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Research Report

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Comparative Analysis of U.S. and PRC Efforts to Advance Critical Military Technology

Volume 1, Analytic Approach for Conducting Comparative Technology Assessments

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About This Report

U.S. lawmakers and defense policymakers need a standard set of processes and approaches for comparing efforts by the United States and the People's Republic of China (PRC) to advance critical military technologies and to understand the implications for U.S. national security. This report outlines a methodology for comparatively assessing the capacity, progress, and impact of critical military technologies under development in the U.S. and PRC. This approach is designed to be applicable across a diverse range of technologies and is leveraged to conduct comparative analyses of U.S. and PRC efforts to develop and deploy critical technologies for military use. This approach was developed to support Section 1251 of the 2022 U.S. National Defense Authorization Act, which requires U.S. and PRC comparative technology assessments of directed energy systems, hypersonics, emerging biotechnologies, quantum science, and cyberspace capabilities.

RAND National Security Research Division

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For more information on the RAND Acquisition and Technology Policy Program, see www.rand.org/nsrd/atp or contact the director (contact information is provided on the webpage).

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Summary

In this era of strategic competition between the United States and the People's Republic of China (PRC), emerging critical technologies present both countries with the possibility of disrupting the current balance of forces to achieve significant military advantages. U.S. senior defense and intelligence officials have identified several critical military technologies—such as directed energy, hypersonic systems, emerging biotechnologies, quantum science, and cyberspace capabilities—as not only being essential for national security but also possibly providing a disruptive advantage when applied across warfighting domains. These technologies are in various stages of development in both the U.S. and PRC. While some of the technologies, such as quantum science and biotechnology, appear to be only in the "seed" stages, others—such as hypersonic technologies, directed energy, and cyberspace capabilities—may be further along in transitioning to mature military capabilities that are more-readily available.

Lawmakers and defense policymakers need a standard set of processes (or a replicable methodology) for comparative assessments of the U.S. and PRC efforts to advance critical military technologies—and for assessing the implications of those efforts for U.S. national security. At the same time, understanding the complex U.S.-PRC competition underway in each critical technology area and its underlying ecosystem within each country requires the integration of diverse approaches and data sources. The outcomes of these competitions will include not just the development and deployment of military technologies within each country but also, crucial to this assessment, the underlying technological innovation and advancement that can lead to a military advantage on a battlefield. Because all these outcomes—innovation, development, and deployment—will be shaped by the interaction of technological, operational, economic, organizational, and other variables, a multidisciplinary comparative analysis is needed.

This report outlines the methodology used for comparatively assessing the capacity, progress, and impact of critical military technologies under development in the U.S. and PRC. This approach, which is designed to be applicable across a diverse range of technologies,[1,2] is

[1] The Department of Defense (DoD) has identified several critical technologies, which vary considerably. See Under Secretary of Defense for Research and Engineering, "USD(R&E) Technology Vision for an Era of Competition," U.S. Department of Defense, February 1, 2022.

[2] The approach for conducting comparative assessments described in this report, and the comparative assessments themselves, are complementary to several analytic efforts underway within OUSD(R&E) for assessing technology competition and measuring technological progress. For example, OUSD(R&E) OSI&A is conducting a multiyear series of net technical assessments (NTAs)—independent assessments of the strategic and military implications of R&E's critical technology areas for the United States, Russia, and China—with support from Federally Funded Research and Development Centers (FFRDCs) and University-Affiliated Research Centers (UARCs).

subsequently applied to directed energy systems, hypersonic systems, emerging biotechnologies, quantum science, and cyberspace capabilities.[3]

This report and the comparative technology assessments are organized into five research tasks that align with research questions about U.S. and PRC efforts to advance critical military technologies:

1. *Establishing an analytic baseline for a critical technology area.* We frame why the countries are pursuing the technology, define the technology, scope the technology, identify critical technology elements essential for transitioning technology into fully operational capabilities, and assess current statuses and trends.
2. *Assessing research and development (R&D) activities.* We refine a generic model of defense innovation, describe and quantitatively or qualitatively measure 15 elements of innovation within R&D, and compare R&D efforts and activities across the two countries in the specified technology areas.
3. *Assessing operational effectiveness.* For both countries, we define operational problems, define missions/tasks or applications for emerging technologies, assess the relationships of the technologies to the missions/tasks, and assess the operational effectiveness of a critical military technology given multiple factors and considerations.
4. *Analyzing countermeasures.* For both countries, we identify and describe current and future countermeasures, assess the use of these countermeasures, and assess their related implementation challenges and technical risks.
5. *Identifying other notable activities, uncertainties, limitations, and recommendations.* In this cross-cutting analysis of the prior tasks, we account for R&D efforts outside of the U.S. and PRC that could advance the critical military technologies, discuss the uncertainties and limitations of the prior tasks, and recommend ways to address the results of the comparative analyses.

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[3] The sequencing of these assessments is consistent with Section 1251 of the 2022 NDAA. LAW 117-81, Sec. 1251, "Comparative Analyses and Reports on Efforts by the United States and the People's Republic of China to Advance Critical Modernization Technology with Respect to Military Applications," December 27, 2021.

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Chapter 1. Establishing an Analytic Baseline for a Critical Technology Area

Background

In this era of strategic competition between the United States and the People's Republic of China (PRC), emerging critical technologies present both countries with the possibility of disrupting the current balance of forces to achieve significant military advantages. U.S. senior defense and intelligence officials have identified several critical military technologies—such as directed energy, hypersonic systems, emerging biotechnologies, quantum science, and cyberspace capabilities—as not only being essential for national security but also possibly providing a disruptive advantage when applied across warfighting domains. These technologies are in various stages of development in both the U.S. and PRC. While some of the technologies, such as quantum science and biotechnology, appear to be only in the "seed" stages, others—such as hypersonic technologies, directed energy, and cyberspace capabilities—may be further along in transitioning to mature military capabilities that are more-readily available.

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5. *Identifying other notable activities, uncertainties, limitations, and recommendations.* In this cross-cutting analysis of the prior tasks, we account for R&D efforts outside of the U.S. and PRC that could advance the critical military technologies, discuss the uncertainties and limitations of the prior tasks, and recommend ways to address the results of the comparative analyses.

Establishing an Analytic Baseline for a Critical Technology Area

Fundamental to any assessment of a critical technology area is to establish a baseline from which to conduct the assessment. The first task, outlined in the remainder of this chapter, describes how to establish such an analytic baseline for each critical technology area in each country as a foundation for the comparative assessment. This first task comprises five subtasks:

- framing why the U.S. and PRC are pursuing the technology
- defining the technology
- scoping the technology
- identifying critical technology elements for transitioning to fielded capabilities
- assessing status and trends.

R&E's critical technology areas for the United States, Russia, and China—with support from Federally Funded Research and Development Centers (FFRDCs) and University-Affiliated Research Centers (UARCs).

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Framing the Technology

The comparative analyses of any technology area should start with answering the following question: Why are the U.S. and PRC pursuing this critical technology for military use? Each country is motivated for different reasons related to their national security, and the *why* behind each country's national security interest in the technology helps to explain significant differences in the technology development efforts and programs of each country. The *why* also helps to identify system alternatives that may be available to one side or the other to execute critical defense missions. Therefore, it is important to provide the strategic and operational framing in the context of each country's intended goals and how the critical technology area supports the goals, because each country may measure success in different ways for specific technology areas. Understanding the *why* provides the basis for a comparison that is derived by objective analysis instead of unfounded assumptions that each country is conducting a race intended to meet the same goal.

Defining the Technology

Next, we describe how the U.S. Department of Defense (DoD) and the People's Liberation Army (PLA) have historically defined the technology area of interest and how those definitions have evolved. To trace this evolution, we conduct a broad literature and program review to understand past work in each technology area within each country's research and development (R&D) establishments.

The U.S. literature review focuses on R&D and program activity in the DoD, the military services, and related entities, including federally funded research and development centers (FFRDCs) and university affiliated research centers (UARCs). The PRC literature review focuses on Chinese-language sources and other related sources. In aggregate, the literature review aims to ensure that the comparative assessment builds upon existing streams of research and reflects how the U.S. and PRC currently view the technology area from a strategic and national security perspective.

Scoping the Technology

For the comparative analyses, we leverage the literature review and resulting technology definition to scope the technology to current and planned programs or systems within the U.S. and PRC. Specifically, we answer the question: What are the current technology development plans, relevant programs, and system deployment plans for the U.S. and PRC?

Identifying Critical Technology Elements Necessary for Transitioning into Operational Capabilities

We identify critical technology elements (CTEs), which constitute an essential component or system necessary for transitioning the critical technology into fully operational capabilities. Identifying and understanding CTEs helps inform what critical technology challenges the U.S. and PRC must overcome to deploy these critical technologies effectively as part of a fielded military capability. Because the CTEs refer to the elements needed to deliver military capabilities envisioned by the DoD or the PLA for each technology area, the CTEs play key roles in the subsequent tasks of this analytic approach.

Assessing Current Status and Trends

Finally, we describe the status and trends of DoD and PLA programs and systems for each critical military technology through quantitative and qualitative analysis. We address several questions:

- If programs or military capabilities exist, what is their status for each country?
- What are notable differences between the programs or systems that the U.S. is developing and deploying compared with those of the PRC?
- What challenges are both countries facing in the development and deployment of these critical military technologies?
- What do current trends suggest for U.S. and PRC efforts in the technology area of interest?

For each critical technology area, the collection of information gathered in Task 1—on the strategic framing, technology definitions, CTEs, current plans and programs and the status of those—serves as the analytic baseline underpinning subsequent analytic tasks for the comparative technology assessment of the U.S. and PRC.

Chapter 2. Assessing Research and Development Activities

To effectively transition technologies into fielded military capabilities requires the involvement of dozens—or even hundreds—of distinct organizations and efforts over a sustained period. This organizational R&D ecosystem, or the national defense innovation system (NDIS), is *the set of actors, linkages, and the country-level contextual environment in which they operate, that work to develop new defense technolog*y.

For this task (Task 2 in our approach), we define the NDISs for the U.S. and PRC. We then focus on how each country deploys its NDIS to advance the research and development (R&D) of a specific technology area military use. We then empirically assess the activity of NDIS organizations across three dimensions: research, development, and fielding. We conclude with a comparative R&D assessment for the U.S. and PRC to understand how effective these countries have been at transitioning technologies for a critical technology area into fielded capabilities.[7] In short, Task 2 comprises four subtasks:

- refining a generic model
- developing metrics for the model
- populating the model
- comparing R&D activities.

This chapter gives a brief overview of the four subtasks involved in assessing and comparing R&D activities.

Refining a Generic Model

To assess R&D activities in the U.S. and PRC in a comparative fashion, we begin with a generic theoretical model known as the national defense innovation system (NDIS). As noted in the definition above, the NDIS can represent any network of actors that transforms and recombines resources, ideas, knowledge, and existing technology into a new military technology.[8]

We then refine conceptual models of the U.S. and PRC NDIS processes so that they are empirically grounded—and thus reflecting the way each country currently selects, develops, and

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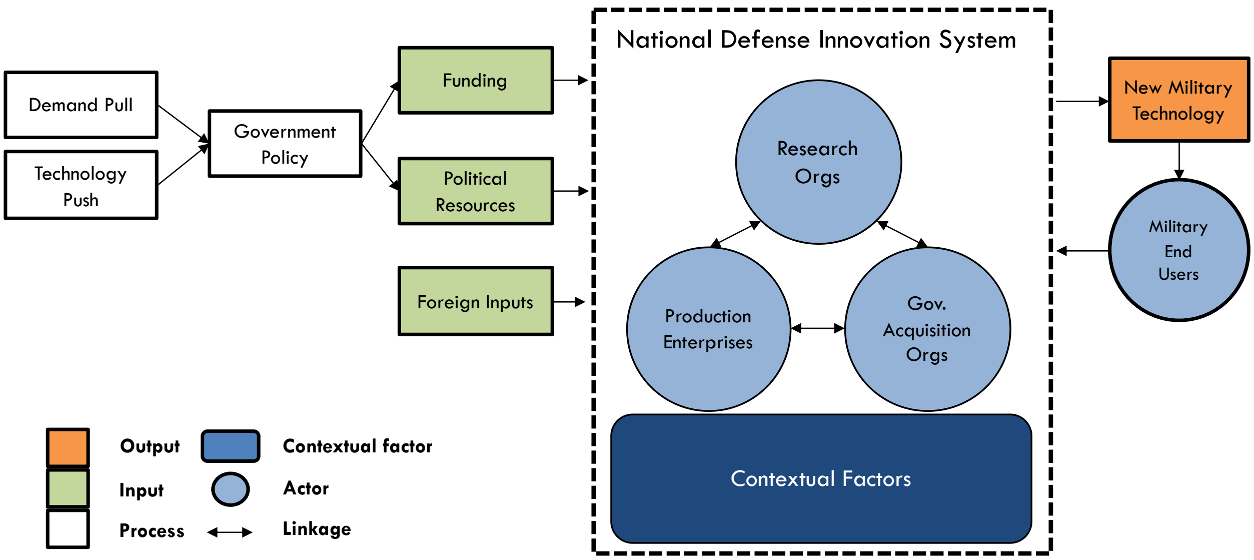
[7] See Appendix B (page 57) for more discussion on technology transition.

[8] The NDIS has its theoretical foundations in the national innovation systems literature (Freeman, 1982; Freeman, 1987; Lundvall, 1992; and Nelson, 1993). Tai Ming Cheung (Cheung, 2013; 2018) has applied the NIS framework to military innovation. Popper et al. (2020) have drawn from the national innovation systems literature to build a model of Chinese innovation potential and innovation propensity. Weinbaum et al. (2022) apply the NDIS notion to the U.S. and Chinese industrial bases writ large.

fields military technologies in practice. Each country's model, however, remains sufficiently generic to allow its application to a full range of critical technology areas.

Figure 2.1 depicts a country-agnostic NDIS to illustrate the type of model we use. It comprises a set of actors, contextual factors, and linkages. The exact numbers and kinds of these components are determined by assessing how each country develops its military technologies. Each critical technology area also drives which system components are emphasized. For example, technologies such as microelectronics and mobile communications (i.e., 5G/FutureG) are developed primarily by global commercial enterprises, whereas hypersonic technology is advanced largely by key government organizations and defense contractors. Meanwhile, broad areas of technology, such as biotechnology, depend on combinations of research organizations, government laboratories, and commercial enterprises.

Figure 2.1. Generic National Defense Innovation System



SOURCE: RAND.

The generic NDIS roughly depicts how we define and measure national defense innovation. In short, we base the definition and measurements of national defense innovation on a country's R&D activities and its transition of those activities to military applications. The generic NDIS model can be customized for measuring innovation in any technology area in any country. Appendix B breaks down the logic, components, and measurements of the U.S. and PRC variations of the NDIS model that we designed for this comparative assessment. Subsequent volumes in this series describe how we apply both the U.S. and PRC variations of the NDIS model to specific critical technology areas.

Developing Metrics for the Model

The purpose of refining country-specific NDIS models is to ensure that the R&D assessment accurately reflects how each country undertakes the military technology innovation process for each critical technology area. In this subtask, we develop measurement strategies for assessing the NDIS components. Where possible and appropriate, we measure them using quantitative metrics. For a given CTE, the linkage between *Research Organizations* and *Government Acquisition Organizations* might be measured by the number of scientific publications co-authored by contributors from these organization types. *Enterprises* might be assessed by patent counts or market shares. In certain cases, qualitative assessments will likely be appropriate. Comparative assessments of defense acquisitions systems are likely to be based, at least in part, on qualitative assessments of system efficacy or on qualitative intelligence assessments.

Populating the Model

Once we have measurement strategies for all NDIS components for the U.S. and PRC, we populate each country's model with data. For the most part, we measure at the level of a CTE. For certain CTEs, it is suitable to measure them at a higher level of aggregation (e.g., at the level of the capability or of an entire critical technology area). For example, a country's institutional and legal context may remain constant over the whole technology area and thus may be appropriately assessed at the level of the area rather than that of the granular CTE.

If necessary, we further refine the NDIS model to assure its "fit" for the technology area in question. Technologies vary regarding the testing and evaluation infrastructure required for development and the role of the commercial sector in driving technological progress. The secondary refinement process ensures that the model and its measurements reflect such heterogeneities.

Comparing R&D Activities

The output is a pair of data-populated models for CTEs within each technology area of interest. For certain CTEs, such as the number of active CTE researchers in each country, the metrics are commensurable (i.e., measurable by the same standard). For other CTEs, comparison depends on analytical judgment. Therefore, for each technology area, we engage subject matter experts (SMEs) through interviews, surveys, or workshops. SME engagements often reveal important caveats and qualifications. For example, both the U.S. and PRC are global leaders in quantum technology, but experts clarify that the PRC leads in quantum communications and quantum key distribution while the United States leads in quantum computing. The final stage of research on R&D activities compares each country's NDIS measurements, as informed by analytical judgments and SME engagements, to arrive at an overall comparative assessment of each critical technology area for the U.S. and PRC.

Table 2.1 summarizes the data and tools we use in Task 2. These sources inform all phases of the task: refining the generical model, developing metrics for the model, populating the model, and comparing R&D activities.

Table 2.1. Summary of Data and Tools Used for R&D Activities Analysis

Data or Tool	Description	Subtask
Web of Science	Scientific publication data (English language)	Metric Development, Model Population
Scopus	Scientific publication data (English and Chinese language)	Metric Development, Model Population
China National Knowledge Infrastructure	Scientific Publication Data (Chinese language)	Model Refinement, Model Population
Derwent Innovation Index	Patent data (all major patent jurisdictions)	Metric Development, Model Population
World Intellectual Property Organization	Patent data	Metric Development, Model Population
Vantage Point	Data mining software	Metric Development, Model Population
Bibliometrix (R Package)	Bibliometric analysis software	Metric Development, Model Population
Vos Viewer	Bibliometric analysis software	Metric Development, Model Population
Gephi	Social network analysis software	Metric Development, Model Population
RANDlex	Natural language processing software (RAND-developed)	Metric Development, Model Population
Polyglot	Chinese-language translation tool (RAND-developed)	Model Refinement, Model Population

Chapter 3. Assessing Operational Effectiveness

The U.S. and PRC are dedicating significant resources to developing and advancing critical technologies for military use. To understand the potential implications of these current and planned efforts relative to stated goals and objectives, we assess their operational significance and effectiveness. We define operational significance as the *potential for a given technology area to make unique contributions to operational outcomes, in general or in specific missions/tasks, in cost-effective ways.* At its most essential, operational significance is a function of the roles and missions a system performs as well as the effectiveness with which it performs those missions.

This chapter describes how we assess the operational significance and effectiveness of each technology for each country (Task 3 in our approach). Task 3 comprises three subtasks:

- defining operational problems for each country and the corresponding missions/tasks for each critical technology
- assessing the relationships of the critical technologies to the missions/tasks, including consideration of alternative tools and capabilities
- assessing the operational effectiveness of the critical technologies (using the framework described below in Table 3.1).

We perform the subtasks for the U.S. and PRC. In most cases, the assessments for the U.S. and PRC are entirely distinct.

This chapter gives a brief overview of the subtasks involved in assessing operational significance and effectiveness.

Defining Operational Problems and Relevant Missions/Tasks

This task is premised on specifying what operational problems the U.S. and PRC are trying to solve—that is, what motivates their pursuit of the critical military technology. Since the comparative focus is on the PRC, we limit U.S. operational problems to those relevant to the Indo-Pacific region. Once a comprehensive list of operational problems is identified for both the U.S. and PRC, the team assembles a set of relevant missions/tasks that the technologies can support. This component of the analysis is a variant of the classic strategies-to-tasks analytical approach.[9]

[9] David E. Thaler, *Strategies to Tasks: A Framework for Linking Means and Ends,* Santa Monica, Calif.: RAND Corporation, MR-300-AF, 1993, https://www.rand.org/pubs/monograph_reports/MR300.html

Assessing Relationships of Critical Technologies to Missions/Tasks

For each U.S. and PRC mission-task, we identify objective measurements of the necessity and significance of the critical technologies for generating operational effectiveness. These measurements offer a repeatable approach for assessing the operational significance of many kinds of critical military technologies. The measurements incorporate four elements:

1. ***General Assessment***: We list the criteria for assessing the utility and significance of each technology of interest for fulfilling each mission-task. We use the criteria to evaluate each application of the technology. The criteria encompass these variables:
   - general predicted operational effects, based on objective benchmarks
   - geographic range of effects
   - defense industrial base (DIB) status, DIB production rates, and mission implications
   - predicted utility and reliability over a given timeframe
   - survivability assumptions about the likelihood that a capability will reach the intended target despite any known defenses and countermeasures of a potential adversary
   - targeting assumptions about the likelihood that a capability will hit the intended target with the necessary degree of accuracy
   - lethality assumptions about the likelihood that a capability will have the intended effect on the target.
2. ***Alternative Tools and Capabilities***: The importance of each military system or capability associated with a critical military technology is a function, in part, of its uniqueness for solving operational problems. What missions, if any, can be performed by only these military systems or capabilities? What other systems or capabilities can perform the missions? For the United States, is it possible to develop a joint package that addresses the operational problems without relying on these critical military technologies? Is the PRC potentially more dependent on these critical military technologies than the United States?
3. ***Challenges in Achieving Desired Operational Effects***: The team's technical experts consult with technical experts in relevant DoD offices, FFRDCs/UARCs, defense firms, and intelligence agencies to construct quantifiable measurements of the probability of success in achieving missions/tasks by using the critical technologies. For instance, a confidence index can measure each military system's ability to perform. Information fed into a confidence index can include scores in answer to these questions:
   - How much has the government or the developing firm demonstrated the utility of the military systems in training and operations?
   - What other systems does the technology depend on—e.g., find-and-fix sensing, space-based sensors—and how reliable and resilient are those other systems?
   - How many systems need to be procured, and what are the implications of this required quantity on operational effectiveness?
   - What roles do these systems play in their larger missions—e.g., directed energy in air and missile defense, hypersonics in long-range precision-fire missions?

– (Although countermeasures are key components of this challenge assessment, because they could radically alter the cost-effectiveness and thus the value of new technological systems, the countermeasures are addressed separately in Task 4 of our five-step approach.)

4. ***Cost:*** We assess each system's cost, and whether the cost curve will bend over time.

Assessing Operational Effectiveness

The framework in Table 3.1 incorporates all the key questions and elements discussed as part of this operational effectiveness analysis. This framework has evolved based on feedback from DoD sponsors, other subject matter experts, and research findings. As it suggests, the foundation for assessing operational significance is the combination of the roles and missions performed by a weapons system plus the effectiveness of the system in performing those missions.

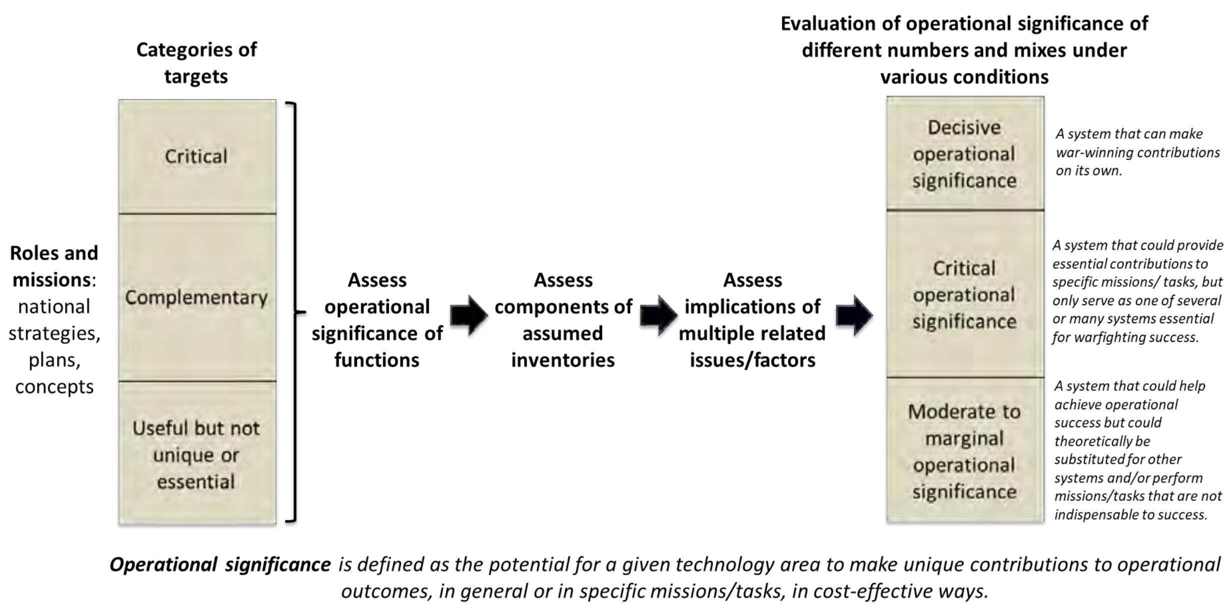
Table 3.1. Framework for Assessing the Operational Effectiveness of a Critical Military Technology

Baseline Assessment	
What missions/tasks do the systems serve? How essential are those tasks to campaign and strategic success—i.e., how much does it matter if the systems perform their missions effectively?	Identify purposes and missions on the strategies-to-tasks spectrum: national military objectives, campaign objectives, operations objectives, and operational tasks.
General effectiveness score of weapons relative to missions	For each mission a system will perform, can the weapons perform the mission reliably; has the country demonstrated the system in exercises or in use; does the system have the necessary personal/talent to operate it; do its testing outcomes validate effectiveness?
Added Considerations	
Secondary operational effect value	Apart from the primary mission, what operational effects can be identified that affect the overall campaign; what is the weapons' value in enhancing the holistic effect of U.S. operations?
Adversary perceptions	To what degree will a potential adversary be influenced by the presence of the weapons, either being deterred from war or shifting operational plans? Does the system allow actions in peace or crisis with signaling value?
Substitutability vs. redundancy	What other systems could fulfill the intended missions? How do those capabilities relate to a value of redundancy for certain missions?
Dependence on other systems	How reliable and resilient are the other systems on which this system will rely for its effectiveness, such as targeting?
Production and industrial considerations	Can the defense industrial base produce the necessary numbers over time; does the United States have sufficient technical personnel for the task; and is the weapons dependent on foreign technology or materials?
Vulnerability	Are the launching or operational deployed systems vulnerable to strike or other interference (cyber)?
Cost	What is the cost per item, for both development and production, relative to meeting the operational objectives?

This framework is leveraged to produce an overall assessment of the operational effectiveness of each critical military technology for each country. Expected outputs of this task for each country are shown in Figure 3.1. The figure reads from left to right. The assessment begins on the left, with the identification of roles and missions derived from national strategies, plans, and concepts. From those roles and missions, a set of plausible targets is identified and organized by their criticality to the mission. Immediately, the factors in the Table 3.1 framework introduce uncertainties in the ability of any single system to definitively demonstrate operational significance. The issue of dependencies is especially important: Any system will depend on other capabilities for its effectiveness. Hypersonic weapons, for example, will depend on a reliable and precise sensing, targeting, and weapons control architecture; therefore, such factors pointed us to the kinds of issues we would need to assess in determining hypersonic weapon effectiveness. Considering the various factors across the assessment framework ultimately helped us provide judgments on the operational significance of systems or capabilities under various conditions. We consider three categories of operational significance in our evaluation:

- Decisive operational significance: A system that can make war-winning contributions on its own.
- Critical operational significance: A system that could provide essential contributions to specific missions/ tasks but serve as only one of several or many systems essential for warfighting success.
- Moderate to marginal operational significance: A system that could help achieve operational success but could theoretically be substituted for other systems and/or perform missions/tasks that are not indispensable to success.

Figure 3.1. Expected Outputs of Operational Effectiveness Analysis



SOURCE: RAND.

As a result of the complexity of this framework and the uncertainties involved, the expected outputs of this analysis are not definitive, measurable findings about the operational significance of particular systems or capabilities. The actual significance in a conflict will depend on many factors that cannot be predicted in advance, including the performance of complementary systems, the nature of the conflict, the specific scenario, the operational concepts employed, and much more. We designed this analysis to generate usable insights to inform judgments about the relative PRC and U.S. standing in the systems and capabilities of interest, but we could not make fine-tuned forecasts of the significance of these systems in wartime.

Chapter 4. Analyzing Countermeasures

An actor with substantial technology resources will likely develop countermeasures to a potential adversary's current or planned capabilities. Such countermeasures to defeat these capabilities could be entirely new systems or modifications of existing systems. As weapon systems relying on new technologies become more precise and focused on specific targets, it becomes possible for an actor to develop countermeasures that defeat the precision and focus of such capabilities.

Task 4 in our approach is to determine whether the U.S. and PRC have developed and implemented—or will develop and implement—countermeasures to current and planned capabilities in a technology area of interest. Task 4 comprises three subtasks:

- identifying and describing current and future countermeasures
- assessing the use of countermeasures
- assessing implementation challenges and technical risks.

This chapter gives a brief overview of the three subtasks involved in identifying countermeasures.

Identifying and Describing Current and Future Countermeasures

We use a literature review and engagements with various subject matter experts within DoD, defense and intelligence agencies, industry, FFRDCs, and UARCs to identify, assess, and understand countermeasures of interest to the U.S. and PRC in a technology area of interest. For the analysis of PRC's countermeasures, we also survey Chinese-language publications from the PLA and state-linked academic, industry, and scientific organizations. Based on these efforts, we determine what countermeasures exist for a military technology and the status of such countermeasures pursued by the U.S. and PRC.

Assessing the Use of Countermeasures

We analyze how the U.S. and PRC intend to use or are using countermeasures against a critical technology. We rely on analyses and assessments from the DoD and other defense and intelligence agencies pertaining to U.S. and PRC countermeasures in each technology area. We also review Chinese-language publications from the PLA and state-linked academic, industry, and scientific journals to inform our understanding of PRC activities. If available, we include data on countermeasure status, schedules, and budgets.

Assessing Implementation Challenges and Technical Risks

To identify and characterize implementation challenges and technical risks, we review available operational and technical assessments from a variety of sources on DoD and PRC countermeasure activities. If possible, this includes a review of Chinese-language publications from the PLA and state-linked academic, industry, and scientific journals.

Chapter 5. Identifying Other Notable Activities, Uncertainties, Limitations, and Recommendations

A final cross-cutting task takes account of other notable R&D activities, caveats to the comparative analyses, and recommended ways to address the results of the comparative analyses.

Other Notable R&D Activities

Based on the analysis conducted in earlier tasks, this section aims to address two questions:

- What significant R&D efforts outside of the U.S. and PRC could advance the critical military technologies of interest?
- What are other relevant R&D efforts for the critical military technologies of interest?

Our approach to answering these questions consists of the following:

- collecting data on notable international R&D activities through discussions with, and data provided by, DoD R&E stakeholders in their respective critical technology areas
- reviewing current and historical international agreements or partnerships by area
- for the countries identified through stakeholder discussions and literature review, selectively measuring R&D activity (e.g., high-quality publications and patents) within those countries to gauge their activities in a critical technology area
- identifying and assessing issues and opportunities for, and barriers to, collaboration.

Caveats to the Comparative Analyses

We also apply appropriate caveats to the comparative analyses by:

- identifying areas of uncertainty
- describing limitations, constraints, and challenges in conducting the analyses.

Recommended Ways to Address the Results of the Comparative Analyses

The comparative assessment is largely diagnostic in nature, providing an informed understanding of U.S. and PRC efforts to develop and deploy critical technologies for military use. However, informed by the findings from the comparative analyses and the identified caveats, we conclude the comparative assessment with recommended DoD activities. These recommended activities could include development efforts, analytic efforts, or data collection requirements to support future assessments of a specific technology area. Additionally, the recommendations could point toward opportunities for DoD to shape efforts in a critical technology area to yield greater strategic and operational advantages.

Appendix A. Summary of Stakeholder Engagement, Data Collection, and Documentation

Critical military technology areas are diverse, ranging from seeds of emerging opportunity (e.g., quantum, biotechnologies) to effective adoption areas where there is widespread commercial activity (e.g., artificial intelligence and autonomy, microelectronics) to defense-specific areas (e.g., directed energy, hypersonics).[10] Similarly, strategic shocks can shape the technology or security landscape in new or unexpected ways. Efforts to understand how the U.S. and PRC advance critical technologies for military use require deep and broad expertise that accounts for the inherent similarities and differences in national R&D ecosystems, national defense and security priorities, and uncertainties or new areas of emerging development. To be sure, the outcomes of these technology competitions and of how each country develops and deploys military technologies will be shaped by a confluence of technological, operational, economic, demographic, organizational, and other factors—which need to be accounted for as part of the underlying approach. While a general analytical approach can be used for each comparative technology assessment, the specific types of data, metrics, and methods may vary. This appendix outlines a basic approach for stakeholder engagement, data collection, and documentation efforts for conducting a comparative technology assessment.

Stakeholder Engagement

Stakeholder engagement is required throughout the assessment to support initial scoping, data collection and analysis, and the review and coordination of the analysis and findings. To begin, each comparative assessment requires a deliberate partnership up-front between USD(R&E) and the lead research organization to understand (1) existing methods, metrics, and data that can be used to conduct the assessment, (2) gaps that can be accounted for with new methods, metrics, or data, and (3) limitations, uncertainties, and risks that may not be resolvable within the timeframe of the study but could inform development efforts or requirements to support future assessments.[11] Based on this understanding, USD(R&E) will support the lead research organization's efforts to obtain relevant data in a timely manner to conduct the comparative assessment.

The lead research organization will work with USD(R&E) to develop a plan for engaging a broad range of experts to inform the different tasks. Such experts will include the following:

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[10] Under Secretary of Defense for Research and Engineering, "USD(R&E) Technology Vision for an Era of Competition," U.S. Department of Defense, February 1, 2022.

[11] If the development of new metrics or methods is required for the comparative technology assessment given the study plan and approach, these will be accounted for as a recommended DoD activity outlined in the assessment.

- ***DoD and intelligence community professionals*** who can provide authoritative information or assessments on U.S. and PRC efforts and activities in a critical technology area
- ***technologists*** who understand the fundamental science and engineering associated with the critical technology area and the technological challenges associated with developing and transitioning the technology into operational capabilities
- ***regional experts*** who can identify and evaluate country interest and activities associated with the critical technology area, the organizational R&D ecosystem that underpins the ability to develop and deploy these technologies, and the challenges a country faces in developing and deploying these technologies
- ***military experts*** who understand the types of missions to which these technologies can apply, particularly relative to other alternatives, and the potential counters for those technologies
- ***R&D and industrial base experts*** who can identify and evaluate U.S. and PRC R&D activities associated with the critical technology area, the organizational R&D ecosystem that underpins the ability of both countries to develop and deploy these technologies, and the challenges these countries face in developing and deploying these technologies.

The types of stakeholder engagements will vary depending on task, purpose, and technology. But here are examples of such engagements:

- ***periodic "touchpoints" with USD(R&E) leadership*** to provide an update on the comparative assessment and discuss and remedy any issues associated with its execution
- ***technical information exchanges with subject matter experts*** to discuss data needs, products, gaps, and uncertainties
- ***industry engagement with industrial base experts*** to understand the U.S. and PRC industrial bases for a critical technology, similarities, and differences between the R&D ecosystems within both countries, and challenges associated with transitioning technologies into operational capabilities
- ***operational engagement with military experts*** through tabletop exercises, wargames, or analytic workshops to understand what operational problems the U.S. and PRC are trying to solve, what missions are most relevant for which alternative capabilities, and how operationally effective and significant the technology is for the DoD or PLA
- ***engagement with other DoD stakeholders (services, defense agencies, national labs)*** through analytic working groups, small group meetings, or DoD- or industry-sponsored conferences to understand U.S. and PRC programs, systems, status, and trends, along with counters for critical technology areas
- ***informal reviews with partner FFRDCs/UARCs*** that have notable experts and related efforts underway in each critical technology area.

Data Collection

While data collection efforts may vary depending on the critical technology area, Table A.1 summarizes the data needs for each task to support the comparative assessment.

Table A.1. Summary of Data Needs for Comparative Technology Assessments

Task	Data Needs
Task 1: Baseline	Data on strategic framing for why the U.S. and PRC are pursuing a critical technology • For DoD assessment: DoD strategic guidance and planning documents, Congressional testimony, DoD technology roadmaps • For PRC assessment: PLA strategic guidance and planning documents; open-source assessments of PRC primary sources
	Data on current/planned programs associated with the technologies for the U.S. and PRC • For DoD programs: DoD technology roadmaps, DoD/service/agency data (and other relevant U.S. government and industry data) • For PLA programs: relevant assessments, reports, and databases
Task 2: R&D Activities	Data on R&D organizations and activities for critical technologies • Relevant technology assessments • Assessments of development and operational T&E activities and infrastructure • R&D assessments by DoD, FFRDCs/UARCs
Task 3: Operational Effectiveness	Data on U.S. and PRC operational use and effectiveness of critical technologies • Assessments of how the technologies are or will be used in an operational context • Assessments of the operational effectiveness of capabilities associated with critical technologies given an operational context
Task 4: Countermeasures	Data on current/planned countermeasures (programs, technology protections, or other related activities) of the U.S. and PRC • For DoD programs: DoD technology roadmaps, DoD/service/agency data (and other relevant U.S. government and industry data) • For PLA programs: relevant assessments, reports, and databases
Task 5: International R&D Activities	Data on international agreements, partnerships, and areas of focus between the U.S., PRC, and other countries in a critical technology area

Documentation

The intended output of the comparative analysis is a document that includes:

- an **executive summary**, which summarizes findings and recommendations from the comparative assessment;
- an **introduction**, which defines the critical technology and provides background and context related to the importance of this technology for each country;
- an analytic **technology baseline** of current and planned efforts for each country, to include status and trends;
- an **R&D assessment** of the organizational ecosystem and activities underway for this critical technology;
- an assessment of **operational effectiveness**;
- an assessment of **countermeasures**;
- a description of other notable **international R&D activities** for this critical technology.

Appendices may be included with additional details relative to the comparative assessment.

Appendix B. U.S. and PRC Variations of the NDIS Model

This appendix describes how we define and measure national defense innovation. In short, we base the definition and measurements on a country's R&D activities and its transition of those activities to military applications.

A country can attain new defense technology in two ways: by importing the technology from abroad or by developing the technology domestically. Importing technologies or subcomponents from partners and allies to fill critical gaps could offer important advantages for strategic competition. However, importing defense technology from abroad could forestall a country's ability to attain global technological advantage for a given technology because the imported technology will already be held by the exporting country. Achieving global technological leadership in the long-term is likely to require indigenous defense technology innovation. Leveraging technology leadership to advance military capabilities requires additional organizations, concepts, processes, and resources (workforce and funding) to develop and field capabilities in operationally relevant numbers to achieve critical military advantages.

The next section lays the foundation for our methodology of measuring and comparing defense innovation in the U.S. and PRC. This foundation:

- depicts the *process* of attaining innovation (indigenous or otherwise)
- defines a generic domestic innovation *system*—referred to here as a national defense innovation system (NDIS)—that is responsible for executing the innovation process
- describes five types of functional *contributions* to such a system.

The subsequent two sections, constituting the bulk of this appendix, detail the components of the contemporary NDISs of the U.S. and PRC. Each section assigns the U.S. or PRC components of innovation to the five functional areas within each respective NDIS.

The appendix concludes by describing how we measure the innovation of each country's NDIS in given technology areas. We set out to quantify or qualitatively describe 15 elements of three major dimensions of military technology innovation—i.e., research, development, and fielding—across a variety of specified technology areas.

National Defense Innovation Process, System, and Contributions

National Defense Technology Innovation Process

To conceptualize the process of attaining defense technology innovation, we begin with the process output (**new defense technology**) and ask the question: How is this output generated? Defense technology is defined here by its relationship to its end-user; we define defense technology as technology that is intended to be used by country-level armed forces. This definition is intentionally broad and includes wholly new weapons systems, new weapon system modules or munitions, scheduled upgrades to existing weapons systems, platforms, non-weapon military systems (e.g., communication or surveillance technology), and even intangible advancements such as software, waveforms, data links, and algorithms meant to be used by a national military.

There is an important relationship between defense technology innovation and military innovation. Defense technology innovation is intended to improve the performance of military forces for important national security missions through direct or indirect means, but the effects of technology advancement cannot be understood by considering just hardware (the types and numbers of military equipment). As argued by Stephen Biddle in 2004, "technology's effects are thus secondary to force employment's and cannot be properly understood except in interaction with force employment: technology alone is a poor predictor of capability."[12] Other factors, such as software (to include concepts of operation, organizational structures, and training) must be accounted for to harness the potential for defense technology innovation to create critical military advantages and military power and influence at scale. Michael Horowitz makes a similar argument that defense technology innovation must be combined with a willingness to adapt organizationally (to include operations and training) to translate such technology advancements into military power.[13] We therefore acknowledge that defense technology innovation does not provide military advantage on its own. Understanding a country's process of defense technology innovation, however, is still essential for conducting broader assessments of the potential military operational significance of that innovation.

Figure B.1 depicts a stylized defense technology innovation process. The remainder of this section describes the process components, moving from left to right.

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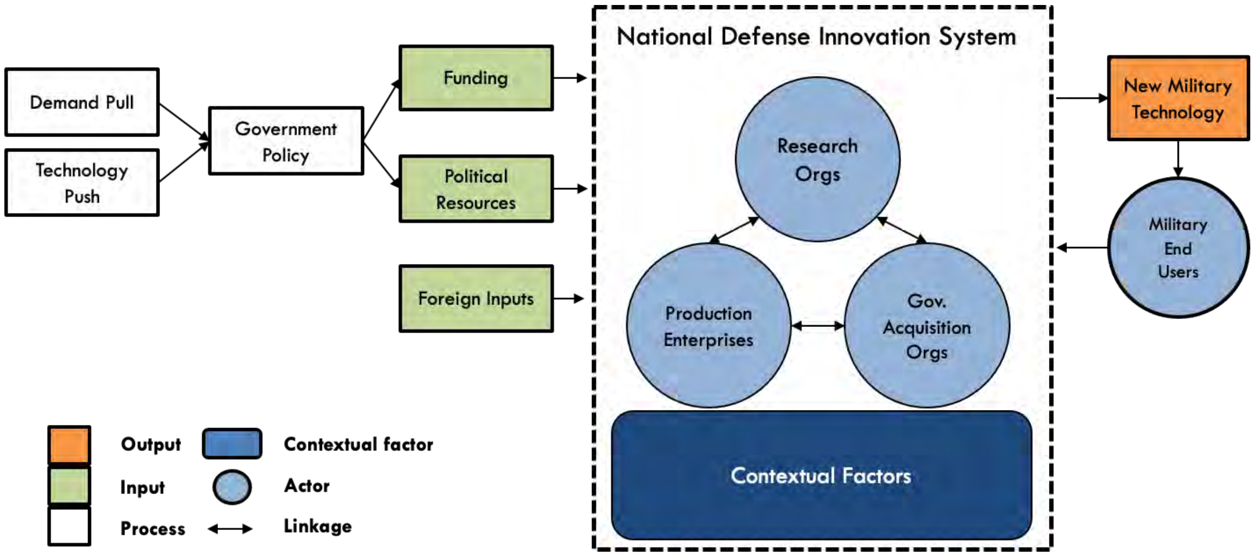
[12] Stephen Biddle, *Military Power: Explaining Victory and Defeat in Modern Battle,* Princeton University Press, 2004, p. 190.

[13] Michael C. Horowitz, *The Diffusion of Military Power: Causes and Consequences for International Politics*, Princeton University Press, 2010.

Figure B.1. A General Defense Technology Innovation Process



SOURCE: RAND.

A new defense technology can be initiated by either **demand pull** or **technology push**. In the case of demand pull, the motivation to develop a new defense technology is the result of an identified military need. The military innovation literature identifies several factors that can trigger this demand pull: "presence of serious external threats, revisionist ambitions, or relative resource constraints."[14] The identification of a given military need might be the result of a complex formal or informal decisionmaking process. For example, the military need might take the form of a validated military requirement (e.g., an operational requirement for a longer-range anti-ship missile) that results from a country's risk assessment of its current force posture given a potential adversary threat for a specific region.[15] Alternatively, a military need might be less acute, and instead be manifest in a country's long-term defense technology strategy. Even for this latter type of demand pull, certain factors need to be in place to facilitate innovation—factors such as a "champion" for the demand and both an organizational path and a workforce to pursue

[14] Jeffrey A. Isaacson, Christopher Layne, John Arquilla, *Predicting Military Innovation*, Santa Monica, Calif.: RAND Corporation, 2007, p. vii.

[15] In the United States, the formal requirements generation process is initiated within the Joint Capabilities Integration and Development System (JCIDS). In China, requirements are set by the Central Military Commission (CMC) after an evaluation of the resources and capabilities needed to achieve strategic objectives in both peacetime and war. After evaluating military capabilities, the CMC develops the Outline of the Five-Year Program for Military Development, which the services and theaters use to develop annual and multiyear subplans. Requirements are also submitted from the "bottom-up" by the financial departments of military units, based on baseline and anticipated expenditures.

a solution.[16] The identification of a military demand initiates an intentional, typically highly-structured process of scientific and technological discovery.

In the technology push case, the discovery process precedes the identification of a military application. In the process depicted in Figure B.1, the pushed technology simply appears, although likely as the result of an intentional discovery process exogenous to the conceptual model. For a technology to be incorporated into a country's defense technology portfolio, the technology will typically undergo extensive modification through government-funded development activities.[17] For example, Rosen proposes that development of intercontinental ballistic missiles (ICBMs) in the United States was driven by breakthroughs in the civilian scientific system, noting, "It was not a Soviet threat, or a civilian scientific intervention in the context of fixed technological possibilities that pushed the innovation of the ICBM, but a new and unforeseen technological innovation created by civilian physicists."[18]

Before an identified military need (i.e., before a demand-pull process) can result in material inputs to a government-funded science and technology (S&T) effort, the need must be assessed for utility and translated into action by some **government policy**. Examples of such policies include initiating formal acquisition programs; appointing a government official; investing in testing and evaluation infrastructure; beginning national S&T initiatives; and investing in science, technology, engineering, and mathematics (STEM) education.[19] Importantly, in our model, the process by which government actors translate a military need into concrete policy action need not involve a unitary government actor. In practice, distinct government agencies have partially overlapping portfolios, are imperfectly aligned, or even have competing interests and distinct organizational cultures. Government actors also vary with respect to the policy levers that they can influence.

In our model, the outcome of the government-led process of translating demand into policy is a set of three resource inputs.[20]

Funding refers to government-provided money that contributes to defense technology innovation. Funding might take the form of direct funding of scientific research, public spending

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[16] Jeffrey A. Isaacson, Christopher Layne, John Arquilla, *Predicting Military Innovation*, Santa Monica, Calif.: RAND Corporation, 2007, p. vii.

[17] Bellais and Guichard 2006; Alic 2007.

[18] Stephen Peter Rosen, *Winning the Next War: Innovation and the Modern Military,* Cornell University Press, 1991, p. 248.

[19] Conceptually, the government policy need not be overtly military-focused. For example, a policy to fund graduate student education may increase the human capital base available to the National Defense Innovation System. Such a policy may also increase instances of technology-push defense technology innovation independent of any explicit military goals.

[20] These resource inputs are assumed to yield positive returns for defense technology innovation. That is, holding other factors constant, increasing the quantity of a given resource is assumed to increase defense technology innovation. The model makes no assumptions regarding the marginal returns to resource inputs—merely that overall returns are positive.

on an acquisition program, research grants, public provision of innovation infrastructure, favorable tax status and subsidies for NDIS actors, or investment in graduate research.

Political resources refer to the non-financial resources allocated by a country's political leadership to realize a defense technology goal. Political resources include intervening to accelerate government processes, shepherding a project through government bureaucracy, creating novel committees or working groups, and allocating skilled human resources. Empirical research has shown that high-level political support or the presence of a well-placed champion is associated with improved defense technology innovation outcomes (Fowler 1997; Van Atta et al., 2003; Cheung 2019).

The third resource input consists of **foreign inputs,** or those that originate aboard. Examples of foreign inputs include explicit and implicit knowledge held or generated by individuals or organizations located outside of the focal country, plus knowledge embodied within existing foreign technology. Foreign knowledge might enter a domestic innovation system in myriad legitimate ways, including international research collaboration, the scientific publication process, international student and faculty flows, technology licensing, the acquisition of foreign firms, or simply observing foreign militaries' actions. In addition to attaining foreign inputs to defense technology innovation legally, a domestic NDIS might gain access to foreign inputs illicitly through intellectual property theft or industrial espionage.

Figure B.1 then outlines a generic NDIS comprised of three types of actors—**research organizations, production enterprises,** and **government acquisition organizations**—three linkages among the types of actors, and a set of **contextual factors**. These components are country-agnostic, and they exist in two modern military powers: the U.S. and PRC.

Definition of a National Defense Innovation System

The notion of a generic NDIS borrows from the insights of national innovation system (NIS) scholars (Freeman 1982; Freeman 1987; Lundvall 1992; Nelson 1993). These researchers have observed that innovation is the result of a complex set of actions and interactions among scientific, economic, and government actors who are embedded in a contextual environment that—through its established incentives, laws, rules, and norms—shapes the innovation process.[21] The concept is centered around the notion of a *system* in that it views innovation as a complex, and typically non-linear, process involving multiple actors with differing capabilities, incentives, and motives. The system is *national* because many of the contextual factors are the result of country-level institutions (e.g., legal codes).[22] Applying these concepts to the topic of

[21] Often, the contextual environment is described in terms of "institutions" in the Northean sense. However, given that the term institution is often used as a synonym for organization, we prefer the term contextual environment or contextual factors to refer to the nation-level variables that establish the "rules of the game" for innovation.

[22] Other innovation system definitions focus on sub- or super-national geographies. In the case of defense technology innovation, the nation is selected because of the importance of country-level institutions (e.g., defense

defense technology innovation,[23] we define NDIS as *the set of actors, and the country-level contextual environment in which they operate, that work to develop new defense technology*.[24] Thus, we define NDIS as the outlined area of Figure B.1.

Functional Contributions to a National Defense Innovation System

We distinguish the three types of NDIS actors based on their primary functional contributions to the defense technology innovation process. For example, government labs and universities typically have different legal statuses. But instead of categorizing them by their legal statuses, we categorize them both as research organizations because the primary functional contribution of each to defense technology innovation is knowledge creation. We include contextual factors and linkages as additional functional contributions, as described below.

Research Organizations

The primary functional contribution of research organizations to the NDIS is to generate, scrutinize, mature, and diffuse new defense-relevant[25] scientific or technical knowledge. These organizations realize this objective by conducting myriad forms of basic and applied research.[26]

Production Enterprises

The principal functional contribution of production enterprises to the NDIS is to develop and produce new military technology and deliver it to the end user. The development and production process typically involves activities such as product development, system integration, prototyping, and manufacturing.

Government Acquisition Organizations

The principal functional contribution of government acquisition organizations is to establish the rules for participation in the NDIS, set technology priorities, communicate demand, provide oversight, and allocate resources.

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procurement laws) and the fact that most defense firms face a monopolistic market with a country-level buyer (e.g., the DoD).

[23] Scholars of defense innovation often include doctrinal and organizational innovation within their analyses. Here, we focus exclusively on defense technology. See Schmid (2018) for an explanation as to why these distinct types of defense innovation should be disaggregated.

[24] Cortney Weinbaum, Caolionn O'Connell, Steven W. Popper, M. Scott Bond, Hannah Jane Byrne, Christian Curriden, Gregory Weider Fauerbach, Sale Lilly, Jared Mondschein, Jon Schmid, *Assessing Systemic Strengths and Vulnerabilities of China's Defense Industrial Base: With a Repeatable Methodology for Other Countries*, Santa Monica, CA: RAND Corporation, 2022.

[25] The knowledge in question need not anticipate a defense technology application. In fact, much knowledge created via basic research predates application by years or decades.

[26] Basic research refers to research that seeks to improve understanding of natural phenomena. Applied research focuses on investigating practical questions to answer specific problems.

Contextual Factors

Contextual factors refer to the relevant institutional conditions (e.g., norms and laws) under which the NDIS actors operate. Examples of contextual factors include the domestic intellectual property rights regime, contract law, the commercial code, and the rules, laws, and regulations regarding defense acquisition and government procurement.

Linkages

Linkages refer to the formal and informal channels by which NDIS actors transmit and receive resources and information among one another. Linkages may take the form of long-standing interorganizational relationships (e.g., research collaboration between a production enterprise and a research organization) or prevailing channels of communicating to enterprises about military demand (e.g., a request for proposals, or a broad agency announcement). The innovation system literature underscores the importance of strong linkages to the performance of an innovation system.[27]

U.S. National Defense Innovation System

The U.S. NDIS is very well resourced and comprised of thousands of specialized and diverse organizational actors. In 2020, the DoD spent $16 billion on basic and applied research and $57 billion on development, a quantity that surpasses, by a significant margin, that of any other country.[28]

The U.S. NDIS contains a large and varied set of research organizations. U.S.-based research organizations vary in terms of their focus along the basic-to-applied research spectrum and in terms of the nature of their relationship to the DoD. For example, in the U.S. system, universities tend to make large relative contributions to basic research and have transitory ties to the DoD (e.g., contract-specific funding streams). In contrast, defense labs such as the Air Force Research Laboratory (AFRL) specialize in applied research in response to a service branch's needs and are within the reporting structure of a DoD entity.

Production enterprise functions within the U.S. NDIS, are for the most part, played by private firms. The prevailing industrial arrangement for producing large weapons systems in the United States is to rely on a small set of defense prime contractors (primes) that manage complex networks of suppliers and that sell to a single buyer (the DoD) via a highly structured acquisition

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[27] Henry Etzkowitz and Chunyan Zhou, *The Triple Helix: University–Industry–Government Innovation and Entrepreneurship*, Routledge, September 21, 2017.

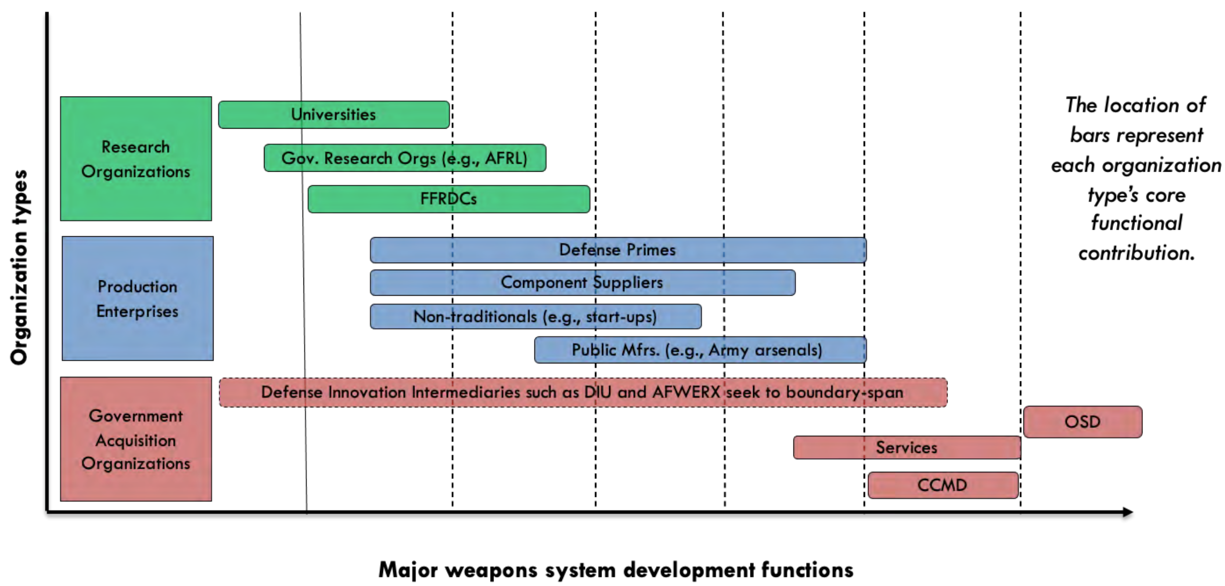
[28] The basic and applied research figure is the sum of the 2020 Science and Technology (S&T) Budget Areas (BA) 6.1, 6.2, and 6.3. The development figure is the DoD budget category of "Weapons Development and Other." For more on the comparison to other countries' R&D spending, see Eugene Gholz and Harvey M. Sapolsky. "The defense innovation machine: Why the US will remain on the cutting edge." *Journal of Strategic Studies* 44, no. 6 (2021): 854-872.

process. However, in recent years, nontraditional vendors have played an increasingly important role in supplying the DoD with novel technology.[29]

Government acquisition organizations in the U.S. NDIS are highly varied in terms of their functional contributions. The principal functions performed by these organizations are conducting oversight and setting rules for acquisition, determining what technologies are needed (i.e., setting requirements), resourcing purchases, and promoting information and resource exchange among other actors in the system (i.e., innovation intermediation).

The sections to follow consider these actor types in greater detail by defining the major subtypes, identifying examples of each subtype, and discussing each subtype. The subsequent sections describe, in brief, the relevant major contextual factors and linkages at play within the U.S. NDIS. Figure B.2 depicts the major functional contributions of the U.S. NDIS actors across the three major weapons system development functions.

Figure B.2. Core Contributions of U.S. NDIS Organizations



SOURCE: RAND.

U.S. Research Organizations

As described above, the role of research organizations within the U.S. NDIS is to generate new defense technology-relevant knowledge. These research organizations can be split into three groups: universities, government research organizations, and federally funded research and

[29] Melissa Heikkilä, "Why business is booming for military AI startups," *MIT Technology Review*, July 7, 2022.

development centers (FFRDCs).[30] Table B.1 shows the functional contributions of each group and examples of organizations in each group. The text below the table discusses each group.

Table B.1. Contributions and Examples of U.S. Research Organizations

Organizations	Contributions	Examples
Research universities	fundamental knowledge	Stanford University, University of Michigan, Massachusetts Institute of Technology (MIT), Georgia Institute of Technology
Government research organizations	applied knowledge, mature technology, testing, and evaluation	Naval Research Laboratory (NRL), Air Force Research Laboratory (AFRL), Army Research Laboratory (ARL), Defense Advanced Research Projects Agency (DARPA)
FFRDCs	applied research, disinterested analysis, systems engineering	MIT Lincoln Labs, Georgia Tech Research Institute, MITRE, National Defense Research Institute (RAND Corporation)

U.S. Research Universities

The primary functional contribution of research universities to the U.S. NDIS is to generate new fundamental knowledge.[31] In 2022, according to one open-source metric, the United States hosted 39 of the top 100 global research universities.[32] For military innovation, new fundamental knowledge matters because it generates and enables novel applications. For example, the application of quantum key distribution would be impossible without the foundational knowledge base built by quantum information science researchers. High-energy lasers depend on basic photonics research. And fundamental mathematical concepts, developed over centuries, underly every field of science and engineering.

U.S. Government Research Organizations

In the U.S. NDIS, government research organizations play several functional roles, and there are many distinct types of government research organizations. Defense research labs such as the Naval Research Laboratory (NRL), Army Research Laboratory (ARL), and Air Force Research Laboratory (AFRL) tend to specialize in research with clearly defined end users and use cases. As these organizations sit within the organizational structure of U.S. military service branches, they respond to specific, often service-specific, technology needs. Non-defense government research organizations such as the National Institutes for Health or the Centers for Disease Control and Prevention build the domestic knowledge and skill base, which can have a positive effect on the NDIS if the new knowledge and skill is utilized for military technology innovation.

The Defense Advanced Research Projects Agency (DARPA) is a government research organization that plays a unique role in the U.S. NDIS. DARPA's 2021 budget was $3.5 billion,

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[30] For ease of presentation, we typically use the acronym FFRDCs to include both FFRDCs and University Affiliated Research Centers (UARCs).

[31] While universities play a critical role in educating individuals that make important contributions to the NDIS, we focus here on the research mission of universities.

[32] See Center for World-Class Universities, "2022 Academic Ranking of World Universities", Shanghai Jiao Tong University. As of July 7, 2022: https://www.shanghairanking.com/rankings/arwu/2021

the vast majority of which was dedicated to basic research (BA 6.1), applied research (BA 6.2), and advanced technology development (BA 6.3).[33] DARPA's innovation model is to empower highly expert tenure-limited program managers to make high-risk scientific or technological investments. DARPA is also intentionally insulated from bureaucratic impediments.[34]

Government research organizations also perform critical testing and evaluation (T&E) functions. Service branch and contractor research organizations operate a wide variety of T&E infrastructure, including modeling and simulation facilities, measurement facilities such as wind tunnels and signature measurement facilities, systems integration laboratories for testing hardware/software integration, controlled (often extreme) environments for hardware testing, installed system test facilities able to conduct controlled tests of integrating multiple systems, and field testing ranges.[35] The "core" of this system of testing facilities is the DoD's major range and test facilities, a set of over 20 large-scale facilities used for a variety of operational and developmental tests, including many full-scale field tests of completed weapons systems.[36]

U.S. FFRDCs

Federally Funded Research and Development Centers (FFRDCs) and University Affiliated Research Centers (UARCs) play unique roles in the U.S. NDIS. FFRDCs and UARCs are nonprofit research organizations that serve the applied research needs of U.S. government agencies. There are currently 43 FFRDCs and 14 UARCS.[37] Eleven FFRDCs have an overt defense focus and receive most of their funding through some part of the U.S. defense enterprise.[38]

Because they are nonprofits and external to military or corporate reporting structures, FFRDCs serve as sources of objective and disinterested analysis. Gholz and Sapolsky summarize the contribution of FFRDCs and UARCS to the U.S. NDIS by stating that these organizations "[p]reserve the institutional memory about past R&D efforts, cultivating multiple design-team philosophies that enable diverse approaches to technological challenges, and using their

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[33] Marcey E. Gallo, "Defense advanced research projects agency: Overview and issues for congress," Congressional Research Service, 2021.

[34] William B. Bonvillian, "DARPA and its ARPA-E and IARPA clones: a unique innovation organization model," *Industrial and Corporate Change*, Vol. 27, No. 5, September 12, 2018.

[35] Bernard Fox, Michael Boito, John C. Graser, and Obaid Younossi, *Test and Evaluation Trends and Costs for Aircraft and Guided Weapons*, Santa Monica, Calif.: RAND Corporation, MG-109-AF, 2004. pp. 28-30. As of September 23, 2022: https://www.rand.org/pubs/monographs/MG109.html

[36] C. David Brown, *Memorandum for Secretaries of the Military Departments: Composition of the Major Range and Test Facility Base,* Department of Defense Test Resource Management Center, March 31, 2016; U.S. Department of Defense, *Directive 3200.11*, December 27, 2007, updated October 15, 2018.

[37] See National Center for Science and Engineering Statistics, "Master Government List of Federally Funded R&D Centers," National Science Foundation, February 2022; and DoD Innovation Marketplace, ":Federally Funded Research and Development Centers and University Affiliated Research Centers," webpage, U.S. Department of Defense, last updated March 2021.

[38] Ibid.

independence to prevent the capture of the U.S. R&D effort by rent-seeking activities of government customers and private-sector suppliers.[39]

U.S. Production Enterprises

Table B.2 shows the functional contributions of each group of U.S. production enterprises and examples of enterprises in each group. The text below the table discusses each group.

Table B.2. Contributions and Examples of U.S. Production Enterprises

Enterprises	Contributions	Examples
Defense prime contractors	systems integration, applied research, subcontractor coordination, navigation of defense contracting rules, manufacturing	Lockheed Martin, Northrop Grumman, Raytheon, Boeing, General Dynamics
Component producers	highly specialized components, novel technology	Federal Electronics (aerospace electronics components for navigation and guidance), Eaton Metal Products (pressure vessels), Bonney Forge Corporation (steel valves)
Nontraditional defense contractors	novel technology	Palantir (analytics), Epirus (directed energy), Anduril (autonomous systems)
Public manufacturers	late-stage development, manufacturing	Watervliet Arsenal, Crane Army Ammunition Activity, Norfolk Naval shipyard

U.S. Defense Prime Contractors

Defense prime contractors (primes) make several distinct functional contributions to the U.S. NDIS. Modern weapons systems are enormously complex technologies comprised of myriad components, produced by myriad organizations. In the modern U.S. NDIS, primes perform the technical task of integrating these systems as well as the administrative tasks of coordinating, identifying, selecting, and contracting component producers. Final construction of battle-ready platforms is completed both at facilities owned by these firms and at facilities that they operate on behalf of the government.[40] Gholz and Sapolsky describe the extent of these technical and administrative tasks: "The primes' job is to bring together a network of subcontractors with the appropriate technology and skills and manage them [component producers] to an exacting schedule and within certain budget limits to build systems that can survive and dominate in the

[39] Eugene Gholz and Harvey M. Sapolsky, "The defense innovation machine: Why the U.S. will remain on the cutting edge," *Journal of Strategic Studies*, Vol. 44, No. 6, June 24, 2021, p. 860.

[40] Environmental Protection Agency, "Air Force Plant #4 (General Dynamics) Fort Worth, TX Cleanup Activities," webpage, undated. As of September 26, 2022: https://cumulis.epa.gov/supercpad/SiteProfiles/index.cfm?fuseaction=second.cleanup&id=0603610#content; U.S. Army, "Lake City Army Ammunition Plant," webpage, undated. As of September 26, 2022: https://www.jmc.army.mil/thumbnails/pdfs/Lake%20City%202019%20WEB.PDF; U.S. Army, "U.S. Army Watervliet Arsenal: Building On Excellence. Forging the Future," webpage, undated. As of September 26, 2022: https://wva.army.mil/; Newport News Shipbuilding, "Facilities and Capabilities," webpage, undated. As of September 26, 2022: https://nns.huntingtoningalls.com/who-we-are/facilities-and-capabilities/.

harshest environment of them all, a battlefield, usually after traversing another difficult environment like space or the ocean to get to the fight."[41]

U.S. Component Producers

Defense primes are aided by a dizzying array of thousands of subcontractors, many of which provide specialized technological or manufacturing expertise for particular components.[42] Component producers design and produce components of military technology systems. They are often small- or medium-sized firms, though in some cases they can be quite large. These organizations specialize in producing components that meet exacting military specifications to be integrated into a final weapons system, including everything from magnesium sand-cast aluminum structural parts to ammonium perchlorate for propulsion systems to anti-radar chaff.[43]

U.S. Nontraditional Defense Contractors

The primary functional contribution of nontraditional defense contractors[44]—typically start-ups or technology-focused firms that have not traditionally sold to the U.S. government—is to introduce cutting-edge technologies to the U.S. arsenal.[45] Defense startups typically initially orient their businesses around a single or a small set of technologies. Another type of nontraditional defense contractors are civilian-facing firms that begin to sell to the DoD. These might include large tech-focused firms such as Microsoft or IBM or smaller firms such as Skydio or Saildrone that provide a specific final product to the DoD.

U.S. Public Manufacturers

The DoD runs a small number of weapons manufacturing facilities or arsenals. Such facilities, which are often operated by private contractors, include many of the Army's munitions

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[41] Eugene Gholz and Harvey M. Sapolsky, "The defense innovation machine: Why the U.S. will remain on the cutting edge," *Journal of Strategic Studies*, Vol. 44, No. 6, June 24, 2021, pp. 865-866.

[42] Amanda and Alex Bresler identified over 13,000 defense subcontractors, some of which were awarded hundreds of millions of dollars in contracts. See Alex Bresler, and Amanda Bresler, "Analyzing the Composition of the Department of Defense Small Business Industrial Base," *Excerpt from the Proceedings of the Nineteenth Annual Acquisition Research Symposium,* Naval Postgraduate School, May 11-12, 2022.

[43] Interagency Task Force in Fulfillment of Executive Order 13806, *Assessing and Strengthening the Manufacturing and Defense Industrial Base and Supply Chain Resiliency of the United States,* U.S. Department of Defense, September 2018.

[44] To track contractor participation by performer type, a DoD nontraditional defense contractor is an entity that has not performed for the DoD, or as a DoD contractor, within the past year. Our definition here is different; we define NTDCs as firms without a significant history of DoD contracts or firms for which the majority of revenue is not from government contracts.

[45] Defense Innovation Unit, "Commercial Solutions Catalogue," webpage, undated. As of September 24, 2022: https://www.diu.mil/solutions/portfolio/catalog.

manufacturing plants and U.S. nuclear weapons production facilities.[46] For example, the Watervliet Arsenal in New York and the Crane Army Ammunition Activity in Indiana manufacture munitions and artillery for the U.S. Army. The U.S. military service branches also operate a system of depots and shipyards in which existing platforms are repaired and modernized, incorporating new technological advances and subcomponents.[47]

U.S. Government Acquisition Organizations

Table B.3 shows the functional contributions of each group of U.S. government acquisition organizations and examples of organizations in each group. The text below the table discusses each group.

Table B.3. Contributions and Examples of U.S. Government Acquisition Organizations

Organizations	Contributions	Examples
Defense innovation intermediaries	boundary spanning	Defense Innovation Unit (DIU), Defense Innovation Board, AFWERX, Hacking for Defense
Office of the Secretary of Defense	oversight, rule setting	Office of the Undersecretary (Research and Engineering), Office of the Undersecretary (Acquisition and Sustainment), Cost Assessment and Program Evaluation (CAPE)
Military services	resourcing	U.S. Army, U.S. Navy, U.S. Air Force
Combatant commands	set demand, field technology	Central Command, Indo-Pacific Command, Northern Command

U.S. Defense Innovation Intermediaries

The primary functional contribution of defense innovation intermediaries (DIIs) is to boundary span—i.e., to promote strong information and resource linkages among the other system actors. In recent years, DoD and the services have established many new organizations that serve, at least in part, as DIIs. Examples include the Defense Innovation Unit (DIU), the National Security Innovation Network, National Security Innovation Capital, the Defense Innovation Board, AFWERX, and Hacking for Defense. One of the primary intended roles of these organizations is to establish linkages between the DoD and the large set of nontraditional defense contractors. To this end, they aid in navigating government procurement regulations (e.g., the Federal Acquisition Regulation and the Defense Federal Acquisition Regulation

[46] U.S. Army, "Lake City Army Ammunition Plant," webpage, undated. As of September 26, 2022: https://www.jmc.army.mil/thumbnails/pdfs/Lake%20City%202019%20WEB.PDF; U.S. Army, "U.S. Army Watervliet Arsenal: Building On Excellence. Forging the Future," webpage, undated. As of September 26, 2022: https://wva.army.mil; Y12 National Security Complex, "About", webpage, undated. As of September 28, 2022: https://www.y12.doe.gov/about.

[47] Myra McKitrick, *The Army's Organic Industrial Base: What is the Future for Depots and Arsenals*, Lexington Institute, February 2005; Defense Acquisition University, "Life Cycle Logistics," webpage, undated. As of September 28, 2022: https://www.dau.edu/cop/log/Pages/Topics/Depot%20Level%20Maintenance.aspx.

Supplement); communicating defense demand via events, competitions, and announcements; and investing in firms.[48]

U.S. Office of the Secretary of Defense

The role of the Office of the Secretary of Defense (OSD) in the U.S. NDIS is to establish the rules by which defense acquisition takes place and conduct oversight of the services. The Office of the Undersecretary (Research and Engineering)—OUSD(R&E)—and the Office of the Undersecretary (Acquisition and Sustainment)—OUSD(A&S)—establish policy and oversee the acquisition system as executed by each service. The office of Cost Assessment and Program Evaluation (CAPE) focuses more on oversight of the Planning, Programming, Budgeting, and Execution (PPBE) system and the Joint Capabilities Integration and Development System (JCIDS). The Defense Acquisition System (DAS), PPBE system, and JCIDS all overlap and interact with final authority resting in the Secretary of Defense, which in recent years has been exercised by the Deputy Secretary of Defense via the Deputy Action Management Group.

U.S. Military Services

The primary function of the military departments (i.e., Army, Navy, Air Force) and their service branches is to man, train, and equip military forces that are allocated to the CCMDs. Each service has a distinct acquisition organization that executes the equipping function to develop the technology, engineer the systems, and procure the equipment. The services also administer the resource allocation process—i.e., the PPBE system. In the United States, the services communicate the need for resources via the Program Objective Memorandum (POM), a document that describes how the service plans to allocate resources over a five-year period. The POM is a key input to the President's budget that is ultimately delivered to Congress. Congress has the final word in the resourcing process via authorization and appropriation, but the services do the core planning and execution.

U.S. Combatant Commands

The primary functional contribution of the combatant commands (CCMDs) to the U.S. NDIS is to set demand. A CCMD sends a demand signal by expressing a requirement for military capabilities directly applicable to its area of responsibility. Typically, the needs are derived from highest-priority operational problems and plans. The requested capabilities, which are provided by the military services, can be met by either additional allocation of force structure or by the insertion of additional technology or equipment to enable the force structure already allocated. The capabilities are allocated through a global force management process overseen by the Chairman of the Joint Chiefs of Staff to advise the Secretary of Defense on the allocation of

[48] Jon Schmid and Jonathan Wong, "The Role of New Defense Innovation Intermediaries in the Emerging Defense Innovation Ecosystem," *Proceedings of the Seventeenth Annual Acquisition Research Symposium*, Naval Postgraduate School Acquisition Research Program, April 13, 2020.

forces to support national security objectives. Additional technology or equipment requirements can take numerous forms such as the traditional requirements process—i.e., the JCIDS process that starts with an Initial Capability Document, a Joint Urgent Operational Need, or a Joint Emergent Operational Need. If the needs are specific to a service, the requirements can also go directly to a service requirements process. Special Operations Command and Cyber Command have special acquisition authorities that allow slightly more independence.[49]

U.S. Contextual Factors

Defense acquisition (sometimes referred to as "big A acquisition") in the United States is typically conceptualized as comprising three major components: requirements, resourcing, and acquisition. These components, in turn, are governed by three respective management systems. The requirements process—the process by which a military need is identified—is governed by the JCIDS.[50] The resourcing process—the process of requesting and allocating resources to particular acquisition activities—is governed by the PPBE system.[51] The acquisition process—the process of managing the procurement relationship between contractors and the government—is governed by Department of Defense Directive (DoDD) 5000.01, Department of Defense Instruction (DoDI) 5000.02, and the Adaptive Acquisition Framework.[52]

Nondefense contextual factors for the U.S. NDIS include state and federal commercial codes, antitrust policy, and the U.S. intellectual property (IP) system. Generally, the U.S. legal and regulatory institutions are strong.[53] In 2021, the United States ranked in the 90th percentile in the regulatory quality sub-index and the 89th percentile in the rule of law sub-index of the World Bank's 2021 Worldwide Governance Indicators.[54]

IP protections are a contextual factor of particular importance to the U.S. NDIS. Many of the important products (e.g., new basic or applied knowledge) produced by NDIS actors are non-excludable (i.e., it is difficult to restricting access or use by other firms), meaning firms typically require IP protection to assure their exclusive use of newly produced knowledge. Without IP

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[49] Chairman of the Joint Chiefs of Staff, *Charter of the Joint Requirement Oversight Council and Implementation of the Joint Capabilities Integration and Development System*, Joint Staff, CJCSI 5123.01I, October 30, 2021.

[50] JCIDS Manual, *Joint Capabilities Integration and Development System*, U.S. Department of Defense, August 2018.

[51] U.S. Department of Defense Directive (DODD) 7045.14, *The Planning, Programming, Budgeting, and Execution (PPBE) Process*, U.S. Department of Defense, August 29, 2017.

[52] U.S. Department of Defense Directive (DODD) 5000.01, *The Defense Acquisition System*, Executive Services Directorate, Office of the Under Secretary of Defense for Acquisition and Sustainment, September 9, 2020; DODD 5000.2, *Operation of the Adaptive Acquisition Framework*, Office of the Under Secretary of Defense for Acquisition and Sustainment, January 23, 2020; DODI 5000.02T, *Operation of the Defense Acquisition System*, U.S. Department of Defense, January 23, 2020.

[53] Across all five of the Worldwide Governance Indicators, the U.S. percentile ranking has continuously fallen from 2016 to 2021.

[54] World Bank, "Worldwide Governance Indicators," webpage, last updated September 23, 2022. As of May 1, 2023: https://info.worldbank.org/governance/wgi/.

protection, these actors would not likely be able to capture the full returns to their efforts. Strong IP protection incentivizes NDIS actors by increasing the likelihood they will be able to appropriate the returns to their outputs. Strong IP protection has been empirically linked to higher rates of innovation.[55] In the United States, IP protections are relatively strong; in 2022, the United States ranked 13th globally on the International Property Rights Index score.[56]

U.S. Linkages

The functional contribution of linkages is the facilitation of information and resources throughout the U.S. NDIS. There is significant variability in the character and strength of these linkages. A full assessment of NDIS linkages would require investigation into myriad bilateral relationships among thousands of NDIS actors. Because this appendix is concerned primarily with defining the NDIS as a conceptual framework for use in subsequent empirical assessment at the level of technology domains (e.g., quantum science), we characterize linkages at a high level of aggregation. Specifically, we briefly describe the overall status of the bilateral relationships between the three major NDIS actor types: research organizations, production enterprises, and government acquisition organizations.

In the United States, the relationship between research organizations and government acquisition organizations is generally strong. For example, FFRDCs and government acquisition organizations have historically had a close relationship, as the former has responded to the research and developments needs of the latter. Similarly, defense research labs such as NRL, ARL, AFRL sit within the organizational structure of U.S. military service branches and are thus highly responsive to service-specific, technology needs. The primary formal ties between U.S. research universities and the DoD are limited-term contracts by which the DoD funds university faculty research—in contrast to the PRC, where certain research universities sit within the military bureaucracy and the Chinese Communist Party (CCP) has strong influence over all universities.

The relationship between production enterprises and government acquisition organizations is mixed. Firms that are oriented around government contracting tend to have strong, and mutual, ties to government acquisition organizations, but firms that are not oriented around government contracting do not. For example, defense primes are keenly aware of DoD demand, and the DoD is typically aware of the ongoing development activities and capabilities of the defense primes.

In contrast, firms that mostly service a civilian market tend to be unaware of government demand, tend to be unwilling to navigate burdensome government contracting requirements, or tend to have ethical concerns about the military's lethal use of a technology.[57] In recent years, the

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[55] Cassandra Mehlig Sweet and Dalibor Sacha Eterovic Maggio, "Do Stronger Intellectual Property Rights Increase Innovation?", *World Development* 66, February 1, 2015, pp. 665-677.

[56] Property Rights Alliance, International Property Rights Index, 2022.

[57] Molly Wood, "Some tech employees don't want their work used by the military," *Marketplace Tech Blogs*, February 27, 2019.

DoD has sought to strengthen the linkages between government acquisition organizations and nontraditional defense contractors.[58] Seeking to gain access to state-of-the-art technology—which is viewed as occurring primarily in the commercial sector, especially in high-priority sectors such as machine learning, advanced software, and autonomous systems—the DoD has stood up innovation intermediaries and taken measures to reduce the administrative burden for would-be contractors (e.g., relying increasingly on Other Transaction Authority, a less burdensome contracting method).

In the United States, the relationship between research organizations and production enterprises tends to be relatively strong. For example, co-authorship between researchers based within firms and those based at universities is more than four times as common in the United States as in the People's Republic of China.[59] Further, many U.S. universities have longstanding formal or informal relationships with U.S. firms; in such partnerships, the universities tend to provide cutting-edge scientific and technical knowledge, while the firms provide funding and experience in commercialization.[60]

PRC National Defense Innovation System

Increasing PRC's indigenous technology innovation capacity is central to Xi Jinping's economic development strategy.[61] Efforts to cultivate an indigenous innovation capacity reflect a well-resourced and high-priority attempt to move away from a fast-follower model, by which the PRC specialized in reverse engineering and sophisticated production processes, to the generation of new-to-the-world invention.[62] Attendant policies seek to build a robust domestic scientific and technological ecosystem through targeted investment, the establishment of research facilities, the attraction of Chinese and non-Chinese talent from abroad, and the subsidization of science parks and science cities. Specific policy actions to this end are promulgated in strategic policy bundles

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[58] Schmid and Wong, 2020.

[59] Cortney Weinbaum, Caolionn O'Connell, Steven W. Popper, M. Scott Bond, Hannah Jane Byrne, Christian Curriden, Gregory Weider Fauerbach, Sale Lilly, Jared Mondschein, and Jon Schmid, Assessing Systemic Strengths and Vulnerabilities of China's Defense Industrial Base: With a Repeatable Methodology for Other Countries. Santa Monica, CA: RAND Corporation, 2022.

[60] Jan Youtie and Philip Shapira, "Building an innovation hub: A case study of the transformation of university roles in regional technological and economic development," *Research Policy*, Vol. 37, No. 8, September 1, 2008, pp. 1188-1204; Jon Schmid, Sergey A. Kolesnikov, and Jan Youtie, "Plans versus experiences in transitioning transnational education into research and economic development: a case study," *Science and Public Policy,* Vol. 45, No. 1, February 1, 2018, pp. 103-116; Shahid Yusuf, "Intermediating knowledge exchange between universities and businesses," *Research Policy*, Vol. 37, No. 8, September 1, 2008, pp. 1167-1174.

[61] Increased emphasis on technological innovation as a source of economic growth in China is articulated in *Xinhua News Agency*, "The CCP Central Commission and State Council Release the National Innovation-Driven Development Strategy Outline" [中共中央 国务院印发《国家创新驱动发展战略纲要》], ed. by Wang Jianing, May 19, 2016 within Elsa B. Kania, "China's quest for quantum advantage—Strategic and defense innovation at a new frontier," *Journal of Strategic Studies,* Vol. 44, No. 6, December 27, 2021.

[62] Elsa B. Kania, "China's quest for quantum advantage—Strategic and defense innovation at a new frontier," *Journal of Strategic Studies,* Vol. 44, No. 6, December 27, 2021.

that include Made in China 2025 and the 13th Five-Year (2016-2020) Scientific and Technological Innovation Plan.

Building indigenous innovation capacity is also central to PRC's military modernization agenda, which seeks to make the PLA a "world class military" by 2049.[63] The PRC seeks to realize military modernization through both the overall innovation promotion strategies mentioned above, and military-specific policies aimed at reforming the defense industrial base and building linkages between civilian and military actors.

General PRC innovation promotion policies often target dual-use scientific domains such as quantum communications, artificial intelligence, and microelectronics. Promotion of these domains is often motivated both by their anticipated commercial importance and by their potential applications to military capabilities. These initiatives have, at least in certain sectors, paid off, as the PRC has become the global leader in the important dual-use sectors of quantum communications, ceramic matrix composites, and advanced complementary metal oxide semiconductor (CMOS) devices. The defense researcher Tai Ming Cheung (2022) has succinctly summarized PRC's progress: "China's defense and dual-use S&T system is demonstrating that it can ingeniously develop high-quality products that—from appearances at least—are getting close to advanced global levels."[64]

PRC's most important overtly military innovation policy is the civil-military fusion (CMF) initiative, which seeks to integrate civilian firms, universities, and government research institutes with the existing defense establishment.[65] CMF is motivated by a perceived weakness in the PRC military innovation model: a segregation between the legacy military and civilian actions, knowledge, and resources. CMF seeks to integrate the military and civilian systems to allow the military sector to leverage the often-more-advanced innovative resources of the burgeoning PRC civilian technology economy.

The three major NDIS actor types—research organizations, production enterprises, and government acquisition organizations—perform the same basic functions in the PRC NDIS as in the U.S. NDIS. However, the types of organizations that perform these functions differ greatly between the countries. Several sections below will describe the functional contributions of the major organization types within the contemporary PRC NDIS. However, given PRC's dramatic, continuing economic transformation and an energetic state that often implements its innovation

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[63] *Xinhuanet*, "Xi Jinping: strive to achieve the party's goal of strengthening the army in the new era and building the People's Army into a world-class army in an all-around way" [习近平：为实现党在新时代的强军目标把人民军队全面建成世界一流军队而奋斗], ed. by Xue Tao, October 26, 2017 within Elsa B. Kania, "China's quest for quantum advantage—Strategic and defense innovation at a new frontier," *Journal of Strategic Studies,* Vol. 44, No. 6, December 27, 2021.

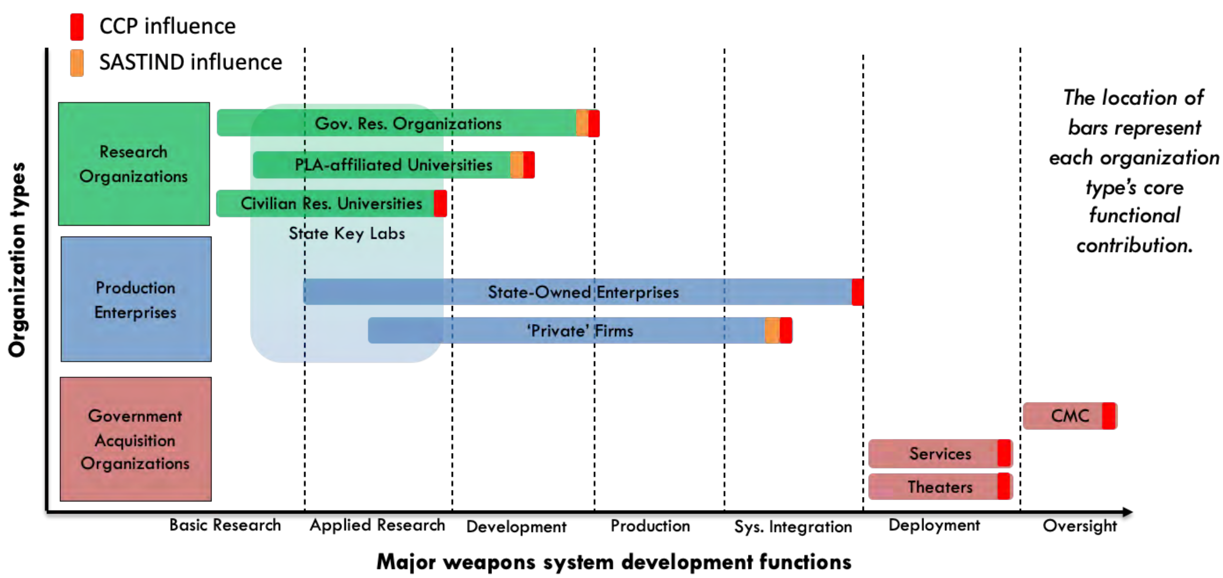
[64] Tai Ming Cheung*, Innovate to Dominate: The Rise of the Chinese Techno-Security State*, Cornell University Press, August 15, 2022, p. 46.

[65] Illustrative of the integration promoted by CMF is a 2016 agreement signed by the National Natural Science Foundation of China and the CMC and the Central Science and Technology Commission (CSTC) to increase civilian-military cooperation in basic science.

agenda by creating new organizations, the organizations and contextual factors that make up the PRC NDIS are younger than those of the United States.[66] Such dynamism also makes the PRC NDIS a moving target. What follows is thus a characterization of how the PRC organizes military technology innovation as of 2023.

Figure B.3 depicts the major PRC NDIS actor types relative to their contributions to the military technological innovation process. Prior to breaking out the contributions of each subgroup of actor types, along with specific members of each subgroup, the next two sections will discuss (1) the ubiquity of the Chinese Communist Party (CCP) throughout PRC's NDIS and (2) the cross-cutting role performed by one PRC government agency: the State Administration of Science, Technology, and Industry for National Defense (SASTIND). Figure B.3 flags the pervasiveness of the CCP and the prevalence of the SASTIND in PRC's NDIS.

Figure B.3. Core Contributions of PRC NDIS Organizations



SOURCE: RAND.

Ubiquity of Chinese Communist Party

The influence of the CCP in the PRC NDIS is ubiquitous. Perhaps the principal difference between PRC's NDIS and that of the United States is the extent to which the government can exert control over, and in some cases even coordinate, NDIS actors. Figure B.3 depicts the role of the CCP in PRC's NDIS as red bands on all the organization types to convey the omnipresence of CCP influence across the system.

[66] Xi describes the PLA strengthening process as a systems engineering project. "Xi views innovation from a top-down systems perspective, which means that there are numerous moving parts, a complex structural layout, and close linkages among the different components." Cheung, 2022.

The influence of the CCP on PRC's NDIS production is found in legislation (i.e., the 1993 PRC Company Law) that requires all firms with three or more party members to establish a party organization at the firms. Similarly, universities in the PRC have CCP committees and secretaries, who are responsible for many major decisions regarding university personnel and overall strategic direction.[67] The PLA is the CCP's military arm, so even the military services and commands are run by their respective party committees and congresses.

Importantly, the influence of the CCP is not absolute and, in fact, varies over time and across NDIS actor types. Illustrative of the limitations of CCP control over military industrial configuration is the relatively recent phenomenon of re-monopolization. Concerned about market concentration and the resultant dearth of innovation, the CCP broke up the state-owned enterprise (SOE) for aviation in 1999, only to see its elements merge again in 2008.[68] Similarly, PRC's nuclear and shipbuilding industries reconsolidated in the late 2010s. The rationale for these reconsolidations is not fully understood at this point, but it could be to exert further control or to reinvigorate innovation.

State Administration of Science, Technology, and Industry for National Defense

The State Administration of Science, Technology, and Industry for National Defense (SASTIND) also plays a cross-cutting role in PRC's NDIS. SASTIND is the successor to the Commission for Science, Technology, and Industry for National Defense (COSTIND), which has had responsibilities for regulating the defense sector since the 1980s.[69] SASTIND is a civilian body that operates under the direct supervision of the Chinese Ministry of Industry and Information Technology.[70]

The primary contributions of SASTIND are administering important NDIS components such as PLA-affiliated universities and government research organizations, engaging with private companies through CMF initiatives, and setting strategic priorities. Thus, Figure B.3 depicts the strong influence of SASTIND in PRC's NDIS as orange bands on three organization types: PLA-affiliated universities, government research organizations, and "private" firms.

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[67] Hua Jiang and Xiaobin Li, "Party Secretaries in Chinese Higher Education Institutions: What Roles Do They Play?" *Journal of International Education and Leadership,* Vol. 6, No. 2, Summer 2016; Mia Ping Chieh Chen, "China's Ruling Party Takes More Direct Control of Colleges, Universities," trans. by Luisetta Mudie, *Radio Free Asia*, April 30, 2021.

[68] Cheung, 2022.

[69] For more information on the formation of COSTIND and the defense sector reforms of the 1980s and 1990s, see Keith Crane, Roger Cliff, Evan S. Medeiros, James C. Mulvenon, and William H. Overholt, *Modernizing China's Military: Opportunities and Constraints*, RAND Corporation, MG-260-1-AF, 2005. As of May 6, 2023: https://www.rand.org/pubs/monographs/MG260-1.html.

[70] State Council of the People's Republic of China, "State Administration for Science, Technology and Industry for National Defense," webpage, last updated October 6, 2014. As of May 6, 2023: http://english.www.gov.cn/state_council/2014/10/06/content_281474992893468.htm.

SASTIND plays an important role in shaping the research agenda of PLA-affiliated universities. SASTIND directly administers the seven sons of national defense (国防七子), a set of seven research universities. These universities contain many strong science and engineering departments and are disproportionately engaged in military technology research.[71] Many civilian universities with large defense research portfolios have established agreements with SASTIND, giving the agency some oversight over their operations as well.[72]

SASTIND also manages the defense-focused parts of the government research laboratory system. These include the Defense S&T National Laboratories, the Defense Key S&T National Laboratories, and the Defense Core Discipline Laboratories.[73] Since 2019, SASTIND has established at least 60 new defense-focused laboratories.[74]

Another primary role of SASTIND is to involve nontraditional contractors in the PRC defense acquisition process as part of the CMF initiative. To this end, SASTIND administers the weapons and equipment research and production license (WERPL) process, which seeks to open defense acquisition to nontraditional contractors (i.e., organizations other than SOEs). SASTIND also publishes the Weapons and Equipment Research, Development, and Production License Catalog (WERDPLC), which aims to open procurement to a wider range of contractors. SASTIND publishes the WERDPLC jointly with the Equipment Development Department (EDD) of the Central Military Commission (CMC).

Finally, SASTIND plays a role in setting strategic military R&D priorities.[75] To this end, SASTIND has published important policy documents,[76] stood up key strategy-setting bodies such as the National Defense Science and Technology Development Strategy Committee and drafted a Defense S&T Industry 2025 plan.[77]

PRC's Research Organizations

Table B.4 shows the functional contributions of each group of PRC's research organizations and examples of organizations in each group. The text below the table discusses each group.

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[71] Jon Schmid and Nathaniel Edenfield, *Scientific and Technological Flows Between the United States and China*, Santa Monica, CA: RAND Corporation, RR-A2308-1, 2023. As of June 20, 2023: https://www.rand.org/pubs/research_reports/RRA2308-1.html

[72] Australia Strategic Policy Institute, "China Defense Universities Tracker," webpage, last updated May 2021. As of May 7, 2023: https://unitracker.aspi.org.au/.

[73] Alex Stone and Ma Xiu, The PRC State & Defense Laboratory System: An Overview. April 2022.

[74] Cheung, 2022.

[75] Cheung, 2022, pp. 114, 156, 168.

[76] Original CSET Translation of "Project to Strengthen Development of the Defense Technology Industry at the Grassroots Level: Guidelines for Basic Research and Cutting-Edge Technology Projects" [国防科技工业强基工程基础研究与前沿技术项目指南（2018年）], China's State Administration of Science, Technology and Industry for National Defence, June 2018.

[77] Cheung, 2022.

Table B.4. Contributions and Examples of PRC Research Organizations

Organizations	Contributions	Examples
Government research organizations	applied defense research and development, mature technology, testing and evaluation	Jinan Institute of Quantum Technology, Institute of High Energy Physics, National Center for Nano Science and Technology, Institute of Software, Institute of Semiconductors
PLA-affiliated research universities	fundamental knowledge, applied defense research and development	National University of Defense Technology, Harbin Engineering University, Beijing Institute of Technology, Beihang University
Civilian research universities	fundamental knowledge	Zhejiang University, Shanghai Jiao Tong University, University of Science and Technology of China, Fudan University
State key labs; Defense key labs	funding stream for major research institutions at universities, enterprises, and the Chinese Academy of Sciences (CAS)	National Key Laboratory of Applied Optics, State Key Laboratory of Tropical Crop Biotechnology, State Key Laboratory of Quantum Optics and Light Quantum Devices, State Key Laboratory of Cognitive Intelligence

PRC's Government Research Organizations

The PRC hosts a very large number of government research institutes. The primary functional contribution of these institutes is to conduct basic and applied research on domains of government interest. In the PRC, government research institutes are often organized by subject area (e.g., high-energy physics, semiconductors, or advanced materials).

The Chinese Academy of Sciences (CAS) is the most important player within this ecosystem. The CAS is the world's largest research-based national science academy, with nearly 68,000 staff, the majority of whom are classified as researchers.[78] The CAS is an umbrella organization that administers over 100 distinct discipline-focused research institutes such as the Institute of High Energy Physics and the National Center for Nano Science and Technology. The CAS has featured prominently in important national S&T policy initiatives, including the PRC's 13th Five-Year Plan (2016-2020) and Made in China 2025.

The PRC has also founded at least 20 national labs and research centers. These focus mostly on relatively broad areas of basic research (as opposed to state key labs, which tend to be more narrowly focused) and can host hundreds of researchers. The national labs and research centers are managed by a variety of CAS institutes, other government research organs, private universities, and private companies.[79]

The PLA has inherited a large system of these national laboratories and test ranges. These facilities include very large missile test facilities,[80] large air force test and training ranges,[81] the

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[78] Chinese Academy of Sciences, "About Us," webpage, undated. As of July 10, 2022: http://english.cas.cn/about_us/introduction/201501/t20150114_135284.shtml

[79] Emily S. Weinstein, Channing Lee, Ryan Fedasiuk, and Anna Puglisi, *China's State Key Laboratory System,* Center for Security and Emerging Technology, June 2022.

[80] Ma Xiu, *PLA Rocket Force Organization,* China Aerospace Studies Institute, 2022; Sam LaGrone and H.I. Sutton, "China Builds Missile Targets Shaped Like U.S. Aircraft Carrier, Destroyers in Remote Desert," *USNI News*, November 7, 2021.

[81] Kenneth Allen and Jana Allen, *Four Key Training Brands,* China Aerospace Studies Institute, 2018. pp. 14, 20.

largest ground forces training base in Asia,[82] large amphibious warfare training ranges,[83] the world's largest unmanned surface vehicle testing facility,[84] and more than a dozen cyber test ranges.[85]

Beyond basic research, the PRC has at least 374 National Engineering Technology Research Centers (NETRCs) that are dedicated to facilitating the development and assimilation of "chokepoint" technologies, especially those that are vulnerable to foreign export controls.[86] These research centers are currently undergoing reform to meet current policy objectives. For instance, reports published by the Ministry of Science and Technology (MOST) indicate that accomplishments in "self-developed R&D" and "indigenous innovation" have been occupying a greater percentage of the centers' overall innovation, from 70 percent in 2014 to 89 percent in 2016.[87] This increase in homegrown innovation aligns with the CCP Central Committee's 2016 Innovation-Driven Development Strategy and the "13th Five-Year Plan for Science and Technology Innovation" to promote technological "self-reliance."

Finally, the PLA can make use of a variety of government scientific institutions not connected to the CAS. These include the China Academy of Engineering Physics (mostly involved in PRC's nuclear program), the Northwest Institute of Nuclear Technology, and the country's satellite launch and control centers, as well as a host of provincial-level institutes.

PRC's PLA-Affiliated Research Universities

Research universities with strong formal military ties are a differentiating feature of PRC's NDIS. The primary functional contribution of PLA-affiliated research universities is to conduct applied research at the direction of the PLA. They also train many of the technical personnel who go on to staff the PRC defense industrial base. The primary difference between this organization type and PRC's civilian research universities is the strength of the relationship with the PLA and the attendant role of these universities in advancing PLA priorities.

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[82] Jane's Group, "China - Army," webpage, May 2022. As of November 15, 2022: https://customer.janes.com/Janes/Display/JWARA133-JWAR.

[83] Ibid.

[84] Kristen Hwang, "China starts work on world's biggest test site for drone ships at gateway to South China Sea," *South China Morning Post,* February 12, 2018.

[85] Dakota Cary, *Downrange: A Survey of China's Cyber Ranges,* Washington D.C.: CSET, September 2022.

[86] Michael Laha, "In Search of Self-Reliance: Xi Overhauls China's Innovation System", China Brief, Jamestown Foundation, webpage, February 17, 2023. As of May 8, 2023: https://jamestown.org/program/in-search-of-self-reliance-xi-overhauls-chinas-innovation-system/

[87] National Engineering Research Center: 2014 Annual Report, Ministry of Science and Technology; National Engineering Research Center: 2016 Annual Report, Ministry of Science and Technology

We classify two sets of PLA-affiliated universities: the seven sons of national defense and military universities.[88] The seven sons of national defense (国防七子)[89] are formally subordinate to the SASTIND. They consider themselves to be "defense science, technology and industry work units" and instruments of the "defense system."[90] The PRC also hosts a set of military universities, or universities that are within the same organizational structure as the PLA. While most of these focus on training officers, some have strong research capacity and seek to advance PLA military modernization objectives through research. For example, whereas the primary role of the PLA Air Force Command College is to train mid- and senior-ranking officers, military universities such as the National University of Defense Technology and the Academy of Military Science conduct significant research operations, to include scientific research.

PRC's Civilian Research Universities

The primary functional contribution of PRC's civilian research universities is to produce new knowledge by conducting basic and applied research. Civilian research universities are defined as the subset of research universities in the PRC that are not PLA-affiliated. While civilian universities may receive funding from the PLA to conduct military-relevant research, or even host PLA-affiliated (and -funded) laboratories, they are not principally organs of the PLA.[91] As mentioned, universities in the PRC have CCP committees and secretaries that are responsible for many major decisions regarding personnel and strategy.[92] These committees give the party a great degree of control over, and visibility onto, university campuses.

The quality of PRC research universities has improved significantly over the past two decades. In 2003, the PRC hosted none of the top 100 global research universities, whereas in 2022, the PRC hosted nine.[93] Since 2016, the PRC has surpassed the United States in terms of total scientific output and produced the highest share of scientific papers in the top percent of cited publications in 2018, 2019, and 2020.[94] PRC's recent lead in highly cited publications

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[88] Australia Strategic Policy Institute, 2021.

[89] Seven sons of national defense: Beihang University, Beijing Institute of Technology, Harbin Engineering University, Harbin Institute of Technology, Nanjing University of Aeronautics and Astronautics, Nanjing University of Science and Technology, Northwestern Polytechnical University

[90] Alex Joske, *The China Defence Universities Tracker*, Canberra: Australian Strategic Policy Centre: International Cyber Policy Centre, No. 23, 2019, p. 6.

[91] Australia Strategic Policy Institute, 2021.

[92] Jiang and Li, 2016, pp. 6-7; Chen, 2021.

[93] Based on 2022 Academic Ranking of World Universities calculated by Shanghai Jiao Tong University https://www.shanghairanking.com/rankings/arwu/2021

[94] Jeffrey Brainard and Dennis Normile, "China rises to first place in most cited papers," *ScienceInsider,* August 17, 2022.

extends to the most high-impact segment of the citation distribution: In 2019 and 2020, the PRC produced more publications than any other country in the top 0.1 percent of citations received.[95]

PRC's State Key Labs and Defense Key Labs

PRC's state key labs and defense key labs are generally hosted by academic institutions, CAS institutes, or private companies (including SOEs).[96] Most state key labs (SKLs) were pre-existing laboratories or facilities that applied for and were granted SKL status. SKL status generally comes with a dedicated stream of funding from a government agency, usually the Ministry of Science and Technology, the Ministry of Education, or the CAS.[97] There are hundreds of these labs throughout the PRC, and they tend to focus on relatively narrow subject areas or problems. PRC's SASTIND oversees a parallel system of defense key labs, also mostly hosted at existing research institutions or companies.[98] These arrangements provide promising research institutions additional resources, prestige, and connections with the PRC government and military.

PRC's Production Enterprises

Table B.5 shows the functional contributions of each group of PRC's production enterprises and examples of organizations in each group. The text below the table discusses each group.

Table B.5. Contributions and Examples of PRC Production Enterprises

Enterprises	Contributions	Examples
State-owned enterprises	applied research and development for the PLA	China Aerospace Science and Technology Corporation (CASC), Aviation Industry Corporation of China (AVIC), China North Industries Group Corporation Limited (Norinco), China Aerospace Science and Industry Corporation (CASIC)
"Private" enterprises	novel technology	DJI Technology Co., Huawei Technologies Co., Tencent Holdings Ltd.

PRC's State-Owned Enterprises

The primary functional contribution of state-owned enterprises (SOEs) to PRC's NDIS is to develop and produce new military technology. These organizations typically serve both civilian and military buyers; in recent years, roughly two-thirds of their profits have come from civilian

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[95] Cortney Weinbaum, Caolionn O'Connell, Steven W. Popper, M. Scott Bond, Hannah Jane Byrne, Christian Curriden, Gregory Weider Fauerbach, Sale Lilly, Jared Mondschein, and Jon Schmid, Assessing Systemic Strengths and Vulnerabilities of China's Defense Industrial Base: With a Repeatable Methodology for Other Countries. Santa Monica, CA: RAND Corporation, 2022. https://www.rand.org/pubs/research_reports/RRA930-1.html. Also available in print form.

[96] Weinstein, Lee, Fedasiuk, and Puglisi, 2022, p. 13.

[97] Weinstein, Lee, Fedasiuk, and Puglisi, 2022 pp. 9, 14-17

[98] Weinstein, Lee, Fedasiuk, and Puglisi, 2022; Australia Strategic Policy Institute, "Defense Laboratories," webpage, undated. As of November 17, 2022: https://unitracker.aspi.org.au/defence-laboratories/.

sales.[99] As opposed to U.S. defense primes that have a wide range of military products, SOEs tend to specialize on a narrow range of defense technologies, which limits competition for these technologies. In fact, SOEs are often awarded contracts through single-source selection processes.[100]

Historically, SOEs have not been at the technological frontier. To ameliorate this situation, the CCP has taken actions to expose these organizations to market forces and has broken up large SOEs. Since the mid-2000s, SOEs have been profitable, with annual profit margins varying within a narrow range of 4.5 percent to 5.8 percent.[101]

SOEs have taken steps to increase their innovative capacities, establishing at least 14 defense S&T industrial technology innovation centers in the past decade. For example, the China Academy of Launch Vehicle Technology (CALT) established the Defense Science and Technology Industry Strategic Rocket Innovation Center, and the China Shipbuilding Industry Corporation established the Defense Technology Maritime Innovation Center. (Cheung, 2022).[102]

While SOEs in the PRC have made significant progress toward modernization and profitability, PRC's NDIS still faces a monopoly problem. Cheung summarizes this problem succinctly: "Little competition exists in the awarding of contracts for major weapons systems and defense equipment because each of the country's six traditional defense industrial sectors are closed to outside competition and dominated by one or two state-owned defense industrial corporations" (Cheung, p. 171).[103]

PRC's "Private" Enterprises

The PRC has a relatively large number of civilian organizations involved in developing defense technologies: 39 such organizations were granted at least one military technology patent in the PRC in 2019, compared with just 12 in the United States.[104] While SOEs remain, far and away, the most important advanced development and production contributors to the PRC NDIS, PRC's burgeoning civilian economy is beginning to make inroads into the defense sector. The civilian firms have been aided by CMF efforts such as the publishing of a military needs catalog, the hosting of trade fairs and exhibitions, the increasing transparency of the acquisition process, and the opening of procurement vehicles such as WERPLs and equipment contractor certificates

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[99] Cheung, 2022.

[100] Cheung, 2022.

[101] Ibid.

[102] Ibid.

[103] Ibid.

[104] Cortney Weinbaum, Caolionn O'Connell, Steven W. Popper, M. Scott Bond, Hannah Jane Byrne, Christian Curriden, Gregory Weider Fauerbach, Sale Lilly, Jared Mondschein, and Jon Schmid, *Assessing Systemic Strengths and Vulnerabilities of China's Defense Industrial Base: With a Repeatable Methodology for Other Countries*. Santa Monica, CA: RAND Corporation, 2022.

(ECCs) to private firms. Evidence is found in the growing numbers of such licenses and certificates granted to private firms. In 2016, more than 1,000 commercial firms were awarded WERPLs, according to SASTIND, indicating significant growth from previous totals.[105]

Commercial entry into the military sector has been particularly evident in the field of unmanned aerial systems (UASs). The civilian firms, Xi'an Aisheng Technology Group and AEE Technology Co., have produced several UASs for the PLA.[106]

Many PRC companies are confirmed to have strong ties to the PRC military, including entities that are owned, controlled by, or affiliated with the PLA. In 2020, the Pentagon listed several PRC companies that claim to be "independently operated enterprises" that are affiliated in some capacity with the PLA, including Huawei, Hikvision, and Panda Electronics Group.[107] Since 2019, the U.S. Department of Treasury has linked 41 technology companies to the PLA, including SZ DJI Technology Co., Aviation Industry Corporation of China, Ltd. (AVIC), and Megvii Technology Limited.[108] SZ DJI Technology Co., Cloudwalk Technology, and six other PRC companies have been identified by the U.S. Department of the Treasury as operating with the PLA to develop and deploy tracking technology domestically and internationally to countries including Zimbabwe, Thailand, and Pakistan.[109]

PRC private firms have also been shown to have ties with important research organizations within PRC's NDIS. In 2019, Bloomberg reported that Huawei personnel were directly collaborating with The National Defense University of Technology and with ten research endeavors with the PLA.[110] The report noted that CNKI, a private publishing company in the PRC, had published papers with PLA support and with Huawei listed at the top of the papers and as contributors to the research, but Huawei denied any R&D collaboration with the PLA.[111]

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[105] Cheung, 2022.

[106] Ibid.

[107] Tony Capaccio and Jenny Leonard, "Huawei on List of 20 Chinese Companies That Pentagon Says Are Controlled by People's Liberation Army," *TIME*, June 25, 2020.

[108] U.S. Department of Defense, "DOD Releases List of Peoples Republic of China (PRC) Military Companies in Accordance With Section 1260H of the National Defense Authorization Act for Fiscal Year 2021," press release, October 5, 2022.

[109] The data from international deployments is exported back to the PLA for intelligence gathering and technological improvements. U.S. Department of the Treasury, "Treasury Identifies Eight Chinese Tech Firms as Part of The Chinese Military-Industrial Complex," press release, December 16, 2021.

[110] Bloomberg News, "Huawei Personnel Worked with China Military on Research Projects," *Bloomberg*, June 27, 2019; Jun Chen, Jie Li, and Li-bo Nan, "Summary of GIS Development and Application," paper presented at New Development of Communication Theory and Technology, Dalian, 2009.

[111] Bloomberg News, "Huawei Personnel Worked with China Military on Research Projects," *Bloomberg*, June 27, 2019.

PRC's Government Acquisition Organizations

Table B.6 shows the functional contributions of each group of PRC's government acquisition organizations and examples of organizations in each group. The text below the table discusses each group.

Table B.6. Contributions and Examples of PRC Government Acquisition Organizations

Organizations	Contributions	Examples
Central Military Commission	strategic priorities, acquisition plans, acquisition management/oversight, acquisition resourcing	Equipment Development Department (EDD), Science and Technology Commission
Armed services	implementation of defense acquisition and R&D plans, execution of testing and evaluation	PLA Navy (PLAN), PLA Army (PLAA), and PLA Air Force (PLAAF)
Theater commands	set demand	Eastern Theater Command, Southern Theater Command, Western Theater Command, Northern Theater Command, Central Theater Command

PRC's Central Military Commission

The CMC is the most important government actor in PRC's NDIS. The CMC is chaired by President Xi Jinping, whose 2016 reforms have considerably increased his and the CMC's direct authority over its subordinate departments.[112]

The CMC is responsible for updating the country's Military Strategic Guidelines, a document that identifies PRC's key opponents, defines the likely nature of future wars, identifies and prioritizes likely contingencies for which the PLA must prepare, and provides general guidance on PLA modernization.[113] These guidelines form the basis of a national Weapons Equipment Development Strategy formulated by the CMC's EDD. The EDD's national development strategy includes an assessment of global strategic trends, PRC's key adversaries, likely regional conflicts, global technological developments and trends, and the equipment demands that the PLA is likely to face in future wars.[114]

The EDD is responsible for managing PRC's acquisition system across the lifecycle of a defense system.[115] The EDD also oversees procurement and information systems for the armed forces.[116] Several rounds of military reforms have taken place to enable the EDD to better match funding to defense technology innovation needs while reducing waste. For instance, in 2021,

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[112] Mark Ashby, Caolionn O'Connell, Edward Geist, Jair Aguirre, Christian Curriden, and Jonathan Fujiwara, *Defense Acquisition in Russia and China*. Santa Monica, CA: RAND Corporation, 2021. https://www.rand.org/pubs/research_reports/RRA113-1.html.

[113] Cheung, 2022, pp. 145-146.

[114] Cheung, 2022, pp. 153-154.

[115] Ashby, O'Connell, Geist, Aguirre, Curriden, and Fujiwara, 2021.

[116] The predecessor to the EDD, the General Armaments Department (GAD), was viewed as partial to PLA ground forces, whereas the EDD seeks to balance acquisition decisions across the Chinese services.

new regulations were passed to streamline the centralized procurement process and to supply weapons and equipment based on combat needs.[117] Oversight of the EDD is assigned to the Audit Bureau, Politics and Law Commission, and the Discipline Inspection Commission.[118]

One of the 2016 reforms under Xi Jinping was to remove the Science and Technology Commission from the old General Armaments Department (predecessor of the EDD) and to place the commission under direct CMC control. This reform signaled the PLA's renewed emphasis on technological development and on coordination with the defense industry.[119]

PRC's Armed Services

While the EDD develops a national Weapons Equipment Development Strategy, the PLA service branches develop their own Weapons Equipment Development Strategies.[120] The service-specific strategies form the basis of PRC's national and service-level 10-year, 5-year, and 1-year Weapons Equipment Construction Plans. These documents contain the details of equipment research plans, new equipment funding, and equipment maintenance.[121]

The PLA comprises four service branches (PLA Army, PLA Navy, PLA Air Force, and PLA Rocket Force) and two support forces (the Strategic Support Force and the Logistics Support Force). The PLA service branches are the organizations that, to a great extent, implement the Weapons Equipment Development Strategies and the Weapons Equipment Construction Plans. This implementation likely includes gathering input in drafting and updating the service-specific plans; for instance, service-level research institutes such as the PLA Navy's Research Institute and the Navy Equipment Demonstration Center help turn broad plans into specific requirements.[122]

The service branches also provide uniformed "military representatives" who oversee research, development, and production at defense laboratories and factories across the country.[123] These representatives help the entities they oversee handle the administrative tasks necessary for

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[117] Liu Xuanzun, "New regulations to provide PLA with rapid, combat-oriented equipment deliveries," *The Global Times*, November 2, 2021.

[118] Wuthnow, Joel, and Phillip Charles Saunders. *Chinese military reform in the age of Xi Jinping: Drivers, challenges, and Implications*. Government Printing Office, 2017.

[119] Joel Wuthnow and Phillip C. Saunders, "Introduction Appendix: Central Military Commission Reforms," National Defense University, February 8, 2019. As of May 6, 2023: https://ndupress.ndu.edu/Media/News/News-Article-View/Article/1752065/introduction-appendix-central-military-commission-reforms/.

[120] Cheung, 2022, p. 151.

[121] Cheung, 2022, p. 155.

[122] Little information is available as to how the EDD and service-level equipment development departments interact to update and draft the service-level Weapons Equipment Development Strategies and Weapons Equipment Construction Strategies. National-level technical institutes also help in this process. See Tai Ming Cheung, *Innovate to Dominate: The Rise of the Chinese Techno-Security State*, Cornell University Press, August 5, 2022, p. 155.

[123] Tai Ming Cheung, "An Uncertain Transition: Regulatory Reform and Industrial Innovation in China's Defense Research, Development, and Acquisition System," in Tai Ming Cheung, ed., *Forging China's Military Might: A New Framework for Assessing Innovation*, Johns Hopkins University Press, February 24, 2014, pp. 49–52.

defense work. In addition, the representatives oversee experiments, oversee tests, and work to protect their service branches' interests.[124] The services are responsible for operational testing and feedback, often resulting in changes to equipment design.[125]

Although the service branches manage funds to commission scientific research projects, the services are still branches of the PLA, and the PLA is an arm of the CCP. All PLA officers must be party members, and ideological training is required to hold posts. The services are relatively new additions to the PLA, with the current organization of services and priorities reconfigured in 2015.[126] Many of the 2015 reforms were designed to tighten CCP control at all levels of operation.[127]

PRC's Theater Commands

The PRC has five region-based theater commands: Eastern, Southern, Western, Northern, and Central. The theater commands are responsible for wartime operations and war planning. The primary functional contribution of the theater commands to PRC's NDIS is to set demand via annual and multiyear subplans. As part of the 2016 reforms, the theater commands were formed to improve the services' abilities to conduct joint operations and to increase military readiness.

The Eastern Command covers Taiwan, the East China Sea, and Japan; the Southern Command covers the South China Sea and Southeast Asia; the Western Command focuses on India, western and northwestern border territories; the Northern Command focuses on North Korea, South Korea, and (to a lesser extent) Russia; the Central Command defends the capital and serves as a strategic reserve.[128]

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[124] Li Xin [李鑫], "Third Academy 8358 Institute Hosts 2022 PLAAF Military Office Coordination Meeting" ["三院8358所召开2022年空军军所协调会"], CASIC Third Academy, March 21, 2022: http://www.fhjs.casic.cn/n7160835/n7161156/c23194116/content.html; Hu Kaibing [胡锴冰] and Jin Yongchan [金永昰], "Navy Equipment Development Department Builds Cross-Service Military Representative Contract Oversight System" ["海军装备部坚持质量至上以战领建原则 探索构建跨军兵种军代表合同监管体系"], China Military Online [中国军网], October 29, 2019: http://www.81.cn/jpdbfy2019/ywyl_206455/9663060.html; Hu Kaibing [胡锴冰], Lei Zhu [雷柱], and Wang Haofan [王皓凡], "Taking a Closer Look at a Navy Military Representative Office and Getting a Feel for the 'Battlefield Perspective' of the New Age" ["让我们走进海军某军代室，感受新时代监造官们的"战位观"], China Military Online [中国军网], April 21, 2021: http://www.81.cn/yw_208727/10026068.html.

[125] Mark Ashby, Caolionn O'Connell, Edward Geist, Jair Aguirre, Christian Curriden, and Jonathan Fujiwara, *Defense Acquisition in Russia and China*, RAND Corporation, RR-A113-1, 2021, pp. 17-18, https://www.rand.org/pubs/research_reports/RRA113-1.html.

[126] James Char, "Reclaiming the Party's Control of the Gun: Bringing Civilian Authority Back in China's Civil-Military Relations," Journal of Strategic Studies, Vol. 39, No. 5-6, September 18, 2016, pp. 608-636.

[127] Wuthnow and Saunders, 2016.

[128] Timothy R. Heath, "An Overview of China's National Military Strategy," in ed. by Joe McReynolds, *China's Evolving Military Strategy*, Brookings Institution Press, 2016, pp. 1-39.

PRC's Contextual Factors

Little is known about the laws that govern defense acquisition, resourcing, and requirements in the PRC. More is known about the process by which these functions are executed. PRC's requirement process begins with the CMC's *military strategic guidelines,* a codified set of instructions that identify national security threats, goals for military modernization, and general principles for the use of force.[129] The CMC then evaluates the *military strategic capabilities* needed to execute these guidelines. According to military scholars Luo Jiancheng and Geng Kui, this evaluation involves three tasks:

1) Recognize the existing level of military capabilities.
2) Clarify the gap between actual and desired capabilities.
3) Support the formulation of national strategic objectives.

The CMC uses this evaluation to develop a set of requirements, which are then used to inform service and theater command planning.

In accordance with the plans, with performance indicators from the previous year, and with the forecast of revenue and expenditure for the current year, units submit their budget requests from the bottom-up. Financial departments at all levels of command in the theaters and services—from national to regimental levels—carry out the detailed budgetary work for military units. The National People's Congress (NPC) reviews and formally approves the budget every year. Once the budget is approved, the Ministry of Finance disperses funds down to the troops. The National Defense Department within the Ministry of Finance is especially involved in the management of defense-related funds.

Compared with comparable U.S. institutions, PRC's legal and regulatory institutions are weak. In 2021, the PRC ranked in the 41st percentile in the regulatory quality sub-index and the 54th percentile in the rule of law sub-index of the World Bank's 2021 Worldwide Governance Indicators.[130]As described above, IP protections are of critical importance in allowing NDIS actors to realize financial returns on their investments. PRC's IP protections are weak compared with those of the United States; the People's Republic of China ranked 47th globally on the International Property Rights Index score.[131]

PRC's Linkages

Recent RAND research finds that overall linkages among major NDIS entities in the PRC are weak.[132] However, the specific character of inter-organization linkages varies by technology

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[129] Joel Wuthnow and M. Taylor Fravel, "China's Military Strategy for a 'New Era': Some Change, More Continuity, and Tantalizing Hints," *Journal of Strategic Studies*, March 1, 2022.

[130] World Bank, "Worldwide Governance Indicators," webpage, undated. As of May 1, 2023.

[131] Property Rights Alliance, International Property Rights Index, webpage, undated (accessed June 1, 2023).

[132] Cortney Weinbaum, Caolionn O'Connell, Steven W. Popper, M. Scott Bond, Hannah Jane Byrne, Christian Curriden, Gregory Weider Fauerbach, Sale Lilly, Jared Mondschein, and Jon Schmid, *Assessing Systemic Strengths and Vulnerabilities of China's Defense Industrial Base: With a Repeatable Methodology for Other Countries*,

sector. Our characterization of the NDIS linkages is highly generalized. As we did for the United States, below we characterize broadly the major bilateral relationships among the three major NDIS actor types: research organizations, production enterprises, and government acquisition organizations.

The linkage between research organizations and government acquisition organizations is strong in the PRC. The PRC government has significant control over its research organizations. In recent years, over one hundred PRC universities (which typically act as research organizations within PRC's NDIS) have amended their charters to proclaim loyalty to the CCP.[133] In 2022, the CCP instituted laws giving CCP committees within universities broad control over university operations, including the requirements to provide instruction on political ideology, quell political dissent, and establish minimum ratios of party-member representation on university faculties and in student bodies.[134]

Although not strictly a linkage, PRC universities are heavily involved in military technology patenting (a measure of development activity). Of the top military patenting organizations in the PRC in 2019, three were universities, including Nanjing University of Science and Technology, which ranked first globally in military patents received in 2019.[135] Involving universities in the development activities allows the co-mingling of research and development activity and is a positive feature of an innovation system.[136]

PRC's research funding system is highly dependent on a single organization: the National Natural Science Foundation of China (NNSFC). In 2020, the NNSFC was listed as a funder on over 70 percent of PRC scientific publications indexed in the Web of Science.[137] Calculating the Herfindahl–Hirschman Index (HHI) for funding sources to measure the extent of funding concentration also reveals PRC's high degree of reliance on a few funders. In 2020, PRC's HHI for funders was 0.55 (highly concentrated), compared with 0.10 for the United States.[138]

RAND Corporation, RR-A930-1, 2022. As of June 30, 2023: https://www.rand.org/pubs/research_reports/RRA930-1.html

[133] Emily Feng, "Chinese Universities Are Enshrining Communist Party Control In Their Charters," *NPR*, January 20, 2020.

[134] Chen, 2021.

[135] RAND analysis using data from the Derwent Innovation Index.

[136] Jon Schmid and Ayodeji Fajebe, "Variation in patent impact by organization type: An investigation of government, university, and corporate patents," *Science and Public Policy* Vol. 46, No. 4, August 1, 2019; Henry Etzkowitz and Chunyan Zhou, *The Triple Helix: University–Industry–Government Innovation and Entrepreneurship*, Routledge, September 21, 2017.

[137] Cortney Weinbaum, Caolionn O'Connell, Steven W. Popper, M. Scott Bond, Hannah Jane Byrne, Christian Curriden, Gregory Weider Fauerbach, Sale Lilly, Jared Mondschein, and Jon Schmid, *Assessing Systemic Strengths and Vulnerabilities of China's Defense Industrial Base: With a Repeatable Methodology for Other Countries*, RAND Corporation, RR-A930-1, 2022. As of June 30, 2023: https://www.rand.org/pubs/research_reports/RRA930-1.html

[138] Ibid.

In contrast, the relationship between research organizations and production enterprises in the PRC is relatively weak. For example, firm-university collaboration on scientific publications is uncommon in the People's Republic of China compared with the United States. In 2020, the PRC had just 1,946 scientific publications co-authored by firms and universities, compared with 8,162 firm-university co-authorships in the United States.[139]

As in the United States, the relationship between production enterprises and government acquisition organizations is mixed in the PRC. Ties between SOEs and government acquisition organizations are strong. Recent legislation has increased the role of the CCP within PRC SOEs, stipulating that party committees within SOEs outrank the boards of directors, that a SOE's party secretary be appointed as chairman of the board, and that firms operate to advance the interest of the CCP.[140] The CCP's influence extends beyond SOEs. The 1993 PRC Company Law requires that all "private" firms with three or more party members establish a party organization within the firm. However, the PRC has struggled to integrate these organizations into its defense acquisition process.

Just as the United States has identified a need to incorporate nontraditional defense contractors into its military innovation process, the PRC has identified a need to integrate its traditional defense establishment with its more-vibrant commercial and civilian enterprise and research functions. The primary means by which the CCP seeks to integrate these actors is through the high-priority CMF initiative, which is targeting the historically weak linkage between production enterprises and the PRC military technology acquisition apparatus. Specific CMF activities designed to strengthen this relationship include hosting exhibitions for commercial vendors; establishing CMF zones, which include infrastructure to test products against military specifications;[141] and hosting competitions such as The China Military-Civilian Dual Use Technology Innovation Application Competition (中国军民两用技术创新应用大).

Measuring Defense Innovation by Technological Field

The previous sections describe how the U.S. and PRC undertake defense innovation in general. We are interested, however, not only in how these countries organize defense innovation generally but also how these systems work in practice to develop practical defense technologies. To make this jump—from the conceptual to the empirical—requires focusing on the observable markers of innovation.

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[139] Ibid.

[140] Orange Wang and Zhou Xin, "China cements Communist Party's role at top of its SOEs, should 'execute the will of the party,'" *South China Morning Post*, January 8, 2020.

[141] Liu Jing, "Military-Civilian Integration from a Training Fever to See the Way of Breaking the Cocoon of the Traditional Military Industry," *PLA Daily*, July 18, 2018; Network Information Military Civil Fusion [网信军民融合]，"2018 Military and Civilian Integration Events" [2018军民融合大事盘点], webpage, January 2019.

Much of the activity associated with innovation goes unobserved. A researcher's conceptual breakthrough, the hundreds of undocumented tweaks to experimental design, and myriad necessary false starts prior to discovery—all critical inputs to an eventual new technology—are simply not readily observable to those attempting to describe or explain technological change. In the case of defense technology, this problem is exacerbated along all portions of the R&D process by the priority of secrecy. Still, much scientific and technological development activity does leave observable markers: evidence that a given activity has, in fact, taken place.

We focus on these external markers for measuring technological innovation processes in selected technological fields. Specifically, we measure the activity of a country's NDIS as it progresses from research to fielding (i.e., as the country moves rightward on the horizontal axes in Figures B.1 and B.2). We set out to measure elements of three major dimensions of military technology innovation: research, development, and fielding.[142] Each dimension refers to highly complex innovation processes that elude measurement via a single metric. We thus propose to measure particular elements of the dimensions separately, selecting metrics that complement each other to capture a more complete description of each dimension.

Research

Research refers to the undertaking of scientific investigation with the objective of producing new knowledge. Our measurement strategy spans five research elements: scientific output, organizational activity, conference activity, "superstar researchers," and research centrality.

Scientific output is a measure of the quantity of new science a country produces on a given topic. It is measured as the number of Web of Science (WOS)-indexed publications published by organizations from within a country on the focal topic during an analysis period. A wide range of new knowledge can find its way into the overall innovation process. It is hard to determine what increments of new basic knowledge will enable a country to advance a new technology. For example, while a theoretical breakthrough in the field of adaptive optics may push advancement in telescope or high-energy-laser applications, it is less likely, though not uncommon, that development testing of a given telescope will yield a high-energy laser. To capture the uncertain quality of basic knowledge, our search strategy on scientific publications databases aims to capture not only the technologies under consideration, but also the underlying scientific fields.

Organizational activity refers to the organizational resources a country brings to bear on a topic. There is a documented link between S&T-focused organizations and national innovative output.[143] To measure research organization capacity, we catalog how many of the top global

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[142] Because our task here is focused on measurement of progress in military technology innovation, we leverage military-specific markers such as weapons programs starts and fielding. To apply the framework to a commercial technology would require the identification of analogous markers, such as corporate R&D efforts or final products made available in market.

[143] Etzkowitz and Zhou, 2017.

publishing organizations a country hosts in a technological field and how central these organizations are within the global scientific publishing network for the field.

Conference activity measures the domestic academic conference environment. In many scientific fields, conferences serve a critical role in diffusing knowledge and promoting research collaboration.[144] We measure conference activity by identifying the number and approximate size of conferences hosted in a country within the field under consideration.

The superstar researcher element aims to measure the extent to which a country hosts a field's elite researchers. Superstar researchers have been shown to be highly effective not only in producing new knowledge but in diffusing it, especially to universities and firms.[145] We count the number of a country's researchers who fall into the top 0.1 percent of the H-index for a given period. The H-index is measured as the number of papers (H) within the focal field that have been cited at least H times.

Research centrality measures a country's location within the global research ecosystem. Research centrality depends on the metrics of degree, weighted degree, and eigenvector centrality. Degree is simply the number of collaborations (or edges) in a country-level co-authorship network. Weighted degree is the number of international collaborations in such a network. Eigenvector centrality measures not only the number of edges that a node (or country) has, but how many edges its collaborators have throughout the full network.

Development

Development here refers to a process of using existing knowledge to produce a new useful technology or improve on existing technology. We measure six elements of development: program activity, technological output, development organization ecosystem, testing infrastructure, CTE development, and development funding.

Program activity measures the extent to which a country's government has stood up official development programs around the focal technology. Program activity is measured by cataloging the relevant programs from open sources and describing the ongoing development activities.

Technological output measures a country's patenting activity within the focal technology area. Whereas program activity is a measure of development activity limited to government-initiated development efforts, the technological output element is a broader measure of national development activity that captures all patents granted within a topic area regardless of whether they were developed under the auspices of a government development program. Technological

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[144] John G. Gunnell, David Easton, and Luigi Graziano, *The Development of Political Science: A Comparative Survey*, Routledge, 1991; Kalle Hauss, "What are the social and scientific benefits of participating at academic conferences? Insights from a survey among doctoral students and postdocs in Germany," *Research Evaluation*, Vol. 30, No. 1, August 27, 2020.

[145] Lynne G. Zucker and Michael R. Darby. "Star scientists and institutional transformation: Patterns of invention and innovation in the formation of the biotechnology industry." *Proceedings of the National Academy of Sciences* 93, No. 23 (1996); Harriet Zuckerman, *Scientific elite: Nobel laureates in the United States*, Transaction Publishers, October 1, 1977.

output is measured as the total number of patents granted within the focal technology area to organizations hosted by the country during the analysis period.

Development organization capacity measures the organizational resources a country brings to bear on a development task. This element is analogous to the research organization capacity measure but focuses on patenting rather than publishing organizations. To measure development organization capacity, we count the top global patenting organizations within the host country.

Testing infrastructure is a measure of the physical infrastructure (sometimes referred to as scientific capital) a country has available for the focal sector. Many technological fields rely heavily on testing infrastructure, and the presence of such infrastructure has been linked to more-productive systems of innovation.[146] Examples of testing infrastructure include live fire test ranges, wind tunnels, supercomputers, testing facilities, research vessels, clean rooms, and particle colliders. We measure national testing infrastructure by cataloging the number and character of a country's testing infrastructure facilities that are relevant to the focal field.

The kind of technologies considered here are highly complex and typically the result of a variety of distinct development processes aimed at maturing what we call critical technology elements (CTEs), or components of final integrated technologies. The CTE development element measures the extent to which a country is making progress in maturing a particular CTE. We measure CTE development in two ways. First, we gather data on the number of patents granted to a country's organizations that are focused on a given CTE. Second, where possible, we identify and describe the character of ongoing development efforts at the level of the CTE.

The development funding element seeks to measure the extent of government financial resources a country has dedicated to a technology area. For the United States, we use government data on spending on contracting for the focal technology area. For the PRC, because such data is not available, we rely on rough estimates of total R&D spending.

Fielding

Our final dimension assesses the fielding (or deployment) of military capabilities using the focal technology. We measure four elements of fielding: fielded systems, force structure, international sales, and technology transition.

Fielded systems refers to the number of integrated systems that leverage the technology and that have reached completion. Fielded systems can range from deployed operational prototypes to acquisition programs that have reached initial operational capability (IOC). We measure fielded systems as the number of unique systems available to a country's military, based on the systems having been evaluated in a reference time frame.

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[146] Knut Blind and Hariolf Grupp, "Interdependencies between the science and technology infrastructure and innovation activities in German regions: empirical findings and policy consequences," *Research Policy,* Vol. 28, No. 5, June 1, 1999; Keith Smith, "Economic infrastructures and innovation systems," *Systems of innovation: Technologies, institutions and organizations,* ed. by Charles Edquist, 1997.

Force structure refers to the extent and distribution of the systems under consideration. Whereas the fielded systems element refers to the number of unique *types* of systems available to a national military, force structure is focused on the *quantity* of systems available and their distribution across a nation's military forces. We measure force structure by describing the number of operational systems and the military units to which the systems are assigned.

International sales refer to exports of the focal technology. Because arms sales must be declared for some technologies, tracking international sales provides a useful view into an otherwise opaque topic: the technical character of a country's final military technologies. We measure international sales as a country's quantity and value of foreign military sales of systems involving the focal technology.

The task of turning a development effort into a useful military capability is not trivial. This task of technology transition—sometimes referred to as bridging the valley of death—is a critical feature of a country's NDIS, as it determines the extent to which a country's various development inputs reach their goal: a fielded weapons system.

Technology transition is a perennial problem in defense technology development.[147] Technology transition is the process by which a technology that is in demand passes from the development phases to use by an end user. Given the importance of technology transition in assuring that a military is equipped with the most effective technology and the perennial challenges in realizing transition, a substantial body of research has gone into identifying the factors that enable successful transition. Examples, of factors linked to technology transition success include the existence of a military or commercial demand, active collaboration during development and testing with potential transition partners, the incorporation of early input and feedback from end users, and high-level support (i.e., a champion) for the technology.[148]

The common feature of these enablers of successful transition is that they involve the creation and exercise of linkages between phases of the overall technology development process. Ultimately, the ability of an NDIS to transition technologies depends on the inter-organization and inter-process channels of information exchange. In the U.S. system, defense innovation intermediaries (DII) have been stood up to span institutional and functional boundaries.[149] In the

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[147] Sullivan, M., Diana Moldafsky, Christopher R. Durbin, Emily Bond, Nathan Foster, Aaron M. Greenberg, John Krump et al. *Defense Advanced Research Project Agency: Key factors drive transition of technologies, but better training and data dissemination can increase success*. GAO-16-5). Government Accountability Office, 2015.

[148] Sullivan, M., Diana Moldafsky, Christopher R. Durbin, Emily Bond, Nathan Foster, Aaron M. Greenberg, John Krump et al. *Defense Advanced Research Project Agency: Key factors drive transition of technologies, but better training and data dissemination can increase success*. GAO-16-5). Government Accountability Office, 2015.; Fowler, Charles Albert. "The standoff observation of enemy ground forces from Project Peek to JointSTARS-A prolusion." IEEE Aerospace and Electronic Systems Magazine 12.6 (1997): 3-17.; Schmid, Jon, Bonnie L. Triezenberg, James Dimarogonas, and Samuel Absher, The Role of Standards in Fostering Capability Evolution: Does Design Matter? Insights from Interoperability Standards. Santa Monica, CA: RAND Corporation, 2022.

[149] Schmid, Jon, and Jonathan Wong. "The Role of New Defense Innovation Intermediaries in the Emerging Defense Innovation Ecosystem." (2020). Acquisition Research Program, March 30, 2020.

PRC, CMF attempts, amongst other objectives, to span boundaries by integrating innovative non-traditional defense industry players into all phases of the defense technology development process.

We measure technology transition by assessing, qualitatively, the extent to which a country has been able to turn promising development efforts into fielded systems and by considering the existence and character of inter-organization and inter-processes linkages. We acknowledge, however, that this measurement alone does not convey whether a country has been successful at military innovation and at marrying the necessary equipment and fielded systems with the appropriate operational concepts and training necessary to harness the technology to achieve real military advantages.[150]

Table B.7 presents the measurement approaches for the 15 NDIS elements. We employ a common overall measurement approach across all critical technology areas—e.g., hypersonics and directed energy. However, following the measurement approach for certain elements within each critical technology area requires the use of different data sources. For example, the type of S&T infrastructure required to advance development varies by critical technology area. Hypersonic weapons systems depend largely on wind tunnels, while directed energy systems require live fire test ranges. Thus, Table B.7 does not specify the data sources used; rather, it describes the data types used as well as the method by which each element is assessed.

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[150] For more background on military innovation and the relationship between technology and military power, see Stephen Biddle, *Military Power: Explaining Victory and Defeat in Modern Battle,* Princeton University Press, 2004. Michael C. Horowitz, *The Diffusion of Military Power: Causes and Consequences for International Politics*, Princeton University Press, 2010.

Table B.7. Measurement Approach for NDIS Elements

NDIS Element	Measurement Methodology
1. Research	
1.1 Scientific output	annual scientific publications within a focal field: a country's number of publications produced by authors from organizations located within that country
1.2 Organizational activity	• top publishing organizations within a focal field: a country's number of organizations with the most publications produced by authors affiliated with those organizations during the period of analysis • centrality of top publishing organizations within a collaboration network in a focal field: eigenvector centrality and degree centrality of top publishing organizations, based on a full collaboration network (of co-authorships)
1.3 Conference activity	conferences within a focal field: a country's number of conferences that produce a report or conference proceeding and occur on a regular basis
1.4 "Superstar researchers"	authors ranked in the top 0.1 percent for H-index for the 2013–2022 period: a country's number of authors whose number of papers (H) within a focal field have been cited at least H times[a]
1.5 Research centrality	eigenvector centrality and degree for top 15 publishing organizations based on the full collaboration network (co-authorship) for the field in question
2. Development	
2.1 Program activity	number and descriptions of a country's official military development programs for focal technologies
2.2 Technological output	annual patent grant output within a focal field: a country's number of patents, based on the location of the patent assignee (i.e., the patent's owner)
2.3 Development organization ecosystem	• number of patents awarded to a country's organizations in a focal field over the period of analysis • qualitative assessment of the development activities of a country's most important organizations in a focal field
2.4 Testing infrastructure	number and descriptions of a country's major relevant S&T infrastructure activities
2.5 Critical technology element development	• a country's number of patents pertaining to a CTE, including any patent that contains, in its title or abstract, a keyword designated by a subject matter expert as indicative of language used in the technology characteristic of the CTE • qualitative assessment of a country's major CTE-specific development activities
2.6 Development funding	a country's public spending on a focal technology
3. Fielding	
3.1 Fielded systems	number and key technical specifications of a country's completed systems that leverage a focal critical technology area, including operational prototypes and acquisition programs that have reached initial operational capability
3.2 Force structure	• quantity of fielded systems that a country's military has available • distribution of a country's assigned systems across military units
3.3 International sales	quantity and value of a country's foreign military sales of systems involving a focal technology
3.4 Technology transition	qualitative assessment of a country's ability to turn development activity into fielded military systems

NOTE: [a] H-index publication data are from the Web of Science Core Collection. Citation counts based on Web of Science citation counts as of October 27, 2022.

Abbreviations

AFRL	Air Force Research Laboratory
ARL	Army Research Laboratory
AVIC	Aviation Industry Corporation of China
BA	budget area
CALT	China Academy of Launch Vehicle Technology
CAPE	Cost Assessment and Program Evaluation
CAS	Chinese Academy of Sciences
CASC	China Aerospace Science and Technology Corporation
CASIC	China Aerospace Science and Industry Corporation
CCMD	combatant command
CCP	Chinese Communist Party
CMC	Central Military Commission
CMF	civil-military fusion
CMOS	complementary metal oxide semiconductor
COSTIND	Commission for Science, Technology, and Industry for National Defense
CSTC	Central Science and Technology Commission
CTA	critical technology area
CTA	critical technology assessment
CTE	critical technology element
DARPA	Defense Advanced Research Projects Agency
DAS	Defense Acquisition System
DIB	defense industrial base
DII	defense innovation intermediary
DIU	Defense Innovation Unit
DoD	Department of Defense
DoDD	Department of Defense Directive
DoDI	Department of Defense Instruction
DTIC	Defense Technical Information Center
ECC	equipment contractor certificate
EDD	Equipment Development Department
FFRDC	federally funded research and development center
GAD	General Armaments Department
HHI	Herfindahl-Hirschman Index
IADB	international agreement database
IC	intelligence community

IOC	initial operational capability
IP	intellectual property
JCIDS	Joint Capabilities Integration and Development System
KPP	key performance parameter
MIT	Massachusetts Institute of Technology
MOST	Ministry of Science and Technology
NDAA	National Defense Authorization Act
NDIS	national defense innovation system
NDRI	National Defense Research Institute
NETRC	National Engineering Technology Research Center
NIS	national innovation system
NNSFC	National Natural Science Foundation of China
NPC	National People’s Congress
NRL	Naval Research Laboratory
NSRD	National Security Research Division
OSD	Office of the Secretary of Defense
OSI&A	Office of Strategic Intelligence and Analysis
PLA	People’s Liberation Army
PLAA	PLA Army
PLAAF	PLA Air Force
PLAN	PLA Navy
POM	Program Objective Memorandum
PPBE	Planning, Programming, Budgeting, and Execution (system)
PRC	People’s Republic of China
R&D	research and development
S&T	science and technology
SASTIND	State Administration of Science, Technology, and Industry for National Defense
SKL	state key lab
SME	subject matter expert
SOE	state-owned enterprise
STEM	science, technology, engineering, and mathematics
T&E	testing and evaluation
UARC	university affiliated research center
UAS	unmanned aerial system
USD(A&S)	Undersecretary of Defense for Acquisition and Sustainment
USD(R&E)	Undersecretary of Defense for Research and Engineering

WERDPL	Weapons and Equipment Research, Development, and Production License Catalog
WERPL	weapons and equipment research and production license
WOS	Web of Science

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