at R&D intensive industries, the estimates imply, somewhat surprisingly, that the positive effect of procurement on company-sponsored R&D spending found previously stems from non-R&D procurement alone; R&D procurement is always insignificant (model 5). It seems that R&D procurement in R&D intensive industries affects a firm's R&D expenditure only through its correlation with non-R&D procurement. In the case of R&D employment in R&D intensive industries, R&D and non-R&D procurement retain their significance (model 10). Nevertheless, it holds for both R&D expenditure and R&D employment that a large part of the effect on private R&D that was previously attributed to R&D procurement actually comes from non-R&D procurement; compared to models (3) and (8), when controlling for non-R&D procurement in models (5) and (10) the coefficient of R&D procurement shrinks by 66 percent (R&D expenditure) and by 59 percent (R&D employment), respectively.[45]

Although the sharp decrease in the coefficient value/level of significance of R&D procurement once non-R&D procurement is included in the regression model is somewhat puzzling, one should notice that this result is in line with the theoretical model. The model suggests that the technological composition of government procurement (not distinguishing, however, between R&D and non-R&D government purchases) affects the market size of an industry. The increased market size incentivizes firms to invest in R&D and to become the market leader. Since the average value of R&D procurement is only about 10 percent of the value of non-R&D procurement, we would expect from theory a market-size effect for non-R&D procurement considerably stronger than for R&D procurement. Another reason for why it is mainly non-R&D procurement that stimulates company R&D might be the difference in public tendering procedures applied in R&D versus non-R&D contracts (GSA et al., 2005).

[45] Moreover, R&D employment is measured as total company R&D employment, encompassing both private and public sources of founding. This might be another reason for the difference in significance levels of R&D procurement in the R&D expenditure regression vis-à-vis the R&D employment regression. R&D expenditure is defined as company R&D that is privately funded only.

U.S. procurement regulations mandate that price be the most important criterion to judge a tender for an already existing product. Thus, sealed bidding and fixed-price contracts are most commonly used in non-R&D procurement. In R&D procurement, in contrast, precise specifications often do not exist and difficulties in estimating costs with accuracy normally precludes using fixed-price contracting for R&D, the use of cost-reimbursement contracts is usually appropriate. Since the price of a product or a service is the main evaluation criterion in non-R&D procurement, firms have a strong incentive to conduct process innovation to produce more efficiently. This incentive is absent in case of R&D procurement. The insignificance of the effect of R&D procurement on company R&D expenditure might indicate that government R&D procurement is somewhat idiosyncratic, in the sense that it does not match well private demand. Firms that undertake contract R&D for the government may have found themselves a profitable niche with little incentive to venture into commercial markets. When government is the sole customer and is willing to support the R&D necessary to develop that product, there is little incentive for the supplier to invest any additional own money in such projects[46] – Feldman and Kelley (2006) speak of “captive” suppliers.[47]

The remainder of the empirical analysis is devoted to extending and amplifying the major finding that a considerable volume of private R&D investment is induced by government procurement. Table 2 illustrates the regression results for the one-year lagged impact of procurement on both private R&D expenditure and R&D employment. Qualitatively, the results for the estimated effects of lagged procurement on private R&D activities are similar to those obtained above. This gives some first indication that reverse causality is unlikely to be a serious problem in our data. Again, the differences between the coefficients on the procurement variables in R&D intensive industries versus non-R&D intensive industries are always highly significant. If we include both contemporaneous and once lagged values of procurement (Table 3), we can shed light on the question whether it is procurement in the current or in the previous year that is decisive for a company’s R&D behavior.[48] Interestingly, firm-financed R&D expenditure reacts differently than company R&D employment on procurement of different lags. On the one hand, (non-R&D) procurement in R&D intensive industries remains positive in the private R&D expenditure regression. However, the estimated coeffi-

[46] Recall that the cost component related to government demand is fully reimbursed under the R&D contract and does not show up as privately sponsored R&D in our data.
[47] However, Kelley & Watkins (1995) find that many defense contractors make products for commercial (non-government) customers as well. Moreover, firms that fulfil defense contracts for the government may even profit for their engagement in non-government markets from the technical support and information-sharing norms of the defense contractors’ network (Kelley & Cook, 1998).
[48] We do not report the estimates with one-year lagged values of private sales since this variable turned out to be insignificant in all cases.

cients of the lagged procurement variables are higher in magnitude and always more significant than those of contemporaneous procurement. This result implies that changes in federal procurement continue to influence company R&D expenditure in the subsequent year, having an even greater stimulating effect than contemporaneous government sales. On the other hand, in the case of R&D employment, only contemporaneous procurement exerts a significantly positive influence on a firm's decision to hire scientists and engineers in R&D intensive industries. Lagged procurement remains insignificant or even seems to crowd-out company R&D employment, which is the case for (non-R&D) procurement in R&D intensive industries (models 7 and 9).

Twice-lagged procurement effects seem to be absent (Table 4).[49] The only significant results for the twice-lagged procurement values suggests that contracting for R&D induces a substantial crowding-out of privately-funded R&D expenditure, while non-R&D procurement affects company-sponsored R&D expenditure positively (model 5). Most often, however, the two-year lagged values of the procurement variables turn out to be insignificant, indicating that the effect of government sales fades out over time.

Table 5 reports the results on the hypothesis of "contract-seeking" firm R&D. We do not find any evidence for Lichtenberg's (1987, 1988) previous finding that companies invest in R&D in order to signal to the government that they are capable of fulfilling government contracts. Private R&D activities are unresponsive to changes in procurement contracts awarded one year in the future. Given that the process of selecting government contractors can take a considerable amount of time (Lichtenberg, 1986; Kelman, 1990), one might expect that that private R&D responds to procurement contracts awarded more than one year in the future. We test for this conjecture, and the results are shown in Table 6. Company-sponsored R&D outlays remain unaffected by future procurement. For R&D employment, the only significant results even point towards crowding-out of private R&D funding due to government contracts. Changes in (non-R&D) procurement in R&D intensive industries affect negatively private employment of scientists and engineers two years in the past.

In the last step, we try to control for the fact that industry-level procurement may be endogenous, in the sense that industries with high levels of current R&D relative to their industry average are more likely to face an increase in procurement in the following period. We cannot rule out this case of an absence of strict exogeneity so far in the empirical design. Thus, we re-estimate the model using an Instrumental Variable (IV) estimator as proposed by Anderson and Hsiao (1982). This approach regresses the first difference in the endogenous

[49] Due to their insignificance, we do not report the estimates with one-year and two-years lagged values of private sales.

variable on the first difference in the exogenous variable and lags of the difference in the endogenous variable, using the lagged level of the endogenous variable as instrument. Our IV results, reported in Table 7, confirm that the FD estimates are approximately unbiased. All main results remain the same as above, with respect to both the magnitude of coefficients and the estimates' level of significance.[50] These results give us some confidence that upward biased coefficients due to reverse causality are not a serious issue in our empirical approach.

6. Conclusions

In this paper, we have developed a generalized version of a Schumpeterian growth model that incorporates a typical trait of real economies, namely the presence of industries characterized by different innovation size. This asymmetry causes the distribution of monopoly profits from successful innovation to be highly skewed toward the low-value side, with a long tail to the high-value side. We use the model to analyze the dynamic effects of a change in the technological content of government demand spending.

Our paper provides some arguments that bring the inter-industrial composition of public purchases within the realm of the debate on innovation and growth policy. We theoretically derive that a change in the composition of public demand expenditure that relatively favors industries with above-average quality jumps temporarily fosters technological change and economic growth due to an *R&D incentive* effect. A government that channels its demand toward industries with a relatively high innovation capacity increases aggregate expected profits. The higher reward for successful innovation activities stimulates technological change because firms allocate relatively more resources to R&D, thereby inducing a higher demand for R&D labor.

We then test empirically the theoretical model's main implication, which suggests that a shift in the composition of public demand toward industries with a comparatively high innovation potential stimulates private R&D. We use R&D intensity as a proxy for innovative potential. The value of federal prime contract actions, obtained from official U.S. statistics, proxies for the extent of an industry's government market. We match the federal contract data, by industry and year, to the corresponding data on total sales (to control for revenues from customers other than the government) as well as firm-financed R&D expenditure and R&D employment provided by the National Science Foundation. Our final dataset covers 25 U.S.

[50] The main difference between the FD and the IV estimation is that in the latter approach non-R&D procurement always significantly affects private R&D expenditure, irrespective of the type of the industry. However, the positive effect of non-R&D procurement is more pronounced in R&D intensive industries than in their non-R&D intensive counterparts.

industries in the period 1999-2007, while government sales are cross-classified by type of industry (R&D intensive versus non-R&D intensive) and by commodity (R&D versus other).

Our results offer support for the theoretical prediction that federal procurement spending stimulates company R&D activity at the industry level. Federal procurement in R&D intensive industries affects positively company R&D outlays (measured as firm-financed R&D expenditure or as R&D employment), while we cannot observe any effect of procurement in non-R&D intensive industries. In other words, a reshuffling of federal procurement toward more R&D intensive industries works as a de facto innovation policy tool, since it spurs firms' own R&D investment. However, the main stimulus to company-sponsored R&D does not stem from procurement in general, but seems to be mainly an effect of procurement for non-R&D-related products and services. This finding can be easily reconciled with the theoretical model, where the increase in market size due to government purchases is the primary stimulus for private R&D. Being on average about 10 times as high as R&D procurement, non-R&D procurement has a much larger impact on market size than government purchases of R&D results.

One main concern in the empirical design is reverse causality. If the federal government is more likely to award contracts in industries where R&D is high, our procurement variables would exhibit upward-biased coefficients. We control for such reverse causality bias by employing the Anderson-Hsiao (1982) IV estimator. The IV estimation yields basically the same results as obtained in the fixed-effects setting, suggesting that reverse causality is unlikely to cause any significant bias.

Our results suggest that the government's purchasing behavior plays an important role in determining the allocation of a country's R&D resources, whether or not this is actively sought by the government. The government signals by its procurement behavior to the private market that certain technological paths to economic development and growth are perceived to have greater potential than others. In consequence, private firms invest more in certain technological areas that these would in the absence of government intervention. That presents government with the burden of selecting very carefully which technologies to back, to avoid potential lock-ins into inferior technologies.

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Appendix A: Determining the unique ratio between ε₁ and ε₂

In this Appendix, we derive the relation between ε_1 and ε_2 for the public demand rule to be feasible. By definition, $\int_0^1 G(\omega)d\omega \equiv \bar{G}$. Substituting the public demand rule for $G(\omega)$ yields:

$$\int_0^1\int_1^\infty (1-\gamma)\bar{G}+\gamma\left(\bar{G}+\varepsilon\right)d\lambda d\omega$$

$$=\int_0^1\left\{(1-\gamma)\int_1^\infty \bar{G}g(\lambda)d\lambda+\gamma\left[\int_1^{\frac{1}{1-\kappa}}(\bar{G}-\varepsilon_1)g(\lambda)d\lambda+\int_{\frac{1}{1-\kappa}}^\infty(\bar{G}+\varepsilon_2)g(\lambda)d\lambda\right]\right\}d\omega, \qquad \text{(A.1)}$$

where $g(\lambda)$ is the Pareto density function with scale parameter equal to one and share parameter equal to $1/\kappa$. According to (10), we can express $g(\lambda)$ as $1/\kappa\,\lambda^{-(1+\kappa)/\kappa}$, which allows us to rewrite (A.1) as:

$$\int_0^1\left\{\frac{(1-\gamma)}{\kappa}\bar{G}\int_1^\infty \lambda^{-\frac{1+\kappa}{\kappa}}d\lambda+\frac{\gamma}{\kappa}\left[(\bar{G}-\varepsilon_1)\int_1^{\frac{1}{1-\kappa}}\lambda^{-\frac{1+\kappa}{\kappa}}d\lambda+(\bar{G}+\varepsilon_2)\int_{\frac{1}{1-\kappa}}^\infty\lambda^{-\frac{1+\kappa}{\kappa}}d\lambda\right]\right\}d\omega.$$

Computing the integral above gives:

$$\int_0^1 G(\omega)d\omega=(1-\gamma)\bar{G}+\gamma\left[\varepsilon_1(-1+(1-\kappa)^{\frac{1}{\kappa}}+\varepsilon_2(1-\kappa)^{\frac{1}{\kappa}}\right]. \qquad \text{(A.2)}$$

By definition, the term on the RHS of (A.2) is equal to $\bar{G}$. It is now straightforward to show that this relation determines a unique ratio between ε_1 and ε_2 equal to:

$$\frac{\varepsilon_1}{\varepsilon_2}=\frac{(1-\kappa)^{\frac{1}{\kappa}}}{1-(1-\kappa)^{\frac{1}{\kappa}}}. \qquad \text{(A.3)}$$

Because the RHS of (A.3) is strictly positive but smaller than one, it follows that $\varepsilon_1<\varepsilon_2$.

Appendix B: Calculation of the expected profit stream earned by an industry leader

When we take into account (6), the expected value of the profit flow that accrues to the winner of a R&D race in industry ω at time t can be written as (suppressing time arguments):

$$\pi^e(\omega,t)=\int_1^\infty\left[(\lambda-1)\frac{cL}{\lambda}g(\lambda)+(\lambda-1)\frac{G(\omega)L}{\lambda}g(\lambda)\right]d\lambda. \qquad \text{(B.1)}$$

The first term in the integral on the RHS of (B.1) represents the profits an industry leader gains from private demand, while the second term captures the profits resulting from government purchases. We can substitute for the Pareto density function, $g(\lambda)$, and for public demand spending, $G(\lambda)$, by using (10) and (14). Equation (B.1) becomes:

$$\pi^e(\omega,t)=\int_1^\infty\left\{\frac{cL}{\kappa}(\lambda-1)\frac{1}{\lambda}\lambda^{-\frac{1+\kappa}{\kappa}}+\frac{L}{\kappa}(\lambda-1)\frac{1}{\lambda}\lambda^{-\frac{1+\kappa}{\kappa}}\left[(1-\gamma)\bar{G}+\gamma\left(\bar{G}+\varepsilon\right)\right]\right\}. \tag{B.2}$$

The term $(\lambda-1)(1/\lambda)\lambda^{-(1+\kappa)/\kappa}$ can be simplified to $(\lambda-1)\lambda^{-2-1/\kappa}$. Having this in mind, we can compute integral (B.2) as being equal to:

$$\pi^e(\omega,t)=\frac{\kappa}{1+\kappa}cL+(1-\gamma)\frac{\kappa}{1+\kappa}\bar{G}L+\gamma\frac{\kappa}{1+\kappa}L\left\{(\varepsilon_1-\bar{G})\left[-1+2(1-\kappa)^{\frac{1}{\kappa}}\right]+2(\varepsilon_2+\bar{G})\left[(1-\kappa)^{\frac{1}{\kappa}}\right]\right\}$$

In Appendix A, we showed that there exists a specific relation between ε_1 and ε_2, given in (A.3). We now make use of this result to eliminate ε_1. Using (A.3), the integral above boils down to:

$$\pi^e(\omega,t)=\frac{\kappa}{1+\kappa}cL+\frac{\kappa}{1+\kappa}L\left[\bar{G}+\gamma\varepsilon_2\left(-1+\frac{1}{1-(1-\kappa)^{\frac{1}{\kappa}}}\right)\right]. \tag{B.3}$$

Notice that $0<1-(1-\kappa)^{1/\kappa}<1$ for all $\kappa\in(0,1)$, and thus $1\big/\left[1-(1-\kappa)^{1/\kappa}\right]>1$, leaving the term in round brackets on the RHS of (B.3) positive. Rearranging (B.3) eventually allows us to write the expected profit stream as:

$$\pi^e(\omega,t)=\frac{\kappa}{1+\kappa}L\left(c+\bar{G}+\gamma\Gamma\right), \tag{B.4}$$

where $\Gamma\equiv\varepsilon_2\left\{1\big/\left[1-(1-\kappa)^{1/\kappa}\right]-1\right\}>0$ was defined for notational simplicity and is completely determined by parameter values.

Table 1: Estimates of the effect of procurement on private R&D activities (contemporaneous effect)

	Dependent: private R&D expenditure					Dependent: R&D employment				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Proc_total	0.1757**	0.1366				0.2681	-0.0702			
	(0.085)	(0.085)				(0.273)	(0.163)			
Proc_total * R&D int ind		0.6448***					5.5744**			
		(0.202)					(2.589)			
Proc_R&D			0.1955		0.0332			-0.4731		-0.4020
			(0.232)		(0.303)			(0.442)		(0.488)
Proc_R&D * R&D int ind			8.3653**		2.7992			68.4131**		28.0537*
			(3.677)		(2.898)			(27.401)		(16.243)
Proc_non-R&D				0.1680	0.1635				-0.0518	0.0167
				(0.105)	(0.130)				(0.207)	(0.232)
Proc_non-R&D * R&D int ind				0.6415***	0.5379**				5.7104**	4.5941*
				(0.216)	(0.211)				(2.707)	(2.779)
Sales_private	0.0080***	0.0074***	0.0079***	0.0074***	0.0073***	0.0269**	0.0215*	0.0235*	0.0216*	0.0210*
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.013)	(0.012)	(0.012)	(0.012)	(0.012)
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Obs	200	200	200	200	200	200	200	200	200	200
R-squared	0.211	0.270	0.205	0.270	0.273	0.094	0.188	0.151	0.185	0.192
Number of industries	25	25	25	25	25	25	25	25	25	25
F	2.949	4.016	3.038	4.174	3.555	1.626	2.355	2.103	2.321	2.552

Notes: R&D expenditure, procurement, and sales are measured in millions of constant (2000) dollars. Results from estimation in first differences. Robust standard errors in parentheses.
*** p<0.01, ** p<0.05, * p<0.1.

Table 2: Estimates of the effect of procurement on private R&D activities (one-year lagged effect)

	Dependent: private R&D expenditure					Dependent: R&D employment				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
L1.Proc_total	0.1860**	0.1454				0.2878	-0.0658			
	(0.089)	(0.090)				(0.288)	(0.172)			
L1.Proc_total * R&D int ind		0.6404***					5.5729**			
		(0.200)					(2.599)			
L1.Proc_R&D			0.2552		0.0794			-0.4756		-0.4417
			(0.285)		(0.358)			(0.491)		(0.547)
L1.Proc_R&D * R&D int ind			9.1126**		1.6234			72.6043**		18.4808
			(4.408)		(3.437)			(33.835)		(18.880)
L1.Proc_non-R&D				0.1729	0.1615				-0.0426	0.0269
				(0.108)	(0.135)				(0.214)	(0.241)
L1.Proc_non-R&D * R&D int ind				0.6440***	0.5896***				5.7423**	4.9890*
				(0.214)	(0.203)				(2.720)	(2.895)
L1.Sales_private	0.0077***	0.0070***	0.0074***	0.0069***	0.0069***	0.0259*	0.0200	0.0220*	0.0201	0.0196
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.014)	(0.013)	(0.013)	(0.013)	(0.013)
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Obs	175	175	175	175	175	175	175	175	175	175
R-squared	0.205	0.265	0.195	0.265	0.266	0.091	0.189	0.145	0.188	0.191
Number of industries	25	25	25	25	25	25	25	25	25	25
F	2.811	4.167	2.782	4.348	4.006	1.627	2.339	1.933	2.319	2.296

Notes: R&D expenditure, procurement, and sales are measured in millions of constant (2000) dollars. Results from estimation in first differences. Robust standard errors in parentheses.
*** p<0.01, ** p<0.05, * p<0.1.

Table 3: Estimates of the effect of procurement on private R&D activities (contemporaneous and one-year lagged effect)

	Dependent: private R&D expenditure					Dependent: R&D employment				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Proc_total	0.1625*	0.1143				0.0753	-0.1254			
	(0.087)	(0.083)				(0.217)	(0.183)			
Proc_total * R&D int ind		0.3551**					5.0975***			
		(0.163)					(1.336)			
Proc_R&D			0.1709		-0.0198			-0.3684		-0.3136
			(0.221)		(0.276)			(0.430)		(0.517)
Proc_R&D * R&D int ind			5.2973*		1.1139			48.3780***		30.9549*
			(3.097)		(2.391)			(16.396)		(18.579)
Proc_non-R&D				0.1418	0.1432				-0.1267	-0.0868
				(0.103)	(0.125)				(0.228)	(0.256)
Proc_non-R&D * R&D int ind				0.3496*	0.3285*				5.0885***	4.1341**
				(0.177)	(0.190)				(1.469)	(1.709)
L1.Proc_total	-0.0863	-0.1383				-0.0411	-0.1387			
	(0.084)	(0.090)				(0.228)	(0.227)			
L1.Proc_total * R&D int ind		0.4758***					-2.3616*			
		(0.177)					(1.208)			
L1.Proc_R&D			-0.1062		0.0451			0.2842		0.6426
			(0.200)		(0.204)			(0.507)		(0.646)
L1.Proc_R&D * R&D int ind			6.7331**		1.8605			-20.1678		-15.7307
			(2.850)		(2.517)			(19.041)		(28.122)
L1.Proc_non-R&D				-0.1840*	-0.1909*				-0.2266	-0.3344
				(0.099)	(0.099)				(0.295)	(0.344)
L1.Proc_non-R&D * R&D int ind				0.5249***	0.4366**				-2.1997*	-1.9116
				(0.192)	(0.191)				(1.300)	(1.946)
Sales_private	0.0088***	0.0084***	0.0092***	0.0083***	0.0083***	0.0256*	0.0201	0.0220	0.0204	0.0187
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.015)	(0.014)	(0.014)	(0.014)	(0.014)
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Obs	175	175	175	175	175	175	175	175	175	175
R-squared	0.250	0.329	0.243	0.337	0.339	0.086	0.141	0.121	0.138	0.152
Number of industries	25	25	25	25	25	25	25	25	25	25
F	2.610	5.519	2.493	5.570	4.805	1.272	3.843	2.107	3.250	4.115

Notes: R&D expenditure, procurement, and sales are measured in millions of constant (2000) dollars. Results from estimation in first differences. Robust standard errors in parentheses.
*** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table 4: Estimates of the effect of procurement on private R&D activities (contemporaneous and two-years lagged effect)

	Dependent: private R&D expenditure					Dependent: R&D employment				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Proc_total	0.1786*	0.1450				0.0824	-0.0950			
	(0.095)	(0.096)				(0.207)	(0.171)			
Proc_total * R&D int ind		0.6200**					3.7096***			
		(0.261)					(0.898)			
Proc_R&D			0.2157		0.0470			-0.4254		-0.3165
			(0.261)		(0.364)			(0.431)		(0.535)
Proc_R&D * R&D int ind			9.2515**		1.1244			35.9078**		16.7058
			(4.288)		(2.472)			(15.418)		(20.219)
Proc_non-R&D				0.1752	0.1679				-0.0937	-0.0415
				(0.117)	(0.145)				(0.221)	(0.254)
Proc_non-R&D * R&D int ind				0.6096**	0.5915**				3.7712***	3.1953**
				(0.274)	(0.254)				(0.990)	(1.459)
L2.Proc_total	-0.0109	-0.0279				-0.2269	-0.0780			
	(0.077)	(0.085)				(0.317)	(0.297)			
L2.Proc_total * R&D int ind		0.1248					-2.0973			
		(0.179)					(1.313)			
L2.Proc_R&D			-0.1691		-0.1532			-0.2809		-0.3970
			(0.369)		(0.336)			(1.283)		(1.169)
L2.Proc_R&D * R&D int ind			3.0464		-5.3172*			-15.4466		-7.9626
			(4.224)		(2.939)			(25.367)		(21.983)
L2.Proc_non-R&D				-0.0106	-0.0081				-0.0763	-0.0256
				(0.079)	(0.082)				(0.293)	(0.276)
L2.Proc_non-R&D * R&D int ind				0.1265	0.3274*				-2.1352	-1.8931
				(0.182)	(0.174)				(1.461)	(1.767)
Sales_private	0.0074***	0.0065***	0.0072***	0.0065***	0.0064***	0.0278	0.0206	0.0241	0.0208	0.0200
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.018)	(0.016)	(0.016)	(0.016)	(0.016)
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Obs	150	150	150	150	150	150	150	150	150	150
R-squared	0.196	0.262	0.193	0.261	0.275	0.091	0.147	0.117	0.145	0.150
Number of industries	25	25	25	25	25	25	25	25	25	25
F	2.663	5.208	2.603	4.947	4.768	1.383	4.031	1.680	3.222	7.612

Notes: R&D expenditure, procurement, and sales are measured in millions of constant (2000) dollars. Results from estimation in first differences. Robust standard errors in parentheses.
*** p<0.01, ** p<0.05, * p<0.1.

Table 5: Estimates of the effect of procurement on private R&D activities (contemporaneous and one-year forward effect)

	Dependent: private R&D expenditure					Dependent: R&D employment				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Proc_total	0.1922**	0.1469				0.3345	-0.0444			
	(0.089)	(0.091)				(0.292)	(0.175)			
Proc_total * R&D int ind		0.5697***					6.4965**			
		(0.164)					(2.776)			
Proc_R&D			0.2090		0.0063			-0.2527		-0.2455
			(0.269)		(0.366)			(0.451)		(0.523)
Proc_R&D * R&D int ind			7.9186*		1.9609			58.4314**		16.2770
			(4.079)		(3.283)			(25.236)		(18.656)
Proc_non-R&D				0.1779	0.1683				-0.0280	0.0540
				(0.113)	(0.144)				(0.220)	(0.255)
Proc_non-R&D * R&D int ind				0.5687***	0.4835**				6.8404**	5.5795**
				(0.178)	(0.230)				(2.975)	(2.702)
F.Proc_total	0.0469	0.0095				0.3523	0.1103			
	(0.057)	(0.052)				(0.226)	(0.148)			
F.Proc_total * R&D int ind		0.1056					-1.6208			
		(0.174)					(1.147)			
F.Proc_R&D			-0.1798		-0.2110			0.4936		0.5905
			(0.144)		(0.187)			(0.355)		(0.386)
F.Proc_R&D * R&D int ind			4.4626*		0.5389			47.6446		39.2084
			(2.614)		(2.246)			(38.538)		(46.684)
F.Proc_non-R&D				0.0351	0.0653				0.0696	-0.0006
				(0.071)	(0.089)				(0.178)	(0.189)
F.Proc_non-R&D * R&D int ind				0.0871	0.0659				-1.8733	-2.8441
				(0.192)	(0.222)				(1.369)	(2.365)
Sales_private	0.0077***	0.0071***	0.0073***	0.0070***	0.0071***	0.0259*	0.0192	0.0200	0.0191	0.0170
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.014)	(0.013)	(0.013)	(0.013)	(0.013)
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Obs	175	175	175	175	175	175	175	175	175	175
R-squared	0.208	0.267	0.210	0.267	0.274	0.095	0.194	0.173	0.193	0.210
Number of industries	25	25	25	25	25	25	25	25	25	25
F	2.674	4.137	2.559	4.424	3.350	1.480	1.868	1.969	1.843	2.665

Notes: R&D expenditure, procurement, and sales are measured in millions of constant (2000) dollars. Results from estimation in first differences. Robust standard errors in parentheses.
*** p<0.01, ** p<0.05, * p<0.1.

Table 6: Estimates of the effect of procurement on private R&D activities (contemporaneous and two-years forward effect)

	Dependent: private R&D expenditure					Dependent: R&D employment				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Proc_total	0.2756***	0.2266**				0.5194	-0.0268			
	(0.093)	(0.101)				(0.411)	(0.222)			
Proc_total * R&D int ind		0.5515***					6.7236***			
		(0.190)					(2.301)			
Proc_R&D			0.8648		0.7161			-0.8649		-0.6857
			(0.569)		(0.650)			(0.989)		(0.955)
Proc_R&D * R&D int ind			10.2269**		0.6915			75.5106**		19.2546
			(5.001)		(3.937)			(28.942)		(28.971)
Proc_non-R&D				0.2180*	0.1773				-0.0039	0.1155
				(0.119)	(0.142)				(0.237)	(0.257)
Proc_non-R&D * R&D int ind				0.5802***	0.5793**				6.9070***	6.0897**
				(0.205)	(0.251)				(2.475)	(2.851)
F2.Proc_total	0.0367	0.0298				-0.2508	-0.0550			
	(0.055)	(0.050)				(0.316)	(0.201)			
F2.Proc_total * R&D int ind		0.0421					-4.8024**			
		(0.203)					(2.140)			
F2.Proc_R&D			0.1749		0.0384			-0.5745		-0.8948
			(0.201)		(0.245)			(0.624)		(0.705)
F2.Proc_R&D * R&D int ind			4.1051		0.1185			-22.1657		-13.4245
			(3.317)		(3.167)			(39.094)		(26.366)
F2.Proc_non-R&D				0.0348	0.0305				0.0216	0.1532
				(0.059)	(0.076)				(0.249)	(0.265)
F2.Proc_non-R&D * R&D int ind				0.0457	0.0268				-4.9465**	-4.5979**
				(0.220)	(0.261)				(2.231)	(2.260)
Sales_private	0.0073***	0.0067***	0.0075***	0.0067***	0.0069***	0.0241	0.0235	0.0233	0.0233	0.0234
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.017)	(0.016)	(0.015)	(0.016)	(0.016)
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Obs	150	150	150	150	150	150	150	150	150	150
R-squared	0.270	0.319	0.264	0.304	0.333	0.133	0.311	0.206	0.307	0.317
Number of industries	25	25	25	25	25	25	25	25	25	25
F	3.210	4.627	2.444	4.554	3.680	1.350	2.386	1.826	2.371	2.408

Notes: R&D expenditure, procurement, and sales are measured in millions of constant (2000) dollars. Results from estimation in first differences. Robust standard errors in parentheses.
*** p<0.01, ** p<0.05, * p<0.1.

Table 7: IV estimates of the effect of procurement on private R&D activities

	Dependent: private R&D expenditure					Dependent: R&D employment				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Proc_total	0.1743***	0.1382***				0.1613	-0.0719			
	(0.051)	(0.050)				(0.322)	(0.317)			
Proc_total (R&D int ind)		0.6557***					4.2651***			
		(0.187)					(1.162)			
Proc_R&D			0.1915		0.0085			-0.2389		-0.1386
			(0.168)		(0.177)			(1.012)		(1.102)
Proc_R&D (R&D int ind)			7.8102***		3.1305			65.8876***		45.1747**
			(2.878)		(3.240)			(17.518)		(20.565)
Proc_non-R&D				0.1717***	0.1711***				-0.0837	-0.0496
				(0.060)	(0.066)				(0.382)	(0.414)
Proc_non-R&D (R&D int ind)				0.6524***	0.5394**				4.2967***	2.6616*
				(0.196)	(0.230)				(1.218)	(1.424)
LDV	-0.0280	-0.0878	-0.0542	-0.0915	-0.0973	-0.2748***	-0.3116***	-0.3321***	-0.3082***	-0.3355***
	(0.069)	(0.069)	(0.072)	(0.069)	(0.070)	(0.065)	(0.063)	(0.064)	(0.063)	(0.064)
Sales_private	0.0087***	0.0079***	0.0085***	0.0079***	0.0078***	0.0259***	0.0219**	0.0226**	0.0221**	0.0212**
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.010)	(0.009)	(0.009)	(0.009)	(0.009)
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Obs	175	175	175	175	175	175	175	175	175	175
R-squared	0.112	0.350	0.217	0.344	0.342	0.0242	0.152	0.109	0.152	0.142
Number of industries	25	25	25	25	25	25	25	25	25	25

Notes: R&D expenditure, procurement, and sales are measured in millions of constant (2000) dollars. Results from IV estimation (Anderson-Hsiao). Robust standard errors in parentheses.
*** $p<0.01$, ** $p<0.05$, * $p<0.1$.