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ABSTRACT

The U.S. government incentivizes firms to develop innovative technologies by awarding R&D contracts that often carry an implicit promise of “guaranteed demand.” Firms that demonstrate strong technological capabilities are rewarded with noncompetitive production contracts for the resulting products and services. Using newly assembled data on $4.2 trillion in government procurement contracts from all federal agencies, matched to U.S. publicly traded firms, we document a “crowding-in” effect, where government R&D contracts lead to increased investment in corporate scientific research. Firms co-invest with the government at the R&D stage to enhance their chances of securing these lucrative production contracts. We develop a theoretical framework to explain when it is optimal for the government to bundle R&D and production contracts. Our analysis shows that guaranteed demand can produce higher quality at a lower total cost for upstream R&D projects when the R&D firms have production capabilities. Our empirical results confirm these predictions. Additionally, we find that the crowding-in effect has weakened over time as the government has increasingly separated R&D contracts from production contracts. We discuss the potential implications of this decoupling.

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1 Introduction

The government influences corporate innovation by providing subsidies for research and development (R&D), directly through tax credits, R&D contracts, or grants, or indirectly through spillovers from government-funded R&D and support for education. A less studied channel is the ability of the government to increase the private value of scientific research (henceforth, "upstream R&D") and technology development (henceforth, "downstream R&D") through procurement of innovative products and services (henceforth, "government production contracts"). This paper examines the effect of government R&D contracts on upstream and downstream corporate R&D and shows that the effect operates through *guaranteed demand*: rewarding firms that demonstrate technological superiority in R&D with noncompetitive production contracts.

Understanding how government procurement affects corporate innovation is important due to procurement's massive size, wide scope, and unique characteristics. Government procurement is large and growing. Between 1980 and 2015 (the last year of our sample), the U.S. government more than doubled its annual procurement, from $207 billion to $420 billion.[1] The 2015 amount included $37.5 billion in R&D contracts, as compared to $3.6 billion in federal grants awarded to businesses that year. Moreover, government procurement touches many industries and encompasses much more than military acquisition, especially in recent decades. Between 1980 and 2015, the U.S. government awarded contracts to firms in 351 SIC3 industries. The share of nonmilitary procurement dollars in all government procurement rose from 49% in 1982 to 72% in 2015.

Yet, despite its size and scope, government procurement has been understudied in the innovation literature. Existing work has advanced our understanding of how grants affect scientific research and technology development by individual researchers and small firms (e.g., Howell, 2017; Myers & Lanahan, 2022; Wallsten, 2000). However, it has largely neglected the effect of demand-side policies on corporate R&D. While both grants and R&D contracts subsidize R&D (a supply-side effect), only R&D contracts carry the implicit promise of future government demand (a demand-side effect). Unlike grants, R&D contracts create knowledge that *must be implemented* in production contracts. Federal Acquisition Regulation (FAR) Section 35.003 specifically notes that R&D contracts "shall be used only when the principal purpose is the acquisition of supplies or services for the direct benefit or use of the Federal Government." The need for implementation means the government must design contracts that not only encourage innovation but also overcome frictions in implementing knowledge in production. Such frictions may arise when there is high complementarity between R&D and production; the government faces contractual problems due to tacit knowledge and asymmetric information (e.g., Bhattacharya, 2021; Che, Iossa, & Rey, 2021); or firms face problems due to incomplete contracts between R&D specialists and producers (e.g., Hart & Moore, 1988, 1999).

Our research question examines the effect of R&D contracts on corporate innovation, focusing on whether these contracts crowd in corporate R&D investment through the mechanism of guaranteed demand—an implicit promise to compensate firms for successful R&D efforts by awarding them

[1] All dollar amounts in this paper are reported in constant 2012 dollars.

noncompetitive production contracts. The main challenge is that guaranteed demand is not directly observable; its implicit nature leaves little paper trail.

To address this challenge, we develop a conceptual framework to analyze when it is optimal for the government to use guaranteed demand as an incentive for R&D. This includes considerations of the (un)observability of corporate R&D efforts and the heterogeneous R&D and production capabilities of contractors. The government chooses between two procurement regimes: unbundled procurement, where it pays separately for R&D and production, and bundled procurement, where it offers lower R&D payments but lets the successful R&D firm secure the production contract and its profits. In the R&D stage, two R&D firms compete to develop the best prototype, with quality based on their unobservable research efforts. In the production stage, a second-price auction awards the contract to the lowest-cost producer.

The model shows that when R&D firms lack production capabilities, the government typically achieves better outcomes by keeping R&D and production contracts separate, which fosters competition and reduces costs, even with contractual frictions in the R&D stage (i.e., the R&D prototype quality is unobserved ex-ante). However, when R&D firms have production capabilities, bundling becomes advantageous under two conditions: for more upstream R&D projects (more likely to have unobservable research effort) and when the cost of production entry is low enough to make it attractive for the R&D winner to enter (but not so low that the R&D loser would enter). Under those conditions, it is optimal for the government to let the R&D winner manage the production stage, as the firm can achieve lower production costs by entering the production competition—an ability the government lacks. This is crucial for better outcomes through bundling, as it reduces the information rents that other producers would capture. Anticipating these savings, the government lowers the payment to the R&D winner, whose research effort remains unchanged (a pattern consistent with crowding in) because it expects to make up the missing profit in production. The government achieves the same desired quality at a lower total cost.

Empirically, a positive effect of R&D contracts on corporate R&D suggests that firms co-invest with the government, implying that the government does not fully cover R&D costs and relies on guaranteed demand as a complementary funding mechanism. This crowding in should occur when R&D projects are more upstream (resulting in more publications) and involve larger firms (more likely to have production capabilities). Our empirical results support this theory, showing a positive effect of R&D contracts on publications (but not on patents) for large firms.

The acquisition of the Human Landing System (HLS) that will take people back to the Moon provides an example of guaranteed demand incentives in government procurement. In April 2020, the National Aeronautics and Space Administration (NASA) awarded $1 billion in upstream R&D contracts to SpaceX, Blue Origin, and Dynetics to start development of the HLS during ten months. In April 2021, due to budgetary pressures, NASA awarded a single $2.9 billion upstream R&D contract to SpaceX to continue HLS development (instead of awarding two, as anticipated). Blue Origin and Dynetics protested this award with the Government Accountability Office but lost. In July 2021, Blue Origin offered to invest up to $2 billion in company-funded R&D to remain in the

HLS R&D competition.

Why did this company offer to co-invest in government R&D? To improve its chances of winning the R&D race, which all but guaranteed Blue Origin billions in future government demand. Blue Origin was well-positioned to satisfy this demand because it: (i) was an integrated firm with both R&D and manufacturing capabilities; (ii) had significant capital resources from its founder, billionaire Jeff Bezos; and (ii) listed Lockheed Martin and Northrop Grumman—two of the largest government contractors—as subcontractors on the HLS. While NASA did not respond to Blue Origin's offer, the agency did award it an R&D contract worth up to $3.4 billion in May 2023 for developing a second HLS.

We estimate the effect of R&D contracts on corporate R&D expenditures, upstream R&D measured by scientific publications and employment of renowned and award-winning scientists, and downstream R&D measured by patents. We extend the panel of 4,520 firms and 60,885 firm-year observations from Arora, Belenzon, and Sheer (2021) by adding data on $4.2 trillion in procurement contracts and $8.8 billion in grants awarded by dozens of federal agencies.

A key challenge in our analyses is dealing with the endogeneity of contracts (David, Hall, & Toole, 2000). Common positive (negative) technology or demand shocks can affect both government procurement and corporate R&D, leading to OLS estimates that are upward-biased (downward-biased). To mitigate this concern, we use variation in industry-level procurement, agency-level windfall funding resulting from the congressional appropriations process, and product-level procurement to predict firm-level R&D contracts. We also exploit a quasi-natural experiment—the end of the Cold War, which triggered substantial reallocation in government contracts due to changes in national priorities rather than technology or demand shocks—in an event study design.

With our newly assembled data and methodology, we present three sets of results. First, we show that military products and services no longer dominate federal procurement. The share of procurement dollars awarded by the Department of Defense (DoD) in all federal procurement dollars declined from 86% in 1982 to 62% in 2015. At the same time, the share of procurement dollars for military products and services in all DoD procurement dollars declined from 64% in 1980 to 45% in 2015. Nonmilitary procurement represented 49% of all procurement dollars awarded in 1982 but a much larger share of 72% in 2015, as shown in Figure 1. Correspondingly, we found that federal procurement touches a broad set of R&D-performing firms, not just military contractors.

Second, we show that R&D contracts crowd in upstream corporate R&D investments. In our sample, a $10 million increase in R&D contracts increased company-funded R&D expenditures by $5.3 million. Specifically, the $10 million increase in R&D contracts led to a 3% increase in publications authored by corporate scientists and a 12% increase in renowned scientists employed by the firm. However, we found no effect on downstream R&D, as measured by patents.

We explore the guaranteed demand mechanism behind these results: R&D contracts crowd in company-funded investment in R&D because they carry the implicit promise of future noncompetitive production contracts. This promise is unobserved in federal procurement data, both *ex ante* (R&D contracts do not explicitly include it) and *ex post* (noncompetitive production contracts

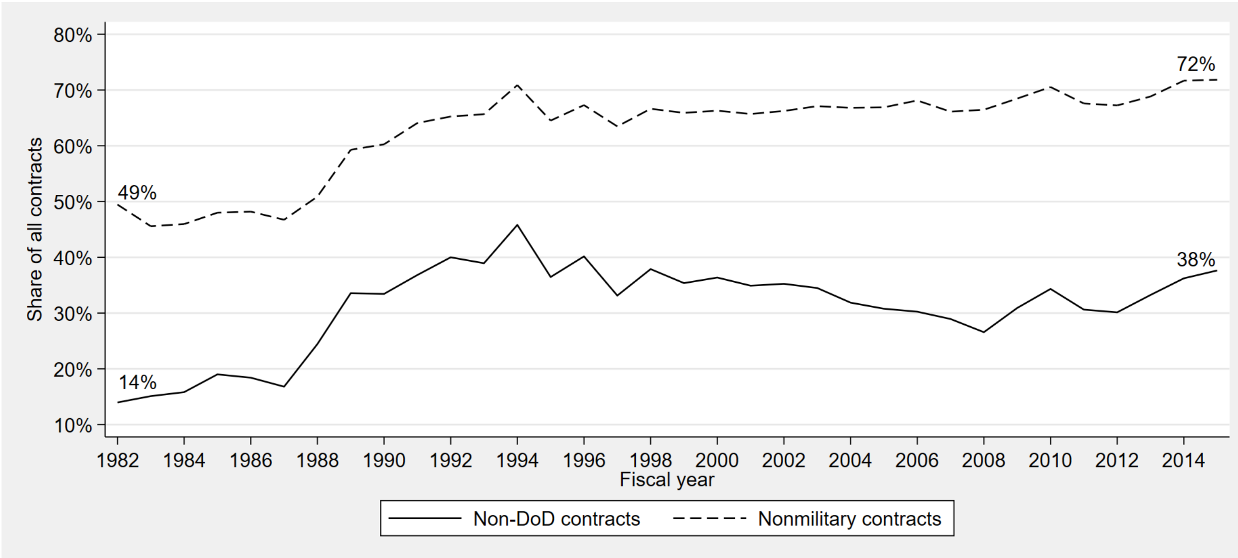

Figure 1: Share of Non-DoD and Nonmilitary Procurement in All Contracts
This figure plots the shares of non-DoD contract dollars (solid line) and nonmilitary contract dollars (dotted line), respectively, in all contract dollars obligated by federal agencies to all recipients (not limited to our sample firms) over time. The classification of DoD contracts into military and nonmilitary is described in Appendix D.

cannot be linked, at scale, to R&D contracts that led to them). Therefore, the guaranteed demand mechanism must be inferred indirectly by showing that the crowding-in effect is present when guaranteed demand is more salient and absent when it is unlikely to be used. We expect crowding-in when R&D projects are more upstream (resulting in more publications) and involve larger firms (which are more likely to be vertically integrated). Upstream efforts should be more unobservable and, therefore, less contractible. Moreover, upstream knowledge should be harder to implement, making guaranteed demand more salient. Consistent with this, we find a crowding-in effect in large firms for R&D associated with more scientific publications and the hiring of additional renowned scientists, but not with more patents.

Our third set of results focuses on the weakened effect of R&D contracts on corporate innovation over time due to the decoupling of R&D contracts from production contracts and the implications of this decoupling. Policy reforms implemented in the 1980s and 1990s changed the nature and composition of federal procurement. The Federal Acquisition Streamlining Act of 1994 shifted procurement *away from* mission-focused technologies that met unique government specifications (which accounted for the majority of procurement dollars in the 1960s and 1970s) and *toward* commercial and dual-use technologies that had both military and commercial applications (Weiss, 2014). We document a drop in noncompetitive production contracts (a direct measure of guaranteed demand) and a larger allocation of contracts to firms that do not participate in scientific research over time. These trends suggest that the government has increasingly decoupled R&D races from production, thus weakening guaranteed demand. We also present evidence suggesting that the implementation of R&D in production might have become more difficult due to this decoupling. We document (i) a negative relationship between subcontracting and competitive contracts: the share of contracts that are subcontracted to other firms in total contracts is lower in industries with a higher share of competitive contracts. This pattern is inconsistent with efficient decoupling, which predicts more subcontracting between specialized R&D and production firms when production contracts are awarded competitively. (ii) There is a larger allocation of R&D contract dollars to research projects that are further from implementation. And (iii) we find a substantial rise in contractual deobligations, our most direct measure of failed implementation. These trends suggest that decoupling R&D races from production may have adversely affected project success.

We contribute to the literature on how government policy affects innovation (e.g., Bloom, Van Reenen, & Williams, 2019; Edler & Georghiou, 2007; Mowery, 2010; Rogerson, 1989; Slavtchev & Wiederhold, 2016). We focus on procurement policy, an area that has received less scholarly attention. From the Buy American Act of 1933 to President Biden's 2021 Executive Order on Ensuring the Future Is Made in All of America by All of America's Workers, legislative actions have used production contracts to stimulate domestic economic activity and support specific industries or regions. Our research is the first to demonstrate the effect of government procurement on both the "R" and "D" components of corporate R&D, with a particular emphasis on the guaranteed demand mechanism. Understanding this mechanism is crucial because it reveals how the government can strategically influence corporate R&D investment by offering production contracts as incentives rather than just paying for R&D directly. A key contribution of this paper is identifying when large firms have an advantage over smaller firms in responding to such incentives. By highlighting those conditions, we provide insight into the broader dynamics of innovation ecosystems, showing how government demand-side policies shape the strategic decisions of firms and, consequently, the direction and intensity of corporate R&D efforts.

In terms of managerial implications, our findings highlight the strategic advantage large firms gain from the guaranteed demand mechanism, which allows them to align R&D activities with production opportunities. The ability to integrate R&D with production capabilities provides a substantial competitive edge. Conversely, small firms face structural disadvantages due to their limited production capabilities, which hinder their ability to capitalize on government R&D contracts. It is, therefore, important for managers of smaller firms to recognize these constraints and develop strategies to mitigate them.

Potential strategies include forming alliances with larger firms, known as "teaming agreements," which can provide access to necessary production capacity. Additionally, small firms can focus on subcontracting opportunities with larger firms, a practice closely related to strategic alliances. Another approach is targeting downstream R&D projects, where the guaranteed demand mechanism is less likely to be employed, allowing them to compete more effectively. Future theoretical and empirical research should explore the effectiveness of these strategies in helping small firms overcome the challenges posed by limited production capabilities.

Finally, as shown in this paper, recent procurement reforms have weakened the guaranteed demand mechanism, potentially reducing the disadvantages faced by small firms. This shift creates new opportunities for small firms to bid on R&D contracts, particularly from agencies less reliant on guaranteed demand, thereby leveling the playing field. Future research should explore these reforms' implications for the scale and nature of small firm participation in government procurement.

2 Related Literature

A voluminous literature examines how the government affects corporate R&D through tax credits (e.g., Bloom, Griffith, & Van Reenen, 2002), grants (e.g., Azoulay, Graff Zivin, Li, & Sampat, 2019; Howell, 2017; Packalen & Bhattacharya, 2020; Wallsten, 2000), and spillovers from federal laboratories and universities (e.g., Adams, Chiang, & Jensen, 2003; Cohen, Nelson, & Walsh, 2002). Government procurement is also covered in theoretical studies on optimal procurement design (e.g., Arve & Martimort, 2016; Bhattacharya, 2021; Che & Gale, 2003; Che et al., 2021; Decarolis, 2014; Kremer, Levin, & Snyder, 2022; Riordan & Sappington, 1989), competition (e.g., Kang & Miller, 2022), and efficiency (e.g., Bandiera, Prat, & Valletti, 2009; Liebman & Mahoney, 2017). Few studies empirically examine procurement contracts (e.g., Lichtenberg, 1988; Moretti, Steinwender, & Van Reenen, 2021; Slavtchev & Wiederhold, 2016). These studies do not estimate the separate effects of R&D contracts on upstream and downstream R&D or test the guaranteed demand mechanism.

Most prior studies focus on funding from the Small Business Innovation Research (SBIR) program or the National Institutes of Health (NIH). For example, research shows that SBIR awards crowd out company-funded R&D expenditures (Wallsten, 2000). Yet, early-stage SBIR awards increase forward citation-weighted patents, particularly for financially constrained firms (Howell, 2017). Howell, Rathje, Van Reenen, and Wong (2021) evaluate policy reforms on how the U.S. Air Force SBIR program procures new technologies. They compare the conventional R&D contracting approach, where firms respond to specific solicitations, with an open approach allowing proposals on any topic. Using data on proposals submitted from 2017 to 2019 and a regression discontinuity design, they find that winning an open-topic R&D contract increases the likelihood of raising venture capital and improves chances of winning a subsequent non-SBIR DoD contract. This supports the premise that winning R&D races leads to subsequent production contracts.

Azoulay et al. (2019) show that NIH grants positively affect corporate R&D. An additional $10 million in NIH grants for a research area generates 2.3 additional biopharmaceutical firm patents in that area, or about one patent per 2-3 grants. This shows that patents are effective for appropriating returns from corporate R&D in the biopharmaceutical industry. Yet, NIH's focus on new ideas has declined over time. From the 1990s to the 2000s, grant support shifted from "edge science" to more traditional science (Packalen & Bhattacharya, 2020).

A few studies on procurement contracts are more relevant to our paper. Lichtenberg (1988) investigates procurement contracts' effect on firm R&D expenditures using a panel of 169 U.S. contractors from 1979-1984. He estimates that a $1 increase in competitive procurement (R&D and production contracts) increases company-funded R&D expenditures by $0.54. He suggests this is due to winning contractors receiving larger follow-on noncompetitive contracts.

Slavtchev and Wiederhold (2016) study how the technological intensity of production contracts (excluding R&D contracts) affects private R&D expenditures using a panel of U.S. states from 1999-2009. They estimate that each procurement dollar the government shifts from low-tech to high-tech industries induces an additional $0.21 in private R&D expenditures. This crowding-in effect arises not from an increase in overall government demand but from increased high-tech government demand. This suggests that the government can incentivize private R&D investment by altering the composition of its procurement.

Moretti et al. (2021) study the effect of government-funded R&D on private R&D using industry-level data from OECD countries and firm-level data from France during 1980-2015. They find a crowding-in effect, where increases in government-funded R&D subsidies (R&D grants and contracts) drive additional private R&D investment. In their analyses of 12,539 French firms, they use industry-level defense R&D subsidies as an instrument for public R&D funding. They estimate that a €1 increase in government-funded R&D generates €0.85 of additional corporate R&D.

Our work diverges from previous studies in several key ways. First, we examine the effect of R&D contracts separately on upstream corporate R&D (scientific research or "R") and downstream corporate R&D (technology development or "D") and systematically explore the guaranteed demand mechanism behind the effect. Second, we advance data and identification by matching contracts from dozens of agencies to thousands of R&D-performing American firms and their subsidiaries over decades. We use industry-level contracts to predict firm-level contracts, similar to Moretti et al. (2021), and also provide causal evidence from procurement changes driven by geopolitical forces. Third, to our knowledge, we are first to analyze how the nature and composition of government procurement have changed over recent decades. Documenting these changes helps us understand the implications of procurement policy reforms from the 1980s and 1990s.

3 Background on Government Procurement

The U.S. government, the world's largest customer, purchased products and services worth 9.3% of GDP in 2015 (OECD, 2017, Table 9.1). The typical procurement process involves an agency identifying needs, determining the purchase method, and carrying out the acquisition per the Federal Acquisition Regulation (see Online Appendix A). To understand government procurement's impact on corporate innovation, we must first understand (i) which agencies buy, (ii) what they buy, (iii) from whom, and (iv) how they use R&D contracts to develop new technologies.

Contract distribution by awarding agency is highly skewed. The DoD accounts for 69% of contract dollars from 1980-2015, while the Department of Energy (DoE), NASA, General Services Administration (GSA), and Health and Human Services (HHS) account for another 16% (see Appendix Table C1). Even within the DoD, there is significant heterogeneity in contract size and composition by subagency. The U.S. Navy, Army, and Air Force each awarded over $2 trillion in contracts from 1980-2015, with 79-90% for production. Conversely, the Defense Advanced Research Projects Agency (DARPA) awarded less than $14 billion, with 91% for R&D services. Thus, the military subagencies were able to guarantee demand, while DARPA was not.

Despite the DoD's strong position, government procurement is no longer dominated by military needs. The DoD's share of federal procurement dollars has declined from 86% in 1982 to 62% in 2015. Additionally, the DoD is increasingly procuring commercially available and dual-use products and services. The share of military procurement dollars within the DoD has fallen from 64% in 1980 to 45% in 2015. Together, these trends have shifted federal procurement towards nonmilitary products and services, as shown in Figure 1.

Government procurement touches many industries and firms. During 1980-2015, federal agencies awarded contracts to firms in 351 industries (identified by three-digit SIC code), including 21 receiving over $100 billion, 54 receiving $10-99 billion, and 58 receiving $1-9 billion. During this period, ten industries received over $1 billion each in R&D contracts. These ten R&D-intensive industries received $541 billion in R&D contracts and $2.8 trillion in production contracts from 1980-2015.

This paper focuses on the effect of R&D contracts because they represent how federal agencies express demand for innovative products and services. FAR Section 35.003 states that R&D contracts "shall be used only when the principal purpose is the acquisition of supplies or services for the direct benefit or use of the Federal Government." However, the work, methods, and success probabilities cannot be fully specified in advance. As shown in Figure 2, R&D contracts (solid line) are a significant public investment in innovation, comparable to the R&D performed by the federal sector (intramurally and in federally-funded research and development centers, dashed line).

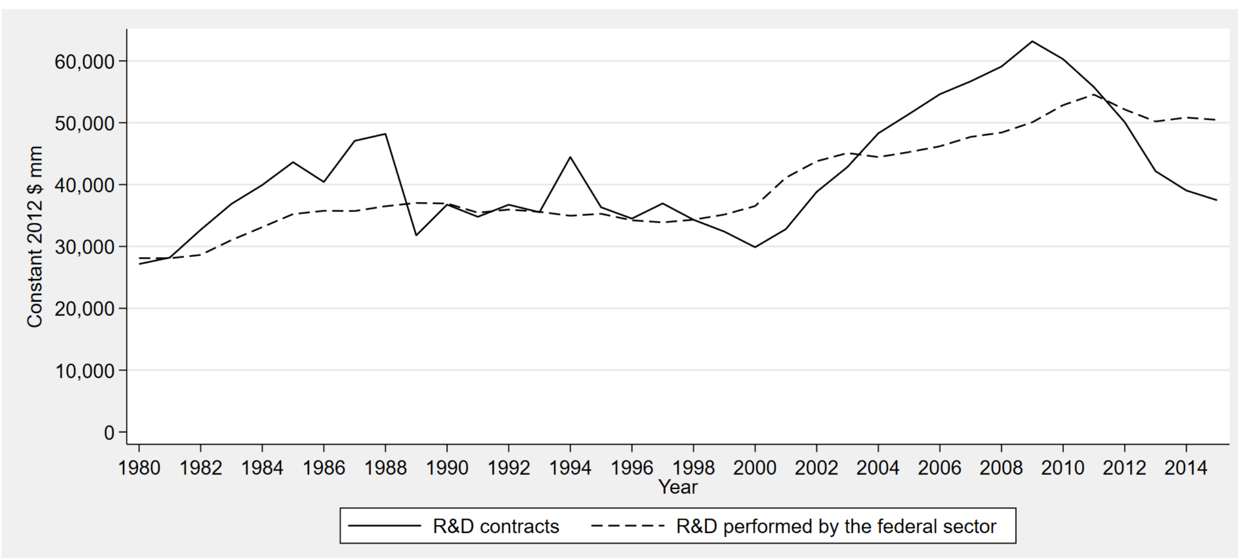

Figure 2: R&D Contracts vs. R&D Performed by the Federal Sector

This figure compares the value of R&D contracts (solid line) with the value of R&D performed by the federal sector (dashed line) over time. Federal sector data are from Table 2 of the National Patterns of R&D Resources: 2017-2018 series available at https://ncses.nsf.gov/pubs/nsf20307.

4 Conceptual Framework

We seek to understand when firms co-invest with the government to address technological problems. According to the guaranteed demand mechanism, this occurs when firms expect a noncompetitive production contract after successful R&D. We cannot directly test this mechanism because the bundling of R&D and production contracts is unobservable in procurement data. We theorize *when* it is optimal for the government to bundle R&D and production contracts and empirically examine if crowding in occurs under those conditions. Crowding in means the government does not cover the full R&D cost, indicating the production contract is part of the reward for successful R&D.

4.1 Setup

We present a framework to analyze when it is optimal for the government to bundle R&D and production contracts instead of awarding them separately. Contractors create innovative products and services in three stages: (i) research, (ii) development, and (iii) production. For analytical convenience, we model the *research* stage as a contest between two symmetrical R&D firms where the firm with the highest-quality prototype wins a prize. We assume prototype quality is a stochastic function of research effort, observable *ex-post*, but not contractible (as the effort itself is not observable and contractible). We relax this assumption in Online Appendix B. We model the *development* stage as a cost-plus contract, assuming development effort is observable and contractible. We model the *production* stage as a second-price auction among many producers, where the lowest-cost producer wins and is paid the second-lowest production cost. We assume production costs are stochastic and private information.

The government chooses between two procurement regimes: (i) unbundled and (ii) bundled. In the *unbundled* regime, R&D outcomes are delinked from production profits. The government pays separately for R&D and production. In the *bundled* regime, the R&D winner automatically receives the production contract. Thus, the government can use production profits as part of the reward for successful R&D. Empirically, this elicits a crowding-in effect, where R&D firms use private funds for research in expectation of the production reward.

See Table 1 for notation. In the research stage, R&D firms invest effort to create proof-of-concept prototypes. Each prototype's quality, q_i, is revealed. The highest-quality prototype is chosen. The winner receives a prize, P_u in the unbundled regime and P_b in the bundled regime. In the development stage, the firm with the highest-quality prototype receives an R&D contract to develop, test, and evaluate it. It earns a profit of P_d. In the production stage, firms draw the cost of producing the operational prototype. In the unbundled regime, the production contract goes to the lowest-cost firm, which receives a price equal to the second-lowest cost. In the bundled regime, the production contract goes to the research stage winner, who chooses to produce internally or subcontract to a lower-cost producer.

There are two R&D firms, $i = 1, 2$. Each firm creates a proof-of-concept prototype. Prototype quality is $q_i = r_i + \nu_i$, where r_i is the research effort and ν_i is a stochastic term. Research effort is not observable, while its cost is $g\exp(r_i)$, with $g > 0$. For analytical convenience, we assume ν_i has a type I extreme value distribution with parameters $\mu = 0, \beta = 1$ so that $Pr[q_1 > q_2] = \frac{\exp(r_1)}{\exp(r_1) + \exp(r_2)}$. Using $exp(r_i) = e_i$, we can write $Pr[q_1 > q_2] = \frac{e_1}{e_1 + e_2}$.

Table 1: NOTATION

Concept	Notation
R&D firms	$i \in \{1, 2\}$
Research effort	e_i
Cost per unit of research effort	g
Quality of proof-of-concept prototype	q_i
Research prize under unbundled regime	P_u
Combined payment under bundled regime	P_b
Producers	$k \in \{1, 2, ..., m\}$
Fixed cost of entry into production	F
Production cost	C_k
Production cost of the lowest-cost of m producers	$\underline{C}_m$
Production cost of the second-lowest-cost of m producers	$\overline{C}_m$
Gross production profit (when there are m producers)	Δ_m

We assume the R&D firm with the highest-quality proof-of-concept prototype automatically receives the development contract. Empirical evidence shows that 77% of R&D contract dollars from 1980-2015 were cost-reimbursement contracts. This indicates that development effort is observable and contractible. Thus, the firm with the highest-quality proof-of-concept prototype earns a profit of P_d for developing the operational prototype. Since development does not affect research effort, we set $P_d = 0$.

We assume the government needs one unit of the final product, simplifying the distinction between marginal cost and average cost. Producing the operational prototype varies in cost among potential producers. There are m potential producers, $k = 1, 2, ..., m$, each with a cost C_k revealed in the production stage. Each producer incurs a fixed entry cost of F to understand and bid on producing the operational prototype.

We consider two cases: (i) the R&D firms lack production capabilities, and (ii) the R&D firms have production capabilities.

4.2 R&D Firms Lack Production Capabilities

4.2.1 Unbundled Procurement Regime

In the unbundled regime, R&D outcomes are delinked from production profits (i.e., the government does not use production profits to reward research). The government awards the production contract to the lowest-cost producer, which earns a gross profit of $\Delta_m = \overline{C}_m - \underline{C}_m$, where $\overline{C}_m$ is the cost of the second-lowest producer and $\underline{C}_m$ is the lowest. If the production cost is verifiable, Δ is the allowed markup on the production cost. A producer has an expected payoff of:

$$\Pi(m) = \frac{1}{m}\Delta_m - F = \frac{1}{m}(\overline{C}_m - \underline{C}_m) - F \tag{1}$$

We assume the expected production payoff is positive ($\Pi(m) > 0$).

Let q_u be the quality of the winning proof-of-concept prototype. This is the maximum of two random variables whose means depend on the research effort. The research effort depends on the incentives faced by the R&D firms.

For simplicity, we assume the government's payoff from quality is a linear function $V(q_u) = \alpha + \beta q_u$ so that $V'(q_u) = \beta$, a constant. The government's expected payoff is:

$$W = \mathbb{E}_{q_u}[V(q_u)] - P_u - \overline{C}_m = \mathbb{E}_{q_u}[V(q_u)] - P_u - \underline{C}_m - \Delta_m \tag{2}$$

The government chooses $\{P_u, \Delta_m\}$ to maximize W.

R&D firm $1's$ expected payoff is:

$$\Pi_1 = \frac{e_1}{e_1 + e_2} P_u - g e_1 \tag{3}$$

Assuming that the participation constraint is satisfied (i.e., $\Pi_i \geq 0$), the optimal research effort for firm 1 is given by the first order condition:

$$\frac{e_2}{(e_1 + e_2)^2} P_u - g = 0 \tag{4}$$

At a symmetric Nash Equilibrium, $e_1 = e_2 = e = \dfrac{P_u}{4g}$. The participation constraint is satisfied as each R&D firm's equilibrium expected payoff is $\frac{1}{2}P_u - \frac{1}{4}P_u = \frac{1}{4}P_u > 0$. To extract the R&D rents, the government can charge a fixed entry fee of $\frac{1}{4}P_u$. This fee can only affect the decision to participate, not the research effort. Therefore, it leaves the government's choice between bundling and unbundling unaffected.

The winning prototype's expected quality is $\mathbb{E}[\max\{q_1, q_2\}] = A + \ln(2e) = A + \ln(\frac{P_u}{2g})$, where A is a constant.[2] Therefore, the government's objective function is:

$$\max_{P_u, \Delta_m} \{V(A + \ln(\frac{P_u}{2g})) - P_u - \underline{C}_m - \Delta_m\} \tag{5}$$

The first order condition requires that:

$$\begin{aligned} V'(A + \ln(\frac{P_u}{2g}))\frac{\partial \ln P_u}{\partial P_u} - 1 = 0 \\ \implies P_u = \beta \end{aligned} \tag{6}$$

[2]Recall $q_i = r_i + \nu_i$. The expected value of $\max\{q_1, q_2\} = A + \ln(\exp(r_1) + \exp(r_2)) = A + \ln(2e)$, where $e_i = \exp(r_i) = e$, $A = \mu + \gamma$, μ is the mean of ν and is assumed to be zero, and γ is Euler's constant.

The government's payoff is maximized when $\Delta = 0$, as it induces no research effort and the R&D firms' participation constraint is trivially satisfied. However, a second-price auction implies the expected value of Δ is strictly positive. In general, the government will seek to pay the lowest production cost.

4.2.2 Bundled Procurement Regime

In the bundled procurement regime, the government commits to purchase the final product from the research winner for a combined payment, P_b. Setting $P_b = P_u + \overline{C}_m$ when R&D firms lack production capabilities yields outcomes identical to the unbundled regime.

The research stage winner now holds the production contract and will subcontract to the lowest-cost producer at $\overline{C}_m$. We assume the government and the research stage winner are equally efficient at the second-price auction. Each of the m producers has an expected payoff of $\frac{1}{m}(\overline{C}_m - \underline{C}_m) - F = \frac{1}{m}\Delta_m - F$, as before. The research winner's gross payoff is $P_b - \overline{C}_m = P_u$. The symmetric Nash Equilibrium research effort is $e = \dfrac{P_b - \overline{C}}{2g} = \dfrac{P_u}{4g}$. The expected R&D profit, and hence also the research effort and the quality of the proof-of-concept prototype, are the same. The government's expected payoff remains unchanged.

A single combined payment, P_b, rewards both research and production in the bundled regime. This payment can be split into a research incentive I and a production price P, as long as $I + P = P_b = P_u + \overline{C}_m = P_u + \underline{C}_m + \Delta_m$. The research winner subcontracts production on behalf of the government. As long as the government sets the compensation appropriately, there is no advantage to the research winner from bundled procurement.

An important insight is that **when R&D firms lack production capabilities, bundling the R&D and production stages offers no advantage**, even if proof-of-concept prototype quality is not contractible. Contractual frictions alone cannot explain the crowding-in effect of government R&D contracts.

4.3 R&D Firms Have Production Capabilities

When the successful R&D firm can also produce, awarding both contracts to it can be optimal for the government. The intuition is that the ability of the winning research firm to compete in production allows it to lower production costs, increasing its profits. Anticipating this, the government can pay less for R&D, leaving it better off relative to an unbundled regime.

4.3.1 Unbundled Procurement Regime

Integrated firms can perform R&D and implement the operational prototype in production. In the unbundled regime, the (integrated) R&D firms may also choose to enter the production stage. R&D firms have three profit streams: research, development (normalized to 0), and production. However, since the stages are separate, there is no effect on research effort, quality, or the government's payoff.

4.3.2 Bundled Procurement Regime

Suppose the government commits to buy the final product from the research winner, and both R&D firms can produce. The research winner awards the production contract to the lowest-cost producer at $\overline{C}_{m+1}$. We use $\overline{C}_{m+1}$ for the lowest cost among $m+1$ production participants. Although it could produce itself, the research winner benefits from subcontracting (unless it is the lowest-cost firm).

As before, by entering the production auction, it can earn a positive expected production profit. However, unlike earlier, its total profits increase by more than the production profit. The research winner's expected profit is $(P_b - \overline{C}_{m+1} - ge) + \{\frac{1}{m+1}(\overline{C}_{m+1} - \underline{C}_{m+1}) - F\}$. The first profit stream (in parentheses) is from supplying the bundled product. The second profit stream (in curly brackets) is the production profit.

The production profit is also available to the losing R&D firm with production capability. (It is also available in the unbundled regime.) Thus, the production profit does not impact research stage returns or effort.

The first profit stream increases with more producers. Thus, participating in the auction offers two benefits. If the research winner is the lowest-cost firm, it receives a positive payoff. If it is the second-lowest-cost firm, it pays less to the winner of the production auction. Consider the case when R&D firms have a higher fixed cost than existing producers. That is, $\tilde{F} > F$ so that $\frac{1}{m+1}(\overline{C}_{m+1} - \underline{C}_{m+1}) - \tilde{F} = 0$. The research winner's expected gross profit is $(P_b - \overline{C}_{m+1}) = (P_b - \overline{C}_m) + (\overline{C}_m - \overline{C}_{m+1})$. If P_b is set so that $P_u = P_b - \overline{C}_m$, **the research winner's expected profits are higher with a bundled contract by the amount it lowers the second-lowest cost**.[3] This benefit occurs only in the bundled regime and only if the research winner has production capability and participates in the production auction.

Impact on the research effort. Firm 1's expected payoff is:

$$\Pi_1 = \frac{e_1}{e_1 + e_2}(P_b - \overline{C}_{m+1}) + \frac{1}{m+1}(\overline{C}_{m+1} - \underline{C}_{m+1}) - F - ge_1 \tag{7}$$

At a symmetric Nash Equilibrium, research effort is $e = \dfrac{P_b - \overline{C}_{m+1}}{4g}$, which is greater than in the unbundled regime because $P_b - \overline{C}_{m+1} = P_u + \overline{C}_m - \overline{C}_{m+1} = P_u + X$, where $X > 0$. Since the total cost to the government, $P_u + \overline{C}_m$, is the same in both regimes, the government benefits from the bundled regime, which yields a higher quality prototype. **A key takeaway is that the government prefers bundling when there are production rents and R&D firms have production capability.** However, the government could do better.

Government policy. We assumed the government set $P_b = P_u + \overline{C}_m$, leaving the winner with an additional R&D profit of $X = \overline{C}_m - \overline{C}_{m+1}$. The government can account for this profit and reduce the bundled payment. Given that optimal quality is $V' = \beta = P_u$, it will. Formally, in a

[3] To illustrate this, suppose $m = 2$. Suppose the research winner can participate in the production auction under the unbundled regime. In that case, its profits increase by $\frac{1}{3}(\overline{C}_3 - \underline{C}_3 - F)$ because with probability $\frac{1}{3}$, it will be the lowest cost firm. In the bundled regime, it garners an additional benefit because it pays $P_b - \overline{C}_3$ instead of $P_b - \overline{C}_2$ to the subcontractor. In other words, it has to pay $\overline{C}_2 - \overline{C}_3$ less to its subcontractor.

bundled regime where the participants have production capability, the government maximizes:

$$W = \max_{P_b}\{V(A + \ln(\frac{P_b - \overline{C}_{m+1}}{2g})) - P_b\} \tag{8}$$

The government will set $P_b = P_u + \overline{C}_{m+1} = P_u + \overline{C}_m - (\overline{C}_m - \overline{C}_{m+1}) = P_u + \overline{C}_m - X$ to reduce its cost by X while maintaining the same expected quality, $\frac{P_u}{2g}$, as in the unbundled case. In other words, there is a pattern consistent with "**crowding-in**." The government reduces the payment to the research winner by X, whose research effort remains unchanged because it anticipates making up the missing profit in production.

This assumes production entry costs are low enough to attract the research winner but not so low that the loser also enters. Given that $X = \overline{C_m} - \overline{C}_{m+1}$, the following condition must hold:

$$\left(\frac{1}{m+1}(\overline{C}_{m+1} - \underline{C}_{m+1})\right) \leq F \leq X + \left(\frac{1}{m+1}(\overline{C}_{m+1} - \underline{C}_{m+1})\right) \tag{9}$$

If the first inequality is not satisfied, R&D firms will enter the production auction even if they lose, preventing the government from extracting those rents by reducing the bundled payment. If the second inequality is not satisfied, the winning research firm will not enter the production auction.

A key takeaway is that the government prefers bundling if R&D firms have production capabilities but will participate in production only if they win the research stage (i.e., when Equation 9 is satisfied). The government would lower the bundled price to keep the research effort unaffected. In other words, when R&D firms can enter production, the government may bundle but lower prices to reduce costs without affecting the research effort. Intuitively, when the successful R&D firm can lower expected production costs, it will internalize this expected reward in its R&D decisions. Anticipating this, the government will lower its R&D payment without affecting the expected prototype quality. Bundling reduces the government's cost without reducing the research effort.

Appendix B extends this framework by considering contractible research quality. In short, the government fares better with contractible quality. Conditions for bundling the R&D and production stages remain as outlined, with identical implications for crowding in.

4.4 Empirical Predictions

Empirically, crowding in (i.e., using private funds to co-invest in R&D with the government) should be present when R&D firms expect additional profits from production. This suggests that crowding-in should be stronger when the government relies more on bundled procurement. That should occur when two conditions are met simultaneously:

1. When the R&D project is more upstream (and effort is less likely to be observable). This suggests a positive effect of R&D contracts on corporate publications and renowned scientists but not on patents.

2. When R&D firms have production capabilities. This suggests a positive effect of R&D con-

tracts on corporate publications and renowned scientists for large firms but not for small firms.

We assumed the development stage has no incentive effect. In reality, both research and development may be stochastic functions of unobserved effort. However, this is likely higher for research than for development (overall uncertainty is higher in upstream R&D). Consequently, the government has fewer opportunities to crowd in development investments compared to research investments.

5 Data

We combine data from four primary sources: (i) corporate R&D data, including matched publications and patents (Arora, Belenzon, & Sheer, 2021); (ii) biographical data from the American Men & Women of Science (AMWS) directory; (iii) government procurement data from the Federal Procurement Data System (FPDS); and (iv) government grant data from the Treasury DATA Act Broker. Data construction is summarized below and detailed in Online Appendix C.

5.1 R&D Expenditures, Publications, and Patents

We extend the Arora, Belenzon, and Sheer (2021) panel by matching firms to prime federal procurement contracts (1980-2015) and grants (2001-2015). The Arora, Belenzon, and Sheer (2021) panel accounts for changes in company names and ownership (e.g., due to mergers, acquisitions, or spinoffs), enabling accurate contract and grant flows.

Our sample includes 4,520 U.S. publicly traded firms with at least (i) one year of R&D expenditures, (ii) one granted patent, and (iii) three years of consecutive financial records from their first patent. We use data on firm accounting measures (e.g., sales and R&D expenditures from Standard & Poor's Compustat North America), publications (Clarivate's Web of Science), and patents (European Patent Office's PATSTAT). We measure firms' upstream R&D by corporate scientific publications and employment of renowned scientists, and downstream R&D by granted patents (similar to Arora, Belenzon, & Patacconi, 2018; Arora, Belenzon, & Sheer, 2021). Our variable construction work is detailed in Online Appendix D.

A limitation is that our sample includes only publicly traded firms, which may not represent all U.S. innovating firms. We capture a large share of R&D investments. In 2015, U.S. businesses funded \$333,243 million in R&D (AAAS, 2022), while our sample firms reported \$296,914 million in R&D expenditures to the Securities and Exchange Commission. These figures suggest our sample captures up to 89% of business innovation investments that year. Our framework predicts that only vertically integrated firms (i.e., with both R&D and production capabilities) are likely to crowd in company-funded R&D under a bundled procurement regime. Most privately held firms are small and unlikely to have both R&D and production capabilities. To the extent large privately held firms respond similarly to the guaranteed demand mechanism as large publicly traded firms, our conclusions about the demand-pull incentive for innovation in federal procurement should generalize.

5.2 Renowned Scientists

We collect biographical information from AMWS, a directory of renowned North American scientists in physical, biological, and related sciences. In 39 editions (1906-2021), AMWS has profiled over 300,000 people, including field of specialty, education, professional experience, memberships, research, and contact information. We match records in AMWS's digital editions separately to account for deceased scientists dropped from recent editions (yet, once identified, AMWS provides a full employment history for the scientist). We match scientists' employers to subsidiaries and ultimate owners from our firm panel. We identify 20,552 renowned scientists who worked for 1,727 firms in our panel. We aggregate renowned scientists at the firm-year level by counting those employed by an ultimate owner and its subsidiaries annually. AMWS also collects information on major awards won by scientists, which we use to analyze award-winning scientists in our sample firms.

The two measures of corporate science—publications and renowned scientists employed—are highly correlated (Pearson coefficient of 0.69). However, each measure imperfectly captures the scientific activities of the firm. Table 2 shows that 49% of the firms that publish do not employ renowned scientists, while 10% of the firms that employ renowned scientists do not publish. This suggests that using both measures of upstream R&D is warranted.

Table 2: Cross Tabulation of Measures of Corporate Science

	(1) Do not employ scientists	(2) Employ scientists	(3) Total
Do not publish	1,325	172	1,497
Publish	1,468	1,555	3,023
Total	2,793	1,727	4,520

Notes: This table provides a cross-tabulation of measures of corporate science for the 4,520 firms in our sample. The unit of analysis is a firm.

5.3 Federal Procurement Contracts

We collect federal procurement contracts and indefinite delivery vehicles (hereafter, "contracts") from SAM.gov (1980-2000) and USAspending.gov (2001-2015). We match contract recipient firms and their parent companies to subsidiaries and ultimate owners from our firm panel (see Online Appendix C). We identify 8.6 million contracts totaling $4.2 trillion awarded by 72 federal agencies to 2,578 R&D-performing, publicly traded U.S. firms (henceforth, "contractors"). These contracts represent 33% of the total contract value awarded during 1980-2015. Contractors often receive multiple contracts per year. We aggregate contract values at the firm-year level by summing all contracts and modifications awarded to an ultimate owner and its subsidiaries annually.

Agencies use a four-digit *Product or service code* to describe the principal product or service in each transaction. The 78 two-digit numerical codes for product groups and 24 letter codes for service categories are listed in Appendix Tables D3 and D4, respectively. We use this system to separate *R&D contracts* from *Production contracts* (i.e., non-R&D contracts). We use crosswalks between product and service codes, the North American Industry Classification System (NAICS), and the Standard Industrial Classification (SIC) to identify the primary four-digit industry (SIC4) for each transaction. This allows us to calculate the aggregate value of procurement contracts for each industry-year, which is essential for constructing our instrumental variables.

The Federal Acquisition Streamlining Act of 1994 establishes a statutory preference for procuring commercially available products and services. As a result, agencies acquire products and services as diverse as computers, transportation, and medicine using simplified requirements and streamlined practices intended to resemble those used in commercial markets (e.g., exempting contractors from the requirement to submit certified cost or pricing data). We use the *Commercial items acquisition procedures* field to divide production contracts into *commercial* and *noncommercial*. This allows us to explore how the effect of R&D contracts has evolved with increased procurement of commercially available technologies and decreased procurement of new technologies designed to meet unique agency specifications.

5.4 Guaranteed Demand

Guaranteed demand rewards firms that demonstrate technological superiority in R&D races with noncompetitive production contracts. Although federal agencies generally require full and open competition, the Competition in Contracting Act of 1984 authorized noncompetitive contracts under specific exceptions. Notable exceptions include *follow-on contracts* for continued development or production of major systems, specialized equipment, or (for DoD, NASA, and the Coast Guard) specialized services. This framework lets the government bundle R&D races with production by awarding noncompetitive follow-on contracts. We use the *Extent competed* field to distinguish between competitive and noncompetitive contracts. This lets us classify industries with top quartile shares of noncompetitive production contracts in all production contracts (relative to other industries' shares in the same fiscal year) as industries with high guaranteed demand. The remaining industries have low guaranteed demand.

5.5 Federal Grants

We collect financial assistance awards (grants, cooperative agreements, and direct payments, but not loans or insurance; henceforth, "grants") awarded by all federal agencies during 2001-2015 from USAspending.gov. Unfortunately, no comparable grant data are available for fiscal years 1980-2000. We match the names of grantees to our firm panel. We identify 388 firms that receive \$8.8 billion in grants from 25 federal agencies during 2001-2015. Like contractors, grant recipients often receive multiple grants per year. We aggregate grants values at the firm-year level by summing all the grants and modifications awarded to an ultimate owner and its subsidiaries annually. This lets us control for government funding when testing the guaranteed demand mechanism.

5.6 Descriptive Statistics

Table 3 presents descriptive statistics for the main variables used in our econometric analyses. Approximately 71% of sample firms performed scientific research (i.e., employed at least one renowned scientist or had at least one scholarly publication). These firms employed 5 renowned scientists on average and published 17 publications annually. All firms had at least one patent by construction. Firms produced 22 patents annually on average.

Procurement touched a broad set of R&D-performing firms. In our sample, 1% were military-only contractors, 29% supplied both military and nonmilitary needs, 27% were nonmilitary-only contractors, and 43% were noncontractors. Overall, 57% of firms received at least one contract during 1980-2015, 22% received at least one R&D contract during 1980-2015, and 9% received at least one federal grant during 2001-2015.

Table 3: Descriptive Statistics

	(1)	(2)	(3)	(4)	(5)	(6)
				Distribution		
	Obs.	Mean	Std. dev.	10th	50th	90th
R&D expenditures ($ mm)	54,238	111	557.2	0.5	10.0	147.4
Renowned scientists	47,329	5	33.5	0.0	0.0	6.0
Publications	47,329	17	94.9	0.0	1.0	19.5
Patents	60,885	22	132.2	0.0	1.0	31.5
All contracts ($ mm)	41,456	101	1,144.9	0.0	0.1	25.4
R&D contracts ($ mm)	41,456	17	263.1	0.0	0.0	0.6
Production contracts ($ mm)	41,456	84	916.6	0.0	0.1	22.8
Commercial contracts ($ mm)	27,022	12	104.4	0.0	0.0	4.1
Noncommercial contracts ($ mm)	27,022	82	1,013.9	0.0	0.0	9.9
All grants ($ mm)	4,809	2	14.8	0.0	0.0	3.0
Sales ($ mm)	60,557	2,603	12,747.3	2.9	146.3	4,334.6
R&D stock ($ mm)	60,885	428	2,495.1	0.6	26.0	483.3
All contracts / Sales (%)	40,895	3	11.0	0.0	0.0	4.3
R&D contr. / (R&D contr. + R&D exp.) (%)	37,177	3	14.7	0.0	0.0	2.2

Notes: This table presents descriptive statistics for the main variables used in the econometric analyses. The unit of analysis is a firm-year. Renowned scientists and publications are summarized for firms that perform scientific research, while contract statistics are only provided for contractors. Commercial and noncommercial contracts are only summarized for fiscal years 1995-2015. Grant statistics are only provided for fiscal years 2001-2015 and firms that receive at least one grant during this period.

Contractors received an average of $101 million in contracts annually, including $17 million for R&D services. Contractors received contracts from 6 federal agencies on average (median of 4 agencies). Consistent with the guaranteed demand mechanism, 81% of firms that won an R&D contract later received at least one noncompetitive production contract. Among firms that never won an R&D contract, only 35% later received at least one noncompetitive production contract.

Federal contracts averaged 3% of total firm sales. Similarly, R&D contracts made up 3% of total government- and company-funded R&D. However, 77 firms received at least 25% of total sales from the government, and 23 received at least 50%. These 23 firms were larger ($6,059 million in annual sales), received more R&D contracts ($728 million per year), published more (49 publications per year), and patented more (28 patents per year) compared to the average sample firm. They operated in the Instruments (7 firms), Business services (4 firms), Chemicals (2 firms), Electronics (2 firms), and other main industries (8 firms). The concentration of government R&D contracts among the top four firms rose nearly 25 percentage points from 1980 to 2006, then fell 17 percentage points from 2006 to 2015 (see Appendix Figure E1). The change in trend is consistent with federal agencies increasingly implementing competitive procurement practices in the latter sample years.

We carefully evaluated whether government R&D contracts were concentrated in just a few firms. After accounting for inter-industry differences in the minimum efficient scale of operations, we found that 69% of *very large* R&D contracts (firm-year R&D contracts above the 90th percentile of same-industry R&D contracts) were awarded to firms that were not *very large* (where very large firms had annual sales above the 90th percentile of same-industry annual sales). We concluded that government R&D contracts were not overly concentrated in the largest of firms.

There was substantial heterogeneity in contracts by awarding agency (see Appendix Table H18). The average R&D contract value ranged from $8,362 (Federal Maritime Commission) to $15,999,149 (U.S. Agency for International Development). Average R&D contracts from the DoD, NASA, and DoE were $4.8 million, $7.3 million, and $3 million, respectively. These agencies also awarded larger noncompetitive production contracts than the average. Moreover, agencies that awarded a significant share of basic and applied R&D contracts in all contracts (which suggests high demand for innovative technologies) also awarded a significant share of production contracts without competition (see Appendix Figure H4). This pattern is consistent with firms having strong incentives to win R&D races as a pathway to government demand.

There was heterogeneity in the characteristics of R&D contractors working for different agencies (see Appendix Table H19). Firms that won R&D contracts from the Department of Commerce (DoC) tended to publish more than other R&D contractors. Firms that won large R&D contracts from one agency tended to also win large R&D contracts from other agencies (see Appendix Tables H20 and H21). Defense R&D contractors tended to work also for NASA (see Appendix Table H22). Firms that were R&D contractors for a non-defense agency tended also to be defense R&D contractors. At the high end, 93% of DoC R&D contractors were defense R&D contractors, while at the low end, 52% of HHS R&D contractors were also defense R&D contractors.

Our sample was drawn from a wide distribution of industries (see Appendix Table G13). The two-digit industries (SIC2) most represented were Chemicals (796 firms), Electronic Equipment (680 firms), and Instruments (672 firms). We classified those industries into five main groups: Chemicals, Electronics, Instruments, Business services, and Others (see Appendix Table G14). The largest average annual R&D contracts were in the Others group ($45 million), while the smallest were in Chemicals ($1 million, see Appendix Table G15). Among contractors, the number of publications per $1 million in contracts ranged from a low of 0.05 in the Others group to a high of 3.95 in Chemicals. Industry groups with the lowest and highest numbers of patents per $1 million in contracts were Instruments and Chemicals, respectively. Among R&D contractors, publications per

$1 million in R&D contracts ranged from 0.29 in Others to 63.45 in Drugs. Meanwhile, patents per $1 million in R&D contracts ranged from 0.51 in Instruments to 37.39 in Chemicals.

The composition of government contracts varied by main industry and over time. In 1994, the industries with the highest share of R&D contracts in all contracts were the Others group (35%) and Instruments (23%). In 2015, the industries with the highest share of commercial contracts in all contracts were Chemicals (76%) and Electronics (38%).

On average, R&D contractors were larger ($6 billion vs. under $1 billion in annual sales, see Appendix Table E8). They invested more in R&D ($265 million vs. $33 million) but had lower R&D intensity ($1.4 million vs. $5.9 million per $1 million in sales).[4] They conducted more scientific research (0.4 vs. 0.3 publications per $1 million in R&D expenditures) and about half as much downstream development (0.6 vs. 1.2 patents per $1 million in R&D expenditures). These differences persisted compared to other firms within the same industry (see Appendix Table G16).

Our analyses are conducted at the firm-year level. The main dependent variables, *R&D expenditures, Renowned scientists, Publications*, and *Patents*, are highly correlated (see Appendix Table E9). The same is true of the main control variables, *Sales* and *R&D stock*. However, their correlations with the independent variable *R&D contracts* are relatively low, easing potential concerns about multicollinearity.

6 Econometric Specifications

6.1 R&D Expenditures, Publications, Renowned Scientists, and Patents Equations

We estimate the following specifications for the relationship between R&D contracts and corporate R&D expenditures, publications, renowned scientists, and patents (denoted by $Y_{i,t}$):

$$\ln(Y_{i,t}) = \alpha_0 + \alpha_1 \ln(R\&D\ contracts_{i,t-3}) + \boldsymbol{Z}'_{i,t-3}\boldsymbol{\omega} + \boldsymbol{\eta}_i + \boldsymbol{\tau}_t + \epsilon_{i,t} \tag{10}$$

$R\&D\ contracts_{i,t-3}$ is the dollar value of R&D contracts awarded to firm i (and its subsidiaries) in year $t-3$. Robustness checks in Online Appendix I show that our results are not sensitive to the lag structure used. The vector $\boldsymbol{Z}$ includes time-varying controls like the natural logarithms of *Sales* and *R&D stock*. The vectors $\boldsymbol{\eta}$ and $\boldsymbol{\tau}$ are firm fixed effects and year fixed effects, respectively, and ϵ is an *iid* error term. All dollar values are adjusted using the GDP Implicit Price Deflator to reflect constant 2012 dollars (U.S. Bureau of Economic Analysis, 2021). When calculating natural logarithms, we add $1 to millions-measured variables (e.g., R&D expenditures, R&D contracts, and instrumental variables) and one unit to publications, renowned scientists, and patents. Standard errors are clustered at the firm level.

[4]The average R&D intensities are greater than one due to the presence of very large outliers—publicly traded firms that invested heavily in R&D expenditures before they achieved significant sales. In our data, these outliers were primarily firms in the drugs and biotechnology industries.

Corporate R&D activities can be "company-funded" (using firm funds) or "customer-funded" (under contracts with federal agencies or other customers). We use the fact that company-funded R&D costs are included in *R&D expenditures*, while customer-funded R&D costs are expensed under *Cost of sales* as incurred. Independent company-funded R&D costs can be recovered as general and administrative overhead (i.e., indirect costs) on federal procurement contracts, if allowable, allocable, and reasonable. However, the firm still bears the risk of performing the R&D in hopes of recovering it from future contracts. A crowding-in effect of R&D contracts implies $\hat{\alpha_1} > 0$.

6.2 Identification Strategies

A major econometric challenge is how to deal with the endogeneity of R&D contracts. Common shocks can affect federal procurement and corporate R&D activity. If the U.S. government targeted firms with positive (negative) technology or demand shocks, the OLS estimate of α_1 would be upward-biased (downward-biased). We use two identification strategies to address this concern. First, we construct several instrumental variables that exploit variation in industry-level procurement, agency-level windfall funding resulting from the congressional appropriations process, and product or service code (PSC)-level procurement. We use these instruments to predict R&D contracts at the firm level. Second, we exploit the end of the Cold War as a quasi-natural experiment in a panel event study. Robustness checks in Online Appendix I also use procurement shocks from the end of the *Cold War*, the *Global War on Terrorism*, and the *Financial Crisis* in instrumental variable estimations.

6.2.1 Instrumental Variables

Our first instrument uses industry-level R&D contracts to predict firm-level R&D contracts. R&D contracts to a firm's SIC4 industry may still be endogenous (e.g., if a firm dominates its industry, both industry R&D contracts and firm R&D activity may respond to the same technology shocks). To address this, we use changes in R&D funding at the SIC3 industry level. We "distribute" these changes across SIC4 industries by time-invariant industry shares, following Moretti et al. (2021). This approach lowers the instrument's power in the first stage but increases its validity.[5]

We build $Industry\ R\&D\ funding_{i,t} = (Industry\ R\&D\ contracts_{SIC3,t} - Firm\ R\&D\ contracts_{i,t}) \times Industry\ share_{SIC4,SIC3}$. $Industry\ R\&D\ contracts_{SIC3,t}$ is the total R&D contracts awarded to firm i's SIC3 industry in year t. $Firm\ R\&D\ contracts_{i,t}$ is the value of R&D contracts awarded to firm i in year t. $Industry\ share_{SIC4,SIC3}$ is calculated by dividing the total value of R&D contracts awarded to firm i's SIC4 industry during 1980-2015 by the total value of R&D contracts awarded to firm i's SIC3 industry during 1980-2015. Note that these total values include R&D contracts awarded by all federal agencies to all recipients, not just to sample firms. Additional details about

[5] Moretti et al. (2021) use the term "*predicted* defense R&D subsidies" to describe their instrument. However, the instrument is not predicted via a first-stage regression. Rather, the instrument combines nationwide changes to defense R&D with fixed (i.e., time-invariant) allocations across industries. We implement the same approach without using the term "predicted."

this instrument are included in Online Appendix F.

Industry-level R&D contracts may be linked to unobserved or mismeasured technology or demand shocks affecting firm-level R&D decisions. To address this, our second instrument uses variation in the R&D budget authority of 12 federal agencies (plus an "Other" category) from the American Association for the Advancement of Science (AAAS). We construct $Agency\ R\&D\ budget_{i,t}$ by replacing $Industry\ R\&D\ contracts_{SIC3,t}$ with $\sum_{Agencies} R\&D\ budget_{Agency,t} \times Share_{Agency,SIC3,t}$. Here, $R\&D\ budget_{Agency,t}$ is the focal agency's R&D budget authority in year t. $Share_{Agency,SIC3,t}$ is the ratio of R&D contracts awarded by the focal agency to firm i's SIC3 industry to total R&D contracts awarded by the focal agency in year t.

Since agency R&D budgets may reflect technological shocks affecting firm R&D, our third instrument uses the difference between *requested* and *actual* budget authority appropriated by Congress for each federal agency, following Dugoua, Gerarden, Myers, and Pless (2022). The annual *Budget of the U.S. Government* discloses both requested and actual amounts. The difference between them is the windfall budget authority. We hand-collect this information for the 12 main agencies and the "Other" category.

This instrument assumes that demand for funding (the requested amount) reflects a common technology shock affecting both public procurement and corporate R&D activity. However, the actual budget appropriated by Congress includes a component that is independent of this shock. Thus, we use an agency's windfall (or shortfall) from political negotiation between the executive branch and Congress as a source of exogenous variation in its R&D budget authority. We build $Windfall\text{-}predicted\ R\&D\ budget_{i,t}$ by replacing $R\&D\ budget_{Agency,t}$ with $Windfall\text{-}predicted\ R\&D\ budget_{Agency,t}$, the predicted value of the agency's R&D budget authority in year t, obtained after regressing the agency's R&D budget authority on its total budget windfall.

The first three instruments use a similar approach (i.e., subtracting the firm's R&D contracts, multiplying by $Share_{SIC4,SIC3}$). To address common-method potential bias, we construct a fourth instrument with a different approach and report results in Online Appendix F. Following Bartik (1991), we build a shift-share instrument, $PSC\ R\&D\ funding_{i,t} = \sum_{PSCs} R\&D\ contracts_{PSC,t} \times Share_{i,PSC}$. The shift, $R\&D\ contracts_{PSC,t}$, represents R&D contracts awarded by federal agencies in the focal PSC in year t. The shift varies over time but not across firms. The exposure shares, $Share_{i,PSC}$, are calculated by dividing the value of R&D contracts awarded to firm i in the focal PSC during the pre-period by the total R&D contracts awarded to firm i during the pre-period. The exposure shares vary across firms but not over time. Due to an unbalanced panel, we cannot use the same pre-period for all firms. Instead, firm i's pre-period is $[\tau_i, \tau_i + 4]$, where τ_i is the first year firm i receives a government R&D contract. We drop years before $\tau_i + 4$ from subsequent analyses for firm i.

6.2.2 Event Study

During the Cold War (1948-1989), federal procurement aimed at sustaining technological superiority for national security (Weiss, 2014). The scale and duration of Cold War threats led to large procurement budgets dominated by the DoD (Mowery, 2012). The end of the Cold War eliminated the perception of an existential threat and drove a massive reallocation of government procurement.[6] For example, DoD procurement obligations dropped 38% (from \$225.9 billion in 1988 to \$140.1 billion in 1992), while HHS obligations nearly tripled (from \$830 million to \$2.3 billion).

Overall, government demand fell between 1988 and 1992. Industries saw an average \$84 million reduction in procurement contracts. Not all industries were equally affected (see Appendix Figure F3 and Appendix Table F12). "Winners" of increased funding included IT industries (e.g., computer systems design) and health industries (e.g., medicinal chemicals). "Losers" included national security industries (e.g., guided missiles). Since the reallocation was due to geopolitical factors rather than technology shocks, we use the end of the Cold War as a quasi-natural experiment in a panel event study. We estimate the following specifications:

$$ln(Y)_{it} = \sum_{j=2}^{5} \gamma_j \, (Lead\ j)_{it} + \sum_{k=0}^{5} \delta_k \, (Lag\ k)_{it} + \boldsymbol{Z'_{i,t}\omega} + \boldsymbol{\eta_i} + \boldsymbol{\tau_t} + \epsilon_{i,t} \tag{11}$$

Y_{it} denotes *R&D expenditures*, *Renowned scientists*, *Publications*, and *Patents* for firm i in year t. Leads and lags are indicator variables: $(Lead\ j)_{it} = \mathbb{1}[t = Event_{shock} - j]$ and $(Lag\ k)_{it} = \mathbb{1}[t = Event_{shock} + k]$. $Event_{shock} \in \{1991,\ ...,\ 1994\}$ is the shock year. The vector $\boldsymbol{Z}$ includes controls for the natural logarithm of *Private demand* (calculated as *Sales* − *All contracts*) and its percentage change. The vectors $\boldsymbol{\eta}$ and $\boldsymbol{\tau}$ are firm fixed effects (to absorb firm-specific, time-invariant heterogeneity) and year fixed effects (to absorb time trends in our staggered treatment design), respectively, and ϵ is an *iid* error term.

To isolate the effect of increased government R&D demand without a total demand increase, our event study focuses on firms in SIC3 industries with large R&D contract increases but moderate total demand changes. A "large" increase in R&D contracts is a year-over-year change in R&D contract value in the top 20% of changes between 1991 and 1994. A "moderate" change in total demand is a year-over-year sales change in the middle 60% of changes between 1991 and 1994.[7]

The event study sample includes 1,395 firms in 26 industries meeting these criteria. Private demand did not increase for treated firms relative to controls after the R&D shock (see Panel A of Appendix Figure I5). This confirms that we successfully controlled for changes in private demand when constructing our event study sample. Treatment is the positive R&D contract shock, staggered across industries in the 1991-1994 period. The 111 firms (from 24 industries) with R&D contracts

[6] The end of the Cold War may have been precipitated by strategic DoD investments (e.g., the Strategic Defense Initiative or the "Star Wars program," introduced by President Reagan in 1983 to neutralize the Soviet nuclear arsenal). To test this, we exclude DoD R&D contracts and examine those from civilian agencies, whose funding should not have accelerated the Soviet collapse. We also test R&D contracts' effect on publications using two alternative shocks. The Global War on Terrorism and the Financial Crisis both triggered massive redeployment of federal procurement funds. These shocks are unlikely to have the same endogeneity problem as the Cold War shock.

[7] The median year-over-year R&D contract change during 1991-1994 was a 31% decrease. Top 20% industries saw an increase greater than 44.8%. Over the same period, the median year-over-year change in sales to a SIC3 industry was a 2.4% increase. Bottom 20% industries had a sales decrease of -6.7% or more, while top 20% industries saw a sales increase of 15.1% or more. We used these thresholds (increase in R&D contracts $\geq$ 44.8%, change in sales between -6.7% and 15.1%) to identify SIC3 industries for the study.

in 1980-1985 are the treated group, while the remaining 1,284 firms (from 26 industries) are the controls. Once treated, firms remain so throughout the sample. Estimations use firms with data for the full 9-year period to control industry composition changes. Consistent with the assumption that firms do not anticipate the R&D shock, treated and control firms follow parallel pre-trends (see Figure 3).

7 Estimation Results

Our results point to a strong crowding-in effect of R&D contracts on company-funded upstream R&D, consistent with the guaranteed demand mechanism. Detailed analyses are included below.

7.1 R&D Expenditures Equation

Table 4 presents within-firm estimates for R&D expenditures. OLS estimates from Columns 1-2 show *R&D expenditures* were positively related to *R&D contracts* (p-value < 0.01), regardless of firm size control. We lagged *Sales* an additional year to avoid double-counting R&D contract dollars. Unreported specifications show similar coefficient estimates on *R&D contracts* with *R&D stock* as a size control. Our estimates are similar to Moretti et al. (2021)'s findings on government R&D subsidies (both R&D contracts and grants) and company-funded R&D in French firms.

Table 4: Estimation Results for the R&D Expenditures Equation

	(1)	(2)	(3)	(4)	(5)	(6)
	ln(R&D expenditures)$_t$					
	OLS: Within firms	OLS: Within firms (Sales control)	IV: Industry R&D funding	IV: Industry R&D funding (Sales control)	IV: Agency R&D budget	IV: Windfall-predicted R&D budget
ln(R&D contracts)$_{t-1}$	0.011	0.005	0.075	0.062	0.061	0.060
	(0.003)	(0.002)	(0.026)	(0.024)	(0.023)	(0.023)
ln(Sales)$_{t-2}$		0.369		0.350	0.351	0.351
		(0.016)		(0.016)	(0.016)	(0.016)
Sample years	1980-2015	1980-2015	1980-2015	1980-2015	1980-2015	1980-2015
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Weak identif. (Kleibergen-Paap)			108.82	100.29	101.45	102.25
Firms	4,285	3,827	4,228	3,771	3,772	3,774
Observations	48,835	43,389	45,730	40,473	40,496	40,509
Adjusted R-squared	0.892	0.919	-0.038	0.118	0.119	0.120

Notes: This table presents the estimation results for the relationship between R&D contracts and company-funded R&D expenditures. Columns 3-6 present the second stage of 2SLS, where R&D contracts are instrumented using *Industry R&D funding*, *Agency R&D budget*, and *Windfall-predicted R&D budget*, as noted. Standard errors (in parentheses) are clustered at the firm level.

Columns 3-6 show the 2SLS estimates. For Column 3, we predicted *R&D contracts* using the *Industry R&D funding* instrument (F statistic = 56, see Column 1 of Appendix Table F10). In the second stage, we regressed *R&D expenditures* on predicted R&D contracts. As expected, $\hat{\alpha_1} > 0$ (p-value < 0.01). A larger 2SLS estimate (OLS is downward-biased) suggests R&D contracts targeted areas affected by negative shocks, consistent with government procurement aiming to maintain the military-industrial base (Peters, 2021).

At the sample means, Column 4's estimate implies that a \$10 million increase in R&D contracts crowded in \$5.3 million in company-funded R&D expenditures. Average R&D expenditures and R&D contracts were \$99.9 million and \$11.6 million, respectively. Since $\alpha_1 = \frac{\partial R\&D\ expenditures}{\partial R\&D\ contracts} \frac{Avg.\ R\&D\ contracts}{Avg.\ R\&D\ expenditures}$, the marginal effect of a \$10 million increase in R&D contracts was $10 \times \alpha_1 \frac{Avg.\ R\&D\ expenditures}{Avg.\ R\&D\ contracts} = 10 \times 0.062 \frac{99.9}{11.6} = 5.3$ million increase in R&D expenditures. Similar estimates were obtained when instrumenting for *R&D contracts* using *Agency R&D budget* and *Windfall-predicted R&D budget* (Columns 5 and 6). Excluding R&D contracts from each of the seven largest federal agencies showed that our results were not driven solely by the DoD or any single agency (see Appendix Table H23).

In summary, we found that R&D contracts crowded in additional company-funded R&D investments. Next, we examine the effect of R&D contracts separately for upstream and downstream R&D. Consistent with the guaranteed demand mechanism—which should be used more when the effort is unobservable and implementing knowledge in production is harder—we expect the effect of R&D contracts to be strong for upstream R&D (measured using publications and renowned scientists), but not for downstream R&D (measured using patents).

7.2 Publications Equation

Table 5 shows estimation results for corporate publications, our measure of upstream R&D output. Column 1 shows *Publications* were positively related to *R&D contracts* (p-value < 0.001). In unreported specifications, we obtained similar coefficient estimates for *R&D contracts* when *R&D stock* was replaced by *Sales* or omitted.

Columns 2 and 3 present 2SLS results using *Industry R&D funding* and *Windfall-predicted R&D budget* as instruments, respectively. Unreported specifications show a coefficient estimate of 0.029 when omitting the *R&D stock* control. At sample means, Column 2's estimate implies that \$23.3 million in additional R&D contracts yields one more corporate publication. We report additional results using *PSC R&D funding* as an instrument for R&D contracts in Appendix Table F11. Across all these specifications, the 2SLS estimate exceeds OLS, indicating that government R&D contracts target firms facing negative technology or demand shocks.

Columns 4 and 5 analyze subsamples of firms that published at least one paper or employed an award-winning renowned scientist. These firms were more likely to engage in upstream R&D. Consistent with the guaranteed demand mechanism, we expect the co-investment incentive to be stronger for these firms. Indeed, the R&D contracts coefficient estimate was larger. At sample

Table 5: Estimation Results for the Publications Equation

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	ln(Publications)$_t$					ln(Citation-weighted publications)$_t$	
	OLS: Within firms	IV: Industry R&D funding	IV: Windfall-predicted R&D budget	IV: Windfall-predicted R&D budget (Publishing firms)	IV: Windfall-predicted R&D budget (Award-winning scientist employers)	IV: Industry R&D funding	IV: Windfall-predicted R&D budget
ln(R&D contracts)$_{t-3}$	0.012	0.034	0.034	0.038	0.073	0.039	0.039
	(0.002)	(0.018)	(0.018)	(0.019)	(0.026)	(0.021)	(0.021)
ln(R&D stock)$_{t-3}$	0.131	0.116	0.116	0.149	0.257	0.107	0.107
	(0.011)	(0.010)	(0.010)	(0.013)	(0.032)	(0.011)	(0.011)
Sample years	1980-2015	1980-2015	1980-2015	1980-2015	1980-2015	1980-2015	1980-2015
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Weak identif. (Kleibergen-Paap)		102.24	104.04	93.86	38.32	102.24	104.04
Firms	3,631	3,584	3,587	2,649	597	3,584	3,587
Observations	43,883	41,093	41,130	32,378	9,460	41,093	41,130
Adjusted R-squared	0.873	0.019	0.020	0.024	0.006	0.007	0.007

Notes: This table presents the estimation results for the relationship between R&D contracts and publications. Columns 2-7 present the second stage of 2SLS, where R&D contracts are instrumented using *Industry R&D funding*, *Agency R&D budget*, and *Windfall-predicted R&D budget*, as noted. Column 4 uses a subsample of firms that published at least one paper during 1980-2015. Column 5 uses a subsample of firms that employed at least one award-winning renowned scientist during 1980-2015. In Columns 6 and 7, the publication flow is weighted by citations received from other publications, normalized by average journal-year citations. Standard errors (in parentheses) are clustered at the firm level.

means, Column 5's estimate implies that, for firms that employed award-winning scientists, it took only $13.0 million in additional R&D contracts to produce one additional publication.

So far, we have focused on the number of corporate publications, not their quality. Columns 6 and 7 use a quality-adjusted measure of upstream R&D, weighting each publication by citations received from other publications. Normalized citations are calculated as (Forward citations received up to 2016) / (Average forward citations received by all publications published in the same journal and year). Appendix Table I26 includes two other quality measures: publications authored by renowned scientists or cited by renowned scientists. The estimates suggest firms did not just increase the number of publications while lowering quality in response to government R&D contracts.

Additional robustness checks are in Online Appendix Sections G-I. The effect of R&D contracts on publications was consistent across industries (Table G14) and robust to excluding contracts from the seven largest agencies (Table H24), other funding shocks (Table I27), alternative specifications (Table I28), and different time lags (Table I30). We found no evidence that R&D contracts crowded out unrelated research areas (Table I33).

In summary, we document a positive effect of R&D contracts on upstream R&D output. Since upstream R&D is harder to implement (e.g., due to unobservable effort), this finding aligns with the guaranteed demand mechanism.

7.3 Renowned Scientists Equation

Table 6 shows the results for renowned scientists, our second measure of upstream R&D. Columns 2-4 present 2SLS estimates using *Industry R&D funding*, *Agency R&D budget*, and *Windfall-predicted R&D budget* as instruments for *R&D contracts*. At the sample means, the estimate in Column 2 implies that $10 million in additional R&D contracts led to a 12% increase in renowned scientists.

Column 5 uses firms that employed at least one renowned scientist from 1980 to 2015. As expected, the coefficient estimate was significant and larger than in the full sample. Our results are also robust to using changes in renowned scientist employment as the dependent variable (Columns 6 and 7).

Table 6: Estimation Results for the Renowned Scientists Equation

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	ln(Renowned scientists)$_t$					ln(Change in renowned scientists)$_t$	
	OLS: Within firms	IV: Industry R&D funding	IV: Agency R&D budget	IV: Windfall-predicted R&D budget	IV: Windfall-predicted R&D budget (Scientist employers)	IV: Industry R&D funding	IV: Windfall-predicted R&D budget
ln(R&D contracts)$_{t-1}$	0.005	0.025	0.025	0.025	0.030	0.005	0.005
	(0.001)	(0.009)	(0.009)	(0.009)	(0.012)	(0.002)	(0.002)
ln(R&D stock)$_{t-1}$	0.045	0.040	0.040	0.040	0.077	-0.001	-0.001
	(0.006)	(0.006)	(0.006)	(0.006)	(0.012)	(0.001)	(0.001)
ln(Renowned scientists)$_{t-1}$						-0.088	-0.088
						(0.006)	(0.006)
Sample years	1980-2015	1980-2015	1980-2015	1980-2015	1980-2015	1980-2015	1980-2015
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Weak identif. (Kleibergen-Paap)		110.87	112.68	113.26	77.27	110.04	112.48
Firms	4,370	4,317	4,319	4,321	1,677	4,317	4,321
Observations	52,876	49,702	49,732	49,745	22,898	49,702	49,745
Adjusted R-squared	0.922	-0.012	-0.011	-0.012	-0.005	0.051	0.049

Notes: This table presents the estimation results for the relationship between R&D contracts and renowned scientists. Columns 2-7 present the second stage of 2SLS, where R&D contracts are instrumented using *Industry R&D funding*, *Agency R&D budget*, and *Windfall-predicted R&D budget*, as noted. Column 5 uses a subsample of firms that employed at least one renowned scientist during 1980-2015. Standard errors (in parentheses) are clustered at the firm level.

In summary, the results for renowned scientists complement those for publications, easing concerns that publications are a noisy measure of upstream R&D.

7.4 Patents Equation

Table 7 presents results for corporate patents, our measure of downstream R&D output. Column 1 shows a positive relationship between *Patents* and *R&D contracts* (p-value < 0.001). However, the coefficient estimate was not significantly different from zero once we instrumented *R&D contracts* with *Industry R&D funding* and *Windfall-predicted R&D budget* (Columns 2 and 3).

Table 7: Estimation Results for the Patents Equation

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
		ln(Patents)$_t$		ln(Citation-weighted patents)$_t$		ln(Breakthrough patents)$_t$	
	OLS: Within firms	IV: Industry R&D funding	IV: Windfall-predicted R&D budget	IV: Industry R&D funding	IV: Windfall-predicted R&D budget	IV: Industry R&D funding	IV: Windfall-predicted R&D budget
ln(R&D contracts)$_{t-3}$	0.012	-0.040	-0.039	-0.052	-0.050	-0.003	-0.004
	(0.002)	(0.023)	(0.022)	(0.025)	(0.024)	(0.008)	(0.008)
ln(R&D stock)$_{t-3}$	0.252	0.242	0.242	0.225	0.225	0.034	0.035
	(0.015)	(0.015)	(0.015)	(0.015)	(0.015)	(0.005)	(0.005)
Sample years	1980-2015	1980-2015	1980-2015	1980-2015	1980-2015	1980-2015	1980-2015
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Weak identif. (Kleibergen-Paap)		102.24	104.04	102.24	104.04	102.24	104.04
Firms	3,631	3,584	3,587	3,584	3,587	3,584	3,587
Observations	43,883	41,093	41,130	41,093	41,130	41,093	41,130
Adjusted R-squared	0.847	0.045	0.046	0.017	0.019	0.007	0.007

Notes: This table presents the estimation results for the relationship between R&D contracts and patents. Columns 2-7 present the second stage of 2SLS, where R&D contracts are instrumented using *Industry R&D funding* or *Windfall-predicted R&D budget*, as noted. In Columns 4 and 5, the patent flow is weighted by citations received from other patents, normalized by the International Patent Classification (IPC) class-year. In Columns 6 and 7, breakthrough patents are in the top 1% of forward citations in a five-year window relative to other patents from the same application cohort. Standard errors (in parentheses) are clustered at the firm level.

The last four columns use quality-adjusted patent measures. Columns 4 and 5 weight corporate patents by citations received from other patents. Normalized citations are calculated as (Forward citations received from other patents up to 2016) / (Average forward citations received by all granted patents in the same 4-digit International Patent Classification and year). Columns 6 and 7 use the flow of top-cited patents. These are patents in the top 1% of forward citations over five years (relative to the same application cohort), often termed *breakthrough* patents. The coefficient estimates imply that firms were not simply becoming more selective in their patenting in response to winning R&D contracts. We obtained similar results when using *PSC R&D funding* as an instrument for R&D contracts (see Appendix Table F11).

Finding no effect on patents aligns with guaranteed demand being less likely in downstream R&D. Since effort is more observable (and implementation concerns less pressing) in downstream R&D, the government should use guaranteed demand less in these projects. Thus, firms should not co-invest in downstream knowledge. Instead, firms may fully substitute their investments in downstream R&D with funding from R&D contracts. Our results are consistent with this logic.

Prior studies finding a positive effect on patenting either estimated federal grants (e.g., Azoulay et al., 2019; Howell, 2017) or focused on small firms (e.g., Howell et al., 2021). Conversely, we estimated the effect of R&D contracts (which are fundamentally different from grants) on patenting in large firms (which are less likely to be resource-constrained, to depend on continued funding from the federal government, or to rely on markets for technology to appropriate value from their inventions). Our results align with Knott, Josephson, and Lee (2024), who studied publicly traded U.S. firms awarded R&D contracts during 2001-2021. They similarly found no effect of R&D contracts on the rate of patenting or the mean number of citations per patent.

Besides the government using guaranteed demand less in downstream R&D, several alternative explanations exist for the limited effect on patents. First, government demand may reduce the need for costly patenting to exclude rivals. Second, some R&D contracts might prohibit patenting to protect sensitive technologies, though Howell et al. (2021) suggest this is not a major concern for most contractors. Third, guaranteed demand might lead R&D contractors to rely more on trade secrets to increase information rents in the production-stage auction. Fourth, patent racing might boost patenting for both R&D contractors and other firms. In our model, producers must prepare to bid in the second-price production auction, potentially developing capabilities to produce based on the winning prototype. Such racing behavior suggests a patenting reaction from firms not receiving R&D contracts.

In summary, we find no evidence that R&D contracts increased downstream R&D (as measured by corporate patents). Given our results on publications and renowned scientists, this highlights the importance of distinguishing between upstream scientific research ("R") and downstream technology development ("D") in corporate R&D.

7.5 Event Study Analysis: The End of the Cold War

Figure 3 shows results from the Cold War event study. The point estimates capture the difference between treated and control firms relative to the base period (year -1, marked with a vertical line). Coefficient estimates for pre-treatment years (years -4, -3, -2, and -1) show parallel pre-trends, suggesting firms did not anticipate the procurement shock.

Panel A shows corporate R&D expenditures were unaffected by the Cold War shock. This contrasts the results reported in Table 4. It is worth noting that the sample for the event study was drawn from industries that experienced moderate sales growth in the R&D shock year. It is possible that treated firms shifted the composition of their R&D investments toward scientific research and away from downstream development while leaving their overall level of R&D expenditures unchanged.

The remaining panels show that any crowding-in effect of R&D contracts on corporate innovation occurred in upstream R&D (Panels B and C, consistent with Tables 5 and 6) and not in downstream R&D (panel D, consistent with Table 7). These results are robust to dropping controls for the level and percentage change in private demand (see Appendix Figure I5). They are also robust to using a sample of 260 firms in ten SIC3 industries that received a top 20% increase in R&D contracts and a bottom 20% change in total demand (see Appendix Figure I6). Although coefficient estimates in this smaller sample were less precise, we found a positive effect on upstream R&D (publications) and no effect on downstream R&D (patents).

Our event study design is characterized by staggered treatment, as firms in SIC3 industries are shocked at different times in the 1991-1994 time frame. We address potential contamination of our estimates by other period effects (Sun & Abraham, 2021) using the staggered event study design of Callaway and Sant'Anna (2021). We use never-treated firms as the comparison group and implement the doubly robust difference-in-differences estimator from the *csdid* package. Appendix Figure I7 shows that the results from aggregating group time average treatment effects by R&D contracts exposure length were similar to those in Figure 3.

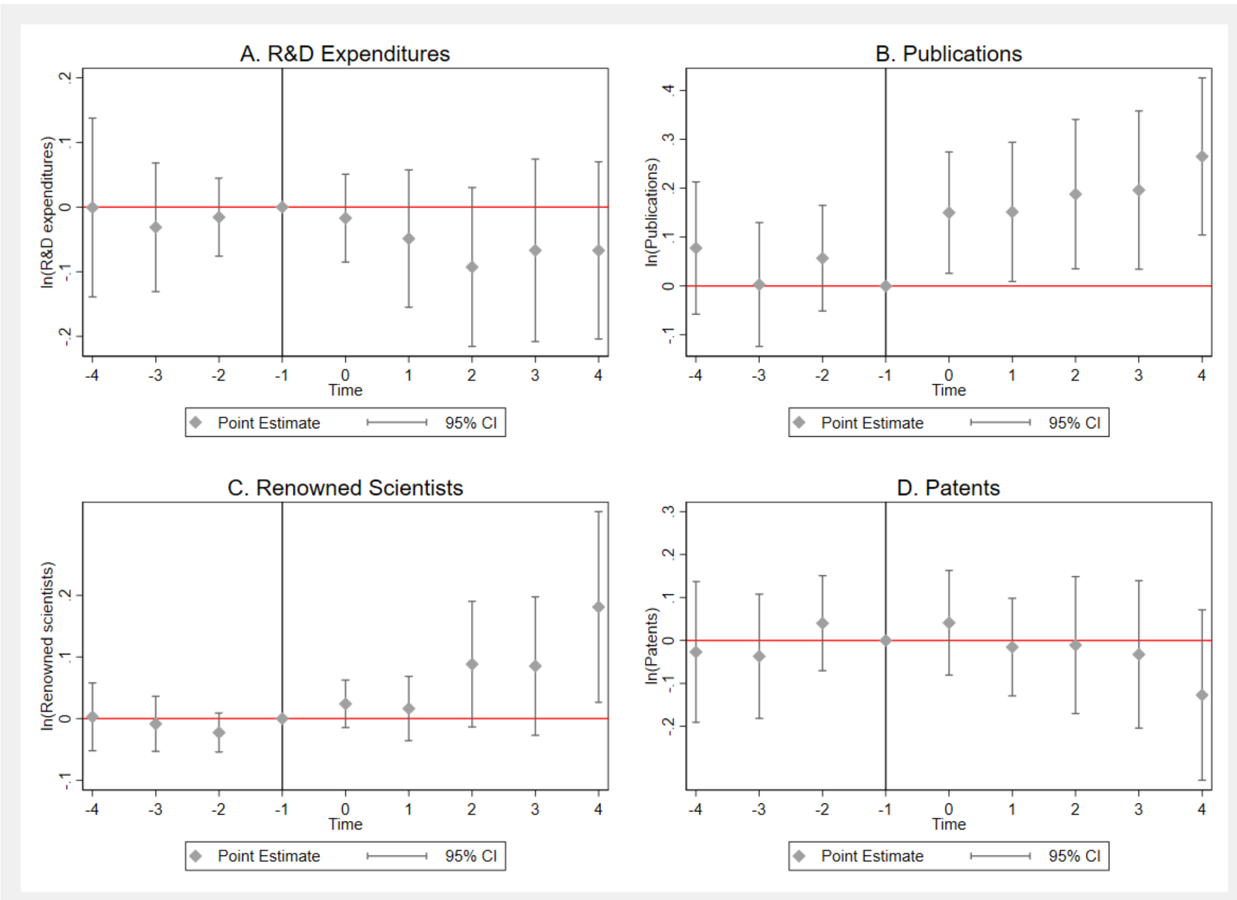

Figure 3: Event Study Around the End of the Cold War

This figure presents an event study around the end of the Cold War. All specifications use firm fixed effects and year fixed effects, as well as controls for the level and percentage change in private demand (i.e., firm sales net of all government procurement contracts). All specifications are estimated using firms that have data for the entire 9-year period to control for changes in the composition of industries over time. Standard errors are clustered at the firm level.

7.6 Additional Evidence on Guaranteed Demand

Since the promise of future government demand is unobserved *ex ante* (not specified in R&D contracts) and *ex post* (we cannot link R&D contracts to future noncompetitive production contracts), we identify guaranteed demand indirectly. We provide additional evidence consistent with this mechanism by examining how R&D contracts affect upstream and downstream corporate R&D based on firm size, industry-level guaranteed demand, and private market incentives.

7.6.1 Firm Size

Our framework predicts that only firms that have both R&D and production capabilities will crowd in company-funded scientific research in response to a bundled government procurement regime. Assuming large firms are more likely to be vertically integrated, we split our sample by firm size.

Table 8 examines the effect of R&D contracts on corporate publications and patents for small firms (Columns 1, 2, 5, and 6) and large firms (Columns 3, 4, 7, and 8). *Small* firms have below-median sales (relative to all firms in the same SIC4 industry over 1980-2015). *Large* firms have above-median annual sales. Government R&D contracts increased publications for large firms but not for small firms. R&D contracts did not affect patents, regardless of size.

Table 8: Variation by Firm Size

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	ln(Publications)$_t$				ln(Patents)$_t$			
	Small (IV: Industry R&D funding)	Small (IV: Windfall-predicted R&D budget	Large (IV: Industry R&D funding)	Large (IV: Windfall-predicted R&D budget	Small (IV: Industry R&D funding)	Small (IV: Windfall-predicted R&D budget	Large (IV: Industry R&D funding)	Large (IV: Windfall-predicted R&D budget
ln(R&D contracts)$_{t-3}$	-0.003	-0.004	0.050	0.049	-0.061	-0.057	-0.021	-0.023
	(0.026)	(0.026)	(0.023)	(0.022)	(0.042)	(0.040)	(0.026)	(0.025)
ln(R&D stock)$_{t-3}$	0.021	0.021	0.192	0.192	0.095	0.095	0.341	0.341
	(0.007)	(0.007)	(0.019)	(0.019)	(0.012)	(0.012)	(0.026)	(0.026)
Sample years	1980-2015	1980-2015	1980-2015	1980-2015	1980-2015	1980-2015	1980-2015	1980-2015
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Weak identif. (K-P)	37.79	37.68	72.45	73.07	37.79	37.68	72.45	73.07
Observations	19,297	19,308	21,240	21,265	19,297	19,308	21,240	21,265
Adjusted R-squared	-0.001	-0.001	0.029	0.031	-0.030	-0.027	0.094	0.092

Notes: This table presents the estimation results for the relationship of R&D contracts with publications and patents by firm size. Columns 1, 2, 5, and 6 use a subsample of firms with below-median annual sales (relative to all firms in the same SIC4 industry over 1980-2015). Columns 3, 4, 7, and 8 use a subsample of firms with above-median annual sales (relative to all firms in the same SIC4 industry over 1980-2015). Standard errors (in parentheses) are clustered at the firm level.

7.6.2 Industry Guaranteed Demand

Table 9 examines how the effect of R&D contracts varies with industry prevalence of noncompetitive production contracts. *High guaranteed demand* industries have top quartile shares of noncompetitive production contracts in all production contracts (relative to all industries in the same year). The remaining industries have *Low guaranteed demand*. Columns 1-4 present 2SLS results using the *Industry R&D funding* instrument. R&D contracts strongly affected publications in high guaranteed demand industries (Column 1, p-value = 0.056). Similar results were obtained in unreported specifications when controlling for quality by weighing publications by their citations. No effect on patents was observed (Columns 3 and 4).

Columns 5-7 show that winning an R&D contract was positively associated with future noncompetitive production contracts (p-values < 0.001), unlike winning a grant. This result is important because guaranteed demand should differ from a financing mechanism. Column 7 shows R&D contracts were more than financial resources that reduced R&D costs. They carried an implicit promise of future noncompetitive production contracts.

Table 9: Variation by Industry Guaranteed Demand

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	$\ln(\text{Publications})_t$		$\ln(\text{Patents})_t$		$\ln$(Noncompetitive production contracts)$_t$		
	High guaranteed demand (IV: Ind. R&D fund.)	Low guaranteed demand (IV: Ind. R&D fund.)	High guaranteed demand (IV: Ind. R&D fund.)	Low guaranteed demand (IV: Ind. R&D fund.)	Contract indicator (OLS: Within firms)	Grant indicator (OLS: Within firms)	Both indicators (OLS: Within firms)
$\ln(\text{R\&D contracts})_{t-3}$	0.102	0.037	0.118	-0.047			
	(0.051)	(0.019)	(0.072)	(0.023)			
$[\text{Has R\&D contracts} = 1]_{t-1}$					0.570		0.561
					(0.130)		(0.129)
$[\text{Has grants} = 1]_{t-1}$						0.214	0.171
						(0.163)	(0.160)
$\ln(\text{R\&D stock})_{t-3}$	0.098	0.118	0.248	0.233	0.119	0.119	0.119
	(0.023)	(0.011)	(0.037)	(0.015)	(0.061)	(0.062)	(0.061)
Sample years	1980-2015	1980-2015	1980-2015	1980-2015	2001-2015	2001-2015	2001-2015
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Weak identif. (Kleibergen-Paap)	16.94	89.88	16.94	89.88			
Firms	1,219	3,362	1,219	3,362	2,518	2,518	2,518
Observations	6,542	33,977	6,542	33,977	22,970	22,970	22,970
Adjusted R-squared	-0.135	0.018	-0.084	0.033	0.783	0.782	0.783

Notes: This table presents results from estimating how the effect of R&D contracts on publications and patents varies by industry guaranteed demand (Columns 1-4). It also presents the relationship between winning R&D contracts and federal grants with future noncompetitive production contracts (Columns 5-7). The sample years in Columns 5-7 are truncated to 2001-2015 because federal grant data are not available at scale before 2001. Standard errors (in parentheses) are clustered at the firm level.

Additional robustness checks examined how the effect of R&D contracts varied with a subagency's ability to guarantee demand (see Appendix Table I34). The share of noncompetitive production contracts by the U.S. Air Force, Navy, and Army during 1980-2015 was 52%, 58%, and 50%, respectively. DARPA's was only 0.2%. Consistent with the guaranteed demand mechanism, R&D contracts from the U.S. Air Force, Navy, and Army strongly affected publications, while those from DARPA did not.

7.6.3 Private Market Incentives to Invest in Upstream R&D

The R&D contractors in our sample sell in both public and private markets. Finding an effect of R&D contracts on upstream R&D with low or no private market incentives provides further evidence of guaranteed demand.[8] We expect R&D contracts to increase publications that (i) are not cited by the firm's patents (missing downstream applications), (ii) are cited by rivals' patents (spilling over to product-market competitors), and (iii) are not protected by the firm's patents (harder to appropriate). We construct measures of internal use, rival use, and patent protection, detailed in Online Appendix D.

R&D contracts increased publications not cited by the firm's patents, cited by rivals' patents, and with low patent protection, as reported in Appendix Table I35. Conversely, government R&D contracts did not increase upstream R&D with internal use, no rival use, or easier appropriation. In summary, R&D contracts increased corporate science with weaker private market incentives, consistent with guaranteed demand.

7.7 Changes Over Time

Policy reforms in the 1980s and 1990s, like the Federal Acquisition Streamlining Act of 1994 (see Online Appendix A), changed the nature and composition of federal procurement. We document these changes and their implications, focusing on the decoupling of R&D from production contracts and the weakened guaranteed demand mechanism.

Figure 4 highlights three trends: (i) reduced importance of R&D races in procurement; (ii) increased competitive procurement; and (iii) larger allocation of contracts to firms not involved in scientific research. Using data on all contracts (not just contracts awarded to our panel of firms), we find that the U.S. government has reduced reliance on developing innovative technologies and increased reliance on those with existing private market applications. The share of R&D contract dollars in all contracts has fallen from 13% in 1980 to 8% in 2020 (Panel A), while the share of commercial contract dollars has increased to 27% in 2020 (Panel B). Commercial contracts use streamlined acquisition procedures resembling commercial market transactions. In unreported analyses, we find similar evidence when focusing on contracts awarded to our panel of firms.

Historically, the government awarded most production contracts noncompetitively to firms that demonstrated strong technical capabilities. Pressures to reduce costs and increase efficiency and transparency led to legislative mandates for competition whenever practicable (Manuel, 2011). The share of noncompetitive production contract dollars (a proxy for guaranteed demand) has decreased from 57% in 1980 to 34% in 2020 (Panel C). In unreported analyses, we find similar evidence when focusing on contracts awarded to our panel of firms.

Winning large procurement contracts no longer requires strong scientific capabilities. The share of contract dollars to nonproducers of science has increased from 6% in 1980 to 42% in 2015 (Panel D). Arora et al. (2018) document a decline in the stock market and mergers and acquisitions value of scientific capabilities. Our evidence suggests that scientific capabilities may also have fallen out of favor with the government.

Table 10 shows the same trends from within-firm OLS regressions. Estimates indicate total

[8] Private market incentives depend on anticipated returns. Lacking *ex-ante* measures, we use *ex-post* measures, which should correlate with unobserved *ex-ante* incentives.

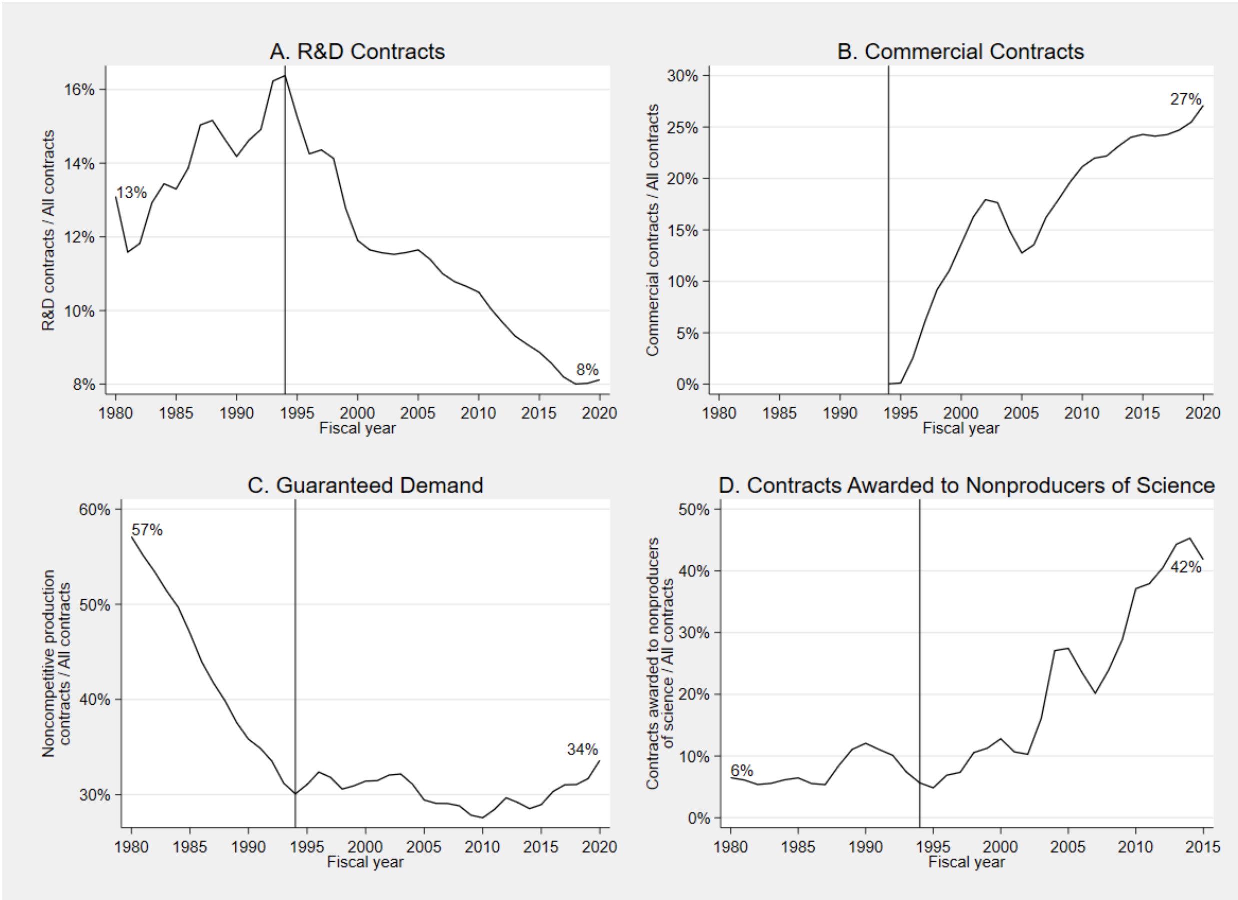

Figure 4: Trends in the Composition of Contracts Over Time

This figure shows changes in the nature and composition of contracts over time. Commercial contracts are awarded using simplified requirements designed to resemble transactions in commercial markets. A firm is a *nonproducer of science* if its annual number of publications over annual sales is below industry median value. The vertical lines mark the passage of the Federal Acquisition Streamlining Act of 1994.

contract size increased by 34% per decade (Column 1, p-value < 0.05), driven by production and commercial contracts (Columns 2-5). These changes remain robust to nonlinear time effects (see Appendix Table I37). While firm scientific capabilities—measured by the stock of corporate publications—had a positive relationship with total contracts (Column 6, p-value < 0.01), this relationship has weakened over time (Column 7, p-value < 0.001).

Appendix Table I36 provides additional evidence that R&D contracts are increasingly awarded to specialized R&D contractors rather than large, vertically integrated firms. In our sample, firms with top quartile annual sales had higher odds of winning R&D contracts. However, this advantage weakened over time, as shown by the negative coefficient estimate on the interaction term between *Large* and the *Time trend*.

In summary, the government has decoupled R&D from production contracts, potentially eroding its ability to incentivize upstream corporate R&D through the mechanism of guaranteed demand.

Table 10: Contract Composition and Scientific Capabilities Over Time

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Contract value			Contract composition		Scientific capabilities	
	ln(All contracts)$_t$ (OLS: Within firms)	ln(R&D contracts)$_t$ (OLS: Within firms)	ln(Comm. contracts)$_t$ (OLS: Within firms)	Share R&D/ All contracts$_t$ (OLS: Within firms)	Share comm./ All contracts$_t$ (OLS: Within firms)	ln(All contracts)$_t$ (OLS: Within firms)	ln(All contracts)$_t$ (OLS: Within firms)
Time trend	0.224	-0.122	2.239	-0.020	0.243	0.160	0.386
	(0.092)	(0.066)	(0.098)	(0.005)	(0.014)	(0.094)	(0.111)
ln(Publications stock)$_{t-1}$						0.299	0.607
						(0.085)	(0.122)
Time trend × ln(Publications stock)$_{t-1}$							-0.126
							(0.034)
ln(R&D stock)$_{t-1}$	0.421	0.131	0.315	-0.005	-0.006	0.326	0.308
	(0.058)	(0.037)	(0.057)	(0.005)	(0.008)	(0.061)	(0.061)
Sample years	1980-2015	1980-2015	1995-2015	1980-2015	1995-2015	1980-2015	1980-2015
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	No	No	No	No	No	No	No
Firms	4,366	4,368	3,728	2,127	1,737	4,366	4,366
Observations	52,762	52,842	38,427	22,612	15,951	52,762	52,762
Adjusted R-squared	0.741	0.659	0.689	0.263	0.157	0.741	0.742

Notes: This table presents OLS estimates for changes in contract value, contract composition, and the relationship between government contracts and firm scientific capabilities over time. *Time trend* is divided by 10. Columns 3 and 5 use data from fiscal years 1995-2015 because the data element that allows us to identify commercial contracts was only introduced following the Federal Acquisition Streamlining Act of 1994. Standard errors (in parentheses) are clustered at the firm level.

7.8 Implications for Implementation

Designers of R&D contests must balance incentives, competition, and the structure of contests (Bhattacharya, 2021). Since R&D knowledge must be implemented in production, the transfer of knowledge between R&D and production activities is crucial in government procurement. A solution to implementation challenges is to couple R&D contracts with production contracts.

Over time, we observe increased decoupling. Did implementation become more difficult, or did the the government maintain success due to better institutions (e.g., small firms, the market for technology) or because R&D contracts are now easier to implement? We explore these questions by analyzing trends in subcontracting, the composition of R&D contracts, and contractual deobligations.

Figure 5 shows that subcontracting is a major component of federal contracting (Panel A). In 2021, 60% of contract dollars required a subcontracting plan. Those plans allocated 29% of prime R&D contract dollars and 28% of prime production contract dollars to subcontractors. Subcontracting negatively correlates with competition (Panel B). Aggregating production contract dollars from 2012-2021 by NAICS industry shows that industries with high rates of competitive procurement have low rates of subcontracting. Low subcontracting rates may signal challenges in knowledge transfer between R&D specialists and producers, suggesting that increased competitive procurement may have amplified implementation inefficiencies.

Moreover, the composition of R&D contracts has changed over time (Panel C). The share of

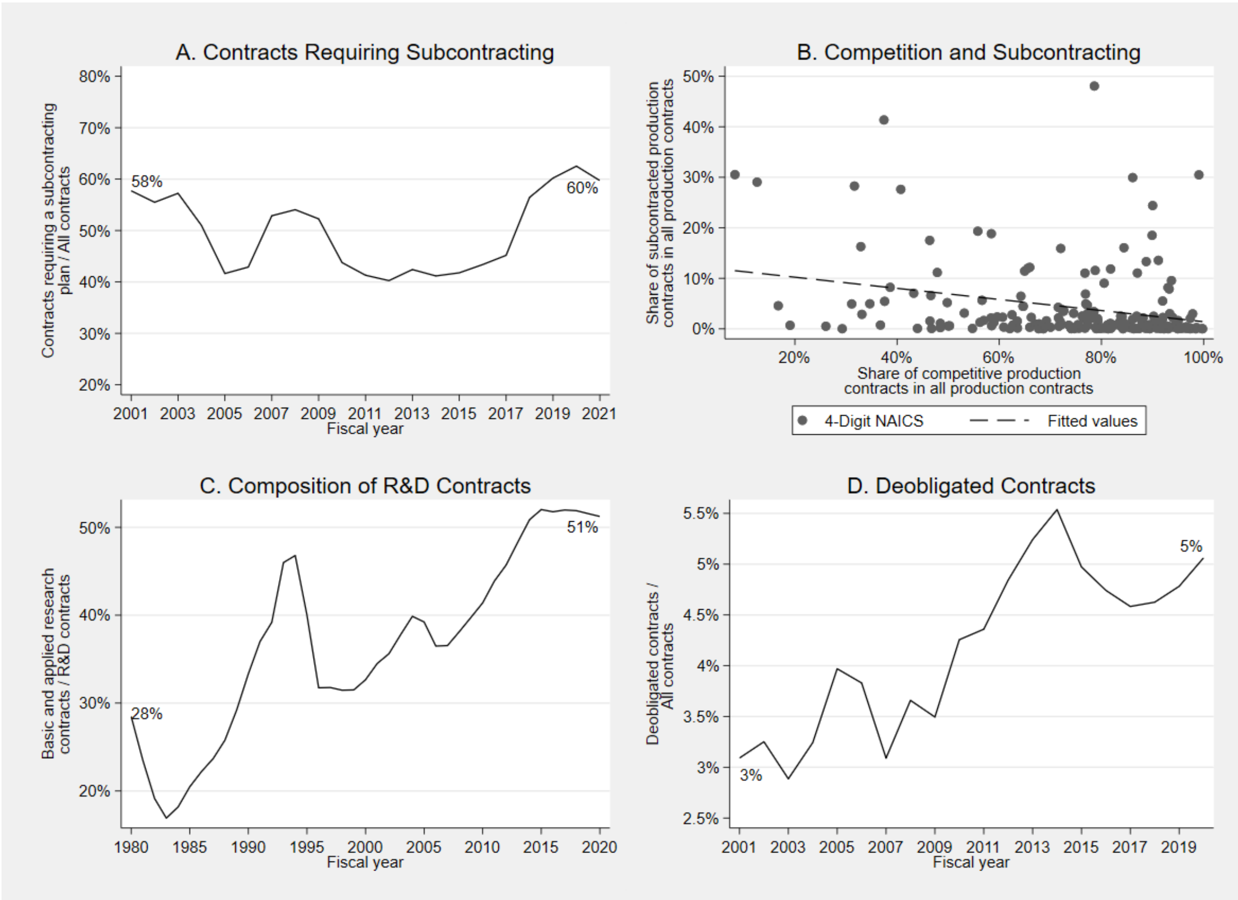

Figure 5: Implementation Challenges

This figure presents trends in the share of contract dollars that require a subcontracting plan (Panel A), the share of R&D contract dollars awarded for basic and applied research (Panel C), and the share of contractual obligations that are eventually deobligated (Panel D). It also presents the relationship between competition and subcontracting in 4-digit NAICS industries (Panel B).

basic or applied research dollars in R&D contracts grew from 28% in 1980 to 51% in 2020. Since scientific research is further from implementation, this shift in R&D contracts *toward* research and *away from* development may have complicated implementing new knowledge.

Additional evidence is found in contractual deobligations. When awarding a contract, the government records an obligation, promising to spend the money now or later. A *deobligation* is the cancellation or reduction of previously obligated funds. Deobligations can be triggered by contract closeout, termination for default, cause, or convenience, and legal contract cancellation, among other reasons. The share of deobligated contract dollars rose from 3% in 2001 to 5% in 2020 (Panel D). In constant 2012 dollars, deobligations were $8.9 billion in 2001 and $31.2 billion in 2020. If deobligations reflect failed implementation, project failure rates may have increased.

Table 11 shows within-firm OLS estimates indicating that the value of deobligations increased over time (Column 1, p-value $<$ 0.001). More importantly, industries with high decoupled demand (i.e., top quartile shares of competitive production contracts) experienced larger increases in deobligations over time (Columns 2 and 3).

Table 11: Deobligations Over Time

	(1)	(2)	(3)
		$\ln(\text{Deobligations})_t$	
	Control for Obligations (OLS: Within firms)	Add interaction with indicator (OLS: Within firms)	Add interaction with share (OLS: Within firms)
Time trend	0.881	0.848	0.520
	(0.055)	(0.055)	(0.062)
Time trend × High decoupled demand$_t$		0.257	
		(0.078)	
Time trend × Share decoupled demand$_t$			0.652
			(0.077)
High decoupled demand$_t$		-0.569	
		(0.173)	
Share decoupled demand$_t$			-1.067
			(0.125)
$\ln(\text{Obligations})_t$	0.184	0.184	0.183
	(0.007)	(0.007)	(0.007)
$\ln(\text{Sales})_{t-1}$	0.238	0.239	0.232
	(0.027)	(0.027)	(0.027)
Sample years	1980-2015	1980-2015	1980-2015
Firm fixed effects	Yes	Yes	Yes
Year fixed effects	No	No	No
Firms	4,442	4,442	4,442
Observations	54,575	54,575	54,575
Adjusted R-squared	0.659	0.659	0.661

Notes: This table presents OLS estimates for changes in contractual deobligations over time. *High decoupled demand* industries have top-quartile shares of decoupled demand (i.e., competitive production contracts in all production contracts) relative to all industries that year. *Time trend* is divided by 10. Standard errors (in parentheses) are clustered at the firm level.

In summary, project implementation may have become harder over time, as indicated by (i) low subcontracting rates associated with competitive contracts, (ii) increased R&D funding for research further from implementation, and (iii) rising contractual deobligations. Decoupling R&D from production may have improved transparency and fairness in federal procurement—objectives of several policy reforms—but may also have hindered the implementation of upstream knowledge in production.

8 Conclusion

This paper provides evidence suggesting that the anticipation of government production contracts incentivizes corporations to co-invest with the government in upstream R&D. We document a positive effect of R&D contracts on publications and employment of renowned scientists ("R") but not on patents ("D") and show that the effect is strong for large corporations, when production contracts are likely to be awarded without competition, and when private market incentives are relatively weak. The effect was stronger before the mid-1990s when reforms like the Federal Acquisition Streamlining Act of 1994 changed procurement and decoupled R&D from production contracts.

Future research could explore how government procurement affects small firms through two main channels. The first is direct support, where procurement policies like set-asides and subcontracting requirements ensure that at least 23% of prime contracts go to small businesses. These policies are intended to ensure that small firms secure a significant share of government contracts, providing them with opportunities to grow, innovate, and overcome some of the inherent disadvantages they face.

The second channel is indirect, where large firms invest in or partner with small firms to access their innovative technologies, which can be pivotal in securing lucrative production contracts. For example, in 2011, Lockheed Martin signed a multi-year agreement with the Canadian startup D-Wave Systems to access its quantum annealing technology. Such partnerships demonstrate how large firms can depend on the cutting-edge innovations of small firms to enhance their competitiveness in government procurement.

Future research should also examine small firms' strategic choices, such as whether they partner with large firms or participate independently in government procurement. Understanding these decisions could reveal how small firms tackle government contracting challenges and identify effective strategies. Additionally, further research is needed to understand how procurement reforms are altering the nature of small firm participation in public markets.

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ONLINE APPENDIX

Appendix A Federal Procurement Background

Procuring products and services for the U.S. government through an advertised, competitive process goes back as far as the Revolutionary War (Wittie, 2003). For example, the Continental Congress passed a resolution on November 20, 1775, to appoint a committee responsible for advertising, receiving proposals, and contracting rations for two new military battalions. In modern times, the Armed Services Procurement Act of 1947 and the Federal Property and Administrative Services Act of 1949 provided comprehensive legislative frameworks for defense and civilian procurement, respectively. Also noteworthy was the Competition in Contracting Act of 1984, which established "full and open competition" as the standard for federal procurement contracts.

A.1 Procurement Process

The U.S. government is composed of three distinct branches—legislative, executive, and judicial—whose powers and duties are executed through 15 cabinet-level executive departments (Agriculture, Commerce, Defense, Education, Energy, Health and Human Services, Homeland Security, Housing and Urban Development, Interior, Justice, Labor, State, Transportation, Treasury, and Veterans Affairs) and hundreds of independent agencies, government corporations, commissions, and committees. For simplicity, we refer to all these organizations as federal agencies.

The U.S. government's procurement process typically begins with acquisition professionals determining a federal agency's requirements for goods and services and the most appropriate method for purchasing them (Congressional Research Service, 2021). In general, solicitations for contracts above \$25,000 are posted on the System for Award Management website, SAM.gov.[9] In response, interested firms prepare and submit offers.[10] Agency personnel then evaluate the offers using the source selection method and criteria described in the solicitation, in accordance with the Federal Acquisition Regulation (FAR).[11] The agency awards a contract to a firm only after determining that the company is responsible, meaning it has adequate resources to perform the contract (financial, organizational, technical skill, production facilities, etc.) as well as a satisfactory record of performance, integrity, and business ethics. The next steps include contract performance and administration (e.g., invoice processing and payments, performance monitoring, and contract modifications), followed by contract closeout.

A.2 Policy Changes

During the Cold War (1948-1989), government procurement focused on achieving and sustaining technological superiority for the purpose of national defense (Weiss, 2014). Federal agencies acquired products and services that met government requirements and specifications and were often unproven in commercial markets (Howell et al., 2021). In the case of defense R&D, which represented the majority of R&D contracts, the DoD was often the sole customer (Mowery, 2012). The government's acquisition procedures could be very complex. R&D races were often used to develop new products

[9]Other procurement methods include using a government purchase card (i.e., a credit card), placing a task or delivery order against an existing contract, or ordering from a GSA schedule. For R&D contracting, firms can also submit unsolicited proposals or compete in government-sponsored challenges and prize competitions.

[10]Firms can also participate in government procurement by serving as subcontractors to "prime" contractors.

[11]Almost all federal contracting is governed by the FAR, which consists of Parts 1-53 of Title 48 of the Code of Federal Regulations. The two primary methods of source selection are sealed bidding and negotiated contracting. The latter is typically used for R&D contracts.

at the technological leading edge. Winners were rewarded with noncompetitive production contracts. This incentivized firms to perform upstream R&D and enabled contractors to mitigate the market risk of performing scientific research that didn't yet have commercial applications.

The composition of procurement contracts began shifting toward commercial items and dual-use technologies in the 1980s and accelerated in the 1990s. Numerous policy changes were made in response to the end of the Cold War, increased global trade, constrained defense budgets, and the need to attract nontraditional, innovative suppliers from the much larger commercial markets, especially those in the growing IT sector (Weiss, 2014). Specifically, the U.S. government implemented sweeping patent and intellectual property reforms, acquisition reforms, and organizational reforms. For example, the Bayh-Dole Act of 1980 and its extensions allowed contractors to retain ownership of inventions made with federal funding. The Stevenson-Wydler Technology Innovation Act of 1980 and its extensions gave businesses access to technologies developed in federal laboratories. The Competition in Contracting Act of 1984 mandated that all procurement contracts be awarded based on full and open competition unless regulatory or statutory exclusions were applied. The Goldwater-Nichols Department of Defense (DoD) Reorganization Act of 1986 reworked the military command structure and implemented shared procurement across the military branches. The Defense Acquisition Workforce Improvement Act of 1990 established education and training standards for government acquisition professionals. The organizational reforms included the creation of new "hybrid" forms of public-private partnering (Weiss, 2014). One example is the SEMATECH industrial consortium, which was formed in 1987 with funding from the Defense Advanced Research Projects Agency (DARPA) and the involvement of 14 American semiconductor manufacturers.

These policy changes culminated in the Federal Acquisition Streamlining Act of 1994, which enabled simplified acquisition procedures and established a statutory preference for government procurement of commercial items. Procurement dollars were reallocated *away from* mission-focused technologies that met government specifications and *toward* dual-use technologies that had both government and commercial potential. Driven by pressures to reduce cost and increase efficiency and transparency, the government began competing with the commercial markets for technologies that already had proven commercial success.

Appendix B Conceptual Framework With Contractible Quality

When research quality is contractible, unbundling leads to the first best outcome because the government can specify the prize as a function of the quality of the winning prototype.[12] Letting $q_u = \max\{q_1, q_2\}$, the government gives a prize of $P(q_u)$ to the winning R&D firm, where the payoff depends on the quality of the winning proof-of-concept prototype. The government's payoff is:

$$W = \mathbb{E}_{q_u}[V(q_u)] - \overline{C} - P(q_u) = \mathbb{E}_{q_u}[V(q_u)] - \underline{C} - \Delta - P(q_u) \tag{12}$$

Specifying the research prize as a function of quality induces additional research effort from the R&D firms, whose payoffs now depend not only on whether they win but also on the quality they achieve. (Earlier, it only mattered whether the focal firm's quality was higher than that of the rival.) R&D firm 1's expected payoff, for given levels of research effort r_1, r_2, is the probability it wins times the expected quality if it wins, minus the cost of effort.

This is more complicated to write. Recall that $q_1 = r_1 + v_1$, where the cost of effort is $\exp(r_1)$ and v_1 is a random variable with a distribution $f(v)$.

$$\Pi_1(r_1, r_2) = \int_{-\infty}^{\infty} \int_{r_2+v_2-r_1}^{\infty} P(r_1 + v_1) f(v_1) dv_1 f(v_2) dv_2 - \exp(r_1) = \frac{e_1}{e_1 + e_2} P(r_1, r_2) - g e_1 \tag{13}$$

Compared to the non-contractible quality case, the expected payoff is no longer fixed but also a function of the effort levels, which is represented by the term $P(r_1, r_2)$.

At a symmetric Nash Equilibrium, the first-order condition will satisfy:

$$(\frac{e_2}{(e_1 + e_2)^2} P_u - g) \frac{\partial e_1}{\partial r_1} + \frac{e_2}{(e_1 + e_2)} \frac{\partial P_u}{\partial r_1} = 0 \tag{14}$$

Compared to the non-contractible quality case, the difference is the additional term $\frac{e_2}{(e_1+e_2)} \frac{\partial P}{\partial r_1}$. The first part is simply the probability of winning, while the second part is the increase in expected payment due to higher research effort. The equilibrium level of effort is higher and so is the equilibrium expected quality. **Since the government can always set $P(q_u) = P_u$, it is always better off when research quality is contractible.**

Turning to the choice of bundling or unbundling, the government can set a bundled price $P_b(q_u) = P(q_u) + \overline{C}$, which will yield the same outcomes as in the non-contractible quality case. Intuitively, the only reason to bundle is if the government can promise some of the production rent Δ to the research winner. As we showed, this promise works only if the R&D firm does not enter the production auction unless it wins the research competition. In turn, that requires that the production auction not be attractive for the losing R&D firm (as outlined in Equation 9).

[12] As before, the government can extract any R&D rents through a fixed fee charged to both R&D firms. To keep things simple, we ignore this fixed fee because it does not affect research effort.

Appendix C Data Construction

C.1 Collecting Contracts

The General Services Administration (GSA) manages the Federal Procurement Data System (FPDS), the central repository of information on U.S. government procurement contracts. The FPDS contains detailed information on all contract transactions above the micro-purchase threshold, which generally ranges from $2,000 to $25,000, depending on the fiscal year, type of award recipient, and place of performance.[13] FPDS also maintains a list of valid contracting offices, including their corresponding agencies.

The Federal Funding Accountability and Transparency Act of 2006 (FFATA) required that federal contract, grant, loan, and other financial assistance awards of more than $25,000 be displayed on a publicly accessible website.[14] In response, the U.S. Department of the Treasury developed USAspending.gov as the official public source of federal government contract data (pulled from FPDS) and grant, loan, and other financial assistance data (reported to the Data Act Broker managed by the U.S. Department of the Treasury). The "Custom Award Data" section of the USAspending.gov website allows the public to view and download award transactions for fiscal years starting in 2001.[15] We used it to download .csv files containing transactions for all prime procurement contracts awarded by all federal agencies in all locations during fiscal years 2001-2021.[16,17]

We supplemented these data with historical contract transactions from SAM.gov, a website managed by the GSA. The website allows the public to download FPDS award transactions after creating user accounts. We used it to download .csv files containing prime award transactions for procurement contracts awarded by all federal agencies in all locations during fiscal years 1980-2000.

To identify the government entity that awarded each procurement contract, acquisition professionals use a four-digit Awarding Agency ID.[18] The FPDS provides a list of 6,725 contracting offices that were active and valid as of November 2, 2020. These offices are grouped into 227 agencies that are subordinated to 99 first-level "departments." We link each Awarding Agency ID to the corresponding first-level department. Our resulting dataset contains 81.9 million transactions for procurement contracts awarded during fiscal years 1980-2021 by 72 different federal agencies.[19] As

[13] Other exceptions to the reporting rule include classified contracts, as well as contracts that contain sensitive information about recipients, locations, and operations. For obvious reasons, we cannot estimate the precise value of these unreported contracts.

[14] FFATA was amended by the Government Funding Transparency Act of 2008, which required prime contractors to report details on their first-tier subcontractors and expanded with the Digital Accountability and Transparency Act of 2014, which established government-wide financial data standards.

[15] An award usually is made up of a series of transactions, which include the initial award and any subsequent modifications, such as additions or continuations of funding and changes to the scope of work.

[16] Award types include prime awards for contracts, contract indefinite delivery vehicles (IDV), grants, direct payments, loans, insurance, and other financial assistance.

[17] An indefinite delivery vehicle (IDV) is a type of contract in which the government agrees to buy a product or service from a certain vendor for a certain quantity or time frame. The government does not obligate funding when the contract is signed but rather when a supply or service order is placed. Examples of IDVs include blanket purchase agreements, government-wide acquisition contracts, and indefinite delivery contracts.

[18] The data also include information about the awarding department/office and funding department/agency/office. However, the procurement contracts are uniquely identified—using the Procurement Instrument Identifier or PIID—at the awarding agency level. Therefore, we use the awarding agency as the primary data element for classifying contracts by source.

[19] Transactions where the Awarding Agency ID (i) was missing or (ii) did not match any of the active agencies were grouped under the "Other" category. For example, the Tennessee Valley Authority is a wholly owned government corporation; while it awarded procurement contracts during 1980-2015, it was not included in the November 2, 2020, list of active agencies.

can be seen in Table C1, 12% of the $12.5 trillion in procurement contracts were for R&D services.

The federal government reports *obligations* for procurement contracts, not actual *outlays*. An obligation is the government's promise to spend funds (immediately or later) as a result of entering into a contract, so long as the agreed-upon actions take place. An outlay takes place when those funds are actually paid out to the contractor (Datalab, 2018). If the entire amount initially obligated is not used, the last modification will display a negative dollar amount, called a *deobligation*. For example, if an initial contract award was for $100,000 and an agency only used $90,000 of that initial obligation, the last transaction associated with the award would display a deobligation of -$10,000 (Datalab, 2018). We use deobligated dollars to test the effect of decoupling R&D races from production on project implementation success.

C.2 Matching Contracts to Firms

We merged the contract data with the panel of U.S.-headquartered publicly traded firms from Arora, Belenzon, and Sheer (2021). We string-matched more than 1.7 million contractor names (including recipients and their parent companies) against almost 60,000 firm names (including ultimate owners and their subsidiaries).[20] Specifically, we performed vectoral decomposition of firm names using five-character grams. Then, we applied Jaccard similarity scoring. For each contractor, we retained the five best potential matches (in decreasing order of similarity score, as long as the score was above 0.5) and completed a four-step process to clean them.

Step 1. We removed unicode and special characters, as well as legal suffixes (e.g., inc, corp, ltd) and conjunctions (e.g., and, on, at) from names, generating "core" versions of contractor and firm names. We reapplied the matching command to evaluate the quality of the match between these "core" names. This time, we used bigrams in the vectoral decomposition and dropped potential "core" matches that had a Jaccard similarity score below 0.65.

Step 2. We removed generic words from firm names (e.g., terms describing an industry or activity), generating "nongeneric" versions of contractor and firm names. We reapplied the matching command to evaluate the quality of the match between these "nongeneric" names. We used bigrams in the vectoral decomposition and dropped potential "nongeneric" matches that had a Jaccard similarity score below 0.65.

Step 3. We calculated the Levenshtein distance between "nongeneric" names and dropped potential matches with an edit distance greater than 15. For each contractor, we retained only the best potential match (in decreasing order of "core" and "nongeneric" similarity scores).

Step 4. We manually cleaned potential matches that had similarity scores below 0.9, discarding any obvious mismatches.

We obtained a dataset of 33,828 contractor names matched to 12,507 ultimate owner and subsidiary names. Overall, we matched 33% of all procurement contracts awarded during 1980-2015 to our sample of publicly traded, R&D performing, U.S.-headquartered firms. We aggregated contracts by firm-year, then allocated contracts matched to subsidiaries to the appropriate ultimate owners using the dynamic match produced by Arora, Belenzon, and Sheer (2021). In summary, we identified 2,578 firms (i.e., ultimate owners) that received a total of $4.2 trillion in procurement contract obligations during 1980-2015.

[20] We standardized recipient names using the same code used by Arora, Belenzon, and Sheer (2021) to identify the best possible matches to the panel of firms.

C.3 Collecting Renowned Scientists' Biographies

American Men and Women of Science (AMWS) is a biographical directory of renowned North American scientists in the physical, biological, and related sciences (including public health science, engineering, mathematics, statistics, and computer science). Entries include such information as the full name, field of specialty, education, professional experience, memberships, research information, mailing address, fax number, and email address of each entrant. Entrants are scientists who have made significant contributions in their fields, meeting the following criteria:

1. "Distinguished achievement, by reason of experience, training or accomplishment, including contributions to literature, coupled with continuing activity in scientific work; or

2. Research activity of high quality in science as evidenced by publication in reputable scientific journals; or, for those whose work cannot be published due to governmental or industrial security, research activity of high quality in science as evidenced by the judgment of the individual's peers; or

3. Attainment of a position of substantial responsibility requiring scientific training and experience." (Nemeh, 2022, p. vii)

We acquired 17 electronic versions of the AMWS directory, covering editions published from 2005 through 2021. Each edition included the most up-to-date information on living scientists, as well as a reference to the most recent previous edition for deceased scientists. We combined information on the 203,000 living scientists from the 2021 edition with information on the 37,800 deceased scientists from the 2005-2020 editions.[21]

C.4 Matching Renowned Scientists to Firms

We matched the renowned scientists from AMWS with the panel of U.S.-headquartered publicly traded firms from Arora, Belenzon, and Sheer (2021) in two stages. First, we organized the unstructured, paragraph-based AMWS data into a structured, tabular format. A scientist's professional experience typically included multiple positions, where each position was described using the job title, main organization, up to six sub-organizations, and years of employment (e.g., "sr microbiologist, Lilly Res Labs, Eli Lilly & Co, 1971-1978"). We leveraged the fact that semicolons typically separated positions to create separate entries for each position held by a focal scientist. We cleaned these entries manually to address instances of missing semicolons, incomplete years of employment, etc. This process identified approximately 1.3 million positions, corresponding to 240,800 scientists. After discarding positions unique to academia (e.g., job titles containing prof, assistant professor, associate professor, editor, lecturer), we retained approximately 840,000 positions in 244,000 unique organizations or sub-organizations.

Second, we string-matched the 244,000 unique organizations or sub-organizations with the 60,000 firm names in our panel (including both ultimate owners and their subsidiaries). We calculated the Levenshtein distance between name strings using the Python package *TheFuzz*. Potential matches with token set ratios below 90 (on a 0-100 scale) were discarded, while the remaining matches were manually checked. We produced a dataset of 12,817 accurate employer organization-firm name matches. These matches were used to identify 20,552 renowned scientists who worked for our panel of firms, as well as their years of employment.

[21]We are indebted to Hansen Zhang, whose work was instrumental in collecting and matching AMWS data.

Table C1: Agencies That Awarded Contracts During 1980-2015

Federal agency	All contracts ($ mm)	Share R&D / All contracts	Share matched to firm panel
Defense, Department of	8,620,931	13%	39%
Navy	2,578,562	14%	48%
Army	2,527,360	10%	30%
Air Force	2,108,680	21%	51%
Missile Defense Agency (MDA)	83,877	45%	83%
Defense Threat Reduction Agency (DTRA)	23,790	57%	27%
Defense Adv. Res. Proj. Agency (DARPA)	13,474	91%	18%
Other DoD	1,285,188	1%	18%
Energy, Department of	934,083	7%	16%
National Aeronautics and Space Admin.	489,770	41%	44%
General Services Administration	296,604	<1%	15%
Health and Human Services, Department of	271,731	19%	21%
Veterans Affairs, Department of	267,162	<1%	28%
Homeland Security, Department of	170,507	5%	22%
Transportation, Department of	130,350	13%	25%
Treasury, Department of the	128,931	1%	12%
Justice, Department of	128,083	2%	14%
State, Department of	112,697	1%	9%
Interior, Department of the	100,210	5%	9%
Agriculture, Department of	86,287	1%	14%
Agency for International Development	60,993	7%	7%
Commerce, Department of	55,144	5%	21%
Labor, Department of	49,664	1%	6%
Environmental Protection Agency	40,985	6%	9%
Education, Department of	36,067	7%	20%
Office of Personnel Management	26,331	<1%	6%
Housing and Urban Development, Dept. of	24,862	4%	16%
Social Security Administration	20,104	<1%	31%
National Science Foundation	10,105	28%	27%
Smithsonian Institution	5,306	2%	3%
Nuclear Regulatory Commission	4,300	10%	16%
Securities and Exchange Commission	3,285	1%	15%
Pension Benefit Guaranty Corporation	3,175	<1%	7%
National Archives and Records Admin.	2,954	<1%	19%
Small Business Administration	2,075	1%	13%
Peace Corps	1,892	14%	6%
United States Agency for Global Media, BBG	1,763	<1%	10%
Equal Employment Opportunity Commission	1,676	<1%	3%
Federal Communications Commission	1,257	1%	7%
Executive Office of the President	1,175	1%	24%
Federal Trade Commission	822	1%	21%
Corp. for National and Community Service	788	3%	5%
Millennium Challenge Corporation	772	14%	3%
National Labor Relations Board	748	<1%	35%
Intl. Boundary and Water Commission: U.S.-Mexico	609	11%	4%
Commodity Futures Trading Commission	515	<1%	27%
Railroad Retirement Board	452	0%	14%
National Gallery of Art	394	38%	2%
Government Accountability Office	382	10%	3%

Notes: This table displays federal agencies that awarded procurement contracts during 1980-2015. Contracts are deflated using the GDP Implicit Price Deflator to reflect millions of constant 2012 dollars (U.S. Bureau of Economic Analysis, 2021).

Table C1: Agencies That Awarded Contracts During 1980-2015 (Continued)

Federal agency	All contracts ($ mm)	Share R&D / All contracts	Share matched to firm panel
Consumer Product Safety Commission	365	2%	8%
Court Services and Offender Supervision Agency	346	8%	4%
J. F. Kennedy Center for the Performing Arts	248	0%	1%
Consumer Financial Protection Bureau	214	0%	7%
National Transportation Safety Board	128	1%	22%
United States Trade and Development Agency	125	54%	1%
Federal Election Commission	119	1%	7%
Export-Import Bank of the U.S.	109	2%	3%
International Trade Commission	108	<1%	13%
Overseas Private Investment Corporation	90	1%	5%
National Mediation Board	71	0%	4%
National Endowment for the Humanities	66	0%	10%
Merit Systems Protection Board	45	8%	4%
Defense Nuclear Facilities Safety Board	44	10%	2%
Federal Housing Finance Agency	29	0%	3%
National Endowment for the Arts	27	2%	15%
Selective Service System	25	0%	8%
The Institute of Museum and Library Services	17	0%	1%
Federal Maritime Commission	15	0%	25%
Federal Mediation and Conciliation Service	15	5%	7%
Armed Forces Retirement Home	14	0%	0%
Federal Labor Relations Authority	9	1%	6%
National Capital Planning Commission	8	2%	8%
Chemical Safety and Hazard Investigation Board	7	0%	5%
Occupational Safety and Health Review Commission	5	16%	4%
Committee for Purchase From People Who Are Blind or Severely Disabled	4	0%	4%
Election Assistance Commission	2	24%	11%
Office of Special Counsel	2	27%	20%
Library of Congress	2	0%	1%
American Battle Monuments Commission	0	0%	31%
Other	357,929	4%	9%
Total	12,456,132	12%	33%

Notes: This table displays federal agencies that awarded procurement contracts during 1980-2015. The "Other" category identifies contracts where the awarding federal agency is (i) not identified in the FPDS data or (ii) no longer active as of December 2020. Contracts are deflated using the GDP Implicit Price Deflator to reflect millions of constant 2012 dollars (U.S. Bureau of Economic Analysis, 2021).

Appendix D Variable Construction

Table D7 includes definitions and sources for the main variables used in our econometric analyses. The steps used to split procurement contracts into various types (e.g., R&D vs. production), assign contracts to industries, and create variables for several characteristics of science are detailed below.

D.1 Contract Variables

The types and names of data fields collected in the FPDS have changed over our sample period. For example, prime award data include 169 variables for fiscal years 1980-2000 and 282 variables for fiscal years 2001-2021. To ensure the comparability of our analyses over time, we manually mapped the variables obtained from SAM.gov against the corresponding variables obtained from USAspending.gov. To do so, we used the Data Dictionary Crosswalk available from USAspending.gov, as well as the FPDS-NG User's Manual (version 1.5, issued in October 2020) and the FPDS-NG Data Element Dictionary (version 1.4, issued in March 2020) available from FPDS.gov. Table D2 displays the resulting crosswalk between variables.

To describe the products and services acquired in each procurement award, agencies use four-digit Product and Service Codes (PSC) that mirror the Federal Supply Classification (FSC) codes.[22] As of March 2020, the PSC/FSC classification consists of 78 product groups (see Table D3) and 24 service categories (see Table D4). The product groups are further subdivided into 645 classes, as defined in the FPDS Product and Service Codes Manual (U.S. General Services Administration, 2021).

We link the PSC/FSC classification to NAICS industries using the crosswalk from the U.S. Defense Logistics Agency (U.S. Defense Logistics Agency, 2020) and then link NAICS industries to SIC industries using the concordances available from the U.S. Census Bureau (U.S. Census Bureau, 2019). This allows us to identify the SIC4 industry for 68% of procurement contract dollars awarded between 1980 and 2015.

We use the *Product or service code* field to categorize contracts as either R&D contracts (service codes starting with the letter A) or production contracts (service codes starting with letters B through Z and product codes starting with any number).[23] In the procurement contract data, codes for R&D services are composed of two alphabetic and two numeric digits:

- 1st digit: always the letter A to identify R&D services,
- 2nd digit: alphabetic A to Z to identify the major category,
- 3rd digit: numeric 1 to 9 to identify a subdivision of the major category, and
- 4th digit: numeric 1 to 7 to identify the appropriate stage of R&D:
    1. Basic research,
    2. Applied research and exploratory development,
    3. Advanced development,
    4. Engineering development,
    5. Operational systems development,

[22]The FSC is a government-wide commodity classification system designed for grouping, classifying, and naming all personal property items.

[23]When a contract transaction includes more than a single product or service, the awarding agency uses the code corresponding to the predominant product or service.

Table D2: Variable Crosswalk

SAM.gov variable	USAspending.gov variable	Description
contractingagencyid	awarding_sub_agency_code	Awarding Agency ID
contractingagencyname	awarding_sub_agency_name	Awarding Agency Name
contractingofficeid	awarding_office_code	Awarding Office ID
contractingofficename	awarding_office_name	Awarding Office Name
fundingdepartmentid	funding_agency_code	Funding Department ID
fundingdepartmentname	funding_agency_name	Funding Department Name
fundingagencyid	funding_sub_agency_code	Funding Agency ID
fundingofficeid	funding_office_code	Funding Office ID
piid	award_id_piid	PIID
transactionnumber	transaction_number	Transaction Number
modificationnumber	modification_number	Modification Number
reasonformodification	action_type_code	Reason for Modification
referencedidvpiid	parent_award_id_piid	Parent Award ID
datesigned	action_date	Date Signed/Action Date
actionobligation	federal_action_obligation	Action Obligation
baseandalloptionsvaluetotal contr	base_and_all_options_value	Base and All Options Value
baseandexercisedoptionsvalue	base_and_exercised_options_value	Base and Exercised Options Value
vendorname	recipient_name	Recipient Name
dunsnumber	recipient_duns	Recipient DUNS
globalvendorname	recipient_parent_name	Recipient Parent Name
globaldunsnumber	recipient_parent_duns	Recipient Parent DUNS
naicscode	naics_code	NAICS Code
naicsdescription	naics_description	NAICS Description
periodofperformancestartdate	period_of_performance_start_date	Period of Performance Start Date
estultimatecompletiondate	period_of_performance_potential_	Est. Ultimate Completion Date
lastdatetoorder	ordering_period_end_date	Last Date to Order
completiondate	period_of_performance_current_en	Completion Date
productorservicecode	product_or_service_code	Product or Service Code
descriptionofrequirement	award_description	Description of Requirement/Award Description
awardtype	award_type_code	Award Type
typeofcontract	type_of_contract_pricing_code	Type of Contract
commercialitemacquisition procedu	commercial_item_acquisition_proc	Commercial Item Acquisition Procedures
extentcompeted	extent_competed_code	Extent Competed
otherthanfullandopen competition	other_than_full_and_open_competi	Other Than Full and Open Competition
domesticorforeignentity	domestic_or_foreign_entity_code	Domestic or Foreign Entity
evaluatedpreference	evaluated_preference_code	Evaluated Preference
fairopportunitylimitedsources	fair_opportunity_limited_sources	Fair Opportunity/Limited Sources
foreignfunding	foreign_funding	Foreign Funding
inherentlygovernmentalfunction	inherently_governmental_function	Inherently Governmental Function
isperformancebasedserviceacquisi	performance_based_service_acquis	Is Performance Based Service Acquisition
localareasetaside	local_area_set_aside_code	Local Area Set Aside
numberofactions	number_of_actions	Number of Actions
samexceptiontype	sam_exception	SAM Exception Type
solicitationprocedures	solicitation_procedures_code	Solicitation Procedures
typeofsetaside	type_of_set_aside	Type of Set Aside
typeofsetasidesource	type_of_set_aside_code	Type of Set Aside Source

Notes: This table displays a crosswalk between contract variables available for 1980-2000 from SAM.gov and variables available for 2001-2020 from USAspending.gov.

6. Management and support, and
7. Commercialization (U.S. General Services Administration, 2021).

We use these patterns to categorize R&D contracts as either research contracts or development contracts. Specifically, we code the first two stages of R&D (i.e., basic research and applied research and exploratory development) as upstream R&D contracts, and the other five stages as downstream

Table D3: Classification Codes for Products

Code	Product group	Code	Product group
10	Weapons	53	Hardware and Abrasives
11	Nuclear Ordinance	54	Prefabricated Structures and Scaffolding
12	Fire Control Equipment	55	Lumber, Millwork, Plywood, and Veneer
13	Ammunition and Explosives	56	Construction and Building Materials
14	Guided Missiles	58	Communications, Detection and Coherent Radiation Equipment
15	Aircraft and Airframe Structural Components	59	Electrical and Electronic Equipment Components
16	Aerospace Craft Components and Accessories	60	Fiber Optics Materials and Components, Assemblies and Accessories
17	Aerospace Craft Launching, Landing, and Ground Handling Equipment	61	Electric Wire, and Power and Distribution Equipment
18	Space Vehicles	62	Lighting Fixtures and Lamps
19	Ships, Small Craft, Pontoons, and Floating Docks	63	Alarm, Signal and Security Detection Systems
20	Ship and Marine Equipment	65	Medical, Dental, and Veterinary Equipment and Supplies
22	Railway Equipment	66	Instruments and Laboratory Equipment
23	Ground Effect Vehicles, Motor Vehicles, Trailers, and Cycles	67	Photographic Equipment
24	Tractors	68	Chemicals and Chemical Products
25	Vehicular Equipment Components	69	Training Aids and Devices
26	Tires and Tubes	70	ADP Equipment Software, Supplies and Support Equipment
28	Engines, Turbines, and Components	71	Furniture
29	Engine Accessories	72	Household and Commercial Furnishings and Appliances
30	Mechanical Power Transmission Equipment	73	Food Preparation and Serving Equipment
31	Bearings	74	Office Machines
32	Woodworking Machinery and Equipment	75	Office Supplies and Devices
34	Metalworking Machinery	76	Books, Maps, and Other Publications
35	Service and Trade Equipment	77	Musical Instruments, Phonographs, and Home Radios
36	Special Industry Machinery	78	Recreational and Athletic Equipment
37	Agricultural Machinery and Equipment	79	Cleaning Equipment and Supplies
38	Construction, Mining, Excavating, and Highway Maintenance Equipment	80	Brushes, Paints, Sealers, and Adhesives
39	Materials Handling Equipment	81	Containers, Packaging, and Packing Supplies
40	Rope, Cable, Chain, and Fittings	83	Textiles, Leather, Furs, Apparel and Shoes, Tents, Flags
41	Refrigeration, Air Conditioning and Air Circulating Equipment	84	Clothing, Individual Equipment, and Insignia
42	Fire Fighting, Rescue, and Safety Equipment	85	Toiletries
43	Pumps and Compressors	87	Agricultural Supplies
44	Furnace, Steam Plant, and Drying Equip, Nuclear Reactors	88	Live Animals
45	Plumbing, Heating and Sanitation Equipment	89	Subsistence (Food)
46	Water Purification and Sewage Treatment Equipment	91	Fuels, Lubricants, Oils, and Waxes
47	Pipe, Tubing, Hose, and Fittings	93	Nonmetallic Fabricated Materials
48	Valves	94	Nonmetallic Crude Materials
49	Maintenance and Repair Shop Equipment	95	Metal Bars, Sheets, and Shapes
51	Hand Tools	96	Ores, Minerals, and Their Primary Products
52	Measuring Tools	99	Miscellaneous

Notes: This table displays the 78 high-level groups used to classify the products purchased by the federal government (as of March 2020). Groups 21, 27, 33, 50, 57, 64, 82, 86, 90, 92, 97, and 98 are unassigned.

R&D contracts.

We also use the *Product or service code* field to categorize DoD contracts as either *military* or *nonmilitary* based on (i) the Product and Service Codes Manual and (ii) the Government-Wide

Table D4: Classification Codes for Services

Code	Service category	Code	Service category
A	Research and development	N	Installation of equipment
B	Special studies and analyses – not R&D	P	Salvage services
C	Architect and engineering services – construction	Q	Medical services
D	Automatic data processing and telecommunication services	R	Professional, administrative and management support services
E	Purchase of structures and facilities	S	Utilities and housekeeping services
F	Natural resources and conservation services	T	Photographic, mapping, printing, and publications services
G	Social services	U	Education and training services
H	Quality control, testing, and inspection services	V	Transportation, travel and relocation services
I	Maintenance, repair and rebuilding of equipment	W	Lease or rental of equipment
K	Modification of equipment	X	Lease or rental of facilities
L	Technical representative services	Y	Construction of structures and facilities
M	Operation of government owned facility	Z	Maintenance, repair or alteration of real property

Notes: This table displays the 24 high-level categories used to classify the services purchased by the federal government (as of March 2020).

Category Management Taxonomy. First, the Product and Service Codes Manual classifies R&D services into the 20 subcategories included in Table D5. Correspondingly, we categorize an R&D contract from the DoD as *military* if its PSC code belongs to subcategory AC (R&D- Defense systems) or AD (R&D- Defense other), and as *nonmilitary* otherwise.[24] Second, the Government-Wide Category Management Taxonomy classifies production contracts into the 10 "common spend" categories and the eight "defense-centric spend" categories included in Table D6.[25] Accordingly, we categorize a production contract from the DoD as *military* if its PSC code belongs to a defense-centric spend category and as *nonmilitary* otherwise.

Table D5: Classification Codes for R&D Services

Code	Subcategory	Code	Subcategory
AA	R&D- Agriculture	AL	R&D- Income security
AB	R&D- Community service/development	AM	R&D- International affairs and cooperation
AC	R&D- Defense systems	AN	R&D- Medical
AD	R&D- Defense other	AP	R&D- Natural resource
AE	R&D- Economic growth	AQ	R&D- Social services
AF	R&D- Education	AR	R&D- Space
AG	R&D- Energy	AS	R&D- Modal transportation
AH	R&D- Environmental protection	AT	R&D- Other transportation
AJ	R&D- General science/technology	AV	R&D- Mining
AK	R&D- Housing	AZ	R&D- Other research and development

Notes: This table displays the 20 sub-categories used to classify the R&D services purchased by the federal government (as of March 2020).

We use the *Commercial items acquisition procedures* field to categorize production contracts into either commercial contracts or noncommercial contracts.[26] Contracts were awarded using com-

[24] All contracts awarded by other agencies than the DoD are *nonmilitary* by definition.

[25] Category management is the practice of buying common products and services as a unified federal government enterprise to eliminate redundancies and improve the efficiency and effectiveness of acquisition activities. The Government-Wide Category Management Taxonomy was downloaded from https://hallways.cap.gsa.gov/app/#/gateway/category-management/8825/government-wide-category-taxonomy on September 22, 2022.

[26] This field indicates whether the solicitation used the special requirements for the acquisition of commercial items, supplies, or services. Those requirements are intended to more closely resemble the commercial markets as defined

Table D6: Government-Wide Category Management Taxonomy

Type of spend	Category	PSC example
Common spend	Facilities and construction	3710 Soil preparation equipment
	Human capital	U001 Education/training- Lectures
	Industrial products and services	3010 Torque converters and speed changers
	Information technology	5820 Radio and television communication equipment, except airborne
	Medical	6505 Drugs and biologicals
	Office management	3610 Printing, duplicating, and bookbinding equipment
	Professional services	B502 Special studies/analysis- Air quality
	Security and protection	5660 Fencing, fences, gates and components
	Transportation and logistical services	2210 Locomotives
	Travel	V302 Transportation/ travel/ relocation- Relocation: travel agent
Defense-centric spend	Aircraft, ships/submarines, and land vehicles	1510 Aircraft, fixed wing
	Clothing, textiles, and subsistence services and equipment	8970 Composite food packages
	Electronic and communication equipment	5825 Radio navigation equipment, except airborne
	Electronic and communication services	H158 Quality control- Communication, detection, and coherent radiation equipment
	Equipment related services	H110 Quality control- weapons
	Miscellaneous services and equipment	H176 Quality control- Books, maps, and other publications
	Sustainment services and equipment	1550 Unmanned aircraft
	Weapons and ammunition	1015 Guns, 75mm through 125mm

Notes: This table displays the *common spend* and *defense-centric spend* categories included in the Government-Wide Category Management Taxonomy (as of March 2020).

mercial item procedures only after the passage of the Federal Acquisition Streamlining Act of 1994. Therefore, our data separating commercial vs. noncommercial production contracts only span fiscal years 1995-2015. While some R&D service contracts were awarded using streamlined commercial item procedures, they represent less than 1% of the value of all R&D contracts awarded to sample firms. Therefore, we do not break down R&D contracts into commercial vs. noncommercial R&D contracts.

We use the *Extent competed* field to distinguish contracts that were awarded competitively from those awarded noncompetitively. In general, federal agencies are required to use full and open competition when awarding procurement contracts. Competitive procedures include sealed bids, competitive proposals, or a combination of competitive procedures. However, the Competition in Contracting Act of 1984 authorized noncompetitive contracting under certain conditions.[27]

We use the *Award description* text field to correctly identify contractual deobligations. Deobligations represent cancellations or downward adjustments of previously obligated funds (e.g., due to default or closeout). Yet not all negative transactions are meaningful deobligations; some are simply corrections of clerical errors. For example, an acquisition professional may omit the decimal point

by the Federal Acquisition Regulation Part 12.

[27] There are seven exceptions to full and open competition: (i) only one responsible source and no other supplies or services will satisfy agency requirements; (ii) unusual and compelling urgency; (iii) industrial mobilization; engineering, developmental, or research capability; or expert services; (iv) international agreement; (v) authorized or required by statute; (vi) national security; and (vii) public interest (Federal Acquisition Regulation, 2019).

when recording an obligation for $10 million, turning it into $1 billion. To correct this error, the professional would subsequently record a deobligation for -$990 million and add a comment about it in the *Award description* field. We identify all transactions described using the keywords "correct," "error," "mistake," "inadvertently," or "accidentally" and exclude them from deobligation analyses.[28]

Table D7 summarizes the definitions and data sources for the main variables used in our econometric analyses.

Table D7: Variable Definitions

Variable	Definition	Source
Publications	Sum of scholarly, peer-reviewed publications that have at least one author affiliated with the focal firm and were published in the focal year. Appendix Section D.2 details how we split the publication flow into *Internal use* vs. *No internal use* (to capture the focal firm's own use of science), *High rival use* vs. *Low rival use* (to capture product-market rivals' use of science), and *High protection publications* vs. *Low protection publications* (to capture the scope of protection offered by the focal firm's own patents).	Clarivate Analytics' Web of Science (Arora, Belenzon, & Sheer, 2021)
Publications stock	Calculated using a perpetual inventory method with a 15% depreciation rate (Hall et al., 2005), such that the stock in year t is $Publications\ stock_t = Publications_t + (1-\delta) Publications\ stock_{t-1}$, where $\delta = 0.15$.	
Renowned scientists	Sum of renowned scientists employed by the focal firm in the focal year.	American Men & Women of Science
Award-winning renowned scientists	Sum of award-winning renowned scientists employed by the focal firm in the focal year.	American Men & Women of Science
Patents	Sum of patents granted by the U.S. Patent and Trademark Office to the focal firm in the focal year.	European Patent Office's PATSTAT database (Arora, Belenzon, & Sheer, 2021)
All contracts	Sum of all contract awards associated with a firm-year ($ mm).	USAspending.gov, beta.SAM.gov
Deobligations	Sum of all negative contract modifications associated with a firm-year ($ mm).	USAspending.gov, beta.SAM.gov
R&D contracts	Sum of R&D contract awards associated with a firm-year ($ mm).	
Non-R&D contracts	Sum of non-R&D contract awards associated with a firm-year ($ mm).	
Commercial contracts	Sum of commercial contract awards associated with a firm-year ($ mm).	
Noncommercial contracts	Sum of noncommercial contract awards associated with a firm-year ($ mm).	
All grants	Sum of all project grants and cooperative agreements associated with a firm-year ($ mm).	USAspending.gov
Time trend	Focal year minus 1980 (in decennial units).	
Sales	Sales for the focal firm-year ($ mm).	Standard & Poor's Compustat North America (Arora, Belenzon, & Sheer, 2021)

Notes: This table displays definitions and sources for the variables used in our econometric analyses. Dollar values are deflated using the GDP Implicit Price Deflator to reflect constant 2012 dollars (U.S. Bureau of Economic Analysis, 2021).

[28]The *Award description* field is consistently available for contract transactions made during 2001-2015, but not during 1980-2000.

Table D7: Variable Definitions (Continued)

Variable	Definition	Source
R&D expenditures	R&D expenditures for the focal firm-year ($ mm).	Standard & Poor's Compustat North America (Arora, Belenzon, & Sheer, 2021)
R&D stock	Calculated using a perpetual inventory method with a 15% depreciation rate, such that the stock in year t is $R\&D\ stock_t = R\&D\ expenditures_t + (1-\delta)R\&D\ stock_{t-1}$, where the focal firm's *R&D expenditures* in year t are based on Compustat data and $\delta = 0.15$. Expressed in $ mm.	Standard & Poor's Compustat North America (Arora, Belenzon, & Sheer, 2021)
Industry R&D funding	Calculated by multiplying the level of R&D contracts obligated to the focal firm's SIC3 industry (not including the contracts obligated to the focal firm that year) times the share of R&D contracts obligated to the focal firm's SIC4 industry (averaged over the sample period of 1980-2015). Expressed in $ mm.	USAspending.gov, beta.SAM.gov
Agency R&D budget	Calculated by replacing the level of R&D contracts obligated to the focal firm's SIC3 industry in the *Industry R&D funding* instrument with $\sum_{Agencies} R\&D\ budget_{Agency,t} \times Share_{Agency,SIC3,t}$. Here, $R\&D\ budget_{Agency,t}$ is the focal agency's R&D budget authority in year t. $Share_{Agency,SIC3,t}$ is calculated by dividing the total value of R&D contracts awarded by the focal agency to firm i's SIC3 industry in year t by the total value of R&D contracts awarded by the focal agency in year t. Expressed in $ mm.	USAspending.gov, beta.SAM.gov, American Association for the Advancement of Science
Windfall-predicted R&D budget	Calculated by replacing $R\&D\ budget_{Agency,t}$ in the *Agency R&D budget* instrument with $Windfall\text{-}predicted\ R\&D\ budget_{Agency,t}$, the predicted value of the focal agency's R&D budget authority in year t, obtained after regressing the focal agency's R&D budget authority on its total budget windfall. Expressed in $ mm.	USAspending.gov, beta.SAM.gov, American Association for the Advancement of Science, FRED
PSC R&D funding	Calculated as $\sum_{PSCs} R\&D\ contracts_{PSC,t} \times Share_{i,PSC}$. Here, $R\&D\ contracts_{PSC,t}$ is the total value of all R&D contracts awarded by all federal agencies in the focal PSC in year t. $Share_{i,PSC}$ is calculated using an initial five-year period by dividing the total value of R&D contracts for the focal PSC awarded to firm i by the total value of R&D contracts awarded to firm i. Expressed in $ mm.	USAspending.gov, beta.SAM.gov
Cold War shock	Calculated using the difference in average contract values between pre (1986-1988) and post (1990-1992) periods for each SIC4 industry, weighted by the focal firm's sales exposure to different SIC4 industries. Expressed in $ mm. The sales exposure is calculated as the share of the focal firm's sales during 1982-1985 that came from each SIC4 industry.	USAspending.gov, beta.SAM.gov, Standard & Poor's Compustat North America
Global War on Terrorism shock	Calculated using the difference in contract values between pre (2000) and post (2004) periods for each SIC4 industry, weighted by the focal firm's sales exposure to different SIC4 industries. Expressed in $ mm. The sales exposure is calculated as the share of the focal firm's sales during 1994-1997 that came from each SIC4 industry.	USAspending.gov, beta.SAM.gov, Standard & Poor's Compustat North America
Financial Crisis shock	Calculated using the difference in contract values between pre (2007) and post (2008) periods for each SIC4 industry, weighted by the focal firm's sales exposure to different SIC4 industries. Expressed in $ mm. The sales exposure is calculated as the share of the focal firm's sales during 2000-2003 that came from each SIC4 industry.	USAspending.gov, beta.SAM.gov, Standard & Poor's Compustat North America

Notes: This table displays definitions and sources for the variables used in our econometric analyses. Dollar values are deflated using the GDP Implicit Price Deflator to reflect constant 2012 dollars (U.S. Bureau of Economic Analysis, 2021).

D.2 Market Incentives Variables

We measure several characteristics of corporate science that allow us to estimate the effect of procurement contracts on corporate R&D under different private market conditions.

First, we split the annual publication flow into (i) publications cited by the firm's own patents and (ii) publications not cited by the firm's own patents. We use the non-patent literature citations file from Arora, Belenzon, and Sheer (2021) to do so. The number of unique publications that receive one or more citations from the firm's own patents is aggregated at the firm-year level into the variable *Internal use publications*. The remaining annual publication flow is captured in the variable *No internal use publications*.

Second, we identify publications that are cited by one or more patents assigned to other panel firms. We split a firm's annual publication flow into (i) publications with low rival use and (ii) publications with high rival use. To do so, we use a measure of the product-market rivalry between the publishing firm and the patenting firms (up to three corporate assignees per patent) sourced from Arora, Belenzon, and Sheer (2021). Product-market rivalry is calculated as the Mahalanobis similarity of vectors representing the shares of industry segment sales for each pair of firms. A publication has high rival use if its highest similarity score is in the top quartile of the distribution of similarity scores. The number of unique publications that have high rival use is aggregated at the firm-year level into the variable *High rival use publications*. The remaining annual publication flow is captured in the variable *Low rival use publications*.

Third, we split the annual publication flow into (i) publications that have low patent protection and (ii) publications that have high patent protection. We use a measure of the textual similarity between Web of Science publications (abstract and title) and USPTO patents (claims) from Arora, Belenzon, Marx, and Shvadron (2021). For each corporate publication published between 1980 and 2015, we retain up to five of the most similar granted patents. We identify which of those patents are owned by the publishing firm and retain the top matching publication-patent pair. Publications with proximity scores above the median (relative to the publication year) are coded as "protected" by a patent, while those with scores below the median and those unmatched to firm patents are coded as "unprotected" by a patent.[29] The number of unique publications that are "protected" by the firm's patents is aggregated at the firm-year level into the variable *High protection publications*. The remaining annual publication flow is captured in the variable *Low protection publications*.

[29] Our choice of cutoff—the median publication-patent proximity score for all the publications published by sample firms in a given year—allows us to consider how the proximity between publications and patents changes over time.

Appendix E Additional Descriptive Statistics

Figure E1 plots the four-firm concentration (C4) ratio in company-funded R&D expenditures over time (Panel A). To construct it, we first identified the four firms with the largest R&D expenditures in our sample each year. These top four firms accounted for 20-26% of total R&D expenditures made by sample firms in the 1980s, but only 14-17% in the 2010s. A downward trend in the concentration of R&D expenditures is clearly visible.

We used a similar procedure to plot the C4 ratio in government R&D contracts over time (Panel B). The concentration of R&D contracts changed over time. The top four R&D contractors accounted for 12-31% of all R&D contracts (awarded to any recipient) in the 1980s and 28-39% in the 2010s. A marked increase in concentration occurred between 1991 (C4 of 16.0%) and 1996 (C4 of 39.2%). During that post-Cold War period, the Department of Defence encouraged consolidation among the top defense contractors.[30] The trend of increasing concentration reversed in 2006. Since then, the concentration in R&D contracts has dropped 17 percentage points as federal agencies have increasingly implemented competitive procurement.

[30] Two of the largest mergers included Northrop and Grumman in 1994 and Lockheed and Martin Marietta in 1995 (Carril & Duggan, 2020).

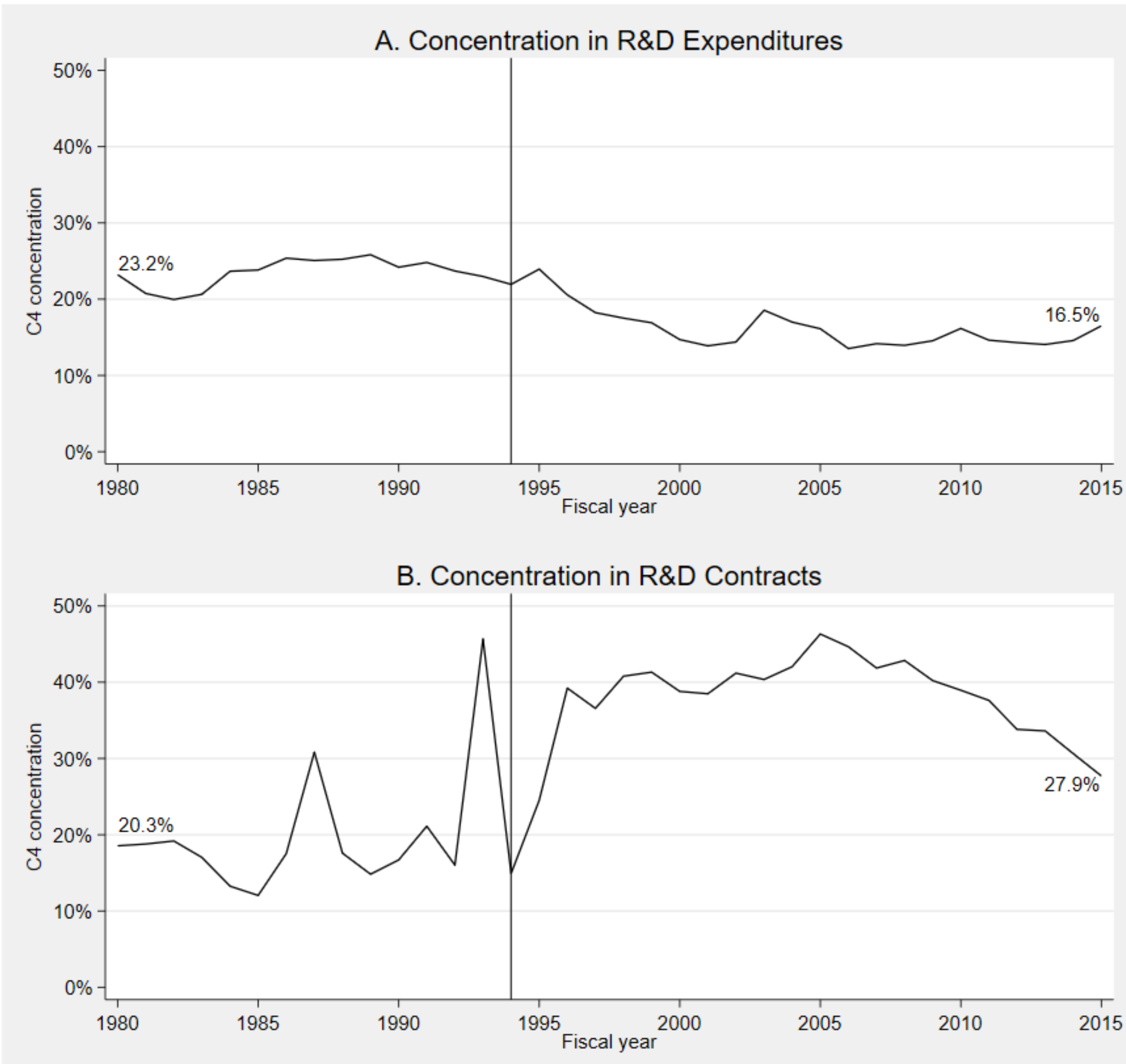

Figure E1: Concentration Ratios in R&D Expenditures and R&D Contracts

This figure plots the four-firm concentration ratios (C4) in R&D expenditures (Panel A) and government R&D contracts (Panel B) for sample firms over time. The vertical lines mark the passage of the Federal Acquisition Streamlining Act of 1994.

Table E8 presents mean comparison tests between R&D contractors and other firms.

Table E8: R&D CONTRACTORS VS. OTHER FIRMS

	(1)	(2)	(3)	(4)	(5)	(6)
	Difference in means		R&D contractors		Other firms	
	R&D contractors - Other firms	t	Mean	Std. dev.	Mean	Std. dev.
Sales ($ mm)	5,100.56	46.68	6,080.6	21,176.0	980.0	4,562.3
R&D expenditures ($ mm)	234.21	46.91	267.9	934.7	33.7	129.4
R&D intensity	-4.52	-3.43	1.3	29.6	5.9	174.0
Publications per $1 mm in R&D exp.	0.17	3.93	0.4	5.4	0.3	4.2
Patents per $1 mm in R&D exp.	-0.65	-1.62	0.6	3.5	1.2	53.4
All grants ($ mm)	0.77	9.81	0.8	10.1	0.1	2.9

Notes: This table presents mean comparison tests between R&D contractors and other firms in our sample. *R&D intensity* is calculated as R&D expenditures divided by Sales. *All grants* are summarized for fiscal years 2001-2015. The two-sample t-tests use unequal variances.

Table E9 displays correlations between the main variables included in the econometric analyses.

Table E9: CORRELATIONS

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
(1) R&D expenditures	1.00										
(2) Renowned scientists	0.49	1.00									
(3) Publications	0.72	0.69	1.00								
(4) Patents	0.63	0.40	0.58	1.00							
(5) R&D contracts	0.11	0.13	0.11	0.10	1.00						
(6) Sales	0.61	0.36	0.45	0.46	0.13	1.00					
(7) R&D stock	0.95	0.48	0.71	0.66	0.11	0.61	1.00				
(8) Industry R&D funding	0.04	0.03	0.02	0.02	0.13	0.05	0.04	1.00			
(9) Agency R&D budget	0.05	0.04	0.02	0.02	0.20	0.06	0.05	0.98	1.00		
(10) Windfall-predicted R&D budget	0.04	0.04	0.02	0.01	0.17	0.05	0.04	0.89	0.91	1.00	
(11) PSC R&D funding	0.00	0.00	-0.00	0.08	0.14	0.00	0.01	0.11	0.12	0.11	1.00

Notes: This table displays pairwise Pearson correlations between the main variables included in the econometric analyses. The construction of the instrumental variables (8-11) is described in Section 6.2 and Appendix F.

Appendix F Instrumental Variable Estimation

F.1 Industry R&D Funding

Our first instrument exploits variation in aggregate industry R&D contracts to predict R&D contracts awarded to a focal firm. It is important to recognize that R&D contracts awarded to a firm's SIC4 industry may still be endogenous (e.g., when a firm dominates its SIC4 industry, it is possible that industry R&D contracts and firm R&D activity respond to the same technology shocks). To mitigate this concern, we take advantage of changes in R&D funding at a higher level of aggregation, the firm's SIC3 industry. We "distribute" these changes across SIC4 industries according to time-invariant industry shares, closely following Moretti et al. (2021). Doing so lowers the power of our instrument in the first stage, but increases its validity.

We construct our instrumental variable (IV) in three stages. First, we identify the SIC4 industry for each procurement contract awarded during 1980-2015 (not just those matched to sample firms). For transactions that do not list the recipient firm's NAICS code, we use the *Product or service code* (PSC) field and the PSC-to-NAICS crosswalk from the U.S. Defense Logistics Agency to identify the NAICS code. Then, we use the NAICS-to-SIC concordances available from the U.S. Census Bureau to identify the SIC4 code. We aggregate all R&D contracts awarded to all firms (not just our panel firms) at the SIC4-year and SIC3-year levels, respectively.

Second, we calculate the share of R&D contracts awarded to the SIC4 industry relative to the R&D contracts awarded to the SIC3 industry that contains it. Specifically, we divide the total value of R&D contracts awarded to the SIC4 industry during 1980-2015 by the total value of R&D contracts awarded to the higher-level SIC3 industry during 1980-2015.

Third, we calculate the instrument as $Industry\ R\&D\ funding_{i,t} = (Industry\ R\&D\ contracts_{SIC3,t} - Firm\ R\&D\ contracts_{i,t}) \times Industry\ share_{SIC4,SIC3}$. $Industry\ R\&D\ contracts_{SIC3,t}$ is the total value of all R&D contracts awarded by federal agencies to the focal firm's SIC3 industry in year t. $Firm\ R\&D\ contracts_{i,t}$ is the value R&D contracts awarded to the focal firm in year t. The reason for excluding firm R&D contracts from the construction of the IV is to avoid a mechanical correlation between the endogenous variable we want to instrument and the instrument itself. $Industry\ share_{SIC4,SIC3}$ is calculated by dividing the total value of R&D contracts awarded to the focal firm's SIC4 industry during 1980-2015 by the total value of R&D contracts awarded to the focal firm's higher-level SIC3 industry during 1980-2015. We use a time-invariant share because it allows us to smooth out year-to-year variation in the R&D contracts awarded to the SIC4 industry.

Take Boeing as an example. In 2012, Boeing's SIC3 industry (372 Aircraft and Parts) received \$13.7 billion in R&D contracts, including almost \$3.6 billion for Boeing. Over the sample period of 1980-2015, Boeing's SIC4 industry (3721 Aircraft) received 99% of the R&D contracts awarded to its SIC3 industry (372 Aircraft and Parts). The instrument for Boeing in 2012 was calculated as $(13.7 - 3.6) \times .99 = 10$ (in \$ billions).

Using this industry R&D funding measure (rather than the total value of R&D contracts awarded to the firm's SIC4 industry in year t) strengthens the validity of our instrument because it makes it less likely to be related to the focal firm's idiosyncratic technological opportunities.

F.2 First Stage Results

Table F10 shows the first-stage results of the two-stage least squares (2SLS) instrumental variable estimations reported in this paper.

Table F10: INSTRUMENTAL VARIABLE ESTIMATION (FIRST STAGE)

	(1)	(2)	(3)	(4)
		ln(R&D contracts)$_{t-1}$		
	Industry R&D funding	Agency R&D budget	Windfall-predicted R&D budget	PSC R&D funding
ln(Industry R&D funding)$_{t-1}$	0.070			
	(0.007)			
ln(Agency R&D budget)$_{t-1}$		0.067		
		(0.006)		
ln(Windfall-predicted R&D budget)$_{t-1}$			0.067	
			(0.006)	
ln(PSC R&D funding)$_{t-1}$				0.536
				(0.268)
ln(R&D stock)$_{t-1}$	0.038	0.038	0.038	0.399
	(0.028)	(0.028)	(0.028)	(0.192)
Sample years	1980-2015	1980-2015	1980-2015	1980-2015
Firm fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Observations	49,702	49,732	49,745	10,711
F statistic	56	57	58	5
Adjusted R-squared	0.686	0.688	0.688	0.652

Notes: This table displays first-stage OLS regression results. Standard errors (in parentheses) are clustered at the firm level.

F.3 Bartik Instrument Results

Table F11 shows the 2SLS results for R&D expenditures, publications, and patents when the endogenous R&D contracts are instrumented using the Bartik instrument *PSC R&D funding* (Columns 1-3).

Following Goldsmith-Pinkham, Sorkin, and Swift (2020), we explored the relationship between PSC composition and firm characteristics that may be correlated with demand or technology shocks (Columns 4 and 5). Because the PSC shares were calculated over an initial five-year period, $[\tau, \tau+4]$ for each R&D contractor, we regressed the Bartik instrument in year $\tau+4$ on our measures of firm size that same year. Reassuringly, the initial period instrument was not correlated with the covariates for firm size, even after controlling for industry fixed effects.

F.4 Cold War Shock

An alternative instrument uses changes between the pre- and post-Soviet collapse periods in industry-level contracts to predict firm-level R&D contracts during 1995-2015 (see Figure F2 for the associated timeline). Because this instrument does not vary within firms (i.e., there is only one change per firm), we cannot use firm fixed effects. Instead, we follow Blundell, Griffith, and Van Reenen (1999) and include the pre-sample mean of the dependent variable as a separate control for time-invariant firm heterogeneity. Many sample firms operate in multiple business segments, so they were affected by changes in procurement contracts across multiple industries. To estimate the "average" shock experienced by each firm, we use the shares of firm sales in each industry as weights. We build $Cold\ War\ shock_i = \sum_{Industries} \Delta Contracts_{SIC4} \times Share\ of\ sales_{i,SIC4}$. Here, $Cold\ War\ shock_i$ is

Table F11: R&D, Publications, and Patents Equations Using the Bartik Instrument

	(1)	(2)	(3)	(4)	(5)
	$\ln(\text{R\&D expenditures})_t$	$\ln(\text{Publications})_t$	$\ln(\text{Patents})_t$	$\ln(\text{PSC R\&D funding})_{\tau+4}$	
	IV: PSC R&D funding	IV: PSC R&D funding	IV: PSC R&D funding	OLS: Pooled	OLS: Within industries
$\ln(\text{R\&D contracts})_{t-1}$	0.050	0.210	0.110		
	(0.062)	(0.105)	(0.098)		
$\ln(\text{Sales})_{t-2}$	0.510				
	(0.055)				
$\ln(\text{R\&D stock})_{t-1}$		0.211	0.348		
		(0.072)	(0.064)		
$\ln(\text{R\&D stock})_{\tau+4}$				0.007	0.060
				(0.030)	(0.033)
$\ln(\text{Sales})_{\tau+4}$				0.026	0.006
				(0.030)	(0.030)
Firm fixed effects	Yes	Yes	Yes	No	No
Year fixed effects	Yes	Yes	Yes	Yes	Yes
Industry fixed effects	No	No	No	No	Yes
Weak identif. (Kleibergen-Paap)	4.56	4.01	4.01		
Firms/Industries	809	848	848	186	105
Observations	9,969	10,711	10,711	814	733
Adjusted R-squared	0.122	-2.112	-0.379	0.096	0.377

Notes: This table displays the effect of government R&D contracts on corporate R&D expenditures, publications, and patents using the Bartik instrument *PSC R&D funding*. Standard errors (in parentheses) are clustered at the firm level in Columns 1-3 and the SIC4 industry level in Columns 4 and 5.

the instrument for firm i. $\Delta Contracts_{SIC4}$ is the difference between the average contracts awarded to the focal industry in the pre- (1986-1988) and post- (1990-1992) periods. $Share\ of\ sales_{i,SIC4}$ is the share of firm i's sales during 1982-1985 in the focal industry, calculated using the Compustat Segments dataset.[31] We use a multi-year lag in calculating shares of sales to alleviate concerns that firms might have anticipated the end of the Cold War. Under that scenario, firms might have entered industries where they anticipated growing procurement and exited industries where they anticipated shrinking procurement.

Figure F2 presents the timeline used for estimating the $Cold\ War\ shock$ instrumental variable. Figure F3 and Table F12 present comparisons of procurement contracts awarded to various industries in 1988 and 1992.

[31] For example, Komatsu Ltd. operated only in Construction Machinery and Equipment (SIC 3531) from 1982 to 1985, generating 100% of its sales in that industry. As a result, its $Cold\ War\ shock$ came entirely from reallocations in contracts awarded to SIC 3531. Caterpillar Inc. generated 76% of its sales during 1982-1985 in Construction Machinery and Equipment (SIC 3531), and 24% in Internal Combustion Engines, Not Elsewhere Classified (SIC 2519). As a result, 76% of this firm's $Cold\ War\ shock$ came from reallocations in contracts awarded to SIC 3531, and 24% from reallocations to SIC 2519.

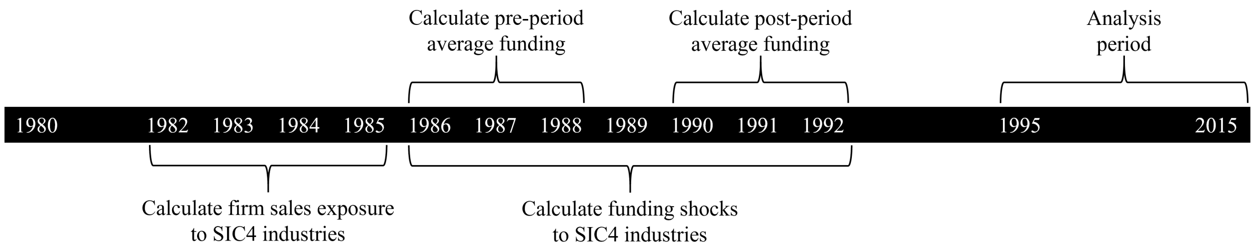

Figure F2: The Cold War Identification Strategy Timeline
This figure presents the timeline used for estimating the *Cold War shock* instrumental variable.

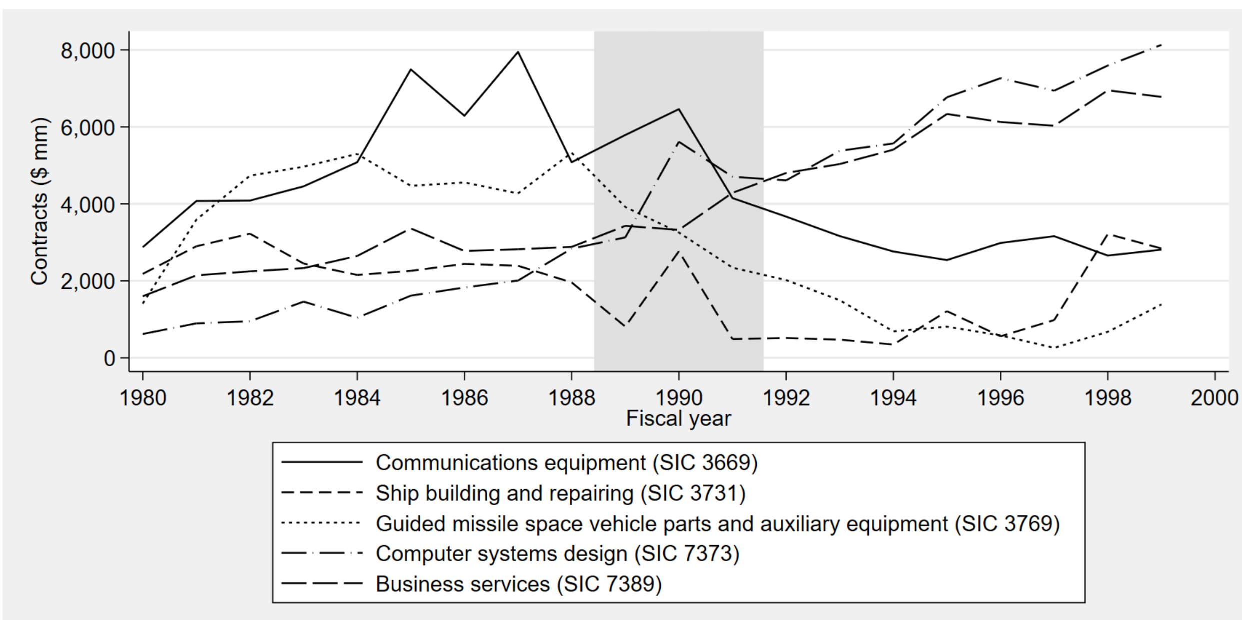

Figure F3: Procurement During and After the Cold War
This figure plots the aggregate value of procurement contracts awarded by federal agencies to various industries. Dollar values are adjusted using the GDP Implicit Price Deflator to reflect constant 2012 dollars (U.S. Bureau of Economic Analysis, 2021).

Table F12: Procurement by SIC4 Industry around the End of the Cold War

Rank	SIC4	1988 Contracts ($ mm)	1992 Contracts ($ mm)	Industry description
1	7389	2,883	4,802	Business Services, Not Elsewhere Classified
2	7373	2,838	4,611	Computer Integrated Systems Design
3	9661	233	1,732	Space Research and Technology
4	2111	191	1,437	Cigarettes
5	4813	402	1,382	Telephone Communications, Except Radiotelephone
6	3523	1,158	2,101	Farm Machinery and Equipment
7	4812	2,056	2,987	Radiotelephone Communications
8	2833	1,097	1,776	Medicinal Chemicals and Botanical Products
9	0131	2	560	Cotton
10	5047	218	755	Medical, Dental, and Hospital Equipment and Supplies
...	...	...	...	...
765	3711	3,449	2,197	Motor Vehicles and Passenger Car Bodies
766	3669	5,082	3,670	Communications Equipment, Not Elsewhere Classified
767	3731	1,961	516	Ship Building and Repairing
768	1311	6,048	4,180	Crude Petroleum and Natural Gas
769	6794	2,065	185	Patent Owners and Lessors
770	3841	3,088	1,056	Surgical and Medical Instruments and Apparatus
771	3769	5,327	2,022	Guided Missile Space Vehicle Parts and Auxiliary Equipment, Not Elsewhere Classified
772	3442	5,031	1,672	Metal Doors, Sash, Frames, Molding, and Trim Manufacturing
773	3812	7,991	3,328	Search, Detection, Navigation, Guidance, Aeronautical, and Nautical Systems and Instruments
774	3721	65,740	39,099	Aircraft

Notes: This table displays the procurement contracts (in constant 2012 dollars) awarded by all federal agencies in 1988 and 1992 to each SIC4 industry. Observations are sorted in descending order of the difference between 1992 and 1988.

Appendix G Industry Variation

Our sample is drawn from a wide distribution of industries (see Table G13). The classification scheme used to group sample firms into several main industries is presented in Table G14. Table G15 presents descriptive statistics by main industry, while Table G16 presents mean comparison tests between R&D contractors other firms within the same main industry.

Table G13: Distribution of Firms by SIC2 Industry

SIC2 code	Number of firms	SIC2 code	Number of firms	SIC2 code	Number of firms
28	796	32	29	14	5
36	680	49	27	21	5
38	672	22	26	60	4
73	567	27	23	63	4
35	540	51	21	10	3
37	145	29	21	75	3
34	101	59	15	12	3
30	79	01	14	76	3
87	70	65	13	61	3
48	67	79	13	42	2
20	64	23	10	45	2
39	60	24	9	54	2
99	59	17	8	72	2
33	58	16	8	47	2
26	50	78	8	07	2
67	46	31	7	64	2
13	46	62	6	44	1
50	34	82	6	02	1
25	31	15	6	70	1
80	30	58	5		

Notes: This table displays the distribution of sample firms by two-digit SIC code.

Table G14: Classification Into Main Industries

Main industry	SIC2 code	Description
Chemicals	28	Firms producing basic chemicals (including acids, alkalies, salts, and organic chemicals), chemical products used in manufacturing (including synthetic fibers, plastics materials, dry colors, and pigments), or finished chemical products used for ultimate consumption (including drugs, cosmetics, and soaps) or as supplies in other industries (including paints, fertilizers, and explosives).
Electronics	35, 36	Firms manufacturing industrial and commercial machinery, equipment, and computers (including engines and turbines; farm and garden machinery; construction, mining, and oil field machinery; elevators and conveying equipment; hoists, cranes, monorails, and industrial trucks and tractors; metalworking machinery; special industry machinery; general industrial machinery; computer and peripheral equipment and office machinery; and refrigeration and service industry machinery), or machinery, apparatus, and supplies for the generation, storage, transmission, transformation, and utilization of electrical energy (including electricity distribution equipment; electrical industrial apparatus; household appliances; electrical lighting and wiring equipment; radio and television receiving equipment; communications equipment; electronic components and accessories; and other electrical equipment and supplies).
Instruments	38	Firms manufacturing instruments (including professional and scientific) for measuring, testing, analyzing, and controlling, and their associated sensors and accessories; optical instruments and lenses; surveying and drafting instruments; hydrological, hydrographic, meteorological, and geophysical equipment; search, detection, navigation, and guidance systems and equipment; surgical, medical, and dental instruments, equipment, and supplies; ophthalmic goods; photographic equipment and supplies; or watches and clocks.
Business services	73, 87	Firms providing business services (including advertising, credit reporting, collection of claims, mailing, reproduction, stenographic, news syndicates, computer programming, photocopying, duplicating, data processing, services to buildings, and help supply services), or engineering, accounting, research, management, and related services (including engineering, architectural, and surveying services; accounting, auditing, and bookkeeping services; research, development, and testing services; and management and public relations services).

Notes: This table displays the classification scheme used to group sample firms into several main industries. Industries not specifically listed were classified as "Others."

Table G15: Descriptive Statistics by Main Industry

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	Chemicals		Electronics		Instruments		Business services		Others	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
R&D expenditures ($ mm)	268	911	120	497	47	139	205	906	169	762
Renowned scientists	16	71	3	18	2	8	6	48	6	28
Publications	55	172	8	44	7	26	23	171	15	85
Patents	31	84	35	149	13	47	43	348	30	116
All contracts ($ mm)	13	99	21	198	119	1,065	31	204	245	1,962
R&D contracts ($ mm)	1	6	3	69	21	221	3	24	42	457
Production contracts ($ mm)	12	98	18	150	98	862	28	186	203	1,567
Commercial contracts ($ mm)	8	90	5	58	10	70	8	50	26	170
Noncommercial contracts ($ mm)	4	45	10	83	110	966	20	144	221	1,817
All grants ($ mm)	1	15	0	4	0	2	0	1	1	8
Sales ($ mm)	3,310	8,816	1,813	7,081	804	2,730	1,997	9,957	8,131	25,731
R&D stock ($ mm)	1,107	4,116	496	2,197	189	547	766	3,915	633	3,485

Notes: This table displays descriptive statistics over the sample period of 1980-2015 by main industry. The unit of analysis is a firm-year. Statistics are only provided for contractors. Grants and commercial contracts are only summarized for the years 2001-2015 and 1995-2015, respectively.

Table G16: R&D Contractors vs. Other Firms by Main Industry

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	Chemicals		Electronics		Instruments		Business services		Others	
	Diff.	t	Diff.	t	Diff.	t	Diff.	t	Diff.	t
R&D expenditures ($ mm)	367.738	25.53	170.475	24.2	69.774	25.6	324.651	15.6	309.939	26.9
Renowned scientists	23.423	21.26	4.947	20.5	3.235	19.8	12.495	12.2	11.603	31.5
R&D intensity (in $ mm)	-21.101	-2.86	-0.373	-2.0	-0.063	-0.1	-3.016	-1.4	-0.482	-2.1
Publications per $1 mm in R&D exp.	0.173	1.55	0.339	5.0	-0.004	-0.0	0.106	0.5	0.105	2.5
Patents per $1 mm in R&D exp.	-0.077	-0.42	-1.100	-0.8	-0.457	-3.0	0.028	0.4	-0.997	-4.0
All grants ($ mm)	1.036	3.29	0.602	6.7	0.389	7.6	0.205	5.5	1.408	8.4

Notes: This table displays mean comparison tests between R&D contractors and other firms within the same main industry. *R&D intensity* is calculated as R&D expenditures divided by Sales. Grants are only summarized for the years 2001-2015. The two-sample t-tests use unequal variances.

Table G17 breaks the main results by industry. Columns 2 and 5 present 2SLS estimates using *Industry R&D funding* and its interactions with industry indicator variables as instrumental variables for *R&D contracts* and its interactions with industry indicator variables. In Columns 3 and 6, we use *Windfall-predicted R&D budget* as the instrumental variable. The coefficient estimates in Columns 2-3 suggest that the causal effect of *R&D contracts* on publications is present across all industries. Conversely, we do not find evidence in Columns 5-6 that *R&D contracts* drive patents across a variety of industries.

Table G17: Variation by Main Industry

	(1)	(2)	(3)	(4)	(5)	(6)
	ln(Publications)			ln(Patents)		
	OLS	IV: Industry R&D funding	IV: Windfall-predicted R&D budget	OLS	IV: Industry R&D funding	IV: Windfall-predicted R&D budget
ln(R&D contracts)$_{t-3}$	0.011	0.139	0.128	0.010	-0.030	-0.028
	(0.004)	(0.048)	(0.045)	(0.004)	(0.066)	(0.062)
ln(R&D contracts)$_{t-3}\times$ [Chemicals = 1]	-0.004	-0.048	-0.040	-0.005	-0.048	-0.053
	(0.007)	(0.039)	(0.040)	(0.006)	(0.058)	(0.058)
ln(R&D contracts)$_{t-3}\times$ [Electronics = 1]	0.001	-0.103	-0.093	0.002	0.026	0.026
	(0.005)	(0.053)	(0.051)	(0.006)	(0.077)	(0.073)
ln(R&D contracts)$_{t-3}\times$ [Instruments = 1]	0.005	-0.127	-0.117	0.007	0.024	0.023
	(0.006)	(0.056)	(0.054)	(0.007)	(0.072)	(0.069)
ln(R&D contracts)$_{t-3}\times$ [Business services = 1]	-0.000	-0.133	-0.124	0.011	-0.081	-0.085
	(0.009)	(0.059)	(0.058)	(0.012)	(0.088)	(0.086)
ln(R&D stock)$_{t-3}$	0.131	0.114	0.114	0.252	0.241	0.241
	(0.011)	(0.011)	(0.011)	(0.015)	(0.015)	(0.015)
Sample years	1980-2015	1980-2015	1980-2015	1980-2015	1980-2015	1980-2015
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Weak identif. (Kleibergen-Paap)		3.68	3.97		3.68	3.97
Firms	3,631	3,584	3,587	3,631	3,584	3,587
Observations	43,883	41,093	41,130	43,883	41,093	41,130
Adjusted R-squared	0.873	-0.091	-0.074	0.847	0.033	0.031

Notes: This table presents the estimation results for the relationship of R&D contracts with publications and patents by main industry. The excluded industry indicator variable is *Other*. Standard errors (in parentheses) are clustered at the firm level.

Appendix H Agency Variation

Federal agencies are heterogeneous in the size and composition of their procurement contracts (Table H18), their propensity to offer noncompetitive production contracts (Figure H4), as well as the characteristics of their contractors (Table H19). Tables H20 and H21 further show that the dollar values of R&D contracts from DoD, NASA, and DoT are positively correlated (p-value $<$ 0.001). Defense R&D contractors tend to also work for NASA, as shown in Table H22. In general, if a firm is an R&D contractor for a non-DoD agency, it is also a DoD R&D contractor.

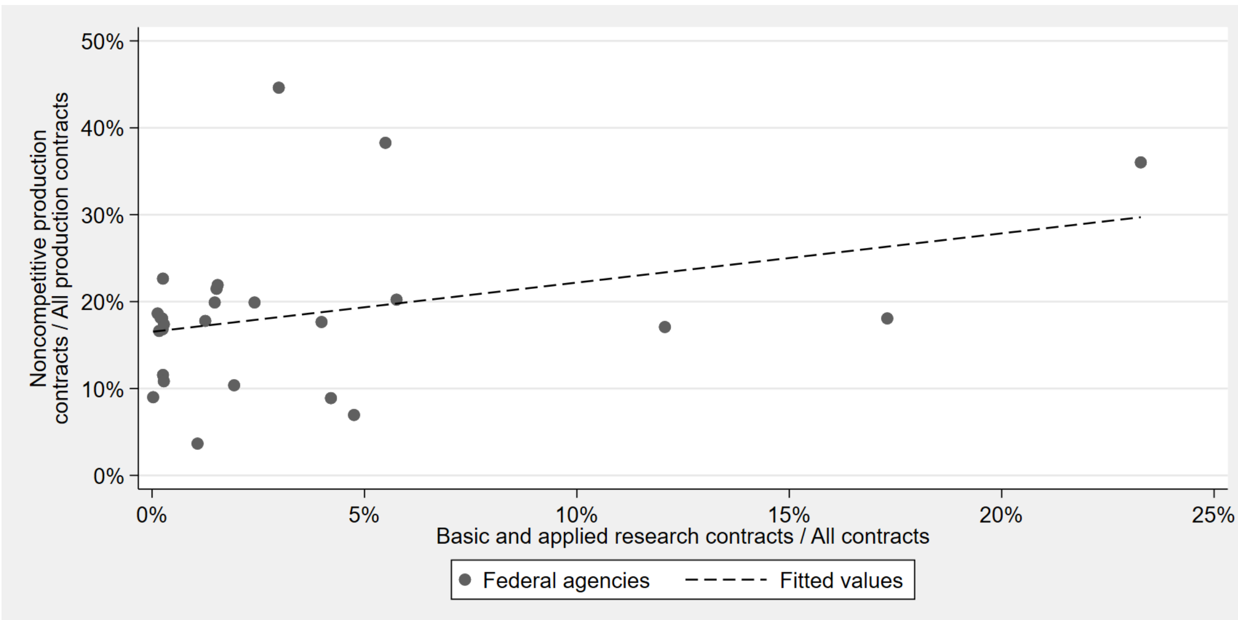

Figure H4: Upstream R&D and Noncompetitive Production Contracts

This figure presents the relationship between upstream R&D and noncompetitive production at the level of agencies that awarded $100+ million in R&D contracts during 1980-2020.

Table H18: Contract Descriptive Statistics by Awarding Agency

	(1)	(2)	(3)	(4)	(5)	(6)
				Distribution		
	No. of contracts	Mean	Std. dev.	10th	50th	90th
DoD						
All contracts ($ mm)	3,634,276	0.9	43.3	0.0	0.0	0.4
R&D contracts ($ mm)	105,561	5.4	148.5	0.1	0.4	4.5
Production contracts ($ mm)	3,380,723	0.8	36.3	0.0	0.0	0.3
Noncompetitive production contracts ($ mm)	1,042,751	1.8	54.0	0.0	0.0	0.7
NASA						
All contracts ($ mm)	55,368	3.9	158.5	0.0	0.1	1.0
R&D contracts ($ mm)	13,151	7.9	227.1	0.0	0.3	3.7
Production contracts ($ mm)	36,908	3.1	138.8	0.0	0.0	0.5
Noncompetitive production contracts ($ mm)	11,061	6.0	244.0	0.0	0.0	0.4
DoT						
All contracts ($ mm)	18,416	1.7	30.6	0.0	0.1	1.0
R&D contracts ($ mm)	1,006	6.9	88.1	0.0	0.1	1.8
Production contracts ($ mm)	16,261	1.6	24.0	0.0	0.1	1.1
Noncompetitive production contracts ($ mm)	5,077	0.7	7.0	0.0	0.1	0.6
HHS						
All contracts ($ mm)	91,355	0.6	19.6	0.0	0.0	0.1
R&D contracts ($ mm)	1,450	2.4	13.0	0.0	0.1	2.2
Production contracts ($ mm)	85,923	0.6	20.1	0.0	0.0	0.1
Noncompetitive production contracts ($ mm)	27,241	0.3	10.3	0.0	0.0	0.1
DoE						
All contracts ($ mm)	11,718	12.7	504.7	0.0	0.0	0.9
R&D contracts ($ mm)	1,169	2.9	16.0	0.0	0.4	4.3
Production contracts ($ mm)	9,520	15.5	559.7	0.0	0.0	0.7
Noncompetitive production contracts ($ mm)	2,247	17.0	205.2	0.0	0.0	1.0
DHS						
All contracts ($ mm)	49,443	0.7	14.1	0.0	0.0	0.4
R&D contracts ($ mm)	627	3.8	34.9	0.0	0.1	3.1
Production contracts ($ mm)	46,301	0.7	14.0	0.0	0.0	0.4
Noncompetitive production contracts ($ mm)	17,293	0.5	15.5	0.0	0.0	0.3
DoC						
All contracts ($ mm)	30,539	0.4	10.3	0.0	0.0	0.2
R&D contracts ($ mm)	197	5.6	69.9	0.0	0.1	0.9
Production contracts ($ mm)	28,722	0.4	8.9	0.0	0.0	0.2
Noncompetitive production contracts ($ mm)	7,445	0.1	0.8	0.0	0.0	0.1
Other						
All contracts ($ mm)	3,241,411	0.2	37.1	0.0	0.0	0.1
R&D contracts ($ mm)	21,532	5.7	178.9	0.0	0.2	2.8
Production contracts ($ mm)	3,060,248	0.2	35.1	0.0	0.0	0.1
Noncompetitive production contracts ($ mm)	692,341	0.2	33.2	0.0	0.0	0.0

Notes: This table displays contract-level descriptive statistics over the sample period of 1980-2015 by awarding agency. The unit of analysis is a contract.

Table H19: R&D Contractor Descriptive Statistics by Awarding Agency

	(1) DoD	(2)	(3) NASA	(4)	(5) DoT	(6)	(7) HHS	(8)
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
R&D expenditures ($ mm)	282	949	431	1,238	825	1,724	483	1,219
Publications	33	139	54	176	84	238	82	240
Patents	64	253	105	365	187	517	102	378
All contracts ($ mm)	267	1,881	677	3,049	1,412	4,402	727	3,344
R&D contracts ($ mm)	45	434	121	711	257	1,038	125	772
Production contracts ($ mm)	221	1,505	555	2,430	1,155	3,498	602	2,668
Commercial contracts ($ mm)	26	160	53	186	111	262	71	280
Noncommercial contracts ($ mm)	219	1,649	586	2,741	1,229	3,937	595	2,837
All grants ($ mm)	1	12	2	9	3	12	2	8
Sales ($ mm)	5,818	18,192	9,527	25,967	18,171	36,339	9,165	21,700
R&D stock ($ mm)	1,195	4,413	1,983	6,218	3,611	8,564	2,055	5,674

Notes: This table displays contractor descriptive statistics over the sample period of 1980-2015 by awarding agency. The unit of analysis is a firm-year. Statistics are only provided for R&D contractors. Grants and commercial contracts are only summarized for the years 2001-2015 and 1994-2015, respectively.

Table H19: R&D Contractor Descriptive Statistics by Awarding Agency (Continued)

	(9) DoE	(10)	(11) DHS	(12)	(13) DoC	(14)	(15) Other	(16)
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
R&D expenditures ($ mm)	614	1,546	609	1,329	668	1,266	435	1,198
Publications	69	181	80	246	108	280	51	167
Patents	109	219	177	534	200	563	98	322
All contracts ($ mm)	1,392	4,453	1,423	4,561	1,693	5,047	463	2,509
R&D contracts ($ mm)	261	1,048	244	1,063	307	1,185	79	580
Production contracts ($ mm)	1,131	3,540	1,179	3,631	1,386	4,016	384	2,004
Commercial contracts ($ mm)	103	263	125	356	120	288	49	218
Noncommercial contracts ($ mm)	1,347	4,182	1,191	3,893	1,414	4,424	377	2,187
All grants ($ mm)	5	29	3	11	4	13	2	14
Sales ($ mm)	15,824	33,920	16,088	31,201	13,911	25,057	10,888	30,211
R&D stock ($ mm)	2,799	7,827	2,583	6,210	2,962	6,125	1,838	5,660

Notes: This table displays contractor descriptive statistics over the sample period of 1980-2015 by awarding agency. The unit of analysis is a firm-year. Statistics are only provided for R&D contractors. Grants and commercial contracts are only summarized for the years 2001-2015 and 1994-2015, respectively.

Table H20: Correlations for R&D Contracts Received from Various Agencies

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
(1) DoD R&D contracts	1.00							
(2) NASA R&D contracts	0.26***	1.00						
(3) DoT R&D contracts	0.56***	0.22***	1.00					
(4) HHS R&D contracts	0.07***	0.02***	0.02***	1.00				
(5) DoE R&D contracts	0.30***	0.10***	0.16***	0.01**	1.00			
(6) DHS R&D contracts	0.12***	0.04***	0.01**	0.00	0.00	1.00		
(7) DoC R&D contracts	0.29***	0.12***	0.50***	0.01**	0.07***	0.01*	1.00	
(8) Other R&D contracts	0.25***	0.06***	0.09***	0.03***	0.10***	0.01**	0.02***	1.00

Notes: This table displays pairwise Pearson correlations for R&D contracts received from various agencies. * $p < 0.05$ ** $p < 0.01$ *** $p < 0.001$

Table H21: Correlations for Normalized R&D Contracts Received from Various Agencies

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
(1) DoD R&D contracts	1.00							
(2) NASA R&D contracts	0.05***	1.00						
(3) DoT R&D contracts	0.02***	0.06***	1.00					
(4) HHS R&D contracts	-0.00	-0.00	-0.00	1.00				
(5) DoE R&D contracts	0.00	0.03***	-0.00	-0.00	1.00			
(6) DHS R&D contracts	0.00	-0.00	0.00	-0.00	-0.00	1.00		
(7) DoC R&D contracts	0.03***	0.25***	0.00	-0.00	-0.00	-0.00	1.00	
(8) Other R&D contracts	0.04***	0.01	0.01	-0.00	0.00	0.07***	0.00	1.00

Notes: This table displays pairwise correlations for R&D contracts received from various agencies. To avoid spurious correlations due to firm size, R&D contract values have been normalized by sales. * $p < 0.05$ ** $p < 0.01$ *** $p < 0.001$

Table H22: R&D Contractors by Awarding Agency

Awarding agency	R&D contractors	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
(1) DoD	753	753 (100%)	214 (28%)	91 (12%)	105 (14%)	80 (11%)	77 (10%)	64 (8%)	239 (32%)
(2) NASA	243	214 (88%)	243 (100%)	61 (25%)	53 (22%)	58 (24%)	48 (20%)	43 (18%)	112 (46%)
(3) DoT	99	91 (92%)	61 (62%)	99 (100%)	36 (36%)	37 (37%)	36 (36%)	30 (30%)	66 (67%)
(4) HHS	204	105 (51%)	53 (26%)	36 (18%)	204 (100%)	30 (15%)	47 (23%)	35 (17%)	110 (54%)
(5) DoE	95	80 (84%)	58 (61%)	37 (39%)	30 (32%)	95 (100%)	23 (24%)	25 (26%)	64 (67%)
(6) DHS	90	77 (86%)	48 (53%)	36 (40%)	47 (52%)	23 (26%)	90 (100%)	26 (29%)	65 (72%)
(7) DoC	69	64 (93%)	43 (62%)	30 (43%)	35 (51%)	25 (36%)	26 (38%)	69 (100%)	51 (74%)
(8) Other	367	239 (65%)	112 (31%)	66 (18%)	110 (30%)	64 (17%)	65 (18%)	51 (14%)	367 (100%)

Notes: This table displays frequency counts and percentages of R&D contractors by awarding agency.

One concern may be that a single agency could drive our results. For example, the DoD accounts for 69% of all procurement contracts awarded between 1980 and 2015. Moreover, the DoD may impose secrecy requirements that could affect patenting behavior, as well as undermine our identification strategy that treats the end of the Cold War as an exogenous shock to sample firms. As shown in Tables H23, H24, and H25, our results are not driven solely by DoD R&D contracts. Our results are also robust to excluding each of the other main agencies.

Our conceptual framework predicts that the crowding-in effect should be stronger when R&D projects are more upstream (resulting in more publications) and involve larger firms (which are more likely to be vertically integrated). As shown in Table H18, R&D contractors for the DoD have the smallest average annual sales in our sample. Therefore, we expect the crowding-in effect to be larger when R&D contracts from the DoD are excluded from analyses. Indeed, the coefficient estimates on *Non-DoD R&D contracts* are significantly larger in both the R&D expenditures equation and the publications equation.

Table H23: R&D Expenditures Equation Excluding Agencies

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	ln(R&D expenditures)$_t$								
	Top 7 Agencies	Other Agencies	Excl. DoD	Excl. NASA	Excl. DoT	Excl. HHS	Excl. DoE	Excl. DHS	Excl. DoC
ln(Top 7 R&D contracts)$_{t-1}$	0.066 (0.025)								
ln(Other R&D contracts)$_{t-1}$		0.429 (0.170)							
ln(Non-DoD R&D contracts)$_{t-1}$			0.182 (0.074)						
ln(Non-NASA R&D contracts)$_{t-1}$				0.066 (0.025)					
ln(Non-DoT R&D contracts)$_{t-1}$					0.062 (0.024)				
ln(Non-HHS R&D contracts)$_{t-1}$						0.070 (0.025)			
ln(Non-DoE R&D contracts)$_{t-1}$							0.063 (0.024)		
ln(Non-DHS R&D contracts)$_{t-1}$								0.062 (0.024)	
ln(Non-DoC R&D contracts)$_{t-1}$									0.062 (0.024)
ln(Sales)$_{t-2}$	0.350 (0.016)	0.353 (0.017)	0.347 (0.017)	0.350 (0.016)	0.350 (0.016)	0.350 (0.016)	0.351 (0.016)	0.350 (0.016)	0.350 (0.016)
Sample years	1980-2015	1980-2015	1980-2015	1980-2015	1980-2015	1980-2015	1980-2015	1980-2015	1980-2015
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Weak identif. (Kleibergen-Paap)	92.40	26.28	40.62	96.22	100.42	93.94	99.76	99.92	99.84
Firms	3,771	3,778	3,775	3,773	3,771	3,772	3,771	3,771	3,771
Observations	40,484	40,725	40,573	40,508	40,477	40,496	40,488	40,477	40,473
Adjusted R-squared	0.116	-0.313	-0.031	0.115	0.118	0.111	0.117	0.118	0.118

Notes: This table presents the robustness of estimation results for the effect of R&D contracts on company-funded R&D expenditures to including or excluding contracts from certain agencies. Columns 1-9 present the second stage of 2SLS, where *R&D contracts* are instrumented using *Industry R&D funding*. Standard errors (in parentheses) are clustered at the firm level.

Table H24: PUBLICATIONS EQUATION EXCLUDING AGENCIES

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	ln(Publications)$_t$								
	Top 7 Agencies	Other Agencies	Excl. DoD	Excl. NASA	Excl. DoT	Excl. HHS	Excl. DoE	Excl. DHS	Excl. DoC
ln(Top 7 R&D contracts)$_{t-3}$	0.035								
	(0.019)								
ln(Other R&D contracts)$_{t-3}$		0.296							
		(0.142)							
ln(Non-DoD R&D contracts)$_{t-3}$			0.104						
			(0.052)						
ln(Non-NASA R&D contracts)$_{t-3}$				0.037					
				(0.019)					
ln(Non-DoT R&D contracts)$_{t-3}$					0.035				
					(0.018)				
ln(Non-HHS R&D contracts)$_{t-3}$						0.037			
						(0.019)			
ln(Non-DoE R&D contracts)$_{t-3}$							0.035		
							(0.018)		
ln(Non-DHS R&D contracts)$_{t-3}$								0.034	
								(0.018)	
ln(Non-DoC R&D contracts)$_{t-3}$									0.034
									(0.018)
ln(R&D stock)$_{t-3}$	0.115	0.127	0.119	0.116	0.116	0.116	0.116	0.116	0.116
	(0.010)	(0.012)	(0.011)	(0.010)	(0.010)	(0.010)	(0.010)	(0.010)	(0.010)
Sample years	1980-2015	1980-2015	1980-2015	1980-2015	1980-2015	1980-2015	1980-2015	1980-2015	1980-2015
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Weak identif. (Kleibergen-Paap)	95.68	24.87	46.50	97.95	102.08	94.43	101.89	101.10	101.75
Firms	3,584	3,586	3,585	3,584	3,584	3,584	3,584	3,584	3,584
Observations	41,099	41,287	41,155	41,125	41,094	41,107	41,108	41,095	41,093
Adjusted R-squared	0.019	-0.387	-0.061	0.017	0.019	0.017	0.018	0.019	0.019

Notes: This table presents the robustness of estimation results for the effect of R&D contracts on corporate publications to including or excluding contracts from certain agencies. Columns 1-9 present the second stage of 2SLS, where *R&D contracts* are instrumented using *Industry R&D funding*. Standard errors (in parentheses) are clustered at the firm level.

Table H25: Patents Equation Excluding Agencies

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
					ln(Patents)$_t$				
	Top 7 Agencies	Other Agencies	Excl. DoD	Excl. NASA	Excl. DoT	Excl. HHS	Excl. DoE	Excl. DHS	Excl. DoC
ln(Top 7 R&D contracts)$_{t-3}$	-0.042								
	(0.024)								
ln(Other R&D contracts)$_{t-3}$		-0.282							
		(0.180)							
ln(Non-DoD R&D contracts)$_{t-3}$			-0.112						
			(0.068)						
ln(Non-NASA R&D contracts)$_{t-3}$				-0.042					
				(0.024)					
ln(Non-DoT R&D contracts)$_{t-3}$					-0.041				
					(0.023)				
ln(Non-HHS R&D contracts)$_{t-3}$						-0.042			
						(0.024)			
ln(Non-DoE R&D contracts)$_{t-3}$							-0.040		
							(0.023)		
ln(Non-DHS R&D contracts)$_{t-3}$								-0.041	
								(0.023)	
ln(Non-DoC R&D contracts)$_{t-3}$									-0.041
									(0.023)
ln(R&D stock)$_{t-3}$	0.242	0.232	0.239	0.242	0.242	0.241	0.241	0.242	0.242
	(0.015)	(0.017)	(0.015)	(0.015)	(0.015)	(0.015)	(0.015)	(0.015)	(0.015)
Sample years	1980-2015	1980-2015	1980-2015	1980-2015	1980-2015	1980-2015	1980-2015	1980-2015	1980-2015
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Weak identif. (Kleibergen-Paap)	95.68	24.87	46.50	97.95	102.08	94.43	101.89	101.10	101.75
Firms	3,584	3,586	3,585	3,584	3,584	3,584	3,584	3,584	3,584
Observations	41,099	41,287	41,155	41,125	41,094	41,107	41,108	41,095	41,093
Adjusted R-squared	0.046	-0.206	-0.024	0.043	0.045	0.044	0.046	0.045	0.045

Notes: This table presents the robustness of estimation results for the effect of R&D contracts on corporate patents to including or excluding contracts from certain agencies. Columns 1-9 present the second stage of 2SLS, where *R&D contracts* are instrumented using *Industry R&D funding*. Standard errors (in parentheses) are clustered at the firm level.

Appendix I Robustness Checks

I.1 Other Measures of Publication Quality

Table I26 reports results for the effect of R&D contracts on corporate publications authored by renowned scientists from the AMWS directory (whether employed by the firm or not, Columns 1 and 2) and corporate publications cited by renowned scientists from the AMWS directory (whether authored by AMWS scientists or not, Columns 3 and 4).

Table I26: Other Measures of Publication Quality

	(1)	(2)	(3)	(4)
	$\ln(\text{Publications with AMWS collab.})_t$		$\ln(\text{Publications cited by AMWS})_t$	
	IV: Industry R&D funding	IV: Windfall-predicted R&D budget	IV: Industry R&D funding	IV: Windfall-predicted R&D budget
$\ln(\text{R\&D contracts})_{t-3}$	0.035	0.033	0.059	0.056
	(0.010)	(0.010)	(0.017)	(0.016)
$\ln(\text{R\&D stock})_{t-3}$	0.030	0.030	0.052	0.052
	(0.007)	(0.007)	(0.010)	(0.010)
Sample years	1980-2015	1980-2015	1980-2015	1980-2015
Firm fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Weak identif. (Kleibergen-Paap)	102.24	104.04	102.24	104.04
Firms	3,584	3,587	3,584	3,587
Observations	41,093	41,130	41,093	41,130
Adjusted R-squared	-0.058	-0.052	-0.071	-0.063

Notes: This table presents 2SLS estimation results for the effect of R&D contracts on high-quality corporate publications. *R&D contracts* are instrumented using *Industry R&D funding* or *Windfall-predicted R&D budget*, as noted. Standard errors (in parentheses) are clustered at the firm level.

I.2 Other Procurement Shocks

Table I27 presents the robustness of the estimation results for the effect of R&D contracts on publications using three alternative procurement shocks. We exploit the *Cold War shock* as a quasi-natural experiment for exogenous changes in government procurement from various industries. In the first stage reported in Column 1, we predict *R&D contracts* awarded to a focal firm using our instrument and obtain an F statistic of 103. In the second stage reported in Column 4, we regress *Publications* against the predicted R&D contracts. Because this instrument does not vary over time, we report pooled estimates and rely on pre-sample information regarding R&D expenditures to replace the unobservable firm fixed effect (similar to Blundell et al., 1999). The coefficient estimate indicates a positive causal effect of R&D contracts on corporate publications (p-value $<$ 0.01).

The estimate is substantially larger than the estimates from the other instrumental variables for three reasons. The set of firms differs across approaches.[32] Our other instruments may not

[32] The analysis sample in Column 4 is restricted to firms for which we can calculate pre-sample mean publications during 1980-1988 and exposure to sales from various industries during 1982-1985. The actual regressions use data for 1995-2015. The range in coefficient estimates likely reflects the changing composition of our sample over a very long panel, with Cold War-era firms being more likely than newer firms to rely on (or respond to) guaranteed demand.

fully resolve the downward bias in OLS because they rely on time-invariant exposure shares that could still be correlated with firm-specific, time-invariant heterogeneity. Alternatively, the Cold War instrument may not fully remove time-invariant firm heterogeneity using the pre-sample mean, making it even more sensitive to the temporal reallocation of contracts away from innovating firms.

Another way to mitigate the concern that the Cold War shock could suffer from endogeneity—if strategic defense investments such as the Star Wars program led to the collapse of the Soviet Union—is to examine two alternative shocks. First, we use changes in procurement that were triggered by the terrorist attacks of September 11, 2001. Government procurement contracts were reallocated to support Operation Iraqi Freedom, Operation Enduring Freedom, and other military campaigns that were part of the new Global War on Terrorism. Second, we use changes in procurement that resulted from federal efforts to manage the financial crisis during the Great Recession of 2007-2008. Government procurement contracts were reallocated to support the hard-hit auto and aircraft industries. Table I27 shows that the effect of *R&D contracts* on publications is robust to instrumenting for the endogenous R&D contracts using either the *Global War on Terrorism shock* or the *Financial Crisis shock*.[33]

Table I27: Other Procurement Shocks

	(1)	(2)	(3)	(4)	(5)	(6)
	$\ln(\text{R\&D contracts})_t$			$\ln(\text{Publications})_t$		
	OLS	OLS	OLS	IV: Cold War shock	IV: Global War on Terrorism shock	IV: Financial Crisis shock
$\ln(\text{R\&D contracts})_{t-3}$				0.386	0.438	0.079
				(0.198)	(0.131)	(0.044)
ln(Cold War shock)	0.015					
	(0.007)					
ln(Global War on Terrorism shock)		0.040				
		(0.012)				
ln(Financial Crisis shock)			0.077			
			(0.015)			
ln(Pre-sample mean publications)	1.038	2.060	2.119	0.568	0.036	0.727
	(0.061)	(0.096)	(0.123)	(0.208)	(0.273)	(0.098)
Sample years	2007-2015	2007-2015	2011-2015	1995-2015	2007-2015	2011-2015
Firm fixed effects	No	No	No	No	No	No
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Weak identif. (Kleibergen-Paap)				4.38	11.51	24.97
Observations	6,389	2,728	1,423	6,389	2,728	1,423
Adjusted R-squared	0.100	0.255	0.276	-0.301	-0.837	0.572

Notes: This table presents the robustness of estimation results for the effect of R&D contracts on publications to using alternative procurement shocks. The *Global War on Terrorism shock* is calculated using the difference in total contract values between pre- (2000) and post- (2004) periods for each SIC4 industry, weighted by the focal firm's sales exposure to different SIC4 industries during 1994-1997. The *Financial Crisis shock* is calculated using the difference in total contract values between pre- (2007) and post- (2008) periods for each SIC4 industry, weighted by the focal firm's sales exposure to different SIC4 industries during 2000-2003. The pre-sample mean publications are calculated using data from 1980-1988. Standard errors (in parentheses) are robust to arbitrary heteroskedasticity.

[33] Table I27 uses the pre-sample mean publications calculated for the original Cold War shock (i.e., during 1980-1988), but results hold for alternative pre-sample periods, such as 1980-1990 or 1980-1995.

I.3 Alternative Specifications

One concern may be that our choice of regression model (OLS) and data transformation (taking the natural logarithm of publications or patents plus one) could be inappropriate, given that *Publications* and *Patents* are over-dispersed count variables. Columns 1 and 4 in Table I28 present estimations using Poisson pseudo-maximum likelihood regressions. Consistent with our OLS results, we find that *R&D contracts* have positive relationships with publications and patents (p-value < 0.05). We also present OLS and 2SLS estimations where we use an inverse hyperbolic sine transformation.[34] Consistent with previous results, Columns 3 and 6 in Table I28 show that R&D contracts have a positive effect on publications (p-value $= 0.058$) but not on patents. Moreover, the coefficient estimate on *R&D contracts* for the publication equation is close in size to our main specification in Table 5.

Table I28: Alternative Specifications

	(1)	(2)	(3)	(4)	(5)	(6)
	Publications_t	Inv. hyperbolic sine$(\text{Publications})_t$		Patents_t	Inv. hyperbolic sine$(\text{Patents})_t$	
	Poisson	OLS	IV: Ind. R&D fund.	Poisson	OLS	IV: Ind. R&D fund.
$\ln(\text{R\&D contracts})_{t-3}$	0.012	0.013	0.041	0.014	0.014	-0.045
	(0.003)	(0.002)	(0.021)	(0.004)	(0.002)	(0.027)
$\ln(\text{R\&D stock})_{t-3}$	0.503	0.152	0.135	0.462	0.289	0.278
	(0.051)	(0.013)	(0.012)	(0.067)	(0.017)	(0.017)
Sample years	1980-2015	1980-2015	1980-2015	1980-2015	1980-2015	1980-2015
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Weak identif. (Kleibergen-Paap)			102.24			102.24
Firms	2,388	3,631	3,584	3,166	3,631	3,584
Observations	32,836	43,883	41,093	40,597	43,883	41,093
Adjusted R-squared		0.862	0.017		0.838	0.044

Notes: This table presents the robustness of estimation results for the relationship between R&D contracts and publications and patents to using Poisson pseudo-maximum likelihood regression (Columns 1 and 4) or transforming publications and patents using an inverse hyperbolic sine (Columns 2, 3, 5, and 6). Standard errors (in parentheses) are clustered at the firm level.

[34] The inverse hyperbolic sine is calculated as $asinh(x) = ln(x + \sqrt{x^2 + 1})$.

I.4 Other Time Lags

Our results are not sensitive to the specific lag structure assumed in our main specifications. Checking the sensitivity to the lag structure is important because we do not observe the actual annual spending associated with contract awards. To construct our panel, we aggregate contract *obligations*—not actual *outlays*—at the firm-year level. Since multi-year procurement projects are common, the outlays may occur one, two, or more years after the original obligation date. Table I29 indicates that R&D contracts have a positive effect on corporate R&D expenditures when using two- or three-year lags. Similarly, Table I31 indicates that R&D contracts have a positive effect on renowned scientists when using two-year lags. As expected, the effects attenuate over time.

Moreover, there is typically a lag between the year when the R&D activity is conducted and the year when the paper is published or the patent is granted. Therefore, the specific lag structure between receiving an award and publishing a scholarly paper or receiving a patent grant is unclear. Table I30 indicates that R&D contracts have a positive effect on publications when using four- or five-year lags. Conversely, we find no effect of R&D contracts on patents when using four- or five-year lags, as shown in Table I32.

In general, the coefficient estimates are similar to Tables 4-7, indicating that our results are robust to using other time lags.

Table I29: R&D Expenditures Equation Using Different Time Lags

	(1)	(2)	(3)	(4)	(5)
	ln(R&D expenditures)$_t$				
	IV: Ind. R&D fund. (Lag = 1)	IV: Ind. R&D fund. (Lag = 2)	IV: Ind. R&D fund. (Lag = 3)	IV: Ind. R&D fund. (Lag = 4)	IV: Ind. R&D fund. (Lag = 5)
ln(R&D contracts)$_{t-lag}$	0.062	0.064	0.051	0.041	0.035
	(0.024)	(0.025)	(0.025)	(0.025)	(0.024)
ln(Sales)$_{t-lag-1}$	0.350	0.307	0.271	0.237	0.208
	(0.016)	(0.017)	(0.017)	(0.018)	(0.018)
Sample years	1980-2015	1980-2015	1980-2015	1980-2015	1980-2015
Firm fixed effects	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes
Weak identif. (Kleibergen-Paap)	100.29	97.68	92.71	85.42	81.77
Firms	3,771	3,422	3,131	2,840	2,618
Observations	40,473	36,756	33,438	30,394	27,689
Adjusted R-squared	0.118	0.082	0.068	0.057	0.043

Notes: This table presents the robustness of estimation results for the relationship between R&D contracts and R&D expenditures using alternative time lags. Standard errors (in parentheses) are clustered at the firm level.

I.5 Related and Unrelated Research Areas

A concern may be that R&D contracts could crowd out unrelated research areas. For example, firms may respond to government R&D competitions by reducing their R&D activities in research areas that do not benefit directly from government spending. To test this possibility, we split the flow of corporate publications into related publications (i.e., those that acknowledge external support) and unrelated publications (i.e., those that do not). Similarly, we split the flow of corporate patents into those that self-cite at least one of the focal firms' related publications and those that do not. As shown in Table I33, we do not find evidence to suggest that R&D contracts crowd out unrelated research areas (although we cannot rule it out due to imprecise estimation results).

Table I30: Publications Equation Using Different Time Lags

	(1)	(2)	(3)	(4)	(5)
	ln(Publications)$_t$				
	IV: Ind. R&D fund. (Lag = 1)	IV: Ind. R&D fund. (Lag = 2)	IV: Ind. R&D fund. (Lag = 3)	IV: Ind. R&D fund. (Lag = 4)	IV: Ind. R&D fund. (Lag = 5)
ln(R&D contracts)$_{t-lag}$	0.014	0.022	0.034	0.046	0.043
	(0.017)	(0.018)	(0.018)	(0.019)	(0.018)
ln(R&D stock)$_{t-lag}$	0.151	0.136	0.116	0.102	0.088
	(0.010)	(0.010)	(0.010)	(0.011)	(0.011)
Sample years	1980-2015	1980-2015	1980-2015	1980-2015	1980-2015
Firm fixed effects	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes
Weak identif. (Kleibergen-Paap)	110.87	107.32	102.24	94.52	93.00
Firms	4,317	3,917	3,584	3,282	3,008
Observations	49,702	45,157	41,093	37,382	33,992
Adjusted R-squared	0.049	0.039	0.019	0.002	0.001

Notes: This table presents the robustness of estimation results for the relationship between R&D contracts and publications using alternative time lags. Standard errors (in parentheses) are clustered at the firm level.

Table I31: Renowned Scientists Equation Using Different Time Lags

	(1)	(2)	(3)	(4)	(5)
	ln(Renowned scientists)$_t$				
	IV: Ind. R&D fund. (Lag = 1)	IV: Ind. R&D fund. (Lag = 2)	IV: Ind. R&D fund. (Lag = 3)	IV: Ind. R&D fund. (Lag = 4)	IV: Ind. R&D fund. (Lag = 5)
ln(R&D contracts)$_{t-lag}$	0.025	0.020	0.011	0.004	0.040
	(0.009)	(0.009)	(0.008)	(0.009)	(0.025)
ln(R&D stock)$_{t-lag}$	0.040	0.034	0.032	0.026	0.191
	(0.006)	(0.006)	(0.004)	(0.006)	(0.020)
Sample years	1980-2015	1980-2015	1980-2015	1980-2015	1980-2015
Firm fixed effects	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes
Weak identif. (Kleibergen-Paap)	110.87	107.32	106.36	94.52	84.44
Firms	4,317	3,917	3,678	3,282	2,806
Observations	49,702	45,157	42,470	37,382	30,422
Adjusted R-squared	-0.012	-0.006	0.007	0.005	0.017

Notes: This table presents the robustness of estimation results for the relationship between R&D contracts and renowned scientific human capital using alternative time lags. Standard errors (in parentheses) are clustered at the firm level.

Table I32: Patents Equation Using Different Time Lags

	(1)	(2)	(3)	(4)	(5)
			ln(Patents)$_t$		
	IV: Ind. R&D fund. (Lag = 1)	IV: Ind. R&D fund. (Lag = 2)	IV: Ind. R&D fund. (Lag = 3)	IV: Ind. R&D fund. (Lag = 4)	IV: Ind. R&D fund. (Lag = 5)
ln(R&D contracts)$_{t-lag}$	-0.059	-0.055	-0.040	-0.013	0.011
	(0.023)	(0.023)	(0.023)	(0.024)	(0.024)
ln(R&D stock)$_{t-lag}$	0.286	0.267	0.242	0.214	0.189
	(0.015)	(0.015)	(0.015)	(0.015)	(0.015)
Sample years	1980-2015	1980-2015	1980-2015	1980-2015	1980-2015
Firm fixed effects	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes
Weak identif. (Kleibergen-Paap)	110.87	107.32	102.24	94.52	93.00
Firms	4,317	3,917	3,584	3,282	3,008
Observations	49,702	45,157	41,093	37,382	33,992
Adjusted R-squared	0.055	0.042	0.045	0.051	0.044

Notes: This table presents the robustness of estimation results for the relationship between R&D contracts and patents using alternative time lags. Standard errors (in parentheses) are clustered at the firm level.

Table I33: Unrelated Research Areas

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	ln(Related publications)$_t$		ln(Unrelated publications)$_t$		ln(Related patents)$_t$		ln(Unrelated patents)$_t$	
	OLS	IV: Ind. R&D fund.	OLS	IV: Ind. R&D fund.	OLS	IV: Ind. R&D fund.	OLS	IV: Ind. R&D fund.
ln(R&D contracts)$_{t-3}$	0.006	0.010	0.011	0.031	0.001	-0.001	0.012	-0.041
	(0.002)	(0.009)	(0.002)	(0.018)	(0.001)	(0.002)	(0.002)	(0.023)
ln(R&D stock)$_{t-3}$	0.037	0.029	0.129	0.114	0.009	0.006	0.251	0.240
	(0.008)	(0.007)	(0.011)	(0.010)	(0.005)	(0.004)	(0.015)	(0.015)
Sample years	1980-2015	1980-2015	1980-2015	1980-2015	1980-2015	1980-2015	1980-2015	1980-2015
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Weak identif. (Kleibergen-Paap)		102.24		102.24		102.24		102.24
Firms	3,631	3,584	3,631	3,584	3,631	3,584	3,631	3,584
Observations	43,883	41,093	43,883	41,093	43,883	41,093	43,867	41,078
Adjusted R-squared	0.531	-0.001	0.872	0.021	0.318	0.000	0.847	0.044

Notes: This table presents the robustness of estimation results for the relationship of R&D contracts with publications and patents to considering related and unrelated research areas. *Related publications* acknowledge external support, while *Unrelated publications* do not. *Related patents* self-cite at least one of the focal firm's *Related publications*, while *Unrelated patents* do not. Standard errors (in parentheses) are clustered at the firm level.

I.6 Other Event Study Specifications

Figure I5 presents the event study around the end of the Cold War without additional controls for the level and percentage change in private demand.

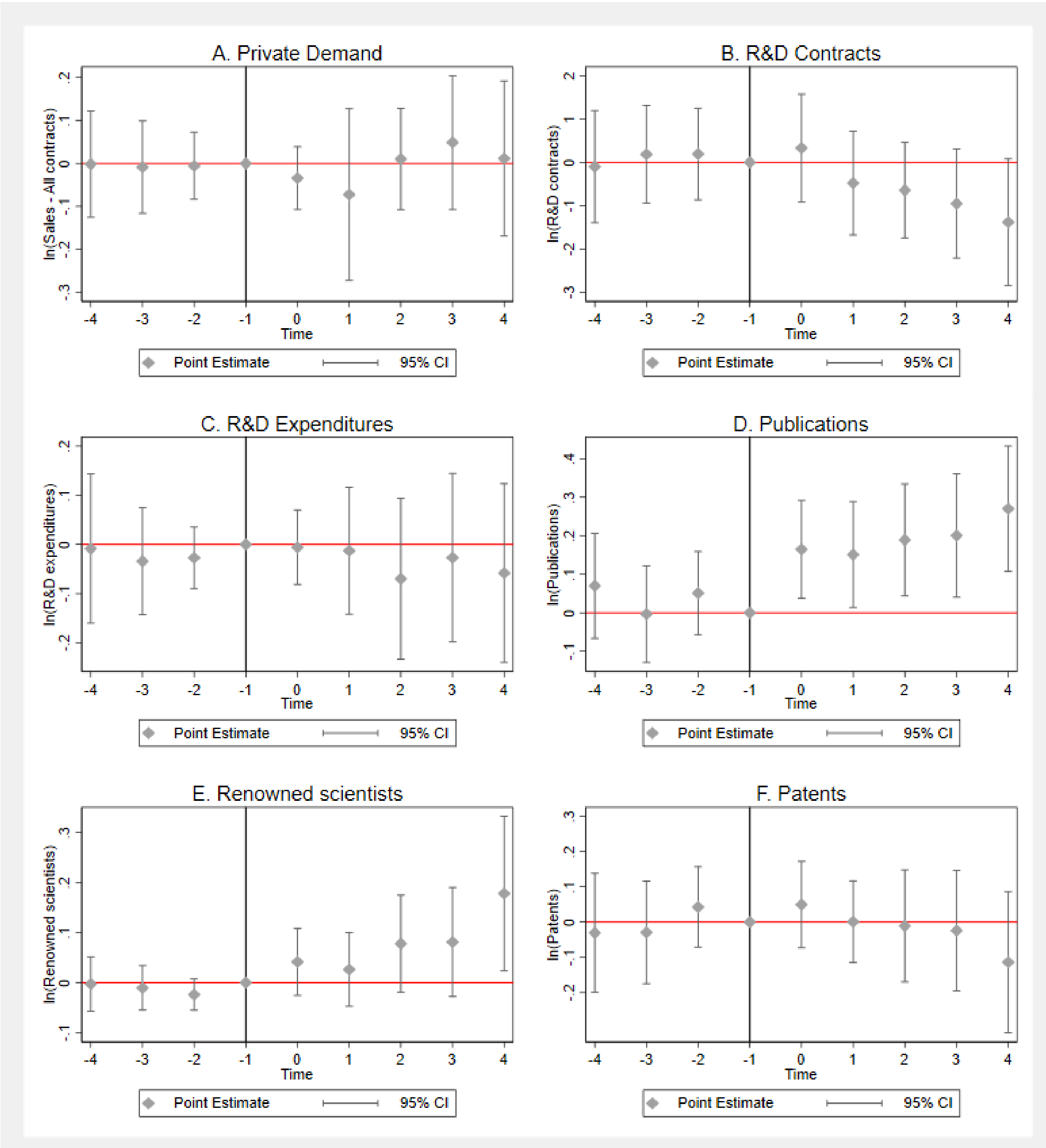

Figure I5: Event Study Without Additional Controls

This figure presents an event study around the end of the Cold War, estimated without using additional controls. All specifications use firm fixed effects and year fixed effects. All specifications are estimated using firms that have data for the entire 9-year period to control for changes in the composition of industries over time. Standard errors are clustered at the firm level.

Figure I6 reproduces the specifications from Figure 3 on a sample of 260 firms in ten SIC3 industries that received a top 20% increase in R&D contracts yet experienced a bottom 20% change in total demand.

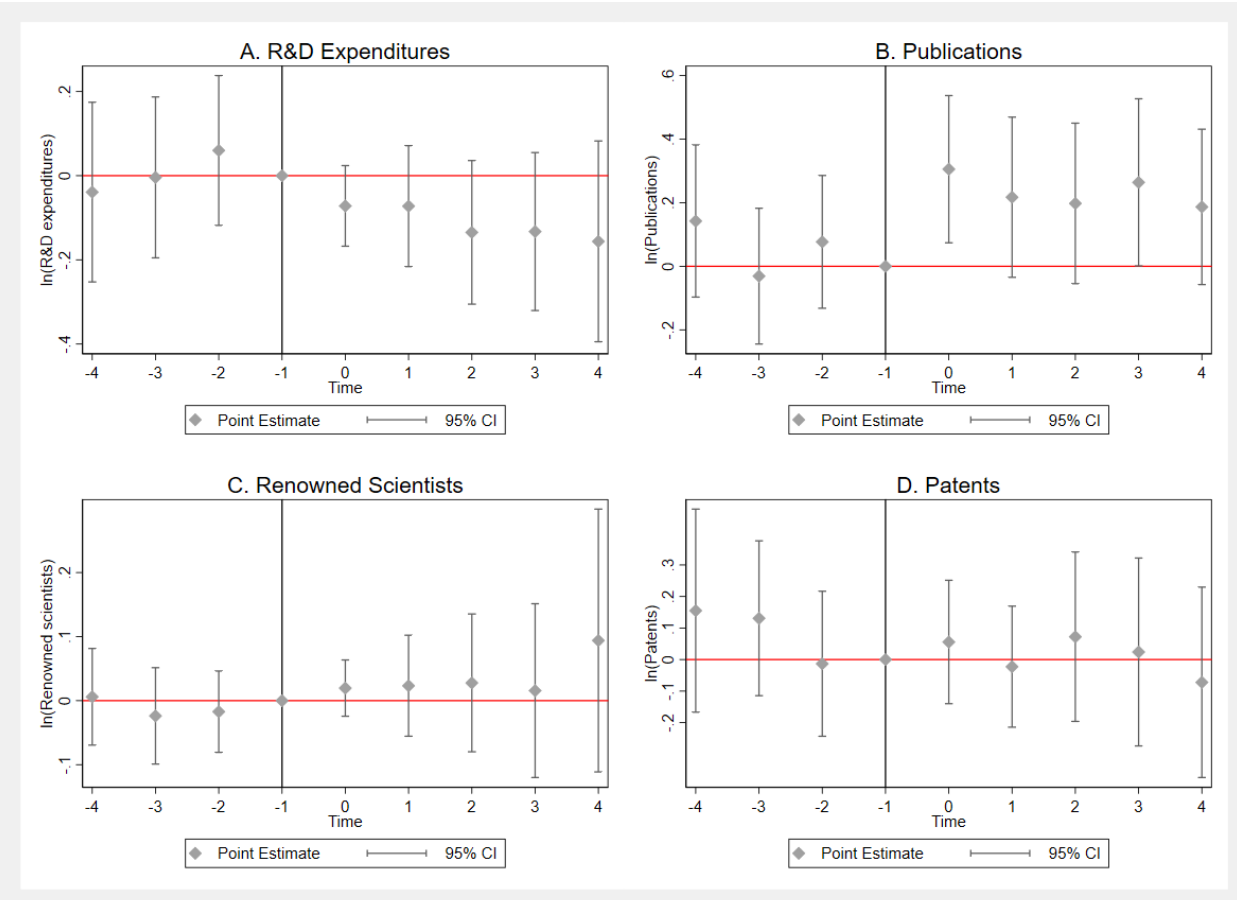

Figure I6: Event Study With a Different Sample

This figure presents an event study around the end of the Cold War, estimated using a sample of firms in SIC3 industries that received a top 20% increase in R&D contracts yet experienced a bottom 20% change in total demand. All specifications use firm fixed effects and year fixed effects. All specifications are estimated using firms that have data for the entire 9-year period to control for changes in the composition of industries over time. Standard errors are clustered at the firm level.

Figure I7 presents a staggered event study using never-treated firms as the comparison group. The point estimates aggregate the group time average treatment effects by the length of exposure to the R&D contracts shock. They are estimated using the doubly robust difference-in-differences estimator from the *csdid* package.

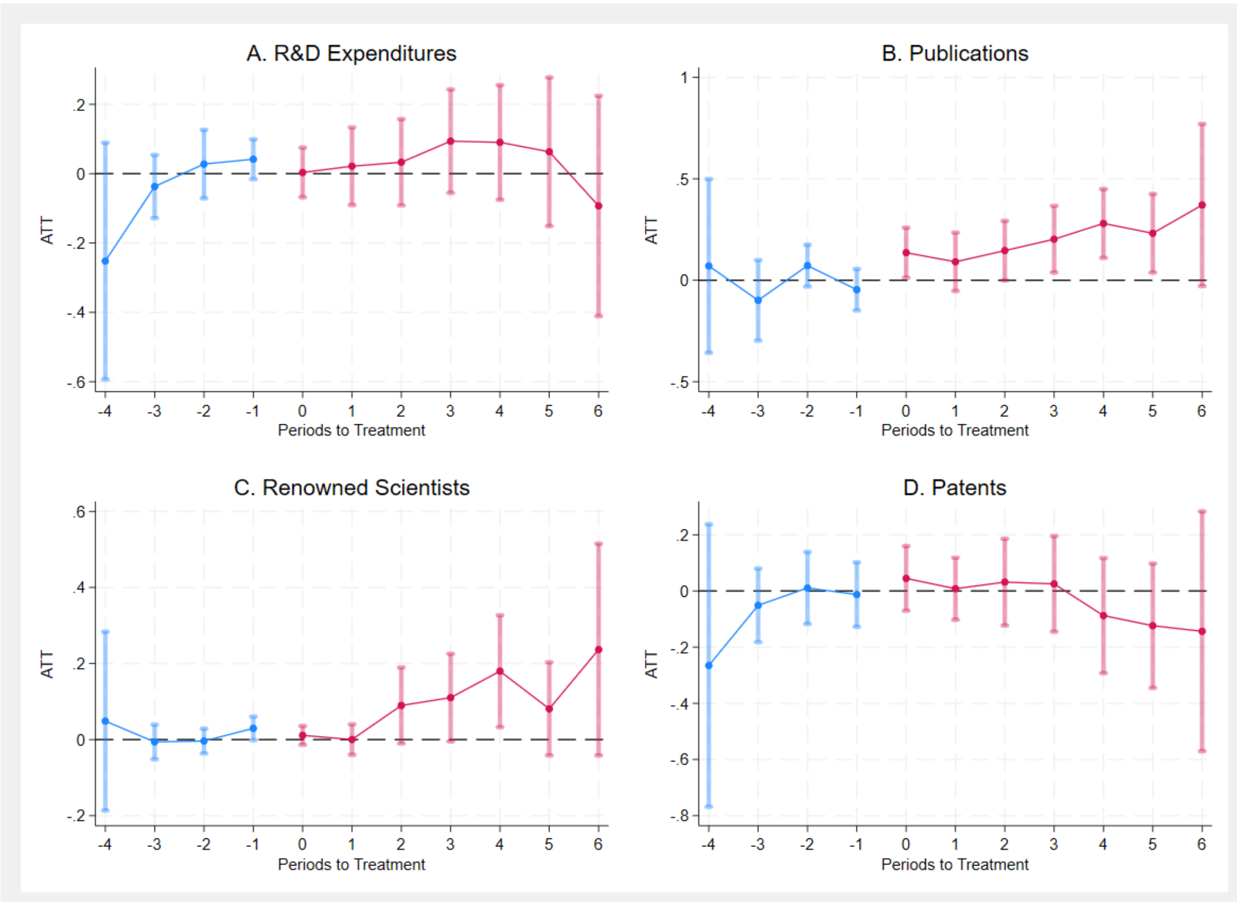

Figure I7: Staggered Event Study Using Never Treated Firms as the Comparison Group

This figure presents a staggered event study around the end of the Cold War, estimated using the doubly robust difference-in-differences estimator from the *csdid* package. All specifications use controls for the level and percentage change in private demand (i.e., firm sales net of all government procurement contracts). All specifications are estimated using firms that have data for the entire 1988-1997 period to control for changes in the composition of industries over time. Standard errors are estimated using a multiplicative WildBootstrap procedure.

I.7 Other Evidence of Guaranteed Demand

Table I34 examines how the effect of R&D contracts on upstream corporate R&D varies with the awarding subagency's ability to guarantee demand. In unreported specifications, we find similar results to Columns 1-4 when we instrument for the endogenous R&D contracts using the *Industry R&D funding* or the *Agency R&D budget* instruments.

Table I34: Variation by Agency Guaranteed Demand

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	ln(Publications)$_t$						
	IV: Windfall-predicted R&D budget	IV: Windfall-predicted R&D budget	IV: Windfall-predicted R&D budget	IV: Windfall-predicted R&D budget	IVs: Windfall-predicted R&D budget; Agency R&D budget	IVs: Windfall-predicted R&D budget; Agency R&D budget	IVs: Windfall-predicted R&D budget; Agency R&D budget
ln(Air Force R&D contracts)$_{t-3}$	0.147				0.136		
	(0.070)				(0.070)		
ln(Navy R&D contracts)$_{t-3}$		0.101				0.101	
		(0.048)				(0.052)	
ln(Army R&D contracts)$_{t-3}$			0.097				0.098
			(0.049)				(0.054)
ln(DARPA R&D contracts)$_{t-3}$				0.974	0.061	0.004	-0.015
				(0.668)	(0.081)	(0.083)	(0.093)
ln(R&D stock)$_{t-3}$	0.117	0.114	0.115	0.135	0.118	0.114	0.115
	(0.011)	(0.011)	(0.011)	(0.019)	(0.011)	(0.011)	(0.011)
Sample years	1980-2015	1980-2015	1980-2015	1980-2015	1980-2015	1980-2015	1980-2015
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Weak identif. (Kleibergen-Paap)	30.79	36.89	38.76	4.11	12.65	8.47	6.66
Firms	3,589	3,589	3,587	3,589	3,588	3,588	3,586
Observations	41,320	41,328	41,278	41,352	41,300	41,308	41,259
Adjusted R-squared	-0.114	-0.040	-0.050	-3.006	-0.106	-0.040	-0.052

Notes: This table presents results from estimating how the effect of R&D contracts on publications varies by the awarding subagency's ability to guarantee demand. All specifications present the second stage of 2SLS, where R&D contracts from DoD subagencies are instrumented as noted. Standard errors (in parentheses) are clustered at the firm level.

Table I35 examines how the effect of R&D contracts on upstream R&D varies with private market incentives to invest in science. In all specifications, Industry R&D funding is used as an instrument for R&D contracts.

Table I36 examines how the odds of winning R&D contracts change over time based on firm size. *Large* is an indicator variable equal to 1 for firms with top quartile annual sales (relative to all firms in the same SIC4 industry over 1980-2015).

Table I35: Variation by Private Market Incentives to Invest in Upstream R&D

	(1)	(2)	(3)	(4)	(5)	(6)
	ln(Publications)$_t$					
	Internal use (IV: Ind. R&D fund.)	No internal use (IV: Ind. R&D fund.)	Low rival use (IV: Ind. R&D fund.)	High rival use (IV: Ind. R&D fund.)	High protection (IV: Ind. R&D fund.)	Low protection (IV: Ind. R&D fund.)
ln(R&D contracts)$_{t-3}$	-0.001	0.035	0.024	0.052	-0.000	0.033
	(0.008)	(0.018)	(0.017)	(0.018)	(0.007)	(0.018)
ln(R&D stock)$_{t-3}$	0.002	0.118	0.057	0.050	0.015	0.115
	(0.004)	(0.011)	(0.013)	(0.015)	(0.004)	(0.010)
ln(Internal use publications)$_t$			0.507	0.356		
			(0.036)	(0.048)		
Sample years	1980-2015	1980-2015	1980-2015	1980-2015	1980-2015	1980-2015
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	No	No	Yes	Yes
Weak identif. (Kleibergen-Paap)	102.24	102.24	32.73	32.73	102.24	102.24
Firms	3,584	3,584	632	632	3,584	3,584
Observations	41,093	41,093	4,358	4,358	41,093	41,093
Adjusted R-squared	-0.001	0.019	0.221	0.072	0.001	0.019

Notes: This table presents second-stage results from estimating how the effect of R&D contracts on publications varies by private market incentives to invest in science. In all specifications, *Industry R&D funding* is used as an instrument for *R&D contracts*. The sample for Columns 3 and 4 is restricted to firm-years with one or more publications cited by corporate patents. Standard errors (in parentheses) are clustered at the firm level.

Table I36: Change in Odds of Winning R&D Contracts Based on Firm Size

	(1)	(2)	(3)	(4)
	Has R&D contracts $= 1_t$			
	Baseline (OLS)	Add industry FE (OLS)	Baseline (Logit)	Add industry FE (Logit)
Large	0.161	0.163	1.219	1.554
	(0.009)	(0.023)	(0.060)	(0.170)
Large x Time trend	-0.020	-0.021	-0.073	-0.130
	(0.004)	(0.009)	(0.029)	(0.080)
Time trend	-0.007	-0.004	-0.097	-0.049
	(0.001)	(0.004)	(0.019)	(0.055)
Sample years	1980-2015	1980-2015	1980-2015	1980-2015
Firm fixed effects	No	No	No	No
Year fixed effects	No	No	No	No
Industry fixed effects	No	Yes	No	Yes
Firms		331		200
Observations	60,885	60,885	60,885	55,592
Adjusted R-squared	0.029	0.182		

Notes: This table presents results from estimating how the odds of winning R&D contracts change over time based on firm size. The dependent variable, *Has R&D contracts*, is an indicator variable equal to 1 if the firm won one or more R&D contracts in the focal year and zero otherwise. *Large* is an indicator variable equal to 1 for firms with top quartile annual sales (relative to all firms in the same SIC4 industry over 1980-2015). *Time trend* is the focal year minus 1980, presented in decennial units. Standard errors (in parentheses) are robust to arbitrary heteroskedasticity in Columns 1 and 3 and clustered at the industry level in Columns 2 and 4.

I.8 Nonlinear Time Effects

Table I37 presents the changing composition of government contracts while allowing for nonlinear time effects.

Table I37: Nonlinear Time Effects

	(1)	(2)	(3)	(4)	(5)
	Contract value			Contract composition	
	ln(All contracts)$_t$	ln(R&D contracts)$_t$	ln(Comm. contracts)$_t$	Share R&D/ All contracts$_t$	Share comm./ All contracts$_t$
Indicator for Decade = 1990s	-0.358	-0.211		0.002	
	(0.132)	(0.089)		(0.012)	
Indicator for Decade = 2000s	0.279	-0.122	1.999	-0.029	0.168
	(0.181)	(0.131)	(0.099)	(0.013)	(0.013)
Indicator for Decade = 2010s	0.103	-0.448	2.584	-0.041	0.398
	(0.215)	(0.150)	(0.136)	(0.014)	(0.024)
ln(R&D stock)$_{t-1}$	0.456	0.122	0.455	-0.007	-0.004
	(0.054)	(0.035)	(0.055)	(0.005)	(0.008)
Sample years	1980-2015	1980-2015	1995-2015	1980-2015	1995-2015
Firm fixed effects	Yes	Yes	Yes	Yes	Yes
Firms	4,366	4,368	3,657	2,127	1,705
Observations	52,762	52,842	36,819	22,612	15,346
Adjusted R-squared	0.741	0.659	0.710	0.263	0.153

Notes: This table presents OLS estimates for changes in procurement contract value and composition over time, accounting for nonlinear time effects. Standard errors (in parentheses) are clustered at the firm level.