



Federal Reserve
Bank of Dallas

The Returns to Government R&D: Evidence from U.S. Appropriations Shocks

Andrew J. Fieldhouse and Karel Mertens

Working Paper 2305

May 2023

Research Department

<https://doi.org/10.24149/wp2305>

Working papers from the Federal Reserve Bank of Dallas are preliminary drafts circulated for professional comment. The views in this paper are those of the authors and do not necessarily reflect the views of the Federal Reserve Bank of Dallas or the Federal Reserve System. Any errors or omissions are the responsibility of the authors.

The Returns to Government R&D: Evidence from U.S. Appropriations Shocks^{*}

Andrew J. Fieldhouse[†] and Karel Mertens[‡]

May 5, 2023

Abstract

We estimate the causal impact of government-funded R&D on business-sector productivity growth. Identification is based on a novel narrative classification of all significant postwar changes in appropriations for R&D funded by five major federal agencies. Using long-horizon local projections and the narrative measures, we find that an increase in appropriations for nondefense R&D leads to increases in various measures of innovative activity, and higher productivity in the long run. We structurally estimate the production function elasticity of nondefense government R&D capital using the SP-IV methodology of Lewis and Mertens (2023), and obtain implied returns of 150 to 300 percent over the postwar period. The estimates indicate that government-funded R&D accounts for about one quarter of business-sector TFP growth since WWII, and generally point to substantial underfunding of nondefense R&D.

JEL Classification: E62, O38, O47

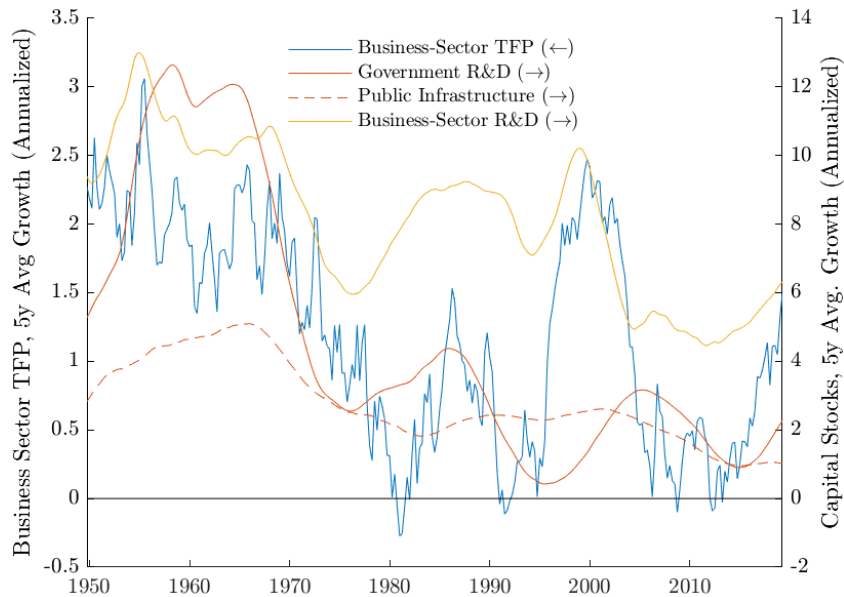
Keywords: Government R&D, Productivity, Growth, Narrative Analysis.

^{*}We are grateful to Peter Beall, Diego Comin, Alexander Field, and Ana Maria Santacreu for helpful discussion. We also thank seminar participants at Middlebury College, Lundquist College of Business, Mays Business School, Clark University, Texas A&M University, the Federal Reserve Bank of Dallas, Ghent University, and the Liberal Arts Macroeconomics 2022 conference for helpful feedback. We thank Roni Lezama, Annie Midthun, Tai Nguyen, Michaela Sullivan, and Nicholas Wagg for their excellent research assistance. Andrew Fieldhouse gratefully acknowledges funding received from Middlebury College for this project. The views in this paper are those of the authors and do not necessarily reflect the views of the Federal Reserve Bank of Dallas or the Federal Reserve System.

[†]Andrew J. Fieldhouse, Mays Business School, Texas A&M University.

[‡]Contact: Karel Mertens, Federal Reserve Bank of Dallas and CEPR, mertens.karel@gmail.com, tel: +(214) 922-6000.

Figure 1: Growth in Business-Sector TFP, R&D Capital, and Public Infrastructure



Notes: Centered five-year moving average annualized growth rates based on quarterly data. Business-sector TFP is the utilization-adjusted measure of Fernald (2012). Public infrastructure consists of nondefense structures and equipment. The definition of R&D capital includes a capitalization of expenditures for software development. See Appendix A for variable definitions. *Sources:* BEA, Fernald (2012).

With the exception of a brief period in the late 1990s and early 2000s, aggregate U.S. productivity growth has slowed markedly since the late 1960s. Figure 1 shows that this slow-down coincides with a decline in public investments in research and development (R&D).¹ The causality underlying this relationship, however, is far from clear, and as Figure 1 shows, higher growth in business R&D capital or public infrastructure prior to the 1970s are plausible alternative contributing factors.

Several significant empirical challenges need to be overcome in order to isolate the causal role of government R&D in driving innovation and productivity growth. Any productivity spillovers likely occur only after long and uncertain lags. Various potential channels for reverse causality need to be accounted for, since policymakers' decisions to boost or cut funding for R&D could be influenced by a wide range of factors with independent effects on innovation. Aggregate estimates must also be interpreted with care, as more government funding for R&D can impact private spending on R&D, or affect other productivity-enhancing public investments.

In this paper, we propose a novel empirical strategy to estimate the aggregate dynamic effects of changes in government R&D spending, and to identify direct versus indirect productivity effects. Because the lags between spending decisions and actual outlays are often long, the starting point of our analysis is a new dataset of all postwar appropriations enacted

¹See also the discussion in Gruber and Johnson (2019) or Bloom et al. (2019), among others.

for the budgetary accounts funding R&D at the major federal agencies: The Department of Defense (DoD), Department of Energy (DoE), National Aeronautics and Space Administration (NASA), National Institutes of Health (NIH) within the Department of Health and Human Services, National Science Foundation (NSF), and their historical precursors. To guard against reverse causality, we perform a narrative classification of all major changes in federal R&D appropriations for these agencies to construct measures that, after conditioning on a suitable set of controls, are largely unanticipated and plausibly free of confounding influences. We use the narrative measures in long-horizon Jordà (2005) local projections with quarterly postwar data to estimate the dynamic causal effects of shocks to R&D appropriations on aggregate TFP and various other indicators of innovative activity.

The knowledge spillovers from defense and nondefense R&D are likely quite different, if only because advancements in military know-how are unlikely to be disseminated as quickly in order to maintain military superiority. For this reason, we distinguish throughout the analysis between defense and nondefense R&D. Based on local projections, we find that a positive shock to appropriations for nondefense R&D robustly leads to a delayed and gradual increase in aggregate TFP that becomes highly statistically significant at long forecast horizons (8 to 15 years). For a shock that induces a one percent increase in government R&D capital, our baseline estimates show eventual increases in the level of TFP of about 0.2 percent. Positive shocks to nondefense R&D also induce increases in various indicators of innovative activity, such as patent grants, the number of doctoral recipients in STEM fields, the number of researchers engaged in R&D, or the number of technology publications. In contrast, we find little evidence that a positive shock to defense R&D leads to any persistent productivity increases, at least not within horizons of 15 years.

To better understand the estimated TFP responses, we investigate various decompositions of the spending changes that occur following shocks to R&D appropriations. As emphasized by Akcigit et al. (2020), public investments that focus more heavily on producing basic knowledge can create important complementarities with private research investments, and have larger spillovers. We find that nondefense shocks lead to relatively larger increases in funding for more fundamental research, and to particularly persistent increases in funding for research performed within government agencies and at universities. The majority of the increase in nondefense R&D funding, in terms of dollars, stems from higher appropriations for NASA, followed by the NIH. Defense shocks instead mostly result in increased funding for development and product improvement, with more of the work performed by businesses.

We find that positive shocks to R&D appropriations for both defense and nondefense activities lead to higher private investment in R&D. As in the theoretical framework of Akcigit et al. (2020), this suggests that private and public R&D investments indeed act as complements rather than substitutes. However, the increases in private R&D are relatively small, particularly in response to nondefense shocks. We find that one channel through which a positive nondefense shock likely has important additional indirect effects on productivity

is a gradual expansion of public infrastructure funded by state and local governments. This expansion is broad-based, with the largest increases in education structures (schools and universities), followed by roads, and power, water, and sewer systems.

In order to isolate the direct productivity effects of government R&D, we formulate an aggregate production function with public infrastructure and government R&D capital as separate arguments, and we structurally estimate the elasticity of government R&D capital. Our identification strategy relies on two key steps. First, we use available estimates of the production function elasticity of public infrastructure to remove its contribution to business-sector TFP growth. We consider values of this elasticity between 0.065 and 0.12, the range deemed plausible by Ramey (2021) in a recent review of the existing evidence. In the second step, we use the SP-IV estimator of Lewis and Mertens (2023) to estimate the production function elasticities of defense and nondefense government R&D capital. Intuitively, this estimator is a GMM estimator that obtains the elasticity as the value that best fits the relationship between the estimated responses of government R&D capital and (infrastructure-adjusted) TFP to the R&D appropriations shocks. Based on the responses to nondefense R&D shocks, the point estimates of the production function elasticity to total government R&D capital across various specifications lie within a relatively tight range of a value of 0.12, and these estimates are generally highly statistically significant under weak-instrument-robust inference procedures.² In contrast, the results for defense R&D are inconclusive, as the estimates vary greatly across specifications, and are very imprecise.

Using the estimates of the production function elasticities, we find that nondefense R&D accounts on average for about one quarter of all TFP growth in the postwar period. Despite the fact that the government invests significantly less in R&D than in public infrastructure, the contribution of government R&D to TFP growth is consistently of a similar magnitude to, and frequently greater than, the contribution of public infrastructure. Depending on the assumed value of the public infrastructure elasticity, slower growth in all forms of public capital explains 0.38 to 0.45 percentage points of the TFP slowdown of around 1 percentage point after the 1960s. Our findings indicate that the slower growth in government R&D was equally important, if not more so, than the slower pace of public infrastructure investment.

Finally, we calculate the rate of return to government nondefense R&D, both indirectly from the production function elasticity estimates and directly from SP-IV estimates in regressions of TFP growth on the ratio of net R&D investment to output. Depending on the method of calculation and empirical specification, we obtain rates of return on nondefense R&D between 150 and 300 percent under a Cobb-Douglas assumption, which are considerably higher than similar calculations for the return on public infrastructure. Our findings therefore point to a misallocation of public capital, and substantial underinvestment in non-defense R&D.

²The value of 0.12 for the elasticity to total government R&D capital translates to an elasticity to nondefense R&D capital of 0.06, given that nondefense R&D averages about one half of total government R&D in the postwar sample.

This paper contributes to a large empirical literature estimating ‘social’ returns to R&D, i.e. returns that include various spillovers on other firms or industries, which are typically found to well exceed the normal return on other investments.³ Firm or industry-level studies, however, are restricted in the scope of spillovers and general equilibrium effects that can be captured. While aggregate data are better suited for estimating the concept of a ‘social’ return, the main challenge is causal identification. Our paper proposes a strategy for causal identification with aggregate data in the context of government-funded R&D.

A number of recent empirical studies focus on industry-specific spillovers or patent responses to specific government R&D programs. For instance, Azoulay et al. (2018) find that NIH spending spurs the generation of private patents, Myers and Lanahan (2022) find large private R&D spillovers from the DoE’s Small Business Innovation Research program, and Kantor and Whalley (2022) find persistent manufacturing output and productivity spillovers from local NASA R&D spending during the moon mission. Moretti et al. (2019) find positive spillovers from defense R&D to private R&D and productivity growth in a panel study of defense R&D spending across OECD countries. Each of these studies provides evidence for some of the spillovers that we aim to measure collectively.

Our paper is also related to several recent studies of the longer-run macroeconomic effects of fiscal policy shocks. Cloyne et al. (2022), for example, find that a corporate tax cut leads to increases in R&D spending by businesses, as well as longer-run increases in TFP. Antolin-Diaz and Surico (2022) study the long-run effects of military spending shocks, and find that these shocks lead to long-run increases in output and productivity. Consistent with our results, the authors argue that the long-run effects are associated with shocks that expand the share of government spending going to R&D, which they identify by maximizing the variance of government R&D spending at forecast horizons of up to one year. De Lipsis et al. (2022) also study the effects of shocks to government R&D spending, in their case identified with short-run restrictions similar to Blanchard and Perotti (2002). As we do, they find that government R&D crowds in private investment and raises output in the long-run. Different from Antolin-Diaz and Surico (2022) or De Lipsis et al. (2022), we focus on shocks to R&D appropriations rather than R&D spending, use a narrative identification scheme, and distinguish between defense and nondefense government R&D. Despite methodological differences, it is reassuring that our conclusions regarding the potential for government R&D spending to boost economic growth are broadly similar.

Finally, this paper contributes to the literature on the productivity effects of public capital, see e.g. Bom and Ligthart (2014) and Ramey (2021) for surveys. Since the early contributions of Aschauer (1989) and Munnell (1990), this literature has typically focused mostly on (nondefense) public infrastructure. Our paper presents estimates of the produc-

³For example, Bloom et al. (2013) use firm-level accounting data and changes in tax incentives for R&D to identify a social rate of return to R&D of 55%. See Hall et al. (2010) or Jones and Summers (2020) for overviews of the evidence.

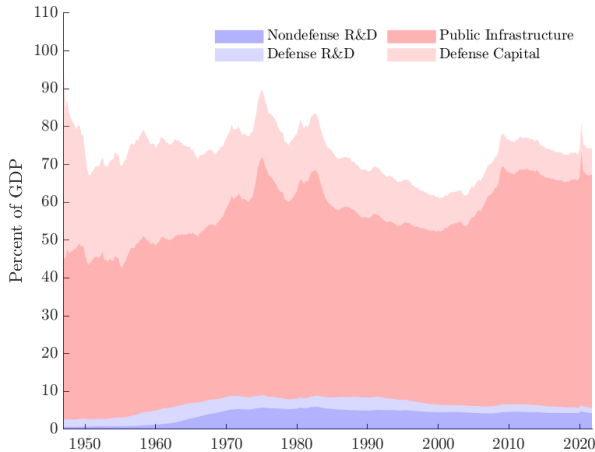
tion function elasticity of government R&D capital that can be used to separately study the role of intangible public capital in quantitative growth models. These estimates are also useful for budgetary analyses of fiscal policy initiatives (e.g. CBO 2016; CBO 2021).

I. Measurement, Definitions and Facts

The measures of public capital used in this paper are based on data from the Bureau of Economic Analysis (BEA). Specifically, we use data on gross investment from the National Income and Product Accounts (NIPAs) to construct quarterly series of the value of government fixed assets (at real cost) that are consistent with the annual series in the BEA’s Fixed Asset Account, see Appendix A for details. We distinguish between (i) defense capital (defense-related equipment and structures), (ii) public infrastructure (federal nondefense and state and local government equipment and structures), (iii) defense R&D capital, and (iv) nondefense R&D capital. Our definition of R&D capital includes a capitalization of expenditures for software development, and therefore corresponds to the concept of ‘intellectual property’ for the government sector in the NIPAs; we use the term ‘R&D capital’ as such throughout the rest of the paper. We refer to the aggregate of (iii) and (iv) as ‘government R&D capital’. R&D expenditures are measured in the NIPA by source of funding, so government R&D capital includes federally-funded ‘contract R&D’ performed by firms, universities, nonprofits, and public-private partnership ‘R&D centers’ (e.g., the Lawrence Livermore National Laboratory). Figure 2 plots the quarterly time series of public capital and its subcomponents as a ratio of GDP. As is clear from the figure, government R&D capital is relatively small compared to other types of public capital, with nondefense and defense R&D capital averaging 3.9 percent and 2.7 percent of GDP, respectively.

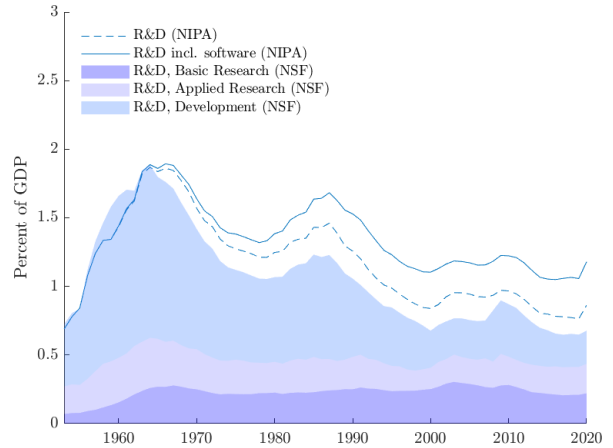
The expenditure data underlying the BEA measures of R&D capital are constructed primarily from annual surveys conducted by the NSF’s National Center for Science and Engineering Statistics (NCSES). Unlike the NIPA data, NCSES data on R&D spending is available by funding agency, performing sector, and type of research activity. The NSF defines R&D as the “creative and systematic work undertaken in order to increase the stock of knowledge ... and to devise new applications of available knowledge.” This wide umbrella for spending on innovative activity is typically separated into three types: basic research, applied research, and experimental development work. The NSF defines basic research as experimental or theoretical work pursuing knowledge “without specific applications toward processes or products” whereas experimental development work is defined as “systematic work, drawing on knowledge gained from research and practical experience and producing additional knowledge, which is directed to producing new products or processes or to improving existing products or processes.” Falling between these two, applied research is defined as “original investigation undertaken in order to acquire new knowledge... directed primarily towards a specific practical aim or objective” (NSF 2022).

Figure 2: Composition of Public Capital



Notes: R&D capital includes software. Public infrastructure is nondefense structures and equipment. See Appendix A for variable definitions. Source: BEA.

Figure 3: Government R&D Expenditures



Notes: Nominal shares of GDP. Fiscal year NSCES data converted to calendar years and excludes plant R&D. Sources: BEA; NSCES, National Patterns of R&D Resources (Tables 7, 8, and 9).

Figure 3 plots the NSCES measures of government R&D spending by type, along with NIPA totals for comparison. Government spending on basic and applied research each averaged 0.23 percent of GDP over the sample period shown, while experimental development averaged 0.61 percent. Government spending on basic research is considerably larger than that of the private sector, which instead spends relatively more on applied research and development.⁴ As emphasized in Akcigit et al. (2020), this compositional difference suggests that distinguishing between private and public R&D spending is potentially important.

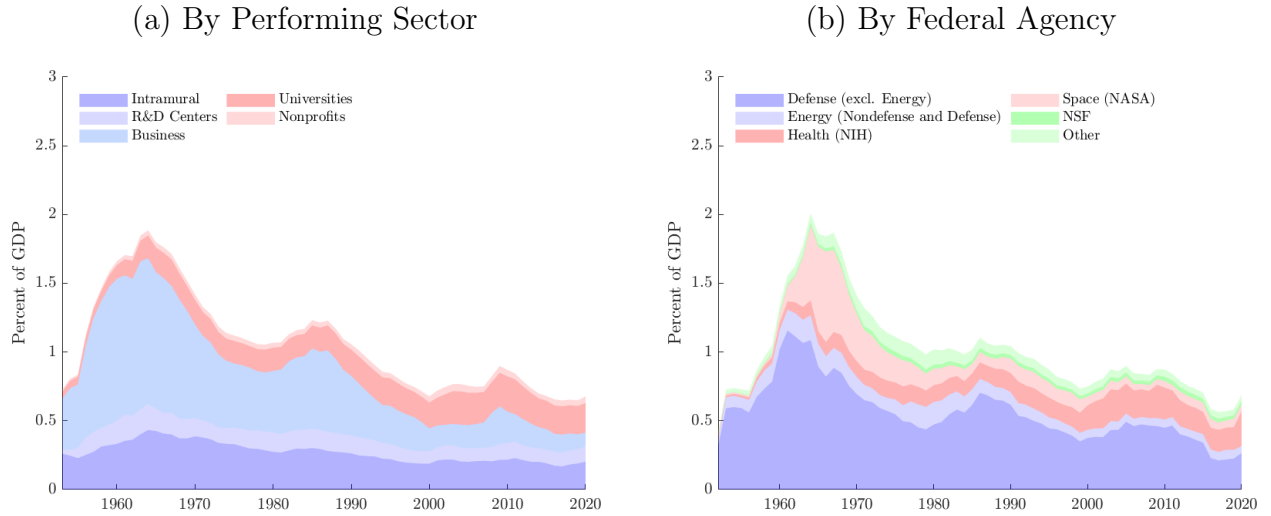
As Figure 3 shows, government R&D expenditures in the NSF surveys do not align perfectly with the corresponding series in the national accounts, as the BEA adjusts the NSF source data and uses additional budgetary data to match required NIPA concepts. ‘Software development,’ in particular, is a broader concept in the NIPAs and includes various non-experimental development expenditures.⁵ Note that not all spending labeled research or development in other data sources, such as the appropriations data we use in our analysis, necessarily flows exclusively into the NIPA measure of government R&D expenditures. For example, DoD spending on ‘operational systems development’ is mostly classified by the BEA as equipment. Similarly, ‘R&D plant,’ i.e., spending on major research facilities and equipment, is also mostly recorded as investment in equipment or structures by the BEA.

Figure 4 plots NSCES data on government R&D spending broken out by performing sectors and the major funding agencies. Panel (a) shows that the bulk of government R&D spending funds activity performed by private businesses, universities, or private-public R&D centers, as opposed to ‘intramural’ R&D conducted within the federal agencies. During the height of the Cold War, most government-funded R&D was performed by businesses, but the

⁴Over the same period, average private expenditures are 0.14 percent of GDP on basic research, 0.30 percent of GDP on applied research, and 0.97 percent of GDP on development (Source: NSCES, National Patterns of R&D Resources).

⁵However, NIPA software development excludes software embedded in other products, e.g., computers or cars.

Figure 4: Government R&D Expenditures



Notes: Nominal shares of GDP, all levels of government. Fiscal year data is converted to calendar years. *Source:* NSCES, National Patterns of R&D Resources (Table 6).

Notes: Nominal shares of GDP, federal R&D outlays by agency excluding plant R&D. Fiscal year data converted to calendar years. *Source:* NSCES, Survey of Federal Funds for R&D (Various tables).

share has fallen substantially since, and a steadily growing share is performed at universities. Government funds for R&D are provided largely by the federal government—more than 90 percent on average in the postwar period; the remainder consists mainly of funding by state and local governments for research at universities.

Panel (b) in Figure 4 provides a breakdown of federal R&D spending by agency. Early in the Cold War, DoD and NASA accounted for the bulk of federal R&D spending, and much of the decline in overall funding since the late 1960s can be attributed to Congress reversing course on funding for these agencies after the nuclear triad was deployed and the moon landing was successfully completed. Another major source of funding is DoE and its historical precursors, covering both defense activities (e.g., nuclear weapons and naval propulsion) and nondefense activities (e.g., civilian energy and physics research); in the NIPAs, DoE’s national security functions are included in defense R&D. In recent decades, NIH funding for medical research has gradually grown in importance. The final agency engaged in significant R&D funding is the NSF. Various other federal agencies also provide funding for R&D, but in much smaller amounts.

II. Measuring Exogenous Variation in Government R&D Spending

Our strategy for identifying the causal effects of government R&D spending on aggregate productivity is based on novel empirical measures of exogenous variation in federal funding for R&D. As is well known in the literature, an important identification concern is that changes in fiscal policy are often anticipated, and mistiming the arrival of news about fiscal policy can lead to misleading results (Ramey 2011; Mertens and Ravn 2013; Leeper et

al. 2013). To address these concerns, we rely on time series of all enacted appropriations authorizing future federal spending on R&D, and not just on current R&D expenditures as in Antolin-Diaz and Surico (2022) or De Lipsis et al. (2022).

The other identification concern is that changes in policy reflect systematic reactions by policymakers to macroeconomic developments that independently affect innovative activity and aggregate productivity growth. We take a two-step approach to isolating changes in appropriations that are plausibly uncorrelated with other influences on productivity trends. First, we adopt a narrative identification strategy and—on the basis of an extensive analysis of historical sources—retain only those changes in appropriations that are not motivated by short-run macroeconomic considerations.⁶ Second, to guard against the possibility that R&D policy responds systematically to other longer-term drivers of productivity trends, we embed the narrative measures in empirical models that remove predictable variation in future productivity growth through a wide variety of lagged controls at a quarterly frequency. As we will show, neither the narrative identification step nor the choice of controls will prove crucial for our main empirical finding that nondefense R&D raises TFP in the long run, which likely helps explain why our results broadly agree with those of Antolin-Diaz and Surico (2022) or De Lipsis et al. (2022). Before we describe the econometric methodology in full detail, the rest of this section first discusses the appropriations data as well as the narrative measures used for identification.

A. Data on Appropriations for R&D

As the overwhelming majority of government R&D funding is by the federal government, we restrict attention to congressional appropriations for R&D activities. To construct a time series on federal R&D appropriations, we rely on information in the *Budget of the U.S. Government* and its appendices. Specifically, we collect information on all enacted appropriations for the budgetary accounts funding R&D activities at federal agencies for all fiscal years from 1947 to 2019. To keep the data collection manageable, we only consider the budget accounts for the five major federal agencies discussed in Figure 4: DoD, DoE, NASA, NIH, and NSF.⁷ Together, these five agencies typically account for roughly 87 to 93 percent of total federal R&D spending in any given fiscal year. For each agency, we obtain the appropriations from the ‘Budget Authority’ (BA) or—prior to the introduction of BA as a budgeting concept—the ‘Appropriation (adjusted)’ line item for each R&D account. The data we collect reflects all annual appropriations bills adjusted for any supplemental appropriations, subsequent transfers between accounts, or sequestration cuts. We date the appropriations to the quarter they take effect, either the start of that fiscal year or when

⁶Examples of similar empirical approaches include applications to monetary policy (Romer and Romer 1989), government spending (Ramey 2011; Ramey and Zubairy 2018), federal tax policies (Romer and Romer 2010; Mertens and Ravn 2013; Mertens and Montiel Olea 2018), and housing credit policies (Fieldhouse et al. 2018).

⁷The Atomic Energy Commission and Energy Research and Development Administration are included as precursors to the Department of Energy.

the appropriations bill was subsequently enacted. As such, most changes are dated to the first quarter of the following fiscal year. To match defense and nondefense spending in the NIPAs, we separate the appropriations for DoD and for the national security functions of DoE from all other appropriations. References to all data sources by agency/year are available in Fieldhouse and Mertens (2023).

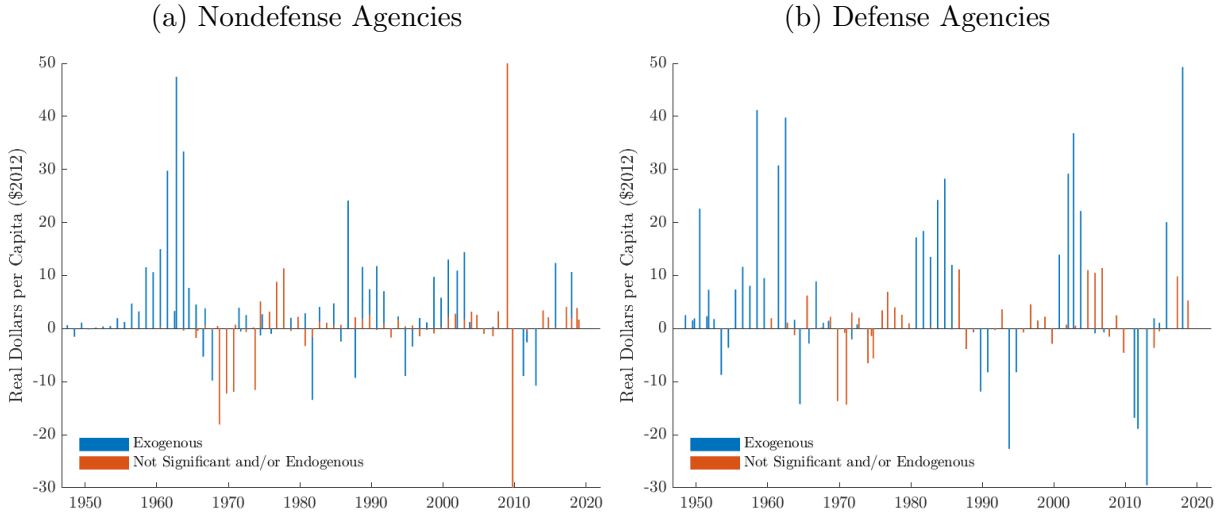
B. Narrative Classification

One potential reason that changes in R&D appropriations are endogenous is that they may be correlated with business cycle shocks. Comin and Gertler (2006) and Bianchi et al. (2019), for example, argue that expansionary business cycle shocks can raise aggregate productivity at longer horizons through endogenous growth channels, while Ilzetzki (2022) provides evidence that high capacity utilization during WWII spurred innovation out of necessity. Government R&D appropriations may be procyclical given that there is more room in government budgets during booms. On the other hand, R&D spending may also rise in recessions if increases in appropriations for R&D are systematically folded into larger fiscal stimulus packages.

As we will rely on quarterly regression specifications that include lagged cyclical indicators as controls, it is possible to appeal to lags in the policymaking process for identification, as in for example Blanchard and Perotti (2002). However, as including lagged cyclical indicators as controls may not suffice to remove all sources of cyclical endogeneity, we prefer to conduct our analysis with a subset of changes in appropriations that are classified as exogenous by a narrative analysis. More specifically, for each of the five agencies, we conduct a narrative analysis for all fiscal years with ‘significant’ changes in (real) appropriations, defined as year-over-year increases of at least 5 percent, or decreases of at least 2.5 percent. We focus on larger changes for two reasons. First, it is easier to infer legislative intent from available historical sources for the more meaningful deviations from current policy. Second, the focus on larger changes substantially reduces the number of agency-fiscal year pairs to analyze. In total, we classify 218 agency-fiscal year pairs with significant real changes in appropriations over the FY1947-2019 sample. Roughly one-third of the policy changes involve decreases in real appropriations for R&D and two-thirds are increases.

For each of the 218 significant agency-fiscal year changes, we rely on a variety of primary and secondary sources to understand the context and motivation. Specifically, we study the *Budget of the U.S. Government*, the *Economic Report of the President*, the *State of the Union address*, and any other related presidential signing statements to learn the administration’s budgetary priorities and specific goals for R&D policy. To infer legislative intent, we analyze the House and Senate Appropriations Committee reports that accompany each appropriations bill, as well as any related committee hearings. Finally, we also scan *CQ Almanac* and newspaper coverage of the relevant appropriations bills, primarily

Figure 5: Changes in Nondefense and Defense R&D Appropriations



Notes: Nondefense agencies include NASA, NIH, NSF, and the nondefense functions of DoE. Defense agencies include DoD and national security functions of DoE. Nominal appropriations are converted to real dollars using NIPA price indices for federal nondefense/defense investment in intellectual property. *Source:* Authors' calculations based on the *Budget of the U.S. Government*, see Fieldhouse and Mertens (2023).

The Washington Post, *The New York Times*, and *The Wall Street Journal*.

Based on a close reading of the various sources, we classify every significant change in real R&D appropriations for each agency as either ‘exogenous’ or ‘endogenous’. Endogenous policy changes are those that are primarily motivated by short-run economic considerations. Examples are increases in R&D spending that are part of a broader fiscal stimulus package (e.g., as in the American Recovery and Reinvestment Act of 2009), increases in energy R&D in response to oil shocks (e.g., when the Department of Energy was created in 1977), or cuts to R&D spending as part of broader austerity measures intended to curb short-run inflationary pressures.

Exogenous policy changes are instead motivated by a variety of other considerations without clear macroeconomic relevance in the short run. For nondefense R&D, examples of such motivations include policymakers’ general concerns about the adequacy of the science, technology, and engineering base (e.g., creation of the NSF), evolving public health concerns (e.g., Nixon’s ‘war on cancer’), multinational scientific efforts (e.g., human genome project), certain geopolitical events (e.g. the launch of Sputnik and the creation of NASA), or initiatives with mixed diplomatic/scientific objectives (e.g., the International Space Station). For defense R&D, examples include concerns about the adequacy of strategic capabilities relative to geopolitical rivals (e.g., Sputnik crisis), the ratification or withdrawal from non-proliferation treaties (e.g., exiting the Anti-Ballistic Missile Treaty), policy preferences of a new administration (e.g., Reagan’s military buildup), or evolving threats to national security (e.g., Global War on Terror). Long-term deficit reduction packages often cut nondefense and/or defense R&D appropriations (e.g., Budget Control Act of 2011); such policies are

classified as exogenous if the intent is long-term fiscal sustainability rather than curbing near-term inflationary pressures.

Figure 5 shows the time series of the yearly changes in defense and nondefense appropriations, expressed in 2012 dollars per capita for ease of comparison across the sample period. The blue bars show those changes that are classified as exogenous in the narrative analysis, aggregated over all five agencies. Appendix B presents the same figures for each agency separately. For the interested reader, the same appendix also provides an overview of postwar federal R&D policy for additional background.

C. Orthogonalized Narrative Measures for Changes in Defense and Nondefense Appropriations

The fact that defense R&D usually aims to maintain the U.S.’s military advantage is one reason why the knowledge spillovers from defense and nondefense R&D are potentially very different. One slight complication to isolating their separate effects empirically is that the changes in defense and nondefense R&D appropriations shown in Figure 5 are positively correlated. In other words, an increase in appropriations for one category tends to be accompanied by an increase in the other. Specifically, the correlation between all changes in defense and nondefense appropriations is 0.31, and the correlation across the exogenous policy changes is also 0.31. To better understand any underlying differences, it is useful to estimate the causal effects of more idiosyncratic movements in each category of government R&D. To that end, we construct versions of the narrative measures that are orthogonalized with respect to one another. More specifically, let $\Delta a_t^{exo,i}$ denote the narrative measures of exogenous changes in appropriations for $i = D, ND$ (defense/nondefense) in quarter t , as shown in blue in Figure 5. The orthogonalized narrative measures are the residual z_t^i in the following regression,

$$(1) \quad \frac{\Delta a_t^{exo,i}}{K_{t-4}^i} = a_i + b_i \frac{\Delta a_t^{exo,-i}}{K_{t-4}^{-i}} + z_t^i, \quad i = D, ND.$$

To construct the orthogonalized narrative measures, we express the (constant) dollar changes in appropriations in category i as a fraction of the total real value of the government R&D capital stock in that budget category four quarters earlier, K_{t-4}^i . We scale the changes in R&D appropriations by the real capital stock as we are interested in elasticities to government R&D capital. To avoid introducing any sources of endogeneity, we scale by the one-year lagged capital stock, although this matters very little for the results. By construction, the sample correlation between z_t^i and the exogenous appropriation change in the other category, $\Delta a_t^{exo,-i}/K_{t-4}^{-i}$, is zero. The orthogonalized narrative measure z_t^i , therefore, represents an exogenous innovation in government R&D appropriations for category i at time t , but leaving appropriations in the other category $-i$ contemporaneously unchanged.

The impulse responses identified with the orthogonalized narrative measures will have the interpretation as the impact of a change in R&D funding targeting one category, while leaving appropriations for the other category unchanged on impact (but not necessarily in future quarters). In practice, the orthogonalization step turns out to matter very little for the results, see Appendix C.2. Note that the positive correlation between defense and non-defense measures implies that the two measures potentially both contain useful identifying variation in defense and nondefense R&D capital. Our estimation of the production function elasticities and rates of return will therefore also include specifications that simultaneously use both narrative measures (without the orthogonalization) for identification.

III. The Dynamic Effects of Changes in R&D Appropriations

A. Empirical Methodology

The first part of our analysis consists of estimating impulse responses of productivity and government R&D capital associated with unanticipated changes—or ‘shocks’—to defense and nondefense R&D appropriations. Given the likely significant delays between an increase in congressional appropriations for R&D, actual outlays for R&D, and any eventual technological improvements as a result of those outlays, we use Jordà (2005) local projections to estimate responses at forecast horizons $h = 0, \dots, H - 1$ of up to 15 years ($H = 60$ quarters).⁸ The impulse response for an outcome variable y_t at horizon h estimated by local projections is simply the OLS coefficient in a direct forecasting regression of y_{t+h} on the period t value of the orthogonalized narrative measures, z_t^i . This estimation approach makes no ex ante assumptions regarding the lags between R&D spending and the productivity effects. Because changes in R&D appropriations are serially correlated, as seen in Figure 5, we include information about past R&D appropriations in the regression. Specifically, we include $p = 4$ quarterly lags of $\ln(a_t^i)$, where a_t^i is the cumulative sum of all past (constant dollar) changes in R&D appropriations in category i . Including lags of $\ln(a_t^i)$ rather than z_t^i provides more information about past R&D policies, and Appendix C.4 shows that additionally including lags of z_t^i has little effect on the results. We also include $p = 4$ lags of the outcome variable y_t in all specifications. Unless mentioned otherwise, the estimation sample consists of 74 years of quarterly observations from 1948Q1 through 2021Q4.

In practice, we estimate the following local projections for $h = 0, \dots, H - 1$ using OLS:

$$(2) \quad \sum_{j=0}^3 \left(\frac{1}{4} \times y_{t+h-j} \right) = c_h + \gamma_h z_t^i + \sum_{j=1}^p \beta_h^j \ln a_{t-j}^i + \sum_{j=1}^p \delta_h^j y_{t-j} + \sum_{j=1}^p \zeta_h^{j'} x_{t-j} + v_{t+h}$$

where $p = 4$, y_{t+h} is the outcome variable of interest at horizon h (e.g. utilization-adjusted

⁸Vector autoregressions (VARs) are a common alternative for impulse response estimation. As shown in Plagborg-Møller and Wolf (2021), local projections avoid potential misspecification in finite-order VAR-based impulse response estimators at forecast horizons beyond the VAR lag length.

TFP), v_{t+h} is a residual at forecast horizon h , and the sequence $\{\gamma_h\}_{h=0}^{H-1}$ contains the impulse response coefficients.

Two features of (2) warrant further discussion: First, the left-hand side is a four-quarter backward moving average, $\sum_{j=0}^3 (\frac{1}{4} \times y_{t+h-j})$, rather than just the quarterly observation y_{t+h} . The averaging smooths out some of the quarterly noise in the impulse response estimates, but is otherwise not important. Since we also include four quarterly lags of y_{t+h} , the estimation is equivalent to using y_{t+h} as the left-hand side variable and subsequently taking the moving average of the estimated impulse response coefficients.

Second, the specification in (2) allows for the inclusion of lags of additional control variables, x_t . As is well known, including lagged predictors of the outcome variables as controls in local projections can serve multiple purposes. One is that, even when identification is valid without conditioning on lagged predictors of y_{t+h} , including these predictors generally sharpens inference on the impulse response estimates by reducing the variance of the forecast residuals, v_{t+h} . Another is that adding a suitable set of lagged controls helps to eliminate past influences on the outcome variable that may be correlated with the regressor of interest, and otherwise would lead to endogeneity bias.

As discussed earlier, one of the controls included in x_t is a cyclical indicator to eliminate any remaining cyclical sources of endogeneity in the narrative measures. In the baseline set of controls x_t , we include the capacity utilization rate from the Fernald (2012) dataset, which captures variation in both labor effort and the workweek of capital, and is strongly correlated with other coincident cyclical indicators. Adding the unemployment rate or the output gap has very little impact on the results, see Appendix C.3.

Even if the narrative classification and cyclical controls successfully address the short-run sources of endogeneity that are typically of greatest concern in the identification of fiscal shocks, it is not clear that they are adequate to address potential longer-run sources of policy endogeneity. R&D policy may, for example, respond to productivity, demographic, or other secular trends. A related possibility is that policy responds to the arrival of new ideas and nascent technologies that, even in the absence of government involvement, are anticipated to raise productivity growth with similar timing in the future.

To address concerns about longer-term sources of endogeneity, the baseline specification includes five additional controls with the aim of removing predictable variation in TFP and other outcome variables of interest. First, we always include lags of utilization-adjusted TFP (in log-level) in the control set. Next, we also include real government and business-sector R&D capital (both in log-levels) in x_t . Including R&D capital stocks, rather than just recent R&D expenditures, is preferable because of the potentially long delays between expenditures and actual improvements in productivity. We further include an average of the cumulative real stock market return for the high-tech, manufacturing, and health industries as a forward-looking indicator of innovation and productivity growth. Several studies

have shown that stock market returns are predictive of output growth and TFP at longer forecast horizons, see for instance Fama (1990) or Beaudry and Portier (2006). The natural explanation is that new ideas and research opportunities are reflected in stock market valuations relatively quickly and well ahead of the eventual productivity improvements. Indeed, Kogan et al. (2017) document evidence of immediate stock market reactions to patent grants. The final element in the baseline control set x_t is the defense spending news variable of Ramey and Zubairy (2018). We include news about total defense spending to remove additional predictable variation in defense R&D, and potentially also in nondefense R&D arising through complementarities or government budget constraints.

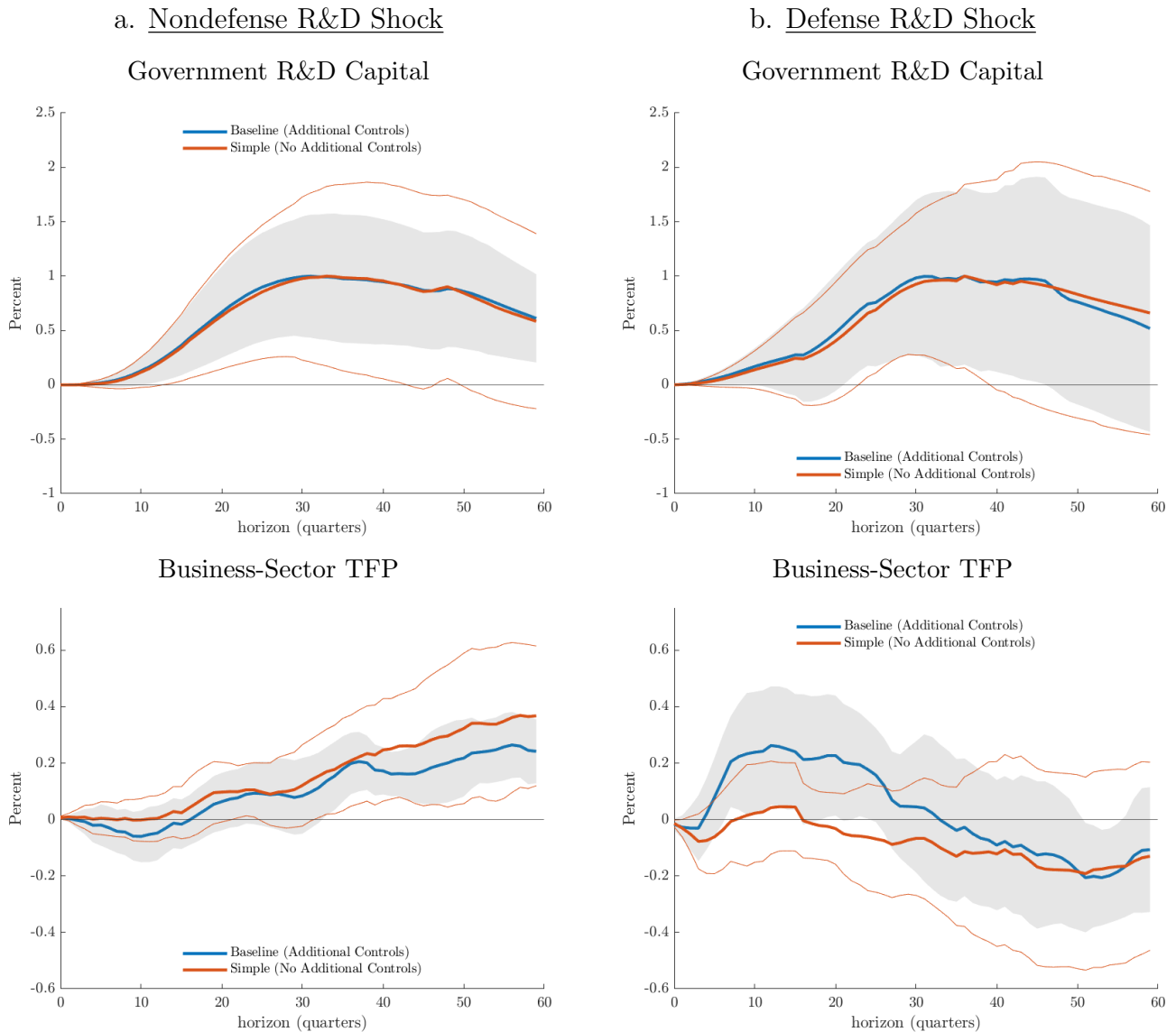
In Appendix C.3, we establish robustness to a large number of additions to this baseline set of controls, including a variety of additional fiscal policy indicators (public infrastructure capital, debt, taxes, spending, etc.), financial market indicators (interest rates, credit spreads, and broader stock market indices), and alternative potential predictors of future TFP and R&D spending (labor quality, non-R&D business-sector capital, patents, and the relative price of R&D).

B. Government R&D and TFP After Shocks to R&D Appropriations

Figure 6 presents impulse responses of government R&D capital and TFP to appropriations shocks based on the estimates of $\{\gamma_h\}_{h=0}^{H-1}$ in the local projections in (2). Each panel shows results for the baseline specification, i.e. with the six baseline controls in x_t described above. To assess the importance of including these additional controls, the panels also report results from a simpler specification without the lags of any of the variables in x_t . For ease of comparison with the production function elasticities presented later, the responses are scaled to imply a one percent peak increase in total government R&D capital. Inference is based on the heteroskedasticity and autocorrelation-robust (HAR) confidence bands recommended by Lazarus et al. (2018).

The top panels in Figure 6 show that both defense and nondefense shocks lead to highly persistent hump-shaped increases in government R&D capital. The build-up in R&D capital after both types of shocks is very gradual, with peak effects that occur 8 to 10 years after the shock. The substantial delays in the capital responses show that there are, on average, relatively long lags between a positive shock to congressional appropriations for R&D and eventual outlays. As we show below, the modest declines in R&D capital towards the end of the forecast horizon not only reflect depreciation, but also eventual reversals in government R&D spending. In the baseline specification, the increase in government R&D capital after a nondefense shock is highly statistically significant for all horizons except very short ones, which indicates that the orthogonalized narrative nondefense measure is a strong predictor of future government R&D spending. The increase in response to a defense shock is also significant at the 5 percent level at horizons between 5 and 11 years, but the confidence bands

Figure 6: Government R&D Capital And TFP Following an Increase in R&D Appropriations



Notes: Estimates based on (2) using the orthogonalized narrative measure of changes in federal nondefense (left panel) and defense (right panel) R&D appropriations, see (1). ‘Baseline’ includes additional lagged controls described in the main text. Lazarus et al. (2018) HAR bands are at the 5 percent significance level. Impulses scaled to imply a 1 percent peak increase in government R&D capital. Sample: 1948Q1–2021Q4.

are overall wider than for the nondefense shock. The fact that congressional appropriations are strongly predictive for future government R&D spending implies that the spending changes are potentially anticipated well in advance. Basing identification on variation in appropriations rather than spending is therefore preferable to avoid possible bias due to anticipation effects. For both shocks, the point estimates vary little across the specifications with and without the additional controls. The main effect of the additional controls is to substantially sharpen inference for the government R&D capital response to a nondefense shock.

The bottom left panel of Figure 6 shows the estimated TFP response to a nondefense R&D shock. The key finding is that, after a substantial delay, a positive shock to appropriations leads to a gradual increase in business-sector TFP. Moreover, the TFP increase becomes highly statistically significant at longer horizons. In our baseline specification, there is initially no significant change in TFP for about seven years, after which TFP slowly increases to a level that is around 0.2 percent higher by the end of the 15-year horizon. In the simpler specification, the TFP response is somewhat larger, up to around 0.35 percent at the end of the forecast horizon. Including the additional controls again considerably increases the precision of the estimates, but the TFP response is overall similar in shape, and it is significant at longer horizons in both specifications.

The bottom right panel of Figure 6 shows that the TFP response to a positive defense R&D shock is meaningfully different from the response to a nondefense shock. In contrast to the nondefense shock, a defense shock leads to a decline in TFP at longer horizons. In the baseline specification, the longer-run decrease in TFP is significant at the 5 percent level at a several horizons around 13 years after the shock. Overall, the estimates of TFP response to a defense shock are considerably more uncertain, and they are insignificant at conventional levels at most horizons. Whereas the simple specification shows essentially no impact on TFP at shorter horizons, the baseline specification shows evidence of a positive TFP response in the near term, with point estimates that are marginally significant between two and eight years. However, the main conclusion is that—unlike for nondefense R&D—there is no evidence that defense R&D has positive TFP spillovers in the longer run, at least not within the 15-year time window that we consider.

As Figure 6 shows, including the additional controls qualitatively has no major effects on the estimated TFP responses at longer horizons. Appendix C.1 and C.2 show that the TFP responses to both shocks also remain very similar if we use all appropriation changes rather than just those classified as exogenous, or if we use the raw narrative measures rather than the orthogonalized ones. Appendices C.3 and C.4 further document that the significant positive long-run TFP response to a nondefense R&D shock is robust to many different additions to the control set x_t , as well as to various other changes in specification. Together, these results suggest that policy endogeneity is probably not as serious a concern as it typically is for broader changes in tax or spending policies. Nevertheless, we include four lags of the six baseline controls in all remaining specifications in this paper, and—unless mentioned otherwise—we continue to use the the same narrative measures for identification.

C. Effects on Other Productivity and Innovation Indicators

Figure 7 reports impulse responses of several other productivity and innovation indicators. The estimates are again based on (2) with the six baseline controls in x_t , and scaled to imply a one percent peak increase in total government R&D capital. For brevity, the results for

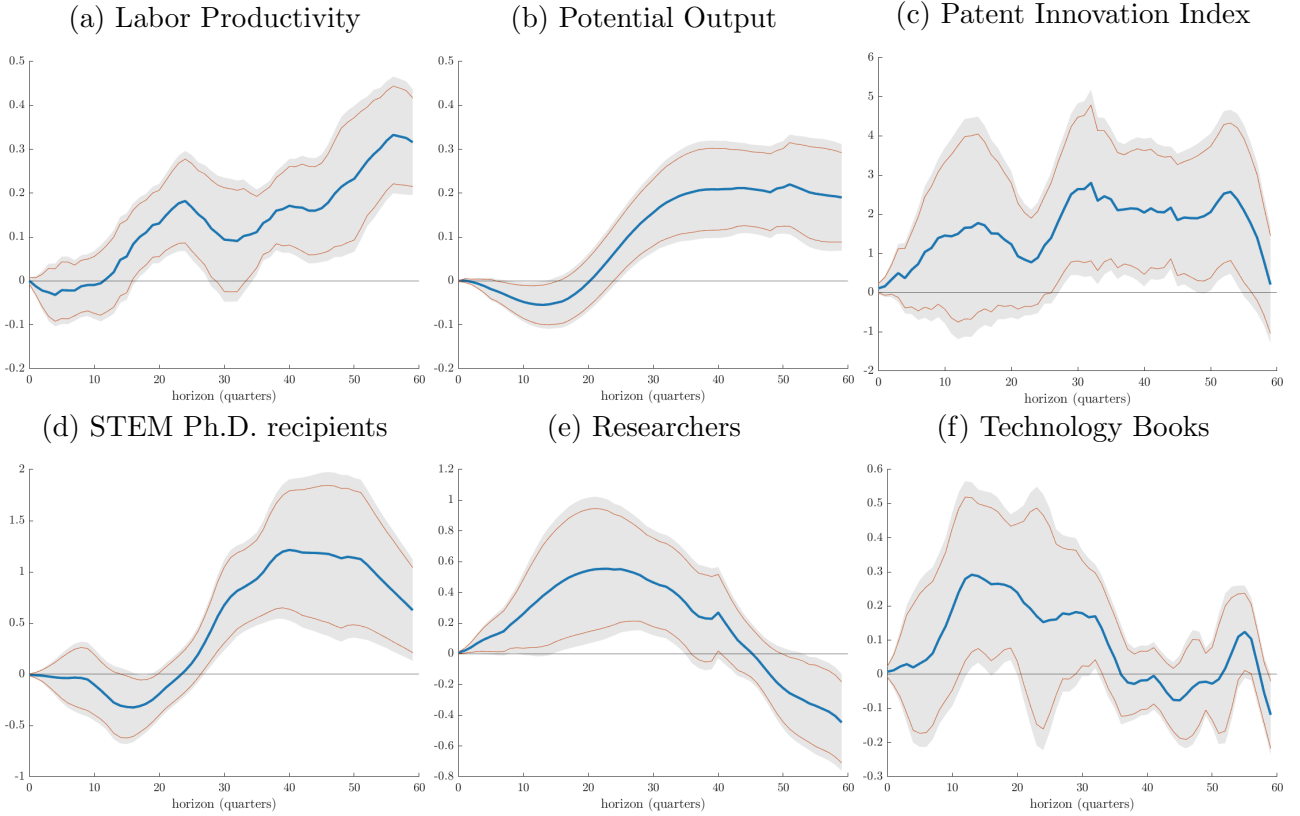
shocks to defense R&D appropriations are reported in Appendix C.5.

Panel (a) in Figure 7 shows the response of business-sector labor productivity (output per hour). Under certain assumptions, technological change is the only source of long-run variation in labor productivity; see e.g. Galí (1999). The response of labor productivity at longer horizons thus provides an alternative signal of the productivity effects of government R&D. As panel (a) shows, labor productivity initially does not react to a nondefense R&D shock, but starts rising after three years, and reaches a level that is higher by around 0.30 percent after 15 years. Just as the TFP response to a nondefense shock in Figure 6, the response of labor productivity is highly statistically significant at longer horizons. Appendix C.6 shows that labor input remains essentially flat after a nondefense R&D shock, although there is some mild evidence of a decline towards end of the 15-year horizon. In contrast, the stock of non-R&D business-sector capital rises significantly at longer horizons, with a peak increase of around 0.2 percent. This pattern of responses is broadly consistent with conventional balanced-growth assumptions in economic models that imply that productivity trends have no permanent effect on hours worked per capita. To the extent that the long-run TFP increase is widely anticipated by economic agents, the absence of any short-run response in labor input implies that news about future TFP from changes in R&D appropriations is not a source of fluctuations at business cycle frequencies. Indeed, Appendix C.6 documents that real GDP shows no short-run response to a nondefense appropriations shock, but simply rises in the longer run along a trajectory that is very similar to that of business-sector labor productivity depicted in panel (a) of Figure 7.

The next panel in Figure 7 shows the response of CBO's measure of potential GDP (in logs), which is an estimate of the economy's maximum sustainable output consistent with stable inflation. TFP is a key determinant of the level of potential output, in addition to the levels of labor and capital inputs being fully utilized at sustainable rates. Similar to the responses of TFP and labor productivity, panel (b) in Figure 7 shows that there is no effect on potential output for the first five or six years after a nondefense shock. In the long run, however, there is a gradual and significant increase in potential output, which expands about 0.2 percent after 8 to 15 years. With no response of labor input and non-R&D business-sector capital increasing by around 0.2 percent, the long-run rise in potential output appears primarily driven by an increase in total factor productivity.

Patent data are a widely used alternative to productivity measures for evaluating the pace of technological innovation across time; see, e.g., Kogan et al. (2017), Bluwstein et al. (2020), and Kelly et al. (2021), among others. Panel (c) in Figure 7 shows the impact of a nondefense R&D shock on the patent-based innovation index of Kogan et al. (2017), using the quarterly version constructed by Cascaldi-Garcia and Vukotić (2022) available through 2010Q4. This index weights new patent grants by stock market reactions to account for their economic value. As seen in panel (c), the patent innovation index temporarily rises by around 2 percent after a positive shock to nondefense R&D, an increase that is significant

Figure 7: Impact of a Nondefense R&D Shock on Other Productivity/Innovation Indicators



Notes: Estimates based on (2) using the orthogonalized narrative measure of changes in federal nondefense R&D appropriations, see (1). Lazarus et al. (2018) HAR bands are for 90 and 95 percent confidence levels. Impulses scaled to imply a 1 percent peak increase in government R&D capital. Sample: (a),(b),(d):1948Q1–2021Q4; (c):1949Q1–2010Q4; (e):1951Q1–2019Q4; (f):1956Q1–1997Q4. See Appendix A for variable definitions.

at several medium-run horizons. The rise in patent grants with economic value occurs well in advance of the increase in TFP in Figure 6, and fades near the end of the 15-year forecast horizon. The timing of the response is consistent with increased government funding for nondefense R&D leading to more patents with economic value followed by improvements in business-sector productivity.

The bottom row of Figure 7 shows responses of several other measures of research activity. Because these measures are only available annually, we construct quarterly versions of these annual series by linear interpolation. Panel (d) first depicts the estimated responses of the (log) number of new Ph.D. recipients in STEM fields to a positive nondefense R&D shock. The response shows a statistically significant increase in new STEM Ph.D. recipients at horizons above seven or eight years. The delay is consistent with the average length of a Ph.D. after allowing for some additional implementation lags. The increase is persistent over longer horizons, with a peak rise in new STEM doctoral degrees of more than one percent after roughly 12 years.

The next panel considers the (log) number of researchers, i.e. the number of full-time equivalent workers engaged in R&D, based on data from the OECD and Bloom et al. (2020). As the panel shows, a nondefense R&D shock leads to gradual increase in the number of researchers by up to around 0.5 percent approximately three- to eight years after the increase in appropriations. Over longer horizons, the number of researchers first returns back to prior levels, and then declines at the end of the 15-year horizon. The long-run decline likely reflects the eventual reversal of government R&D funding.

The last panel in Figure 7 shows the response of an index of new technology book publications, a measure of innovation constructed by Alexopoulos (2011). While the available sample for this series is much shorter (1956 through 1997), there is evidence of a significant increase in new technology books at horizons of three to eight years. As was the case for the innovation index in Panel (c) and the number of researchers in Panel (e), the effect on the number of technology publications is transitory and occurs ahead of the TFP response.

The evidence in Figure 7 indicates that a nondefense R&D shock leads to increases in both inputs (researchers and STEM scientists) and outputs (patents, new technology books) of the knowledge production function. Both in direction and timing, the responses appear consistent with the simplest explanation of the delayed increase in TFP in Figure 6, which is that government funding for research directly leads to innovations that prove valuable in private production. After taking into account the additional lags between R&D appropriations and outlays, the timing of the effects also appears broadly in line with existing evidence that innovation and productivity responses typically lag private R&D spending by two- to five years, see e.g. Hall et al. (2010) for an overview.

Appendix C.5 shows that, in contrast to a nondefense shock, a positive shock to defense R&D does not lead to similarly unambiguous increases in the same productivity and innovation indicators, reinforcing our earlier conclusion that defense R&D spending on average does not appear to have the same positive long-run spillovers on private productivity as nondefense R&D within the horizons that we consider.

D. A Closer Look at the Response of R&D Spending

Figure 6 showed that the shocks to appropriations for nondefense and defense R&D lead to hump-shaped increases in government R&D capital. To gain a better understanding of the nature of both types of R&D shocks, we next take a closer look at the responses of the R&D spending flows using additional information available in the underlying NSCES survey data. Specifically, we study how the shocks affect government R&D spending by type, performer, and funding agency using the series in Figures 3 and 4.

To estimate decompositions of the spending changes, we use the following Törnqvist

index approximation of the log change in total real R&D spending, I_t^{tot} ,

$$(3) \quad \Delta \ln I_t^{tot} \approx \sum_j \frac{s_t^j + s_{t-1}^j}{2} \Delta \ln I_t^j$$

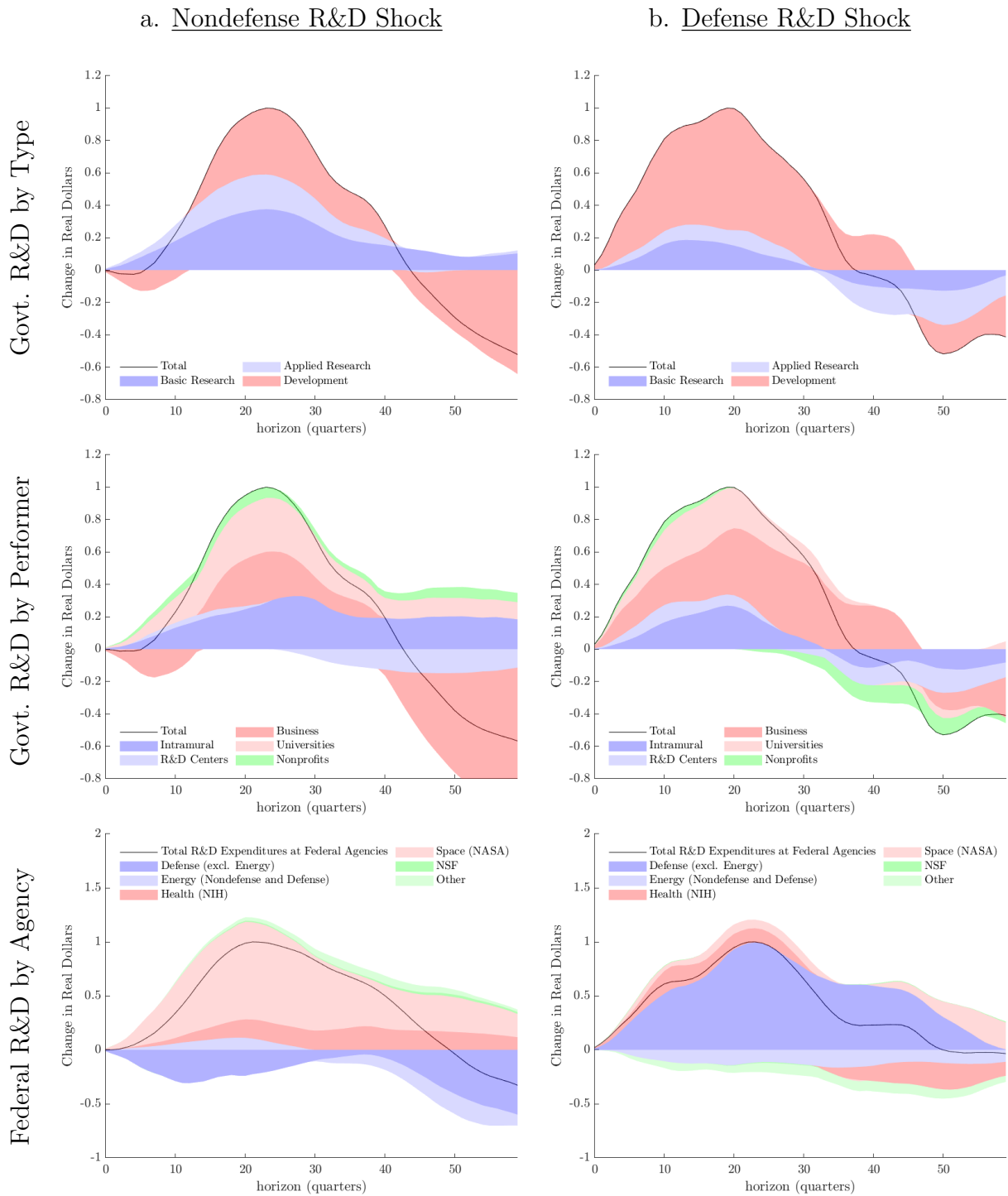
where I^j is gross R&D investment in category j in constant dollars and s^j denotes the nominal expenditure share of category j in total R&D spending ($s^j = I^{n,j}/I^{n,tot}$, where $I^{n,j}$ is gross R&D investment in category j in current dollars). To obtain the individual contributions of each category, we estimate the cumulative impulse response of each of the terms of the summation in (3) using the baseline specification in (2). Because the NSCES survey data is only available for fiscal years, we convert the series to calendar years, and use linear interpolation to obtain quarterly spending shares. We then apply these shares to the BEA expenditures to construct quarterly series for all the subcategories that are consistent with the NIPA totals. The impulses are scaled such that the peak increase in total spending on nondefense (left panel) or defense (right panel) R&D is one real dollar. The resulting estimates can be interpreted as the real dollar changes in spending in category j given a peak increase in nondefense (or defense) spending of one dollar.

The first two rows in Figure 8 show the responses of total government R&D spending, together with the decompositions by type of R&D and by performing sector. As can be seen in the figure, both shocks lead to a gradual build-up in total R&D spending flows, and partial spending reversals in the longer run. In response to a nondefense shock, R&D spending is approximately unchanged for the first six quarters, after which it slowly rises to a peak after about six years, and subsequently gradually declines. After about 10 years, there is a reversal in spending that lasts until the end of the forecast horizon. The response to a defense shock is similar, except that the rise in spending starts immediately on impact.

The decomposition in the first row of Figure 8 shows that both shocks lead to increases in each of the three types of R&D (basic research, applied research, and development) during the boom phase. However, the nondefense shock leads to a substantially larger increase in basic and applied research (up to 38 cents and 22 cents, respectively). A defense shock instead leads mostly to increases in spending on development (up to 75 cents). For the nondefense shock, the eventual reversal in spending is exclusively in development, while funding for basic research remains elevated throughout. For the defense shock, the reversal is instead in all three types of R&D. As mentioned earlier, Akcigit et al. (2020) argue that basic research generates greater knowledge spillovers than non-basic research. Beyond national security prerogatives limiting knowledge spillovers from defense activities, the larger and more persistent impact of the nondefense shock on basic research therefore possibly contributes to the difference between the long-run TFP responses to defense and nondefense shocks in Figure 6.

As shown earlier in Figure 4, most government R&D spending funds activity that is

Figure 8: Response of R&D Spending by Type, Performer and Agency



Notes: Estimates based on (2) using the orthogonalized narrative measure of changes in federal nondefense (left panel) and defense (right panel) R&D appropriations, see (1). Impulses scaled to imply a unit peak increase in government R&D expenditures (row 1 and 2) or federal R&D expenditures (row 3). See notes in Figures 3 and 4 for data sources. Quarterly values are obtained by interpolation of annual data. Real variables based on the NIPA deflator for government intellectual property (R&D and software). Sample: 1954Q1–2021Q1.

not performed at federal agencies, but at private businesses, private-public R&D centers, or universities. The decomposition in the second row of Figure 8 shows that this is also the case for the spending increases induced by the shocks. A nondefense shock that increases total R&D spending by up to one dollar raises intramural spending by at most 33 cents, while a defense shock raise intramural spending by at most 27 cents. In both cases, the bulk of the spending increase funds research conducted by private businesses or universities. For the nondefense shock, the eventual spending reversal is driven exclusively by decreases in funding for businesses and R&D centers. The increase in funding for research at universities and government agencies is instead highly persistent, which likely mirrors the persistent impact of the nondefense shock on funding for more fundamental research. For the defense shock, in contrast, the reversal in spending affects the R&D activity of all performers.

The final row in Figure 8 shows a decomposition of the response of federal R&D spending across the main federal funding agencies. As the left panel shows, a nondefense shock leads to persistent increases in funding by NASA, NIH, and the NSF. Quantitatively, the increase in spending by NASA is by far the largest in size, although NIH funding also sees a meaningful and persistent increase. The increase in nondefense spending also appears to crowd out some of the funding for defense R&D, as there are decreases in DoD outlays for R&D throughout the entire forecast horizon. Energy R&D spending—which covers both defense and nondefense functions—initially increases, but decreases at longer horizons. Unsurprisingly, the bottom right panel of Figure 8 shows that a positive defense R&D shock leads mainly to increases in DoD spending. There is little evidence for large crowding-out effects on funding for the nondefense agencies.

The decomposition by federal agency shows that, in dollar terms, the nondefense shock is dominated by R&D funding for NASA. This finding suggests that changes in appropriations for NASA, especially at the time of the agency’s rapid growth during the space race, are potentially very important as a source of identifying variation. In Appendix C.4, we show that the positive TFP response to a nondefense shock is robust to excluding NASA appropriations during the height of the space race (FY1958-63). Whereas the uncertainty around the estimates increases meaningfully, the long-run TFP increase remains significant and similar in size. In Sections 4 and 5 below, we will consistently report results for specifications that omit the space race from the narrative measures to verify the sensitivity of the results to this potentially influential part of the sample.

E. Indirect Channels for Long-Run TFP Spillovers

The evidence presented so far is consistent with a significant direct effect of government nondefense R&D on the level of innovative activity with spillovers on productivity in the business sector. However, the long-run TFP responses in Figure 6 are potentially also shaped by additional indirect effects. For example, the appropriations shocks may affect other long-

run determinants of productivity growth, such as R&D funding by the private sector or resources allocated to public infrastructure with spillovers on business-sector productivity. We next explore the importance of these indirect channels.

We first investigate how changes in appropriations affect total R&D capital in the economy (private and public). The top row in Figure 9 presents a decomposition of the impulse response of total R&D capital into the individual contributions of each funding sector. These contributions are estimated as in the previous section, using the following approximation of the log change in total R&D capital, K_t^{tot} ,

$$(4) \quad \Delta \ln K_t^{tot} \approx \sum_j \frac{s_t^j + s_{t-1}^j}{2} \Delta \ln K_t^j$$

where K^j is R&D capital of category j in constant dollars and s^j denotes the nominal share of capital of category j in total R&D capital ($s^j = K^{n,j}/K^{n,tot}$, where $K^{n,j}$ is capital in category j in current dollars). The four main funders of total R&D capital are (i) federal defense agencies, (ii) federal nondefense agencies, (iii) state and local governments, and (iv) the private sector. The contributions of each funding category are the cumulative impulse response of the individual terms in (4) estimated with the baseline specification in (2). The impulses are scaled such that the peak increase in federal nondefense R&D capital (left panel) or defense capital (right panel) is one real dollar. The resulting estimates can be interpreted as the dollar change in capital in category j given a peak increase in nondefense (or defense) R&D capital of one dollar.

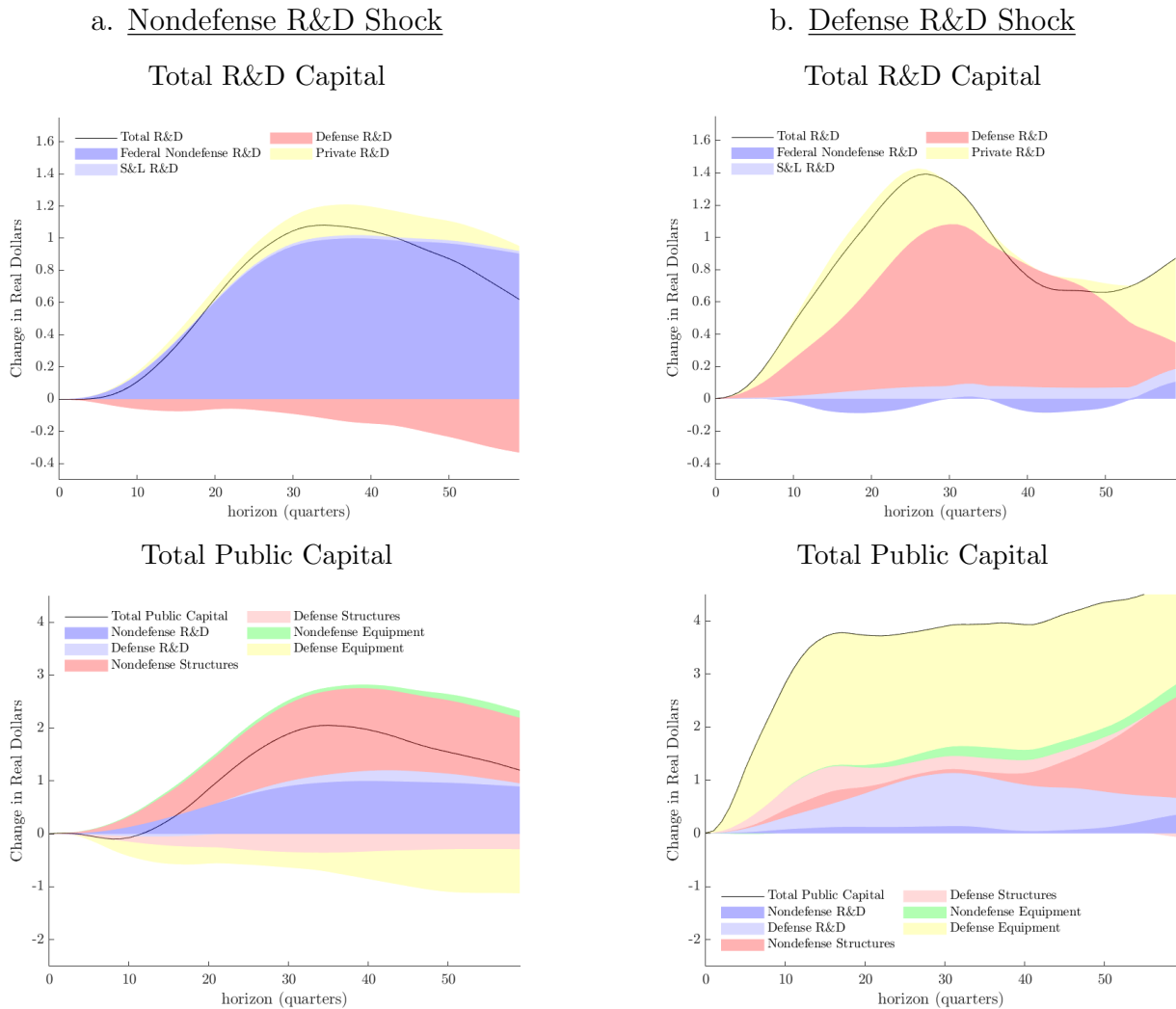
The top panels in Figure 9 show that the defense and nondefense shocks primarily affect R&D capital within the own category. A positive nondefense shock leads to some crowding out of defense R&D capital by up to 20 cents after 15 years, while there is very little effect of a defense shock on nondefense R&D capital. Consistent with the framework in Akcigit et al. (2020) and the evidence in De Lipsis et al. (2022), there are increases in private R&D capital, both for nondefense as well as defense shocks. The increases in private R&D capital following a nondefense shock, however, are relatively small, with a maximum of 19 cents per federally-funded dollar. For defense R&D, the peak increase in private R&D capital is somewhat larger at 52 cents per federally-funded dollar.⁹

To investigate how the shocks to government R&D affect the various other components of the public capital stock, the bottom panels of Figure 9 depict analogous decompositions of the response of the total public capital stock by type of capital. The responses in this case are scaled to induce a one-dollar peak increase in government R&D capital in the nondefense (left) or defense (right) category.

The bottom left panel in Figure 9 shows that, in the decomposition of total public capi-

⁹Changes in domestic R&D spending may also affect R&D spending in the rest of the world, which in turn could lead to spillovers domestically. Because of data availability, we do not look into the role of global spillovers.

Figure 9: Total R&D and Public Capital Following an Increase in R&D Appropriations



Notes: Estimates based on (2) using the orthogonalized narrative measure of changes in federal nondefense (left panel) and defense (right panel) R&D appropriations, see (1). R&D capital includes software. Impulses scaled to imply a unit peak increase in federal nondefense (left) or defense (right) R&D capital. See Appendix A for variable definitions. Sample: 1948Q1–2021Q4.

tal, there is no evidence of crowding out of defense R&D capital. However, the nondefense shock leads to a broader reallocation from defense to nondefense public capital. While the defense capital stock for structures (e.g., military bases and facilities) as well as equipment (e.g., ships and aircraft) declines, there is a relatively large increase in nondefense structures (schools and universities; roads; power, water and sewer systems, etc). For a peak increase in nondefense R&D capital of one dollar, the stock of nondefense structures rises by up to 1.58 dollars after about 8 years. While this increase is much smaller than the average ratio of structures-to-R&D capital in the nondefense category, it is almost certainly too large to be explained exclusively by the reclassification of R&D plant expenditures as ‘structures’ in the national accounts. In Appendix C.7, we present further decompositions showing that about

80 percent of the increase in structures originates with state and local governments, which finance most nondefense public infrastructure. Given the shared funding arrangements for interstate highways, one possibility is that nondefense R&D appropriations are positively correlated with federal transfers for interstate highway spending. However, the federal appropriations bills financing increases in R&D generally do not provide significant funding for public infrastructure investment via transfers to state and local governments. In Appendix C.7, we further show that federal transfers, if anything, decline in response to a positive nondefense R&D shock. The rise in investment expenditures by state and local government is instead financed initially by debt, and later on by increases in tax revenues relative to other expenditures. The rise in state and local structures is also broad-based, with the largest increases in education structures (schools and universities), followed by highways and streets, and power, water, and sewer systems. Overall, the expansion in public infrastructure appears large enough to potentially generate meaningful indirect productivity effects.

The bottom right panel in Figure 9 shows that a defense R&D shock is also associated with increases in other types of public capital. In general, defense shocks cause only negligible changes in the nondefense capital categories, although nondefense structures do increase meaningfully toward the end of the forecast horizon. There is, however, a large and immediate increase in defense equipment (up to 2.48 dollars), and also a smaller increase in defense structures (up to 48 cents). For defense functions, it is easier to point to direct linkages between appropriations for R&D and other military investments. For example, the BEA treats the ‘operational systems development’ component of DoD’s Research, Development, Test, and Evaluation budget accounts, as gross investment in equipment, not R&D.¹⁰ More importantly, the annual DoD appropriations bills that fund defense R&D also fund procurement (i.e., equipment), and funding for developing new military hardware typically leads to purchases of the newly developed equipment. Moreover, the same geopolitical events that motivate significant increases in defense R&D are likely to also motivate other military investments, and these may not be fully predicted by the Ramey and Zubairy (2018) military news variable in the set of controls. In contrast to nondefense public infrastructure, however, there is little evidence in the literature that defense capital has any effects on productivity, and the convention is to assume that these effects are zero, e.g. CBO (2016). The increases in defense capital following defense shocks are therefore unlikely to be a major influence on the long-run TFP response.

The main conclusions regarding the indirect channels for long-run TFP spillovers are the following. First, the impact of shocks to government R&D in one category (i.e. defense or nondefense) on the other is relatively small or absent. The orthogonalized narrative mea-

¹⁰Due to data limitations, our measure of DoD R&D appropriations is based on the full Research, Development, Test, and Evaluation (RDT&E) accounts. Defense structures are largely funded by the separate Military Construction and Veterans Affairs Appropriations bills.

asures therefore appear largely successful in picking up idiosyncratic changes in nondefense or defense R&D, such that reallocations of resources across both categories of R&D are unlikely to be important for the TFP responses in Figure 6. Second, positive shocks to R&D appropriations lead to higher private spending on R&D, such that private and government-funded R&D capital appear to be complements rather than substitutes. At the same time, the increases in private R&D capital are relatively small, especially after a nondefense R&D shock. Finally, the responses of public infrastructure are sizeable. Given the widespread evidence for productivity spillovers of public infrastructure, these responses are potentially important in determining the long-run TFP responses to the appropriations shocks.

IV. The Production Function Elasticity of Government R&D

Figure 6 showed that a nondefense shock raising government R&D capital by one percent increases TFP by around 0.2 percent in the longer run. The results in the previous section suggest that indirect effects may contribute meaningfully to the TFP response, in particular through the impact on nondefense public infrastructure. To isolate the direct spillover effects on business-sector productivity, in this section we structurally estimate the aggregate production function elasticity of government R&D capital.

A. Empirical Methodology and Identification Assumptions

The starting point is the following aggregate production function for quarterly aggregate output growth in the business sector,

$$(5) \quad \Delta f_t = \alpha'_t \Delta m_t + \eta_t \Delta q_t + \phi_t \Delta k_t + \Delta \nu_t$$

where f_t is the log of real business-sector output, the vector m_t collects all business-sector capital (including R&D) and labor inputs in logs, q_t is the log of the public infrastructure capital stock, k_t is the log of government R&D capital, and ν_t is technological progress after accounting for growth in both types of public capital, q_t and k_t . The parameters in α_t are the production function elasticities for all private inputs, η_t is the elasticity to public infrastructure, and ϕ_t is the elasticity to government R&D capital. As is the convention in the literature, it is assumed that defense capital does not generate any TFP spillovers. The notation henceforth assumes that all growth rates are demeaned such that constants are omitted without loss of generality.

Defining $\Delta tfp_t = \Delta f_t - \alpha'_t \Delta m_t - \epsilon_t$, and assuming constant elasticities with respect to public capital, (5) can be rewritten as

$$(6) \quad \Delta tfp_t = \eta \Delta q_t + \phi \Delta k_t + \Delta w_t, \quad \Delta w_t = \Delta \nu_t + \epsilon_t, \quad E[\Delta w_t] = 0$$

where Δtfp_t is the utilization-adjusted measure of business-sector TFP growth (or Solow

residual) constructed by Fernald (2012), and ϵ_t is measurement error. The unobserved residual term Δw_t consists of the productivity growth term $\Delta \nu_t$, as well as any discrepancy ϵ_t between measured TFP and actual productivity growth. Apart from measurement errors in Δf_t and Δm_t , the discrepancy between measured and actual productivity growth could be due to mismeasurement of the elasticities in α_t . As explained in Fernald (2012), the identification of α_t —which in practice is based on factor cost shares—relies on theoretical assumptions that may not hold in reality, e.g. such as the absence of markups. As a result, ϵ_t cannot generally be treated as classical measurement error, as it potentially also contains the influence of all determinants of private factor inputs, including shocks to government R&D. The other endogeneity concern is that movements in the residual productivity term $\Delta \nu_t$ are correlated with government investment decisions.

Our strategy to address endogeneity relies on two steps. First, we treat η as a known constant, and analyze estimates of ϕ across a range of values of η consistent with the empirical literature. A recent survey by Ramey (2021) establishes a plausible range of 0.065 to 0.12 for η . We use these endpoints to estimate a corresponding range for ϕ , and we also consider the intermediate value of $\eta = 0.08$, which is the value that the CBO currently uses to quantify the impact of public infrastructure (CBO 2021). Treating η as known, we define $\widetilde{\Delta t f p}_t \equiv \Delta t f p_t - \eta \Delta q_t$, i.e. the growth in measured TFP adjusted for the productivity effects of public infrastructure capital. Substituting into (6), this definition leads to the structural estimation equation,

$$(7) \quad \widetilde{\Delta t f p}_t = \phi \Delta k_t + \Delta w_t$$

where in general $E[\Delta k_t \Delta w_t] \neq 0$ such that endogeneity remains a concern.

The second step in our identification strategy is to estimate ϕ in (7) using the SP-IV estimator of Lewis and Mertens (2023). The SP-IV estimator is a GMM estimator with an intuitive closed-form solution as the OLS estimate in a regression of estimated impulse responses to shocks that are uncorrelated with the structural error, also see Appendix D.1. In our application, we use the responses to R&D appropriations shocks discussed in the previous section.¹¹ Note that the functional form in (7) makes very specific assumptions about the lags between R&D spending and the productivity effects. Appendix D.1 shows that these assumptions in fact align very well with the impulse responses, which are estimated without imposing any rigid assumptions about timing.

To understand the identifying moments in the GMM problem that generates the SP-IV estimator, let $\Omega_{t-1} \equiv \{\ln a_{t-j}^i, y_{t-j}, x_{t-j}\}_{j=1}^p$ define the full set of lagged controls included in the local projections in (2). Letting z_t denote the $N_z \times 1$ vector containing the N_z narrative

¹¹One minor difference is that the impulses underlying the SP-IV estimator are estimated in balanced samples rather than iteratively, as is required for the inference formulas developed in Lewis and Mertens (2023). Appendix C.4 shows the impulse response estimates are very similar in the balanced sample.

measures used to for identification, the HN_z moment conditions that identify ϕ are

$$(8) \quad E[w_t^\perp(h)z_t^\perp] = 0 ; h = 0, \dots, H-1 \quad , \quad w_t^\perp(h) \equiv \widetilde{tfp}_t^\perp(h) - \phi k_t^\perp(h)$$

where z_t^\perp is the one-step ahead forecast error from the linear projection of z_t on Ω_{t-1} and $\widetilde{tfp}_t^\perp(h)$ and $k_t^\perp(h)$ are the $h+1$ -step ahead forecast errors from linear projection of \widetilde{tfp}_{t+h} and k_{t+h} on Ω_{t-1} . Intuitively, the identifying conditions in (8) exploit the fact that, if the structural relationship in (7) holds in the raw data, it also holds across the $h+1$ -step ahead forecast errors after projection on Ω_{t-1} for any forecast horizon h . The key exogeneity assumption in (8) is that, after projection on Ω_{t-1} , the period t innovations in the narrative measures, z_t^\perp , are uncorrelated with the ex-post deviations $w_t^\perp(h)$ from the structural relationship across the period t forecast errors at all forecast horizons $h = 0, \dots, H-1$.

The conditional forecast errors $w_t^\perp(h)$ arise either because of accumulated technological progress $\Delta\nu$ between period t and $t+h$ that is unpredicted by the projection on Ω_{t-1} , or because of accumulated measurement error ϵ in measured TFP between period t and $t+h$ that is unpredicted by projection on Ω_{t-1} . The first part of the exogeneity requirement is a zero correlation between z_t^\perp and all sources of unpredicted productivity growth between t and $t+H-1$ that are not driven by the accumulation of government R&D capital. Changes in appropriations in quarter t are plausibly uncorrelated with future realizations of technology shocks in quarters $t+h > t$. The narrative classification step is intended to preclude any contemporaneous nonzero correlation between R&D appropriations and technology shocks at $h=0$. In addition, the typical recognition and legislative lags in fiscal policy arguably make any systematic policy reaction to technology shocks within the same quarter unlikely. Finally, we assume that conditioning on the variables in Ω_{t-1} suffices to remove any joint influences of past shocks (realized prior to quarter t) on z_t and future productivity growth.

The second part of the exogeneity requirement is that z_t^\perp is uncorrelated with any unpredicted accumulated measurement error in TFP across the forecast horizon. If the measurement error in TFP is strictly exogenous, the identifying conditions in (8) remain perfectly valid. If the error is the result of mismeasurement of the elasticities of private factor inputs, then $w_t^\perp(h)$ is generally a function of any shock that causes changes in the factor inputs for which the elasticities are mismeasured. In that case, we appeal to the same arguments as above to motivate the assumption that z_t^\perp is not correlated with other shocks: non-causal correlations with future non-technology shocks are implausible, the narrative classification and policy lags eliminate any contemporaneous correlations with non-technology shocks, and the control set Ω_{t-1} removes the confounding influences of correlations with past non-technology shocks, if there are any.

The same arguments do not apply, however, to the shocks to R&D appropriations themselves. If appropriations shocks cause meaningful changes in private factor inputs, and

these changes are not properly accounted for in the measurement of TFP, then (8) would not necessarily hold, and the SP-IV estimate of ϕ would be potentially biased. However, the estimated impulse responses of labor and non-R&D capital inputs to R&D appropriations shocks, reported in Appendix C.6, imply that any errors in the production function elasticities for these factor inputs would have to be very large to introduce a quantitatively significant source of bias.¹² Mismeasurement could be a more serious concern for private R&D capital because of knowledge spillovers, which are not necessarily well captured by the cost share of private R&D capital. As shown earlier, both R&D shocks lead to increases in private R&D capital. If the methodology in Fernald (2012) underestimates the aggregate elasticity of private R&D capital, the estimates of ϕ are likely to be biased upward. Fortunately, Figure 9 showed that the increases in business-sector R&D capital are relatively small, especially for the nondefense R&D shock, such that the bias is likely relatively small. Global spillovers through changes in R&D spending abroad are another potential source of bias, but its importance or direction are not immediately obvious.

The estimation equation in (7) does not distinguish between defense and nondefense government R&D capital, whereas the TFP responses in Figure 6 indicate that the spillovers on business-sector productivity are potentially quite different. We therefore also consider specifications that allow for different elasticities of defense and nondefense government R&D capital. Using the approximation $\Delta k_t \approx s_{ND,t} \Delta k_t^{ND} + (1 - s_{ND,t}) \Delta k_t^D$, where $s_{ND,t}$ is the nominal nondefense share of total government R&D capital averaged over t and $t - 1$, the estimation equation is adjusted as follows:

$$(9) \quad \widetilde{\Delta t f p}_t = \phi_{ND} (s_{ND,t} \Delta k_t^{ND}) + \phi_D (1 - s_{ND,t}) \Delta k_t^D + \Delta w_t, \quad E[\Delta w_t] = 0$$

This specification assumes production function elasticities to Δk_t^{ND} and Δk_t^D that scale with $s_{ND,t}$ and $1 - s_{ND,t}$, such that ϕ_{ND} (ϕ_D) measures the percent change in TFP for a one percent increase in total government R&D capital that is driven exclusively by an increase in nondefense (defense) R&D capital. The scaling has the advantage that the magnitudes of ϕ_{ND} and ϕ_D can be compared to the estimates of ϕ in the simpler specification in (7). For the purpose of calibrating an aggregate production function with constant elasticities on Δk_t^{ND} and Δk_t^D , the estimates of ϕ_{ND} and ϕ_D can be multiplied by 0.5, which is approximately the average of $s_{ND,t}$ across the sample. An alternative approach, pursued in Appendix D.4, treats the elasticities to Δk_t^{ND} and Δk_t^D as constants in the estimation.

When $\phi_{ND} \neq \phi_D$, the estimates of ϕ in the simpler specification in (7) are not necessarily consistent for either ϕ_{ND} or ϕ_D . In that case, the response to a nondefense shock only identifies $\phi = \phi_{ND}$ in two situations: either defense R&D capital does not lead to any

¹²For example, following a nondefense shock that increases government R&D capital by one percent, there is a gradual and statistically significant increase in non-R&D business-sector capital of up to 0.2 percent, see Appendix C.6. Assuming a measured elasticity of non-R&D capital of 0.33, a one-basis-point effect on measured TFP requires a 15 percent error in the capital elasticity ($0.2 \times 0.33 \times 0.15 \approx 0.01$).

changes in nondefense R&D capital, or there are no productivity effects of defense R&D, $\phi_D = 0$. Similarly, the response to a defense shock only identifies $\phi = \phi_D$ if there is no impact on nondefense R&D capital, or else if $\phi_{ND} = 0$. As discussed earlier, the impulse responses do not show much crowding-out of one type of government R&D capital by the other, such that we expect both specifications to provide similar estimates.

As is well known, IV estimation can be unreliable when identification is too weak. Applying the diagnostic test of Lewis and Mertens (2023) reveals that weak instruments are a concern in several of the specifications that we consider below. For this reason, we use the weak-instrument-robust GMM inference methods of Kleibergen (2005), which remain valid regardless of the strength of identification. Other problems can arise when the number of identifying moments is too large (Han and Phillips 2006; Newey and Windmeijer 2009). Given the high persistence in the impulse response estimates for \widetilde{tfp} and k , there is limited additional identifying information in immediately adjacent quarterly horizons. To mitigate potential many-instrument problems, we therefore do not use all horizons for identification, but only those at one-year intervals, at $h = 3, 7, 11, \dots, 59$.¹³

B. Estimation Results

Table 1 reports estimates of ϕ , ϕ_{ND} , and ϕ_D for various specifications, together with 95 percent weak-instrument-robust confidence intervals. The first five rows show estimates of ϕ in (7) with only total government R&D capital, whereas the remaining rows show estimates for ϕ_{ND} and ϕ_D in (9) with nondefense and defense R&D capital stocks included separately. The first two columns report results for TFP adjusted for public infrastructure, \widetilde{tfp}_t , using the benchmark value of $\eta = 0.08$. The remaining columns show the elasticity estimates based on variation in nondefense capital using the lower and higher values of $\eta = 0.065$ and 0.12 , respectively. For brevity, the elasticities based on variation in defense R&D capital for the alternative values of η are omitted.

The first row in Table 1 shows estimates based on the impulse responses identified with the (orthogonalized) narrative measure for nondefense appropriations, z_t^{ND} . For $\eta = 0.08$, the point estimate of ϕ in (7) based on the response to a nondefense shock is 0.12. This estimate is highly statistically significant and fairly precisely estimated, with a 95 percent robust confidence interval ranging from 0.09 to 0.16. The point estimates decrease with the assumed value of η , with $\hat{\phi} = 0.12$ for $\eta = 0.065$ and $\hat{\phi} = 0.11$ for $\eta = 0.12$. Assuming a larger elasticity of public infrastructure means that a greater portion of the TFP increase after a nondefense R&D shock in Figure 6 is attributed to the increase in public infrastructure shown in Figure 9.¹⁴ Consequently, the increase in TFP after adjusting for

¹³Identification is therefore based on 15 moments (rather than 60) for specifications identified with a single impulse response, and 30 moments (rather than 120) for those identified with two. While the application is different, simulation results in Lewis and Mertens (2023) for the estimation of the hybrid New Keynesian Phillips curve indicate that Kleibergen (2005) inference for SP-IV displays only small size distortions in samples of 250 quarters and 20 identifying horizons.

¹⁴The point estimate is $\hat{\phi} = 0.16$ when assuming $\eta = 0$, and $\hat{\phi} = 0.04$ when $\eta = 0.39$. The latter value is based on

TABLE 1: ESTIMATES OF PRODUCTION FUNCTION ELASTICITIES OF GOVERNMENT R&D CAPITAL

Public R&D		Intermediate $\eta = 0.08$		Low $\eta = 0.065$	High $\eta = 0.12$	
Measure	Instruments	$\hat{\phi}/\hat{\phi}_{ND}$	$\hat{\phi}/\hat{\phi}_D$	$\hat{\phi}/\hat{\phi}_{ND}$	$\hat{\phi}/\hat{\phi}_{ND}$	
[1]	Total	Exo ND	0.12*** (0.09,0.16)	0.12*** (0.10,0.16)	0.11*** (0.08,0.15)	
[2]	Total	Exo ND, No Space	0.14*** (0.09,0.31)	0.14*** (0.09,0.32)	0.13*** (0.08,0.29)	
[3]	Total	All ND	0.11*** (0.09,0.15)	0.12*** (0.09,0.16)	0.10*** (0.08,0.14)	
[4]	Total	Exo D		-0.30* (-1.39,0.01)		
[5]	Total	All D		-0.29 (-1.27,0.02)		
[6]	ND/D	Exo ND	0.11*** (0.06,0.22)	-0.01 (-0.25,0.43)	0.12*** (0.06,0.23)	0.10*** (0.05,0.21)
[7]	ND/D	Exo ND/D	0.10*** (0.06,0.17)	-0.06 (-0.26,0.37)	0.10*** (0.06,0.18)	0.09*** (0.06,0.17)
[8]	ND/D	Exo ND, No Space	0.14 (-2.00 [†] ,0.50)	0.20 (-2.00 [†] ,1.62)	0.14 (-2.00 [†] ,0.51)	0.13 (-2.00 [†] ,0.48)
[9]	ND/D	All ND	0.11*** (0.06,0.20)	-0.02 (-0.24,0.40)	0.11*** (0.07,0.21)	0.10*** (0.05,0.19)

Notes: Rows [1]-[5], SP-IV estimates of ϕ (government R&D) in (7); rows [6]-[9] SP-IV estimates of ϕ_{ND} (nondefense) and ϕ_D (defense) in (9). All specifications include the baseline set of lagged controls described in Section 3. Numbers in parentheses are 95 percent weak-instrument-robust confidence intervals based on inverting the KLM statistic of Kleibergen (2005). Test inversion is limited to a grid with endpoints -2 and 2 , \dagger denotes intervals constrained at these endpoints. Subvector inference in rows [6]-[9] is based on the projection method. Stars *, ** and *** denote statistical significance at 10, 5 and 1 percent levels respectively. ‘Exo ND/D’ denotes the orthogonalized narrative measure of exogenous changes in nondefense/defense R&D appropriations. ‘All ND/D’ denotes the orthogonalized series of all changes in nondefense/defense R&D appropriations, ignoring our narrative classification. ‘No Space’ indicates that the instrument is also orthogonalized to all changes in space appropriations between 1958 and 1963. Sample: 1948Q1–2021Q4.

public infrastructure is smaller when η is larger, see also Appendix D.1. However, in practice the estimates of ϕ are very similar across Ramey’s (2021) plausible range of values for $\eta \in [0.065, 0.12]$.

Rows [2] and [3] in Table 1 show results based on impulse responses identified with different measures of nondefense R&D appropriations. Row [2] shows the estimates when the narrative nondefense measure is further orthogonalized to all appropriation changes for space R&D from 1958 to 1963, the period with the fastest growth in public nondefense R&D capital in the sample. The resulting point estimates remain highly significant and are slightly larger than in row [1], around 0.13 to 0.14 depending on η . Without the space race as identifying variation, the robust confidence intervals become notably wider, and in particular, substantially larger values of ϕ cannot be ruled out. Row [3] shows estimates based on responses to all changes in nondefense R&D appropriations (after orthogonalizing to all defense R&D changes), i.e. regardless of their narrative classification. The estimates

Aschauer (1989), and is the highest estimate mentioned in Ramey (2021).

are very similar to those in row [1], and the narrative classification therefore matters little for the identification of ϕ .

The next two rows in Table 1 report estimates of ϕ identified with impulse responses to defense R&D shocks rather than nondefense shocks. Row [4] reports $\hat{\phi} = -0.30$ based on the (orthogonalized) narrative measure of exogenous changes in defense R&D appropriations z_t^D , and row [5] shows that $\hat{\phi} = -0.29$ when using all changes in defense R&D appropriations regardless of their narrative classification. Unlike for the nondefense R&D shocks, both estimates are negative. The confidence bands are very wide, and only the first estimate is marginally significant at the 10 percent level. The narrative classification is again unimportant.

The remaining rows in Table 1 report estimates of ϕ_{ND} and ϕ_D from the specification in (9) that includes both types of government R&D capital simultaneously, with subvector inference based on the projection method (the simultaneous confidence sets are in Appendix D.2). In row [6], ϕ_{ND} and ϕ_D are identified jointly using the same narrative nondefense measure as in row [1]. The resulting estimate of ϕ_{ND} is 0.11 for intermediate η , 0.12 for low η , and 0.10 for high η , all of which are statistically significant and very close to the corresponding estimates in row [1]. In contrast, the point estimate of ϕ_D is small, -0.02, and statistically insignificant.

Rows [7]-[9] in Table 1 provide additional estimates of ϕ_{ND} and ϕ_D identified with different impulse responses. In row [7], identification is based on impulse responses to both defense and nondefense R&D shocks using the two original exogenous narrative measures $\Delta a_t^{exo,i} / K_{t-4}^i, i = D, ND$, i.e. without mutual orthogonalization. Rows [8] and [9] are instead based on the same narrative measures of nondefense R&D shocks as in rows [2] and [3], i.e., excluding the space race and using all changes in nondefense R&D appropriations, respectively. The estimates of ϕ_D range from -0.06 to 0.19, but are statistically insignificant in all specifications. The estimates of ϕ_{ND} , on the other hand, are very close to those in rows [2] and [3], and they also remain highly statistically significant. The only exception is in row [8]: Without the large NASA appropriations early in the space race, identification weakens to the point where the robust confidence intervals become very wide and include zero in all cases. This inference result is the only substantive difference between the weak-IV-robust inference methods and traditional Wald inference, which leads to rejection of no spillovers even when excluding the space race, see Appendix D.3. For the interested reader, the same Appendix provides further robust inference results, including the simultaneous confidence sets associated with the estimates in rows [6]-[9]. Finally, Appendix D.4 reports results for the alternative version of (9) that instead assumes constant elasticities to Δk_t^{ND} and Δk_t^D . The results are broadly consistent with those in Table 1. After scaling appropriately for comparability, the estimates of ϕ_{ND} range from 0.06 to 0.16, but are generally somewhat smaller than those reported in Table 1 for most specifications. The comparable estimates of ϕ_D range from -0.23 to 0.16, and are all insignificant and imprecisely estimated.

A key conclusion from Table 1 is that the various estimates of the elasticity to government R&D capital based on variation in nondefense R&D do not vary greatly, ranging from 0.09 to 0.14 and a midpoint of approximately 0.12. Multiplying by the average share of nondefense R&D capital of 0.5, the estimates imply elasticities to nondefense R&D capital ranging from 0.045 to 0.07, with a midpoint of 0.06. The estimates of the nondefense elasticity are relatively precise (even under weak-instrument-robust inference) and highly statistically significant, with the exception of those in row [8]. Overall, the results point to sizeable direct spillovers of nondefense government R&D on business-sector productivity. In contrast, the elasticity estimates based on variation in defense R&D vary considerably across specifications, from -0.30 to 0.19, and come with wide confidence bands. Unlike for nondefense R&D capital, we cannot draw any sharp conclusions regarding the size—or even the sign—of the direct spillovers of defense R&D.

V. The Macroeconomic Returns to Government R&D

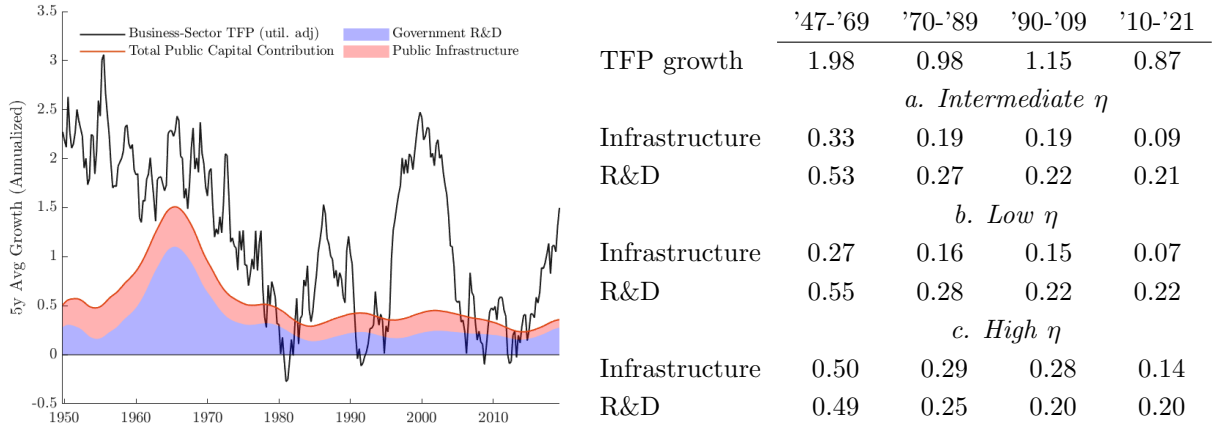
This section discusses the implications of the production function elasticity estimates in Table 1 for the historical contribution of government R&D to postwar productivity growth, and provides estimates of the implied rate of return to government R&D.

A. Historical Contributions to TFP Growth

With the estimates of the TFP spillovers of government R&D in hand, it is possible to assess the contribution of public capital accumulation to postwar business-sector TFP growth. When calculating the contributions of the different types of public capital, we make the assumption that there are no TFP spillovers from defense R&D, i.e. $\phi_D = 0$. While the elasticity for defense R&D is imprecisely estimated, this assumption is consistent with the estimation results in Table 1. We also continue to assume that defense capital (i.e. defense equipment and structures) does not generate any TFP spillovers, as is the convention in the literature. The contribution of nondefense R&D is calculated as $\hat{\phi}_{ND} \times (s_{ND,t} \Delta k_t^{ND})$. For $\hat{\phi}_{ND}$, we use the point estimates from row [1] in Table 1, which are in the middle of the range of estimates across the different specifications, for each of the three different values of η . The contribution of public infrastructure is calculated as $\eta \Delta q_t$. The figure in the left panel of Figure 10 shows the resulting contributions of government R&D and public infrastructure for $\eta = 0.08$. The table in the right panel of Figure 10 reports averages over selected time windows for each of the three values of η .

The main finding is that government R&D has contributed substantially to total TFP growth since WWII R&D —accounting for roughly one quarter of the total, on average—regardless of the value of η within Ramey’s (2021) plausible range. The contribution of government R&D is consistently similar in size to the contribution of public infrastructure, and often larger. Between 1947 and 1969—when both government R&D and public infrastruc-

Figure 10: TFP Growth Contributions of Public Infrastructure and Government R&D



Notes: The left figure shows the annualized five-year average growth rate of utilization-adjusted TFP growth from Fernald (2012) and the contributions of public capital assuming $\eta = 0.08$.

ture grew at a rapid pace—the combined contribution of growth in public capital accounts for 0.82 to 0.99 percentage points of total TFP growth of 1.98 percentage points. For the low value $\eta = 0.065$, the contribution of government R&D is about twice as large as that of public infrastructure: 0.55 versus 0.27 percentage points, respectively. For the high value $\eta = 0.12$, each component of public capital contributes about half a percentage point. Relative to 1947-69, average TFP growth decelerated by 1.0 percentage point in 1979-89. The combined contribution of slower growth in public capital ranges from 0.38 to 0.45 percentage points as η increases from low to high. For low η , around 70 percent of the contribution of public capital $((0.55 - 0.28)/0.38 = 0.71)$ is due to the slowdown in government R&D. For high η , the slowdown in R&D contributes slightly more than half $((0.49 - 0.25)/0.45 = 0.53)$. According to our estimates, therefore, the scaling back of government R&D in the 1970s-80s was at least as important for explaining the slowdown in productivity as the slower pace of public infrastructure investment. The contribution of government R&D to TFP growth is 20 to 22 basis points in both 1990-2009 and 2010-2021. In contrast, the contribution of public infrastructure to TFP growth fell by half in 2010-2021 relative to 1990-2009 as a result of the further slowing of growth in public infrastructure.

The left panel in Figure 10 shows that government R&D spillovers were particularly important in the 1960s and early 1970s. A potential caveat to this finding is that the assumption of constant η throughout the entire postwar sample may not be realistic. Fernald (1999), for example, argues that road construction in the late 1950s and 1960s provided a one-time, unrepeatable, large productivity boost. If that is the case, our calculations likely overstate the contribution of government R&D relative to public infrastructure in that part of the sample. The figure in the left panel also shows that public investment—either in R&D or infrastructure—plays little role in accounting for the high TFP growth immediately after WWII. It is possible that the higher TFP growth in the 1950s was at least partially driven by

wartime defense R&D, which plays no role in our decomposition because of our assumption that $\phi_D = 0$.¹⁵ Government R&D also matters little for the TFP burst during the IT revolution in the 1990s.

B. Rates of Return to Government R&D

The production function elasticities reported in Table 1 can be translated into approximate rates of return to government R&D. The net rate of return on government R&D is $\rho_t^n = \rho_t - \delta_t$, where $\rho_t = \phi Y_t / K_t$ is the marginal product of K_t (or gross return), K_t is the government R&D capital stock, Y_t is output, and δ is the depreciation rate of government R&D capital. We restrict attention to the return to nondefense R&D, and use the estimates reported in the $\hat{\phi} / \hat{\phi}_{ND}$ columns of Table 1 for the calculations. To obtain an average gross rate of return, we divide the elasticity estimates by the average ratio of government R&D capital to GDP (both in constant 2012 dollars), which is around 6 percent. We use real GDP rather than business sector output for calculating the ratio based on an assumption that the productivity spillovers extend identically to production in the non-business sectors.

The rates of return calculated as just described are derived from the earlier estimates of the elasticity ϕ , which is assumed to be constant over the estimation sample. A common alternative approach to estimating returns is instead to estimate ρ as a constant, see e.g. Hall et al. (2010). Using $\Delta k_t \approx \Delta K_t / K_t$ and $\phi_t = \rho K_t / Y_t$, and substituting into (7) yields

$$(10) \quad \Delta t \widetilde{f} p_t = \rho \frac{\Delta K_t}{Y_t} + \Delta w_t$$

To estimate ρ , we follow the same methodology as in the previous section, but now with $\Delta K_t / Y_t$ as the endogenous regressor. Specifically, we estimate (10) using SP-IV regressions of the cumulative impulse responses of $\Delta t \widetilde{f} p$ and $\Delta K_t / Y_t$ to the appropriations shocks. We again use real GDP rather than business output as the measure of Y_t , which means that we assume that the spillovers are the same in all sectors in the economy. We also consider specifications that explicitly allow for different returns on defense and nondefense government R&D capital:

$$(11) \quad \Delta t \widetilde{f} p_t = \rho_{ND} \frac{\Delta K_t^{ND}}{Y_t} + \rho_D \frac{\Delta K_t^D}{Y_t} + \Delta w_t$$

As before, we only use forecast horizons at one-year intervals for the identifying moments to mitigate many-instrument problems, and conduct inference using the weak-instrument-robust procedures of Kleibergen (2005).

Table 2 reports the estimates of the gross rate of return on nondefense R&D, both based on the elasticity estimates and those estimated directly. The various rows in the

¹⁵Including wartime R&D could offer more identifying variation for estimating ϕ^D , but is unlikely to influence the estimates of ϕ^{ND} , as federal R&D expenditures were almost exclusively for defense activities before the 1950s.

TABLE 2: ESTIMATES OF THE RETURN TO GOVERNMENT R&D CAPITAL

Government R&D Measure			Intermediate $\eta = 0.08$		Low $\eta = 0.065$		High $\eta = 0.12$	
	Instruments		$\hat{\phi}_{ND}$ $\times \frac{Y}{K}$	$\hat{\rho}_{ND}$	$\hat{\phi}_{ND}$ $\times \frac{Y}{K}$	$\hat{\rho}_{ND}$	$\hat{\phi}_{ND}$ $\times \frac{Y}{K}$	$\hat{\rho}_{ND}$
[1]	Total	Exo ND	2.04	2.11*** (1.32,2.73)	2.11	2.18*** (1.38,2.77)	1.86	1.94*** (1.16,2.63)
[2]	Total	Exo ND, No Sp.	2.40	2.88*** (1.39,5.00 [†])	2.47	2.94*** (1.47,5.00 [†])	2.21	2.73** (1.18,5.00 [†])
[3]	Total	All ND	1.96	1.94*** (1.29,2.52)	2.03	2.00*** (1.34,2.56)	1.78	1.78*** (1.13,2.43)
[4]	ND/D	Exo ND	1.92	2.40*** (0.79,3.93)	1.99	2.46*** (0.85,3.97)	1.75	2.24*** (0.64,3.86)
[5]	ND/D	Exo ND/D	1.69	2.05** (0.23,3.83)	1.76	2.11** (0.27,3.86)	1.52	1.89** (0.12,3.75)
[6]	ND/D	Exo ND, No Sp.	2.36	3.00 (-2.00 [†] ,5.00 [†])	2.43	3.05 (-2.00 [†] ,5.00 [†])	2.17	2.87 (-2.00 [†] ,5.00 [†])
[7]	ND/D	All ND	1.88	2.02*** (0.71,3.65)	1.94	2.08*** (0.76,3.68)	1.71	1.86*** (0.57,3.57)

Notes: Rows [1]-[3], SP-IV estimates of ρ (government R&D) in (10); rows [4]-[7] SP-IV estimates of ρ_{ND} in (11). All specifications include the baseline set of lagged controls described in Section 3. Numbers in parentheses are 95 percent weak-instrument-robust confidence intervals based on inverting the KLM statistic of Kleibergen (2005). Test inversion is limited to a grid with endpoints -2 and 5 , \dagger denotes intervals constrained at these endpoints. Subvector inference in rows [6]-[9] is based on the projection method. Stars *, ** and *** denote statistical significance at 10, 5 and 1 percent levels respectively. ‘Exo ND/D’ denotes the orthogonalized narrative measure of exogenous changes in nondefense/defense R&D appropriations. ‘All ND/D’ denotes the orthogonalized series of all changes in nondefense/defense R&D appropriations, ignoring our narrative classification. ‘No Space’ indicates that the instrument is also orthogonalized to all changes in space appropriations between 1958 and 1963. Sample: 1948Q1–2021Q4.

Table mirror the specifications in Table 1, with rows [1]-[3] reporting results for (10), and rows [4]-[7] reporting results for (11). Identification is based on the same variations on the instruments as in Table 1, and each row also reports the calculation of the rate of return based on the corresponding elasticity estimate in Table 1. The implied net returns can be obtained by subtracting $\delta \approx 0.15$, which is approximately the average depreciation rate for nondefense R&D calculated by the BEA.

As Table 2 shows, the implied rates of return to nondefense R&D are high. The estimates range from around 150 percent to 300 percent depending on the specification, the assumed value of η , and the method of calculation. The SP-IV estimates of ρ are highly statistically significant regardless of the value of η . As with the elasticity estimates, the only exception is the specification with both R&D types and the narrative measure that excludes the space race as the instrument, see row [6]. For lower values of η , more of the TFP increase is attributed to R&D, and the estimated returns are therefore decreasing in η . However, the returns do not vary greatly across the plausible range for η within each specification. The estimated returns are also roughly the same regardless of whether they are derived from the elasticity estimates or estimated directly.

An implication of the large returns on government R&D is that there is substantial

underinvestment of public funds in nondefense R&D. For comparison, the CBO estimates a gross return on public infrastructure capital of 12.4 percent, and a net return of 9.2 percent after adjusting for depreciation (CBO 2021). Even after adjusting for the higher depreciation rates on R&D, the estimated returns in Table 2 substantially exceed those for public infrastructure, implying significant misallocation of public capital. The estimates also suggest that government funding of nondefense R&D is self-financing from the perspective of the federal budget, at least in the long run. Assuming a return of 200 percent, a \$1 long run increase in government R&D capital would improve the budget as long as the additional tax revenue raised per dollar of additional GDP is at least 7.5 cents ($\delta/\rho = 0.15/2 = 0.075$), which is substantially below the historical ratio of federal tax revenues to GDP.

As mentioned in the introduction, the existing literature often estimates returns on private R&D that well exceed the returns on other investments. In their survey of firm and industry regression evidence, Hall et al. (2010) conclude that rates of return on private R&D are likely in the range of 20 to 30 percent, though some estimates are as high as 75 percent. These estimates usually do not aim to capture all possible spillovers across firms and industries. In that sense, our relatively higher estimates at the aggregate level are perhaps not too surprising. In a stylized framework, Jones and Summers (2020) calculate an average social rate of return on total R&D expenditures of 67 percent based on aggregate U.S. data. Different from Jones and Summers (2020), but like most others in the literature, our estimates of the rate of return rely on functional form (Cobb-Douglas) assumptions about the aggregate production function that may not be realistic. Nevertheless, our evidence based on appropriations shocks suggests that the return on R&D funded by federal agencies may be significantly greater than 67 percent. As discussed earlier, one plausible explanation is that this funding is more directed towards fundamental research with larger knowledge spillovers, as in the framework of Akcigit et al. (2020). An important implication is that federal R&D policy should not be restricted to tax credits and subsidies for private businesses, but also provide adequate resources for R&D funding by federal agencies.

VI. Avenues for Future Research

This paper contributes new time series evidence on the productivity effects of government funding for R&D by studying impulse response to shocks to R&D appropriations for five major U.S. federal agencies. We use the impulse response estimates to structurally estimate the aggregate production function elasticity of government R&D capital. These estimates can be used to discipline quantitative models to study the long-run effects of public investment in research, as well as the optimal allocation of public capital between public infrastructure and knowledge capital. While we find evidence for direct productivity spillovers of non-defense R&D, the results for defense R&D are inconclusive, and it appears important to distinguish between investments in defense and nondefense research. Further distinctions

between the various types of nondefense R&D funding, for instance by type or agency, can be made to investigate the relative magnitude of the productivity spillovers. It is also possible to look at the effects of shocks to R&D appropriations in more disaggregated data, and study the heterogeneous effects across firms or industries. The possible links between government R&D funding and overall trends in research productivity, as documented by Bloom et al. (2020), are also worth exploring. Another interesting avenue is to study R&D appropriations shocks as a potential deeper source of the ‘technology news’ shocks that are widely studied in macroeconomics, see also Jinnai (2014). Finally, our analysis has abstracted from global spillovers and possible international coordination of public investment in R&D. We leave these and other questions for future research.

References

- Akcigit, Ufuk, Douglas Hanley, and Nicolas Serrano-Velarde (Oct. 2020). “Back to Basics: Basic Research Spillovers, Innovation Policy, and Growth”. In: *The Review of Economic Studies* 88.1, pp. 1–43.
- Alexopoulos, Michelle (2011). “Read All about It!! What Happens Following a Technology Shock?” In: *American Economic Review* 101.4, pp. 1144–79.
- Antolin-Diaz, Juan and Paolo Surico (2022). *The Long-Run Effects of Government Spending*. Discussion Paper 15062. Centre for Economic Policy Research.
- Aschauer, David Alan (1989). “Is public expenditure productive?” In: *Journal of Monetary Economics* 23.2, pp. 177–200.
- Azoulay, Pierre, Joshua S Graff Zivin, Danielle Li, and Bhaven N Sampat (June 2018). “Public R&D Investments and Private-sector Patenting: Evidence from NIH Funding Rules”. In: *The Review of Economic Studies* 86.1, pp. 117–152.
- Beaudry, Paul and Franck Portier (2006). “Stock Prices, News, and Economic Fluctuations”. In: *American Economic Review* 96.4, pp. 1293–1307.
- Bianchi, Francesco, Howard Kung, and Gonzalo Morales (2019). “Growth, slowdowns, and recoveries”. In: *Journal of Monetary Economics* 101, pp. 47–63.
- Blanchard, Olivier and Roberto Perotti (2002). “An Empirical Characterization of the Dynamic Effects of Changes in Government Spending and Taxes on Output”. In: *The Quarterly Journal of Economics* 117.4, pp. 1329–1368.
- Bloom, Nicholas, Charles I. Jones, John Van Reenen, and Michael Webb (2020). “Are Ideas Getting Harder to Find?” In: *American Economic Review* 110.4, pp. 1104–1144.
- Bloom, Nicholas, Mark Schankerman, and John Van Reenen (2013). “Identifying Technology Spillovers and Product Market Rivalry”. In: *Econometrica* 81.4, pp. 1347–1393.
- Bloom, Nicholas, John Van Reenen, and Heidi Williams (2019). “A Toolkit of Policies to Promote Innovation”. In: *Journal of Economic Perspectives* 33.3, pp. 163–84.
- Bluwstein, Kristina, Sinem Hacıoglu Hoke, and Silvia Miranda-Agrippino (2020). *When Creativity Strikes: News Shocks and Business Cycle Fluctuations*. Discussion Paper 15062. Centre for Economic Policy Research.
- Bom, Pedro R.D. and Jenny E. Ligthart (2014). “What Have We Learned from Three Decades of Research on the Productivity of Public Capital?” In: *Journal of Economic Surveys* 28.5, pp. 889–916.
- Cascaldi-Garcia, Danilo and Marija Vukotić (Jan. 2022). “Patent-Based News Shocks”. In: *The Review of Economics and Statistics* 104.1, pp. 51–66.

- CBO (2016). *The Macroeconomic and Budgetary Effects of Federal Investment*. Tech. rep. Congressional Budget Office.
- (Aug. 2021). *Effects of Physical Infrastructure Spending on the Economy and the Budget Under Two Illustrative Scenarios*. Tech. rep. Congressional Budget Office.
- Cloyne, James, Joseba Martinez, Haroon Mumtaz, and Paolo Surico (2022). *Short-Term Tax Cuts, Long-Term Stimulus*. Working Paper 30246. National Bureau of Economic Research.
- Comin, Diego and Mark Gertler (2006). “Medium-Term Business Cycles”. In: *American Economic Review* 96.3, pp. 523–551.
- De Lipsis, Vincenzo, Matteo Deleidi, Mariana Mazzucato, and Paolo Agnolucci (2022). *Macroeconomic Effects of Public R&D*. Working Paper 2023-02. UCL Institute for Innovation and Public Purpose.
- Fama, Eugene F. (1990). “Stock Returns, Expected Returns, and Real Activity”. In: *The Journal of Finance* 45.4, pp. 1089–1108.
- Fernald, John G. (1999). “Roads to Prosperity? Assessing the Link between Public Capital and Productivity”. In: *American Economic Review* 89.3, pp. 619–638.
- (2012). *A Quarterly, Utilization-Adjusted Series on Total Factor Productivity*. Working Paper Series 2012-19. Federal Reserve Bank of San Francisco.
- Fieldhouse, Andrew J. and Karel Mertens (2023). “A Narrative Analysis of Federal Appropriations for Research and Development”. mimeo.
- Fieldhouse, Andrew J, Karel Mertens, and Morten O Ravn (Jan. 2018). “The Macroeconomic Effects of Government Asset Purchases: Evidence from Postwar U.S. Housing Credit Policy”. In: *The Quarterly Journal of Economics* 133.3, pp. 1503–1560.
- Galí, Jordi (1999). “Technology, Employment, and the Business Cycle: Do Technology Shocks Explain Aggregate Fluctuations?” In: *American Economic Review* 89.1, pp. 249–271.
- Gruber, Jonathan and Simon Johnson (2019). *Jump-Starting America*. New York, NY: Public Affairs, Hachette Book Group.
- Hall, Bronwyn H., Jacques Mairesse, and Pierre Mohnen (2010). “Chapter 24 - Measuring the Returns to R&D”. In: *Handbook of the Economics of Innovation, Volume 2*. Ed. by Bronwyn H. Hall and Nathan Rosenberg. Vol. 2. Handbook of the Economics of Innovation. North-Holland, pp. 1033–1082.
- Han, Chirok and Peter C. B. Phillips (2006). “GMM with Many Moment Conditions”. In: *Econometrica* 74.1, pp. 147–192.
- Ilzetzki, Ethan (2022). *Learning by necessity: Government demand, capacity constraints, and productivity growth*. Discussion Paper 17803. Centre for Economic Policy Research.
- Jinnai, Ryo (2014). “R&D Shocks and News Shocks”. In: *Journal of Money, Credit and Banking* 46.7, pp. 1457–1478.
- Jones, Benjamin H. and Lawrence H. Summers (2020). *A Calculation of the Social Returns to Innovation*. Working Paper 27863. National Bureau of Economic Research.
- Jordà, Òscar (2005). “Estimation and Inference of Impulse Responses by Local Projections”. In: *American Economic Review* 95.1, pp. 161–182.
- Kantor, Shawn and Alexander Whalley (2022). *Moonshot: Public R&D and Growth*. mimeo. University of Calgary.
- Kelly, Bryan, Dimitris Papanikolaou, Amit Seru, and Matt Taddy (2021). “Measuring Technological Innovation over the Long Run”. In: *American Economic Review: Insights* 3.3, pp. 303–20.

- Kleibergen, Frank (2005). “Testing Parameters in GMM Without Assuming that They Are Identified”. In: *Econometrica* 73.4, pp. 1103–1123.
- Kogan, Leonid, Dimitris Papanikolaou, Amit Seru, and Noah Stoffman (2017). “Technological Innovation, Resource Allocation, and Growth”. In: *The Quarterly Journal of Economics* 132.2, pp. 665–712.
- Lazarus, Eben, Daniel J. Lewis, James H. Stock, and Mark W. Watson (2018). “HAR Inference: Recommendations for Practice”. In: *Journal of Business & Economic Statistics* 36.4, pp. 541–559.
- Leeper, Eric M., Todd B. Walker, and Shu-Chun Susan Yang (2013). “Fiscal Foresight and Information Flows”. In: *Econometrica* 81.3, pp. 1115–1145.
- Lewis, Daniel J. and Karel Mertens (2023). *Dynamic Identification Using System Projections and Instrumental Variables*. Working Paper 2204. Federal Reserve Bank of Dallas.
- Mertens, Karel and José Luis Montiel Olea (Feb. 2018). “Marginal Tax Rates and Income: New Time Series Evidence”. In: *The Quarterly Journal of Economics* 133.4, pp. 1803–1884.
- Mertens, Karel and Morten O. Ravn (2013). “The Dynamic Effects of Personal and Corporate Income Tax Changes in the United States”. In: *American Economic Review* 103.4, pp. 1212–47.
- Moretti, Enrico, Claudia Steinwender, and John Van Reenen (Nov. 2019). *The Intellectual Spoils of War? Defense R&D, Productivity and International Spillovers*. Working Paper 26483. National Bureau of Economic Research.
- Munnell Alicia, H. (Jan. 1990). “Why has Productivity Growth Declined? Productivity and Public Investment”. In: *New England Economic Review*, pp. 3–22.
- Myers, Kyle R. and Lauren Lanahan (2022). “Estimating Spillovers from Publicly Funded R&D: Evidence from the US Department of Energy”. In: *American Economic Review* 112.7, pp. 2393–2423.
- Newey, Whitney K. and Frank Windmeijer (2009). “Generalized Method of Moments with Many Weak Moment Conditions”. In: *Econometrica* 77.3, pp. 687–719.
- NSF (Feb. 2022). *National Patterns of R&D Resources: 2019–20 Data Update*. Tech. rep. National Science Foundation.
- Plagborg-Møller, Mikkel and Christian K. Wolf (2021). “Local Projections and VARs Estimate the Same Impulse Responses”. In: *Econometrica* 89.2, pp. 955–980.
- Ramey, Valerie A. (Feb. 2011). “Identifying Government Spending Shocks: It’s all in the Timing”. In: *The Quarterly Journal of Economics* 126.1, pp. 1–50.
- (2021). “The Macroeconomic Consequences of Infrastructure Investment”. In: *Economic Analysis and Infrastructure Investmentn*. Ed. by Edward L. Glaeser and James M. Poterba. Chicago: University of Chicago Press.
- Ramey, Valerie A. and Sarah Zubairy (2018). “Government Spending Multipliers in Good Times and in Bad: Evidence from US Historical Data”. In: *Journal of Political Economy* 126.2, pp. 850–901.
- Romer, Christina D. and David H. Romer (1989). “Does Monetary Policy Matter? A New Test in the Spirit of Friedman and Schwartz”. In: *NBER Macroeconomics Annual* 4, pp. 121–170.
- (2010). “The Macroeconomic Effects of Tax Changes: Estimates Based on a New Measure of Fiscal Shocks”. In: *American Economic Review* 100.3, pp. 763–801.