

# Measuring the Production of Scientific Human Capital: New Data, Methods, and Evidence on the U.S. Scientific Training Ecosystem \*

Dror Shvadron<sup>†</sup>  
University of Toronto

Hansen Zhang<sup>‡</sup>  
Duke University

Lee Fleming<sup>§</sup>  
UC Berkeley

Daniel P. Gross<sup>¶</sup>  
Duke University  
and NBER

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## Abstract:

Using newly-collected data on the near-population of U.S. STEM PhD graduates since 1950, we develop a dissertation-based methodology for measuring PhD populations and use it to present new evidence on who funds PhD training, how many graduates are trained in areas of strategic national importance, and the effects of public investment in PhD training on the scientific workforce. The U.S. federal government is by far the largest source of financial and in-kind support for STEM PhD training in America. We identify universities and fields where PhD training has high rates of government, industry, or philanthropic support, and the organizations and universities that fund and train the most PhDs in critical technology areas such as AI, quantum information technology, and biotechnology. Leveraging variation in government support across agencies and over time, we provide evidence suggesting that increasing government-funded PhD trainees increases PhD production additively or with modest crowd-in. To support further research, we provide public data at multiple levels of aggregation, reporting PhD graduates by (i) critical technology area and (ii) source of support. These data and methods complement existing data collection efforts by national statistics agencies, producing information which is otherwise costly to collect or not systematically observed, and can be extended forward in time and to other countries.

**JEL Classification:** I23, I28, O31, O32, O33, O38

**Keywords:** Science policy, PhD production, Scientific workforce,  
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<sup>†</sup>University of Toronto, Rotman School of Management, Toronto, Canada; email: dror.shvadron@rotman.utoronto.ca.

<sup>‡</sup>Duke University, Fuqua School of Business, Durham, NC, USA; email: hansen.zhang@duke.edu.

<sup>§</sup>UC Berkeley, Haas School of Business, Berkeley, CA, USA; email: lfleming@berkeley.edu.

<sup>¶</sup>Duke University, Fuqua School of Business, Durham, NC, USA; email: daniel.gross@duke.edu. Corresponding.

# 1 Introduction

One of the primary goals of international research policy, from its post-World War II origins to the present, is the deepening of countries’ research capacity through investments in scientific human capital (e.g., Bush 1945, Steelman 1947, OECD 1963b). The size and shape of the scientific workforce influences not only the pace of scientific advance but also its reduction to practice—particularly in high-tech industries organized around the discovery and commercial application of new science. Reflecting these goals, science and technology (S&T) statistics and cross-national comparisons have long emphasized scientific manpower as a performance indicator (Godin 2002b, 2003). Accordingly, a substantial share of science funding in the U.S. and elsewhere is spent on training new researchers (e.g. National Center for Science and Engineering Statistics 2025b).

The doctoral trainee population has specifically been a subject of analysis since the 1940s, and modern innovation scholarship is increasingly focused on who enters science, to what effect, and how early careers evolve. Much of this research uses either public data, including government surveys and bibliometric datasets, or the UMETRICS sample (Lane et al. 2015). However, what is known is constrained by what is measured. Despite continuous progress—including recent improvements in access to administrative data—many important features of the scientific training ecosystem remain hard to measure. Questions like how many PhDs are trained in frontier or emerging subjects like artificial intelligence (AI) and quantum computing, where they are trained, who funds their training, and who subsequently harnesses this talent are difficult to evaluate using available data and measurement systems. National comparisons over long horizons are also challenged by data limitations. As a result, though the U.S. graduated >37,000 STEM PhDs in 2024 (National Center for Science and Engineering Statistics 2025a), it is difficult to assess whether the U.S. (or other countries) is producing the “right” kind or number of PhDs, what determines the answer to that question, and how policy choices might cause that number to rise or fall.

In this paper, we introduce a new approach to measuring national doctorate production, using the content of PhD dissertations, and apply it to study several features of the U.S. scientific training ecosystem. Dissertation-based measurement presents three advantages: dissertation science provides a marker of the specific expertise a graduate embodies, and a predictor of future scientific research capacity<sup>1</sup>; dissertations are required of all graduates; and recent advances in large language models (LLMs) make their content considerably more accessible. We focus our analysis on U.S. PhD graduates between 1950 and 2022 in the natural sciences and engineering—over one million

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<sup>1</sup>Even Nobel Laureates’ future prize-winning science can sometimes be traced to their graduate research. For example, Jennifer Doudna (2020 laureate in chemistry, for the discovery of CRISPR gene editing technology) wrote a 1989 PhD dissertation on programmable RNA enzymes for RNA cutting and splicing.

graduates in total. Using data on the near-universe of these graduates, we use our methods to establish new evidence on (i) the set of organizations which finance doctoral research, (ii) the set of graduates producing science related to “critical technologies” considered important to U.S. national defense and economic security, including where they train, and who funds their work, and (iii) the relationship of public investments in PhD training to total U.S. PhD production.

The foundation of our analysis is the ProQuest Dissertations & Theses Global (PQDT) dissertation library, from which we obtain dissertation text and metadata for STEM graduates (i.e., those in the life sciences, physical sciences, mathematical sciences, and engineering).<sup>2</sup> The PQDT sample tracks administrative benchmarks closely in both total graduates and graduates by university and field, suggesting that it approximates the target population.<sup>3</sup> For each of the 1.2 million dissertations in this sample, we observe metadata (e.g., year, subject, school, title) and for a majority we also have access to the full text—which is available for much of the sample pre-2000, and nearly 100% of the sample post-2000. We then develop two LLM-based procedures to measure new features. One assesses each dissertation’s association to critical technology areas identified by the White House Office of Science and Technology Policy (OSTP 2024) as U.S. national priorities. The other parses dissertations to identify acknowledgments, extracts the names of organizations which supported the graduate’s work (financially or otherwise), and links these entities to the Research Organization Registry (ROR), an independent, consolidated registry of global research organizations. We validate the resulting measures against manual and external benchmarks.

Using these data, we characterize the evolution of these features of the U.S. scientific training ecosystem over the past 75 years. About 50% of STEM graduates currently acknowledge some source of support in their dissertations, the majority (42%) from the U.S. government—a share which is at its highest level since 1980, but significantly below its >50% peak in the 1960s. We view these shares as a lower bound on true (underlying) rates of support, which are potentially underreported in dissertations—a possibility we return to later in this paper. Disaggregating this evidence, we document the largest sources of support in the government, industry, and non-profit sectors. The four largest sponsors of U.S. STEM PhD trainees in our data are the National Science Foundation (NSF, with >90,000 graduates supported since 2000), National Institutes of Health (NIH, 80,000), Department of Defense (DoD, 34,000), and Department of Energy (DOE, 30,000). In all, 12 different government agencies each support more graduates than the largest firm (Intel)

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<sup>2</sup>ProQuest until recently had agreements with nearly all U.S. universities to acquire rights to republish their graduates’ dissertations, which are now available in ProQuest’s single, consolidated repository. In recent years, U.S. universities have begun transitioning to self-publishing, an industry shift which will require a more diffuse effort to collect dissertations from institutional repositories (e.g., to extend our analysis) in the future.

<sup>3</sup>PQDT graduate counts match the SED through 2005, and continue to add to roughly 90% of SED totals in the 2010s, with the gap explained by the attrition noted in the previous footnote.

and the largest non-profit (HHMI)—reinforcing that U.S. scientific training, and in turn the future scientific workforce, is heavily underwritten by the U.S. government.

Continuing this evidence, we document universities and subjects with higher and lower rates of government and industry support. The relative balance further indicates which universities and fields are more exposed to changes in funding from each sector—with subjects such as astronomy and astrophysics being particularly government-reliant, pharmaceutical sciences and automotive engineering being relatively more industry-supported, and subjects such as geology and materials science being supported by both. In nearly all subjects—and at all U.S. universities—government support outpaces private sector support, but the rates of government and private sector support correlate with each other, likely reflecting either subjects’ scientific potential or resource requirements, but potentially also indicating correlation in demand across sectors.

Using our classification of graduates to critical and emerging technology areas, we identify the top training grounds and sources of support in AI, quantum science, and other areas since 2000. We measure the size of the U.S. PhD pipeline in these areas and highlight institutions and organizations which are ostensibly important to sustaining U.S. leadership in critical technology-related science. In nearly every critical technology area, NSF is the largest recognized source of support, and the top five sources are nearly always government agencies. The institutions which rank highest in their production of critical technology-related PhD graduates are MIT, Stanford, and UC Berkeley, though many other institutions rank highly in specific specialties.

Leveraging variation in individual government agencies’ funding priorities (e.g., NIH primarily funds biomedical and health science, and DoD engineering) and each agency’s total number of graduates supported each year (a reflection of budgets), we estimate the effect of government support for PhD training on total PhD production, using a shift-share design. The elasticities we estimate imply that across the U.S. higher education system, total PhD production scales roughly proportionally with the number of government-supported graduates in each cohort—patterns inconsistent with crowd-out of other categories of graduates, and broadly consistent with what prior research has found for specific programs and settings (e.g., Blume-Kohout and Adhikari 2016).<sup>4</sup> This evidence adds an additional datapoint to the wider literature estimating the impacts of public R&D, in this case reinforcing that public investment in scientific training is one of the main factors

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<sup>4</sup>This result is broadly consistent with the results of Blume-Kohout and Adhikari (2016), who find a roughly 1-for-1 effect of increasing NIH fellowships and traineeships on total PhD enrollment, and with other work relating public funding for PhD training to enrollment (e.g., Freeman et al. 2009) and career outcomes (e.g., Graddy-Reed et al. 2021, Kim et al. 2022). We expand on this work with population-level measures of funding sources and aggregate PhD production across all fields and over longer horizons—providing a view of the overall system—but with the limitation that we cannot reliably measure specific funding mechanisms (e.g., fellowships vs. assistantships), whose impacts can vary (Blume-Kohout and Adhikari 2016, Kim et al. 2022).

shaping the size and composition of the future scientific workforce.

In introducing new measures of U.S. PhD production, this paper adds to a long history of advances in S&T statistics, where the measurement of scientific manpower has been a long-running priority (e.g., see National Science Foundation 1959, Freeman 1962, Freeman and Young 1959 for early discussions, and Godin 2002b, 2003 for a more extended history). As Christopher Freeman (founder of this journal, one of the major early influences on the development of national S&T statistics, and author of the original Frascati Manual; see OECD 1963a and Godin 2008) has written, “The first elementary step towards improving the rationality of this process [science policy], towards making these choices more conscious and more carefully considered, is the systematic collection of statistics on the deployment of scientific manpower, and on the expenditures on different branches of scientific activity,” further noting that “These statistics must be collected in a great variety of breakdowns” (Freeman 1968, as quoted in Godin 2002a, pp. 12-13).

Although the NSF administers large-scale surveys towards this end like the Survey of Earned Doctorates (SED, an annual approximate-census of graduating PhDs) and the Survey of Doctorate Recipients (SDR, a periodic/biennial survey which samples past graduates), surveys are expensive to administer, have gaps in what they measure, and are difficult to link to other data sources. UMETRICS has more detailed measures of how research is financed, but is limited to universities which have opted into reporting, reports financial transactions only (not in-kind and other support), and suppresses personally-identifying information (like names) for privacy reasons, making linkages to external datasets challenging.<sup>5</sup> Against these alternatives, dissertation-based data have multiple strengths (and some weaknesses, which we will discuss momentarily). Outside of the U.S., large surveys and UMETRICS-like projects may also be too expensive or practically infeasible in many countries. Dissertation samples provide an alternative, complementary lens into doctoral training and the early career scientific workforce which can be applied to any national education system—as other scholars have recently begun to do (e.g., Martínez et al. 2025).

With respect to measurement, this paper explores the capabilities that recent advances in LLM-enabled natural language processing offer for extracting information from large, unstructured texts (like dissertations) to identify target features. This can be done for many more features than we considered in this paper, as well as a wider range of scientific texts.<sup>6</sup> With this paper, we are also publishing new data with information on PhD production by university, field, and university-field over time, including measures of (i) graduates associated with each of the critical technology areas

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<sup>5</sup>Although UMETRICS has been linked to PQDT, it omits PQDT identifiers to preserve anonymity, such that we were unable to link our measures to the UMETRICS data for comparison.

<sup>6</sup>Research is already moving in this direction, given new opportunities to evaluate publications (Dagdelen et al. 2024), lab notes (Jalali et al. 2024), and even L<sup>A</sup>T<sub>E</sub>X markup (Yang et al. 2025).

specified by the OSTP (2024) and (ii) graduates supported by specific federal agencies and/or with industry or philanthropic support. Beyond this paper, our methods and data are also extensible to other universities and national education systems, to other degree levels, and to future graduates: the main input required is a sample of theses or dissertations.

There are nevertheless limitations to this approach. One is that it requires complete or representative samples of written work from the population studied. Though PQDT appears to contain the near-universe of U.S. STEM PhD graduates through the mid-2010s, a growing number of universities since then have stopped automatically submitting dissertations to ProQuest and instead publish them in open access university repositories, in response to federal guidance (see OSTP 2013, 2022) and the broader open science movement. This attrition is modest in our sample period, and not systematically related to research funding, making it unlikely to affect our findings beyond a (modest) underaccounting. However, filling these gaps and extending analysis of the U.S. doctoral training system forward will likely require expanding data sources to more of these repositories—a possibility we are exploring in ongoing work.<sup>7</sup> In our particular application of identifying research funders, a second limitation of our approach is that similar to survey data, it measures only the sources of support that graduates self-reported—and our evidence suggests there is some under-reporting. As in similarly-impacted survey settings, however, this limitation can be accommodated with some reweighting on reporting rates, an approach we explore in our analysis.

Notwithstanding these limitations, we believe this paper makes a useful advance in both methods and findings. Despite long-running interest in critical technology assessment across many corners of government (Fuchs 2022), systematic measurement techniques are still developing. The methods we develop can be adapted and applied in other settings. The evidence may also have applied value: evidence on the state and organization of critical technology scientific training in the U.S. can inform academic and public understanding of U.S. science, and potentially influence research funding from all sectors by identifying pockets of strength and gaps in capability. Evidence on sources of funding offer a reference point for understanding the potential impacts of large changes in public funding for doctoral training—and at the time of writing (June 2026), large cuts to U.S. graduate student funding are already in progress (Mervis 2025, Bhatia et al. 2025).

We proceed as follows. Section 2 connects our work to previous research on doctoral training and early career scientists. Section 3 describes our data sources, describes measurement methodologies,

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<sup>7</sup>The contents of this paper point to the value of national dissertation repositories, which some concurrent research is beginning to use—especially research under the European Doc-Track program (see Martínez et al. 2025 for a project report, and Corsini et al. 2025 for an application). National dissertation repositories are more common in countries with national university systems, though the effect could be replicated in the U.S. with a national depository program similar to the Library of Congress’ mandatory deposit requirements.

summarizes the performance of our methods in validation tests, and discusses limitations. Section 4 uses these measures to introduce new facts about U.S. STEM PhD production, examining the level and composition of new trainees and the impacts of public investment in scientific training on PhD production. Section 5 describes the data we are releasing with this paper. In Section 6, we briefly review the paper and then suggest directions for future research.

## 2 Prior Research on the Scientific Training Ecosystem

Scientific manpower has been a central concern of innovation policy since World War II, which has particularly emphasized the importance of public investment in scientific human capital to advancing national defense, economic, and public health objectives (e.g., Bush 1945, Atkinson 1990). Doctoral training has accordingly been a focus of policy studies throughout this period, including a large and growing academic literature. Economically, knowledge workers in STEM fields are broadly recognized as an engine of innovation (e.g., Bianchi and Giorcelli 2020, Lubczyk and Moser 2025), and their finite population a limiting factor on economic growth (Romer 1990, Jones 2009, Akcigit et al. 2025). Consistent with this view, prior research has empirically linked the size of the STEM workforce to broad-based productivity gains, profits, wages, entrepreneurship, and other economic improvements (Winters 2014, Peri et al. 2015, Balsmeier et al. 2025).

Identifying the forces that shape the STEM scientific workforce is thus a first-order interest of both research and policy. A large share of work on this question has gravitated to immigration policy, on the observation that immigrants comprise a large, disproportionate, and disproportionately impactful share of U.S. scientists (e.g., Stephan and Levin 2001), inventors (e.g., Hunt and Gauthier-Loiselle 2010, Kerr and Lincoln 2010, Bernstein et al. 2022), and entrepreneurs (e.g., Azoulay et al. 2022). In the realm of science, prior research has examined not only immigrant scientist productivity (e.g., Kahn and MacGarvie 2016, Agarwal et al. 2023) and spillovers (e.g., Ganguli 2015), but also the arguably more elementary question of which foreign students come to the U.S. for graduate studies, who stays, and why (e.g., Gaulé 2014, Ganguli and Gaulé 2019, Bostwick et al. 2024). A common theme in this literature is that immigration policy is a key determinant of the foreign-born STEM PhD population (Kahn and MacGarvie 2020). Alongside the aforementioned evidence on the impacts of foreign-born scientists, this recognition has driven recurring calls for visa reform as one way to grow the PhD population (Glennon 2024, Nice 2025).

Despite the emphasis on immigrants, a majority of U.S.-trained STEM PhDs are U.S. born. An alternative path to growing the STEM workforce is to encourage homegrown entrants, and a separate body of research has examined the effectiveness of policies supporting entry into STEM fields, from childhood education (Dynarski et al. 2013) to curricular reforms (Goodman 2019). One

of the most direct levers for shaping the scientific workforce is public funding (Bush 1945, Steelman 1947). As Myers (2020) observes, funding can shift the direction of scientists’ work. Though existing researchers’ switching costs are large (Goolsbee 1998, Myers 2020), trainees and potential trainees may be more responsive—especially if younger workers are flexible and adaptive to changes in demand, as is often the case in other sectors. Consistent with this idea, Dugoua et al. (2025) have found that windfalls to the Department of Energy’s R&D budget have historically increased PhD production in DOE-related fields; Cook et al. (2026) relatedly show that university-fields with more federal research grants in a given year expand their capacity and graduate more PhD, MA, and BA students in subsequent years. More generous funding environments in graduate school may also affect students’ career progression (Graddy-Reed et al. 2021).

Reflecting long-running recognition that science is important to national outcomes, the NSF has been tasked with measuring it since the agency’s inception. The NSF-administered Survey of Earned Doctorates specifically focuses on measuring U.S. PhD production. Despite its long history, many features of the U.S. scientific training system are not systematically known or measured—in part due to the intrinsic limitations of surveys, including their length and complexity. Key questions—such as (i) how many graduates does the country train in frontier, nationally-important areas; (ii) where does this training occur; (iii) who funds this training; and (iv) how many trainees leave the U.S., and with what consequences—remain difficult to systematically answer with existing data. Where some of these gaps have been partially filled (e.g., Chang et al. 2019 present statistics on the funding sources of PhD graduates at seven midwestern U.S. universities in 2011-2012, using UMETRICS data, as a demonstration case), data limitations continue to make it difficult to produce comprehensive national accountings, and the limited opportunities to systematically measure graduates’ science have similarly made it difficult to evaluate its nature or impacts.

These are among the gaps we aim to address in this study and a concurrent study of postgraduate migration by U.S.-trained PhDs (Shvadron et al. 2025b). We also introduce new methods and data which others can use to continue exploring these and other themes. Related research loci which we do not address here include scientist career choice (e.g., Roach and Sauermann 2010, 2017, Sauermann and Roach 2012, 2016), how training environments affect career outcomes (e.g., Gaule and Piacentini 2018, Fry and Glennon 2025), and the degree of and consequences of diversity in STEM scientific career pipelines (e.g., Ceci et al. 2014, Buffington et al. 2016, Kahn and Ginther 2017, Bostwick and Weinberg 2022, Stansbury and Rodriguez 2024). The data we are releasing with this paper may be useful for exploring these questions with respect to emerging science-based technologies and the research funding ecosystem.



### 3 Measuring the Scientific Training Ecosystem

Our first goal in this paper is to build a near-population sample of U.S. STEM (Science, Technology, Engineering, and Mathematics) PhD dissertations since the mid-20th century. Using this sample, we then aim to measure characteristics of PhD graduates which are not elsewhere observed or are hard to observe at the same scale, and for which comprehensive statistics therefore cannot otherwise be produced. We accordingly aim to do so in systematic ways which can span universities, fields, funders, and time.<sup>8</sup> Our emphasis is mostly on two features and phenomena: (i) measures of graduates’ financial sponsors, and (ii) measures associating graduates’ dissertation science to technology areas which according to the White House Office of Science and Technology Policy (OSTP) are important to defense and/or economic security.<sup>9</sup>

To produce this sample and these measures, we combine data from three sources: ProQuest (a commercial provider of global dissertation data), OpenAlex (an open-access bibliometric database; Priem et al. 2022), and universities’ own institutional repositories. From these sources we compile a nearly-complete sample of U.S. STEM PhD graduates over the past 75 years, including dissertation text for many of these graduates pre-2000 and nearly all post-2000. To evaluate sample completeness and some dissertation-derived measures we additionally collect more aggregated data from the Survey of Earned Doctorates (SED) and Survey of Graduate Students and Postdoctorates in Science and Engineering (GSS) as well as individual-level data from one large, nationwide fellowship program, the NSF’s Graduate Research Fellowship Program (GRFP).

#### 3.1 Base sample: PQDT

Our main data source is ProQuest Dissertations & Theses Global (PQDT). For nearly a century, ProQuest has been acquiring and re-publishing dissertations of U.S. PhD graduates via licensing agreements with universities. The ProQuest dissertation database is the largest collection of digitally catalogued PhD dissertations in the world, and it includes extensive metadata on each dissertation

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<sup>8</sup>In addition to complementing existing data sources on U.S. PhD graduates—including administrative data, such as NCSES surveys—these data sources and methods can likewise substitute for some administrative measures in other countries or contexts where data collection infrastructure is costly and less developed.

<sup>9</sup>The term “critical technology” is indicative of technology that a policymaking organization considers important to national or economic security. The terminology traces to the U.S. Export Administration Act of 1979, which required the Department of Defense (DoD) to provide a list of “militarily critical technologies” to the Department of Commerce to ensure they are export-restricted. This requirement was eliminated by later legislation, and the terminology has morphed to other applications. The OSTP list we use was developed in 2024 by the U.S. National Science and Technology Council, a committee which coordinates science and technology policy across the executive branch. In parallel, DoD’s Office of Strategic Capital has also published a list of critical technology areas it considers important to national security, many of which overlap with the OSTP list. The CHIPS and Science Act of 2022 enacted by Congress similarly identifies key technology focus areas, which also intersect. One advantage of the OSTP guidance is that it represents cross-governmental policy. A second is that it includes more detailed descriptions which are useful for linking PhD dissertations (or other textual inputs) to technology areas.

(e.g., author, institution, degree earned, title, abstract, subject). We identify 1.2 million STEM PhD dissertations in PQDT between 1950 and 2022 using degree letters, which we manually filter to PhD and PhD-equivalents, and graduates’ self-reported subjects, which we manually crosswalk to SED major fields and filter to natural sciences and engineering.<sup>10</sup> Using IPEDS data, we further restrict to PhDs issued by institutions which ever held an R1 or R2 Carnegie classification post-2000, as well as PhDs from doctorate-granting medical and engineering schools.<sup>11</sup>

By comparison, the SED reports roughly 1.3 million STEM PhD graduates over this period.<sup>12</sup> Relative to the SED (and its underlying, de-identified microdata), a dissertation sample like PQDT presents two distinctive opportunities for analyzing doctoral training systems. First, we observe the dissertation science itself. Second, it provides enough identifying information (most importantly, names) to link graduates to their postgraduate careers. This enables us to do so for more graduates than other NSF instruments such as the SDR, and in more ways.

The SED nevertheless provides a useful benchmark for evaluating the completeness of the PQDT sample. Figure 1 compares annual PQDT STEM dissertation counts to SED totals (defining STEM as above; see Appendix A for a more detailed accounting of the subsumed fields). The PQDT sample tracks the SED population closely until roughly 2010, after which a modest gap emerges—though PQDT still accounts for 90% of the SED population through 2022.<sup>13</sup> Appendix Figure A.2 disaggregates this comparison to individual fields and finds similar patterns at the field level. Together, these comparisons suggest our PQDT-based sample approximates the underlying population, notwithstanding modest undermeasurement since 2010.

[Figure 1 about here]

<sup>10</sup>To link subjects to fields, we use the SED’s own crosswalk between research subjects and major fields to the extent possible—which covers most of the PQDT sample—and judgment otherwise.

<sup>11</sup>These institutions together account for over 99.5% of the unrestricted sample.

<sup>12</sup>The SED is an annual survey of graduating PhD students at U.S. universities, and has been administered to the population of graduates in all fields (nearly 60,000 in 2022) since 1958. In practice it is a near-census of U.S. PhD graduates, with a >95% response rate through the mid-1990s and 90% today.

<sup>13</sup>Closer examination of the PQDT sample suggests this difference is mostly attributable to a small but growing number of universities ending their relationship with PQDT, such that their graduates’ data are no longer automatically included. This change in turn reflects a movement of universities towards making research freely available, typically on university repositories in addition to or in place of commercial publishers. Much of this movement is in response to either state law or to federal guidance from OSTP in 2013 requiring they do so for federally-funded research within one year of publication (OSTP 2013). Updated guidance in 2022 eliminated this embargo (OSTP 2022). PQDT sample completeness may thus decline going forward. In ongoing work, we are developing a data collection and processing pipeline to collect dissertations from university repositories, one at a time, initially to backfill gaps in our PQDT sample since ca. 2010—especially with respect to a handful of important universities which exit the PQDT sample early, such as Georgia Tech (which does so in 2013)—and eventually with the goal of developing a sustainable data collection program that can substitute for PQDT in scholarly research.

### 3.2 Dissertation text

Existing understanding of scientific training in the U.S. innovation system is largely shaped by the available data. Surveys like the SED are nearly complete in their sampling and collect a rich set of information on graduates’ background and immediate future plans, but offer limited insight into their science. PQDT’s tabular data provides basic identifying information about doctoral graduates (e.g., name, institution, subject, graduation year) which can be used in more flexible ways (e.g., linking to other data sources) and is increasingly being used in research, but these data are likewise limited in what they measure. To our knowledge, no prior work has made systematic use of dissertation text, which—as we will show—presents opportunities to measure features of doctoral research, training, and trainees that are not elsewhere observable.

An important feature of PQDT for our purposes is thus that in addition to metadata, it also provides dissertations’ full text. An added benefit of ProQuest having been the main provider of dissertation publishing services over the last century is that dissertations from hundreds of different universities generally share a common document structure, which enforces some consistency in reported information beyond science as well. For example, most dissertations have an “Acknowledgments” section (among others), where authors thank funders and other supporters of their research and training. These acknowledgments are a crucial resource for this paper, as they present an opportunity to systematically measure PhD graduates’ sources of support.<sup>14</sup>

Dissertation text (beyond metadata) is available for most, but not all, of our PQDT sample: of the 1.17 million dissertations in our 1950-2022 sample, we have the text of 870,000 (75%) in total, and roughly 96% since 2000, which will be a focal period for much of our analysis. Where we use pre-2000 data, gaps are unlikely to be a problem for our analysis provided there are no systematic differences in the set for which text is available: as long as sampling is as good as random, the data can be used to produce representative estimates. Even with systematic differences in data availability, sample weights (e.g., inverse propensity score weights) can be constructed and used to rebalance the full text sample to resemble the population (on observables).

An important question is then what explains why some dissertations have full text, and others do not. Guidance from the data provider and evidence from the data vary a bit with respect to this question. According to ProQuest, this variation is a result of (i) differences in indexing methods—with some dissertations historically having been stored by ProQuest with full text, some with abstracts, and some with identifying data only—and (ii) idiosyncratic variation in what dissertations

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<sup>14</sup>Though nearly all dissertations include acknowledgments, there are nevertheless exceptions. When an acknowledgments section is missing, funders are often mentioned in the dissertations’ biography section in footnotes to the text—cases which we can also identify by processing dissertations’ complete text.

have been retrieved from microfilm. Figure 2(A) shows the share of PQDT dissertations over time in each indexing category, as indicated by ProQuest’s dissertation-level identifiers (see Appendix A for details), which suggests that dissertation text may be available for 90%+ of its sample since 1965. In practice, however, we do not reach this level of completeness until ca. 2000. Figure 2(B) shows full text availability in the data, with the share of graduates each year for whom we have dissertation text, by field. Full text is available for around 40% of our sample until 1990, when it discretely jumps to 60-80%, and 1996, when it jumps to  $\approx 100\%$ .

[Figure 2 about here]

We explore one additional effort to grow the full text sample: for seven universities with the most PQDT graduates without dissertation text (MIT, UC Berkeley, UCLA, Cornell, U. of Minnesota, Michigan State U., and U. of Maryland), we visited their online repositories to try to retrieve it. Though Figure 2 indicates that most of these gaps are pre-2000, one exception was MIT, an important institution whose graduates were missing dissertation text throughout our sample. Using this approach we backfilled a large number of dissertation texts for MIT and Michigan State graduates but saw more limited success with other universities (Appendix Table A.1). We incorporate these results into our sample, but given the high cost of one-by-one, university-specific full text retrieval and mostly meager results—and that this mainly fills gaps in the pre-2000 era—we have not expanded this effort to the full sample at this time.

### 3.3 Linking PhD graduates to technologies

Using the data inputs described above, we aim to produce two new measures. One is to associate PhD graduates to critical technology areas, based on the relationship of their dissertation science to the above-noted 18 technology areas identified by OSTP (2024) as militarily and/or economically important. Similar to Aiken et al. (2024), we develop an unsupervised LLM-based classifier which (i) summarizes dissertations, (ii) uses this summary to evaluate whether each dissertation is related to each of the OSTP technology areas, and (iii) filters these candidate associations based on detailed subfields within these technology areas which the OSTP guidance describes.

Roughly 43% of dissertations in our sample post-2000 are linked to OSTP critical technology areas by this method. The largest is *Biotechnology*, the fastest-growing is *Artificial Intelligence* (AI), and other large categories include *Advanced Materials* and *Semiconductors and Microelectronics* (see Appendix Figure A.6 for a full list). Though critical technology classification lacks a ground truth to test against—“critical technologies” do not have an obvious or naturally occurring taxonomy, nor a clear rubric for evaluation—the method nevertheless validates well against both intuition

and independent external measures. The technology linkages our procedure produces are intuitive when read side-by-side with the dissertation titles, abstracts, and text. Using OpenAlex data, we also show in Appendix A that PhD graduates we associate to particular areas are systematically concentrated in universities with the most publications in those areas.<sup>15</sup>

This approach is one among several methods of linking science or scientists to specific categories of technology. A common alternative is patent citations (Marx and Fuegi 2020, 2022), which can be flexibly used with patent classifications as a measure of technology space, though it is limited to science that is cited by patents. More similar to our method, Fry and Glennon (2025) study a sample of PhD graduates in AI based on keyword searches of PQDT dissertations from the 20 highest-ranked U.S. universities in AI-related fields. Our LLM-based classifier essentially systematizes this approach, and may be particularly useful for multidimensional classifications of science (e.g., linking science to many technologies), for classifying large corpora, and for classifying scientific outputs that do not get cited by patents—such as dissertations.

### 3.4 Measuring dissertation sponsors

The second feature we aim to measure is PhD graduates’ research sponsors, including both financial and in-kind support (examples of which might include research inputs, equipment usage, API credits, etc.). Our motivation for doing so is that existing data sources are limited in completeness or resolution. Though the SED includes questions on how respondents financed their doctoral education, the survey has not provided response options to indicate specific funders since 1997. Even then, response options were limited to only a few federal agencies—and as we will show, doctoral training is supported by a much wider range of organizations. Another resource for measuring graduates’ sources of support is UMETRICS (Lane et al. 2015), which provides administrative data on 45 universities’ financial transactions, including funding from specific sources and transfers to specific employees. UMETRICS provides higher resolution information than SED but for a smaller number of universities and years, and with a changing sample as universities join or leave the program (as of April 2024, 27 universities were actively contributing data). Data privacy considerations also limit the degree to which the data can be linked to external sources. As a result, despite its specificity, UMETRICS is also limited in its suitability for making broad assessments of the U.S. higher education system and evaluations over long horizons.

Dissertation acknowledgments present a potential opportunity to do so over a larger sample of graduates and for a wider range of organizations than existing data sources permit. More complete

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<sup>15</sup>We demonstrate this for quantum science in Appendix Figure A.8, plotting universities’ number of quantum science PhD graduates against quantum science publications—whose correlation is 0.9.

data on how doctoral training is funded is of both research and policy interest (e.g., Blume-Kohout and Adhikari 2016). For this reason, we develop a methodology to systematically extract this information from dissertations. This approach may also have drawbacks relative to administrative data such as UMETRICS, including incomplete reporting rates, which we will explore below. On net, however, the evidence suggests that despite some imperfections, the data and methodology we develop towards this end yields a broader, more detailed, and more expansive record of how doctoral education is financed in the U.S. than is currently otherwise available.

Many readers of this paper may recognize dissertation acknowledgments from their own thesis. To distill the basic idea behind our measurement, Figure 3 provides an example acknowledgment from the dissertation of Ian Buck, a 2005 Stanford University computer science graduate (now a senior executive at NVIDIA) who in his PhD created the precursor to NVIDIA’s CUDA platform, a parallel computing architecture that allows GPUs to be used for general computing and is essential to modern AI. Figure 3 identifies several organizations which funded Buck’s work, including DARPA, the Department of Energy (DOE), the Advanced Simulation and Computing program (ASC, a supercomputing facility that is also under DOE), NVIDIA, and ATI Technologies (a former semiconductor company specializing in GPUs, later acquired by AMD). Our task is to identify these funders, consolidate them to their ultimate parents (e.g., grouping ASC up into DOE), and classify them into sectors (government, industry, and non-profits/foundations).

[Figure 3 about here]

To flexibly identify research sponsors across our dissertation corpus, we develop a pipeline that leverages natural language processing tools and large language models (LLMs).<sup>16</sup> We process dissertations one at a time, working initially with the entire text. Our procedure for each dissertation takes the following steps. First, we partition the dissertation into sentences and identify “acknowledgment sentences”. To isolate potential acknowledgment sentences, we applied a rule-based string matching approach by splitting the text into sentences (using NLTK’s Punkt Sentence Tokenizer; Bird et al. 2009) and identifying sentences with tokens such as “fund”, “grant”, “thank”, and so on. This procedure tags roughly 103 million potential acknowledgment sentences.

We next identify named entities within these sentences, classify entities into sectors, and identify the type of support and grant identifiers (where provided), using the recent open-source LLMs Solar 10.7B and Smaug 34B (Kim et al. 2023, Pal et al. 2024). We established a procedure that uses the LLM to verify that a sentence acknowledges support from an external entity, identify the supporting

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<sup>16</sup>A more detailed description of our methodology, including the LLM prompts we use, and our approach to consolidation and classification, is provided in Appendix A. Here we present an abridged summary.

entities, categorize them by organization and support type, and record grant and contract identifiers where applicable. We used the VLLM Python package (Kwon et al. 2023) and the LM format enforcer (Gat 2023) for efficient batch inference and to ensure the model produces a well-structured JSON schema. The LLM output indicates that 11 million of our potential acknowledgment sentences (12%) indeed acknowledged support or were part of a biography section. Among all sentences, the LLM extracted 9.3 million mentions of organizations (4 million unique), with 4.8 million of these mentions originating from sentences classified as support or biography.

We then consolidate named entities (accounting for name and spelling variants by grouping them together) and link them to external firm registries. We consolidate extracted entities using the Smaug 34B model and match them with the Research Organization Registry (ROR) and Wikidata to disambiguate institution names and obtain external identifiers.

### 3.4.1 Example application

Table 1 demonstrates the performance of our procedure on the acknowledgment text in Figure 3. Each row is an extracted funder, and the columns report the name, sector, type of support, and the associated ROR organization (where matched to ROR; otherwise blank). Comparing the text to the first three columns of this table, we find that our procedure correctly extracts nearly all entities by name, and those it identifies are classified into the correct sectors and type of support. The one exception is ASC, which our procedure has difficulty classifying due to ambiguity of the acronym and its relative infrequency as a research funding organization—one which we ourselves were only able to define with further research and contextual understanding.

[Table 1 about here]

### 3.4.2 Validation

We validate this approach in multiple ways. The first is by comparing extracted entities to manual classification. In Appendix A.5.1 we identify funders by hand for a random sample of 500 dissertations and compare the share of this sample with government, non-profit, and industry support according to our manual and automated measures. The results show substantial similarity, with 31-32% of this sample classified as reporting government support under both methods, 11-12% non-profit support, and 8-9% industry support—and further agreement at the entity level—suggesting the LLM classifier can reliably approximate manual extraction.

We undertake two further validation exercises. In Appendix A.5.2, we collect data on all NSF Graduate Research Fellowships (GRFs) awarded since the beginning of the program, link awardees

to PQDT, and evaluate how many of these graduates acknowledge NSF support in their dissertations. Based on a simple textual search, we find that among the matched NSF graduate fellows, 60.8% mention the NSF in their dissertation. Comparing these mentions to our LLM-based extraction, we find that our procedure identified and linked 98.6% of these mentions.<sup>17</sup> These results provide further validation for our approach while also highlighting some of the limitations we face, particularly with respect to underreporting—an issue we will return to momentarily.

Finally, in Appendix A.5.3, we compare our sample to the NSF’s Survey of Graduate Students and Postdoctorates in Science and Engineering (GSS). Under the GSS, university administrations annually report to NCSES the number of enrolled graduate (master’s and doctoral) students in each major field with different sources of funding, including broad categories like institutional support, student loans, or self-support and particular federal agencies like HHS and NSF. Though the GSS sample (which consists of all enrolled students rather than only graduates, and includes master’s students) is broader than the sample we collect in this paper, we can nevertheless test whether the data are broadly consistent across the two sources. We correlate across the two sources the share of federally-supported students with support from specific agencies (e.g., DoD, DOE, HHS, NASA, NSF, USDA), at the university-field-year level, between 2000 and 2022. Appendix Table A.11 shows that these sources correlate strongly, with estimates indicating one-for-one correlations for HHS and NSF funding, and near one-for-one for other federal agencies.

### 3.4.3 Limitations and opportunities for improvement

Collectively, this evidence suggests to us that our procedure can extract acknowledged research sponsors with a high degree of precision and completeness.<sup>18</sup> The resulting data nevertheless have limitations. One of these limitations is a result of our reliance on PQDT: as previously noted, despite being the most comprehensive source of information on U.S. PhD graduates over the last century, the set of universities submitting dissertations to PQDT appears to recently have begun shrinking. In ongoing work we are exploring ways to address this gap, including by collecting dissertations and metadata from individual universities’ institutional repositories.

A second limitation more endemic to our approach is the risk of underreporting: graduates may forget or otherwise neglect to acknowledge all sources of support in their dissertations (much as graduates may do the same in their SED responses, or journal publication authors might in research articles, etc.). The comparison of our measures to official NSF GRFP award lists (Appendix A.5.2) suggests such underreporting can potentially even be substantial.

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<sup>17</sup>The remaining 1.4% of mentions that were not picked up by our LLM-based procedure were due to unconventional wording in acknowledgments or mentions of the NSF without an indication of funding.

<sup>18</sup>Note that this process can also be applied to other scientific corpora as well.



There are two strategies we consider to address underreporting. One is to simply report the data as they are—an approach which will generally yield conservative measures (i.e., underestimates) of the share of graduates supported by any given agency or organization. The second is to use our validation data to estimate the likelihood of accurate reporting as a function of observables (e.g., by university, field, and/or year), and to weight our analysis with inverse propensity weights (IPW), overweighting low propensity populations to obtain representative results—similar to how survey weights are used to attempt to make non-representative survey results reflect the underlying population, or how research using nonrepresentative linked samples reweights on link propensities (Bailey et al. 2020). Across the paper, we opt for reporting the raw data to prioritize transparency and conservatism, and present IPW-weighted results in Appendix B.<sup>19</sup> Our results should thus be treated as a lower bound on underlying (true) rates of support.

Despite these limitations, one final point of comparison is available from Chang et al. (2019), who link SED graduates from seven Midwestern universities between 2011-2012 to UMETRICS data in order to evaluate the share of SED graduates at these universities who were paid with federal funding in the final two years of their PhD—including through research assistantships, teaching assistantships, and fellowships. Much of Chang et al. (2019)’s analysis presents data for all graduates (rather than STEM graduates), but in passing reports that “over three in five students in physical sciences, agriculture/biology, and computer/mathematical sciences are on federal grants in the two years prior to getting their degree” (Chang et al. 2019, p. 1490). By comparison, our IPW-weighted measures indicate 60% of STEM graduates from these university-years report federal support in their dissertations (65% of graduates in physical sciences, 62% in life sciences, and 41% in math and computer science)—consistent with the UMETRICS data.

## 4 New Facts about U.S. STEM PhD production

### 4.1 Who funds PhD training in the United States?

Figure 4, Panel (A) shows the share of graduates supported by different organization types from 1950 to 2022. In 2022, approximately 50% of graduates in our sample acknowledged some source of support. U.S. federal agencies are the most common funders, supporting over 40% of graduates. Roughly 15% of graduates are supported by non-profit organizations, and 10% by private firms. These patterns have changed substantially over time: government support increased rapidly in the 1950s and 1960s, peaked around 1968, retracted in the 1970s, and stabilized (at  $\approx 40\%$ ) in 1980.

<sup>19</sup>In exploring the data descriptively, we have found that within our ground truth sample, variation in reporting cannot be explained by cross-institution differences (which might have been generated by, e.g., institutional dissertation templates or guidance), as most institutions have similarly middling reporting rates. Major field turns out to have the most explanatory power for reporting, and we base our estimated propensity off of these.

It has since modestly grown (2000 onwards). Non-profit and firm support has also fluctuated; the share of graduates supported by firms peaked at 20% around 1960, whereas nonprofit support grew from 10% to 15% between 1980 and 2000 and has since stabilized.

Panels (B1) to (B4) disaggregate these patterns by broad field. Disaggregation reveals that government support was historically especially high in the physical sciences and engineering, but has since largely equalized across most fields. Non-profit support is somewhat higher in the life sciences, and industry support in engineering, though these patterns have also fluctuated: firms, for example, supported 30% of graduates in the physical sciences in 1960—which follow-up analysis indicates was led by Du Pont in chemistry—but under 10% today; conversely, non-profits supported 10% of life sciences graduates in 1980—but more than 20% today.

[Figure 4 about here]

Figure 4 is almost certainly a lower bound on true rates of support, which are undermeasured due to underreporting. In Appendix Figure B.7 we show IPW-weighted shares (i.e., attempting to adjust for this underreporting), which we treat as an upper bound, and which indicate that in 2022, as many as 67% of graduates may have had U.S. government support, 22% non-profit support, and 16% industry support. Using the raw and IPW-adjusted shares, we plot confidence bands, along with the midpoint. Though IPW-weighted values are larger than raw values, the variation across domains and over time remains similar. The appendix also evaluates other dimensions of heterogeneity, including by country of origin, which we observe for a subset of our sample (inferred from pre-doctoral institutions, which are reported in many dissertations, especially post-2000); in Appendix Tables B.2 and B.3, we show that a substantial share of both U.S. and foreign-origin students have U.S. government support, though substantially more U.S.-origin students do—reflecting their eligibility for a broader range of federal support mechanisms.

Table 2 lists the top 15 sources of external support for U.S. PhD graduates, by sector (government, industry, non-profit). The National Science Foundation (NSF), National Institutes of Health (NIH), Department of Defense (DoD), and Department of Energy (DOE) rank high on this list, as do the National Aeronautics and Space Administration (NASA) and Department of Agriculture (USDA). Top non-profit funders include academic societies and philanthropic foundations. The top firms tend to be large, research-intensive multinational corporations. Intel and IBM top this list, but the most represented industries are the chemical, oil & gas, and pharmaceutical industries—indicating that many major corporations in high-tech manufacturing industries invest in developing highly-trained researchers who might augment the stock of relevant knowledge or might contribute directly to their future R&D efforts as future employee researchers.

[Table 2 about here]

#### 4.1.1 Heterogeneity across subjects and universities

Figure 4 points to heterogeneity in the level of support broad subjects receive from different categories of funders. In Appendix B.4 we explore these differences in finer detail, plotting the share of PhD graduates between 2000 and 2022 in specific subjects with government and industry support. Appendix Figure B.5 splits the sample into very large subjects (with >1200 graduates in this period; Panel A) and large subjects (400-1200 graduates; Panel B) to improve readability. The figure provides insight into which areas of science are predominantly funded by either firms or the federal government. Scientific training in automotive engineering and pharmaceutical science, for example, is more heavily industry-supported than government supported. Astronomy and astrophysics, on the other hand, are heavily government-supported and receive essentially no private support. Geology and materials science receive a mix. In nearly all subjects, however, the federal government provides much more support (5 to 10x) of doctoral training than industry.

Appendix Figure B.6 provides similar analysis by university, plotting the share of STEM PhD graduates between 2000 and 2022 in each university with government and industry support. We similarly split the sample into very large universities (with >2000 graduates in this period; Panel A) and large universities (1000-2000 graduates; Panel B). The figure shows a clear positive correlation in rates of government and industry support—suggesting that the doctoral funding system concentrates among the same institutions and students. Technical universities like MIT, Carnegie Mellon, Georgia Tech, and Virginia Tech tend to have higher rates of industry support, but as before, the federal government remains (by far) the larger sponsor of PhD training.

#### 4.1.2 Patterns in government support by gender and nationality

The granularity of our data support analysis of heterogeneity across other margins, including individual student characteristics. In Appendix B.1, we use information on pre-PhD education to identify probable foreign nationals and evaluate the rates at which they report U.S. government support. Although PQDT does not report nationality, many dissertations list where the author received lower degrees (often undergraduate, occasionally master’s), seemingly on the basis of the dissertation template they are given at the time of filing. We find this information in approximately 10% of dissertations in our sample, and 18% of those post-2000, including at high frequency at dozens of institutions. Using lower degree institution locations as a proxy for origin country, Appendix Tables B.2 and B.3 examine the share of graduates in each major field and critical technology area who report a degree from a foreign pre-doctoral institution, and in turn the share of these

(likely-foreign) graduates who report U.S. government support.<sup>20</sup>

The (apparent) foreign-origin share of U.S. PhD graduates varies substantially across fields, with  $\sim 20\%$  in the biological sciences having a non-U.S. BA (or equivalent), and  $\sim 60\%$  in civil engineering—rates which are directionally similar to the SED. Whereas 50% of AI graduates and nearly 60% of data and cybersecurity graduates have a non-U.S. BA, only  $\sim 25\%$  of those related to space technology or hypersonics appear foreign. Perhaps most interestingly, U.S. lower degree holders report government support at higher rates than foreign degree holders—in part due to eligibility restrictions for certain categories of federal support—but non-U.S. degree holders also report U.S. government support for their PhD research at high rates, reflecting that the U.S. government funds PhD research broadly and through a wide array of mechanisms.

#### 4.1.3 Specialization and variation over time at federal agencies

We next turn attention to specific sources of support—especially federal government agencies, focusing on the four largest government supporters of PhD training: NSF, HHS, DoD, and DOE. Figure 5(A) characterizes the share of graduates in each of 17 major fields funded by these agencies. NSF provides relatively even support across subjects (except for health sciences, reflecting NSF’s prioritization of funding basic science) and is an especially large supporter of students in geological (i.e., earth, atmospheric, and ocean) sciences. Other agencies have a clear mission focus. HHS, for example, supports a large fraction of trainees in biological and health science and biomedical engineering, but few in other fields. DoD is the country’s largest funder of doctoral training in aerospace engineering and a large supporter of electrical engineering and computer science. DOE emphasizes physics, chemical engineering, and materials science. Though not shown, similar patterns are present for other agencies—for example, USDA is a major sponsor of agricultural sciences; DOT, of civil engineering; and NASA, like DoD, of aerospace engineering.

[Figure 5 about here]

Figure 5(B) shows how this support has varied over time. The common pattern across most agencies is that their support for PhD training peaked in the late 1960s and has only recently recovered, if at all. Roughly 20% of STEM PhD graduates currently acknowledge support from NSF, 15% from HHS, and 12% from DoD and DOE collectively (roughly 5-7% individually)—shares which we consider conservative (lower bounds, given the potential for underreporting, as discussed above), but which capture the relative rate of support across agencies.

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<sup>20</sup>We are grateful to an anonymous reviewer for suggesting this measurement approach.

## 4.2 PhD production in critical technology areas

An additional important dimension of the U.S. STEM scientific training ecosystem is the cultivation of scientific expertise in critical technology areas. Using the measures introduced in Section 3 we tabulate the number of graduates in our sample associated with each of the 18 OSTP (2024) critical and emerging technology areas by university and source of support between 2000 and 2022. Table 3 lists the top five universities and sources of support for graduates in each of the 12 largest technology areas (excluding AI, which we will examine in more detail momentarily).<sup>21</sup> Despite the ostensible importance of critical technology science to U.S. science policy and economic policy, to our knowledge, for most of these technologies the U.S. doctoral education system has not been systematically and nationally assessed to understand how many such scientists the U.S. trains, where they are trained, and who pays for their training.

[Table 3 about here]

The table offers many insights. First, we find that several universities rank highly in multiple technologies areas, including MIT (in the top 5 for 10 of 12 areas in the table), Stanford (9), and UC Berkeley (7)—highlighting that these universities play an outsize role in the U.S. innovation ecosystem. Maryland, Michigan, Purdue, and UCLA also rank highly for 4+ technology areas. Second, we observe that some universities have strength in specific subjects, some of which are a product of decades of public investment. MIT, Northwestern, NC State, Penn State, and UIUC are the top universities for training PhDs in advanced materials—and all were among the 12 institutions which were selected by DARPA to establish materials science laboratories in the 1960s, when the field was effectively born. Third, with little exception, U.S. federal agencies are the top sources of support for trainees in all of these areas. For all of these facts, it is important to keep in mind that a few universities which are important training grounds for scientists in these areas (e.g., Georgia Tech) may be omitted from the list due to their exiting the PQDT sample early (as seen in Appendix Table A.12). Appendix Table B.6 reproduces Table 3 with data through 2012 only to explore what some of these may be, but the comparison also elucidates how the relative importance of each university to these technology areas may have changed over time.

Table 4 provides a similar analysis for artificial intelligence specifically, expanding the list of reported universities and research sponsors. At the top of the list of universities training researchers in AI are many expected institutions (e.g., Stanford, MIT, and UC Berkeley), which further reinforces

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<sup>21</sup>Technology areas omitted from this table are: human-machine interfaces, positioning, navigation, and timing (PNT) technologies, advanced gas turbine engines, directed energy, and hypersonics.

the face validity of the method. Also in the top 15 schools, however—and especially below the top 5—are many public universities, which collectively train more PhDs in AI than the top 5 schools. As before, a small number of schools which might have otherwise made this list (e.g., Georgia Tech) are likely absent because they exited the PQDT sample early—an intuition supported by Appendix Table B.7, which reproduces this analysis through 2012 (despite being prior to the recent AI renaissance) and finds Georgia Tech ranked in the top three.

[Table 4 about here]

The right half of Table 4 shows that the top six sources of support for AI PhD trainees are government agencies, with NSF and DoD atop the list. The next-largest source of support is large U.S. technology companies such as Google, Microsoft, IBM, Intel, and Nvidia. The differences in magnitude between government and private support, however, are very large: the NSF supports 10x as many graduates as Google, and 20x as many as Intel.

In Figure 6, we aggregate this information up to the technology level, documenting the share of graduates in each technology area reporting government support against the total number of graduates in that area between 2000 and 2022. We color code each technology by the principal agency providing support. Figure 6 shows that there are essentially three clusters of PhD graduates with respect to critical technologies: the defense cluster, relatively low in count but heavily DoD-supported; the civilian mission agency cluster (space, energy, and biotech); and the NSF cluster, which spans a range of subjects but is concentrated around advanced electronics, communications, and computing. NSF is the leading patron of two-thirds of the areas in the OSTP list, and two-thirds of the graduates we associate to any critical technology area.

[Figure 6 about here]

### 4.3 Effect of government funding on PhD production

The very large role that federal funding plays in supporting scientific training in STEM, including in critical technology areas—together with historical fluctuations in the level of public support, including recent cuts (at the time of writing; Bhatia et al. 2025)—naturally raises the question of what happens to PhD production when federal research funding programs expand or contract. Does the production of new scientists change with it? If so, how much?

To study these questions, we use our data to count PhD graduates at the field level and relate annual PhD production to the level of federal support. We estimate the following relationship,

where  $i$  indexes fields and  $t$  indexes years;  $PhDGraduates_{it}$  is total graduates in field-year  $it$ ;  $SupportedGraduates_{it}$  is observed graduates in field-year  $it$  with federal support;  $X_{it}$  represents additional controls; and  $\alpha_i$  and  $\delta_t$  are field and year fixed effects, with a baseline estimation sample spanning all 17 STEM major fields and the years 1970 to 2022:

$$\ln PhDGraduates_{it} = \beta \cdot \ln SupportedGraduates_{it} + X_{it}\phi + \alpha_i + \delta_t + \varepsilon_{it}. \quad (1)$$

We also estimate a variant of this specification at the university-field-year level, where our panel units become university-fields, which affords added precision.

The focal parameter throughout this analysis is  $\beta$ , which represents the elasticity of total PhD production with respect to government-supported graduates in a given cohort. The value of  $\beta$  will indicate whether increases in government-supported graduates displace other graduates (crowd-out), do not affect the number of other graduates (additivity), or increase other graduates (crowd-in). However, this interpretation cannot be made from the estimate of  $\beta$  directly, but rather is a function of the baseline government-supported share. To see this, let  $T$  be shorthand for total graduates,  $G$  for government-supported graduates, and  $N(G)$  for others, where  $T = G + N(G)$ . The crowd-in question is one of the derivative  $N'(G)$ , which could be positive, negative, or zero, or equivalently whether  $\frac{dT}{dG}$  ( $= 1 + N'(G)$ ) is greater than, less than, or equal to one.

Observe that  $\beta$  in Equation (1) can be written as  $\beta = \frac{d \ln T}{d \ln G} = \frac{dT}{dG} \frac{G}{T}$ , such that  $\frac{dT}{dG} = \frac{\beta}{s}$ , where  $s \equiv \frac{G}{T}$ . With estimates of  $\beta$  and  $s$ ,  $\frac{dT}{dG}$  is thus implied. In our data,  $s$  appears to be between 0.4 (as observed; Figure 4) and 0.67 (adjusted for potential underreporting; Appendix Figure B.7), which will bracket the potential crowd-in for any estimate  $\hat{\beta}$ .

#### 4.3.1 Identification and shift-share design

Evaluating the relationship between investments in PhD training and PhD production presents two challenges. The first is the threat of a mechanical relationship in a specification where the outcome is total graduates and the explanatory variable is a category of graduates. The second is that this relationship may be confounded by unobserved factors. For example, federal support may flow to fields with rising scientific opportunity, which may also attract students regardless of the level of government support and lead to overstating the effect of federal funding on PhD production. Conversely, federal agencies may direct support toward mission-relevant fields precisely when those fields are undersubscribed, which would lead us to understate it.

To confront these challenges, we use a shift-share design to instrument for supported graduates (e.g., Goldsmith-Pinkham et al. 2020, Borusyak et al. 2022), combining each agency’s annual

number of supported graduates (the shift) with each field’s share of that agency’s graduates in a predetermined base period (the share). This design exploits the variation in Figures 5(A) and 5(B)—the combination of which creates variation in federal support in each field over time. For example, changes in total DoD and NIH support will (ostensibly) have different effects on aerospace engineering versus biology, given their respective specializations.

Concretely, we (i) calculate field  $i$ ’s share of supported graduates from each agency  $a$  in a base period ( $\omega_{ia}$ ); (ii) interact it with the log number of agency  $a$ ’s supported graduates in  $t$ , computed over all fields other than  $i$  ( $Graduates_{at}^{-i}$ , a leave-one-out shifter); and (iii) sum across agencies to get field  $i$ ’s predicted log number of supported graduates in year  $t$ :

$$\ln \widehat{SupportedGraduates}_{it} = \sum_a \omega_{ia} \cdot \ln Graduates_{at}^{-i} \quad (2)$$

We define the base-period shares  $\omega_{ia}$  in three ways, each predetermined relative to the cohorts they instrument: averaging over (i) the 6 to 10 years prior to year  $t$  (rolling), (ii) 11 to 15 years prior (rolling, granting more distance), and (iii) a static 1960-1969 window. In the static case we restrict the estimation sample to post-1980, ensuring at least a decade between the base period and the earliest cohort. We condense the agency set to the six largest federal funders (DoD, DOE, HHS, NASA, NSF, and USDA), an “other agencies” category, and a “multiple agencies” category to avoid double-counting graduates with more than one federal sponsor. In university-field-year analysis, we construct an analogous variant of this instrument at this level.

Even with this instrumental variable design, residual identification threats can remain, especially if agency budgets fluctuate based on the evolving potential of the fields they support—such as if Congress directs resources to agencies that specialize in a given field when that field’s potential is elevated. Two features of our analysis are designed to reduce this risk. The first is our use of leave-one-out shifters, which avoid direct contamination from same-field changes; the evolving opportunity in field  $i$  would then have to be correlated with that of other fields in the same supporting agencies’ portfolios to confound. The second is that our implementation of Equation (1) will include field  $\times$  year fixed effects (broad field  $\times$  year in the field-year analysis, narrow field  $\times$  year in the university-field-year analysis), which will absorb evolving field-specific factors that might correlate with the instrument and independently drive PhD enrollments.

Though not fully complete—as opportunities may shift over time at levels below our measurement resolution (subfields)—the leave-one-out shifter together with these fixed effects do substantial work to account for latent threats which the shift-share design would not account for. Additional robustness checks in Appendix B.7 will further reinforce that the results are not driven by any



particular field (or its subfields). More broadly, agency-specific fluctuations have also often been driven by exogenous factors that shaped the resources they receive (e.g., reductions in defense R&D funding after the end of the Cold War (post-1991), stimulus funds from the American Recovery and Reinvestment Act (2009), or the politics of biomedical research).

### 4.3.2 Estimation results

Table 5 presents OLS and 2SLS estimates of Equation (1) under each instrument, at the field-year level (Columns 1-4) and the university-field-year level (Columns 5-8). The estimated elasticity of total PhD production with respect to federally-supported graduates is close to one and broadly consistent across columns: estimates range from roughly 0.8 to 1.1 under the 2SLS specifications, with first-stage  $F$ -statistics well above conventional thresholds. Our preferred specification is the university-field-year level estimate in Column (8), generated from the 1960-1969 base year instrument, which we consider our most econometrically conservative result.

[Table 5 about here]

At an observed (overall) government-supported share of  $\sim 40\%$ ,  $\frac{dT}{dG} \approx 2$ , implying that for every government-funded graduate, there is an additional unfunded graduate. At a reweighted (for potential underreporting) share of  $\sim 65\%$ ,  $\frac{dT}{dG} \approx 1.2$ , implying that for every five government-funded graduates, there is an additional unfunded graduate. Our interpretation is thus that the evidence is inconsistent with crowd-out, and instead consistent with additivity or modest crowding in—though given the range above we cannot confidently claim a precise value.<sup>22</sup>

Appendix B.7 presents a range of additional robustness checks. We first decompose our instrument into a scale and an allocative component, where the scale component represents a fields’ differential exposure to swings in total government support and the allocative component represents fields’ exposure to changes in the cross-agency composition of the federal portfolio; for example, physics has a large scale factor loading, as it is supported at relatively high rates by many agencies (DoD, DOE, NASA, NSF), whereas biomedicine has a large allocative factor loading, being sensitive to changes in NIH’s share of total government support. We find that the allocative factor explains our variation on its own, and controlling for scale (i.e., for individual field’s scale of federal support), the results are unchanged. We then perform additional tests to push on allocative confounds (e.g.,

<sup>22</sup>In theory, crowd-in can operate through expansions in capacity and returns to scale—for example, if (i) government-funded graduates are supported under grants that fund faculty, equipment, or infrastructure that other students also use or train from, (ii) grants fund overhead that is spread across programs and students, or (iii) government funding encourages private (philanthropic or industry) funding, whose marginal productivity grows because it can leverage assets that federal funding engenders (e.g., Azoulay et al. 2026).

if NIH support grows specifically when biomedical research possibilities flourish). First, presuming that residual opportunity confounds would concentrate in the fields closest to recent technology booms, we re-estimate the relationship excluding four such fields jointly (computer science, electrical engineering, biomedical engineering, and the biological sciences). Second, we re-estimate our focal specification dropping one field at a time, for all fields. The estimates are essentially unchanged—indicating that no single field, nor a group of technologically proximate fields, drives the result. Finally, we show that the results remain quantitatively and statistically similar when estimated on a sample restricted to universities present in PQDT throughout the estimation period, confirming that the results cannot be attributed to any sample attrition.

These results should nevertheless be interpreted cautiously, given that instrumental-variable designs rely on hard-to-test assumptions of conditional independence. Our view is that the evidence is suggestive rather than dispositive:  $\hat{\beta}$  statistically sustains under multiple instruments, withstands demanding controls, and does not depend on any single field, but it rests on instrument shares being independent of unobserved field-specific shocks that would not otherwise be absorbed by fixed effects. Additionally, given the relatively aggregated level at which this analysis is conducted, the estimated elasticity represents a bundled, equilibrium response of the training ecosystem to public investment—one that includes the induced expansion of non-federally supported graduates implied by the crowd-in discussed above—rather than a direct impact.

## Comparisons to existing literature

The evidence is broadly consistent with prior research finding that fellowship applications and PhD enrollment respond to the availability of funding (e.g., Freeman et al. 2009, Blume-Kohout and Adhikari 2016). The closest prior analysis is arguably Blume-Kohout and Adhikari, who relate NIH-supported PhD students to total PhD enrollment in biomedical sciences after the early 2000s doubling of the NIH using NSF GSS data and find that “NIH-funded traineeships and fellowships increase full-time graduate enrollment by essentially 1:1,” with more attenuated effects for research assistantships (Blume-Kohout and Adhikari 2016, p. 1297). Our finding that total PhD production rises roughly in proportion to federally-supported graduates, with no evidence that other graduates are crowded out, is consistent with these findings, while adding a more systemic, population-level perspective spanning multiple federal funders and long panels.

We view our estimates as adding an additional datapoint on the relationship of public funding to national PhD production—and on the impacts of public R&D more broadly—rather than a singularly decisive result. Differences in samples, measures, sources of variation, and specifications can all generate differences in point estimates, potentially reflecting meaningful heterogeneity. Moreover, as

others have shown (e.g., Kim et al. 2022, Graddy-Reed et al. 2021), these elasticities can vary by funding mechanism, and funding can affect not only enrollments but completion, placement, future productivity, and academic networks. Because our measures speak to overall levels of support rather than specific mechanisms through which students were funded or otherwise supported, we abstract from this heterogeneity to emphasize the total size and breadth of the PhD graduate population as a broad indicator of evolving scientific capacity (OECD 2015).

## 5 Distribution Dataset

Using the above-described data, we compile three public-use datasets measuring PhD production by university, field, and university-field over time. In all three cases we limit the sample to universities which have ever held an R1 (very high research activity) or R2 (high research activity) classification post-2000, or which are dedicated medical schools (e.g., SUNY Downstate or UT Southwestern). For each dataset, we report the total number of PhD graduates in the natural sciences and engineering; the number for which we have full text and for which we have detected acknowledgments (for normalization); the number we identify as supported by the U.S. government, by industry, or by non-profit organizations; and the number supported by specific federal agencies (DoD, DOE, HHS, etc.). For the university-level dataset we further report the number of graduates we associate to OSTP critical technology areas. Data and accompanying documentation have been posted to the Harvard Dataverse and are available for public use (Shvadron et al. 2025a).

The distribution data include information for 338 unique institutions between 1950 and 2022—though the sample is unbalanced, with roughly 100 institutions in the 1950s and nearly 300 by the end of the sample. The field and university-field datasets report graduates for the 17 focal SED major fields described earlier, spanning the life sciences, physical sciences, and engineering. Users of these data who wish to make use of the counts of students with particular sources of funding may want to normalize these counts by either (i) the number of graduates in the given university-year, field-year, or university-field-year for which we have dissertation text (variable `has_ft`), or (ii) the number for which we have identified acknowledgments (`has_ack`).

## 6 Conclusion

In this paper, we use information from the dissertations of nearly 1.2 million U.S. STEM PhD graduates between 1950 and 2022 to examine the U.S. scientific training ecosystem. Leveraging recent advances in LLMs, we (i) link each dissertation to 18 critical and emerging technology areas recently identified as national priorities by the White House OSTP and (ii) process dissertation acknowledgments to identify research sponsors. With these data we show that about half of recent

graduates acknowledge external support, with the U.S. federal government supporting about 42% of graduates—far eclipsing industry ( $\approx 10\%$ ) and non-profits ( $\approx 15\%$ ). NSF and NIH alone individually account for more supported PhDs than the entire commercial sector, and their support is highly concentrated in universities that also dominate critical-technology training (e.g., MIT, Stanford, UC Berkeley, among others). Across the 18 OSTP domains, federal agencies are typically the top funders, though a range of universities train students in these fields.

Exploiting agency-specific variation (in both the primary fields supported and total number of graduates supported over time) in a shift-share design, we estimate an elasticity between government support and PhD production near one, indicating that total PhD production scales proportionally with the number of government-supported graduates, and with a magnitude that implies additivity or modest crowd-in—underscoring public investment as a driver of expansions and contractions in the scientific workforce. These data, methods, and findings together provide a new, scientifically- and policy-relevant map of the U.S. scientific training ecosystem and a foundation for tracking how funding choices influence national science and innovation capacity. The approach we develop can also be extended forward and to other national innovation systems.

Whether more or less public investment (and accordingly, more or fewer PhD trainees) is desirable is not a question this paper specifically speaks to: our goal is to document features and effects. In particular, as in other markets, public subsidies may distort market outcomes. Nelson (1959), Arrow (1962), and others have argued that public investment in R&D can correct inefficiencies more than it introduces them, and policy advisors as far back as Bush (1945) have made the case for funding scientific training. Yet a perennial question and point of concern is whether the U.S. innovation system trains too many PhD scientists. Critics point to the limited number of tenure-track faculty jobs relative to PhD graduates, large number of postdocs, length of postdocs, and the growth of contingent faculty as evidence of oversaturation (e.g., Cyranoski et al. 2011, Powell 2015), especially in light of the prevailing wages these workers accept (Stephan 2013).

On the other hand, the size of the scientific workforce is typically seen as the rate-limiting factor for scientific progress, and in turn for improvements in economic growth and material well-being (Steelman 1947, Atkinson 1990, Romer 1990, Jones 2009). Those who advocate growing the scientific workforce point out that many PhDs enter industry, where they can be important contributors to private sector innovation (Scharfmann et al. 2025). Firms are generally considered unlikely to invest in transferable skills like scientific training, since those skills are broadly marketable (Becker 1964). This intuition may explain why industry funds relatively few PhDs (Table 2)—and where it does, it often only supports science with specific private value (as our example in Figure 3 demonstrates). Given this logic, and evidence that the returns to public R&D (much of which funds training; Sattari

et al. 2022) are often found to be very high (Jones and Summers 2022, Fieldhouse and Mertens 2024), it is easy to make the case for growing the scientific workforce.

We do not stake a claim on the issue, but rather observe that the answer may hinge on which scientists we have in mind—and the data we produce can be helpful to assessing seemingly important categories of trainees. Moreover, our evidence reinforces that public funding plays a central role in determining their supply (Table 5; also cf. Dugoua et al. 2025), and that the data we introduce can be used to further adjudicate this debate—including the possibility that whether public subsidy corrects or distorts markets may vary over time and by field, with critical and emerging scientific fields being riper targets for public investment than more mature ones.

The methods and data of this paper point to other opportunities for future research. The methods we develop can be used more widely to evaluate the content of dissertation science or other scientific corpora directly from the text. Our entity recognition procedure can also be applied more broadly, and in ongoing research (Gross et al. 2025), members of this author team are adapting this approach to extract research funders from historical publications.

Beyond methods, the data accompanying this paper can be used in many ways, including for evaluating where scientific training takes place, how it has evolved over time, what drives changes in its scale and composition, and what its effects are on institutions, regions, scientific fields, and more. For example, how does PhD production interact with regional economies? To what degree do public investments in scientific training spill over into (i) closely related local industries, vs. (ii) less-related industries in the same region, vs. (iii) other regions? How important are PhD programs to universities’ overall research productivity—and how much does research suffer when PhD enrollment declines or programs end? How important are PhD programs to nearby firms—and conversely, what is the role of industry support in doctoral training? Do universities with more industry-funded PhDs produce more commercially oriented research, industry placements, or university startups? And backing out from these more localized effects: what is the importance of PhD production to the wider U.S. innovation system, and what happens to U.S. science and innovation as the PhD population ebbs and flows? In releasing data which maps the U.S. scientific training ecosystem over a long horizon, we hope to enable further research on these questions.

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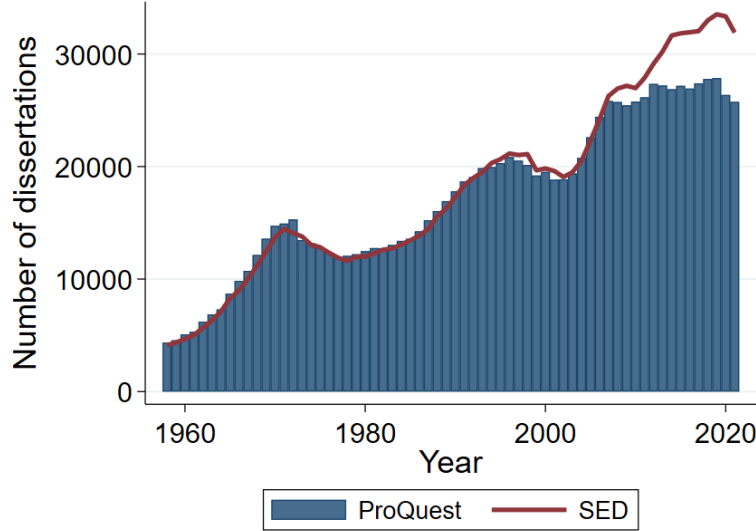
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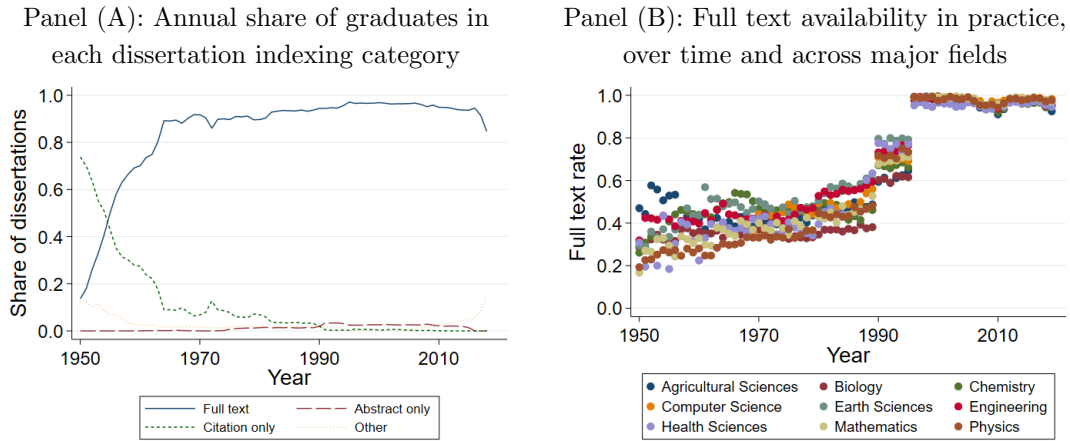
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Figure 1: ProQuest vs. SED graduates in STEM fields, by year



Notes: Figure shows annual PQDT graduate counts in the physical and life sciences and engineering (blue bars) and SED counts (red line) for comparison, from 1958 (the first year of the SED) to 2022.

Figure 2: Availability of dissertation text

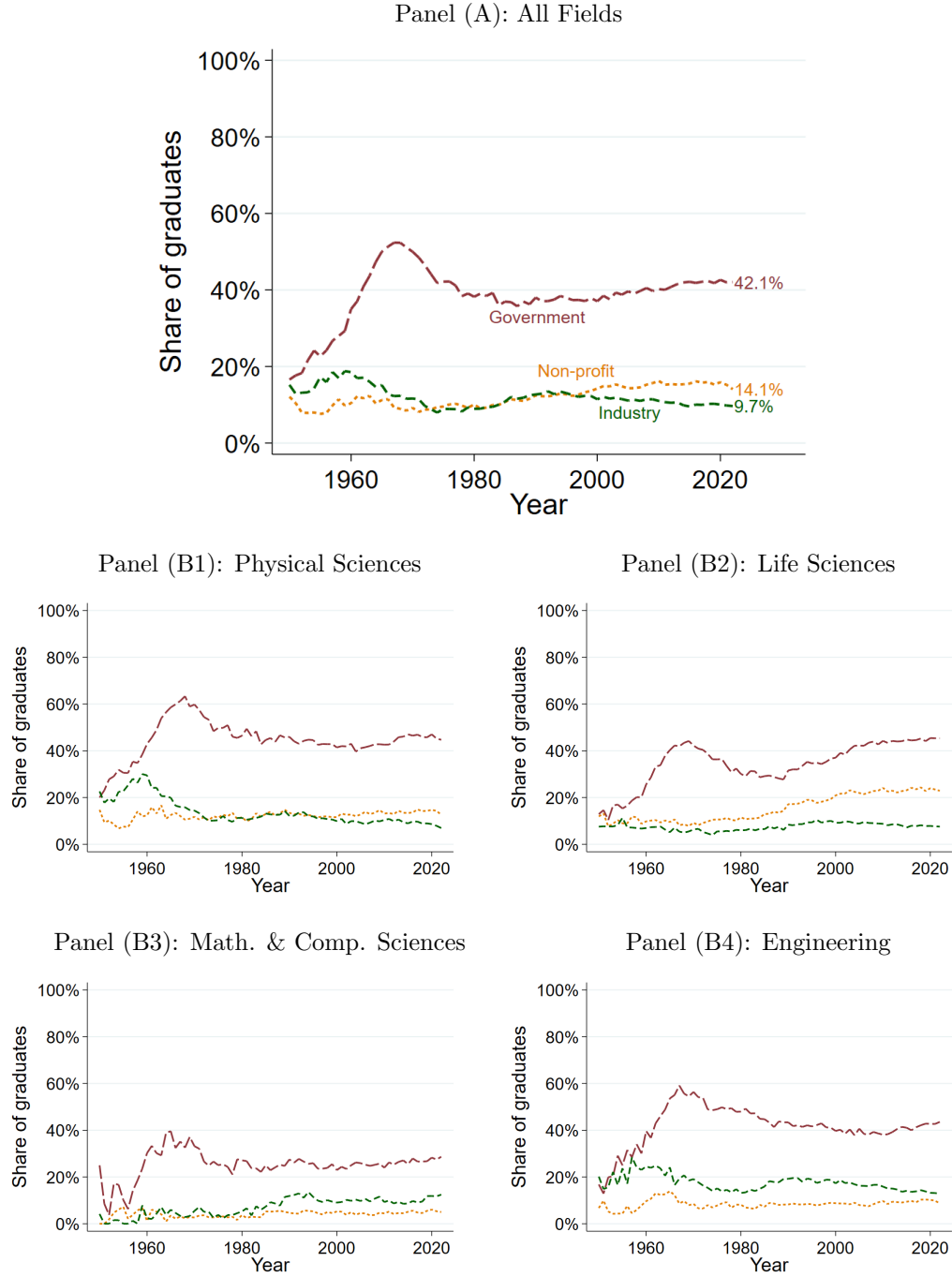


Notes: Panel (A) shows the annual share of dissertations in our sample that ProQuest identifies as having been indexed full text (i.e., ProQuest received metadata (author, title, subject, etc.) and a full copy of the dissertation), abstract-only (metadata plus abstract), or citation only (metadata only). Panel (B) shows the annual share for which we actually have full text.

Figure 3: Example dissertation acknowledgment (Ian Buck, Stanford University, 2005)

I have had a variety of funding sources throughout my graduate career including DARPA, DOE, ASC, NVIDIA, ATI. Specifically, I would like to thank Randy Frank, Bob Graybill, and Mike Macedonia for putting money where my mouth was. I also have been fortunate in receiving fellowships from the Stanford School of Engineering as well as NVIDIA.

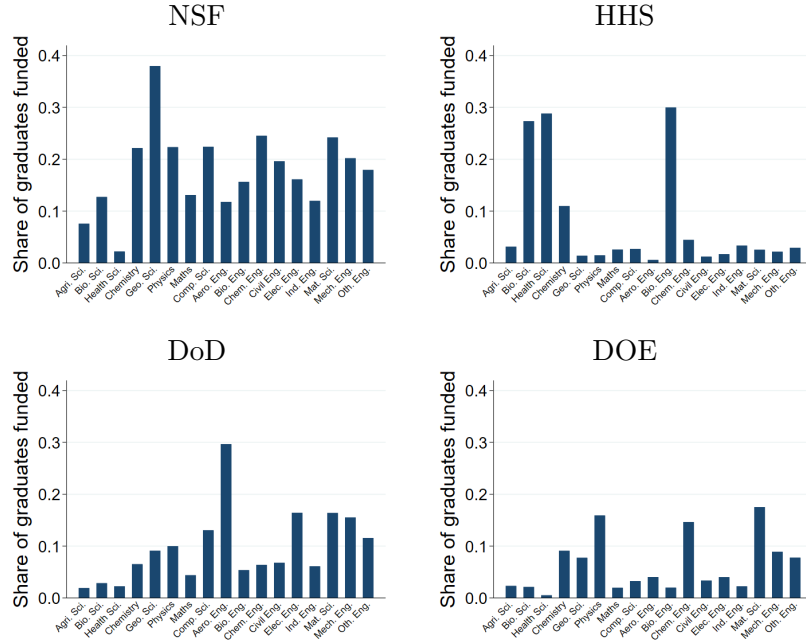
Figure 4: Share of PhD graduates supported over time, 1950-2022, by organization type, based on acknowledgments reported in dissertations (a lower bound)



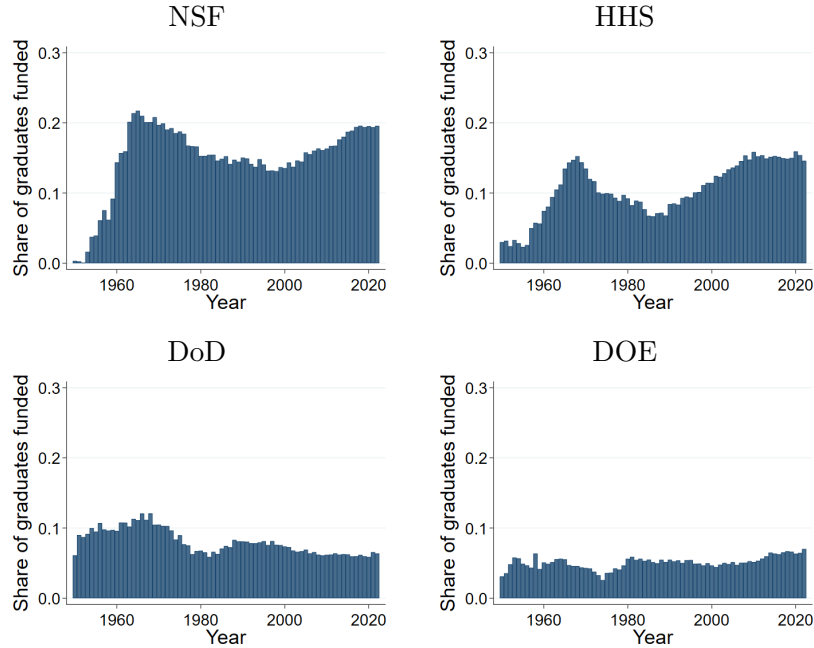
Notes: Figure shows the share of PhD graduates reporting their sources of support who are supported by (i) U.S. federal government agencies, (ii) firms, and (iii) non-profit organizations, from 1950 to 2022. Panel (A) presents overall results. Panels (B1) to (B4) present results by broad field (physical sciences, life sciences, mathematical and computer sciences, and engineering). Sample restricted to dissertations with acknowledgments (>98% of all dissertations). The shares shown here should be interpreted as a lower bound due to underreporting. See text for discussion, and see Appendix Figure B.7 for upper bounds, which use inverse propensity weighting to account for underreporting.

Figure 5: Federal agency variation in PhD graduate support, across fields and over time

Panel (A): Major fields' share of graduates supported by select federal agencies, 1950-2022

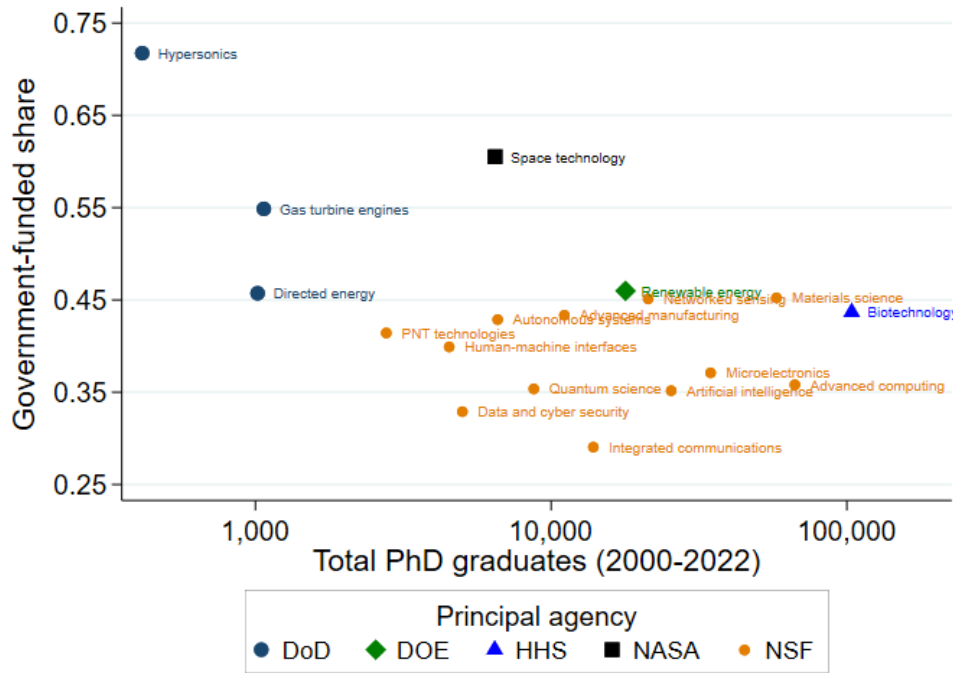


Panel (B): Share of all graduates supported by select federal agencies over time, 1950-2022



Notes: Panel (A) shows the share of PhD graduates in individual major fields supported by each agency listed (NSF, HHS, DoD, DOE), illustrating differences in subject matter priorities across agencies. Panel (B) shows the share of PhD graduates supported over time by each agency listed (NSF, HHS, DoD, DOE), illustrating long-run changes in these agencies' investments in PhD training.

Figure 6: Share of graduates reporting government support, by critical technology area, 2000-2022



Notes: Figure plots the share of graduates in each critical technology area reporting government support against the number of graduates in that technology area, color-coding each technology area’s principal source of government support (DoD, DOE, HHS, NASA, or NSF). See OSTP (2024) for a complete list.

Table 1: Example extraction of acknowledged organizations for Ian Buck (Figure 3)

| Entity Name                    | Entity Type     | Support Type | ROR Organization                          |
|--------------------------------|-----------------|--------------|-------------------------------------------|
| DARPA                          | government      | funding      | Defense Advanced Research Projects Agency |
| DOE                            | federal agency  | funding      | United States Department of Energy        |
| ASC                            | unknown         | funding      | –                                         |
| NVIDIA                         | private company | funding      | Nvidia                                    |
| ATI                            | private company | funding      | Advanced Micro Devices                    |
| Stanford School of Engineering | academia        | fellowship   | –                                         |
| NVIDIA                         | private company | fellowship   | Nvidia                                    |

Notes: Table lists organizations identified in the text in Figure 3 as dissertation sponsors using our LLM-based procedure and provides their links to ROR. The LLM associates ATI with Advanced Micro Devices (AMD) because ATI Technologies was acquired by AMD in 2006.

Table 2: Top 15 acknowledged organizations, by sector, 2000-2022

| Government agencies                           |        | Firms            |       | Non-profit organizations            |       |
|-----------------------------------------------|--------|------------------|-------|-------------------------------------|-------|
| Name                                          |        | Name             | Count | Name                                | Count |
| National Science Foundation                   | 91,813 | Intel            | 2,276 | Howard Hughes Medical Institute     | 3,731 |
| Department of Health and Human Services       | 77,989 | IBM              | 1,942 | American Heart Association          | 3,676 |
| Department of Defense                         | 34,081 | Merck            | 1,417 | Sigma Xi                            | 2,787 |
| Department of Energy                          | 30,528 | Google           | 1,300 | American Cancer Society             | 1,568 |
| National Aeronautics and Space Administration | 15,038 | Microsoft        | 1,221 | American Chemical Society           | 1,453 |
| Department of Agriculture                     | 13,443 | Pfizer           | 1,177 | Geological Society of America       | 1,386 |
| Department of Commerce                        | 8,925  | General Electric | 977   | Robert Wood Johnson Foundation      | 1,178 |
| Department of the Interior                    | 6,887  | Du Pont          | 873   | W. M. Keck Foundation               | 1,104 |
| Environmental Protection Agency               | 5,630  | Dow Chemical     | 847   | Fulbright Program                   | 953   |
| Department of Transportation                  | 5,283  | Eli Lilly        | 822   | David and Lucile Packard Foundation | 943   |
| Department of Education                       | 4,615  | Chevron          | 820   | Welch Foundation                    | 910   |
| Department of State                           | 4,244  | ExxonMobil       | 774   | Burroughs Wellcome Fund             | 897   |
| Department of Veterans Affairs                | 2,218  | GlaxoSmithKline  | 764   | Gordon and Betty Moore Foundation   | 856   |
| Agency for International Development          | 1,615  | Novartis         | 753   | Ford Foundation                     | 815   |
| Department of Homeland Security               | 1,368  | Boeing           | 718   | National Geographic Society         | 759   |

Notes: Table lists the top 15 government, industry, and non-profit sponsors of graduates between 2000 and 2022, as measured by our LLM-based procedure. Government and other sponsors acknowledged in dissertations are consolidated into ultimate parent agencies (e.g., defense agencies are grouped up to the U.S. Department of Defense (DoD); the National Cancer Institute is grouped into the National Institutes of Health, which is in turn grouped up to the U.S. Department of Health and Human Services, etc.).

Table 3: Top 5 universities and sponsors of PhD graduates in U.S. critical technology areas, 2000-2022

| Advanced Computing                  |       |             |        |        | Advanced Manufacturing              |       |             |        |       |
|-------------------------------------|-------|-------------|--------|--------|-------------------------------------|-------|-------------|--------|-------|
| Top universities                    |       | Top funders |        |        | Top universities                    |       | Top funders |        |       |
| University                          | Count | Name        | Sector | Count  | University                          | Count | Name        | Sector | Count |
| Stanford U.                         | 1,971 | NSF         | Govt   | 13,571 | Mass. Inst. of Tech.                | 381   | NSF         | Govt   | 2,842 |
| Mass. Inst. of Tech.                | 1,818 | DoD         | Govt   | 7,038  | U. California, Berkeley             | 362   | DoD         | Govt   | 1,567 |
| Purdue U., West Lafayette           | 1,617 | HHS         | Govt   | 4,400  | Purdue U., West Lafayette           | 326   | DOE         | Govt   | 1,064 |
| U. California, Berkeley             | 1,572 | DOE         | Govt   | 3,411  | U. Michigan, Ann Arbor              | 311   | HHS         | Govt   | 442   |
| U. California, Los Angeles          | 1,500 | NASA        | Govt   | 1,975  | U. Illinois, Urbana-Champaign       | 296   | NASA        | Govt   | 341   |
| Advanced Materials                  |       |             |        |        | Autonomous Systems                  |       |             |        |       |
| Top universities                    |       | Top funders |        |        | Top universities                    |       | Top funders |        |       |
| University                          | Count | Name        | Sector | Count  | University                          | Count | Name        | Sector | Count |
| Mass. Inst. of Tech.                | 1,555 | NSF         | Govt   | 14,770 | Mass. Inst. of Tech.                | 327   | NSF         | Govt   | 1,403 |
| Northwestern U.                     | 1,425 | DOE         | Govt   | 8,777  | Stanford U.                         | 276   | DoD         | Govt   | 1,294 |
| Pennsylvania State U.               | 1,345 | DoD         | Govt   | 7,714  | Carnegie Mellon U.                  | 237   | NASA        | Govt   | 526   |
| North Carolina State U.             | 1,305 | HHS         | Govt   | 2,324  | U. California, Berkeley             | 226   | DOT         | Govt   | 184   |
| U. Illinois, Urbana-Champaign       | 1,290 | NASA        | Govt   | 1,666  | U. Michigan, Ann Arbor              | 203   | HHS         | Govt   | 166   |
| Biotechnology                       |       |             |        |        | Clean Energy Generation and Storage |       |             |        |       |
| Top universities                    |       | Top funders |        |        | Top universities                    |       | Top funders |        |       |
| University                          | Count | Name        | Sector | Count  | University                          | Count | Name        | Sector | Count |
| U. Wisconsin-Madison                | 2,427 | HHS         | Govt   | 27,586 | Stanford U.                         | 528   | DOE         | Govt   | 4,541 |
| Harvard U.                          | 2,308 | NSF         | Govt   | 18,226 | U. California, Berkeley             | 519   | NSF         | Govt   | 4,031 |
| Stanford U.                         | 2,260 | DoD         | Govt   | 4,394  | Mass. Inst. of Tech.                | 506   | DoD         | Govt   | 1,343 |
| U. Washington, Seattle              | 2,082 | DOE         | Govt   | 4,091  | Purdue U., West Lafayette           | 421   | USDA        | Govt   | 421   |
| U. California, Berkeley             | 2,006 | USDA        | Govt   | 4,007  | Pennsylvania State U.               | 415   | NASA        | Govt   | 400   |
| Communications and Networking       |       |             |        |        | Data Privacy and Cybersecurity      |       |             |        |       |
| Top universities                    |       | Top funders |        |        | Top universities                    |       | Top funders |        |       |
| University                          | Count | Name        | Sector | Count  | University                          | Count | Name        | Sector | Count |
| U. California, Los Angeles          | 500   | NSF         | Govt   | 2,512  | Purdue U., West Lafayette           | 164   | NSF         | Govt   | 1,189 |
| Stanford U.                         | 418   | DoD         | Govt   | 1,692  | U. Maryland, College Park           | 124   | DoD         | Govt   | 621   |
| U. California, San Diego            | 384   | Intel       | Firm   | 322    | U. California, Los Angeles          | 101   | DOE         | Govt   | 143   |
| Ga. Inst. of Tech.                  | 361   | DOE         | Govt   | 314    | Arizona State U.                    | 95    | Google      | Firm   | 122   |
| Purdue U., West Lafayette           | 351   | NASA        | Govt   | 284    | Mass. Inst. of Tech.                | 95    | Intel       | Firm   | 109   |
| Microelectronics and Semiconductors |       |             |        |        | Networked Sensing                   |       |             |        |       |
| Top universities                    |       | Top funders |        |        | Top universities                    |       | Top funders |        |       |
| University                          | Count | Name        | Sector | Count  | University                          | Count | Name        | Sector | Count |
| Stanford U.                         | 1,313 | NSF         | Govt   | 7,680  | Stanford U.                         | 603   | NSF         | Govt   | 4,494 |
| U. California, Berkeley             | 1,157 | DoD         | Govt   | 4,661  | Purdue U., West Lafayette           | 572   | DoD         | Govt   | 3,173 |
| Mass. Inst. of Tech.                | 1,014 | DOE         | Govt   | 3,698  | Mass. Inst. of Tech.                | 527   | NASA        | Govt   | 2,147 |
| U. Illinois, Urbana-Champaign       | 857   | Intel       | Firm   | 904    | U. Maryland, College Park           | 474   | DOE         | Govt   | 1,228 |
| U. California, Los Angeles          | 848   | NASA        | Govt   | 754    | U. Michigan, Ann Arbor              | 472   | HHS         | Govt   | 725   |
| Quantum Science                     |       |             |        |        | Space Technology                    |       |             |        |       |
| Top universities                    |       | Top funders |        |        | Top universities                    |       | Top funders |        |       |
| University                          | Count | Name        | Sector | Count  | University                          | Count | Name        | Sector | Count |
| Mass. Inst. of Tech.                | 382   | NSF         | Govt   | 1,985  | U. Colorado Boulder                 | 319   | NASA        | Govt   | 2,745 |
| Stanford U.                         | 329   | DoD         | Govt   | 1,044  | Stanford U.                         | 221   | NSF         | Govt   | 1,265 |
| U. California, Berkeley             | 288   | DOE         | Govt   | 1,017  | Mass. Inst. of Tech.                | 220   | DoD         | Govt   | 836   |
| Harvard U.                          | 277   | HHS         | Govt   | 164    | U. Michigan, Ann Arbor              | 208   | DOT         | Govt   | 567   |
| U. Maryland, College Park           | 258   | NASA        | Govt   | 155    | U. Maryland, College Park           | 201   | DOE         | Govt   | 374   |

Notes: Table lists the top 5 universities and sponsors of graduates between 2000 and 2022 in the 12 largest OSTP critical technology areas. Graduates allocated to technology areas as described in text. For a small number of schools we have limited data from the mid-2010s onwards (see Appendix Table A.12). These schools are thus undercounted, and with more complete data a few of these schools might have appeared more frequently in this table. In Appendix B we regenerate this table using data through 2012 only, which truncates the sample early but avoids systematically undercounting these schools. The results are broadly similar, though they highlight Georgia Tech as a university which ranks highly in many of these technology areas but is missing in this table from most of them, likely due to sample truncation (Georgia Tech stops reporting to PQDT after 2012).

Table 4: Top 15 universities and sponsors of PhD graduates in AI, 2000-2022

| Top universities              |       | Top funders |        |       |
|-------------------------------|-------|-------------|--------|-------|
| University                    | Count | Name        | Sector | Count |
| Stanford U.                   | 760   | NSF         | Govt   | 4,925 |
| Mass. Inst. of Tech.          | 708   | DoD         | Govt   | 2,758 |
| U. California, Berkeley       | 611   | HHS         | Govt   | 1,920 |
| U. Maryland, College Park     | 578   | DOE         | Govt   | 963   |
| Purdue U., West Lafayette     | 564   | NASA        | Govt   | 651   |
| Carnegie Mellon U.            | 562   | Google      | Firm   | 484   |
| U. Washington, Seattle        | 535   | Microsoft   | Firm   | 327   |
| U. California, Los Angeles    | 533   | DOC         | Govt   | 287   |
| U. Michigan, Ann Arbor        | 476   | DOT         | Govt   | 283   |
| U. Illinois, Urbana-Champaign | 443   | IBM         | Firm   | 265   |
| U. California, San Diego      | 435   | Intel       | Firm   | 252   |
| Arizona State U.              | 417   | Nvidia      | Firm   | 228   |
| U. Southern California        | 404   | USDA        | Govt   | 216   |
| North Carolina State U.       | 370   | Amazon      | Firm   | 209   |
| U. Minnesota, Twin Cities     | 368   | Meta        | Firm   | 162   |

Notes: Table lists the top 15 universities and sponsors of graduates between 2000 and 2022 in artificial intelligence (AI). Graduates identified as AI-related based on critical technology assessment (see Section 3).

Table 5: Relationship of PhD production to government-supported graduates, 1970-2022

|                        | Field-year          |                     |                     |                     | University-field-year |                     |                     |                     |
|------------------------|---------------------|---------------------|---------------------|---------------------|-----------------------|---------------------|---------------------|---------------------|
|                        | (1)                 | (2)                 | (3)                 | (4)                 | (5)                   | (6)                 | (7)                 | (8)                 |
|                        | OLS                 | 2SLS                | 2SLS                | 2SLS                | OLS                   | 2SLS                | 2SLS                | 2SLS                |
| Ln(USG-supported PhDs) | 0.839***<br>(0.023) | 0.982***<br>(0.036) | 1.130***<br>(0.097) | 0.993***<br>(0.070) | 0.703***<br>(0.009)   | 1.118***<br>(0.028) | 1.156***<br>(0.045) | 0.781***<br>(0.016) |
| N                      | 901                 | 901                 | 901                 | 731                 | 70423                 | 70423               | 70423               | 63954               |
| F-stat                 |                     | 62.20               | 27.24               | 38.00               |                       | 99.98               | 75.75               | 120.08              |
| Field FEs              | Y                   | Y                   | Y                   | Y                   |                       |                     |                     |                     |
| Univ-Field FEs         |                     |                     |                     |                     | Y                     | Y                   | Y                   | Y                   |
| Year FEs               | Y                   | Y                   | Y                   | Y                   | Y                     | Y                   | Y                   | Y                   |
| Controls               | Y                   | Y                   | Y                   | Y                   | Y                     | Y                   | Y                   | Y                   |
| Sample                 | 1970+               | 1970+               | 1970+               | 1980+               | 1970+                 | 1970+               | 1970+               | 1980+               |
| Instrument             |                     | Roll/6-10           | Roll/11-15          | 1960-69             |                       | Roll/6-10           | Roll/11-15          | 1960-69             |

Notes: Table estimates the relationship of annual PhD production by university, field, and year to government-supported PhD graduates. Columns (1) to (4) do so at the field-year level, and Columns (5) to (8) at the university-field-year level. Columns (1) and (5) estimate Equation (1) by OLS, and the remaining columns by 2SLS, using three shift-share instruments for government-supported PhD graduates, based on (i) agency field shares calculated from 6-10 years prior to a given year (Roll/6-10), (ii) shares calculated from 11-15 years prior (Roll/11-15), and (iii) a static, 1960-1969 base period (1960-69). Estimation sample covers the post-1970 period except in Columns (4) and (8), which are restricted to post-1980 to ensure at least a decade between the shift-share base period and the earliest cohorts in the estimation sample. Columns (1) to (4) additionally control for broad field  $\times$  year fixed effects, and Columns (5) to (8) narrow field  $\times$  year fixed effects, to absorb national trends in PhD production by field. First-stage  $F$ -statistics reported for the 2SLS columns. \*, \*\*, \*\*\* represent significance at the 0.1, 0.05, and 0.01 levels, respectively. Heteroskedasticity-robust SEs in parentheses in Columns (1) to (4) and clustered by university in Columns (5) to (8).



# Online Appendix

## Funding the U.S. Scientific Training Ecosystem: New Data, Methods, and Evidence

Dror Shvadron, Hansen Zhang, Lee Fleming, and Daniel P. Gross

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# A Data Appendix

## A.1 Core sample: ProQuest dissertations

Our goal in this paper is to build as complete a sample of U.S. STEM (Science, Technology, Engineering, and Mathematics) PhD graduates since the mid-20th century as possible. Using this sample, we develop new methods of measuring characteristics of PhD trainees that complement existing data sources on U.S. PhD graduates and can substitute for administrative data in other countries or contexts where data collection infrastructure is less developed.

Our main data source for doing so is ProQuest Dissertations & Theses (PQDT).<sup>1</sup> For nearly a century, ProQuest has been acquiring and re-publishing dissertations of U.S. (and other countries’) PhD graduates. Its dissertation collection has since been digitally catalogued and includes extensive metadata on each dissertation (e.g., author, institution, degree name, title, abstract, subject), and the full text of many of these dissertations. PQDT data have been used in a range of recent research in the science of science, economics of innovation, and other fields studying scientific trainees (e.g., Toole and Czarnitzki 2010, Bikard et al. 2015, Buffington et al. 2016, Jiang et al. 2023, Antman et al. 2023, Arora et al. 2023, among others). As we show below, its contents approximate the universe of U.S. PhD graduates in our focal fields, which is a result of extensive, long-running licensing agreements it has held with many universities across the country.

At the time of acquisition (in 2023), the PQDT database contained nearly six million global master’s theses and doctoral dissertations, including in the natural sciences (i.e., physical and life sciences), engineering, humanities, social sciences, and more. For this paper, we sought to build a sample of doctoral dissertations at U.S. institutions in the natural sciences and engineering—which we term STEM fields as shorthand—for graduates from 1950 to 2022.

We do so as follows. Beginning with the full PQDT corpus, we first removed (i) non-U.S. dissertations and (ii) non-doctoral theses and dissertations. We also manually reviewed degree names to identify those corresponding to research degrees in the natural sciences and engineering.<sup>2</sup> We then crosswalk these graduates’ self-reported subjects (as provided in the PQDT data) to “major fields” defined by the U.S. National Center for Science and Engineering Statistics (NCSES) and filter our sample to dissertations in 17 major fields which are typically considered STEM subjects.<sup>3</sup>

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<sup>1</sup>Note that portions of this appendix—particularly those documenting our sample and our classification of PhD graduates to technology areas—share content in common with the data appendix of Shvadron et al. (2025b), where we use the same data source to study postgraduate migration of U.S. scientific trainees.

<sup>2</sup>Though most doctoral degrees are PhDs, PQDT also includes other doctorates such as DScs or field-specific doctorates (e.g., D.CS. (Doctor of Computer Science) or Chem. D. (Doctor of Chemistry)), as well as certain doctoral professional degrees (e.g., PsyD (Doctor of Psychology) or D.N.P. (Doctor of Nursing Practice)).

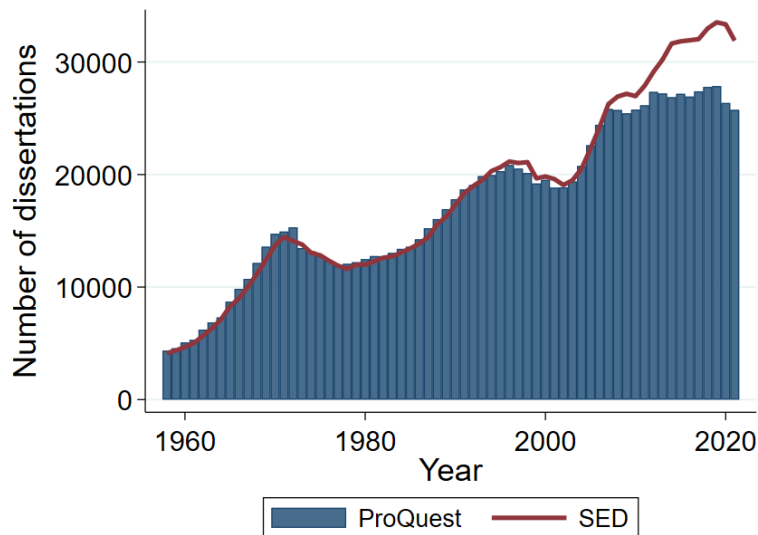
<sup>3</sup>Our focal major fields are: Agricultural sciences and natural resources, Biological and biomedical sciences, and Health sciences (belonging to the broad field “Life Sciences”); Physics and astronomy, Geosciences, atmospheric sciences, and ocean sciences, and Chemistry (belonging to “Physical Sciences”); Computer and information sciences and Mathematics and statistics (belonging to “Mathematical and Computer Sciences”); and Aerospace, aeronautical, and astronautical engineering, Bioengineering and biomedical engineering, Chemical engineering, Civil engineering, Electrical and electronics engineering, Industrial and manufacturing engineering, Materials science engineering, Mechanical engineering, and Other engineering (belonging to “Engineering”). In early years, PQDT reports a single

Lastly, we restrict the sample to graduates of institutions which ever held an R1 or R2 Carnegie classification post-2000, as well as of doctorate-granting medical and engineering schools. Our final sample contains 1.17 million dissertations from 1950 to 2022.

To evaluate the completeness and representativeness of our data, we compare the annual number of PQDT graduates in our final sample to annual counts of U.S. doctoral graduates from the Survey of Earned Doctorates (SED), an annual census of research doctorate recipients from U.S. universities which has been administered by NSF since 1958. Figure A.1 shows that PQDT (the blue bars) tracks the SED (red line) closely to the late 2000s. Even when they diverge slightly post-2005, PQDT still sums to  $>90\%$  of the SED totals. Figure A.2 disaggregates this comparison to individual fields and shows a similar degree of consistency within them.

Figure A.3, Panel (A) extends these comparisons, presenting a binned scatterplot of the log number of graduates in our PQDT sample at the university-field-year level against the log number of graduates according to the SED data. Panel (B) repeats this comparison at the university-year level. The sample in these charts is by construction limited to observations with a nonzero number of graduates in both PQDT and SED—though for the most part, when one source reports zero graduates, and the other nonzero, the latter reports only one or two.

Figure A.1: ProQuest vs. SED graduates in STEM fields, by year

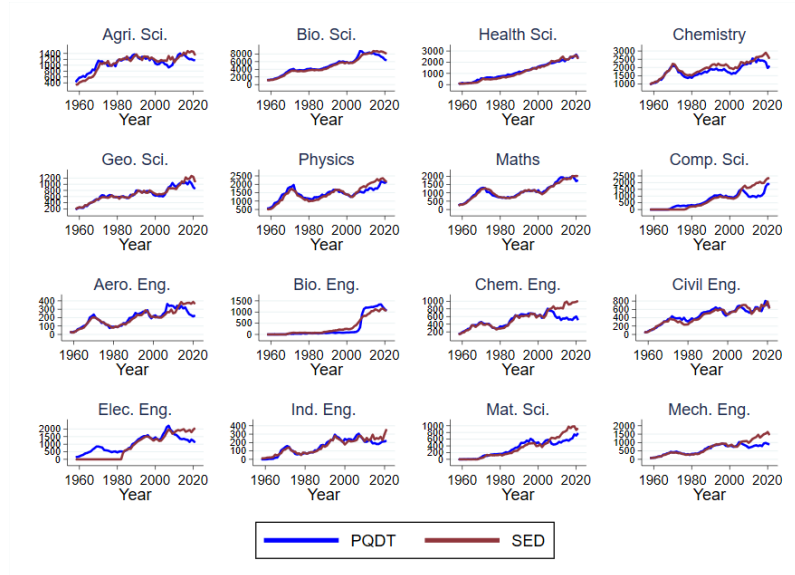


Notes: Figure (reproduced from the body of the paper) shows annual PQDT graduate counts in the physical and life sciences and engineering (blue bars) and SED counts (red line) for comparison, from 1958 (the first year of the SED) to 2022.

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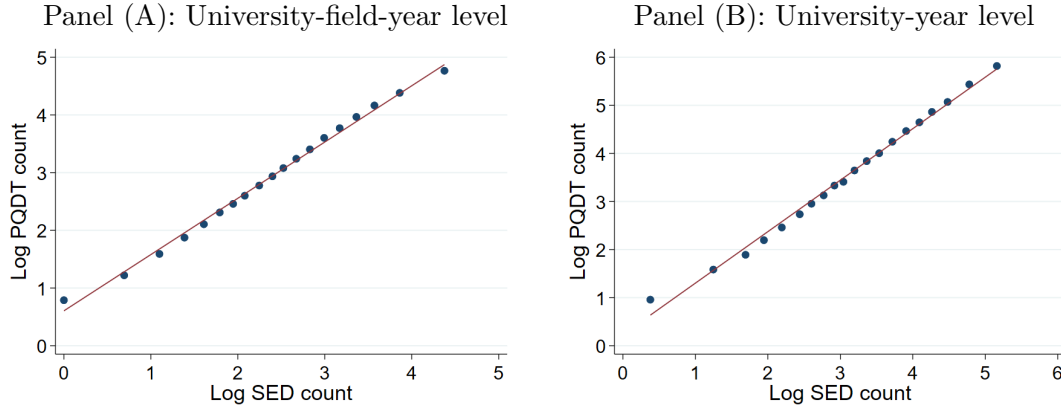
subject for each graduate, but in later years, multiple reported subjects are common. When multiple subjects are provided, we treat the first-listed subject as the graduate's primary subject. We map PQDT subjects to major fields primarily using crosswalks provided by NCSES and used to process its own surveys.

Figure A.2: ProQuest vs. SED graduates in STEM fields, by field and year



Notes: Figure shows annual PQDT graduate counts in the natural sciences and engineering (blue line) and SED counts (red line) for comparison, from 1958 (the first year of the SED) to 2022, disaggregated across 16 SED major fields (all major fields in the sample except for “Other Engineering”). We crosswalk PQDT graduates to these major fields on their author-provided, first-listed subjects, using a manually-curated crosswalk developed from the concordance used by SED to map its PhD graduate survey responses to these fields.

Figure A.3: Correlation of ProQuest vs. SED graduate counts at the university-field-year and university-year level



Notes: Figure shows a binned scatterplot of log PQDT vs. log SED graduate counts at the university-field-year level (left panel) and university-year level (right panel).

## Obtaining dissertation text

An important feature of PQDT is that in addition to metadata, it also has dissertations’ full text. Access to the contents of a dissertation presents an opportunity to obtain direct insight into a graduate’s doctoral training and output. Our focus in this paper is extracting information on graduates’ sources of support—essentially, measuring who pays for scientific training—which to our

knowledge is not otherwise systematically measured or reported.<sup>4</sup>

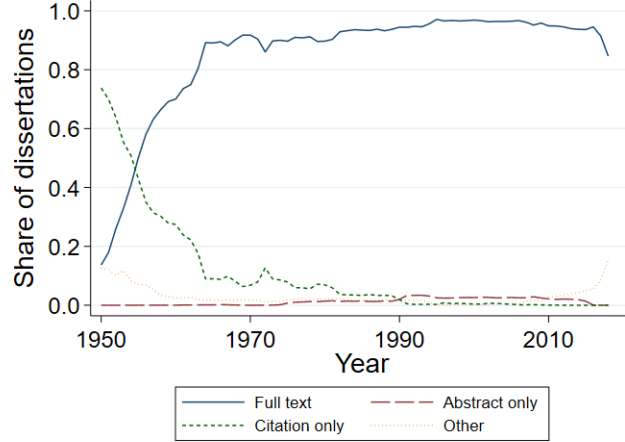
Dissertation structures have for many decades followed a standard publishing template specified by ProQuest, and most dissertations have an “Acknowledgments” section, where authors thank funders and other supporters. These acknowledgments are a crucial resource for this paper: they provide an opportunity to systematically measure sources of PhD graduate support. Even when an acknowledgments section is missing, funders tend to be mentioned in the biography section of the dissertation or in footnotes in the text. Access to the full text of dissertations allows us to identify these cases regardless of where they are mentioned in the text.

Though PQDT provides the full text for most modern dissertations, this is not always the case historically, for two reasons. First, some early dissertations were indexed citation-only. Second, until recently, dissertations were stored on microfilm—not all of which has yet been digitized. Using ProQuest document numbering, we can determine how a dissertation was indexed, and whether full text *may* be available from PQDT. In Figure A.4, we plot these frequencies over time. Though early dissertations were primarily indexed citation-only, by the mid-1960s, 90%+ dissertations have full text indexing. In principle, this set should be an upper bound to an obtainable full text sample. In practice, not all such dissertations have yet been digitized. Figure A.5 shows this, plotting the annual share of dissertations for which full text is available from PQDT, by field. Between 1950 and 1990, the observable full text share of dissertations is around 30-50% in all fields, gradually increasing over time. This rate discretely jumps in 1990 and 1996—to 60-80% and then 100%—and holds near 100% thereafter. Given the quality of recent coverage and intrinsic interest in more recent data, much of our analysis will emphasize the post-2000 period.

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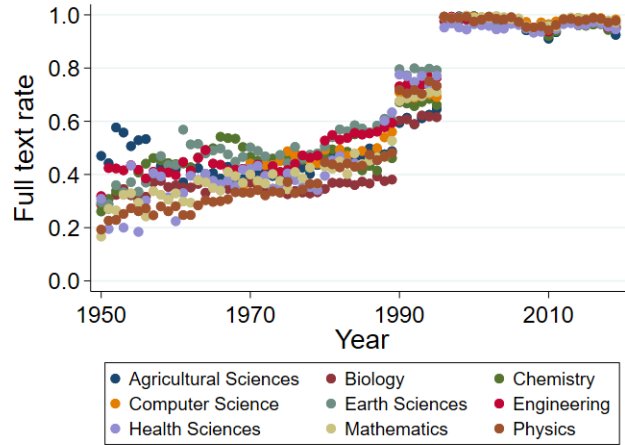
<sup>4</sup>The closest substitute that we are aware of is a question that was historically asked by the NSF’s Survey of Earned Doctorates (SED) questionnaire on graduates’ principal sources of support, where the response options changed over time but generally included a few specific government agencies or funding programs, a few specific philanthropies, and options for business, foreign government, state government, and own resources. However, this question was removed from the SED in 1997, creating an extended gap in measurement. Moreover, the response options were fairly limited in scope relative to what is reported in full text. To better understand these measures, we also applied for and were granted access to restricted-use SED microdata which include responses to this question. Though the SED itself is a near-census of U.S. PhD graduates, we found response rates to this particular question highly variable, and rates of support from specific organizations and categories of support fluctuate substantially year-to-year, whereas our dissertation text-based measures change more gradually. The combination of the question not having been asked in nearly 30 years, and the questionable quality of the responses it received, make us hesitant to use these data—and create a need to find other ways to measure who pays for scientific training.

Figure A.4: ProQuest dissertations by indexing category (according to ProQuest identifiers)



Notes: Figure shows the annual share of PQDT dissertations in our sample that ProQuest identifies as having been indexed full text (i.e., ProQuest received metadata (author, title, subject, etc.) and a full copy of the dissertation), abstract-only (metadata plus abstract), or citation only (metadata only).

Figure A.5: ProQuest dissertations with full text available, by field



Notes: Figure shows the annual share of PQDT dissertations for which we have access to full text: the subset of full-text indexed dissertations (Figure A.4) which were stored electronically or have been digitized from their original physical storage medium (microfilm).

We undertake one additional effort to fill gaps in dissertation availability: retrieving full-text dissertation files for individuals in our PQDT sample from online university repositories. We initially did so for (i) the six universities with the most graduates lacking full text dissertations, and (ii) the University of California system, whose constituent universities' repositories share a common platform. The most important of the back-filled universities is MIT, which had no full text dissertations in PQDT. Other universities for which PQDT was missing at least 10,000 dissertation texts during our sample period include UC Berkeley, UCLA, Cornell, University of Maryland, and University of

Minnesota—though as Figure A.5 indicates, most of these gaps in the available full text dissertations are pre-2000. For each of these institutions we crawl the associated repository, obtain dissertation metadata and PDFs, extract their contents, and merge these records into PQDT on name, field, and year, disambiguating manually as needed. The only universities for which we were able to find a significant number of dissertation texts which were not already available from PQDT were MIT and Michigan State University (see Table A.1). Due to the substantial effort required to crawl university repositories for historical dissertations and the meager returns, we subsequently ended this effort, but incorporated the content we already retrieved into our analysis.

Table A.1: Full text collected from university repositories for PQDT graduates

| University        | PQDT PhDs,<br>1950-2019 | Missing full text |         | Found in repository |                 |
|-------------------|-------------------------|-------------------|---------|---------------------|-----------------|
|                   |                         | Number            | Percent | Number              | Pct. of missing |
| Cornell U.        | 25,061                  | 12,112            | 48%     | 847                 | 7%              |
| Mass Inst. Tech.  | 27,546                  | 27,546            | 100%    | 16,052              | 58%             |
| Michigan State U. | 15,907                  | 6,902             | 43%     | 6,384               | 92%             |
| U. of Maryland    | 18,682                  | 6,183             | 33%     | 288                 | 5%              |
| U. of Minnesota   | 23,085                  | 10,729            | 46%     | 197                 | 2%              |
| U. of Texas       | 15,232                  | 6,085             | 40%     | 840                 | 14%             |
| UC Berkeley       | 32,037                  | 14,456            | 45%     | 20                  | 0%              |
| UC Davis          | 14,936                  | 4,944             | 33%     | 69                  | 1%              |
| UC Irvine         | 7,596                   | 366               | 5%      | 93                  | 25%             |
| UCLA              | 19,893                  | 6,570             | 33%     | 61                  | 1%              |
| UC Merced         | 439                     | 27                | 6%      | 10                  | 37%             |
| UC Riverside      | 5,605                   | 1,856             | 33%     | 75                  | 4%              |
| UC San Diego      | 239                     | 28                | 12%     | 1                   | 4%              |
| UC San Francisco  | 4,460                   | 1,166             | 26%     | 882                 | 76%             |
| UC Santa Barbara  | 6,529                   | 1,180             | 18%     | 50                  | 4%              |
| UC Santa Cruz     | 3,159                   | 641               | 20%     | 19                  | 3%              |

Notes: Table lists the set of universities for which we searched for full text dissertations at online university thesis repositories, in attempt to fill gaps in full text availability in the PQDT sample. Columns report the number of PQDT STEM doctoral graduates associated with each university, the number missing full text in PQDT, and the results of our effort to fill these gaps with university data.

## A.2 Characteristics of PhD graduates

We measure several characteristics of the PhD graduates in our sample. The first is their PhD institution, which we crosswalk to IPEDS UnitIDs (the official institution identifier of the U.S. Department of Education’s Integrated Postsecondary Education Data System). Using these UnitIDs, we can merge in university characteristics from IPEDS—the principal one being each institution’s Carnegie classification (measured as of 2021), which we will use at times to filter our sample to R1 universities (which are the roughly 150 most research intensive U.S. institutions). We also measure graduates’ principal subjects and major fields (as described above).

We supplement the PQDT-reported measures with measures of each graduate’s association with 18 critical technology areas as specified by the White House Office of Science and Technology Policy (OSTP) in 2024. The White House identified these 18 technologies as national security priorities in order to inform science and technology policy across the executive branch. This linkage serves two



purposes: (i) it produces a measure of specific policy interest, enabling us to track the development of human capital across specific technology domains that are currently considered important for national security and technological competitiveness, and (ii) it also demonstrates the possibilities presented by our PQDT-based sample and textual analysis methods.

### A.3 Mapping PhD graduates to critical technology areas

#### A.3.1 Step 1: Reference list of critical technology areas

Our implementation draws from OSTP (2024)’s enumeration of 18 critical and emerging technology areas and 107 constituent subfields. To improve the precision and interpretability of our classification framework, we apply a filtering process to remove subfields that are ambiguous, duplicative, or overly generic.<sup>5</sup> These refinements allow us to focus on a subset of subfields with clearer technical boundaries and greater specificity, ensuring that the resulting classifications are more meaningful for the purposes of policy analysis and measurement of scientific labor. Table A.2 provides a list of the 18 technology areas, with example subfields.

Table A.2: List of OSTP critical technologies

| Technology                                                     | Subtechnology                                        | Included? |
|----------------------------------------------------------------|------------------------------------------------------|-----------|
| <b>Advanced Computing</b>                                      |                                                      |           |
|                                                                | Advanced supercomputing, including for AI...         | Yes       |
|                                                                | Edge computing and devices                           | Yes       |
|                                                                | Advanced cloud services                              | Yes       |
|                                                                | High-performance data storage and data centers       | Yes       |
|                                                                | Advanced computing architectures                     | Yes       |
|                                                                | Advanced modeling and simulation                     | No        |
|                                                                | Data processing and analysis techniques              | No        |
|                                                                | Spatial computing                                    | Yes       |
| <b>Advanced Engineering Materials</b>                          |                                                      |           |
|                                                                | Materials by design and material genomics            | Yes       |
|                                                                | Materials with novel properties...                   | Yes       |
|                                                                | Techniques for material property characterization... | Yes       |
| <b>Advanced Gas Turbine Engine Technologies</b>                |                                                      |           |
|                                                                | Aerospace, maritime, and industrial development...   | Yes       |
|                                                                | Full-authority digital engine control...             | Yes       |
| <b>Advanced and Networked Sensing and Signature Management</b> |                                                      |           |
|                                                                | Payloads, sensors, and instruments                   | Yes       |
|                                                                | Sensor processing and data fusion                    | Yes       |
|                                                                | Adaptive optics                                      | Yes       |
|                                                                | Remote sensing of the Earth                          | Yes       |
|                                                                | Geophysical sensing                                  | Yes       |
|                                                                | Signature management                                 | Yes       |
|                                                                | Detection and characterization of pathogens ...      | Yes       |
|                                                                | Transportation-sector sensing                        | No        |
|                                                                | Security-sector sensing                              | No        |
|                                                                | Health-sector sensing                                | No        |
|                                                                | Energy-sector sensing                                | No        |

<sup>5</sup>For example, under *Advanced Computing*, we exclude “Advanced modeling and simulation” and “Data processing and analysis techniques”. Although these terms reflect important computational practices, they are used broadly across many disciplines, making it difficult to reliably associate such labels with work situated specifically within advanced computing. Similarly, within *Advanced and Networked Sensing and Signature Management*, we remove high-level application categories such as “Health-sector sensing”, “Energy-sector sensing”, “Manufacturing-sector sensing”, etc.—all of which lack specificity to make useful distinctions.

|                                                                               |     |
|-------------------------------------------------------------------------------|-----|
| Manufacturing-sector sensing                                                  | No  |
| Building-sector sensing                                                       | No  |
| Environmental-sector sensing                                                  | No  |
| <b>Advanced Manufacturing</b>                                                 |     |
| Advanced additive manufacturing                                               | Yes |
| Advanced manufacturing technologies and techniques...                         | Yes |
| <b>Artificial Intelligence (AI)</b>                                           |     |
| Machine learning                                                              | Yes |
| Deep learning                                                                 | Yes |
| Reinforcement learning                                                        | Yes |
| Sensory perception and recognition                                            | Yes |
| AI assurance and assessment techniques                                        | Yes |
| Foundation models                                                             | Yes |
| Generative AI systems, multimodal and large language models                   | Yes |
| Synthetic data approaches for training, tuning, and testing                   | Yes |
| Planning, reasoning, and decision making                                      | No  |
| Technologies for improving AI safety, trust, security...                      | Yes |
| <b>Biotechnologies</b>                                                        |     |
| Novel synthetic biology including...                                          | Yes |
| Multi-omics and other biometrology, bioinformatics, computational biology...  | Yes |
| Engineering of sub-cellular, multicellular, and multi-scale systems           | Yes |
| Cell-free systems and technologies                                            | Yes |
| Engineering of viral and viral delivery systems                               | Yes |
| Biotic/abiotic interfaces                                                     | Yes |
| Biomanufacturing and bioprocessing technologies                               | Yes |
| <b>Clean Energy Generation and Storage</b>                                    |     |
| Renewable generation                                                          | Yes |
| Renewable and sustainable chemistries, fuels, and feedstocks                  | Yes |
| Nuclear energy systems                                                        | Yes |
| Fusion energy                                                                 | Yes |
| Energy storage                                                                | Yes |
| Electric and hybrid engines                                                   | Yes |
| Batteries                                                                     | Yes |
| Grid integration technologies                                                 | Yes |
| Energy-efficiency technologies                                                | Yes |
| Carbon management technologies                                                | Yes |
| <b>Data Privacy, Data Security, and Cybersecurity Technologies</b>            |     |
| Distributed ledger technologies                                               | Yes |
| Digital assets                                                                | Yes |
| Digital payment technologies                                                  | Yes |
| Digital identity technologies...                                              | Yes |
| Communications and network security                                           | No  |
| Privacy-enhancing technologies                                                | Yes |
| Technologies for data fusion and interoperability...                          | Yes |
| Distributed confidential computing                                            | Yes |
| Computing supply chain security                                               | No  |
| Security and privacy technologies in AR/VR                                    | Yes |
| <b>Directed Energy</b>                                                        |     |
| Lasers                                                                        | Yes |
| High-power microwaves                                                         | Yes |
| Particle beams                                                                | Yes |
| <b>Highly Automated, Autonomous, and Uncrewed Systems (UxS), and Robotics</b> |     |
| Surface                                                                       | Yes |
| Air                                                                           | Yes |
| Maritime                                                                      | Yes |
| Space                                                                         | Yes |
| Supporting digital infrastructure...                                          | Yes |
| Autonomous command and control                                                | Yes |
| <b>Human-Machine Interfaces</b>                                               |     |
| Augmented reality                                                             | Yes |

|                                                                             |     |
|-----------------------------------------------------------------------------|-----|
| Virtual reality                                                             | Yes |
| Human-machine teaming                                                       | Yes |
| Neurotechnologies                                                           | Yes |
| <b>Hypersonics</b>                                                          |     |
| Propulsion                                                                  | Yes |
| Aerodynamics and control                                                    | Yes |
| Materials, structures, and manufacturing                                    | Yes |
| Detection, tracking, characterization, and defense                          | Yes |
| Testing                                                                     | Yes |
| <b>Integrated Communication and Networking Technologies</b>                 |     |
| Radio-frequency (RF) and... components                                      | Yes |
| Spectrum management and sensing technologies                                | Yes |
| Future generation wireless networks                                         | Yes |
| Optical links and fiber technologies                                        | Yes |
| Terrestrial/undersea cables                                                 | Yes |
| Satellite-based and stratospheric communications                            | Yes |
| Delay-tolerant networking                                                   | Yes |
| Mesh networks/infrastructure independent communications...                  | Yes |
| Software-defined networking and radios                                      | Yes |
| Modern data exchange techniques                                             | No  |
| Adaptive network controls                                                   | No  |
| Resilient and adaptive waveforms                                            | Yes |
| <b>Positioning, Navigation, and Timing (PNT) Technologies</b>               |     |
| Diversified PNT-enabling technologies...                                    | Yes |
| Interference, jamming, and spoofing detection technologies...               | Yes |
| Disruption/denial-resisting and hardening technologies                      | Yes |
| <b>Quantum Information and Enabling Technologies</b>                        |     |
| Quantum computing                                                           | Yes |
| Materials, isotopes, and fabrication techniques for quantum devices         | Yes |
| Quantum sensing                                                             | Yes |
| Quantum communications and networking                                       | Yes |
| Supporting systems                                                          | No  |
| <b>Semiconductors and Microelectronics</b>                                  |     |
| Design and electronic design automation tools                               | Yes |
| Manufacturing process technologies and manufacturing equipment              | Yes |
| Beyond complementary metal-oxide-semiconductor (CMOS) technology            | Yes |
| Heterogeneous integration and advanced packaging                            | Yes |
| Specialized/tailored hardware components for artificial intelligence...     | Yes |
| Novel materials for advanced microelectronics                               | Yes |
| Microelectromechanical systems (MEMS), Nanoelectromechanical systems (NEMS) | Yes |
| Novel architectures for non-Von Neumann computing                           | Yes |
| <b>Space Technologies and Systems</b>                                       |     |
| In-space servicing, assembly, and manufacturing...                          | Yes |
| Technology enablers for ... reusable space launch systems                   | Yes |
| Technologies that enable ... cislunar space and/or novel orbits             | Yes |
| Sensors and data analysis tools for space-based observations                | Yes |
| Space propulsion                                                            | Yes |
| Advanced space vehicle power generation                                     | Yes |
| Novel space vehicle thermal management                                      | Yes |
| Crewed spaceflight enablers                                                 | Yes |
| Resilient and path-diverse space communication systems...                   | Yes |
| Space launch, range, and safety technologies                                | Yes |

---

Notes: Table lists critical technology areas in OSTP (2024) and specific implementations, occasionally abridged to improve readability. Complete list available at <https://www.govinfo.gov/content/pkg/CMR-PREX23-00185928/pdf/CMR-PREX23-00185928.pdf>. Right column indicates whether the given subfield is used in our classification procedure (details below).

### A.3.2 Step 2: Zero-shot classification to technology areas

We begin our classification with the full population of U.S. STEM PhD graduates between 2000 and 2022. Rather than directly classifying PhD graduates based on their dissertations’ raw titles, keywords, or abstract text, we first generate a concise, one-sentence summary for each dissertation using their titles and abstracts. This approach parallels recent work by Aiken et al. (2024), who employed large language models to annotate scientific publications for topic relevance in emerging technologies. Specifically, we use the **gpt-4o-mini** model with a tailored prompt designed to extract the motivation, task, and methodology of each dissertation, while excluding evaluative or impact-based language.<sup>6</sup> The prompt we use is as follows:

Listing 1: LLM prompt for summarizing a dissertation

```
1 You are an expert in science and engineering.
2
3 **Task**: Write a one-sentence summary of a dissertation based on the
   title and abstract. Include the research motivation if evident, and
   clearly describe the task(s) and method(s) used. Do not describe the
   importance or benefits.
4
5 **Input**:
6 {title} and {abstract}
7
8 ### Return the summary as plain text only.
```

This generative summary step allows us to standardize input across a large, heterogeneous corpus of dissertations and provides a foundation for downstream classification into critical technology areas with several methodological advantages. First, it helps normalize heterogeneous textual formats: dissertation abstracts vary widely in length, structure, and verbosity, often containing extraneous information unrelated to core research contributions. Second, summarization encourages the model to foreground research motivation, task, and method, thereby aligning the input more closely with the latent conceptual criteria used in topic classification. Third, as emphasized in Aiken et al. (2024)’s application of large language models to emerging technology classification, generating structured summaries via prompt-based language models enhances both consistency and zero-shot classification performance by filtering out irrelevant content and emphasizing comparable semantic structure across documents. This preprocessing step can thus reduce noise, mitigate bias from field-specific jargon, and improve classification accuracy.

Building on these summaries, we then evaluate whether each PhD graduate’s dissertation science is related to each of the 18 critical and emerging technology areas, allowing a PhD graduate to associate to multiple areas. For this task, we prompt **gpt-4o-mini** to act as an expert in defense

<sup>6</sup>We use the July 18, 2024 version of the **gpt-4o-mini** model. **gpt-4o-mini** is optimized for high-throughput, low-latency tasks and supports both text and image inputs, though only text output was used in our application. Its affordability and responsiveness made it particularly well-suited for summarization of hundreds of thousands of dissertations. See <https://platform.openai.com/docs/models/gpt-4o-mini> for technical details.

and emerging technologies and make an assessment. For each PhD graduate, we supply the model with their dissertation title, summary, subject terms, and paper keywords, and instruct it to return a binary “Yes/No” judgment for each technology area, with instructions which prioritize precision over recall. The user prompt lists all technology categories and presents the metadata for one dissertation at a time. An example prompt is as follows:

Listing 2: LLM prompt for classifying a dissertation

```

1 System: You are an expert in defense and emerging technologies. Your task
  is to determine whether a dissertation is relevant to each of the
  listed critical technology categories. For each category, answer "Yes"
  if it clearly applies; otherwise, answer "No". If uncertain, answer "No".
  Return only a JSON object mapping each category to "Yes" or "No".
2
3 User: You will determine which of the following critical technologies this
  dissertation is related to.
4
5 Critical Technology Categories:
6 1. Advanced Computing
7 2. Advanced Engineering Materials
8 3. Biotechnologies
9 ...
10 18. Space Technologies and Systems
11
12 Dissertation Information:
13 Dissertation Title: [Title here]
14 Summary: [Generated summary]
15 Subject Terms: [Controlled vocabulary terms]
16 Paper Keywords: [Author-provided keywords]
17
18 Please return a JSON object exactly in the following format:
19 {
20   "Advanced Computing": "Yes",
21   "Advanced Engineering Materials": "No",
22   "Biotechnologies": "No",
23   ...
24 }
25 Only return this JSON (no extra text).

```

This approach enables us to assess dissertations in a scalable and consistent way. The end result is a structured dataset where each dissertation can be tagged with a binary “Yes” or “No” measure of its relation to each of the OSTP (2024) technology areas.

### A.3.3 Step 3: Technology subfield matching and filtering

The top-level technology area classification is a first pass at our intended classification. It is also an intentionally broad filter. Several of the OSTP-defined domains—for example, *Advanced Computing*, *Advanced Engineering Materials*, *Advanced Manufacturing*, and *Biotechnologies*—create a broad catchment. The details of the OSTP guidance, however, make clear that the technologies

or applications its authors have in mind are often more specific.

To refine our measures, we implement a second-stage classification that further classifies each PhD graduate within a main technology area to each of its subfields—essentially re-applying our method for more specific target classes. This step helps us not only filter the initial classification to the specific subdomains that are considered “critical”, but also to distinguish them: for example, this step will distinguish AI science related to “Generative AI systems, multimodal and large language models” versus “Technologies for improving AI safety, trust, security, and responsible use”, or biotechnology science related to “Novel synthetic biology including nucleic acid, genome, epigenome, and protein synthesis and engineering” versus “Biotic/abiotic interfaces”.

This second-stage classification is implemented by prompting `gpt-4o-mini` with the previously generated one-sentence summary, along with the dissertation title, subject terms, and keywords. The model is asked to assess whether the work is relevant to each subfield within a given technology area. For example, a dissertation identified under *Semiconductors and Microelectronics* is individually evaluated for its relevance to the following subfields: “Design and electronic design automation tools”, “Manufacturing process technologies and manufacturing equipment”, “Beyond complementary metal-oxide-semiconductor (CMOS) technology”, “Heterogeneous integration and advanced packaging”, “Specialized/tailored hardware components for artificial intelligence”, natural and hostile radiation environments, RF and optical components, high-power devices, and other critical applications”, “Novel materials for advanced microelectronics”, “Microelectromechanical systems (MEMS) and Nanoelectromechanical systems (NEMS)”, “Novel architectures for non-Von Neumann computing”. The full prompt for this step can be seen in Listing 3.

Listing 3: LLM prompt for second-stage classification

```

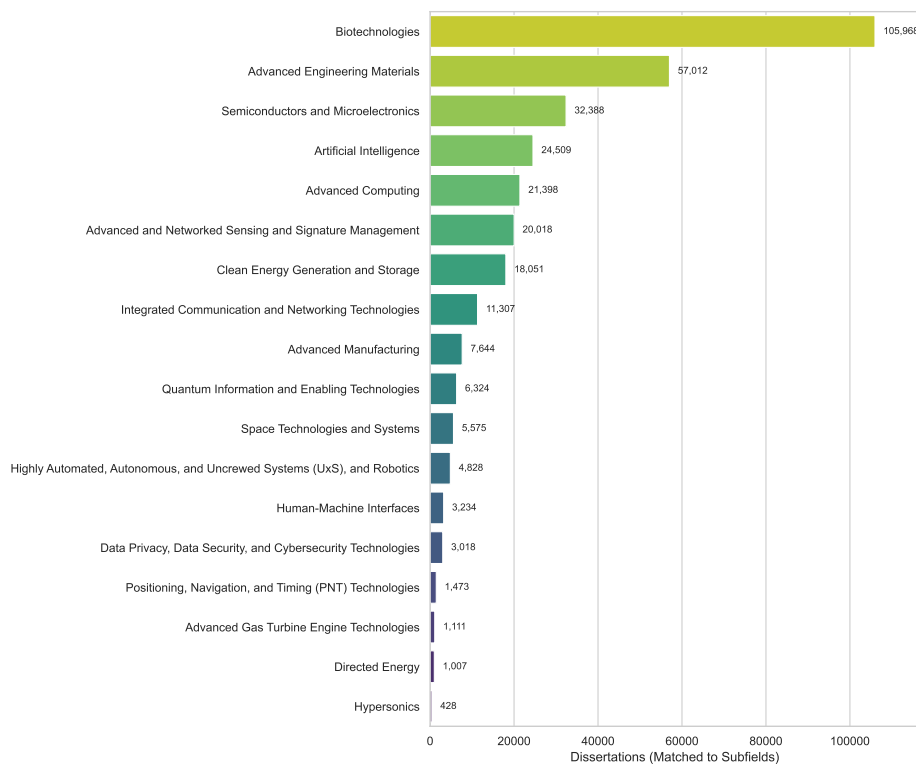
1 System: You are an expert in defense and emerging technologies. Determine
   whether a dissertation is relevant to a specific subtechnology within a
   main technology category.
2 Return a JSON object mapping "{tech} - {subfield}" to "Yes" or "No".
3
4 User: You will determine whether the following dissertation contributes
5 to the subfield "{subfield}" under the main technology category "{tech}":
6
7 Title: {title}
8 Summary: {summary}
9 Terms: {subjterms}
10 Keywords: {dispaperkwd}
11
12 Return exactly one JSON object (no extra text):
13 { "{tech} - {subfield}": "Yes" }
14 or
15 { "{tech} - {subfield}": "No" }
```

### A.3.4 Results

Across the full set of 585,226 PhD graduates in our sample, 454,030 (77.6%) are classified to at least one of the 18 OSTP critical technology areas in the first stage, and 249,674 PhD graduates (42.7%) also classify to at least one subfield in the second stage.

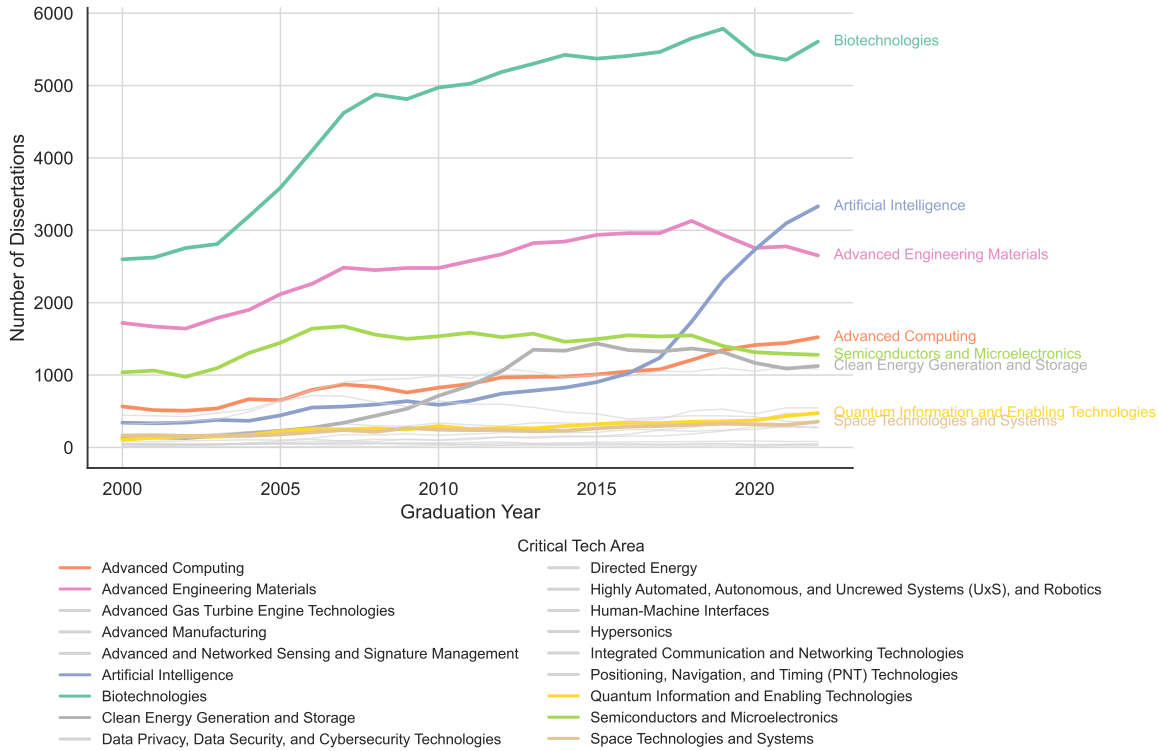
Figure A.6 shows the total number of dissertations that pass the second-stage classification by technology area, and Figure A.7 shows the number over time. *Biotechnologies* is the largest technology area by a significant margin, with roughly 106,000 matched PhD graduates, reflecting the size of the life sciences in the U.S. more generally (Figure A.2, for example, shows that Biological Sciences is the largest SED field of U.S. doctoral graduates, by a similarly wide margin). The second largest (and fastest growing) technology area is AI, which was ranked sixth as recently as 2015 but experienced an inflection point ca. 2017. Other large areas include *Advanced Engineering Materials* and *Semiconductors and Microelectronics*, both of which have been associated with sustained federal and private investment. At the other end of the distribution, technology areas like *Directed Energy*, *Hypersonics*, and *Advanced Gas Turbine Engines* have far fewer associated graduates. This difference could reflect limited university research capacity, greater concentration in non-academic institutions (e.g., national labs, defense contractors), or simply their specificity.

Figure A.6: Total number of graduates by critical technology area, 2000-2022



Notes: Figure shows the total number of U.S. natural science and engineering PhD dissertations between 2000 and 2022 classified to each of 18 OSTP-defined critical technology areas, after applying both the first- and second-stage filters. See text for explanation of methodology.

Figure A.7: Annual number of graduates by critical technology area, 2000-2022



Notes: Figure shows the annual number of U.S. natural science and engineering PhD dissertations between 2000 and 2022 classified to each of 18 OSTP-defined critical technology areas, after applying both the first- and second-stage filters. See text for explanation of methodology.

Unlike SED fields, critical technologies are not mutually exclusive: the OSTP technology list lists categories with coarse and overlapping boundaries. For example, modern advanced computing technology such as GPUs can be closely related to artificial intelligence. Consistent with this logic, under our procedure, dissertations can be classified to multiple areas, and can be classified as such. Of the dissertations we link to critical technology categories, roughly half link to two or more categories. At the extreme, one dissertation (out of hundreds of thousands) is classified to 8 technologies (“Bio-inspired VLSI systems: From synapse to behavior”, by Peng Xu, of the University of Maryland; from the title alone, it is clear this dissertation would link to biotechnology, advanced computing, human-machine interfaces, and advanced sensing; it also gets classified to AI, autonomy, microelectronics, and positioning technologies).

In Table A.3, we show how these categories correlate (coincide). In general, pairwise correlations are low. We highlight in boldface the three pairs with the highest correlations: AI and advanced computing (0.58), AI and microelectronics (0.39), and advanced computing and communications and networking (0.33). These correlations are, in our view, intuitive.



Table A.3: Correlation across critical technology classifications

|                                    | (10)        | (11)  | (12)        | (13)  | (14)  | (15)  | (16)  | (17) | (18)  |
|------------------------------------|-------------|-------|-------------|-------|-------|-------|-------|------|-------|
| (1) Advanced Computing             | 1.00        |       |             |       |       |       |       |      |       |
| (2) Advanced Manufacturing         | 0.00        | 1.00  |             |       |       |       |       |      |       |
| (3) Artificial Intelligence        | <b>0.58</b> | -0.01 | 1.00        |       |       |       |       |      |       |
| (4) Autonomous Systems             | 0.21        | 0.02  | 0.24        | 1.00  |       |       |       |      |       |
| (5) Biotechnology                  | 0.00        | -0.02 | -0.01       | -0.04 | 1.00  |       |       |      |       |
| (6) Communications and Networking  | <b>0.33</b> | -0.01 | 0.04        | 0.06  | -0.07 | 1.00  |       |      |       |
| (7) Data Privacy and Cybersecurity | 0.25        | -0.01 | 0.10        | 0.01  | -0.04 | 0.18  | 1.00  |      |       |
| (8) Directed Energy                | 0.00        | 0.03  | -0.01       | 0.00  | -0.02 | 0.00  | 0.00  | 1.00 |       |
| (9) Clean Energy                   | 0.03        | 0.03  | 0.00        | 0.00  | -0.04 | 0.00  | 0.00  | 0.00 | 1.00  |
| (10) Hypersonics                   | 0.03        | 0.00  | 0.00        | 0.00  | -0.01 | 0.00  | 0.00  | 0.01 | 0.00  |
| (11) Human-Machine Interfaces      | 0.17        | 0.01  | 0.19        | 0.19  | 0.01  | 0.01  | 0.03  | 0.00 | -0.01 |
| (12) Advanced Materials            | -0.08       | 0.28  | -0.06       | -0.02 | -0.05 | -0.04 | -0.03 | 0.02 | 0.17  |
| (13) Microelectronics              | 0.08        | 0.22  | -0.03       | -0.02 | -0.07 | 0.07  | 0.00  | 0.01 | 0.07  |
| (14) PNT Technologies              | 0.12        | 0.00  | 0.05        | 0.22  | -0.03 | 0.08  | 0.03  | 0.00 | -0.01 |
| (15) Quantum Science               | 0.06        | 0.01  | -0.02       | -0.01 | -0.04 | 0.00  | 0.01  | 0.01 | 0.01  |
| (16) Networked Sensing             | 0.20        | 0.03  | 0.10        | 0.16  | -0.03 | 0.19  | 0.06  | 0.00 | 0.00  |
| (17) Space Technology              | 0.06        | 0.00  | 0.01        | 0.08  | -0.04 | 0.02  | -0.01 | 0.01 | -0.01 |
| (18) Advanced Turbine Engines      | 0.01        | 0.01  | 0.00        | 0.00  | -0.02 | -0.01 | 0.00  | 0.00 | 0.01  |
|                                    | (10)        | (11)  | (12)        | (13)  | (14)  | (15)  | (16)  | (17) | (18)  |
| (10) Hypersonics                   | 1.00        |       |             |       |       |       |       |      |       |
| (11) Human-Machine Interfaces      | 0.00        | 1.00  |             |       |       |       |       |      |       |
| (12) Advanced Materials            | 0.00        | -0.02 | 1.00        |       |       |       |       |      |       |
| (13) Microelectronics              | -0.01       | 0.00  | <b>0.39</b> | 1.00  |       |       |       |      |       |
| (14) PNT Technologies              | 0.00        | 0.03  | -0.02       | 0.00  | 1.00  |       |       |      |       |
| (15) Quantum Science               | 0.00        | -0.01 | 0.08        | 0.29  | 0.00  | 1.00  |       |      |       |
| (16) Networked Sensing             | 0.00        | 0.06  | 0.01        | 0.05  | 0.21  | 0.00  | 1.00  |      |       |
| (17) Space Technology              | 0.07        | 0.00  | -0.01       | -0.01 | 0.12  | -0.01 | 0.12  | 1.00 |       |
| (18) Advanced Turbine Engines      | 0.01        | 0.00  | 0.02        | -0.01 | 0.00  | -0.01 | 0.00  | 0.02 | 1.00  |

Notes: Table reports pairwise correlations in dissertations’ technology classifications. The three largest correlations are highlighted in boldface.

### A.3.5 Validation: Evidence and limitations

Validating the results of this classification is made difficult by the absence of any ground truth sample. Whether a given dissertation’s science is related to a particular technology is a simultaneously broad and nuanced question, for which there is no clear rubric, and thus a question that even experts may disagree on.<sup>7</sup> The procedure we outlined above developed iteratively as we assessed the results of different rule-based screens, LLM-based screens, and prompt language. As we did so, we (informally) evaluated the results, comparing title and abstracts to the LLM

<sup>7</sup>“Critical technology areas” itself is not an objective category or taxonomy—as reflected by the fact that different government offices have produced different definitions of critical technologies over time, and have different (but overlapping) assessments of what technologies should be considered critical even today, including with varying degrees of specificity. The concept has traditionally instead been used as a general framework for policy choices and guidance around R&D, immigration, export control, and other implied domains.

classification. Though this experimentation and evaluation was not systematic or scientific, it helped build understanding of the data and some *prima facie* confidence in the results.

To more systematically assess the validity of our LLM-based classification, we conduct a case study focused on dissertations matched to the *Quantum Information and Enabling Technologies* area (henceforth, “quantum science”), examining where these PhD graduates are trained. Quantum science offers a useful testbed due to its topical specificity and its relatively well-documented institutional footprint, research centers, and publication patterns.

We begin by identifying the universities with the most quantum science dissertations between 2000 and 2022. We then examine whether the top PhD-producing universities in quantum science are also home to known quantum computing research centers, institutes, or degree programs. Table A.4, for example, shows that every one of the top 20 universities for quantum science PhDs over the past 20 years currently has a quantum science center.

Table A.4: OpenAlex Top 20 U.S. universities for quantum science, 2000-2022

| Institution                                | Quantum Research Center                   | Dissertations | Publications |
|--------------------------------------------|-------------------------------------------|---------------|--------------|
| Massachusetts Institute of Technology      | MIT Center for Quantum Engineering (CQE)  | 271           | 8,833        |
| University of California, Berkeley         | Berkeley Quantum Info. & Comput. Center   | 225           | 7,728        |
| Stanford University                        | Stanford Q-FARM                           | 221           | 6,643        |
| Harvard University                         | Harvard Quantum Initiative & QSE          | 220           | 5,202        |
| University of Maryland, College Park       | JQI & QuICS (UMD/NIST)                    | 217           | 6,145        |
| University of California, Santa Barbara    | UCSB Quantum Foundry                      | 172           | 6,476        |
| Princeton University                       | Princeton Quantum Initiative              | 164           | 6,381        |
| University of Illinois at Urbana-Champaign | Illinois Quantum Info. Sci. & Tech Center | 160           | 5,847        |
| University of Michigan                     | U-M Quantum Engineering Sci. & Tech       | 144           | 5,318        |
| California Institute of Technology         | Institute for Quantum Info. and Matter    | 129           | 4,586        |
| University of Wisconsin, Madison           | Wisconsin Quantum Institute               | 123           | 3,213        |
| Northwestern University                    | Inst for Quantum Info. Res. & Engineering | 120           | 3,603        |
| University of Washington                   | UW QuantumX                               | 121           | 3,009        |
| Purdue University                          | Purdue Quantum Sci. & Eng. Inst.          | 106           | 3,302        |
| University of Rochester                    | Center for Coherence and Quantum Science  | 96            | 2,571        |
| University of New Mexico                   | UNM Center for Quantum Info. and Control  | 95            | 2,214        |
| University of Chicago                      | Chicago Quantum Exchange                  | 91            | 3,226        |
| Yale University                            | Yale Quantum Institute                    | 115           | 2,983        |
| Cornell University                         | Cornell Quantum Science & Engineering     | 86            | 3,716        |
| University of California, Los Angeles      | UCLA Quantum Sci. & Engineering           | 86            | 3,255        |

Notes: Table lists the top 20 universities by quantum science PhD graduates between 2000 and 2022, as measured by our LLM-based procedure. For each university we also list what we assess to be its (current) principal quantum science research center, based on publicly available information.

Though affirming, this evidence is also limited by its lack of variation: given rapidly growing interest in quantum computing and its underlying science, it may just be that many universities now have quantum science centers. To distinguish universities with stronger and weaker quantum science programs or research environments, we shift our attention from this extensive margin to the intensive margin. To do so, we measure universities’ volume of scientific publications in quantum science. To do so we use OpenAlex data, filtering by publications whose OpenAlex-defined topics include the keyword “quantum” (see Table A.5 for a full list).

Using these data, Figure A.8 plots the total number of quantum science publications at individual universities between 2000 and 2022 against the total number of quantum science PhD graduates

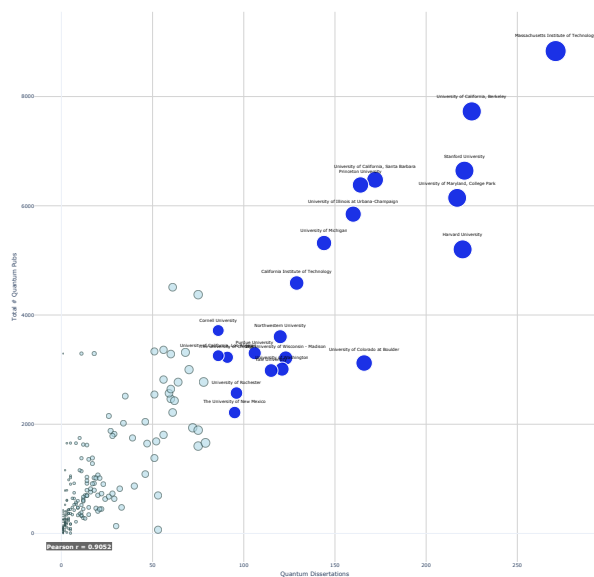
over the same period. The top 20 universities from Table A.4 are colored in blue. The figure shows a very strong correlation between the two ( $\rho=0.9$ ), indicating that the LLM-based procedure captures meaningful variation across universities and PhD graduates in their relation to quantum science. Leading schools such as MIT, UC Berkeley, Stanford, Harvard, and the University of Maryland rank highly on both axes, reinforcing to us the face validity of the approach.

Table A.5: OpenAlex “quantum” research topics + parent fields and subfields

| Field                 | Subfield                                 | Topic                                                          |
|-----------------------|------------------------------------------|----------------------------------------------------------------|
| Chemistry             | Physical and Theoretical Chemistry       | Chemical Reactions Involving Quantum Tunneling                 |
| Computer Science      | Artificial Intelligence                  | Quantum Computing and Simulation                               |
| Computer Science      | Artificial Intelligence                  | Quantum Information and Computation                            |
| Computer Science      | Computational Theory and Mathematics     | Design and Simulation of Quantum-dot Cellular Automata         |
| Materials Science     | Materials Chemistry                      | Applications of Quantum Dots in Nanotechnology                 |
| Materials Science     | Materials Chemistry                      | Synthesis and Applications of Carbon Quantum Dots              |
| Physics and Astronomy | Atomic and Molecular Physics, and Optics | Foundations of Electromagnetic Theory and Quantum Field Theory |
| Physics and Astronomy | Atomic and Molecular Physics, and Optics | Foundations of Quantum Mechanics and Interpretations           |
| Physics and Astronomy | Atomic and Molecular Physics, and Optics | Parity-Time Symmetry in Optics and Quantum Mechanics           |
| Physics and Astronomy | Atomic and Molecular Physics, and Optics | Quantum Coherence in Photosynthesis and Aqueous Systems        |
| Physics and Astronomy | Atomic and Molecular Physics, and Optics | Quantum Dot Devices and Semiconductors                         |
| Physics and Astronomy | Atomic and Molecular Physics, and Optics | Quantum Effects in Helium Nanodroplets and Solids              |
| Physics and Astronomy | Atomic and Molecular Physics, and Optics | Quantum Many-Body Systems and Entanglement Dynamics            |
| Physics and Astronomy | Atomic and Molecular Physics, and Optics | Quantum Size Effects in Metallic Nanostructures                |
| Physics and Astronomy | Atomic and Molecular Physics, and Optics | Semiconductor Spintronics and Quantum Computing                |
| Physics and Astronomy | Atomic and Molecular Physics, and Optics | Slow Light Propagation and Quantum Memory                      |
| Physics and Astronomy | Condensed Matter Physics                 | Quantum Spin Liquids in Frustrated Magnets                     |
| Physics and Astronomy | Statistical and Nonlinear Physics        | Cantorian-Fractal Theory of Quantum Physics                    |
| Physics and Astronomy | Statistical and Nonlinear Physics        | Characterization of Chaotic Quantum Dynamics and Structures    |
| Physics and Astronomy | Statistical and Nonlinear Physics        | Characterization of Chaotic Quantum Dynamics and Structures    |
| Physics and Astronomy | Statistical and Nonlinear Physics        | Quantum Gravity and Noncommutative Field Theories              |

Notes: Table lists OpenAlex publication topics which include the word “quantum”. According to OpenAlex, publications in its database are associated with “Topics” using an automated procedure that takes into account information about the work, including title, abstract, source (journal) name, and citations.

Figure A.8: University quantum science publications vs. PhD graduates, 2000-2022



Notes: Figure plots universities’ number of quantum science publications between 2000 and 2022 (according to OpenAlex) against their number of quantum science PhD graduates (according to our LLM-based classification). Marker size proportional to a university’s number of PhD graduates. The 20 universities with the most graduates colored in blue and labeled.

**Additional validation tests** We complement this evidence with validation tests across three more technology areas: AI, Biotechnology, and Space Technology. We select these areas to expand the exercise to fields with a wider range of maturity, scale, and rate of change, which is useful in assessing whether quantum science is idiosyncratic in its classifiability.

We follow the same approach as before: for each of these technology areas, we compare institution-level dissertation counts between 2000 and 2022 and the institution-level number of publications in the same area over the same period. We identify associated publications in a similar manner, using OpenAlex topics (see Tables A.6 to A.8 for a list), using the same version of the OpenAlex database (July 2024) for consistency. Similar to Figure A.8, Figures A.9 to A.11 plot the total number of publications in each of these three additional areas (AI, biotechnology, space technology) against the total number of associated PhD graduates over the same period, coloring the top 20 universities in blue. These figures continue to show a very strong correlation between the two ( $\rho=0.89$  for AI,  $\rho=0.83$  for biotechnology,  $\rho=0.85$  for space technology), reinforcing that the LLM-based procedure appears to capture the target features and variation effectively.

Table A.6: OpenAlex “AI” research topics + parent fields and subfields

| Field            | Subfield                | Topic                                                                |
|------------------|-------------------------|----------------------------------------------------------------------|
| Computer Science | Artificial Intelligence | Neural Network Fundamentals and Applications                         |
| Computer Science | Artificial Intelligence | Natural Language Processing                                          |
| Computer Science | Artificial Intelligence | Statistical Machine Translation and Natural Language Processing      |
| Computer Science | Artificial Intelligence | Semantic Web and Ontology Development                                |
| Computer Science | Artificial Intelligence | Machine Learning for Mineral Prospectivity Mapping                   |
| Computer Science | Artificial Intelligence | Quantum Information and Computation                                  |
| Computer Science | Artificial Intelligence | Text Compression and Indexing Algorithms                             |
| Computer Science | Artificial Intelligence | Program Analysis and Verification Techniques                         |
| Computer Science | Artificial Intelligence | Model-Based Clustering with Mixture Models                           |
| Computer Science | Artificial Intelligence | Advanced Cryptographic Schemes and Protocols                         |
| Computer Science | Artificial Intelligence | Logic Programming and Knowledge Representation                       |
| Computer Science | Artificial Intelligence | Anomaly Detection in High-Dimensional Data                           |
| Computer Science | Artificial Intelligence | Active Learning in Machine Learning Research                         |
| Computer Science | Artificial Intelligence | Privacy-Preserving Techniques for Data Analysis and Machine Learning |
| Computer Science | Artificial Intelligence | Deep Learning in Medical Image Analysis                              |
| Computer Science | Artificial Intelligence | Learning and Inference in Bayesian Networks                          |
| Computer Science | Artificial Intelligence | Cryptography and Error-Correcting Codes                              |
| Computer Science | Artificial Intelligence | Quantum Computing and Simulation                                     |
| Computer Science | Artificial Intelligence | Particle Filtering and Nonlinear Estimation Methods                  |
| Computer Science | Artificial Intelligence | Machine Learning for Internet Traffic Classification                 |
| Computer Science | Artificial Intelligence | Speech Recognition Technology                                        |
| Computer Science | Artificial Intelligence | Dialogue Act Modeling for Spoken Language Systems                    |
| Computer Science | Artificial Intelligence | Machine Learning for Earthquake Early Warning Systems                |
| Computer Science | Artificial Intelligence | Automatic Keyword Extraction from Textual Data                       |
| Computer Science | Artificial Intelligence | Scientific Computing and Data Analysis with Python                   |
| Computer Science | Artificial Intelligence | Artificial Intelligence Planning and Reasoning                       |
| Computer Science | Artificial Intelligence | Language-based Information Flow Security                             |
| Computer Science | Artificial Intelligence | Autonomic Computing and Self-Adaptive Systems                        |
| Computer Science | Artificial Intelligence | Reinforcement Learning Algorithms                                    |
| Computer Science | Artificial Intelligence | Advances in Transfer Learning and Domain Adaptation                  |
| Computer Science | Artificial Intelligence | Adversarial Robustness in Deep Learning Models                       |
| Computer Science | Artificial Intelligence | Application of Genetic Programming in Machine Learning               |
| Computer Science | Artificial Intelligence | Deep Learning Applications in Healthcare                             |
| Computer Science | Artificial Intelligence | Automated Detection of Hate Speech and Offensive Language            |
| Computer Science | Artificial Intelligence | Effectiveness of Intelligent Tutoring Systems                        |
| Computer Science | Artificial Intelligence | Learning with Noisy Labels in Machine Learning                       |
| Computer Science | Artificial Intelligence | Application of Fuzzy Cognitive Maps in Modeling                      |
| Computer Science | Artificial Intelligence | Photonic Reservoir Computing for Neural Computation                  |
| Computer Science | Artificial Intelligence | Methods and Techniques for Agent-Based Modeling                      |

|                  |                         |                                                                               |
|------------------|-------------------------|-------------------------------------------------------------------------------|
| Computer Science | Artificial Intelligence | Graph Neural Network Models and Applications                                  |
| Computer Science | Artificial Intelligence | Swarm Intelligence Optimization Algorithms                                    |
| Computer Science | Artificial Intelligence | Optimization Methods in Machine Learning                                      |
| Computer Science | Artificial Intelligence | Gaussian Processes in Machine Learning                                        |
| Computer Science | Artificial Intelligence | Cryptanalysis of Block Ciphers and Hash Functions                             |
| Computer Science | Artificial Intelligence | Game Artificial Intelligence Research                                         |
| Computer Science | Artificial Intelligence | Machine Learning Methods for Solar Radiation Forecasting                      |
| Computer Science | Artificial Intelligence | Type-2 Fuzzy Logic Systems and Applications                                   |
| Computer Science | Artificial Intelligence | Explainable Artificial Intelligence                                           |
| Computer Science | Artificial Intelligence | Sentiment Analysis and Opinion Mining                                         |
| Computer Science | Artificial Intelligence | Adaptation to Concept Drift in Data Streams                                   |
| Computer Science | Artificial Intelligence | Automatic Text Simplification and Readability Assessment                      |
| Computer Science | Artificial Intelligence | Artificial Intelligence and Expert Systems                                    |
| Computer Science | Artificial Intelligence | Multi-label Text Classification in Machine Learning                           |
| Computer Science | Artificial Intelligence | Handling Imbalanced Data in Classification Problems                           |
| Computer Science | Artificial Intelligence | Statistical Computing and Data Analysis in R                                  |
| Computer Science | Artificial Intelligence | Data Clustering Techniques and Algorithms                                     |
| Computer Science | Artificial Intelligence | Artificial Intelligence in Service Industry                                   |
| Computer Science | Artificial Intelligence | Cyberbiosecurity and Legal Implications of AI Technology                      |
| Computer Science | Artificial Intelligence | Theory and Applications of Extreme Learning Machines                          |
| Computer Science | Artificial Intelligence | Compilation and Analysis of Spoken Language Corpora                           |
| Computer Science | Artificial Intelligence | Authorship Attribution and User Profiling in Text                             |
| Computer Science | Artificial Intelligence | Deep Learning for Wireless Signal Classification                              |
| Computer Science | Artificial Intelligence | Inductive Modeling in Scientific Research                                     |
| Computer Science | Artificial Intelligence | Theoretical Framework of Cognitive Informatics and Computational Intelligence |
| Computer Science | Artificial Intelligence | Machine Learning in Smart Healthcare                                          |
| Computer Science | Artificial Intelligence | Fuzzy Computing and Intelligent Systems                                       |
| Computer Science | Artificial Intelligence | Robotics Programming Education for Students                                   |
| Computer Science | Artificial Intelligence | Artificial Intelligence in Education and Technology                           |
| Computer Science | Artificial Intelligence | Knowledge Base Graph Embedding for Visual Question Answering                  |
| Computer Science | Artificial Intelligence | Artificial Intelligence and Technology Innovation                             |
| Computer Science | Artificial Intelligence | Neuro-Symbolic Networks in Automation and Robotics                            |
| Computer Science | Artificial Intelligence | Development and Application of Expert Systems                                 |
| Computer Science | Artificial Intelligence | Experience-Based Knowledge Representation and Management                      |
| Computer Science | Artificial Intelligence | Cybernetics and Information Theory                                            |
| Computer Science | Artificial Intelligence | Digital Image Processing and Artificial Neural Networks                       |
| Computer Science | Artificial Intelligence | Optimization of Big Data Processing and Analysis                              |
| Computer Science | Artificial Intelligence | Enhancing E-Learning with Intelligent Agents and Analytics                    |

Notes: Table lists topics within the OpenAlex publication subfield for AI.

Figure A.9: University AI publications vs. PhD graduates, 2000-2022

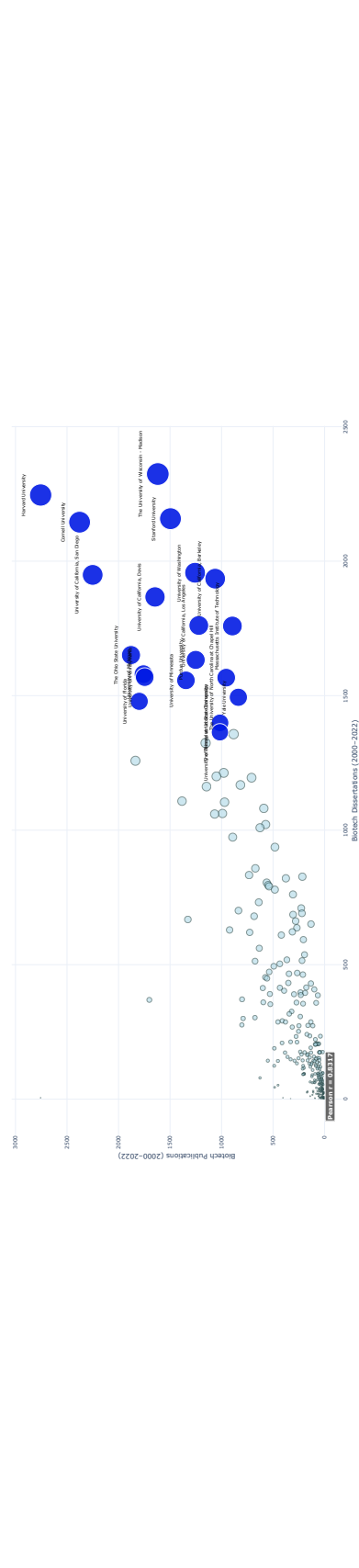


Notes: Figure plots universities' number of AI publications between 2000 and 2022 (according to OpenAlex) against their number of AI PhD graduates (according to our LLM-based classification). Marker size proportional to a university's number of PhD graduates. The 20 universities with the most graduates colored in blue and labeled.

|                           |                                 |                                                                                                      |
|---------------------------|---------------------------------|------------------------------------------------------------------------------------------------------|
| Biochemistry              | Biotechnology                   | Engineering Bacteria for Cancer Treatment, Genetics and Molecular Biology                            |
| Biochemistry              | Biotechnology                   | Production of Recombinant Pharmaceuticals in Plants, Genetics and Molecular Biology                  |
| Biochemistry              | Biotechnology                   | Microbial Enzymes and Biotechnological Applications, Genetics and Molecular Biology                  |
| Biochemistry              | Biotechnology                   | Applications of Electroporation in Biotechnology and Food Processing, Genetics and Molecular Biology |
| Biochemistry              | Biotechnology                   | Listeria Monocytogenes Pathogenesis and Food Safety, Genetics and Molecular Biology                  |
| Biochemistry              | Biotechnology                   | Sponge-Associated Microorganisms and Biotechnological Potential, Genetics and Molecular Biology      |
| Biochemistry              | Biotechnology                   | Microbial Pigments and Their Applications, Genetics and Molecular Biology                            |
| Biochemistry              | Biotechnology                   | Biotechnological Production of Vanillin, Genetics and Molecular Biology                              |
| Biochemistry              | Molecular Biology               | Role of Carbonic Anhydrases in Medicine and Biotechnology, Genetics and Molecular Biology            |
| Immunology and Microbiol. | Applied Microbiol. and Biotech. | Global Burden of Antimicrobial Resistance                                                            |
| Immunology and Microbiol. | Applied Microbiol. and Biotech. | Microbial Tannase Production and Applications                                                        |
| Agr. and Biol. Sciences   | Plant Science                   | Agricultural Biotechnology and Nutrition                                                             |
| Agr. and Biol. Sciences   | Plant Science                   | Plant-Microbe Interactions in Agriculture and Biotechnology                                          |

Notes: Table lists OpenAlex topics we associate to biotechnology.

Figure A.10: University biotechnology publications vs. PhD graduates, 2000-2022



Notes: Figure plots universities' number of biotechnology publications between 2000 and 2022 (according to OpenAlex) against their number of biotechnology PhD graduates (according to our LLM-based classification). Marker size proportional to a university's number of PhD graduates. The 20 universities with the most graduates colored in blue and labeled.

Table A.8: OpenAlex “space technology” research topics + parent fields and subfields

| Field                 | Subfield                        | Topic                                                      |
|-----------------------|---------------------------------|------------------------------------------------------------|
| Engineering           | Aerospace Engineering           | Accelerator Technology and Superconducting Cavities        |
| Engineering           | Aerospace Engineering           | Simultaneous Localization and Mapping                      |
| Engineering           | Aerospace Engineering           | Antenna Design and Applications                            |
| Engineering           | Aerospace Engineering           | Nuclear Reactor Technology and Development                 |
| Engineering           | Aerospace Engineering           | Metasurfaces for Antenna and Radar Applications            |
| Engineering           | Aerospace Engineering           | Aeroacoustic Analysis of Jet Noise                         |
| Engineering           | Aerospace Engineering           | Cryogenic Fluid Storage and Management                     |
| Engineering           | Aerospace Engineering           | Space Suit Design and Ergonomics for EVA                   |
| Engineering           | Aerospace Engineering           | Radiometric Calibration and Performance Monitoring         |
| Engineering           | Aerospace Engineering           | Aluminium Alloys for Aerospace and Automotive Appl.        |
| Engineering           | Aerospace Engineering           | Challenges and Applications of Detonation Propulsion Tech. |
| Engineering           | Aerospace Engineering           | Hybrid Rocket Propulsion and Stability Analysis            |
| Engineering           | Aerospace Engineering           | Optimization Techniques for Antenna Arrays                 |
| Engineering           | Aerospace Engineering           | Evolution and Applications of CubeSat Missions             |
| Engineering           | Aerospace Engineering           | Infrared Small Target Detection and Tracking               |
| Engineering           | Aerospace Engineering           | Space Debris Removal and On-Orbit Servicing Technologies   |
| Engineering           | Aerospace Engineering           | Biological and Biomimetic Flight Dynamics                  |
| Engineering           | Aerospace Engineering           | Air Traffic Management and Conflict Resolution             |
| Engineering           | Aerospace Engineering           | Aerodynamics of High-Speed Trains and Vehicles             |
| Engineering           | Aerospace Engineering           | Thermal Barrier Coatings for Gas Turbines                  |
| Engineering           | Aerospace Engineering           | Global Navigation Satellite Systems (GNSS)                 |
| Engineering           | Aerospace Engineering           | Optimization of Spacecraft Trajectories and Formations     |
| Engineering           | Aerospace Engineering           | Aerodynamics and Heat Transfer in Turbomachinery           |
| Engineering           | Aerospace Engineering           | Plasma Actuators for Aerodynamic Flow Control              |
| Engineering           | Aerospace Engineering           | Unmanned Aerial Vehicles for Wind Estimation and Soaring   |
| Engineering           | Aerospace Engineering           | Multiple-Input Multiple-Output Radar Systems               |
| Engineering           | Aerospace Engineering           | Inertial Navigation Systems and Sensor Fusion Techniques   |
| Engineering           | Aerospace Engineering           | Missile Guidance and Control Strategies                    |
| Engineering           | Aerospace Engineering           | Morphing Aircraft Technology                               |
| Engineering           | Aerospace Engineering           | Wind Energy Technology and Aerodynamics                    |
| Engineering           | Aerospace Engineering           | Synthetic Aperture Radar (SAR) Technology and Appl.        |
| Engineering           | Aerospace Engineering           | Airborne Wind Energy Systems and High-Altitude Platforms   |
| Engineering           | Aerospace Engineering           | Synthetic Aperture Radar Interferometry                    |
| Engineering           | Aerospace Engineering           | Autonomous Aerial Refueling Systems for UAVs               |
| Engineering           | Aerospace Engineering           | Nuclear Thermal Hydraulics in Passive Systems              |
| Engineering           | Aerospace Engineering           | Satellite Communication Networks and Systems               |
| Engineering           | Aerospace Engineering           | Unmanned Aerial Vehicle Communications                     |
| Engineering           | Aerospace Engineering           | Radar Wave Propagation and Refractivity Estimation         |
| Engineering           | Aerospace Engineering           | Electromagnetic Launch Science and Technology              |
| Engineering           | Aerospace Engineering           | Icing Mitigation Techniques for Wind Turbines and Aircraft |
| Engineering           | Aerospace Engineering           | Optimization of Weapon-Target Assignment Problems          |
| Engineering           | Aerospace Engineering           | Inertially Stabilized Platform Technology Concepts         |
| Engineering           | Aerospace Engineering           | Hypersonic Perception and Physiological Response           |
| Engineering           | Aerospace Engineering           | Modernization of Air Force in Warfare                      |
| Physics and Astronomy | Astronomy and Astrophysics      | Stellar Astrophysics and Exoplanet Studies                 |
| Physics and Astronomy | Astronomy and Astrophysics      | Space Weather and Magnetospheric Physics                   |
| Physics and Astronomy | Astronomy and Astrophysics      | Solar Physics and Space Weather                            |
| Physics and Astronomy | Astronomy and Astrophysics      | Radio Astronomy Techniques and Instruments                 |
| Physics and Astronomy | Astronomy and Astrophysics      | Superconducting Detectors for Astrophysical Observations   |
| Physics and Astronomy | Astronomy and Astrophysics      | Global Lightning Distribution and Physics                  |
| Physics and Astronomy | Astronomy and Astrophysics      | Space Exploration and Governance                           |
| Physics and Astronomy | Nuclear and High Energy Physics | High-Energy Astrophysics and Particle Acceleration Studies |
| Physics and Astronomy | Instrumentation                 | Astronomical Instrumentation and Spectroscopy              |
| Physics and Astronomy | Atomic Physics and Optics       | Adaptive Optics in Astronomy and Space Telescopes          |
| Physics and Astronomy | Atomic Physics and Optics       | Acousto-Optic Interaction in Crystalline Materials         |

Notes: Table lists OpenAlex topics we associate to space technology.





Table A.9: Consistency of LLM-based classification in main run and 2% sample: technology areas

| Technology                                                             | Match (Full) | Match (2%) |
|------------------------------------------------------------------------|--------------|------------|
| Biotechnologies                                                        | 2243         | 2249       |
| Advanced Engineering Materials                                         | 1262         | 1252       |
| Semiconductors and Microelectronics                                    | 613          | 614        |
| Artificial Intelligence                                                | 606          | 600        |
| Advanced and Networked Sensing and Signature Management                | 472          | 471        |
| Advanced Computing                                                     | 452          | 443        |
| Clean Energy Generation and Storage                                    | 410          | 414        |
| Integrated Communication and Networking Technologies                   | 238          | 239        |
| Advanced Manufacturing                                                 | 172          | 171        |
| Quantum Information and Enabling Technologies                          | 148          | 148        |
| Space Technologies and Systems                                         | 121          | 120        |
| Highly Automated, Autonomous, and Uncrewed Systems (UxS), and Robotics | 102          | 101        |
| Human-Machine Interfaces                                               | 70           | 66         |
| Data Privacy, Data Security, and Cybersecurity Technologies            | 66           | 63         |
| Positioning, Navigation, and Timing (PNT) Technologies                 | 29           | 29         |
| Directed Energy                                                        | 22           | 23         |
| Advanced Gas Turbine Engine Technologies                               | 20           | 20         |
| Hypersonics                                                            | 7            | 7          |

Notes: Table compares technology area classification outcomes across two independent runs for a randomly sampled subset (2%) of 9,592 dissertations. The comparison assesses whether LLM-generated classification results remain stable when rerun on identical inputs at different times.

Table A.10: Consistency of LLM-based classification in main run and 2% sample: subfields

| Technology                       | Subfield                                                                   | Match (Full) | Match (2%) |
|----------------------------------|----------------------------------------------------------------------------|--------------|------------|
| Artificial Intelligence          | AI assurance and assessment techniques                                     | 16           | 15         |
| Artificial Intelligence          | Deep learning                                                              | 199          | 199        |
| Artificial Intelligence          | Foundation models                                                          | 14           | 16         |
| Artificial Intelligence          | Generative AI systems, multimodal and large language models                | 17           | 19         |
| Artificial Intelligence          | Machine learning                                                           | 556          | 548        |
| Artificial Intelligence          | Reinforcement learning                                                     | 48           | 47         |
| Artificial Intelligence          | Sensory perception and recognition                                         | 132          | 129        |
| Artificial Intelligence          | Synthetic data approaches for training, tuning, and testing                | 22           | 23         |
| Artificial Intelligence          | Technologies for improving AI safety, trust, security, and responsibility  | 60           | 59         |
| Biotechnologies                  | Biomanufacturing and bioprocessing technologies                            | 108          | 110        |
| Biotechnologies                  | Biotic/abiotic interfaces                                                  | 881          | 873        |
| Biotechnologies                  | Cell-free systems and technologies                                         | 23           | 21         |
| Biotechnologies                  | Engineering of sub-cellular, multicellular, and organ-level systems        | 993          | 1004       |
| Biotechnologies                  | Engineering of viral and viral delivery systems                            | 157          | 158        |
| Biotechnologies                  | Multi-omics and other biometeorology, bioinformatics, and -omics platforms | 520          | 519        |
| Biotechnologies                  | Novel synthetic biology including nucleic acid technologies                | 394          | 399        |
| Quantum Info. and Enabling Tech. | Materials, isotopes, and fabrication techniques for quantum devices        | 86           | 85         |
| Quantum Info. and Enabling Tech. | Quantum communications and networking                                      | 14           | 16         |
| Quantum Info. and Enabling Tech. | Quantum computing                                                          | 54           | 55         |
| Quantum Info. and Enabling Tech. | Quantum sensing                                                            | 35           | 36         |

Notes: Table compares subfield classification outcomes across two independent runs for a randomly sampled subset (2%) of 9,592 dissertations. We do so for three representative technology areas: *Artificial Intelligence*, *Biotechnologies*, and *Quantum Information and Enabling Technologies*. The comparison assesses whether LLM-generated classification results remain stable when rerun on identical inputs at different times.

## A.4 Identifying dissertation sponsors

A second category of features we aim to measure is PhD graduates’ sources of financial (and other) support during their doctoral training—information which can be used to evaluate who pays for scientific training. Using our STEM PhD graduate sample and dissertation text, we seek to identify research sponsors in this text. This is in essence a named entity recognition problem. However, because acknowledgments are highly variable and unstructured, a fully rule-based computational approach is ineffective. We instead use large language models to flexibly identify research supporters acknowledged in dissertation text.

To retrieve this information, we develop a six-step data processing pipeline:

Step 1. *Isolate potential acknowledgment sentences*

Step 2. *Identify named entities in these sentences*

Step 3. *Classify entities into sectors (government, industry, non-profit)*

Step 4. *Identify support type and extract grant identifiers, where available*

Step 5. *Consolidate named entities into parent organizations*

Step 6. *Match extracted organizations to external registries (ROR)*

The procedure we develop uses LLMs in several steps, particularly Upstage.ai’s Solar 10.7B and Abacus.ai’s Smaug 34B models (Kim et al. 2023, Pal et al. 2024).

### A.4.1 Isolating acknowledgment sentences in dissertation full text

To isolate sentences that acknowledge funding in the dissertation texts, we employ a rule-based string matching approach. First, we split the raw dissertation text into sentences using NLTK’s Punkt Sentence Tokenizer (Bird et al. 2009). We modify the tokenizer to ignore common academic abbreviations such as “Dr.,” “Prof.,” and “univ.” Next, we iterate through each sentence, searching for words that indicate a potential acknowledgement or support mention. After careful refinement, we arrived at the list of keywords as appears in Listing 4 below.

Listing 4: Keyword list for acknowledgement sentence extraction

```
1 keywords = ["contract", "fund", "grant", "financ", "fellow", "scholarship",  
    "internship", "award", "generous", "generos", "support", "thank", "  
    grateful", "appreciate", "assist", "help", "mentor", "journey", "  
    guidance", "effort", "encourag", "opportunity", "provide", "gratitude",  
    "committee", "advisor", "sponsor", "appreciat", "paying", "investing",  
    "invested", "indebt", "obtain", "money", "stipend", "facilitat", "  
    blessed", "acknowledgements", "biography", "vita", "preface"]
```

### A.4.2 Identifying and classifying named entities in acknowledgment text

In steps 2 through 4, we utilize a Named Entity Recognition (NER) process employing a generative large language model (LLM). Specifically, we use Upstage.ai’s Solar 10.7B Instruct v1.0 (Kim et al. 2023), a fine-tuned model based on the Mistral 7B model (which, in turn, is based on the

Llama-2 architecture). We chose these models in early 2024 based on their cost and performance characteristics, which at this time compared well to others. Open source (rather than proprietary) LLMs were selected for both cost and reproducibility reasons.

After considerable experimentation and refinement, we established a procedure that takes each sentence as input and initially evaluates if the sentence acknowledges support from an external entity. If so, we then prompted the model to identify the supporting entities mentioned in this text, categorize them by sector and type of support (funding vs. other/in-kind support), and retrieve grant and contract identifiers when available. For batch inference, we utilize the VLLM Python package (Kwon et al. 2023) and the LM format enforcer (Gat 2023). These tools facilitate efficient inference and require the model to produce a well-structured JSON schema that we predefined. Our prompt to the model is structured as appears in Listing 5 below.

Listing 5: LLM prompt for extracting supporting entities

```
1  ### System:
2  You are a helpful assistant. Always answer as helpfully as possible.
3
4  ### User:
5  Below is a sentence taken from a doctoral dissertation.
6
7  Instructions:
8  1. Determine whether in the provided text, the author expresses gratitude
9     or mentions support from some organization.
10     - set 'gratitude_support' to true if yes, and false otherwise.
11
12  2. Determine whether in the provided text is part of a CV or biography.
13     Set 'biography_vita' to true if yes and false otherwise.
14     - Note that biographies typically list awards and recognitions.
15
16  3. Extract names of supporting organizations mentioned in the text. Notes:
17     - Skip people's names. I don't care about advisors, mentors, committee
18       members etc.
19     - Ensure complete extraction of grant, contract, and award identifiers
20       , if present.
21     - Where necessary, infer the organization's name and type based on the
22       grant name.
23     - Represent each financial support and funding source as a distinct
24       entity.
25     - Ignore doctoral committees, academic departments, colleagues, lab
26       members, unaffiliated individuals, family and friends.
27     - Ensure that each organization is listed separately.
28     - Return an empty list if no supporting organizations are mentioned.
29
30  Text:
31  {sentence}
32
33  You MUST answer using the following json schema:
34  {extractionFormat.schema_json()}
35
36  ### Assistant:
```

To validate the structure of the LLM output, we use two Pydantic models as described in Listing 6 below. The `orgFormat` model includes fields for the organization’s name and type, as well as the type of support provided. The organization and support types are restricted to a set of predefined values. The `extractionFormat` model incorporates the `orgFormat` model as a list, allowing for multiple organizations to be associated with each analyzed sentence. Additionally, it includes boolean fields for indicating whether the sentence expresses gratitude or support, or is a part of a biography. These models serve the purpose of standardizing the representation of extracted support entities and facilitate subsequent data processing.

Listing 6: Pydantic model for LLM output

```

1 class extractionFormat(BaseModel):
2     gratitude_support: bool
3     biography_vita: bool
4     organizations: List[orgFormat]
5
6 class orgFormat(BaseModel):
7     organization_name: str
8     organization_type: Literal['government', 'federal agency', 'non-profit',
9     'private company', 'foundation', 'academia', 'research lab', 'consortium', 'center', 'association', 'other', 'unknown']
9     support_type: Literal['funding', 'grant', 'financial support', 'internship', 'scholarship', 'fellowship', 'training', 'materials', 'facilities', 'data', 'in-kind support', 'technical support', 'administrative support', 'employment', 'unspecified', 'other', 'unknown']
10    grant_contract_numbers: str

```

After running the first step of this procedure on our full text dissertation sample, we recovered over 92 million sentences that potentially included acknowledgments of supporting entities. We then performed batch inference on these sentences, one at a time, using language models as described above. The language model output indicated that 11 million sentences (about 12%) were indeed sentences that acknowledged support or were part of a graduate’s biography. Among all sentences, the language model extracted 9.3 million mentions of organizations, with 4.8 million of these mentions originating from sentences classified as support or biography. Collectively, the retrieved entities consist of 4 million unique organization names.

#### A.4.3 Consolidate named entities and match to external registries

The resulting set of organizations includes many inter-related entities (e.g., parents and subsidiaries of firms and government agencies) and practically innumerable spelling variants. The next step in the data processing pipeline is therefore to consolidate these names (grouping strings representing the same organization) for subsequent analysis.

To do so, we match these entities to two external registries. The first is the Research Organization Registry (ROR), which maintains a registry of over 100,000 global research organizations, with

persistent identifiers. ROR was created to disambiguate institution names and to be used in bibliometric datasets linking researchers, research organizations, and research outputs. It also identifies parent/child relationships between ROR entities. Together, these features make it a near-ideal reference for consolidating the organizations we extract from doctoral dissertations. For named entities which we could not match to ROR, we attempt to link them to Wikidata, a free and open knowledge base hosted by Wikimedia that acts as a central database of topics, concepts, and objects referenced in Wikimedia projects (like Wikipedia).

### Government Entities

We consolidate organizations that are part of the U.S. government and match them to ROR entities. First, we filter our sample for names that the LLM classified as “government” or “federal agency”. We apply some standardization using regex (e.g., dropping the “U.S.” at the beginning of strings) and cluster together similar names. Among 739,494 clustered government organization names, we end up with 242,382 names associated with at least one sentence that the LLM classified as related to support or part of the author’s biography.

To further consolidate this set, we run it through a large language model again. For this task, we use Abacus.ai’s Smaug 34B v0.1 model (Pal et al. 2024). This model is larger than the one we used for the first round. It requires more resources to run, but performs better in correctly identifying organizations and linking them to their parent organizations. Our prompt for doing so is shown in Listing 7. The required schema includes fields for the organization name, the parent organization, indicators for federal government agencies, and location.

Listing 7: LLM prompt for consolidating government organizations

```

1  ### System:
2  You are a helpful assistant. Always answer as helpfully as possible.
3
4  ### User:
5  Below is a name of a funding organization, most likely in the US.
6  Return a json schema that includes:
7  1. The official, clean, unabbreviated name of the organization.
8  2. The ultimate federal government department or agency (if relevant).
9  3. Indicators for whether the organization is a federal organization and/
   or an independent agency.
10 4. Country and state. If irrelevant return "-".
11
12 Don't make stuff up. If you are unsure, return "unknown".
13
14 You MUST answer using the following json schema:
15 {entityFormat.schema_json()}
16
17 Organization name: {organization}
18
19 ### Assistant:
20 " " "

```

Among the initial consolidated list of 242,382 entities, the model identified 90,655 as agencies and organizations in the U.S. federal government. The model produced 3,550 unique parent organization names. We matched these names to a list of government organizations from the ROR dataset. Weighted by the number of mentions, the match resolved 81% of the mentions of U.S. government organizations and matched them with a ROR identifier.

### Private Companies

The list of extracted entities includes 448,745 unique names that the LLM classified as private companies. Within them, 170,009 names are associated with at least one sentence that the LLM classified as related to support or part of the author’s biography. We start the matching process by using the Smaug 34B LLM to consolidate these names. The results were further validated using an additional run through the LLM and manual comparisons.

Listing 8: LLM prompt for consolidating private companies

```

1  ### System:
2  You are a helpful assistant. Always answer as helpfully as possible.
3
4  ### User:
5  Below is a name of a grant or award.
6
7  Return a json schema that includes:
8  1. The ticker name for the firm. Return past ticker where relevant.
9  2. The name of the firm, associated with the ticker.
10 3. The relevant stock exchange.
11
12 Don't make stuff up. If you are unsure, return "unknown".
13
14 You MUST answer using the following json schema:
15 {entityFormat.schema_json()}
16
17 name: {organization}
18
19 ### Assistant:
20 ""

```

The consolidation process resulted in 10,802 names. Working with these results, we then used the ROR REST API to search for ROR identifiers associated with these names. Second, we used the SemTab API to find additional matches with the Wikidata identifiers (Nguyen et al. 2021). Third, we ran additional API searches using the original, unconsolidated list of names, filtered to names that were not previously matched. This step allowed for matches of firms that are not publicly traded and startups. Finally, we validated the list of resulting matches using similar techniques to those described above. The resulting match includes a ROR or Wikidata ID for 217,013 mentions of firms, corresponding to 123,366 dissertations. The matched records are associated with 3,275 unique ROR identifiers and 7,638 unique Wikidata identifiers.

## Non-profit Organizations

We matched mentions of non-profit organizations in our data with external identifiers. The original list included 549,329 unique strings that were classified as foundations, philanthropic organizations, non-profits, associations or centers. Among them, 322,901 names were associated with at least one sentence that the LLM classified as related to support or part of the author’s biography. For matching these mentions, we used a similar process to the one used for firms. Overall, we were able to match 333,603 mentions, corresponding to 157,884 dissertations. These matches are linked to 2,139 unique ROR identifiers and 8,126 Wikidata identifiers.

## A.5 Validation

### A.5.1 Comparison of Manual and LLM Entity Recognition

To validate the accuracy and completeness of our entity extraction and classification methods, we compare the results on a random sample of dissertations to manual processing. To do so, we randomly sample 500 dissertations and identify funders in them by hand.

Figure A.12 compares the share of this sample with government, non-profit, and industry support according to our manual and automated measurement (in red and teal, respectively). As we explain in the body of the paper, the results show substantial similarity, with 31-32% of this sample classified as reporting government support under both methods, 11-12% non-profit support, and 8-9% industry support. At the entity level, we also find near-exact agreement. We interpret this evidence as supporting this methodology and the quality of the measures it returns.

Figure A.12: Comparison of Manual and LLM Entity Recognition



Notes: Figure compares manual and automatic entity recognition from dissertation texts. The figure shows the percentages of dissertations acknowledging support by organization type for a sample of 500 dissertations, by classification source. Note that a dissertation can acknowledge support from multiple organization types.

### A.5.2 Validating measures against NSF graduate fellowships

To validate specific references, we need a systematic ground truth sample to compare extracted sponsors against. Though ground truth data are hard to find—the lack of systematic, administrative data is the very reason we are developing these methods—large, organized fellowship programs with published lists of awardees offer a potential benchmark. One such program is the NSF graduate research fellowship (GRF) program, which spans many fields and has been administered continuously from 1952 to the present. Specifically, we wish to know how many of NSF GRF awardees are in our PQDT sample, how many do we measure as having NSF support, and for those we don’t, why not: is it due to incomplete measurement or incomplete reporting?

To answer these questions, we retrieve all NSF GRF awardees from the NSF’s website<sup>8</sup>, link them to PQDT, and evaluate our measures against this link. To prepare for linking, we first clean the PQDT and NSF data under common parameters, standardizing names and separating names into first names, surnames, and middle names/initials. We then crosswalk the subjects reported by each awardee to the SED major fields and institutions to which we have harmonized our PQDT data. Importantly, the usefulness of this information, and in turn the quality of the links, is limited by the fact that awardees’ reported fields often represent intended (rather than actual) fields of study. Nevertheless, these fields have information, which we will selectively use.<sup>9</sup> The NSF data present other challenges, including that individuals are sometimes awarded multiple times (implying that they chose not to use the award in one year, and later applied again); to deal with these challenges we attempt to de-duplicate the data by identifying awards to same-named individuals within ten years and restricting the sample to the latest award for every individual.

We then link NSF GRF awardees to PQDT in an iterative procedure. We first attempt to link on last name (LN), first name (FN), and middle initial (MI). Among the unlinked set, we then link on LN and FN; then, on LN, first initial (FI), and MI. At every step we keep only links where the PQDT graduation year was within 10 years of the NSF GRF award year, and we discard links where available, unused information would rule them out (e.g., when linking on LN and FN, if MI does not match we discard the link). When multiple links are made from the NSF GRF list to PQDT or vice versa, we use subjects to disambiguate, and we then attempt to manually disambiguate any remaining ambiguous cases. Our goal is to produce a highly precise link for validation, including at the expense of recall—and given these conservative choices, the share of GRF awardees which we link to PQDT will necessarily be lower than it could otherwise be.

Through this process we successfully (i.e., without ambiguity) link 65% of GRF awardees to our PQDT sample. Figure A.13 shows how this link rate varies across NSF GRF awardees’ reported subjects and over time, where it varies between 40% and 75% across subjects and steadily declines over time, from  $\approx 75\%$  in the 1950s to  $\approx 55\%$  in the 2010s. There are several reasons why these

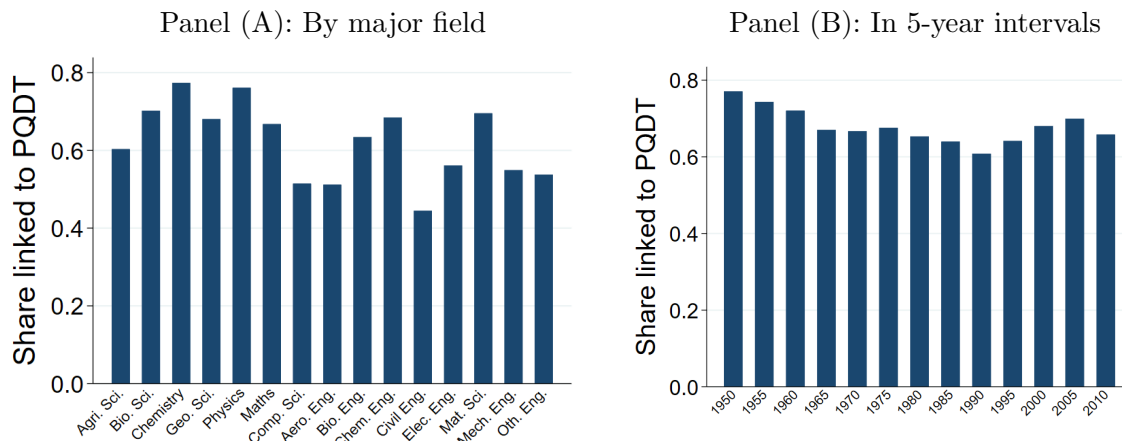
<sup>8</sup>See <https://www.research.gov/grfp/AwardeeList.do?method=loadAwardeeList>.

<sup>9</sup>The NSF data also include reported institutions; however, because many GRF applicants are pre-PhD, awardees’ current institutions are often their baccalaureate or master’s program rather than their PhD program. We found the institution data to be too ambiguous to use in this exercise.



link rates may be below 100%. The most salient among them are that the NSF sample can include awardees who are not accepted to PhD programs, decline to enroll, or never graduate. Given this, a 100% link rate is an unrealistic (and incorrect) benchmark. A second reason links are less than 100% is residual ambiguity in name-based links. However, because the NSF and PQDT samples are specific slices of the general population, sampled on a common feature (potential or actual PhD trainees in the hard sciences), and because full names and specializations are provided in both datasets, we believe this link is relatively precise and mostly complete.

Figure A.13: Link rates of NSF GRF awardees to our PQDT sample (awards through 2014)

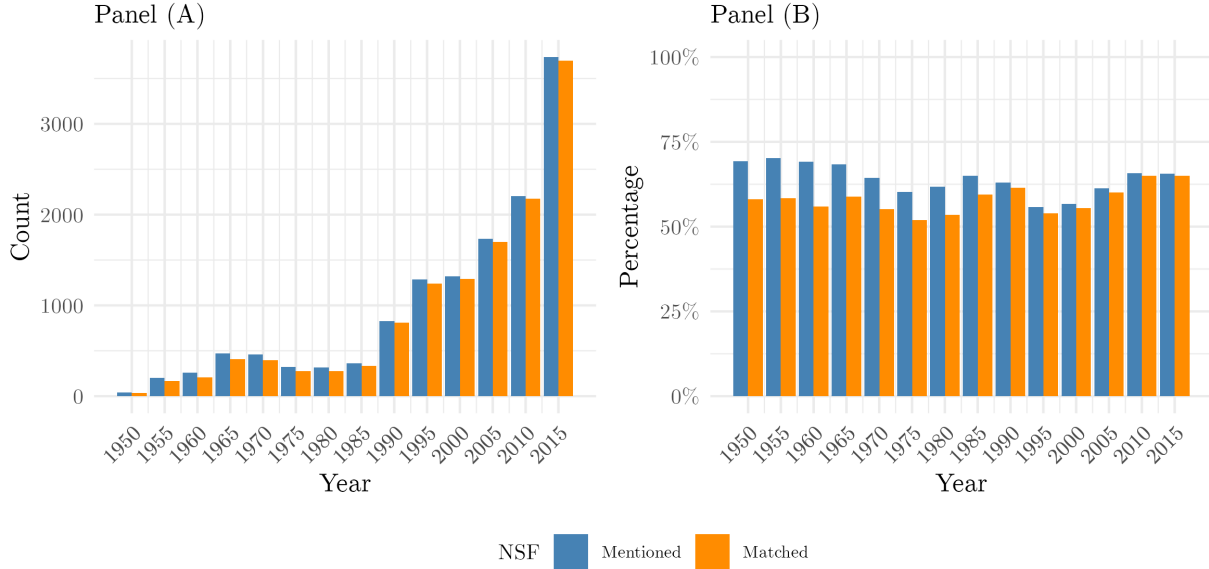


Notes: Figure shows the share of NSF graduate research fellows that we are able to link to the PQDT sample, by major field (Panel A) and in five-year intervals (Panel B), where every year shown represents the upcoming five years (i.e., 2010 = 2010-2014). The sample in these charts is restricted to awards through 2014 to allow at least five years, such that all awardees can graduate and be present in our PQDT sample. Link rates below unity may reflect awardees who are not accepted to PhD programs, decline to enroll, or never graduate.

We then undertake our main validation exercise: evaluating how our text-based measurement of dissertation sponsors performs within this linked sample. Within our sample of roughly 900,000 dissertations with full text, we identify 25,039 dissertations whose authors are linked to the NSF GRF awardee list. Figure A.14 presents an analysis of NSF dissertations mentions and the ROR link rates within this sample. Panel (A) shows five-year counts of NSF-acknowledging dissertations and of the subset of these cases where we can link to the ROR (in blue and orange, respectively). Panel (B) shows the share of our linked NSF-PQDT sample for which we find NSF acknowledgments and can link to the ROR. Among these 25,039 graduates, 15,229 (60.8%) mention the NSF somewhere in the text.<sup>10</sup> Our subsequent matching process links 15,026 (98.6%) of these mentions to the NSF identifier in ROR. Panel (B) shows that these rates are relatively stable over time, with acknowledgment rates between 55-65% over the past 70 years.

<sup>10</sup>For this test, we perform a simple search for “National Science Foundation” or “NSF” in acknowledgment sentences we extract from the dissertation text to identify NSF-acknowledging dissertations.

Figure A.14: NSF graduate fellows matched to NSF funding



Notes: Figure shows the counts (Panel A) and shares (Panel B) of NSF Graduate Fellows mentioning NSF funding support (in blue) and matched to the NSF by our matching process (in orange). Sample restricted to NSF fellows which we can link to PQDT.

Importantly, although these reporting rates are less than 100%, they are stable over time, even as the number of awardees (and PhD graduates) has grown significantly. In our analysis, there are two ways to approach potential underreporting: one is to restrict analysis to the reporting population—i.e., to PhD graduates with full text dissertations that include acknowledgments. The other is to estimate observable predictors of reporting, project the odds of reporting from observables, and use inverse propensity weighting to reweight the measured sample to represent the population. We report weighted results in the body of the paper and unweighted results in Appendix B, though our findings are qualitatively similar under both approaches.

### A.5.3 Validating measures against GSS

A second opportunity for validation is possible using the NSF’s Survey of Graduate Students and Postdoctorates in Science and Engineering (GSS). The GSS is an annual census of U.S. institutions granting research-based master’s degrees or doctorates in science and engineering (National Science Foundation 2022). Usefully for our purposes, the data report primary sources of support for graduate students at doctorate-granting institutions, providing annual counts of graduates in each major field with specific sources of funding: DoD, DOE, NIH and other HHS funders, NASA, NSF, USDA, other government agencies, institutional support, other U.S. or foreign sources, and self-support. Our goal here is to compare the field-year share of graduates in GSS funded by each of these agencies to the share we measure in our PQDT-based dissertation sample.

Though these comparisons make use of systematic administrative data, this exercise faces several structural limitations. First is the obvious caveat that the GSS measures enrolled students, whereas

our PQDT sample measures graduates. An implication is that the GSS sample in a given year is much larger than PQDT. To a first order approximation, however, we expect that doctoral students' sources of support in a given year will correlate strongly with graduates' sources of support. A second, potentially more important caveat is that although we restrict the GSS measures to doctorate-granting institutions, this sample will include master's and doctoral students at these institutions. Sources of financial support can differ significantly across degree levels, and federal funding is particularly focused on supporting doctoral training (whereas master's training is often self-funded). In light of this, we will focus on comparing agency shares of federally-funded students (rather than all students) in GSS and our PQDT sample. Finally, we restrict our attention to 2000 to 2022, when GSS reported supports for all six of our focal agencies for this exercise (DoD, DOE, HHS, NASA, NSF, USDA; DOE wasn't added until 1999).

Specifically, we regress (i) the share of federally-funded PhD graduates in a given field and year which we measure as being supported by each of these agencies, on (ii) the share of federally-funded GSS-reported students at doctoral institutions primarily supported by these agencies. If the samples perfectly aligned, and our measurement were accurate, we would expect these to correlate roughly one-for-one (i.e.,  $\beta = 1$ ). Given sampling differences, as well as the fact that GSS measures primary sources of funding and our methodology will measure all sources of support reported in dissertations, these shares may not vary one-for-one, but they should correlate.

Table A.11 provides the results. We see strong and highly significant correlations across the table. For every 10 percentage point (p.p.) increase in federally-funded students in GSS with DoD support, we see a 9.1 p.p. higher share of DoD funding in our PQDT data. The analogous results for a 10 p.p. increase in other agency support are: 14.1 p.p. for DOE, 10.1 p.p. for HHS, 14.0 p.p. for NASA, 10.2 p.p. for NSF, and 8.1 p.p. for USDA. For HHS and NSF (the two largest funders of doctoral training today), we cannot reject that the GSS and PQDT-based measures correlate one-for-one. More broadly, we view the correlation between the GSS and PQDT-based measures as validation of our approach to measuring research sponsors.

Table A.11: Comparing PQDT-based measures to GSS

|                        | (1)<br>DoD          | (2)<br>DOE          | (3)<br>HHS          | (4)<br>NASA         | (5)<br>NSF          | (6)<br>USDA         |
|------------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|
| Share of GSS graduates | 0.879***<br>(0.043) | 1.392***<br>(0.051) | 1.014***<br>(0.018) | 1.437***<br>(0.050) | 1.021***<br>(0.026) | 0.834***<br>(0.028) |
| N                      | 374                 | 374                 | 374                 | 374                 | 374                 | 374                 |
| $R^2$                  | 0.70                | 0.78                | 0.95                | 0.89                | 0.82                | 0.94                |
| P-val: $\beta = 1$     | 0.01                | 0.00                | 0.42                | 0.00                | 0.43                | 0.00                |

Notes: Table correlates (i) the share of PhD graduates in each major field and year which we measure as having been supported by a given agency to (ii) the GSS-reported share of enrolled PhD students in that field and year reporting support from that agency. Sample includes 17 major fields measured between 2000 and 2022. Variables are not perfectly comparable because one measures PhD graduates and the other measures enrolled students, but if our dissertation-based measurement of PhD support is precise, we anticipate they will strongly correlate, and if complete, regression coefficients ( $\beta$ ) should be near 1. \*, \*\*, \*\*\* represent significance at the 0.1, 0.05, and 0.01 levels, respectively. Robust SEs in parentheses.

## A.6 Limitations

As we note in the paper, one limitation of PQDT is a recent decline in the number of universities which submit dissertations to ProQuest. This attrition is not necessarily problematic for most of our analysis: the PQDT sample still appears to cover 90% of the population in recent years, and the sample attrition is not related to funding sources and is therefore unlikely to influence our findings. On the margin, however, it does preclude a complete accounting. In Table A.12 we list the principal universities in our sample and provide a window into which ones appear to have ended automatic or mandatory ProQuest licensing. For parsimony we limit the list to institutions with at least 20 STEM graduates every year between 2000 and 2022. For each such institution we report the number of PQDT graduates in our post-2000 sample, the number of SED graduates, and the difference and ratio, as well as the last year we substantially observe the university in the PQDT sample (defined as the last year where the number of PQDT graduates is  $>10\%$  of the SED total<sup>11</sup>). Note that minor differences in PQDT and SED counts may arise from discrepancies in STEM field definitions and accounting periods (calendar years vs. academic years, respectively).

Consistent with Figure A.1, the evidence in Table A.12 suggests that the PQDT sample is relatively complete. Some exceptions nevertheless stand out, including the following schools (among others): Texas Tech (which exits the sample after 2004), UT Southwestern (2004), U. of Tennessee (2007), Brown U. (2010), U. of Central Florida (2010), Georgia Tech (2012), U. of Connecticut (2012), U. of Texas Medical Branch (2012), U. of Virginia (2013), Oregon State U. (2013), U. of Oklahoma (2013), UMass Amherst (2014), Georgia State U. (2014), Virginia Tech (2016), and Baylor College of Medicine (which is never reported in PQDT).

<sup>11</sup>We set this threshold to reflect observed evidence that even after a university ends its agreement with ProQuest, some graduates occasionally submit their own dissertations to PQDT anyway

Table A.12: PQDT vs. SED STEM PhD counts for principal universities in this paper's sample

| University                    | Carnegie Classification | Total graduates, 2000-2022 |           |          | Years Missing | Final year in PQDT |
|-------------------------------|-------------------------|----------------------------|-----------|----------|---------------|--------------------|
|                               |                         | PQDT Count                 | SED Count | PQDT:SED |               |                    |
| Arizona State U.              | R1                      | 4,778                      | 4,184     | 114%     | 0             |                    |
| Auburn U.                     | R1                      | 2,763                      | 2,778     | 99%      | 0             |                    |
| Baylor C. of Medicine         | Med.                    | 1                          | 1,560     | 0%       | 23            | n.a.               |
| Boston U.                     | R1                      | 4,281                      | 4,081     | 105%     | 0             |                    |
| Brandeis U.                   | R1                      | 936                        | 862       | 109%     | 0             |                    |
| Brown U.                      | R1                      | 1,013                      | 2,394     | 42%      | 12            | 2010               |
| C. of William and Mary        | R2                      | 627                        | 634       | 99%      | 0             |                    |
| CUNY Graduate Center          | R1                      | 2,546                      | 2,399     | 106%     | 0             |                    |
| Cal. Inst. of Tech.           | R1                      | 3,156                      | 3,728     | 85%      | 0             |                    |
| Carnegie Mellon U.            | R1                      | 3,339                      | 4,559     | 73%      | 0             |                    |
| Case Western Reserve U.       | R1                      | 3,015                      | 3,266     | 92%      | 0             |                    |
| Clemson U.                    | R1                      | 2,738                      | 2,715     | 101%     | 0             |                    |
| Colorado School of Mines      | R1                      | 1,549                      | 1,497     | 103%     | 0             |                    |
| Colorado State U.             | R1                      | 3,507                      | 3,384     | 104%     | 0             |                    |
| Columbia U.                   | R1                      | 5,757                      | 5,744     | 100%     | 0             |                    |
| Cornell U.                    | R1                      | 6,704                      | 7,262     | 92%      | 0             |                    |
| Weill Cornell Med. Coll.      | Med.                    | 1,126                      | 1,104     | 102%     | 0             |                    |
| Dartmouth C.                  | R1                      | 1,529                      | 1,556     | 98%      | 0             |                    |
| Drexel U.                     | R1                      | 2,036                      | 2,017     | 101%     | 0             |                    |
| Duke U.                       | R1                      | 4,691                      | 4,492     | 104%     | 0             |                    |
| Emory U.                      | R1                      | 2,292                      | 2,306     | 99%      | 0             |                    |
| Florida State U.              | R1                      | 2,804                      | 2,689     | 104%     | 0             |                    |
| George Mason U.               | R1                      | 1,740                      | 1,764     | 99%      | 0             |                    |
| George Washington U.          | R1                      | 2,122                      | 1,920     | 111%     | 0             |                    |
| Georgetown U.                 | R1                      | 926                        | 875       | 106%     | 0             |                    |
| Ga. Inst. of Tech.            | R1                      | 4,549                      | 8,743     | 52%      | 10            | 2012               |
| Georgia State U.              | R1                      | 566                        | 1,166     | 49%      | 8             | 2014               |
| Harvard U.                    | R1                      | 7,548                      | 7,318     | 103%     | 0             |                    |
| Howard U.                     | R1                      | 639                        | 697       | 92%      | 0             |                    |
| Icahn School of Medicine      | Med.                    | 487                        | 707       | 69%      | 11            |                    |
| Ill. Inst. of Tech.           | R2                      | 1,303                      | 1,191     | 109%     | 0             |                    |
| Indiana U.                    | R1                      | 3,184                      | 3,100     | 103%     | 0             |                    |
| Iowa State U.                 | R1                      | 5,223                      | 5,037     | 104%     | 0             |                    |
| Johns Hopkins U.              | R1                      | 5,221                      | 7,405     | 71%      | 2             | 2020               |
| Kansas State U.               | R1                      | 2,313                      | 2,268     | 102%     | 0             |                    |
| Kent State U.                 | R1                      | 937                        | 1,103     | 85%      | 0             |                    |
| Lehigh U.                     | R1                      | 1,435                      | 1,459     | 98%      | 0             |                    |
| Louisiana State U.            | R1                      | 3,509                      | 3,351     | 105%     | 0             |                    |
| Loyola U. of Chicago          | R1                      | 617                        | 588       | 105%     | 0             |                    |
| Mass. Inst. of Tech.          | R1                      | 10,036                     | 10,551    | 95%      | 0             |                    |
| Michigan State U.             | R1                      | 5,577                      | 5,474     | 102%     | 0             |                    |
| Mississippi State U.          | R1                      | 1,712                      | 1,680     | 102%     | 0             |                    |
| Missouri U. of Sci. and Tech. | R2                      | 1,576                      | 1,623     | 97%      | 0             |                    |
| NJ Inst. of Tech.             | R1                      | 907                        | 1,310     | 69%      | 1             |                    |
| New Mexico State U.           | R1                      | 1,142                      | 1,146     | 100%     | 0             |                    |
| New York U.                   | R1                      | 3,272                      | 3,080     | 106%     | 0             |                    |
| North Carolina State U.       | R1                      | 7,149                      | 6,995     | 102%     | 0             |                    |
| North Dakota State U.         | R1                      | 1,218                      | 1,183     | 103%     | 0             |                    |
| Northeastern U.               | R1                      | 1,719                      | 2,041     | 84%      | 6             |                    |
| Northwestern U.               | R1                      | 5,278                      | 5,199     | 102%     | 0             |                    |
| Nova Southeastern U.          | R2                      | 448                        | 864       | 52%      | 1             |                    |
| Ohio State U.                 | R1                      | 8,701                      | 8,700     | 100%     | 0             |                    |
| Ohio U.                       | R1                      | 1,032                      | 982       | 105%     | 0             |                    |
| Oklahoma State U.             | R1                      | 2,148                      | 2,134     | 101%     | 0             |                    |
| Old Dominion U.               | R1                      | 1,125                      | 1,069     | 105%     | 0             |                    |
| Oregon State U.               | R1                      | 1,880                      | 3,493     | 54%      | 9             | 2013               |
| Pennsylvania State U.         | R1                      | 8,258                      | 8,646     | 96%      | 0             |                    |
| Princeton U.                  | R1                      | 4,077                      | 3,958     | 103%     | 0             |                    |
| Purdue U.                     | R1                      | 10,022                     | 10,253    | 98%      | 0             |                    |
| Rensselaer Polytech. Inst.    | R1                      | 2,603                      | 2,586     | 101%     | 0             |                    |
| Rice U.                       | R1                      | 2,779                      | 2,672     | 104%     | 0             |                    |
| Rutgers U., New Brunswick     | R1                      | 4,762                      | 5,413     | 88%      | 0             |                    |
| Binghamton U.                 | R1                      | 1,290                      | 1,201     | 107%     | 0             |                    |
| Stony Brook U.                | R1                      | 4,106                      | 3,876     | 106%     | 0             |                    |

|                                |    |        |        |      |    |      |
|--------------------------------|----|--------|--------|------|----|------|
| U. Albany                      | R1 | 1,200  | 1,159  | 104% | 0  |      |
| U. Buffalo                     | R1 | 3,681  | 3,636  | 101% | 0  |      |
| Southern Illinois U.           | R1 | 1,086  | 1,039  | 105% | 0  |      |
| Stanford U.                    | R1 | 10,391 | 10,594 | 98%  | 0  |      |
| Syracuse U.                    | R1 | 1,357  | 1,328  | 102% | 0  |      |
| Temple U.                      | R1 | 1,662  | 1,594  | 104% | 0  |      |
| Texas A&M U.                   | R1 | 8,388  | 9,385  | 89%  | 0  |      |
| Texas Tech U.                  | R1 | 336    | 2,262  | 15%  | 18 | 2004 |
| Texas Woman's U.               | R2 | 630    | 800    | 79%  | 0  |      |
| Tufts U.                       | R1 | 1,582  | 1,794  | 88%  | 0  |      |
| Tulane U.                      | R1 | 1,483  | 1,505  | 99%  | 0  |      |
| U. Akron                       | R2 | 1,294  | 1,585  | 82%  | 0  |      |
| U. Alabama, Birmingham         | R1 | 2,717  | 2,640  | 103% | 0  |      |
| U. Alabama, Huntsville         | R1 | 596    | 712    | 84%  | 0  |      |
| U. Alabama, Tuscaloosa         | R1 | 1,482  | 1,362  | 109% | 0  |      |
| U. Arizona                     | R1 | 5,305  | 5,214  | 102% | 0  |      |
| U. Arkansas                    | R1 | 1,784  | 1,779  | 100% | 0  |      |
| U. California, Berkeley        | R1 | 10,831 | 11,243 | 96%  | 0  |      |
| U. California, Davis           | R1 | 7,830  | 7,736  | 101% | 0  |      |
| U. California, Irvine          | R1 | 4,907  | 4,707  | 104% | 0  |      |
| U. California, Los Angeles     | R1 | 8,897  | 8,499  | 105% | 0  |      |
| U. California, Riverside       | R1 | 3,086  | 2,944  | 105% | 0  |      |
| U. California, San Diego       | R1 | 6,852  | 6,695  | 102% | 0  |      |
| U. California, San Francisco   | R2 | 2,426  | 2,463  | 98%  | 0  |      |
| U. California, Santa Barbara   | R1 | 3,795  | 3,616  | 105% | 0  |      |
| U. California, Santa Cruz      | R1 | 1,972  | 1,930  | 102% | 0  |      |
| U. Central Florida             | R1 | 774    | 2,572  | 30%  | 12 | 2010 |
| U. Chicago                     | R1 | 3,427  | 3,235  | 106% | 0  |      |
| U. Cincinnati                  | R1 | 3,184  | 3,111  | 102% | 0  |      |
| U. Colorado, Boulder           | R1 | 4,805  | 4,672  | 103% | 0  |      |
| U. Colorado, Denver            | R1 | 1,685  | 1,618  | 104% | 0  |      |
| U. Connecticut                 | R1 | 2,086  | 3,883  | 54%  | 10 | 2012 |
| U. Delaware                    | R1 | 2,949  | 2,842  | 104% | 0  |      |
| U. Florida                     | R1 | 8,826  | 9,678  | 91%  | 0  |      |
| U. Georgia                     | R1 | 883    | 4,055  | 22%  | 16 |      |
| U. Hawaii, Manoa               | R1 | 1,892  | 1,709  | 111% | 0  |      |
| U. Houston                     | R1 | 1,680  | 2,961  | 57%  | 7  | 2020 |
| U. Idaho                       | R1 | 1,052  | 1,054  | 100% | 0  |      |
| U. Illinois, Chicago           | R1 | 4,118  | 4,066  | 101% | 0  |      |
| U. Illinois, Urbana-Champaign  | R1 | 8,769  | 10,340 | 85%  | 0  |      |
| U. Iowa                        | R1 | 3,870  | 3,834  | 101% | 0  |      |
| U. Kansas                      | R1 | 2,568  | 2,493  | 103% | 0  |      |
| U. Kentucky                    | R1 | 2,277  | 3,385  | 67%  | 4  | 2018 |
| U. Maine                       | R1 | 750    | 801    | 94%  | 0  |      |
| U. Maryland, Baltimore         | R2 | 1,073  | 1,479  | 73%  | 0  |      |
| U. Maryland, Baltimore County  | R1 | 996    | 1,153  | 86%  | 1  |      |
| U. Maryland, College Park      | R1 | 6,902  | 6,798  | 102% | 0  |      |
| U. Massachusetts, Amherst      | R1 | 2,034  | 3,354  | 61%  | 8  | 2014 |
| U. Miami                       | R1 | 1,909  | 2,018  | 95%  | 2  | 2020 |
| U. Michigan, Ann Arbor         | R1 | 9,343  | 11,154 | 84%  | 0  |      |
| U. Minnesota, Twin Cities      | R1 | 8,770  | 8,700  | 101% | 0  |      |
| U. Mississippi, Oxford         | R1 | 1,171  | 1,206  | 97%  | 0  |      |
| U. Missouri, Columbia          | R1 | 2,179  | 3,114  | 70%  | 0  |      |
| U. Nebraska, Lincoln           | R1 | 2,878  | 2,727  | 106% | 0  |      |
| U. Nevada, Reno                | R1 | 1,298  | 1,231  | 105% | 0  |      |
| U. New Hampshire               | R1 | 897    | 861    | 104% | 0  |      |
| U. New Mexico, Albuquerque     | R1 | 2,148  | 2,110  | 102% | 0  |      |
| U. North Carolina, Chapel Hill | R1 | 6,295  | 6,050  | 104% | 0  |      |
| U. North Texas                 | R1 | 866    | 1,197  | 72%  | 0  |      |
| U. Notre Dame                  | R1 | 2,477  | 2,441  | 101% | 0  |      |
| U. Oklahoma                    | R1 | 990    | 2,290  | 43%  | 9  | 2013 |
| U. Oregon                      | R1 | 1,254  | 1,152  | 109% | 0  |      |
| U. Pennsylvania                | R1 | 5,388  | 5,104  | 106% | 0  |      |
| U. Pittsburgh                  | R1 | 5,145  | 5,196  | 99%  | 0  |      |
| U. Rhode Island                | R1 | 1,182  | 1,162  | 102% | 0  |      |
| U. Rochester                   | R1 | 2,962  | 2,990  | 99%  | 0  |      |
| U. South Carolina              | R1 | 2,860  | 2,876  | 99%  | 0  |      |
| U. South Florida               | R1 | 2,973  | 2,731  | 109% | 0  |      |

|                                   |      |        |       |      |    |      |
|-----------------------------------|------|--------|-------|------|----|------|
| U. Southern California            | R1   | 5,203  | 5,772 | 90%  | 0  |      |
| U. Tennessee, Knoxville           | R1   | 795    | 3,553 | 22%  | 15 | 2007 |
| U. Texas HSC, Houston             | Med. | 1,228  | 2,283 | 54%  | 4  | 2018 |
| U. Texas HSC, San Antonio         | Med. | 587    | 815   | 72%  | 0  |      |
| U. Texas Medical Branch           | Med. | 395    | 821   | 48%  | 10 | 2012 |
| U. Texas Southwestern Med. Center | Med. | 197    | 1,379 | 14%  | 18 | 2004 |
| U. Texas, Arlington               | R1   | 1,909  | 2,031 | 94%  | 0  |      |
| U. Texas, Austin                  | R1   | 4,636  | 8,773 | 53%  | 6  |      |
| U. Texas, Dallas                  | R1   | 2,062  | 1,981 | 104% | 0  |      |
| U. Toledo                         | R1   | 1,250  | 1,346 | 93%  | 0  |      |
| U. Utah                           | R1   | 4,250  | 4,203 | 101% | 0  |      |
| U. Virginia, Charlottesville      | R1   | 2,123  | 3,759 | 56%  | 9  | 2013 |
| U. Washington, Seattle            | R1   | 8,791  | 8,751 | 100% | 0  |      |
| U. Wisconsin, Madison             | R1   | 10,070 | 9,926 | 101% | 0  |      |
| U. Wisconsin, Milwaukee           | R1   | 1,246  | 1,221 | 102% | 0  |      |
| U. Wyoming                        | R1   | 1,059  | 1,044 | 101% | 0  |      |
| Utah State U.                     | R1   | 1,167  | 1,090 | 107% | 0  |      |
| Vanderbilt U.                     | R1   | 3,156  | 3,498 | 90%  | 0  |      |
| Virginia Commonwealth U.          | R1   | 1,500  | 2,058 | 73%  | 4  | 2018 |
| Virginia Polytech. Inst.          | R1   | 3,146  | 5,974 | 53%  | 6  | 2016 |
| Wake Forest U.                    | R2   | 950    | 954   | 100% | 0  |      |
| Washington State U.               | R1   | 2,875  | 2,781 | 103% | 0  |      |
| Washington U., St. Louis          | R1   | 3,706  | 3,568 | 104% | 0  |      |
| Wayne State U.                    | R1   | 2,532  | 2,547 | 99%  | 0  |      |
| West Virginia U.                  | R1   | 1,994  | 2,013 | 99%  | 0  |      |
| Yale U.                           | R1   | 5,172  | 4,205 | 123% | 0  |      |

Notes: Table lists universities in our PQDT sample, filtering to those with at least 20 STEM graduates every year from 2000 to 2022. Table provides number of associated PQDT- and SED-reported STEM grads over this period, as well as the number of years for which we observe graduates in PQDT and the final year we observe the university in the PQDT sample, if the university permanently exits the sample before 2022. We consider a university-year missing if the PQDT graduate count is less than 10% of the SED count. Carnegie designations are as follows: R1 = Very high research activity universities, R2 = High research activity universities, Med. = Medical schools and centers.

Though these gaps are modest, there is nevertheless a possibility of filling them from other sources—especially by retrieving (scraping) dissertations and information about their authors from university repositories. Doing so is a substantial challenge, due to structural differences across them, which necessitates a custom program for each university.

To better understand the feasibility of doing so, and how many additional graduates and dissertations it could deliver, we undertook this data collection. We specifically crawled online repositories for the universities listed in Table A.13 for years where we believed we were missing a significant number of graduates (based on our SED benchmark), and gathered data on all graduates from those years, targeting all fields PQDT provides (e.g., name, title, abstract, subject(s), and dissertation text if available). In this case, we mapped subjects to SED major fields using an LLM. We then used these data to identify doctoral degrees issued in STEM fields. Reproducing Figure A.1 in Figure A.15, we see that this procedure appears to close roughly half the gap between our PQDT sample and SED graduate counts in recent years.

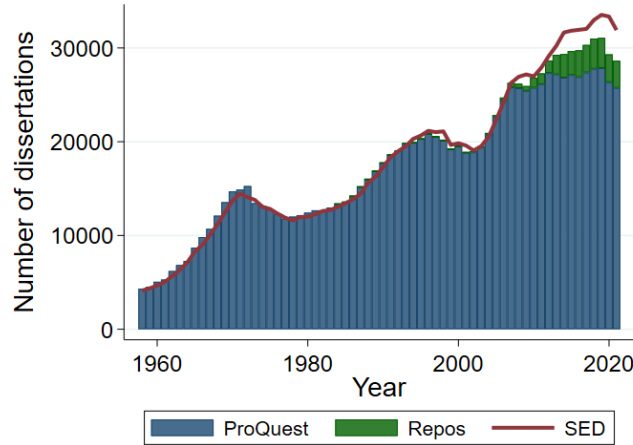
We do so for now as a proof of concept, especially for assessing whether this sampling can be extended forward. We opt to not append these graduates to the PQDT-derived sample in this paper primarily to maintain a consistent sampling procedure, especially with respect to the individuals accounted for, the subjects they are associated with (whose data generating process may vary between PQDT and university repositories), and how we allocate them to SED major fields, which will affect the calculated overall STEM graduate counts.

Table A.13: Backfilled graduates retrieved from university repositories

| University                        | Retrieved graduates | First year | Last year |
|-----------------------------------|---------------------|------------|-----------|
| The U. of Texas at Austin         | 6,050               | 2010       | 2024      |
| Ga. Inst. of Tech.                | 5,754               | 2013       | 2024      |
| U. Tennessee, Knoxville           | 3,689               | 2007       | 2025      |
| Virginia Polytech. Inst.          | 3,429               | 2016       | 2025      |
| U. of Georgia                     | 2,783               | 2002       | 2019      |
| U. Central Florida                | 2,446               | 2010       | 2025      |
| U. Houston                        | 2,137               | 2012       | 2025      |
| Texas Tech U.                     | 2,128               | 2005       | 2025      |
| U. Massachusetts, Amherst         | 1,868               | 2014       | 2025      |
| U. Connecticut                    | 1,532               | 2013       | 2020      |
| U. Texas Southwestern Med. Center | 1,357               | 2005       | 2024      |
| U. Kentucky                       | 1,163               | 2018       | 2025      |
| U. Oklahoma                       | 1,137               | 2014       | 2024      |
| U. Texas HSC, Houston             | 813                 | 2010       | 2025      |
| U. Louisville                     | 804                 | 2014       | 2025      |
| Virginia Commonwealth U.          | 638                 | 2018       | 2025      |
| Rockefeller U.                    | 580                 | 2004       | 2025      |
| Wright State U.                   | 388                 | 2011       | 2024      |
| Med. Coll. Ga.                    | 191                 | 2012       | 2022      |
| South Dakota State U.             | 172                 | 2011       | 2025      |
| U. Texas Medical Branch           | 65                  | 2013       | 2024      |

Notes: Table lists the set of universities and years which are absent from PQDT entirely (no information on their graduates; per Table A.12) and for which we can backfill data on their STEM PhD graduates from university repositories.

Figure A.15: ProQuest vs. SED graduates in STEM fields, with backfilled graduates



Notes: Figure shows annual PQDT graduate counts in the physical and life sciences and engineering (blue bars) plus graduates we can backfill from university repositories (stacked green bars, see Table A.13) versus SED counts (red line) for comparison. This backfill can close roughly half the gap between PQDT and SED in recent years.



## B Supplementary Results

### B.1 Foreign share of U.S. STEM PhD graduates

In this paper, we have restricted our attention to which PhDs the U.S. higher education system trains and who supports them. An important parallel set of questions is where they come from and where they go after their studies conclude. Immigrant scientists are a subject of perennial interest, and a substantial body of research indicates that immigrant scientists (including those trained in the U.S.) make outsized contributions to national science and innovation.

Though not our principal focus here—we instead examine patterns in PhD graduate out-migration in concurrent work (Shvadron et al. 2025b)—some context on the foreign-born PhD graduate population may be useful. As Figure B.1 shows, the foreign national share of U.S. STEM PhD graduates is currently around 45%, based on citizenship reported in the SED (an annual census of U.S. PhD graduates). These shares vary by field, with higher shares in engineering and lower shares in biomedicine, but across all fields are large and have increased since the beginning of our study period. Foreign nationals are not eligible for some categories of U.S. federal research funding (namely, fellowship funding, such as from the NSF or NIH), but they are eligible for other categories of federal support, including research grants, assistantships, and more.

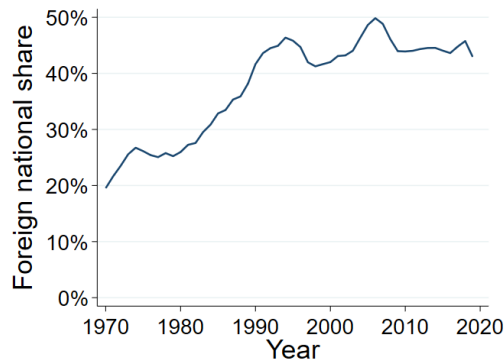
A structural limitation of the PQDT data is that they do not systematically measure or report country of origin (nor any other demographic features). However, this data gap does not necessarily rule out the possibility of identifying foreign-origin graduates; as MacGarvie (2007) has argued, information included in students’ dissertations reporting lower degree institutions can suggestively indicate graduates’ country of origin. Though some graduates may complete a bachelor’s degree in a country other than their home country—including many in the U.S. itself—this information presents an opportunity to make progress in identifying foreign origin students through their dissertations (and more generally, in the absence of administrative/SED data).

We processed the dissertations in our sample to extract lower degree institutions, measuring the degree level (bachelor’s and master’s equivalents, henceforth denoted as BA and MA, though many degrees will be in science and engineering, including BS and MS degrees) and country where listed. We find this information in dissertations of many students (around 10% of the sample, and nearly 20% of post-2000 graduates) at many universities (70-90 per year after 2000)—substantially more than the 11 universities recognized by MacGarvie (2007) as being systematically reported. Because foreign trainees and immigration patterns are not a principal focus of this paper, we have used these data only in exploratory analysis. But within the sample of graduates for whom we have lower degree institution data, we can, for example, calculate the number of such graduates by field or with dissertation work related to specific critical technologies, and the share of such graduates with non-U.S. lower degree institutions, suggesting foreign origin.

In Table B.2 we do so by broad and major field, and in Table B.3 for critical technology areas. Note that these data comprise a roughly 20% sample, and may not be representative, but

they nevertheless provide a datapoint. The (apparent) foreign-origin share of U.S. PhD graduates varies substantially across fields, with roughly 20% in the biological sciences having a non-U.S. BA (or equivalent), and roughly 60% in civil engineering. Across all fields and technology areas, a substantially larger share of graduates with U.S. BAs have government support during their PhD than those with foreign BAs—partly due to eligibility restrictions. However, non-U.S. BA graduates also report U.S. government support for their research at high rates, reflecting that the U.S. government funds PhD research broadly. Moreover, the returns to these investments often accrue domestically: as we show in Shvadron et al. (2025b), a substantial share of these (apparent) foreign-origin graduates continue working in the U.S. for a decade or more post-graduation.

Figure B.1: Foreign share of U.S. STEM PhD graduates, 1970-2019 (SED)



Notes: Figure shows share of STEM PhD graduates over time who are foreign nationals, from 1970 to 2019. Foreign national share computed as the share of graduates who are temporary or permanent U.S. residents, using the NCSES Doctorate Record File (which is in turn compiled from the SED).

Table B.1: Foreign share of PhD graduates by field and decade

|              | Field            | 1970s | 1980s | 1990s | 2000s | 2010s |
|--------------|------------------|-------|-------|-------|-------|-------|
| Broad fields | Life Sci.        | 19%   | 20%   | 34%   | 32%   | 31%   |
|              | Physical Sci.    | 21%   | 27%   | 40%   | 44%   | 41%   |
|              | Math/Comp. Sci.  | 22%   | 42%   | 51%   | 56%   | 56%   |
|              | Engineering Sci. | 39%   | 55%   | 57%   | 63%   | 59%   |
| Major fields | Agr. Sci.        | 36%   | 38%   | 51%   | 47%   | 46%   |
|              | Bio. Sci.        | 14%   | 15%   | 32%   | 32%   | 30%   |
|              | Health Sci.      | 17%   | 18%   | 25%   | 26%   | 25%   |
|              | Chemistry.       | 19%   | 25%   | 39%   | 43%   | 41%   |
|              | Geo. Sci.        | 19%   | 22%   | 35%   | 37%   | 34%   |
|              | Physics          | 23%   | 34%   | 45%   | 50%   | 45%   |
|              | Maths.           | 22%   | 43%   | 52%   | 54%   | 50%   |
|              | Comp. Sci.       | 22%   | 40%   | 50%   | 59%   | 61%   |
|              | Aero. Eng.       | 35%   | 56%   | 46%   | 55%   | 40%   |
|              | Bio. Eng.        | 18%   | 26%   | 37%   | 40%   | 36%   |
|              | Chem. Eng.       | 43%   | 48%   | 52%   | 54%   | 53%   |
|              | Civil Eng.       | 53%   | 64%   | 67%   | 69%   | 69%   |
|              | Elec. Eng.       | 35%   | 54%   | 57%   | 71%   | 72%   |
|              | Ind. Eng.        | 33%   | 64%   | 61%   | 71%   | 72%   |

Notes: Figure shows share of STEM PhD graduates across broad and major fields who are foreign nationals, by decade, from 1970 to 2019. Foreign national share is computed as the share of graduates who are temporary or permanent U.S. residents, using the NCSES Doctorate Record File (which is in turn compiled from the SED).

Table B.2: Foreign pre-PhD degree share of graduates, by field, 2000-2019

|                 | Field            | Sample size | Share of graduates<br>with non-US ... |     | Share w/ USG support,<br>by BA country: |        |
|-----------------|------------------|-------------|---------------------------------------|-----|-----------------------------------------|--------|
|                 |                  |             | BA                                    | MA  | US                                      | Non-US |
| Broad<br>fields | Life Sci.        | 26,916      | 23%                                   | 13% | 46%                                     | 34%    |
|                 | Physical Sci.    | 12,010      | 33%                                   | 16% | 49%                                     | 37%    |
|                 | Math/Comp. Sci.  | 7,464       | 44%                                   | 19% | 29%                                     | 22%    |
|                 | Engineering Sci. | 18,092      | 48%                                   | 22% | 47%                                     | 37%    |
| Major<br>fields | Agr. Sci.        | 3,031       | 35%                                   | 20% | 42%                                     | 34%    |
|                 | Bio. Sci.        | 18,361      | 21%                                   | 12% | 48%                                     | 34%    |
|                 | Health Sci.      | 5,524       | 19%                                   | 10% | 41%                                     | 34%    |
|                 | Chemistry        | 5,254       | 35%                                   | 17% | 40%                                     | 33%    |
|                 | Geo. Sci.        | 2,397       | 28%                                   | 17% | 73%                                     | 57%    |
|                 | Physics          | 4,359       | 34%                                   | 16% | 45%                                     | 34%    |
|                 | Maths.           | 4,140       | 39%                                   | 17% | 25%                                     | 17%    |
|                 | Comp. Sci.       | 3,324       | 51%                                   | 21% | 36%                                     | 26%    |
|                 | Aero. Eng.       | 891         | 29%                                   | 17% | 62%                                     | 46%    |
|                 | Bio. Eng.        | 2,261       | 37%                                   | 15% | 46%                                     | 32%    |
|                 | Chem. Eng.       | 1,603       | 44%                                   | 18% | 51%                                     | 45%    |
|                 | Civil Eng.       | 1,733       | 61%                                   | 37% | 49%                                     | 38%    |
|                 | Elec. Eng.       | 3,881       | 53%                                   | 22% | 41%                                     | 31%    |
|                 | Ind. Eng.        | 528         | 57%                                   | 26% | 35%                                     | 21%    |

Notes: Table lists (i) the number of U.S. PhD graduates in each broad and major field over the 2000-2019 period for whom we can measure pre-PhD locations, (ii) the share with a foreign pre-PhD degree (BA or MA, and equivalents), and the share of those with a U.S. vs. non-U.S. BA who acknowledge some U.S. federal government support.

Table B.3: Foreign pre-PhD degree share of graduates, by technology, 2000-2019

| Technology                | Sample size | Share of graduates<br>with non-US ... |     | Share w/ USG support,<br>by BA country: |        |
|---------------------------|-------------|---------------------------------------|-----|-----------------------------------------|--------|
|                           |             | BA                                    | MA  | US                                      | Non-US |
| Advanced computing        | 8,307       | 49%                                   | 21% | 43%                                     | 31%    |
| Advanced manufacturing    | 1,400       | 50%                                   | 23% | 55%                                     | 48%    |
| Artificial intelligence   | 3,031       | 50%                                   | 22% | 42%                                     | 33%    |
| Autonomous systems        | 854         | 41%                                   | 20% | 51%                                     | 37%    |
| Biotechnology             | 11,860      | 31%                                   | 15% | 47%                                     | 34%    |
| Integrated communications | 1,770       | 57%                                   | 24% | 37%                                     | 28%    |
| Data and cyber security   | 653         | 58%                                   | 20% | 39%                                     | 26%    |
| Directed energy           | 156         | 35%                                   | 19% | 38%                                     | 38%    |
| Hypersonics               | 29          | 28%                                   | 14% | 76%                                     | 50%    |
| Human-machine interfaces  | 571         | 40%                                   | 17% | 43%                                     | 36%    |
| Materials science         | 6,349       | 47%                                   | 22% | 53%                                     | 42%    |
| Microelectronics          | 3,960       | 49%                                   | 21% | 44%                                     | 36%    |
| PNT technologies          | 409         | 37%                                   | 18% | 51%                                     | 32%    |
| Quantum science           | 1,119       | 38%                                   | 15% | 38%                                     | 32%    |
| Renewable energy          | 2,124       | 45%                                   | 21% | 51%                                     | 42%    |
| Networked sensing         | 2,870       | 42%                                   | 19% | 53%                                     | 41%    |
| Space technology          | 972         | 27%                                   | 15% | 64%                                     | 54%    |
| Gas turbine engines       | 134         | 47%                                   | 17% | 56%                                     | 43%    |

Notes: Table lists (i) the number of U.S. PhD graduates in each critical technology area over the 2000-2019 period for whom we can measure pre-PhD locations, (ii) the share with a foreign pre-PhD degree (BA or MA, and equivalents), and the share of those with a U.S. vs. non-U.S. BA who acknowledge some U.S. federal government support.

## B.2 Female share of U.S. STEM PhD graduates

In addition to our measures of foreign vs. U.S. origin, we also develop measures of PhD graduate gender, using the name-based classifier `genderize.io`, which assigns names a gender probability based on empirical frequencies in a training corpus. In Figures B.2 and B.3 we report the gender composition of graduates in our sample between 2000 and 2022 by major field and by technology area, respectively. In doing so, we restrict to the 80% of our sample that our classifier predicts is either male or female with >90% probability.

Figure B.2: Female share of graduates, by field, 2000-2022

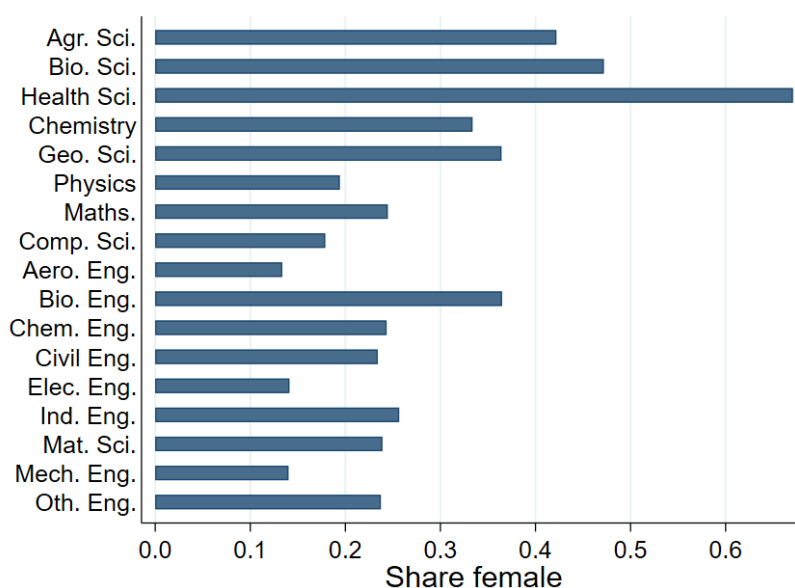
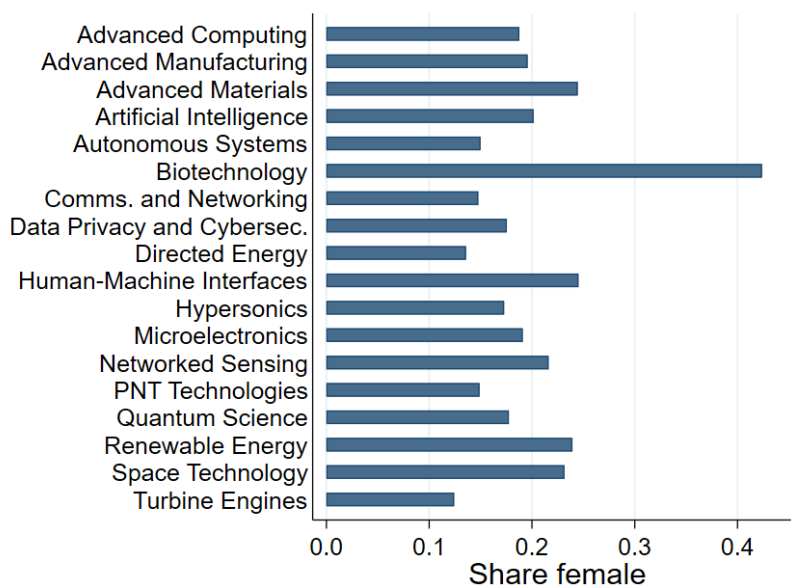


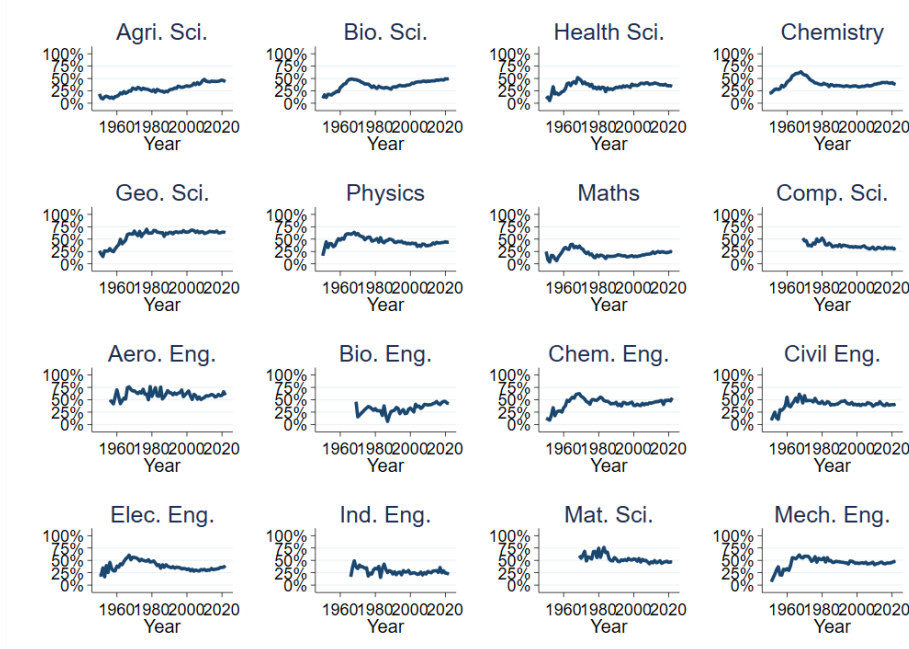
Figure B.3: Female share of graduates, by technology, 2000-2022



### B.3 U.S. government support over time, by field

Figure B.4 reports the share of graduates in each major field between 1950 and 2022 acknowledging U.S. government support, conditional on having any dissertation acknowledgments.

Figure B.4: U.S. government-funded share of dissertations, by field, 1950-2022

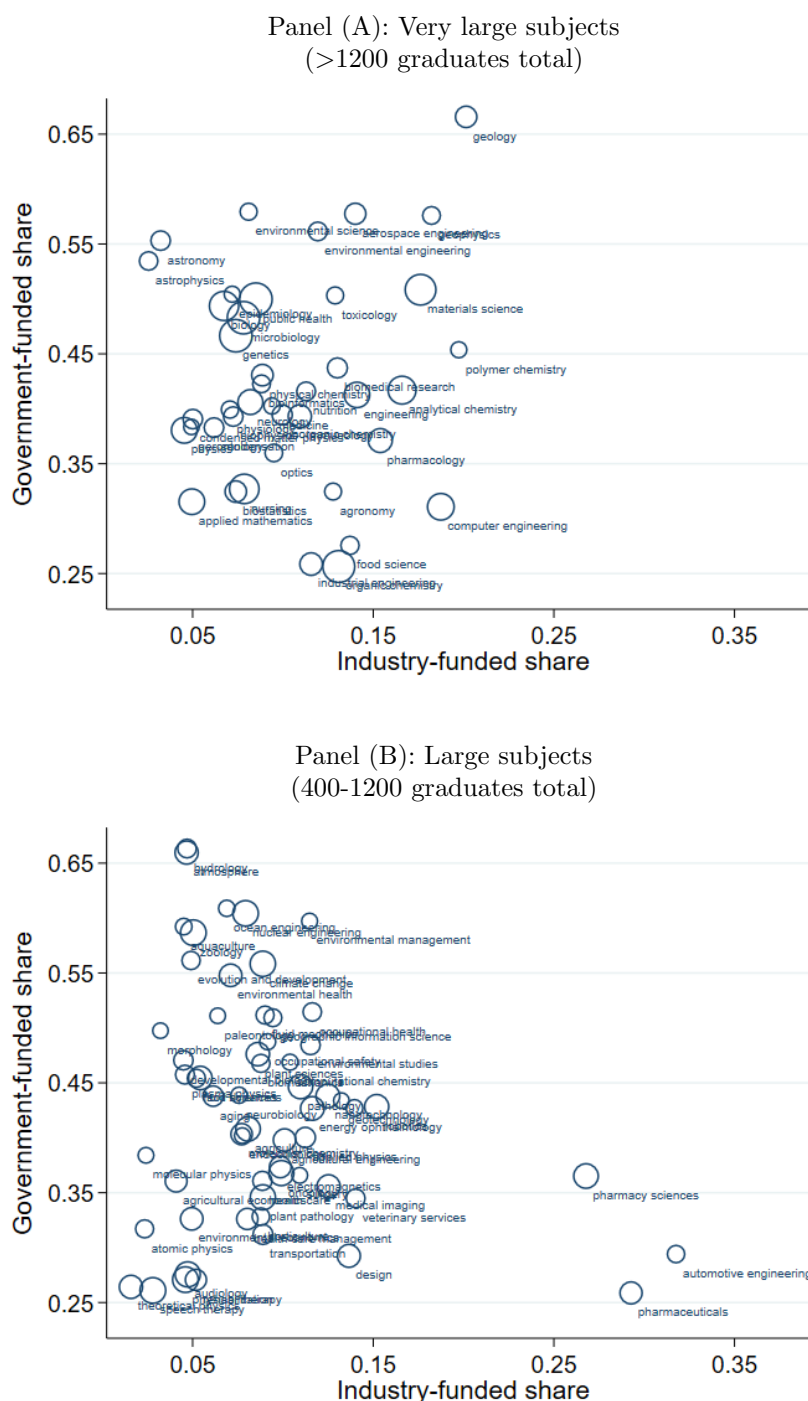


Notes: Figure shows government-funded share of dissertations by major field, from 1950 to 2022.

### B.4 Heterogeneity across subjects and universities

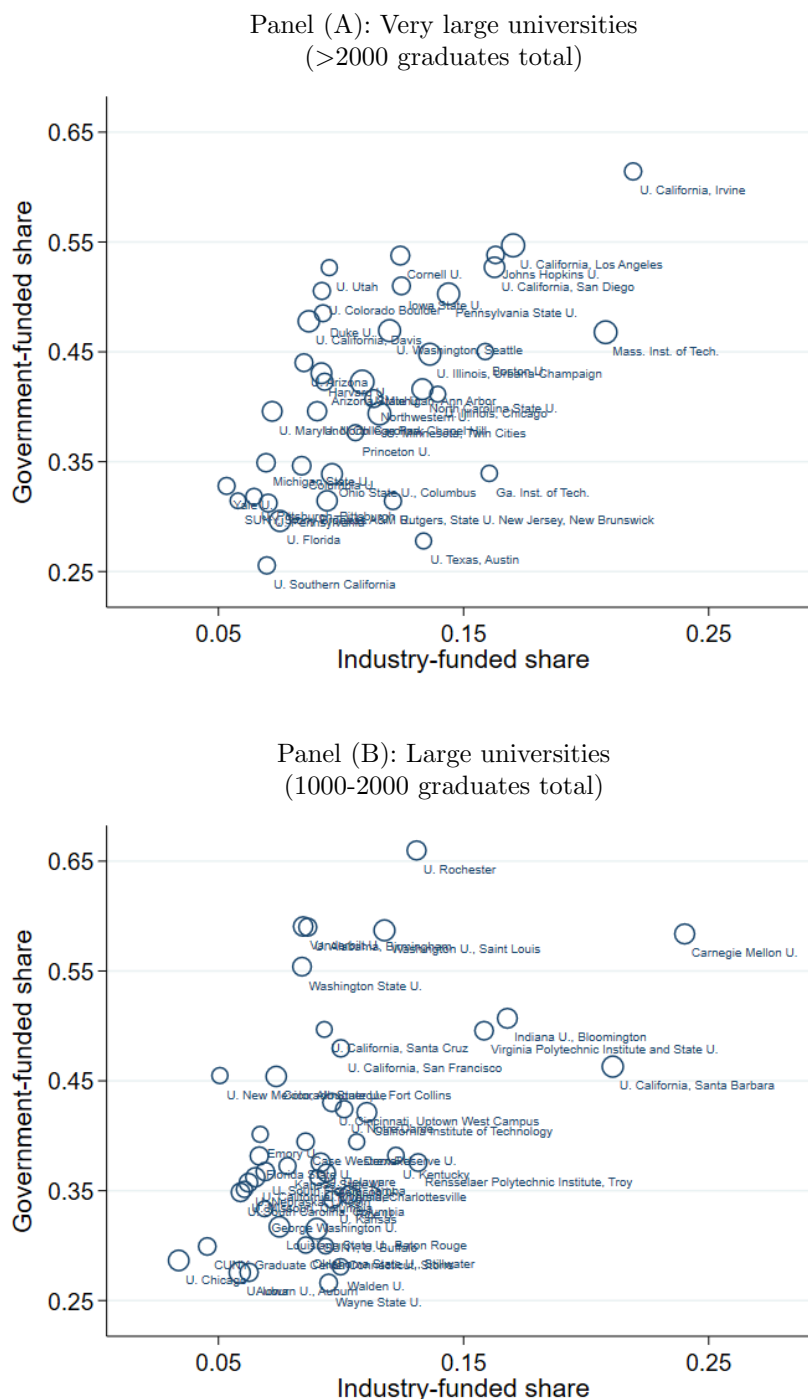
Here we explore differences across detailed subjects and across universities in sources of support. Figure B.5 plots the share of PhD graduates between 2000 and 2022 in specific subjects with government and industry support, associating graduates to subjects based on self-reported information in the PQDT data (see Appendix A). To improve readability, we split the sample into very large subjects (with >1200 graduates in this period; Panel A) and large subjects (400-1200 graduates; Panel B), omitting smaller subjects. Appendix Figure B.6 provides similar figure for universities, plotting the share of PhD graduates between 2000 and 2022 in each university with government and industry support. We similarly split the sample into very large universities (with >2000 graduates in this period; Panel A) and large universities (1000-2000 graduates; Panel B), omitting smaller universities. Both figures provide evidence of substantial cross-sectional heterogeneity, which may be interesting leads for follow-on work, while also highlighting that the U.S. government is the larger sponsor of PhD training across nearly all subjects and universities.

Figure B.5: Share of graduates reporting government vs. industry support, by subject, 2000-2022



Notes: Figure plots the share of graduates in a given subject reporting government support against the share reporting industry support. Panel (A) does so for subjects with >1200 graduates between 2000 and 2022, and Panel (B) for subjects with 400 to 1200 graduates. Marker size proportional to subjects' number of graduates.

Figure B.6: Share of graduates reporting government vs. industry support, by university, 2000-2022



Notes: Figure plots the share of graduates from a given university reporting government support against the share reporting industry support. Panel (A) does so for universities with >2000 graduates between 2000 and 2022, and Panel (B) for universities with 1000 to 2000 graduates. Marker size proportional to universities' number of graduates.

In Table B.4 we more systematically examine this visual correlation in government, industry, and

non-profit rates of support. We produce a battery of regressions relating the government-supported share of graduates and the industry- and nonprofit-supported share at different levels of aggregation and with different assortments of fixed effects. Concretely, we estimate:

$$PctGovernment_{it} = \beta_1 \cdot PctIndustry_{it} + \beta_2 \cdot PctNonprofit_{it} + \alpha_i + \delta_t + \varepsilon_{it} \quad (B.1)$$

and variants thereof, with  $i$  indexing universities or fields (or  $ij$  indexing university-fields) and  $t$  indexing years, and the remaining parameters representing fixed effects. We find large and relatively precise correlations in support rates across sectors, with magnitudes that reflect the relative size of each sector as seen in Figure 4 above. The evidence suggests that the PhD education funding system in the U.S. is more concentrated than diversified, with sponsors from all sectors focusing on the same universities, fields, and ultimately students.

Table B.4: Correlation of share of graduates who have govt. support with share who have industry or non-profit support, 2000-2022; estimated across various units of analysis

| Panel (A): Estimated at the university-field and university-year level |                     |                     |                     |                       |                     |                     |                     |                     |
|------------------------------------------------------------------------|---------------------|---------------------|---------------------|-----------------------|---------------------|---------------------|---------------------|---------------------|
|                                                                        | (1)                 | University-field    |                     | (4)                   | (5)                 | University-year     |                     | (8)                 |
|                                                                        |                     | (2)                 | (3)                 |                       |                     | (6)                 | (7)                 |                     |
| Industry-funded share                                                  | 0.373***<br>(0.046) | 0.218***<br>(0.048) | 0.227***<br>(0.056) | 0.131**<br>(0.053)    | 0.461***<br>(0.028) | 0.229***<br>(0.026) | 0.486***<br>(0.028) | 0.244***<br>(0.026) |
| Nonprof-funded share                                                   | 0.729***<br>(0.035) | 0.637***<br>(0.030) | 0.890***<br>(0.043) | 0.763***<br>(0.039)   | 0.705***<br>(0.019) | 0.471***<br>(0.022) | 0.696***<br>(0.019) | 0.454***<br>(0.021) |
| N                                                                      | 4055                | 4043                | 4055                | 4043                  | 6251                | 6241                | 6251                | 6241                |
| $R^2$                                                                  | 0.33                | 0.60                | 0.49                | 0.72                  | 0.33                | 0.73                | 0.35                | 0.75                |
| Univ. FEs                                                              |                     | Y                   |                     | Y                     |                     | Y                   |                     | Y                   |
| Field FEs                                                              |                     |                     | Y                   | Y                     |                     |                     |                     |                     |
| Year FEs                                                               |                     |                     |                     |                       |                     |                     | Y                   | Y                   |
| Panel (B): Estimated at the university-field-year level                |                     |                     |                     |                       |                     |                     |                     |                     |
|                                                                        | (1)                 | (2)                 | (3)                 | University-field-year |                     | (6)                 | (7)                 | (8)                 |
|                                                                        |                     |                     |                     | (4)                   | (5)                 |                     |                     |                     |
| Industry-funded share                                                  | 0.220***<br>(0.008) | 0.141***<br>(0.008) | 0.204***<br>(0.008) | 0.222***<br>(0.008)   | 0.140***<br>(0.008) | 0.141***<br>(0.008) | 0.209***<br>(0.008) | 0.143***<br>(0.008) |
| Nonprof-funded share                                                   | 0.541***<br>(0.008) | 0.452***<br>(0.007) | 0.545***<br>(0.008) | 0.540***<br>(0.008)   | 0.422***<br>(0.007) | 0.450***<br>(0.007) | 0.540***<br>(0.008) | 0.416***<br>(0.007) |
| N                                                                      | 56006               | 55997               | 56006               | 56006                 | 55997               | 55997               | 56006               | 55997               |
| $R^2$                                                                  | 0.16                | 0.30                | 0.23                | 0.16                  | 0.35                | 0.30                | 0.23                | 0.36                |
| Univ. FEs                                                              |                     | Y                   |                     |                       | Y                   | Y                   |                     | Y                   |
| Field FEs                                                              |                     |                     | Y                   |                       | Y                   |                     | Y                   | Y                   |
| Year FEs                                                               |                     |                     |                     | Y                     |                     | Y                   | Y                   | Y                   |

Notes: Table estimates the correlation of government support rates against industry and non-profit support rates at the university-field and -year levels (Panel A) and the university-field-year level (Panel B). Each column controls for alternative sets of fixed effects, and the estimation period in all columns is 2000-2022. \*, \*\*, \*\*\* represent significance at the 0.1, 0.05, and 0.01 levels, respectively. Robust SEs in parentheses.



## B.5 Support rates adjusted for potential underreporting

One challenge to using dissertations to measure PhD graduates’ sources of support is the risk of underreporting, which we conjecture is more likely inadvertent than deliberate. Insofar as such omissions are as good as random, correlational results are unlikely to be affected, but the raw data will underestimate true rates of support from different organizations.

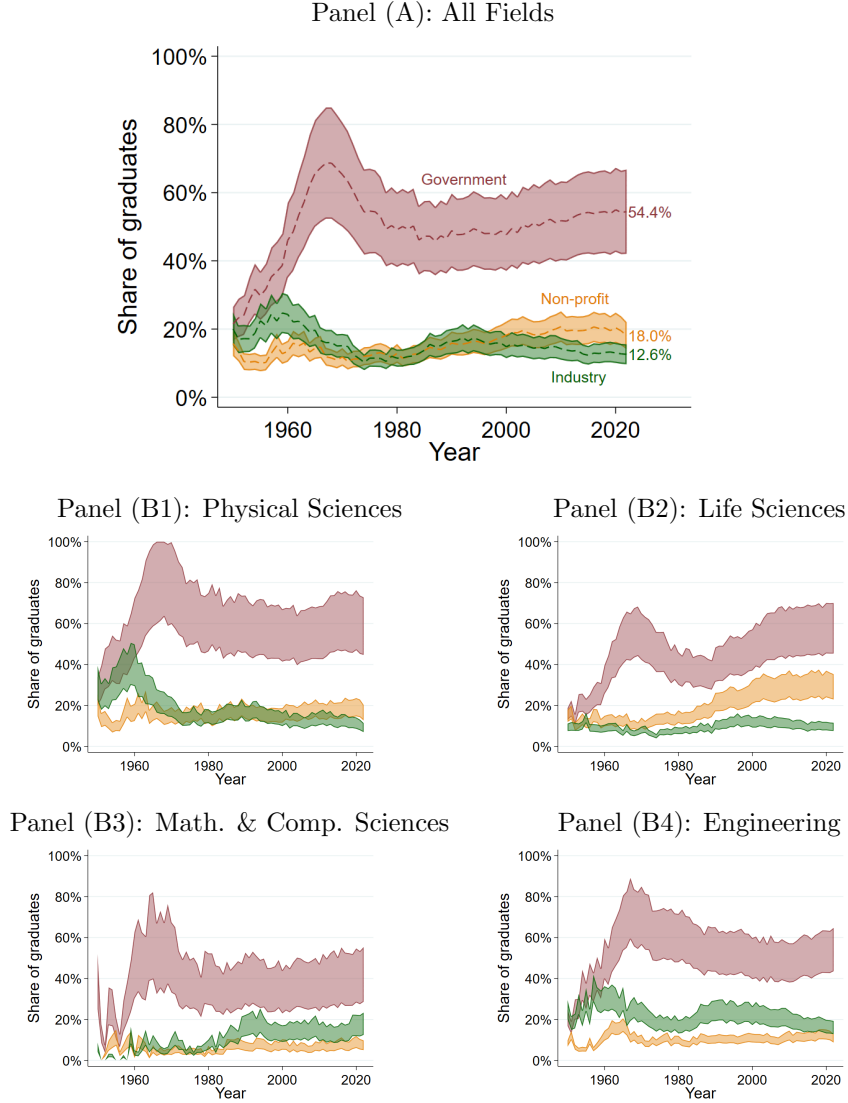
One approach to correct for underreporting is to reweight the sample to produce representative measures. We use our NSF GRFP validation data to estimate the likelihood of accurate reporting as a function of observables. More concretely, we run a probit regression of whether a GRFP awardee reports NSF support in their dissertation on degree field fixed effects, and use the results to estimate the likelihood of an accurate report.<sup>12</sup> We use these probabilities to calculate inverse propensity weights (IPW), which we can apply to our data to overweight low propensity-to-report groups (and underweight others)—similar to how survey weights are used to attempt to make non-representative survey results reflect the underlying population. Though re-weighting is imperfect and second-best to accurate reports, it helps us put an upper bound on latent values.

Figures B.7 to B.9 and Table B.5 reproduce results from similar charts and tables in the paper using IPW-weighted shares of graduates with government, industry, and non-profit support. Of these, Figure B.7 is in our view the key figure, adapting Figure 4 of the paper to show both raw and IPW-weighted shares of graduates with each source of support over time as lower and upper bounds, and the midpoint between them (dashed line). Figures B.10 and B.11 provide IPW-weighted shares of graduates with support from specific federal agencies.

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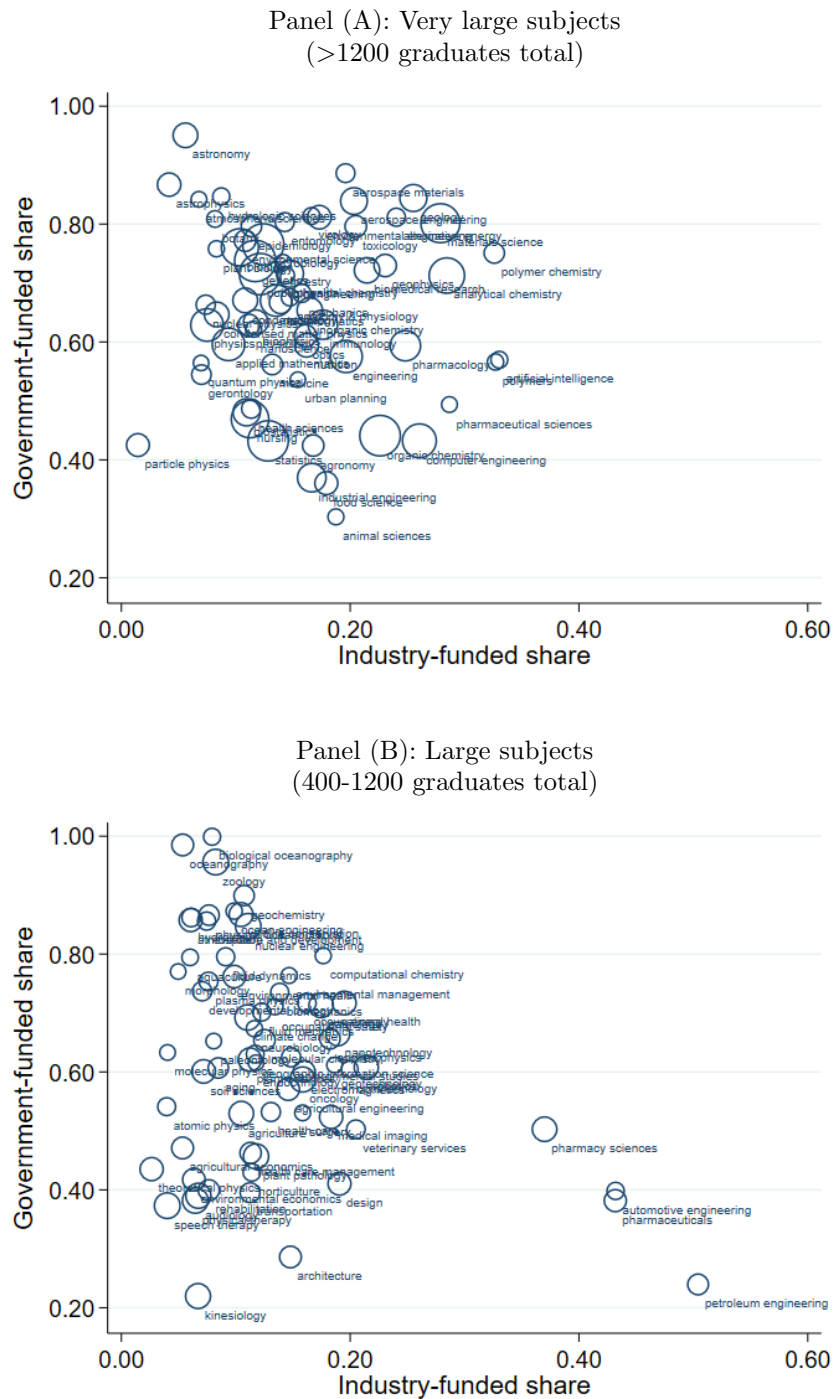
<sup>12</sup>This propensity specification was selected after evaluating a range of alternatives. Some predictors which we could in principle include, like university fixed effects, are too sparse to use in propensity estimation because they would create an incidental parameters problem (e.g., for small institutions). Others, like decade fixed effects, have large standard errors and are thus prone to misdirecting the reweighting.

Figure B.7: Bounds on share of PhD graduates supported over time, 1950-2022



Notes: Figure shows the share of PhD graduates reporting their sources of support who are supported by (i) U.S. federal government agencies, (ii) firms, and (iii) non-profit organizations, from 1950 to 2022. Shaded area demarcates lower and upper bounds, where lower bounds are shares observed in the raw data and upper bounds use inverse propensity weighting to account for underreporting; dotted lines mark the midpoint between bounds. Panel (A) presents overall results. Panels (B1) to (B4) present results by broad field (physical sciences, life sciences, mathematical and computer sciences, and engineering). Sample restricted to dissertations with acknowledgments (>98% of all dissertations).

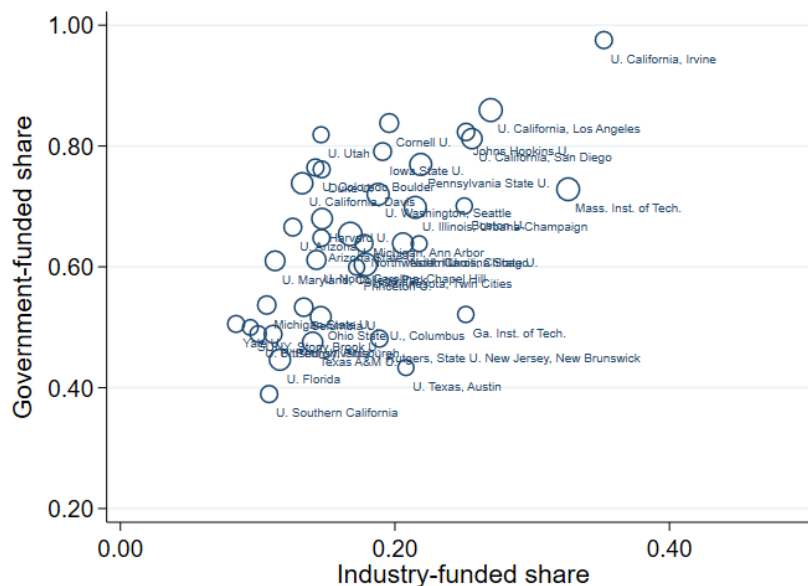
Figure B.8: Share of graduates with government vs. industry support, by subject, 2000-2022; estimated with inverse propensity weighting to account for underreporting



Notes: Figure plots the share of graduates in a given subject with government support against the share with industry support. Panel (A) does so for subjects with >1200 graduates between 2000 and 2022, and Panel (B) for subjects with 400 to 1200 graduates. Marker size proportional to subjects' number of graduates. Population shares calculated using inverse propensity weights to account for potential underreporting.

Figure B.9: Share of graduates with government vs. industry support, by university, 2000-2022; estimated with inverse propensity weighting to account for underreporting

Panel (A): Very large universities  
( $>2000$  graduates total)

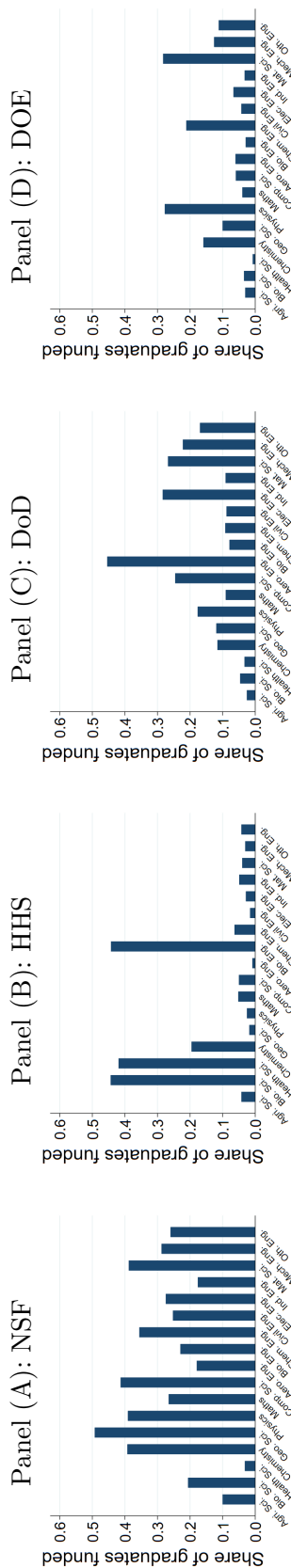


Panel (B): Large universities  
(1000-2000 graduates total)



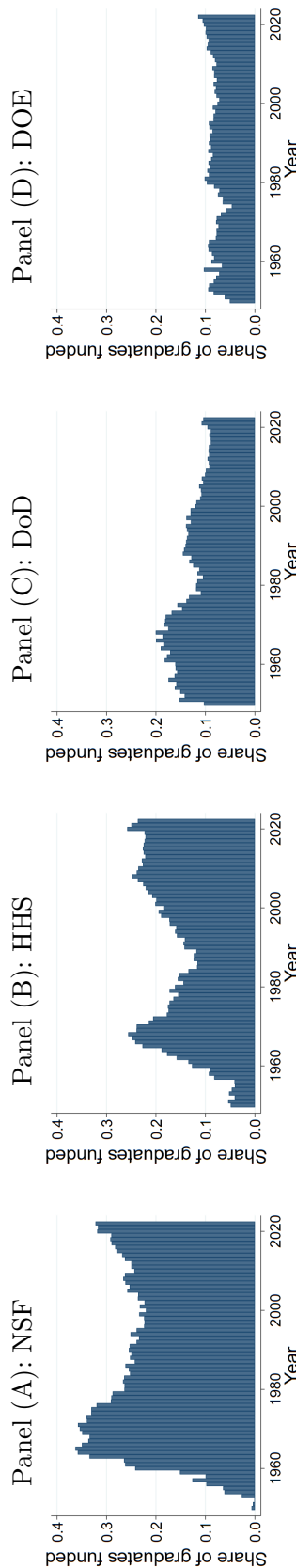
Notes: Figure plots the share of graduates from a given university with government support against the share with industry support. Panel (A) does so for universities with >2000 graduates between 2000 and 2022, and Panel (B) for universities with 1000 to 2000 graduates. Marker size proportional to universities' number of graduates. Population shares calculated using inverse propensity weights to account for potential underreporting.

Figure B.10: Major fields' share of graduates supported by select federal agencies, 1950-2022; estimated with inverse propensity weighting to account for underreporting



Notes: Figure shows the share of PhD graduates in individual major fields supported by each agency listed (NSF, HHS, DoD, DOE), illustrating differences in subject matter priorities across agencies. Population shares calculated using inverse propensity weights to account for potential underreporting.

Figure B.11: Share of all graduates supported by select federal agencies over time, 1950-2022; estimated with inverse propensity weighting to account for underreporting



Notes: Figure shows the share of PhD graduates supported over time by each agency listed (NSF, HHS, DoD, DOE), illustrating long-run changes in these agencies' investments in PhD training. Population shares calculated using inverse propensity weights to account for potential underreporting.

Table B.5: Correlation of share of graduates who have govt. support with share who have industry or non-profit support, 2000-2022; estimated across various units of analysis and estimated with inverse propensity weighting to account for underreporting

| Panel (A): Estimated at the university-field and university-year level |                     |                     |                       |                     |                     |                     |                     |                     |
|------------------------------------------------------------------------|---------------------|---------------------|-----------------------|---------------------|---------------------|---------------------|---------------------|---------------------|
|                                                                        | (1)                 | University-field    |                       |                     |                     | University-year     |                     | (8)                 |
|                                                                        |                     | (2)                 | (3)                   | (4)                 | (5)                 | (6)                 | (7)                 |                     |
| Industry-funded share                                                  | 0.373***<br>(0.046) | 0.218***<br>(0.048) | 0.227***<br>(0.056)   | 0.131**<br>(0.053)  | 0.461***<br>(0.028) | 0.229***<br>(0.026) | 0.486***<br>(0.028) | 0.244***<br>(0.026) |
| Nonprof-funded share                                                   | 0.729***<br>(0.035) | 0.637***<br>(0.030) | 0.890***<br>(0.043)   | 0.763***<br>(0.039) | 0.705***<br>(0.019) | 0.471***<br>(0.022) | 0.696***<br>(0.019) | 0.454***<br>(0.021) |
| N                                                                      | 4055                | 4043                | 4055                  | 4043                | 6251                | 6241                | 6251                | 6241                |
| $R^2$                                                                  | 0.33                | 0.60                | 0.49                  | 0.72                | 0.33                | 0.73                | 0.35                | 0.75                |
| Univ. FEs                                                              |                     | Y                   |                       | Y                   |                     | Y                   |                     | Y                   |
| Field FEs                                                              |                     |                     | Y                     | Y                   |                     |                     |                     |                     |
| Year FEs                                                               |                     |                     |                       |                     |                     |                     | Y                   | Y                   |
| Panel (B): Estimated at the university-field-year level                |                     |                     |                       |                     |                     |                     |                     |                     |
|                                                                        | (1)                 | (2)                 | University-field-year |                     |                     | (6)                 | (7)                 | (8)                 |
|                                                                        |                     |                     | (3)                   | (4)                 | (5)                 |                     |                     |                     |
| Industry-funded share                                                  | 0.220***<br>(0.008) | 0.141***<br>(0.008) | 0.204***<br>(0.008)   | 0.222***<br>(0.008) | 0.140***<br>(0.008) | 0.141***<br>(0.008) | 0.209***<br>(0.008) | 0.143***<br>(0.008) |
| Nonprof-funded share                                                   | 0.541***<br>(0.008) | 0.452***<br>(0.007) | 0.545***<br>(0.008)   | 0.540***<br>(0.008) | 0.422***<br>(0.007) | 0.450***<br>(0.007) | 0.540***<br>(0.008) | 0.416***<br>(0.007) |
| N                                                                      | 56006               | 55997               | 56006                 | 56006               | 55997               | 55997               | 56006               | 55997               |
| $R^2$                                                                  | 0.16                | 0.30                | 0.23                  | 0.16                | 0.35                | 0.30                | 0.23                | 0.36                |
| Univ. FEs                                                              |                     | Y                   |                       |                     | Y                   | Y                   |                     | Y                   |
| Field FEs                                                              |                     |                     | Y                     |                     | Y                   |                     | Y                   | Y                   |
| Year FEs                                                               |                     |                     |                       | Y                   |                     | Y                   | Y                   | Y                   |

Notes: Table estimates the correlation of government support rates against industry and non-profit support rates at the university-field and -year levels (Panel A) and the university-field-year level (Panel B). Each column controls for alternative sets of fixed effects, and the estimation period in all columns is 2000-2022. Population shares calculated using inverse propensity weights to account for potential underreporting. \*, \*\*, \*\*\* represent significance at the 0.1, 0.05, and 0.01 levels, respectively. Robust SEs in parentheses.

## B.6 Top universities in critical technologies, using data through 2012 only

Tables 3 and 4 of the paper list the top universities in specific technology areas by number of graduates produced post-2000. One limitation of this accounting, however, is that for a small number of schools—including some potentially important schools—we have limited data from the mid-2010s onwards (e.g., Georgia Tech exits the PQDT sample after 2012, and Virginia Tech after 2016). These schools are thus undercounted in more recent years.

The systematic patterns in our paper (such as the overall distribution of support, or regression estimates of its relationship to PhD production) are unaffected by this attrition, given that it is relatively modest. However, tables that rank individual universities (e.g., in their training of PhDs related to specific technologies) may see their specific contents affected: schools that exit the sample early may be omitted from these lists merely due to this attrition.

In order to evaluate how this sample melt affects our university rankings, in Tables B.6 and B.7 we reproduce these tables for 2000-2012 only. Though this is an imperfect comparison—measuring PhD production through 2012 in technology areas which were considered critical or emerging over a decade later in 2024—it can mitigate the impacts of attrition on our findings. The results are similar to what was found for the full 2000-2022 sample.

Table B.6: Top 5 universities and sponsors of PhD graduates in U.S. critical technology areas, 2000-2012

| Advanced Computing                  |       |             |        |        | Advanced Manufacturing              |       |             |        |       |
|-------------------------------------|-------|-------------|--------|--------|-------------------------------------|-------|-------------|--------|-------|
| Top universities                    |       | Top funders |        |        | Top universities                    |       | Top funders |        |       |
| University                          | Count | Name        | Sector | Count  | University                          | Count | Name        | Sector | Count |
| Mass. Inst. of Tech.                | 915   | NSF         | Govt   | 5,240  | Mass. Inst. of Tech.                | 247   | NSF         | Govt   | 1,366 |
| Ga. Inst. of Tech.                  | 897   | DoD         | Govt   | 3,405  | U. California, Berkeley             | 241   | DoD         | Govt   | 851   |
| Stanford U.                         | 885   | HHS         | Govt   | 1,417  | Ga. Inst. of Tech.                  | 240   | DOE         | Govt   | 462   |
| U. Illinois, Urbana-Champaign       | 809   | DOE         | Govt   | 1,105  | U. Michigan, Ann Arbor              | 212   | HHS         | Govt   | 169   |
| U. California, Berkeley             | 738   | NASA        | Govt   | 959    | U. Illinois, Urbana-Champaign       | 197   | NASA        | Govt   | 151   |
| Advanced Materials                  |       |             |        |        | Autonomous Systems                  |       |             |        |       |
| Top universities                    |       | Top funders |        |        | Top universities                    |       | Top funders |        |       |
| University                          | Count | Name        | Sector | Count  | University                          | Count | Name        | Sector | Count |
| Ga. Inst. of Tech.                  | 865   | NSF         | Govt   | 6,908  | Carnegie Mellon U.                  | 143   | DoD         | Govt   | 547   |
| Mass. Inst. of Tech.                | 861   | DoD         | Govt   | 4,051  | Mass. Inst. of Tech.                | 141   | NSF         | Govt   | 434   |
| U. Illinois, Urbana-Champaign       | 824   | DOE         | Govt   | 3,867  | Stanford U.                         | 108   | NASA        | Govt   | 223   |
| Pennsylvania State U.               | 780   | HHS         | Govt   | 989    | Ga. Inst. of Tech.                  | 106   | HHS         | Govt   | 58    |
| U. Florida                          | 732   | NASA        | Govt   | 859    | U. California, Berkeley             | 75    | DOT         | Govt   | 53    |
| Biotechnology                       |       |             |        |        | Clean Energy Generation and Storage |       |             |        |       |
| Top universities                    |       | Top funders |        |        | Top universities                    |       | Top funders |        |       |
| University                          | Count | Name        | Sector | Count  | University                          | Count | Name        | Sector | Count |
| U. Wisconsin-Madison                | 1,181 | HHS         | Govt   | 12,545 | U. California, Berkeley             | 200   | DOE         | Govt   | 1,331 |
| U. California, Berkeley             | 1,107 | NSF         | Govt   | 7,650  | Mass. Inst. of Tech.                | 182   | NSF         | Govt   | 983   |
| Mass. Inst. of Tech.                | 1,021 | DoD         | Govt   | 2,113  | Ga. Inst. of Tech.                  | 175   | DoD         | Govt   | 526   |
| Johns Hopkins U.                    | 1,016 | DOE         | Govt   | 1,869  | Pennsylvania State U.               | 150   | NASA        | Govt   | 133   |
| Stanford U.                         | 1,009 | USDA        | Govt   | 1,662  | Texas A&M U.                        | 138   | USDA        | Govt   | 122   |
| Communications and Networking       |       |             |        |        | Data Privacy and Cybersecurity      |       |             |        |       |
| Top universities                    |       | Top funders |        |        | Top universities                    |       | Top funders |        |       |
| University                          | Count | Name        | Sector | Count  | University                          | Count | Name        | Sector | Count |
| Ga. Inst. of Tech.                  | 360   | NSF         | Govt   | 1,298  | Ga. Inst. of Tech.                  | 55    | NSF         | Govt   | 366   |
| U. California, Los Angeles          | 331   | DoD         | Govt   | 1,065  | Purdue U., West Lafayette           | 55    | DoD         | Govt   | 247   |
| Stanford U.                         | 303   | Intel       | Firm   | 226    | U. Maryland, College Park           | 47    | IBM         | Firm   | 47    |
| U. Southern California              | 236   | NASA        | Govt   | 196    | U. California, Berkeley             | 45    | Intel       | Firm   | 45    |
| U. California, Berkeley             | 224   | IBM         | Firm   | 136    | Mass. Inst. of Tech.                | 44    | Microsoft   | Firm   | 39    |
| Microelectronics and Semiconductors |       |             |        |        | Networked Sensing                   |       |             |        |       |
| Top universities                    |       | Top funders |        |        | Top universities                    |       | Top funders |        |       |
| University                          | Count | Name        | Sector | Count  | University                          | Count | Name        | Sector | Count |
| Stanford U.                         | 754   | NSF         | Govt   | 3,790  | Stanford U.                         | 301   | NSF         | Govt   | 1,927 |
| U. California, Berkeley             | 731   | DoD         | Govt   | 2,671  | Mass. Inst. of Tech.                | 288   | DoD         | Govt   | 1,672 |
| Ga. Inst. of Tech.                  | 682   | DOE         | Govt   | 1,633  | Ga. Inst. of Tech.                  | 278   | NASA        | Govt   | 1,047 |
| Mass. Inst. of Tech.                | 596   | Intel       | Firm   | 612    | U. California, Berkeley             | 255   | DOE         | Govt   | 525   |
| U. Illinois, Urbana-Champaign       | 586   | NASA        | Govt   | 427    | U. Michigan, Ann Arbor              | 248   | DOC         | Govt   | 325   |
| Quantum Science                     |       |             |        |        | Space Technology                    |       |             |        |       |
| Top universities                    |       | Top funders |        |        | Top universities                    |       | Top funders |        |       |
| University                          | Count | Name        | Sector | Count  | University                          | Count | Name        | Sector | Count |
| Mass. Inst. of Tech.                | 183   | NSF         | Govt   | 830    | U. Colorado Boulder                 | 127   | NASA        | Govt   | 1,297 |
| Stanford U.                         | 173   | DoD         | Govt   | 515    | U. Michigan, Ann Arbor              | 120   | NSF         | Govt   | 503   |
| U. Illinois, Urbana-Champaign       | 157   | DOE         | Govt   | 378    | Mass. Inst. of Tech.                | 116   | DoD         | Govt   | 439   |
| U. California, Berkeley             | 140   | HHS         | Govt   | 78     | Stanford U.                         | 110   | DOT         | Govt   | 244   |
| Harvard U.                          | 115   | NASA        | Govt   | 78     | U. Maryland, College Park           | 92    | DOE         | Govt   | 148   |

Notes: Table lists the top 5 universities and sponsors of graduates between 2000 and 2012 in the 12 largest OSTP critical technology areas. Graduates allocated to technology areas as described in text.

Table B.7: Top 15 universities and sponsors of PhD graduates in AI, 2000-2012

| Top universities              |       | Top funders                |        |       |
|-------------------------------|-------|----------------------------|--------|-------|
| University                    | Count | Name                       | Sector | Count |
| Carnegie Mellon U.            | 296   | NSF                        | Govt   | 1,280 |
| Mass. Inst. of Tech.          | 284   | DoD                        | Govt   | 1,003 |
| Ga. Inst. of Tech.            | 240   | HHS                        | Govt   | 455   |
| U. Illinois, Urbana-Champaign | 204   | NASA                       | Govt   | 227   |
| Stanford U.                   | 190   | DOE                        | Govt   | 173   |
| U. California, Berkeley       | 179   | IBM                        | Firm   | 103   |
| U. Southern California        | 176   | Microsoft                  | Firm   | 90    |
| U. Maryland, College Park     | 163   | DOC                        | Govt   | 87    |
| U. Washington, Seattle        | 136   | Google                     | Firm   | 71    |
| Purdue U., West Lafayette     | 123   | Intel                      | Firm   | 66    |
| U. Florida                    | 123   | DOT                        | Govt   | 63    |
| U. California, Los Angeles    | 118   | USDA                       | Govt   | 43    |
| Ohio State U., Columbus       | 112   | DOEd                       | Govt   | 42    |
| Pennsylvania State U.         | 112   | Boeing                     | Firm   | 39    |
| Columbia U.                   | 108   | Department of the Interior | Govt   | 39    |

Notes: Table lists the top 15 universities and sponsors of graduates between 2000 and 2012 in artificial intelligence (AI). Graduates identified as AI-related based on critical technology assessment (see Section 3).

## B.7 Regression results: robustness checks

This appendix presents robustness checks on Table 5: a scale-versus-allocation decomposition of the instrument (Table B.8), estimates on the stable-university sample (Table B.9), estimates excluding the four most technology-exposed fields (Table B.10), and a leave-one-field-out jackknife (Figure B.12). The outcome throughout is total PhD production, and the reported coefficient is the elasticity  $\beta$  of Equation (1); robust standard errors (SEs) are reported at the field-year level and SEs clustered by university at the university-field-year level.

### B.7.1 Scale-versus-allocation decomposition

Even with leave-one-out shifters and field, year, and field-by-year fixed effects, the instrument can move a field for two distinguishable reasons that rest on different identifying assumptions. Write the (log) shift-share instrument as  $Z_{it} = \sum_a \omega_{ia} \ln(g_{at}^{-i})$ , where  $\omega_{ia}$  is field  $i$ 's base-period share of agency  $a$ 's graduates and  $g_{at}^{-i}$  is agency  $a$ 's (leave-one-out, excluding field  $i$ ) supported-graduate count in year  $t$ . Letting  $G_t^{-i} = \sum_a g_{at}^{-i}$  denote total government support (for all fields other than  $i$ ) and  $W_i = \sum_a \omega_{ia}$  field  $i$ 's summed exposure weights across agencies, adding and subtracting  $\ln(G_t^{-i})$  to and from  $g_{at}^{-i}$  yields the following decomposition identity:

$$\begin{aligned}
Z_{it} &= \sum_a \omega_{ia} (\ln(g_{at}^{-i}) + \ln(G_t^{-i}) - \ln(G_t^{-i})) \\
&= \sum_a \omega_{ia} \ln(G_t^{-i}) + \sum_a \omega_{ia} \ln(g_{at}^{-i}/G_t^{-i}) \\
&= \underbrace{W_i \ln(G_t^{-i})}_{\text{scale}} + \underbrace{\sum_a \omega_{ia} \ln(g_{at}^{-i}/G_t^{-i})}_{\text{allocation}}
\end{aligned}$$



These two terms (*scale* and *allocation*) represent different sources of variation in the instrument  $Z_{it}$ . In the *scale* term,  $G_t^{-i}$  is the total number of government-supported graduates in year  $t$  (omitting field  $i$ ), representing the total scale of government support in a given year (minus field  $i$ , to avoid a mechanical relationship). Fields with a large total footprint across agencies ( $W_i$ ) will be proportionally more exposed to the broader, government-wide rising or falling tide: as government-wide R&D ebbs and flows, fields which are large recipients of federal support across agencies will be the most exposed to these fluctuations. This is what the scale factor represents. The *allocation* term, on the other hand, is based on each agency’s share of government-supported graduates in a given year, and varies when the particular agencies a field relies on (per  $\omega_{ia}$ ) grow or shrink relative to others. For example, if NIH’s budget doubles (as in the early 2000s), biomedicine (a large  $\omega_{ia}$  field when  $a = \text{NIH}$ ) will be more exposed to this increase; if it declines by 40% (as was recently proposed), it would be more exposed to this decrease.

Our main goal in separating these components is to limit the influence of fields’ government-wide weight on our analysis, isolating the instrumental variation to the allocative channel. Table B.8 re-estimates Equation (1) using the allocative component as the instrument, and again using the full instrument while controlling for the scale component. For parsimony we present results for the static 1960-69 base year shift-share instrument only. Columns (1) and (4) (labeled “Full”) reproduce the 2SLS estimate in Table 5, Columns (2) and (5) (“Realloc.”) identify  $\beta$  off allocative variation only, and Columns (3) and (6) (“Scale ctrl”) use the full instrument while controlling for the scale component. The relationship remains large and significant when estimated from the allocative variation alone and is consistently around 0.8-0.9 across variants, indicating that it is not an artifact of differential exposure to government-wide fluctuations.

Table B.8: Scale-versus-allocation decomposition of the shift-share instrument

|                        | Field-year          |                     |                     | University-field-year |                     |                     |
|------------------------|---------------------|---------------------|---------------------|-----------------------|---------------------|---------------------|
|                        | (1)                 | (2)                 | (3)                 | (4)                   | (5)                 | (6)                 |
|                        | Full                | Realloc.            | Scale ctrl          | Full                  | Realloc.            | Scale ctrl          |
| Ln(USG-supported PhDs) | 0.993***<br>(0.070) | 0.895***<br>(0.037) | 0.874***<br>(0.041) | 0.781***<br>(0.016)   | 0.783***<br>(0.021) | 0.793***<br>(0.062) |
| N                      | 731                 | 731                 | 731                 | 63954                 | 63954               | 63954               |
| F-stat                 | 38.00               | 55.73               | 47.43               | 120.08                | 136.39              | 27.94               |
| Field FEs              | Y                   | Y                   | Y                   |                       |                     |                     |
| Univ-Field FEs         |                     |                     |                     | Y                     | Y                   | Y                   |
| Year FEs               | Y                   | Y                   | Y                   | Y                     | Y                   | Y                   |
| Controls               | Y                   | Y                   | Y                   | Y                     | Y                   | Y                   |
| Sample                 | 1980+               | 1980+               | 1980+               | 1980+                 | 1980+               | 1980+               |
| Instrument             | 1960-69             | 1960-69             | 1960-69             | 1960-69               | 1960-69             | 1960-69             |

Notes: Table decomposes the shift-share instrument for government-supported PhD graduates into a scale component (a field’s predetermined exposure to federal support x the common movement in agency support) and an allocative component (the residual), evaluating this decomposition for the static 1960-69 base year shift-share instrument. Columns (1) to (3) do so at the field-year level, and Columns (4) to (6) at the university-field-year level. Columns labeled “Full” estimate Equation (1) using the full instrument; “Realloc.”, using only the allocative component; and “Scale ctrl”, using the full instrument while controlling for the scale component. First-stage  $F$ -statistics reported in all columns. \*, \*\*, \*\*\* represent significance at the 0.1, 0.05, and 0.01 levels, respectively. Heteroskedasticity-robust SEs in parentheses in Columns (1) to (3) and clustered by university in Columns (4) to (6).

### B.7.2 Stable university sample

Table B.9 re-estimates Table 5 of the paper on field-year and university-field-year samples constructed solely from universities present in PQDT in all years of our study period. The results remain quantitatively and statistically similar to those in Table 5.

Table B.9: Relationship of PhD production to government-supported graduates, 1970-2022, estimated on a sample of universities present in PQDT throughout the study period

|                        | Field-year          |                     |                     |                     | University-field-year |                     |                     |                     |
|------------------------|---------------------|---------------------|---------------------|---------------------|-----------------------|---------------------|---------------------|---------------------|
|                        | (1)                 | (2)                 | (3)                 | (4)                 | (5)                   | (6)                 | (7)                 | (8)                 |
|                        | OLS                 | 2SLS                | 2SLS                | 2SLS                | OLS                   | 2SLS                | 2SLS                | 2SLS                |
| Ln(USG-supported PhDs) | 0.844***<br>(0.018) | 0.983***<br>(0.036) | 1.135***<br>(0.097) | 1.035***<br>(0.071) | 0.698***<br>(0.009)   | 1.101***<br>(0.028) | 1.138***<br>(0.045) | 0.771***<br>(0.016) |
| N                      | 900                 | 900                 | 900                 | 730                 | 65179                 | 65179               | 65179               | 59152               |
| F-stat                 |                     | 64.50               | 27.27               | 39.16               |                       | 105.07              | 78.51               | 124.27              |
| Field FEs              | Y                   | Y                   | Y                   | Y                   |                       |                     |                     |                     |
| Univ-Field FEs         |                     |                     |                     |                     | Y                     | Y                   | Y                   | Y                   |
| Year FEs               | Y                   | Y                   | Y                   | Y                   | Y                     | Y                   | Y                   | Y                   |
| Controls               | Y                   | Y                   | Y                   | Y                   | Y                     | Y                   | Y                   | Y                   |
| Sample                 | 1970+               | 1970+               | 1970+               | 1980+               | 1970+                 | 1970+               | 1970+               | 1980+               |
| Instrument             |                     | Roll/6-10           | Roll/11-15          | 1960-69             |                       | Roll/6-10           | Roll/11-15          | 1960-69             |

Notes: Table reproduces Table 5 of the paper, estimating the relationship of annual PhD production by university, field, and year to government-supported PhD graduates, restricting the sample to universities present in PQDT in all years of our study period. Columns (1) to (4) do so at the field-year level, and Columns (5) to (8) at the university-field-year level. Columns (1) and (5) estimate Equation (1) by OLS, and the remaining columns by 2SLS, using the Roll/6-10, Roll/11-15, and static 1960-69 instruments (see Table 5 for definitions). Columns (1) to (4) additionally control for broad field x year fixed effects, and Columns (5) to (8) narrow field x year fixed effects, to absorb national trends in PhD production by field. First-stage  $F$ -statistics reported for the 2SLS columns. \*, \*\*, \*\*\* represent significance at the 0.1, 0.05, and 0.01 levels, respectively. Heteroskedasticity-robust SEs in parentheses in Columns (1) to (4) and clustered by university in Columns (5) to (8).

### B.7.3 Excluding the most technology-exposed fields

Table B.10 re-estimates Table 5 of the paper, excluding four fields which are most closely related to downstream technology and potential technology-driven opportunity or demand swings (computer science, electrical engineering, biomedical engineering, and the biological sciences). These are the fields where any residual opportunity confound would ostensibly be most likely to influence our results—though recall that such a confound would have to arise *within fields*, as our regressions already control for broad or narrow field-year fixed effects that account for field-level trends. The estimates in Table B.10 are essentially unchanged from Table 5, suggesting that our results are not explained by fluctuations in opportunity or demand in these fields that might drive both enrollment trends and the direction of federal educational investments.

Table B.10: Relationship of PhD production to government-supported graduates, 1970-2022, excl. computer science, electrical engineering, biomedical engineering, and biological sciences

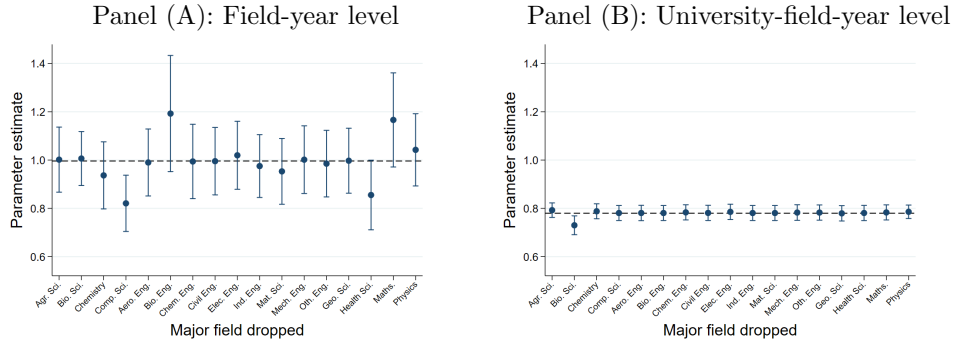
|                        | (1)                 | Field-year          |                     | (4)                 | (5)                 | University-field-year |                     |                     |
|------------------------|---------------------|---------------------|---------------------|---------------------|---------------------|-----------------------|---------------------|---------------------|
|                        | OLS                 | (2)<br>2SLS         | (3)<br>2SLS         | 2SLS                | OLS                 | (6)<br>2SLS           | (7)<br>2SLS         | (8)<br>2SLS         |
| Ln(USG-supported PhDs) | 0.835***<br>(0.025) | 0.859***<br>(0.056) | 0.879***<br>(0.073) | 0.984***<br>(0.077) | 0.695***<br>(0.009) | 1.158***<br>(0.030)   | 1.216***<br>(0.060) | 0.734***<br>(0.020) |
| N                      | 689                 | 689                 | 689                 | 559                 | 51565               | 51565                 | 51565               | 46594               |
| F-stat                 |                     | 62.81               | 55.01               | 47.65               |                     | 60.06                 | 51.20               | 89.17               |
| Field FEs              | Y                   | Y                   | Y                   | Y                   |                     |                       |                     |                     |
| Univ-Field FEs         |                     |                     |                     |                     | Y                   | Y                     | Y                   | Y                   |
| Year FEs               | Y                   | Y                   | Y                   | Y                   | Y                   | Y                     | Y                   | Y                   |
| Controls               | Y                   | Y                   | Y                   | Y                   | Y                   | Y                     | Y                   | Y                   |
| Sample                 | 1970+               | 1970+               | 1970+               | 1980+               | 1970+               | 1970+                 | 1970+               | 1980+               |
| Instrument             |                     | Roll/6-10           | Roll/11-15          | 1960-69             |                     | Roll/6-10             | Roll/11-15          | 1960-69             |

Notes: Table reproduces Table 5 of the paper, estimating the relationship of annual PhD production by university, field, and year to government-supported PhD graduates, excluding computer science, electrical engineering, biomedical engineering, and the biological sciences. Columns (1) to (4) do so at the field-year level, and Columns (5) to (8) at the university-field-year level. Columns (1) and (5) estimate Equation (1) by OLS, and the remaining columns by 2SLS, using the Roll/6-10, Roll/11-15, and static 1960-69 instruments (see Table 5 for definitions). Columns (1) to (4) additionally control for broad field x year fixed effects, and Columns (5) to (8) narrow field x year fixed effects, to absorb national trends in PhD production by field. First-stage  $F$ -statistics reported for the 2SLS columns. \*, \*\*, \*\*\* represent significance at the 0.1, 0.05, and 0.01 levels, respectively. Heteroskedasticity-robust SEs in parentheses in Columns (1) to (4) and clustered by university in Columns (5) to (8).

### B.7.4 Leave-one-field-out jackknife

Figure B.12 reproduces results from Table 5 of the paper at the field-year and university-field-year level (Panels A and B), dropping one field at a time. Estimates are based on a 2SLS estimation using static 1960-1969 base year instrument (constructed from 1960-69 shares; see text for discussion) but are similar under the other instrument variants. These jackknife results reinforce that our core elasticity estimate is not driven by any single field, including fields which might have experienced scientific opportunity or demand swings over our sample period.

Figure B.12: Leave-one-field-out jackknife of the 2SLS estimate



Notes: Figure plots the 2SLS estimate of the elasticity of total PhD production with respect to federally-supported graduates (per Table 5), re-estimated dropping each major fields one-by-one, with 95% confidence intervals. Panel (A) estimates Equation (1) the field-year level and Panel (B) at the university-field-year level, in both cases using the static 1960-1969 base year shift-share instrument. Confidence intervals based on heteroskedasticity-robust SEs at the field-year level and SEs clustered by university at the university-field-year level.

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