Does the Technological Content of Government Demand Matter for Private R&D? Evidence from US States

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Abstract

Governments purchase everything from airplanes to zucchini. This paper investigates the role of the technological content of government procurement in innovation. In a theoretical model, we first show that a shift in the composition of public purchases toward high-tech products translates into higher economy-wide returns to innovation, leading to an increase in the aggregate level of private R&D. Using unique data on federal procurement in US states and performing panel fixed-effects estimations, we find support for the model's prediction of a positive R&D effect of the technological content of government procurement. Instrumental-variable estimations suggest a causal interpretation of our findings.

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1 Introduction

While previous research suggests that R&D and innovation have positive returns[1], it is widely believed that investment in R&D is too low from a social point of view (Jones and Williams, 1998). Recently, an intense discussion among researchers and policymakers has emerged around the globe on whether public procurement can be used as a policy tool to stimulate R&D and innovation. In the United States, several working groups have been established to discuss how to leverage the purchasing power of the federal government to foster innovation (Vonortas, Bhatia and Mayer, 2012). Similarly, in Europe, major initiatives have been launched to stimulate company R&D through public procurement spending (Edler and Georghiou, 2007; EU, 2010, 2011). Also countries like Australia, Brazil, China, and South Korea have started considering public procurement in their innovation policy strategies (OECD, 2011). The main argument for such policy initiatives is that, by enlarging the size of the market, the government can spur private R&D and innovation (for instance, Schmookler, 1966; Rosenberg, 1969; Acemoglu and Linn, 2004; Moser, 2005). Indeed, case-study evidence (Nelson, 1982; Fridlund, 2000; Palmberg, 2002; Ruttan, 2006; Mowery, 2008) and econometric studies at the firm-level (Lichtenberg, 1987, 1988; Aschhoff and Sofka, 2009; Draca, 2012) point toward a positive relationship between government procurement and innovation.[2]

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[1] A positive effect of R&D on output and/or productivity has been found at the country level (e.g., Coe and Helpman, 1995; Barro, 1998), industry level (e.g., Terleckyj, 1980; Griffith, Redding and Van Reenen, 2004; Cameron, Proudman and Redding, 2005), and firm level (e.g., Hall and Mairesse, 1995; Hall and Oriani, 2006; Parisi, Schiantarelli and Sembenelli, 2006).

[2] Geroski (1990), Dalpé, DeBresson and Xiaoping (1992), and Mazzucato (2011) argue that the government has often been an important (and early) customer of technologically advanced products. Nelson (1982), Ruttan (2006), and Mowery (2008) highlight that a number of new technologies—such as semiconductors, large passenger jets, the Internet, and the GPS—have been developed with the impetus from US government demand. Non-US examples of public procurement creating the initial market for new technologies are the cases of digital telephone switching technologies in Sweden and Finland (Fridlund, 2000; Palmberg, 2002) or the X2000 high-speed train in Sweden (Edquist and Zabala-Iturriagagoitia, 2012). Lichtenberg (1987, 1988) and Draca (2012) use US data to show a positive impact of federal government purchases on firms' R&D expenditures. For Germany, Aschhoff and Sofka (2009) provide evidence that government

However, while governments purchase everything from airplanes to zucchini, notably absent in the literature is an empirical investigation of the question whether and how the innovation effects of public demand depend on the types of products purchased by the government.[3] This lack of reported empirical research is surprising, given the differential potential of industries to generate innovation and growth (see, for instance, Mowery and Rosenberg, 1998; Mowery and Nelson, 1999). Only recently, Cozzi and Impullitti (2010) provided a theoretical exploration of the innovation effects of the government spending composition by incorporating public purchases that can vary across industries with different technological intensities in a quality-ladder model of endogenous growth. In the model, a shift in the composition of public purchases toward high-tech products creates an additional market for such products. The rewards for successful innovation increase, which encourages firms to engage in R&D, raising the total amount of private R&D in the economy. Accordingly, Cozzi and Impullitti refer to the technological content of government purchases as a de facto innovation policy instrument. However, they lack detailed industry-level data on government procurement to thoroughly test their model's predictions.[4]

In this paper, we provide a comprehensive econometric assessment of the link between the technological content of government purchases and private R&D activities. The empirical analysis is based on a theoretical model that builds on the previous work by Cozzi and Impullitti (2010). We further develop their framework by modeling how industries differ with respect to their technological content (that is, quality jump). Specifically, using previous findings on the size distribution of innovation (among others, Scherer, 1965, 1998; Harhoff, Scherer and Vopel, 2005; Silverberg and Verspagen, 2007), we model

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purchases increase firms' sales with new products.

[3] Lichtenberg (1988) and Draca (2012) consider firms' sales to the government aggregated over various products, but they do not separate the innovation effects of procurement by product category. Nekarda and Ramey (2011) investigate the impact of industry-level changes in government spending on output and wages, not on innovation.

[4] Cozzi and Impullitti calibrate their model using government investment data from only two coarse-grained sectors (Equipment/Software and Structures), which are supposed to approximate public demand in high-tech and low-tech industries, respectively.

the size of the quality jump after a successful innovation to be Pareto distributed. This modification allows a more rigorous analytical treatment of the model with regard to stability properties, transitional dynamics, and the social optimum (Wiederhold, 2009). However, we are particularly interested in the model's balanced growth properties from which we derive a simple equation for the relationship between the technological content of government purchases and private R&D that can be straightforwardly estimated using econometric techniques.

The empirical analysis is performed at the level of US states for the period 1999–2009. We create a unique panel data set that relates private R&D expenditures in US states to the technological content of federal procurement in these states. We use administrative federal procurement data provided by the US General Services Administration. These data are not only representative of federal procurement spending in the US as they cover all US federal procurement prime contracts valued at more than $2,500, but also contain a detailed industry classification of procurement contracts. Using this information, we measure the technological intensity of public procurement as the share of federal procurement in high-tech industries performed in a state in total federal procurement in that state, considering only non-R&D procurement contracts awarded to private-sector firms.

The results of the econometric analysis show that an increase in the technological content of government procurement induces additional private R&D in the economy. In panel fixed-effects estimations, we find that the elasticity of private R&D with respect to the high-tech procurement share is 0.08. In monetary terms, each procurement dollar that the government shifts from non-high-tech ("low-tech") industries to high-tech industries induces additional 21¢ of private R&D. We also show that an increase in high-tech procurement leads to additional private R&D for any given level of low-tech procurement.

Several robustness tests and instrumental-variable (IV) estimations support a causal interpretation of our findings. We show that the results are robust to (i) further determinants of private R&D (for instance, size of the private market, R&D procurement, universities, and public R&D support measures such as R&D subsidies and taxes); (ii) different sources of spurious correlation; (iii) high-leverage observations; (iv) changes in the construction of main variables. The fixed-effects results are also confirmed by the IV analysis, which addresses further potential endogeneity issues due to omitted variables and reverse causality. In the IV approach, we only consider variation in the technological content of federal procurement that occurs due to changes in the number of senators from a given state who are members of the Appropriations Committee that authorizes and appropriates funds. The instrument relies on the idea that politicians channel government spending to their constituencies to reward their voters and maximize their reelection chances (Aghion et al., 2009; Cohen, Coval and Malloy, 2011). Importantly, politicians choose those types of projects that are highly visible and popular with voters, and effective in raising (or securing) jobs and income in the short run. Typical projects in this respect are social facilities and large infrastructure investments. By funding these projects, politicians change the technological composition of federal procurement in their states. Being subject to individual and political factors (for instance, death, retirement, seniority, and majority-party affiliation), both the arrival of vacancies and vacancy filling on the Appropriations Committee are unrelated to a state's characteristics and current economic strength, so the instrument can be considered exogenous.

The central result of this article is that the government can influence private R&D activities through the technological composition of its purchases. This offers potential to co-opt procurement into the innovation policy portfolio. Specifically, redistributing procurement spending from low-tech to high-tech industries appears to be a particularly appealing strategy as it stimulates private R&D without the need to increase the government budget (for instance, by raising taxes or debt). However, there may be other costs associated with a change in the government's purchasing behavior. For instance, if low-tech and high-tech products are not (close) substitutes, then purchasing at the high-end of technology might hamper the functioning of the public sector. Even for products that are close substitutes there may be additional consequences of shifting spending from low-tech to high-tech industries, such as structural change and (labor-)adjustment processes. While we discuss these costs in the paper, future research needs to quantify them before public procurement for furthering the objectives of innovation policy can be deemed appropriate.

The remainder of the paper is organized as follows. Section 2 introduces the theoretical model that provides the basis for the empirical analysis. In Section 3, we present our identification strategy for the empirical assessment of the model's implications. In Section 4, we introduce the data and describe the construction of the key variables. Section 5 reports the empirical results. Section 6 discusses the implications of our findings for policy and research.

2 The Model

The economy in the model is closed and consists of two sectors: a final goods (or manufacturing) sector and a research sector. To avoid unnecessary complications, and to highlight the basic forces at work, labor is the only input factor used in both sectors and is not further differentiated. There is a continuum of industries in the unit interval indexed by $\omega \in [0,1]$, with each industry producing exactly one consumption good (or product line). The outputs of the different industries substitute only imperfectly for each other. The set of commodities is fixed over time. Innovation is vertical, improving the quality of a consumption good, which requires the R&D efforts of firms targeted at that particular product. Let the discrete variable $j \in \{0, 1, 2, ...\}$ denote the quality level. An innovation in industry ω leads to a quality jump from j to $j+1$. The quality increments, denoted by λ, are independent of each other.

On the consumer side, each household is modeled as a dynastic family whose size grows at an exogenous rate n. Household members' labor supply is inelastic with respect to their wage. The total number of individuals at time $t = 0$ is normalized to unity (that is, labor is the numeraire). Thus, the working population at time t equals $L(t) = e^{nt}$. The life-time utility of a representative household is given by:

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

where ρ (with $\rho > n$) denotes the rate of time preference, and $\log u(t)$ represents the flow of utility per household member at time t. An individual's instantaneous utility is represented by:

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

where $d(j,\omega,t)$ is the consumption of quality j in product line ω at time t. Therefore, the utility derived by an individual from consumption equals the sum of the quality-weighted amounts of consumption in all industries $\omega \in [0,1]$. The preferences in (2) imply that a consumer enjoys 1 unit of good ω that was improved j times as much as $\lambda^j(\omega,t)$ units of the same good as if it had never been improved; $\lambda(\omega,t) > 1$. The logarithmic functional form in (2) is chosen for simplicity and does not affect the main results.

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

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

where $B(0)$ is the *ex ante* endowment of asset holdings of a representative household, $w(t)$ is the individual wage rate, $T(t)$ is a per capita lump-sum tax, and $c(t)$ is the flow of individual consumer expenditures. Under the assumption that when a household member is indifferent between two quality vintages, the higher-quality product is bought, then the household maximization problem yields the following static demand function:

$$d(j,\omega,t) = \left\{ \begin{array}{cc} \frac{c(t)}{p(j,\omega,t)} & j = j^{max}(\omega,t) \\ 0 & otherwise \end{array} \right\}, \tag{3}$$

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

The dynamic optimization problem, that is, the allocation of lifetime expenditures over time, consists of maximizing the discounted utility (1) subject to (2), (3)

$$\frac{\dot{c}(t)}{c(t)} = r(t) - \rho. \tag{4}$$

The intertemporal optimization condition (4) implies that if the market interest rate, r, is above the time preference rate, ρ, consumers increase savings "today" and spend more "tomorrow," resulting in a rise of consumption over time (vice versa for $r < \rho$). A constant consumption expenditures path is optimal when r equals ρ. Because preferences are homothetic, aggregate demand in industry ω at time t is given by $D(j, \omega, t) = d(j, \omega, t)L(t)$.

At any point in time, only one firm possesses the technology to produce 1 unit of the highest-quality product using 1 unit of manufacturing labor, $Y = L_Y$. The best-practice firm has a quality advantage of λ over the next best firm in the industry. The optimal strategy for the quality leader is to set a limit price $p_L(\omega, t)$ that prevents any other firm in the industry from offering its product without losses. The highest price the quality leader can set to capture the entire industry market is their lead over the next best quality follower, implying $p_L(\omega, t) = \lambda(\omega, t)w = \lambda(\omega, t)$. If the quality leader sets a price above the limit price, she will immediately lose all of her customers.

Government procurement is financed by lump-sum tax revenues and is strictly non-negative in all industries at any point in time. The government budget is assumed always to be balanced. Denoting per capita public demand in industry ω at time t by $G(\omega, t)$, and recalling that marginal production costs are unity because labor is the numeraire, the quality leader in each industry earns a profit flow:

$$\pi(\omega, t) = [\lambda(\omega, t) - 1] \times \left[\frac{c(t)L(t)}{\lambda(\omega, t)} + \frac{L(t)G(\omega, t)}{\lambda(\omega, t)}\right], \tag{5}$$

where $\lambda(\omega, t)\left[\frac{c(t)L(t)}{\lambda(\omega,t)} + \frac{L(t)G(\omega,t)}{\lambda(\omega,t)}\right]$ corresponds to market size (sales to private and public customers) in industry ω. The factor $[\lambda(\omega, t) - 1]$ is the markup over the marginal cost.

There is free entry into R&D, so firms can devote their research effort to developing products in any industry. Firms target their R&D resources only to industries in which they are not the current quality leader; this is so that they do not cannibalize their current monopoly rents.[5] Labor is the only input used in R&D, and it can be freely allocated between manufacturing and research, implying that all workers earn the same wage $w = 1$. The aim of each firm's R&D efforts is superior quality and to monopolize the market by achieving a patent of infinite patent length. All firms have access to the same R&D technology. In industry ω at time t, a firm employing $l_i(\omega, t)$ units of labor in R&D faces a Poisson arrival rate of innovation, $I_i(\omega, t)$, equal to:

$$I_i(\omega, t) = \frac{A l_i(\omega, t)}{X(\omega, t)}, \tag{6}$$

where $A > 0$ is a given technology parameter, and $X(\omega, t)$ is a function that captures the exogenously given industry-wide difficulty of conducting R&D.

The innovation process in (6) is stochastic, with $I_i(\omega, t)dt$ being the instantaneous probability of winning the R&D race and thus becoming the next quality leader. We follow Jones (1995) and Segerstrom (1998) in assuming that the R&D difficulty in an industry grows at a rate proportional to the arrival of innovation ("no scale effect" property):

$$\frac{\dot{X}(\omega, t)}{X(\omega, t)} = \mu I(\omega, t), \tag{7}$$

where $I(\omega, t) = \sum_i I_i(\omega, t)$ denotes the industry-wide instantaneous arrival rate of the innovation, $\mu > 0$ is an exogenously given parameter that captures the scientific opportunities in the economy, and $X(\omega, 0) = X_0$ for all ω.

In previous quality-ladder growth models (Grossman and Helpman, 1991*b*,*a*;

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[5] 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 both Industrial Organization (Fudenberg et al., 1983; Fudenberg and Tirole, 1985) and endogenous growth models. However, as discussed by Cozzi (2007*a*), in models with a free-entry competitive R&D environment and Nash competition between researchers (as assumed here), the current quality leaders are actually indifferent between investing or not in R&D, but if they do, the other features of the equilibrium are not affected. See also Etro (2004).

Aghion and Howitt, 1992; Li, 2001, 2003), different industries were usually treated as being structurally identical. Thus, the economy could be regarded as if it consisted of only a single industry. To overcome the symmetric treatment of industries, Cozzi and Impullitti (2010) assume that the size of the quality improvement after a successful innovation is stochastic and industry-specific. We modify Cozzi and Impullitti's modeling framework in that we impose a specific assumption on how industries differ in terms of their innovation potential. This allows us to solve the model for the steady state algebraically, which yields an analytical expression relating the technological content of public procurement to private R&D to guide our econometric analysis. Consistent with the empirical literature on patent values (among others, Scherer, 1965, 1998; Harhoff, Scherer and Vopel, 2005; Silverberg and Verspagen, 2007), we assume the size of the quality jump after a successful innovation to be drawn from a Pareto distribution (Minniti, Parello, and Segerstrom, Forthcoming).[6] The probability density function of a Pareto distribution with a shape parameter of $1/\kappa$, $\kappa \in (0,1)$, and a scale parameter equal to 1 reads:

$$g(\lambda) = \frac{1}{\kappa}\lambda^{-\frac{1+\kappa}{\kappa}}, \lambda \in [1, \infty). \tag{8}$$

For analytical tractability, we assume that the initial distribution of λ values is given by $g(\lambda)$ at $t = 0$, and it does not change over time as the R&D dynamics start and successfully innovating firms draw new values of λ. Notice further that $X(\omega, t) = X_0$ for all ω implies that $I(\omega, 0) = I_0$. Hence, a symmetric equilibrium path exists, along which $I(\omega, t) = I(t)$ and $X(\omega, t) = X(t)$ for all ω. As is common in the literature on quality-improving innovation and growth, in the further analysis we focus on this symmetric equilibrium.

The government allocates procurement across industries according to the following "rule" (Cozzi and Impullitti, 2010):

$$G(\omega, t) = \bar{G} + \gamma\varepsilon(\omega, t), \ 0 \leq \gamma \leq 1, \tag{9}$$

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

where

$$\bar{G} \equiv \int_0^1 G(\omega) d(\omega),$$

$$\varepsilon \equiv \begin{cases} -\varepsilon_1 & \text{for } \lambda(\omega, t) < \frac{1}{1-\kappa} \\ \varepsilon_2 & \text{for } \lambda(\omega, t) \geq \frac{1}{1-\kappa} \end{cases},$$

$$0 < \varepsilon_1 < \bar{G},$$

$$0 < \varepsilon_2 < \bar{G}.$$

In (9), $\bar{G}$ denotes the average per capita public procurement, that is, the amount of public demand a quality leader in industry ω will receive if the government spreads its expenditures $G(\omega)$ evenly across industries.[7] The parameter γ determines the technological content of procurement. In particular, γ indicates the portion of government demand in industries with quality jumps above or below the average in the economy. An equal treatment of all industries occurs for $\gamma = 0$. $\gamma > 0$ implies that public purchases in industry ω will be higher (lower) than in the symmetric case if the quality improvement in this industry is greater (smaller) than the average economy-wide quality increment. For simplicity, we assume that once an industry experiences a quality jump above (below) the economy-wide average and $\gamma \neq 0$ holds, the government spends more (less) in this industry, irrespective of how far above (below) the average the quality jump is in this industry.

It is straightforward to show that the strictly positive values ε_1 and ε_2, which indicate how much government purchases in "low-jump" or "high-jump" industries deviate from the average, cannot be chosen independently (see Appendix A.1). As the distribution of the λ values does not change over time, there is always the same share of industries with quality increments above or below the average. Moreover, to highlight the effects of the technological content of government purchases, we assume that $\bar{G}$ is constant (unless otherwise

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[7] Because there is a continuum of industries indexed on the unit interval, average values in the model equal total values.

noted).

Under the assumption of no arbitrage on the stock market, and using (9) to solve for the expected profits earned by a successful innovator (see Appendix A.2), we obtain the following expression for the discounted value of the expected profit flow of a firm winning an R&D race:

$$\upsilon^e(\omega,t) = \frac{\frac{\kappa}{1+\kappa} L(t)[c(t) + \bar{G} + \gamma\Gamma]}{r(t) + I(t) - \frac{\dot{x}(t)}{x(t)} - n}, \tag{10}$$

where $\Gamma \equiv \varepsilon_2 \left(1 \Big/ \left[1 - (1-\kappa)^{1/\kappa}\right] - 1\right) > 0$ and $x(t) \equiv X(t)/L(t)$ is a measure of the relative, that is, population-adjusted, R&D difficulty. Because the RHS of (10) does not contain any industry-specific variables, $\upsilon^e(\omega,t) = \upsilon^e(t)$ is the average market valuation of a successful innovation in the economy. In (10), the effect of "creative destruction" is revealed; the more research that occurs in an industry, the shorter, *ceteris paribus*, is the duration of the accruing monopoly profits and the smaller are the incentives to innovate. By subtracting the rate of population growth, n, in the denominator of (10), we also take into account that aggregate consumer markets and, thus, profits earned by a successful innovator increase with a growing population.

Equation (10) already highlights the market-size effect in innovation: the greater L, c, or $\bar{G}$ are, that is, the larger the market is for a new product, the more profitable it is to be the producer of that good. Another important implication of (10) is that the profitability of a successful innovation in the economy increases in γ. In other words, it is not only the size of the government market that matters for the valuation of a successful innovator, but also how government expenditures are distributed across industries. Specifically, the relatively more the government purchases in industries with above-average quality jumps, the higher the rewards for successful innovation activities become on average. In what follows, we will show that the positive effect of government market size on expected firm value translates into more research effort in the whole economy.

The R&D equilibrium condition can be derived from the condition for profit maximization in R&D and (10) as:

$$\frac{x(t)}{A} = \frac{\frac{\kappa}{1+\kappa}\left[c(t) + \bar{G} + \gamma\Gamma\right]}{r(t) + I(t) - \frac{\dot{x}(t)}{x(t)} - n}, \tag{11}$$

while the resource constraint (that is, the labor-market clearing condition) of the economy reads (see Appendix A.3):

$$1 = \frac{c(t) + \bar{G} - \gamma\kappa\Gamma}{1+\kappa} + \frac{I(t)x(t)}{A}. \tag{12}$$

The labor-market equilibrium in (12) holds for all t in and outside the equilibrium, because factor markets clear instantaneously.

Along the balanced-growth path (see Appendix A.4), all endogenous variables develop at a constant (although not necessarily at the same) rate and the research intensity, $I(t)$, is common across industries. Using these results, as well as (6) and (A.12), the amount of labor devoted to R&D in the steady state can be derived as:

$$L_I^* = \frac{\kappa n\left(1+\gamma\Gamma\right)}{n\left(1+\kappa-\mu\right)+\mu\rho} \times L. \tag{13}$$

Equation (13) reveals the main result of the model; namely, that a positive relationship exists between the technological content of government procurement, measured by γ, and the amount of private R&D performed in the economy.[8] Keeping everything else constant, an increase in the share of procurement in industries with above-average quality jumps, γ, instantly raises the expected value of becoming a quality leader. This occurs because higher quality jumps imply higher markups over marginal cost and, thus, higher rewards for successful innovators (see (10) and (A.8)). Firms respond by investing more heavily in R&D, so the economy-wide level of company R&D increases. Due to diminishing returns of the R&D technology in (6), the increase in private R&D must be permanent to maintain constant rates of technological change and

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[8] Since economic growth in our model is entirely driven by firms' R&D investment, a positive relationship between γ and the macroeconomic growth rate is trivially established. However, as we are interested in the question of whether government market size affects innovation, we focus on the impact of an increase of γ on private R&D.

economic growth along the balanced-growth path.

Finally, the positive influence of the technological intensity of government procurement on private R&D in the long-run equilibrium suggested by Equation (13) also holds off-steady-state. This can be easily seen from the resource constraint (12), which implies $L_I(t) = \left\{1 - \left[c(t) + \bar{G} - \gamma\kappa\Gamma\right] / (1+\kappa)\right\} L(t)$.[9]

3 Empirical Specification and Estimation Issues

The main result of our theoretical analysis in Section 2 is that an increase in the technological content of public procurement (that is, the share of procurement in industries with above-average quality jumps) stimulates private R&D in the economy. For the purpose of the empirical implementation of the model, we proxy industries with above-average quality jumps by high-tech industries.[10] As shown in Oliveira Martins, Scarpetta and Pilat (1996), markups (which are theoretically equivalent to quality jumps) are indeed above the economy-wide

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[9] A number of other model features are worth noting. First, the long-term growth rate in the economy depends only on the rate of population growth, n, technological research opportunities, μ, and average innovation size, κ. These parameters are, in principle, outside the control of government. Thus, the model yields a policy ineffectiveness proposition according to which the government cannot influence the long-term growth rate (see also Jones, 1995, 1999). Changes in the technological composition of government purchases or other policy measures can nonetheless have temporary effects on growth, that is, they can influence the level of the balanced-growth path. Second, the balanced-growth equilibrium is either locally saddle-path stable or locally indeterminate, but never unstable. In other words, there exists either one or an infinite number of adjustment trajectories toward the steady state (see also Cozzi, 2007*b*). Third, the model exhibits transitional dynamics, and policy can influence the growth rate along the transition to the balanced-growth equilibrium. Fourth, considering the various externalities apparent in the model, *laissez-faire* growth is not optimal. When calculating the social optimum, we find that the relationship between the technological content of government procurement and social welfare is nonlinear. It is, therefore, not welfare-maximizing if the government spend all of its resources on industries with the highest innovative capabilities. See Wiederhold (2009) for more details.

[10] In a theoretical framework similar to ours, Cozzi and Impullitti (2010) also make the assumption that high-tech industries have above-average quality jumps.

average in high-tech industries.[11]

Ideally, we would like to test the implications of the model in a cross-country setting over time. However, reliable international data that permit to distinguish between procurement in high-tech and other industries are hardly available.[12] Only the United States provides high-quality administrative data on federal procurement, cross-classified by year and industry. Making additional use of the fact that the US data contain information about the place where the federal procurement contracts are performed, we construct a unique panel data set that allows us to test our model's predictions at the level of the US states in the period 1999–2009.

Equation (13) provides the starting point for our econometric analysis of the impact of the technological content of government procurement on private R&D. Log-transforming equation (13) and adding state and time fixed effects yields:

$$\begin{aligned} \log R\&D_{i\,t} &= \alpha + \beta_1 \log HIGH\_TECH\_SHARE_{i\,t-1} + \\ &+ \beta_2 \log NON\_R\&D\_PROC_{i\,t-1} + \beta_3 \log POP_{i\,t-1} + \\ &+ \xi_i + \nu_t + u_{i\,t} \end{aligned} \tag{14}$$

where $R\&D_{i\,t}$ is the amount of company-funded R&D expenditures in state i

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[11] Oliveira Martins, Scarpetta and Pilat (1996) estimate markups over marginal cost for 29 manufacturing industries for the G7 countries in the period 1970–1992. For industries that the Bureau of Labor Statistics (BLS) classifies as high-tech (we also adopt the BLS definition, see Section 4.1), the estimated average markup is 34%, while for medium- and low-tech industries the average markup is only 20%. This pattern is even more pronounced in the US. Here, the average markup in high-tech industries is more than three times higher than that in the remaining industries (46% vs. 13%).

[12] For a number of European countries, data on public procurement by industry can be obtained from tender information published in the Official Journal of the European Union. However, a compulsory requirement to publish data exists only for procurement tenders on a Europe-wide scale. Since the share of Europe-wide tenders greatly differs across Member States, these data are not suitable for cross-country comparisons.

in year t.[13] $HIGH\_TECH\_SHARE_{it-1}$ indicates the technological intensity of procurement (γ in equation (13)). It is defined as federal non-R&D procurement in high-tech industries as a share of total federal non-R&D procurement in the private sector in state i at time $t-1$. The $HIGH\_TECH\_SHARE$ is lagged by one period mainly for two reasons: first and foremost, we assign the procurement volume to the year of contract signature, whereas contracts might actually start some time after they are signed (see Section 4.1 for details). Second, including the high-tech procurement share with a lag likely reduces reverse causality bias (see also Draca, 2012).

$NON\_R\&D\_PROC_{it-1}$ is the total amount of federal non-R&D procurement in a state. Including $NON\_R\&D\_PROC_{it-1}$ as a control variable ensures that the estimated coefficient on $HIGH\_TECH\_SHARE$ shows only the effect of a change in the technological composition of government procurement that is suggested by the theoretical model, as opposed to a volume effect resulting from a change in total procurement.[14] Specifically, when keeping the total amount of procurement constant, any increase (decrease) in $HIGH\_TECH\_SHARE$ necessarily implies more (less) procurement in high-tech industries at the expense of procurement in low-tech industries. POP_{it-1} is the number of state inhabitants, accounting for the effect of the total market size on private R&D.[15]

Further, Equation (14) contains a full set of state fixed effects, ξ_i, that

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[13] In the simplified model economy, R&D employment corresponds to R&D expenditures because labor is the only production factor (that is, there are no materials, laboratories, machines or the like). However, we use total R&D expenditures rather than R&D employment in the empirical analysis because in reality, the wages and salaries of R&D employees comprise only part of total firm R&D spending. According to the US Bureau of Economic Analysis, using data from the National Science Foundation, the wages of scientists, engineers, and support personnel accounted for roughly 38% of R&D expenditures in the scientific R&D services sector in the period 1997–2007 (Robbins et al., 2012).

[14] The effect of an increase in procurement in high-tech industries for a given amount of procurement in other industries in analyzed in Section 5.4.

[15] See also Sokoloff (1988), Acemoglu and Linn (2004), and Moser (2005) for previous empirical evidence on the role of market size in innovation. *POP* is lagged by one period to take into account that firms' R&D investment decisions are based on the current market information.

pick up all kinds of unobserved state-specific factors that are constant over time. In addition, a full set of year dummies, ν_t, absorbs unobserved effects that equally affect all states; for instance, business cycles, changes in (national and global) demand and market conditions, or national policy changes. The year dummies also account for changes in technological opportunities (μ in equation (13)). The error term is denoted by u_{it}.[16]

A straightforward way to assess the impact of the technological content of public procurement on private R&D employment is to estimate equation (14) by OLS; we will refer to this specification as panel fixed-effects (FE) estimation. However, drawing causal inferences on the basis of a simple FE estimation of Equation (14) is not foolproof. Specifically, there might be further unobserved factors that are correlated with both private R&D and the technological intensity of government procurement, or that may even jointly determine them. For instance, the amount of federal procurement contracts in high-tech industries might depend on a variety of unobserved time-variant state characteristics (for instance, state-specific policy changes and regulations) that are also systematically related to private R&D. Furthermore, reverse causality problems arise if, for example, the likelihood to receive a procurement contract and firm's R&D capabilities are related (Lichtenberg, 1988).

If such confounding factors exist and are not captured by the included control variables, or by the fixed effects, the FE estimates on the impact of the technological content of public procurement on private R&D might be biased, while the direction and severity of the bias is not clear a priori. To address these endogeneity concerns, we apply an instrumental-variable (IV) strategy that exploits exogenous variation in the share of federal procurement in high-tech industries to identify its effect on private R&D (see Section 5.3).

In both approaches, FE and IV, we cluster standard errors by state and year[17] to account for possible correlations in the error structure within states

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[16] In Section 5.2, we augment Equation (14) to account for other determinants of private R&D, such as sectoral differences between states, R&D procurement, effects from universities, public R&D support measures, and lobbying spending.

[17] See Cameron, Gelbach and Miller (2011) for a theoretical derivation of the two-way clustering method and Acemoglu (2003) and Englmaier, Roider and Sunde (2012) for

over time and within years across states (see also Wilson, 2009).[18]

4 Data and Variable Construction

4.1 Technological Intensity of Public Procurement

We use administrative data on individual federal procurement contracts in the United States from the Federal Procurement Data System—Next Generation (FPDS-NG), provided by the General Services Administration (GSA). In the United States, federal agencies are required, by the Federal Acquisition Regulation, to report directly to the FPDS-NG all prime contract actions above the micropurchase threshold of $2,500 for companies that are separate legal entities (Goldman, Rocholl and So, 2010).[19] In total, our data cover more than 98% of all federal procurement actions of agencies subject to the reporting requirement (FPDS-NG, 2007).[20] In our period of analysis, 1999–2009, the FPDS-NG database contains approximately 21.5 million contract actions. The information in the FPDS-NG procurement data encompasses, inter alia, the contract volume (in current USD), award and completion dates, the place of performance, whether or not a contract is primarily for R&D, Federal Prod-

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empirical applications.

[18] We tested several alternative ways to correct for serial correlation in our sample. First, we performed FGLS regressions using the Prais-Winsten transformation, which explicitly models the serial correlation in the error term. In case of AR(1) serial correlation and if strict exogeneity holds, using the Prais-Winsten transformation is asymptotically more efficient than the FE estimator. However, when T is small and strict exogeneity does not hold, FGLS tends to exacerbate a potential bias (Wooldridge, 2002a, 2002b). Second, we used the method developed by Baltagi and Wu (1999), who derive a transformation of the data that removes the AR(1) component. Results were similar in these additional specifications.

[19] Before 2004, only contracts of more than $25,000 had to be reported. Contracts under $25,000 account for only 2% of total procurement (FPDS-NG, 2007). However, to ensure that the change in the reporting threshold does not affect our results, we additionally estimated all specifications reported below (i) with an additional dummy variable taking the value of 1 after the change in the reporting obligations came into force, and (ii) with the dummy variable interacted with all other explanatory variables. These specifications yielded similar results to those reported below.

[20] There are only a few exceptions to the reporting requirement, the largest being the US Postal Service.

uct and Service Code (PSC), and, since 2001, the NAICS-classified industry to which a contract can be assigned. Procurement contracts awarded by non-federal public entities are not included in the data.[21]

Our indicator for the technological content of government procurement is defined as the share of federal non-R&D procurement in high-tech industries in total federal non-R&D procurement in a state and year. We use only federal non-R&D procurement contracts, because, in accordance with the theoretical model, we are interested in the effect of increasing market size due to government demand on private R&D. Federal R&D procurement, instead, essentially means that firms conduct R&D by the order of the government (David, Hall and Toole, 2000; GSA, 2005).

To construct the indicator for the technological content of procurement, we proceed as follows. First, we assign individual procurement contracts to high-tech industries, using the NAICS information contained in the FPDS-NG data and the high-tech industry definition of the Bureau of Labor Statistics (BLS) (Hecker, 2005). According to the BLS definition, there are fourteen high-tech industries at the four-digit NAICS level (see Table A.1); all remaining industries are classified as non-high-tech.[22] However, in the FPDS-NG data, NAICS codes are not always available for contracts prior to 2001. Thus, to obtain a consistent time series at the NAICS level also for the years before 2001, we

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[21] Procurement by non-federal public agencies (that is, state and local agencies) may constitute a significant part of total public procurement (Audet, 2002). However, non-federal public procurement data are not provided at a level of detail necessary for our analysis. Moreover, there is no evidence of systematic differences in the technological content of purchases by federal and non-federal public agencies (Coggburn, 2003). Finally, federal procurement is more likely to be independent of state-level characteristics than non-federal procurement, thereby reducing the problem of endogeneity discussed in Section 3.

[22] The BLS classifies industries as high-tech if the percentage of science, engineering, and technical occupations in total employment exceeds the average for all industries at least by a factor of 5 (Hecker, 2005). An alternative classification of high-tech industries, based on R&D expenditures, is provided by the BEA in its R&D Satellite Account (Fraumeni and Okubo, 2005). However, in the R&D Satellite Account, a large part of R&D before 2004 was erroneously attributed to the wholesale trade industry sector. In reality, this R&D was mostly undertaken in pharmaceutical and computer manufacturing companies. Despite the fact that since 2004 the NSF has released a revised industry classification, the BEA still uses the unrevised methodology (NSF, 2007; Robbins et al., 2007).

made use of the fact that PSC information is available for the entire observation period. and developed a PSC-NAICS concordance based on contract data from 2001 to 2009 for which both classifications were consistently provided. This allowed us to assign NAICS codes to those procurement contracts where NAICS information was originally missing.[23] Since in our analysis we are interested in the effects on private R&D, we exclude federal procurement contractors in the public sector (NAICS 92).

Second, to assign procurement contracts to states, we use the information on the place of contract performance.[24] We restrict our analysis to the 50 US states and District of Columbia (DC)[25]; federal procurement contracts performed outside the United States are excluded. Third, we assign the total contract value to the year of contract signature reported in the contracts data, even if contracts have a several-year duration.[26] Finally, we aggregate

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[23] If more than one NAICS code corresponded to a PSC, each of the respective NAICS industries received a share of the contract's gross value that equaled its frequency of occurrence.

[24] In the empirical analysis, we use only federal prime contracts, which might cause measurement error in the high-tech procurement share if the likelihood that federal prime contract recipients reward subcontracts to firms in other states differs between low-tech and high-tech contracts. Unfortunately, there was no reporting requirement for subcontracts prior to 2010 (see https://www.fsrs.gov), so we are not able to account for subcontracting in our analysis. To get an idea whether subcontracting could confound our results, we collected data on the value of first-tier sub-awards entered in the Federal Funding Accountability and Transparency Act Subaward Reporting System (FSRS) for the year 2012 (www.USASpending.gov). These data are collected from two sources. First, agencies must report prime contract award information through the FPDS-NG (the data used in this paper). Second, all prime contract awardees must report subcontracts to the FSRS. We find that only 4.1% of the value of prime contracts in a state are subcontracted to other states, while this share is very similar in high-tech industries (3.8%) and low-tech industries (4.2%). Therefore, we are confident that subcontracting does not confound our results.

[25] For the ease of exposition any reference to "state" in this paper also includes DC.

[26] We do so for three reasons. First, the FPDS-NG data do not always contain information on the end date of contracts; hence, it is not always possible to distribute the value of multi-year contracts over the contract duration. Second, once a firm signs a government contract, the total contract value is known and the firm can plan accordingly. We thus think that most of the increase in R&D due to increased government sales will happen up-front. Third, it appears to us that how the total contract value is distributed over the contract duration is a critical issue chiefly at the firm level. Indeed, at the firm level, our strategy would likely cause a "spiky" distribution of procurement volume, as there would always be peaks in the periods of contract signing and no procurement at all in the other

contract value by type of industry, state, and year and compute the share of federal procurement in high-tech industries in total procurement in a state and year.[27] We use the gross value of procurement contracts, that is, the number of dollars initially obligated by an action.[28] Contract values are converted from current into constant USD using the Government Consumption Expenditures and Gross Investment Price Index with base year 2000 from the Bureau of Economic Analysis (BEA).

4.2 Private R&D

We use data on company-funded private R&D spending from the US Survey of Industrial R&D (SIRD), administered by the National Science Foundation (NSF). The NSF surveys a stratified representative sample of firms with five or more employees to collect information on all domestically performed R&D expenditures by the source of funding (private and public) and state of performance.[29] We focus on company-funded private R&D, because we want to investigate whether an increase in the size of high-tech markets due to government procurement creates incentives for additional R&D spending by firms. The SIRD data are biannual from 1981 to 1997 and annual since then.

The R&D series from the NSF has a non-negligible number of missing val-

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periods, a situation that could have important consequences for the econometric analysis. However, at the aggregate level (US states) at which we are operating, whether or not the value of multi-year contracts is distributed over the contract period is less critical because in every period there are firms receiving government contracts. Moreover, the higher the spatial level of aggregation, the smoother the distribution of procurement spending. In fact, we find the volume of government procurement by state to be relatively "smooth."

[27] We dropped two individual contracts, a $68 billion contract awarded in Illinois in 2006 and a $55 billion contract in Pennsylvania in the same year. These values correspond to 16 (Illinois) or 8 (Pennsylvania) times the yearly average value of *all* contracts awarded in these states between 1999 and 2009. However, keeping both contracts in our sample leaves all results unaffected (details available on request).

[28] Subtracting deobligations does not change the results.

[29] Thee SIRD was redesigned in 2008 to provide a richer breakdown of sources of funds for intramural R&D (see Wolfe, 2008, for details). However, since this change in the survey design equally affected all states, the year dummies in Equation (14) ensure that our results are not influenced by the change. In unreported regressions, we also interacted a dummy variable indicating whether the private R&D data were provided by the new survey with all regressors, without any impact on our results.

ues because disclosure restrictions forbid the publication of information when the number of surveyed firms in a state is small (Wolfe, 2012). However, the severity of this problem generally declines over time, so we start our analysis in 1999. This considerably decreases the number of missing values for company-funded R&D, improving the reliability and representativeness of the results.[30] R&D expenditures are converted into constant dollars, using the GDP deflator for the year 2000.[31]

5 Empirical Evidence

5.1 Baseline Results

This section reports the baseline results of our empirical analysis. We begin by providing a visual inspection of the relationship between the technological composition of government procurement and private R&D. Figure 1 shows this relationship for each state individually. It is easy to see that the high-tech procurement share and private R&D follow similar patterns in the majority of states.

The first visual impression of a positive association between the technological content of federal procurement and private R&D is confirmed by Figure 2, which plots the share of federal procurement in high-tech industries (lagged by one year and in logs) against private R&D (in logs); the correlation between both variables is 0.38 ($p < 0.01$).

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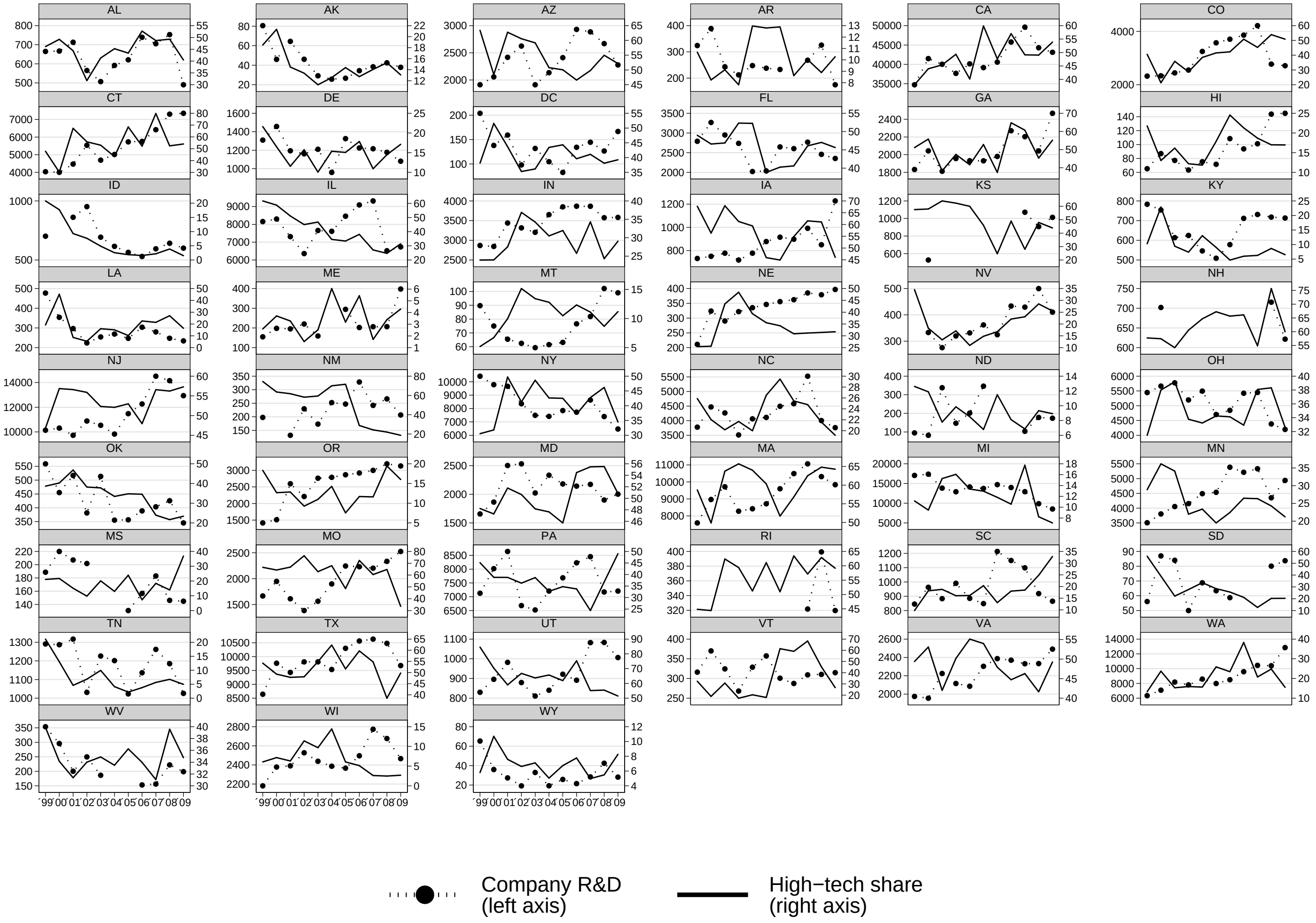
[30] There are 36 missing values in our period of analysis 1999–2009. In three states (Kansas, New Hampshire, and Rhode Island), private R&D is missing in more than half of the cases. Results are robust to dropping these states from the sample.

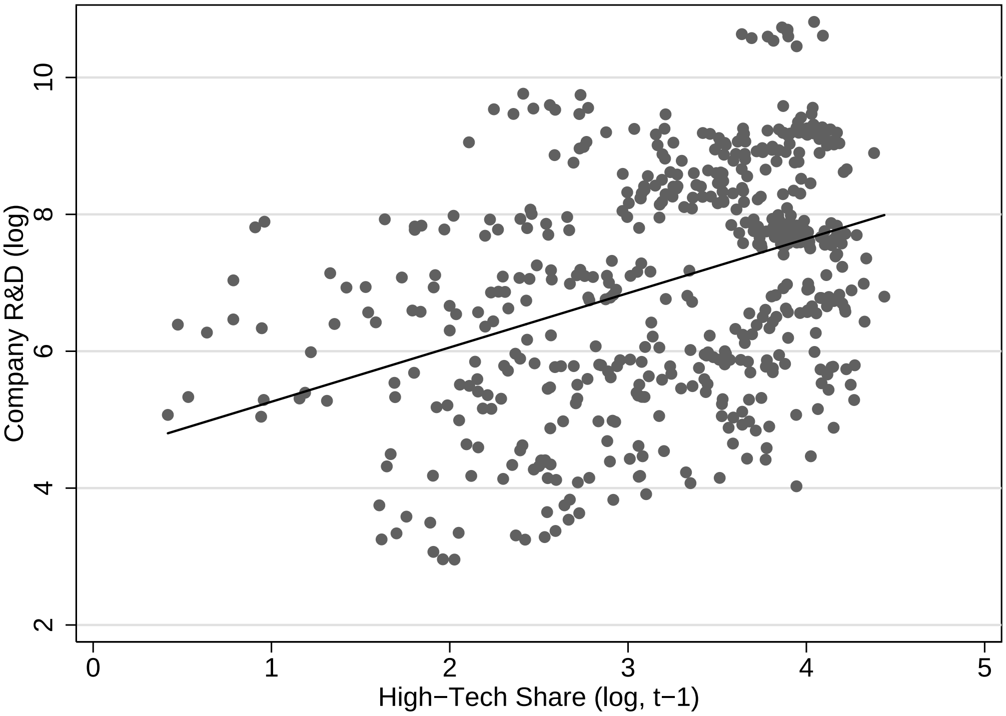
[31] Ideally, we would want to deflate the R&D expenditures data using a price deflator that allows us to take into account productivity gains in the R&D output. However, reliable output-based R&D deflators are currently not available. Because we cannot draw upon any measure of a price index for the 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 a state (we cannot distinguish between R&D performed and R&D paid for by companies), we use R&D spending deflated by the aggregate GDP deflator.

Figure 1: Technological Intensity of Government Demand and Private R&D across States



Notes: The figure plots company R&D and high-tech procurement share across the 50 US states and DC over the 1999–2009 sample period. *Company R&D* is company-funded R&D expenditures in a state (millions of constant USD, base year 2000). *High-tech share* is the share of federal non-R&D procurement in high-tech industries in total federal non-R&D procurement in a state, considering only procurement contracts awarded to private-sector companies. Variables are in levels. Vertical axes are state-specific. *Data sources:* FPDS-NG, SIRD.

Figure 2: Technological Intensity of Government Demand and Private R&D



Notes: The figure is based on pooled cross-sectional data covering 50 US states and DC in the period 1999–2009. *Company R&D* denotes company-funded R&D expenditures in a state (millions of constant USD, base year 2000). *High-tech share* is the share of federal non-R&D procurement in high-tech industries in total federal non-R&D procurement in a state, considering only procurement contracts awarded to private-sector companies. The fitted line maps a log-linear relationship between the lagged high-tech procurement share and company-financed R&D. *Data sources:* FPDS-NG, SIRD.

In Table 1, we report the results obtained from estimating the model in Equation (14) by OLS.[32] In Column (1), we only condition the estimates on state and year fixed effects. In Column (2), we control for the total amount of federal non-R&D procurement; keeping constant total government market size ensures that the coefficient on the high-tech procurement share captures the effect of reallocating procurement between low-tech and high-tech industries

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[32] Summary statistics and pairwise correlations are reported in Table A.2.

on private R&D. In Column (3), we additionally include population to control for the size of the private market.[33]

In line with the predictions of the theoretical model, we find a positive and statistically significant relationship between the technological intensity of federal procurement and company-funded R&D. Across specifications, the coefficient on the high-tech procurement share remains virtually unchanged. According to the estimate in Column (3), the elasticity of private R&D with respect to the high-tech procurement share is 0.079. Given a standard deviation of the high-tech procurement share of 0.20, this result implies that a one-standard-deviation increase in the high-tech procurement share is associated with an average increase in private R&D of 6.3% ($230 million). Put differently, each dollar that the government takes away from low-tech industries to spend it in high-tech industries relates to an increase in private R&D of about 21¢.

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[33] Population data are taken from the BEA's midyear estimates.

Table 1: Technological Intensity of Government Demand and Private R&D: Basic Results

Dependent Variable: Company R&D (log)			
	(1)	(2)	(3)
High-Tech Share (log, t-1)	.074**	.074**	.079**
	(.031)	*(.031)*	*(.031)*
Non-R&D Procurement (log, t-1)		−.026	−.026
		(.036)	*(.036)*
Population (log, t-1)			1.001**
			(.473)
State Fixed Effects	Yes	Yes	Yes
Time Fixed Effects	Yes	Yes	Yes
Observations	525	525	525
States	51	51	51
R-squared (within state)	.02	.02	.03

* p<0.10, ** p<0.05, *** p<0.01

Notes: Fixed-effects estimations. Sample: 50 US states and DC, 1999 to 2009. *Company R&D* is the amount of company-funded R&D in a state (36 observations are missing due to disclosure restrictions). *High-Tech Share* is the share of federal non-R&D procurement in high-tech industries in a state in total federal non-R&D procurement in the private sector in that state. *Non-R&D Procurement* is the state-level amount of non-R&D federal procurement. *Population* is the number of inhabitants in a state. All regressions control for state and year fixed effects. Standard errors (reported in parentheses) are robust to panel (state) heteroskedasticity and within-state autocorrelation. *Data sources:* BEA, FPDS-NG, SIRD.

5.2 Robustness

In Table 2, we report the results from testing the robustness of our baseline findings from Section 5.1. We begin by accounting for the fact that the relevant market for companies—especially high-tech companies—may extend well beyond the states in which they are located. In Column (1), we proxy out-of-state market size by the out-of-state population (that is, for each state, US population minus population of the respective state). In Column (2), we use the weighted sum of the population in all other states, with the weighting matrix based on the share of commodities that each state trades with any other state in the origin state's total commodity trade volume.[34] This specification controls for differences in the importance of the size of out-of-state markets for firms. In Column (3), we replace the year dummies with a time trend (linear and quadratic) and US-wide population to capture aggregate demand shocks to private R&D (see also Wilson, 2009).

In Columns (4)–(7), we control for further determinants of private R&D. In Column (4), we include federal R&D procurement to account for the possibility that our results are driven by government R&D contracts, since the government often simultaneously purchases R&D and "regular" goods and services (Nelson, 1982; Lichtenberg, 1987).[35] Column (5) controls for direct government support for private R&D in an even broader fashion. We use data from the SIRD, which contain R&D subsidies, the amount of work done within the scope of R&D contracts, and the R&D portions that the awarded non-R&D procurement contracts entail. In Column (6), we account for effects on private R&D of R&D tax credits and corporate income tax rates by including a measure of R&D user costs (obtained from Moretti and Wilson, 2014). In Column (7), the number of graduates in science and engineering in a state is included to control for the impact of universities on company R&D (e.g., Jaffe, 1989).[36]

In Columns (8)–(10), we check for further variables that might lead to a spurious correlation between the high-tech procurement share and private R&D. In Column (8), we control for changes in a state's industry structure, adding the GDP shares of 52 industries.[37] For instance, the growth of high-tech

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[34] The data are from the Transportation Commodity Flow Survey administered by the US Bureau of Transportation Statistics. Data are from 1997 to avoid endogeneity.

[35] We lag R&D procurement by one period because contracts start some time after they are signed and to reduce reverse causality problems.

[36] Data stem from the NSF Survey of Graduate Students and Postdoctorates in Science and Engineering.

[37] Data are obtained from BEA. Whenever provided, we use the GDP data at the three-digit NAICS level; otherwise, we draw on two-digit NAICS level data. Eight industries with missing values due to disclosure limitations were dropped.

industries in a state may simultaneously lead to a larger amount of high-tech procurement (for example, as the number of potential contractors increase) and to more private R&D. In Column (9), we include firms' lobbying spending from the Center of Public Integrity, since our results would be biased if firms' lobbying activities influenced the likelihood of being awarded federal procurement contracts and were also related to R&D performance. Column (10) adds federal aid to state from the US Census Bureau as control, which covers all sort of federal assistance to states. By including this variable, we capture that support measures provided to a state could directly affect private R&D. At the same time, states in the need of government support might have fewer high-tech procurement contracts. Finally, in Column (11), we jointly include all main controls.[38]

In all specifications, the estimated coefficient on the high-tech procurement share remains virtually identical to that in our baseline specifications in Table 1, both in terms of magnitude and significance level.

We also test whether the relationship between the share of high-tech procurement and private R&D is driven by specific observations. Figure 2 plots leverage against the (normalized) residuals squared. Points above the horizontal line have higher-than-average leverage (that is, influence on the regression line); points to the right of the vertical line have larger-than-average residuals. We observe that North Dakota and Wyoming have relatively large residuals, while DC, Kansas, New Hampshire, and Rhode Island appear to have a large influence on the regression line. However, excluding DC, Kansas, New Hampshire, North Dakota, Rhode Island, and Wyoming did not change the results. Additionally, we rerun the regressions dropping each state separately; no matter which state we excluded, the high-tech procurement share retained a positive and significant coefficient. Thus, we conclude that our main results are not driven by specific observations.

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[38] We omit R&D procurement due to collinearity with federally-financed R&D and firm lobbying spending due to the large number of missing observations in the lobbying data. Moreover, we use unweighted out-of-state population to measure market size outside the state.

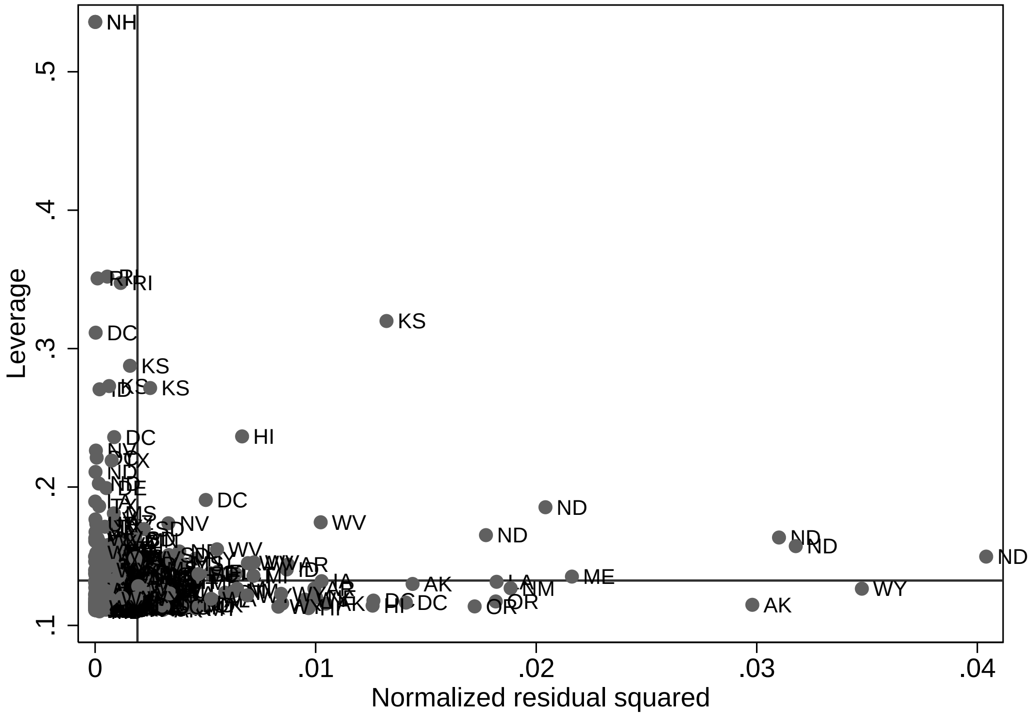
Table 2: Technological Intensity of Government Demand and Private R&D: Robustness Checks

Dependent Variable: Company R&D (log)	Market Size I (1)	Market Size II (2)	Market Size III (3)	R&D Proc (4)	R&D Federal (5)	R&D Costs (6)	Graduates SE (7)	Industry Structure (8)	Lobby (9)	State Aid (10)	Main Controls (11)
High-Tech Share (log, t-1)	.077**	.077**	.081***	.078**	.081**	.079**	.081***	.068**	.085**	.079**	.083**
	(.030)	*(.031)*	*(.031)*	*(.031)*	*(.034)*	*(.032)*	*(.031)*	*(.027)*	*(.043)*	*(.031)*	*(.034)*
Population Out-of-State (log, t-1)	–14.692										–13.316
	(28.498)										*(28.999)*
Population Out-of-State Wgt. (log, t-1)		–3.712									
		(2.683)									
US Population (log, t-1)			–13.937								
			(8.800)								
R&D Procurement (log, t-1)				–.003							
				(.018)							
Federally-Financed R&D (log)					–.020						–.024**
					(.012)						*(.012)*
R&D User Costs (log)						–.390					–.384
						(.895)					*(.955)*
Graduates in S&E (log)							.235				.222*
							(.156)				*(.135)*
Federal Aid to State (log)										–.097	–.087
										(.141)	*(.134)*
Firm Lobbying Spending (log)									–.001		
									(.011)		
Non-R&D Procurement (log, t-1)	–.029	–.034	–.064**	–.026	–.010	–.027	–.024	–.001	.018	–.025	–.010
	(.037)	*(.037)*	*(.030)*	*(.036)*	*(.035)*	*(.037)*	*(.036)*	*(.033)*	*(.035)*	*(.037)*	*(.037)*
Population (log, t-1)	.709	1.227***	1.014**	.990**	.991**	1.058*	.871**	.438	1.649**	1.071**	.716
	(.758)	*(.463)*	*(.464)*	*(.460)*	*(.463)*	*(.557)*	*(.423)*	*(.628)*	*(.799)*	*(.508)*	*(.818)*
State Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time Fixed Effects	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	525	514	525	525	521	525	525	516	298	525	521
States	51	50	51	51	51	51	51	51	44	51	51
R-squared (within state)	.03	.05	.08	.03	.04	.03	.04	.01	.05	.04	.05

* $p<0.10$, ** $p<0.05$, *** $p<0.01$

Notes: In Column (1), we proxy out-of-state markets by out-of-state population (that is, US population minus population of the respective state). In Column (2), we include weighted out-of-state population, using the share of commodities that each state trades with any other destination state in the origin state's total commodity trade volume as weights. The number of observations decreases due to the unavailability of trade data for DC. In Column (3), we replace year dummies by linear and quadratic time trends and the national GDP to control for aggregate demand shocks to private R&D. In Column (4), we include federal R&D procurement in a state. In Column (5), federally sponsored company R&D, as reported in the SIRD, contains R&D subsidies, the amount of work done within the scope of R&D contracts with the government, and the R&D portions of non-R&D procurement contracts. In Column (6), we account for R&D tax credits and corporate income tax rates by including R&D user costs (Moretti and Wilson, 2014). In Column (7), we add the number of graduates in science and engineering in a state. In Column (8), we add the share of the GDP in 52 industries in a state's total GDP. Detailed industry-level GDP data is missing in DC in some years. In Column (9), we include firms' lobbying spending. Data on lobbying spending for years after 2006 are not available. Some states do not publish annual information on firm lobbying spending throughout the observation period. Alabama, Arkansas, New Hampshire, New Mexico, and Rhode Island do not publish any spending data related to lobbying. Federal aid to state in Column (10) is defined as the amount of federal government grants and other payments to state and local governments made during a fiscal year. In Column (11), all main controls are simultaneously included. All monetary variables are measured in constant USD (base year 2000). Unless noted otherwise, we use the aggregate GDP deflator for the year 2000 to express variables in prices of 2000. All regressions control for state and year fixed effects. Standard errors (reported in parentheses) are robust to panel (state) heteroskedasticity and within-state autocorrelation. *Data sources:* BEA, FPDS-NG, Moretti and Wilson (2014), SIRD, US Census Bureau, US Center for Public Integrity.

Figure 3: Outlier detection



Notes: Plot based on a regression with all main control variables (see Table 2, Column (11)). The lines on the chart show the average values of leverage and the (normalized) residuals squared. Points above the horizontal line have higher-than-average leverage (that is, influence on the regression line); points to the right of the vertical line have larger-than-average residuals. *Data sources:* BEA, FPDS-NG, Moretti and Wilson (2014), SIRD, US Census Bureau.

A number of additional exercises, not shown, further confirm the robustness of the positive association between the technological content of government procurement and private R&D. For instance, we use the GDP in absolute or per capita terms instead of population to capture the effect of market size on private R&D.[39] Further, as mentioned above, private R&D data are sometimes

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[39] Data on the real GDP by state are obtained from the BEA and deflated using the state-specific deflator for the year 2000, which better reflects the within-state composition of industries than the aggregate GDP deflator (BEA, 2006).

missing due to disclosure restrictions when the number of surveyed firms in a state is small. We thus estimate a Heckman selection model to account for a potential bias due to non-random missing R&D expenditures data.[40] We also replace the level of private R&D as the dependent variable with R&D intensity, defined as the share of company-funded private R&D in the GDP.

Finally, our baseline FE regressions are likely to capture short-term effects of a change in the high-tech procurement share on private R&D (that is, transitional dynamics), rather than long-term effects. Although this is consistent with the theoretical model, which suggests that the positive influence of the technological intensity of procurement on private R&D holds along the balanced-growth path *and* outside the steady state, assessing the long-term effects on R&D is important for the policy implications of our results. Therefore, we estimated regressions using variables averaged over five-year and three-year intervals, respectively. In the specification with all main controls (analogous to Table 2, Column (11)), the elasticity of private R&D with respect to the high-tech procurement share was 0.174 (significant at 5%) in the specification with five-year averages and 0.123 (significant at 10%) in the specification with three-year averages. To gauge the long-term effects of the high-tech procurement share, we also estimated a dynamic model including the lagged dependent variable and applying a Bias-Corrected Least Squares Dummy Variable (LSDVC) estimator (Wilson, 2009). We found a long-term elasticity of 0.085, significant at 5%.[41] We thus conclude that changing the technological composition of government procurement affects private R&D both in the short-term and in the long-term.

5.3 Instrumental-Variable Estimation

In Section 5.2, we conducted a wealth of tests to prove the robustness of the baseline FE results to further R&D determinants and various sources of spurious correlation. However, we cannot rule out that there are further con-

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[40] In the Heckman procedure, we use the number of firms responding to the SIRD survey as excluding restriction.

[41] System GMM estimations yielded qualitatively similar results.

founding factors omitted from the analysis. For instance, as mentioned in Section 3, there might be (unobserved) state specific policies or regulations affecting both private R&D and high-tech procurement (omitted variable bias) or the likelihood that firms are awarded a procurement contract might depend on their R&D capabilities (reverse causality). We address these endogeneity concerns by employing an IV approach that exploits an exogenous part in the variation of the high-tech procurement share to estimate its impact on private R&D.

We use as instrument the number of senators from a given state who are members of the Senate Appropriations Committee, which decides on payments to agencies that then disburse the money, but also controls the funding of individual (procurement) projects.[42] Our instrument relies on the idea that politicians try to channel public money to their constituencies in order to reward their voters and maximize their chances of reelection (Mayhew, 1974; Levitt and Snyder, 1997). As it is generally difficult to deliver a direct monetary payback, politicians attempt to divert public investments or procurement contracts to their states (Atlas et al., 1995; Mayer, 1995; Levitt and Snyder, 1997; Aghion et al., 2009; Cohen, Coval and Malloy, 2011). For instance, Dalpé (1994) argues that politicians consider gaining electoral support through procurement to be a particularly promising strategy because procurement decisions are more often publicized than are other types of government spending. Moreover, procurement spending can be "targeted" in the sense that politicians can fund particular projects, for instance, infrastructure projects, in their constituency. Other forms of federal spending are formula based, meaning that it is by no means certain that a politician's own constituents would benefit (Aghion et al., 2009). Not surprisingly, newspaper accounts frequently refer to

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[42] We do not use information from the House Appropriations Committee because, although being one of the most influential among the committees of the House, it is regarded as less powerful than the Senate Appropriations Committee and often assumes merely a control function (Shepsle and Weingast, 1987). Moreover, there are historical examples (for instance, during the Nixon era) showing that the power and functioning of the House Appropriations Committee can seriously be undermined, which has not been happened for the Senate Appropriations Committee (Livingston, Dodd and Schott, 1979; Kiewiet and McCubbins, 1988; Kiewiet and Krehbiel, 2002).

government procurement as “pork barrel” spending Wheeler (2004). Generally, our choice of instrument is based on previous literature that uses political conditions to isolate exogenous variation in the distribution of government spending (among others, Aghion et al., 2009; Fishback and Kachanovskaya, 2010; Cohen, Coval and Malloy, 2011).

However, when taking advantage of their position, senators who are members of the Appropriations Committee also influence the technological composition of federal procurement in their states. The reasons is that politicians prefer to fund projects that are visible and effective in terms of raising income and creating (or securing) jobs in the short run, because voters are likely to reward a politician’s contribution to the local economy at the ballot box if yields noticeable benefits before the election (e.g., Arnold, 1979; Cohen and Noll, 1991; Dalpé, 1994). Examples in this respect are public infrastructure (for instance, bridges, highways, recreation areas) and social facilities (for instance, schools, retirement homes, libraries). These projects are typically low-tech in nature. One could argue that politicians are more interested in technology-intensive procurement projects because such projects are expected to increase performance and competitiveness. However, high-tech projects often have an uncertain outcome and become effective only in the long run, if at all. Moreover, high-tech industries typically employ a rather small portion of the workforce[43], which means that only a fraction of a state’s population/voters would reap income and employment benefits from additional government contracts. Indeed, Table A.3 in the Appendix shows that states gaining seats on the Senate Appropriations Committee receive relatively more low-tech procurement contracts.

The instrument can be considered exogenous, because both the arrival of vacancies and vacancy filling on the Appropriations Committee are independent of a state’s characteristics or its current economic strength (for a similar reasoning, see Aghion et al., 2009, 2010). Membership on the Appropriations

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[43] According to the US Census Bureau, employment in high-tech establishments as share of total employment was only 11.5% in 2008. See Science and Engineering Indicators 2012 for more details.

Committee is highly coveted, so vacancies almost solely arise due to personal (mostly health-related) reasons, drop off from the Senate, retirement, significant upgrade in office (president, secretary, etc.), or death. Thus, the timing of new assignments to the Appropriations Committee is unrelated to the characteristics of any particular state. At the same time, appointment to the Appropriations Committee is based on two main conditions.[44] First, party affiliation plays an important role, as parties are allocated seats in the Senate Appropriations Committee in proportion to their share of seats in the Senate and senators affiliated with the majority party are first to fill a vacancy. The second crucial factor for vacancy filling is seniority, which is mainly determined by age and years in public office. For instance, a senator from an economically less important state (say, North Dakota) who has been in office longer than a senator from an economically powerful state (say, California) is more likely to be appointed to the Senate Appropriations Committee when a vacancy arises.

Figure 4 illustrates state representation in the US Senate Appropriations Committee in the period 1998 to 2008.[45] We observe that twenty states always had one member appointed to the committee throughout the entire period of observation, while fifteen states were not represented at all. Sixteen states experienced changes in the number of senators on the committee, while the overall probability to gain a member was as high as the probability to lose a member. Some states also had multiple changes in the number of committee members. Washington was the only state with two members on the committee in the beginning of our observation period.

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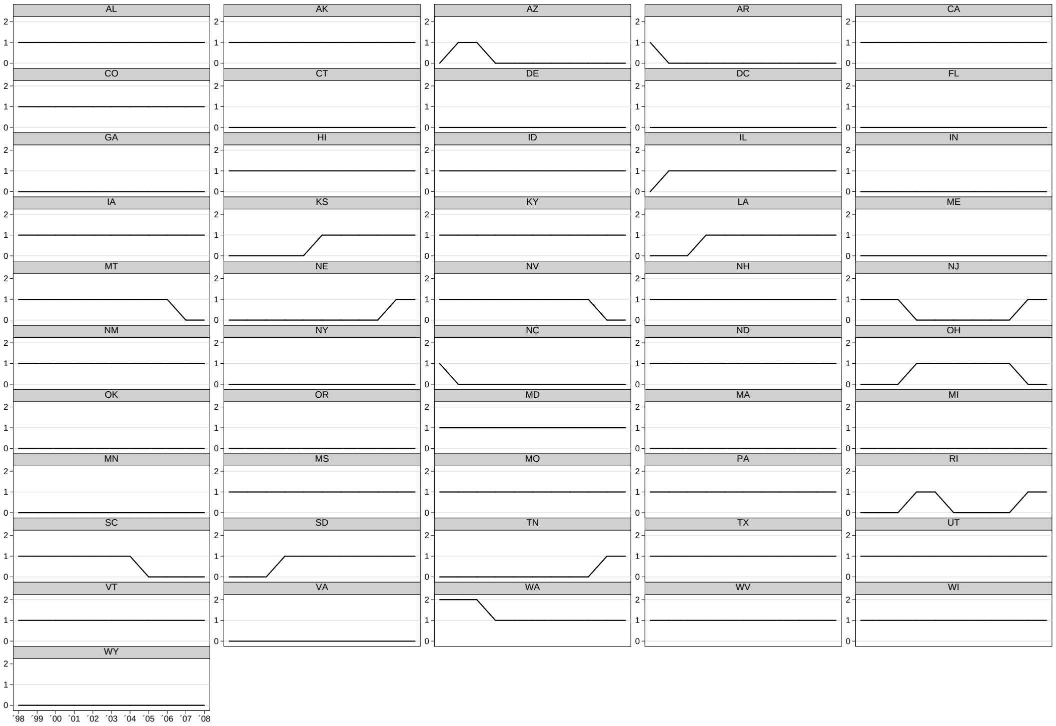
[44] See also http://www.senate.gov/CRSReports/crs-publish.cfm?pid=%26*2%3C4P%5C%3B8%0A and http://faculty.washington.edu/jwilker/353/353Assignments/SenateCommitteeAssignmentProcess.pdf.

[45] The relevant period is 1998 to 2008 because, since the high-tech procurement share enters the regressions with a one-year lag (see Section 3), we lag the instrument accordingly.

Figure 4: Number of Members in Senate Appropriations Committee across States 1998-2008



Notes: DC has no senators.

The results of the IV estimation provide support for a causal interpretation of the relationship between the technological content of federal procurement and private R&D (see Table 3). We estimate two specifications, one including only population as control (Columns (1) and (2)) and one with a full set of control variables (Columns (3) and (4)). The first-stage results in the odd columns suggest that the instrument is indeed a relevant predictor of the technological content of federal procurement; the estimated coefficient is statistically significant, with an F-statistic of 12.4 (Column (1)) and 9.7 (Column (3)), respectively.[46] The second-stage coefficients on the high-tech

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[46] A F-statistic larger than 10 is often suggested as an indication of the reliability of inferences based on the 2SLS estimator (for a discussion, see Staiger and Stock, 1997 and

procurement share, shown in the even columns, are positive and statistically significant at 5% or better.[47]

5.4 Disentangling the Effect of the High-Tech Procurement Share

In the theoretical model, the elasticity of R&D with respect to government demand is higher in high-tech industries than in low-tech industries. Accordingly, when government purchases shift from low-tech to high-tech industries, the increased R&D in high-tech industries outweighs the R&D foregone in low-tech industries. Thus, in the empirical analysis above (see equation (14)), we focus on the *net effect* of redistributing government procurement from low-tech to high-tech industries, and, in line with the theoretical expectations, find that the net effect is positive. However, in order to better understand the mechanisms at work and to learn more about the R&D effects of government procurement in low-tech vs. high-tech industries, we now decompose total government procurement. Specifically, we estimate the following equation:

$$\log R\&D_{it} = \beta^{HT} \log G^{HT}_{i\,t-1} + \beta^{LT} \log G^{LT}_{i\,t-1} + \gamma \log POP_{i\,t-1} + X'_{it}\theta + \xi_i + \nu_t + u_{it},$$

where $G^{HT}_{i\,t-1}$ $\left(G^{LT}_{i\,t-1}\right)$ denotes federal procurement in high-tech (low-tech) industries in state i in year $t-1$. The vector $X_{i\,t}$ contains a set of (log-transformed) state-level control variables.[48] According to the mechanism in the theoretical model, we expect β^{HT} to be positive and larger than β^{LT}.

Table 4 shows the estimation results. In line with the theoretical model, we find that additional procurement in high-tech industries increases private R&D at any level of procurement in low-tech industries; the estimated coefficient on high-tech procurement is positive and significant at 5%. The coefficient

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Stock, Wright and Yogo, 2002).

[47] Durbin-Wu-Hausman χ^2 tests (at the bottom of the table) indicate no statistically significant difference between the FE and the IV estimator.

[48] See notes in Table 4 for an overview of the included controls and Section 3 for details of the empirical specification.

Table 3: Technological Intensity of Government Demand and Private R&D: IV Estimates

Dependent Variable: Company R&D (log)	No Controls First Stage (1)	No Controls Second Stage (2)	Controls First Stage (3)	Controls Second Stage (4)
Seats Appropriations Committee (t-1)	–.222***		–.222**	
	(.063)		*(.071)*	
High-Tech Share (log, t-1)		.219**		.263***
		(.109)		*(.087)*
Federally-Financed R&D (log)			.029	–.030**
			(.034)	*(.015)*
R&D User Costs (log)			.532	–.544
			(1.210)	*(.998)*
Graduates in Science and Engineering (log)			–.312	.279*
			(.224)	*(.160)*
Federal Aid to State (log)			–.071	–.078
			(.127)	*(.131)*
Population Out-of-State (log, t-1)			–53.626	–4.719
			(53.368)	*(32.227)*
Non-R&D Procurement (log, t-1)			–.043	–.003
			(.012)	*(.045)*
Population (log, t-1)	-1.345	1.239**	–2.196	1.003
	(1.162)	*(.513)*	*(2.094)*	*(.906)*
State Fixed Effects	Yes	Yes	Yes	Yes
Time Fixed Effects	Yes	Yes	Yes	Yes
Observations	525	525	521	521
States	51	51	51	51
F-statistic (excluded instrument)	12.36		9.68	
Durbin-Wu-Hausman test p-value		0.35		0.20

* $p<0.10$, ** $p<0.05$, *** $p<0.01$

Notes: Two-stage least squares estimation. *Seats Appropriations Committee* is the number of senators a state has on the US Senate Appropriations Committee. See Table 2 for details on the control variables. All regressions control for state and year fixed effects. Standard errors (reported in parentheses) are robust to panel (state) heteroskedasticity and within-state autocorrelation. *Data sources:* BEA, FPDS-NG, Moretti and Wilson (2014), NSF, SIRD, US Census Bureau.

on low-tech procurement is statistically not significantly different from zero but has a negative sign. A possible explanation for this negative coefficient might be that, by raising its purchases in low-tech industries, the government encourages activities in industries that perform little, if any, R&D. If low-R&D industries grow at the expense of high-R&D industries, the aggregate level of R&D may decrease over time. However, although interesting in its own right, a proper investigation of the impact of government demand on the growth and decline of industries is beyond the scope of the paper.

The coefficients of high-tech and low-tech procurement are jointly significant ($p = 0.07$) and one cannot reject that the coefficients are equal and opposite in sign ($p = 0.79$). The latter result suggests that when the government increases procurement in high-tech and low-tech industries proportionally, aggregate private R&D will not react. However, in the case of a budget-neutral redistribution of procurement from low-tech to high-tech industries, the positive coefficient on high-tech procurement and the negative coefficient on low-tech procurement even suggest a “double dividend” for private R&D.

Overall, these results confirm that an increase in government market size per se does not induce additional private R&D; what matters is the types of products and services purchased by the government.

Table 4: Separating the R&D Effects of High-Tech Procurement and Low-Tech Procurement

Dependent Variable: Company R&D (log)		
	(1)	Hypothesis Tests
High-Tech Non-R&D Procurement (log, t-1)	.056**	H0: $\beta_{\text{High-tech}} = 0$ & $\beta_{\text{Low-tech}} = 0:$
	(.027)	$F = 5.23$ ($p = 0.07$)
Low-Tech Non-R&D Procurement (log, t-1)	−.046	H0: $\beta_{\text{High-tech}} = -\beta_{\text{Low-tech}}:$
	(.032)	$F = 0.07$ ($p = 0.79$)
Population (log, t-1)	.707	
	(.808)	
Controls	Yes	
State Fixed Effects	Yes	
Time Fixed Effects	Yes	
Observations	521	
States	51	
R-squared (within state)	.05	

* p<0.10, ** p<0.05, *** p<0.01

Notes: Fixed-effects estimation. Controls include federally-financed R&D, R&D user costs, graduates in S&E, federal aid to state, and out-of-state population (lagged by one year). All regressions control for state and year fixed effects. Standard errors (reported in parentheses) are robust to panel (state) heteroskedasticity and within-state autocorrelation. *Data sources:* BEA, FPDS-NG, Moretti and Wilson (2014), NSF, SIRD, US Census Bureau.

6 Conclusions

This paper investigates the role of government demand in innovation. The evidence we provide contributes to the recent discussion among researchers and policymakers on whether and how government procurement can be utilized as an innovation policy tool (see Edler and Georghiou, 2007, and the references cited therein). We theoretically show that government procurement can induce additional private R&D; however, these R&D effects depend on the types of products and services purchased. Specifically, an increase in the size of the market for high-tech products translates into higher returns to innovation, providing additional incentives for firms to innovate, which raises the level of private R&D in the economy.

We empirically test the model's predictions using unique US state-level panel data on federal procurement in the period 1999–2009. We find that the allocation of procurement across industries indeed influences private R&D activities. Keeping the total amount of government procurement spending constant, a shift of \$1 in government purchases from low-tech to high-tech industries is associated with an average increase in company-funded R&D of 21¢. We also show that an increase in high-tech procurement induces additional private R&D at any level of procurement in low-tech industries. These findings are robust to (i) controlling for further R&D determinants and various sources of spurious correlation; (ii) dropping high-leverage observations; and (iii) changing the construction of main variables. Finally, an IV estimation that uses political conditions to identify exogenous variation in government spending supports a causal interpretation of the positive relationship between the technological content of government procurement and private R&D.

A main implication of our findings is that the government should not be agnostic about the inter-industry composition of its purchases. If high-tech and low-tech solutions to the same problem are available, public authorities might consider that purchasing the high-tech solution has the additional benefit of encouraging private R&D. Resulting from a change in the procurement composition while keeping the total level of procurement constant, this R&D-inducement effect is even budget-neutral.

However, further analysis is needed before we can recommend to include public procurement into the innovation-policy portfolio. First, the fundamental aim of public procurement is to ensure that the government can sustain, or even improve, its core functions. If low-tech and high-tech products are not (close) substitutes, then purchasing from high-tech industries might hamper the functioning of the public sector. Moreover, public procurement, being part of general demand, might influence not only the pace, but also the direction of R&D (e.g., Acemoglu and Linn, 2004). As governments typically have a poor track record for picking winning technologies (among others, Cabral et al., 2006; Cowan, 1990; Edquist and Zabala-Iturriagagoitia, 2012; Yang and Oppenheimer, 2007), utilizing government procurement as an innovation-policy tool may well guide the direction of research away from socially beneficial technologies. Moreover, our analysis neglects potentially costly (labor-)adjustment processes and the reallocation of resources as a consequence of structural change due to a change in the composition of government purchases. Finally, any reasonable policy advice requires a cost-benefit comparison of procurement with other innovation-policy tools, such as R&D subsidies and R&D tax credits. These are all fruitful avenues for future research to aid our understanding of the role of government procurement in innovation.

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A Appendix

A.1 Determining the Unique Ratio Between ε_1 and ε_2

In this Appendix, we derive the relation between ε_1 and ε_2 for the public demand rule in (9) to be feasible. Recall that, by definition, the following holds: $\int_0^1 G(\omega)d\omega \equiv \bar{G}$. Substituting the public demand rule for $G(\omega)$ yields:

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

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

where $g(\lambda)$ is the Pareto density function with a scale parameter equal to one and a share parameter equal to $1/\kappa$. According to (8), we can express $g(\lambda)$ as $1/\kappa\lambda^{-(1+\kappa)/\kappa}$, which allows us to rewrite (A.1) as:

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

Solving the integral above gives:

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

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

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

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

A.2 Expected Profit Stream of an Industry Leader

Taking into account (5), the expected value of the profit flow to the winner of an R&D race in industry ω at time t can be written as (suppressing time and industry arguments for notational convenience):

$$\pi^e = \int_1^\infty \frac{\lambda - 1}{\lambda} L\,(c + G) g(\lambda) d\lambda. \tag{A.4}$$

Substituting for the Pareto density function, $g(\lambda)$, and for public demand spending, $G(\omega)$, by using (8) and (9), equation (A.4) becomes:

$$\pi^e = \int_1^\infty \frac{L}{\kappa} \frac{\lambda - 1}{\lambda} \lambda^{-\frac{1+\kappa}{\kappa}} \left(c + \bar{G} + \gamma\varepsilon\right) d\lambda. \tag{A.5}$$

The term $(\lambda - 1)\,(1/\lambda)\,\lambda^{-(1+\kappa)/\kappa}$ can be simplified to $(\lambda - 1)\,\lambda^{-2-1/\kappa}$. Hence, solving the integral on the RHS of (A.5) yields:

$$\pi^e = \frac{\kappa}{1+\kappa} L \left\{ c + \bar{G} + \gamma \left[\varepsilon_1 \left(-1 + 2\,(1-\kappa)^{\frac{1}{\kappa}} \right) + \varepsilon_2 2\,(1-\kappa)^{\frac{1}{\kappa}} \right] \right\}. \tag{A.6}$$

Using (A.3) in Appendix A.1 to eliminate ε_1, the integral above boils down to:

$$\pi^e = \frac{\kappa}{1+\kappa} L \left[c + \bar{G} + \gamma\varepsilon_2 \left(\frac{1}{1 - (1-\kappa)^{\frac{1}{\kappa}}} - 1 \right) \right]. \tag{A.7}$$

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 (A.7) positive. Rearranging (A.7) eventually allows us to write the expected profit stream as:

$$\pi^e = \frac{\kappa}{1+\kappa} L \left(c + \bar{G} + \gamma\Gamma \right), \tag{A.8}$$

where $\Gamma \equiv \varepsilon_2 \left(1 \Big/ \left[1 - (1-\kappa)^{1/\kappa} \right] - 1 \right) > 0$. Because the RHS of (A.8) does not depend on industry-specific variables, π^e denotes the average expected profits of an industry leader.

A.3 Labor-Market Equilibrium

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). The total employment in manufacturing is then given by:

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

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

Using the Pareto density function given in (8), as well as the public demand rule as specified in (9) and (A.3), the total employment necessary to satisfy private and public demand can be calculated as:

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

An equation for the R&D labor can be derived from solving (6) for the R&D input of a firm in industry ω and then aggregating over the continuum of industries $\omega \in [0, 1]$. Noting further that the industry-level innovation rate $I(\omega, t)$ is the same across industries at each point in time, R&D labor becomes:

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

Labor-market clearing implies that $L(t) = L_Y(t) + L_I(t)$ is always fulfilled, which, when slightly rewritten, gives (12).

A.4 Existence and Uniqueness of the Steady State

Here, we solve for the steady state of the economy, in which all endogenous variables grow at a constant (although not necessarily at the same) rate and research intensity $I(t)$ is common across industries. We already established in the main text that a constant growth rate constrains I, $\dot{x}/x$, and $\dot{c}/c$ to be constant over time, while the latter implies $r(t) = \rho$. Equations (7), (11), and (12) represent a system of three equations in three unknowns x, c, and I. Solving this system of equations allows us to uniquely determine the steady-state values for all endogenous variables.

We first derive an expression for the equilibrium research intensity, I^*. Taking the logarithm of the RHS of (6) and differentiating with respect to time while using (7) yields:

$$I^* = \frac{n}{\mu}. \tag{A.9}$$

According to equation (A.9), the research intensity in the steady-state is completely pinned down by the population growth rate, n, and the difficulty of R&D, μ.

Having determined the equilibrium value of I, we are now in the position to solve for the steady-state values of x and c. Given (A.9) and that $r = \rho$ holds along the steady state, the R&D equilibrium condition (11) can be written as:

$$\frac{x(t)}{A} = \frac{\frac{\kappa}{1+\kappa}\left[c(t) + \bar{G} + \gamma\Gamma\right]}{\rho + n\left(\frac{1}{\mu} - 1\right)}. \tag{A.10}$$

The resource constraint (12) becomes:

$$1 = \frac{c(t) + \bar{G} - \gamma\kappa\Gamma}{1+\kappa} + \frac{n}{\eta A}x(t). \tag{A.11}$$

Equation (A.10) is an upward sloping line in the (c, x) space while (A.11) is a downward sloping linear function in the (c, x) space. The 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 (A.10) and (A.11) by applying Cramer's rule uniquely determines the steady-state values of x and c as:

$$x^{*}=\frac{A\kappa\mu(1+\gamma\Gamma)}{n(1+\kappa-\mu)+\mu\rho},\tag{A.12}$$

$$c^{*}=\frac{\mu\rho(1+\kappa+\gamma\kappa\Gamma-\bar{G})-n[\bar{G}(1+\kappa-\mu)+(1+\kappa)(\mu-1)+\gamma\kappa\mu\Gamma]}{n(1+\kappa-\mu)+\mu\rho}.\tag{A.13}$$

Finally, we calculate the steady-state 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 the per capita consumption does not change in equilibrium. However, even if the amount of goods consumed per person remains constant, the individual utility in (2) augments when 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 (3):

$$\log u(t)=\int\limits_{0}^{1}\log\left[\frac{c(t)}{\lambda(\omega,t)}\right]d\omega+\int\limits_{0}^{1}j^{\max}(\omega,t)\log\left[\lambda(\omega,t)\right]d\omega,\tag{A.14}$$

where $\int_0^1 j^{\max}(\omega,t)d\omega$ is a measure of 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 engage in 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:

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

Following Davidson and Segerstrom (1998), $\int_0^1 j^{\max}(\omega,t)d\omega$ then equals tI.

Taking this and (A.9) into account, differentiating (A.14) with respect to time yields the following steady-state growth rate of the per capita utility:[49]

$$\frac{\dot{u}(t)}{u(t)} \equiv g^{*} = \frac{n}{\mu}\kappa. \tag{A.15}$$

This completes the characterization of the steady state of this economy.

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[49] Notice that the first integral on the RHS of (A.14) is constant along the balanced-growth path. We further exploit the fact that quality jumps follow a Pareto distribution; thus, using (8), $\int_0^1 \log\left[\lambda\left(\omega, t\right)\right] d\omega = \kappa$.

Table A.1: High-Tech Industries

Four-digit NAICS code	**Description**
3254	Pharmaceutical and medicine manufacturing
3341	Computer and peripheral equipment manufacturing
3342	Communications equipment manufacturing
3344	Semiconductor and other electronic component manufacturing
3345	Navigational, measuring, electro-medical, and control instruments manufacturing
3364	Aerospace product and parts manufacturing
5112	Software publishers
5161	Internet publishing and broadcasting
5179	Other telecommunications
5181	Internet service providers and Web search portals
5182	Data processing, hosting, and related services
5413	Architectural, engineering, and related services
5415	Computer systems design and related services
5417	Scientific research-and-development services

Notes: High-tech industries are identified using the classification provided by the US Bureau of Labor Statistics (Hecker, 2005).

Table A.2: Descriptive Statistics and Pairwise Correlations of Main Variables

	Descriptive statistics				Pairwise correlation (variables in logs)						
	Mean	**Std. Dev.**	**Min**	**Max**	1)	2)	3)	4)	5)	6)	7)
1) Company-funded R&D expenditures (billions $2000)	3.637	6.577	0.019	49.616	1						
2) Federal non-R&D procurement (billions $2000)	4.306	5.655	0.046	42.110	0.597	1					
3) Federal non-R&D procurement in high-tech industries (billions $2000)	1.796	2.883	0.003	17.708	0.603	0.904	1				
4) Federal non-R&D procurement in all other industries (billions $2000)	2.507	2.958	0.042	25.894	0.550	0.968	0.785	1			
5) High-tech procurement share (%)	32.363	19.515	1.520	84.563	0.377	0.406	0.758	0.201	1		
6) GDP (billions $2000)	220.564	258.243	16.714	1,593.577	0.889	0.776	0.747	0.745	0.410	1	
7) Population (millions)	6.030	6.523	0.492	36.962	0.860	0.728	0.702	0.702	0.363	0.973	1

Notes: This table shows the descriptive statistics for the main variables used in the empirical analysis for 50 US states and DC in the period 1999–2009. All values are reported for our main estimation sample (525 observations). See Table 1 for details. *High-tech procurement share* is federal non-R&D procurement in high-tech industries as a share of total federal non-R&D procurement in the private sector. All monetary values are expressed in constant dollars with the base year 2000.

Table A.3: Instrument Validity

Dependent Variable: Government Non-R&D Procurement (log, t-1)				
	Low-Tech		High-Tech	
	(1)	(2)	(3)	(4)
Seats Appropriations Committee (t-1)	.107**	.103**	−.255***	−.251***
	(.051)	*(.049)*	*(.082)*	*(.089)*
Federally-Financed R&D (log)		.053***		.086**
		(.020)		*(.038)*
R&D User Costs (log)		.025		.442
		(.462)		*(1.904)*
Graduates in S&E (log)		−.057		−.481*
		(.151)		*(.271)*
Federal Aid to State (log)		.065		−.076
		(.154)		*(.224)*
Population Out-of-State (log, t-1)		−29.597*		−94.514
		(17.556)		*(60.619)*
High-Tech Non-R&D Procurement (log, t-1)	.100**	.081*		
	(.050)	*(.045)*		
Low-Tech Non-R&D Procurement (log, t-1)			.245*	.195*
			(.130)	*(.112)*
Population (log, t-1)	.670	.099	−1.501	−2.951
	(.569)	*(.776)*	*(1.355)*	*(2.365)*
State Fixed Effects	Yes	Yes	Yes	Yes
Time Fixed Effects	Yes	Yes	Yes	Yes
Observations	525	521	525	521
States	51	51	51	51
R-squared (within state)	.03	.06	.05	.08

* $p<0.10$, ** $p<0.05$, *** $p<0.01$

Notes: Fixed-effects estimations. The dependent variable is federal non-R&D procurement in low-tech industries (Columns (1)–(2)) and in high-tech industries (Columns (3)–(4)), respectively. *Seats Appropriations Committee* is the number of senators a state has on the US Senate Appropriations Committee. See Table 2 for details on the included control variables. All regressions control for state and year fixed effects. Standard errors (reported in parentheses) are robust to panel (state) heteroskedasticity and within-state autocorrelation. *Data sources:* BEA, FPDS-NG, Moretti and Wilson (2014), NSF, SIRD, US Census Bureau.