Research Report

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Measuring China's Science and Technology Progress

A Framework for Assessing Advances Affecting Military Capability

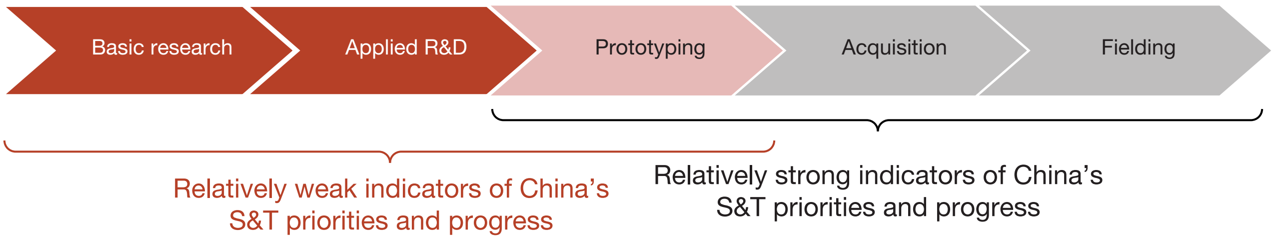
The generic life cycle of a new military capability passes through phases from basic research to operational deployment (Figure 1), incorporating the prototyping phase, moving through acquisition, and concluding with the fielding phase.[1] As this process advances, a competitor's science and technology (S&T) development efforts become increasingly visible because they result in observable, physical artifacts, such as prototypes, test infrastructure, and production lines.[2]

KEY FINDINGS

- RAND Corporation researchers developed a framework that can measure science and technology (S&T) progress of foreign competing nations to help determine what should warrant the attention of U.S. Department of Defense (DoD) decisionmakers.
- By progressing in a structured and transparent way—from the subject country's highest-level strategic goals to the critical technologies supporting its military capabilities to achieve those goals—the four phases of the framework identify requirements, screening S&T activity, comparing baseline historical progress, and supporting decisionmakers.
- A prototype of the framework, which was applied to three case studies in China, demonstrated that it can generate timely and useful insights.
- When integrated into DoD's analytic process, the framework would provide an early warning of a nation's militarily critical S&T programs for multiple communities.

By contrast, the basic research and applied research and development (R&D) phases—and, to some extent, the prototyping phase—represent periods in capability development in which measurable indicators of a competitor's S&T interests might be relatively weak with a poor signal-to-noise ratio. What's more, advanced countries, such as China and the United States, might have so many R&D activities underway that it might be difficult to find the needle in the R&D haystack. The United States might get very little early warning of the specific S&T programs that China intends to use to create important new military capabilities—

FIGURE 1
Generic Capability Development Pipeline



capabilities that U.S. soldiers, sailors, marines, airmen, and guardians might confront in the future. For this reason, a tool that could identify China's R&D that is fundamental to the People's Liberation Army (PLA), fielding some of these capabilities early in the pipeline, is of immense interest to the military and intelligence communities.

During the post–Cold War era of unipolarity, the main security challenges to the United States were presented by regional threats and even less capable subnational actors, such as al Qaeda, that employed primarily derivative military technology that the group had purchased or copied. Outside very specific cases—such as tracking the nuclear weapon programs of North Korea, Iran, and Iraq—there was little need for early warning. The capabilities fielded by these rogue nations were largely of Russian or Chinese origin and were familiar to the Pentagon and its regional commanders. Having an S&T tracking system that was focused on the right-hand side of the capability development life cycle (i.e., acquisition and fielding) was perfectly adequate.

However, the United States faces great-power competitors that are able to innovate independently. China especially is capable of an increasingly sophisticated range of S&T activity. Although China's S&T base lags behind the cutting edge in some areas, in many technological fields of interest to the U.S. Department of Defense (DoD)—including artificial intelligence, biotechnology, and quantum sciences—China is engaged in world-class S&T efforts.

The S&T areas prioritized in China's 14th Five-Year Plan map strikingly well to DoD's modernization priorities as articulated by the Under Secretary of Defense for Research and Engineering (Figure 2).[3] There is enough overlap to suggest that the United States and China are directly competing to make progress in many of the same advanced technology areas. Yet their differences indicate that China is pushing hard in some S&T categories—such as new materials—that DoD does not perceive (as of this writing) as critical. Tracking China's progress in the most militarily significant applications of overlapping technologies is clearly important. So, too, is understanding why China is putting significant effort into other areas and—critically for DoD—whether the PLA has identified some application for those technologies that has been overlooked or neglected by U.S. researchers and force planners.

With the sponsorship of the Strategic Intelligence Analysis Center in the Office of the Under Secretary of Defense for Research and Engineering, RAND researchers developed a framework for gaining insights in these areas. The Military Advances in Science & Technology (MAST) framework is a top-down, analytic approach that begins with the

Abbreviations

CFIUS	Committee on Foreign Investment in the United States
DoD	U.S. Department of Defense
EMP	electromagnetic pulse
HPM	high-power microwave
MAST	Military Advances in Science & Technology
NLP	natural language processing
PLA	People's Liberation Army
R&D	research and development
S&T	science and technology
T&E	testing and evaluation

FIGURE 2

China's National and DoD Technological Priorities

China's 14th Five-Year Plan
from November 2020 draft, adopted March 2021

- "We will focus our aim on artificial intelligence (AI), quantum information, integrated circuits, life and health, brain science, bioengineered breeding, aerospace technology, deep earth and deep sea and other cutting-edge fields …" (p. 8)
- "We will accelerate and expand industries such as new-generation information technology, biotechnology, new energy, new materials, high-end equipment, new energy vehicles and green and environmentally friendly products, as well as the aerospace and marine equipment industries. We will promote deep integration of the internet, big data, AI, etc." (p. 10)

DoD Modernization Priorities

1. AI
2. Biotechnology
3. Autonomy
4. Cyber
5. Directed energy
6. Fully networked command, control, and communications (FNC3)
7. Microelectronics
8. Quantum science
9. Hypersonics
10. Space
11. 5G

Chinese leadership's strategic aspirations for China, works through the future PLA missions implied by those goals, and identifies new or improved capabilities that will be necessary to execute those missions. The researchers specified the technological bases for these capabilities. Then, using a variety of methods and data sources, they dove into what is known about China's S&T activity as far back as the basic research phase shown in Figure 1. The ultimate product of the process is a graphical dashboard, backed up by a wealth of qualitative and quantitative data, which indicates the status and momentum of China's progress in these S&T domains.

These indicators are of potential value to DoD. Specifically, they can

- focus U.S. R&D objectives and shape modernization priorities
- point the intelligence community toward investigating important new areas of China's S&T activity and assist in allocating intelligence assets and resources effectively
- help combatant commands and Pentagon planners to look ahead to assess the potential results of China's S&T undertakings
- help DoD inform its whole-of-government and academic and industrial partners—for example, the Committee on Foreign Investment in the United States (CFIUS)—about S&T areas in which caution should be exercised both in permitting Chinese investment in U.S. firms and in collaborating with Chinese researchers.

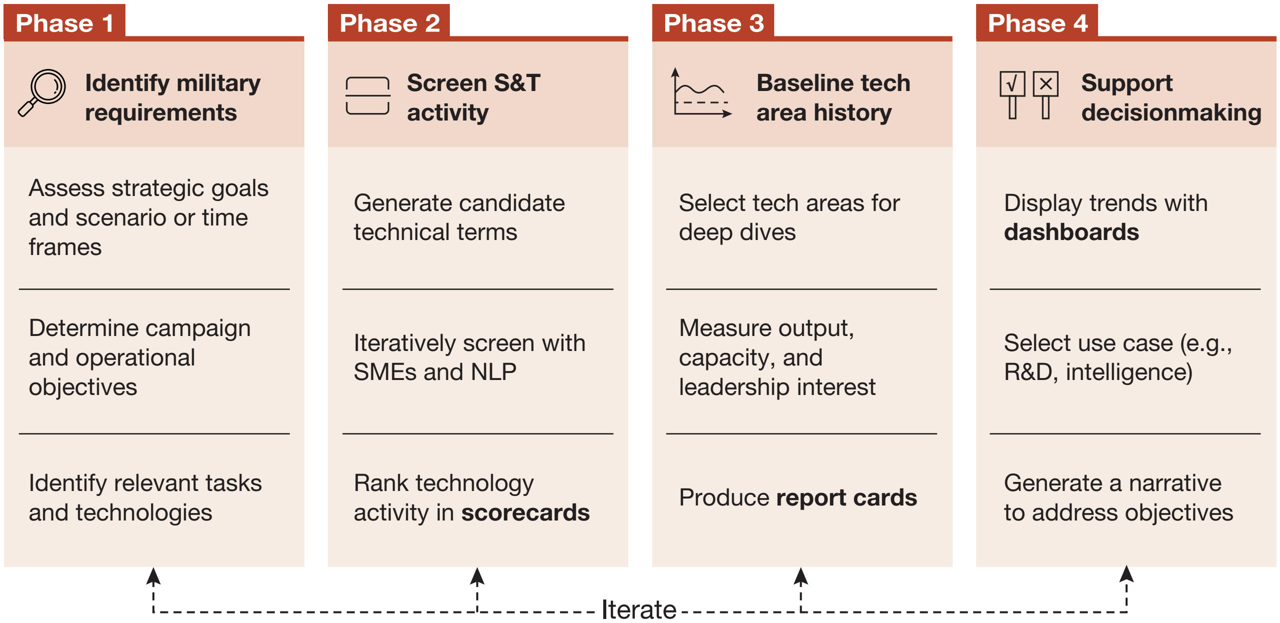
How the MAST Framework Works

The MAST Framework process has four phases (Figure 3):

- ***Identify*** China's future strategic goals and derive critical future PLA capabilities from those goals.
- ***Screen*** critical technology pathways for activity.
- ***Baseline*** China's S&T progress along those pathways and estimate its future capacity for progress.
- ***Support decisionmaking*** by synthesizing insights that inform DoD S&T priorities or direct intelligence collection.

FIGURE 3

MAST Framework for Measuring China's S&T Progress



NOTE: NLP = natural language processing; SME = subject-matter expert.

In developing the framework, we examined three test cases:

1. a retrospective example, for which researchers asked, "How early would the framework have flagged China's military interest in hypersonic weapons technology?" Using only open-source data, researchers assessed that China's interest and effort in this area would have been made evident no later than 2007, as indicated by the red flags for S&T capacity in 2005 and for output in 2007 (Figure 4).
2. a status check example, in which researchers looked at China's efforts to develop quantum science–related technologies. Their investigation revealed that, despite fears to the contrary, China is not leading in the race to develop quantum computers but is the global leader in quantum communications.
3. a forecasting example, in which the researchers began by asking "What do China's current leaders see as their goals for their country in 2045?" Working through the framework from top to bottom, they eventually found themselves assessing China's progress in the field of high-power microwave (HPM) technologies.

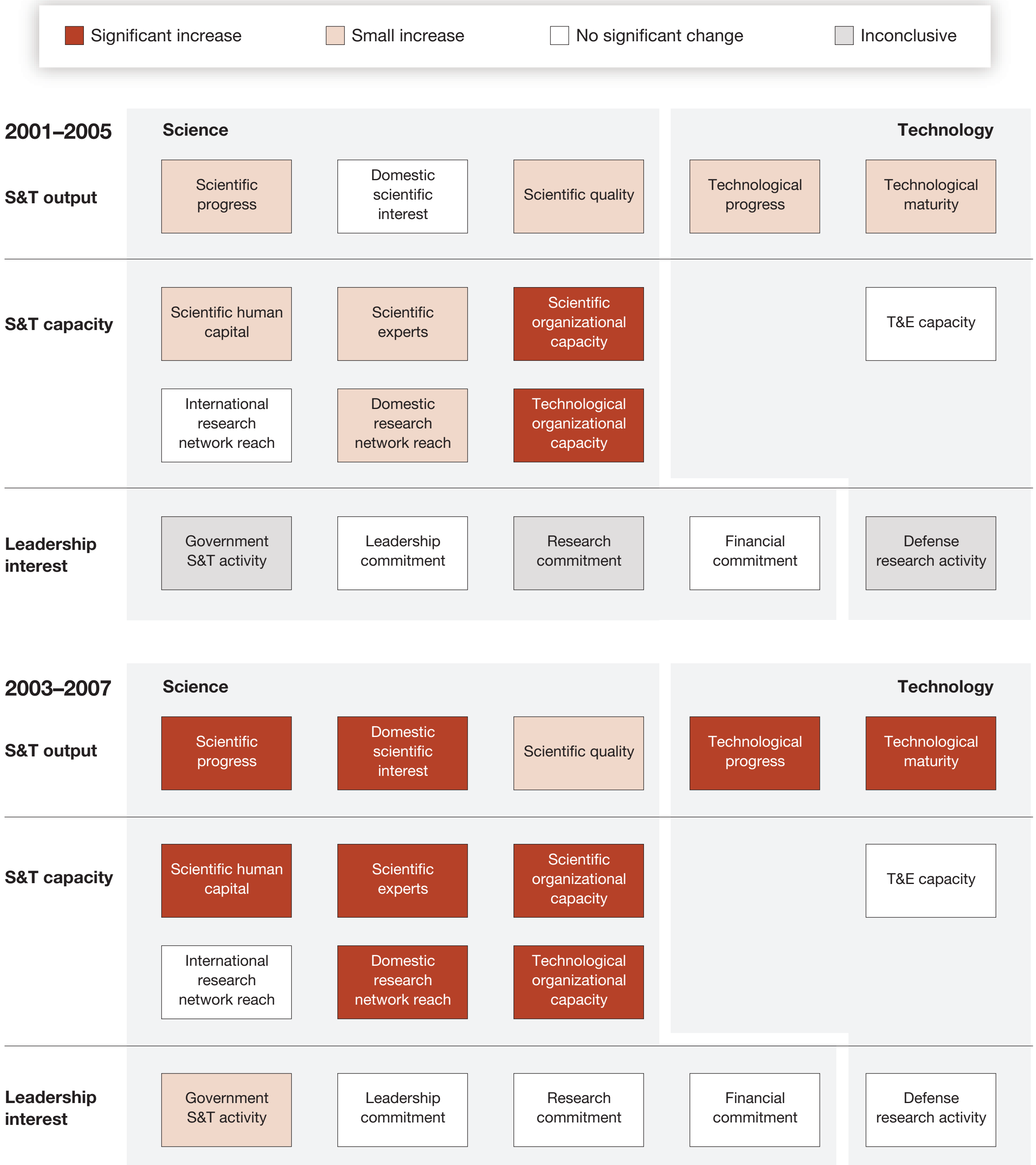
All three cases are described in detail in the related research reports. The remainder of this brief focuses on the forecasting case, which is the only one of the three case studies that exercises all phases of the MAST framework.

Full Test—What Is Out There That We Should Care About?

Unlike the retrospective and status check test cases, which were only partial tests of the framework, the forecasting test case fully exercises the framework from beginning to end. The researchers start by asking: "What vision do China's leaders have for their country, what does that imply for potential PLA missions, and how does that inform S&T activity?"

MAST's first phase, **identify military requirements**, asks "What new capabilities might the PLA leadership regard as vital for accomplishing future missions?" To answer this question, the researchers convened a group of experts on China's strategy and military planning.[4] Working through a structured

FIGURE 4
Flagging China's Interest in Hypersonic Technology



NOTE: T&E = testing and evaluation.

elicitation exercise, the group reached the consensus that China's enduring quest for national unity means that until the China-Taiwan dispute is resolved, maintaining the military capacity to subdue Taiwan will remain a core PLA mission.

The researchers then assembled a mixed group of military experts, including specialists in PLA operations and experts in military technology, and asked the group: "Twenty years from now, are there critical new military tasks that the PLA would need to execute in a campaign against Taiwan, and, if so, how might it seek to address them?" The group concluded that in a future conflict of this type, the PLA would want to defeat the "intelligentization" of the U.S. joint force.[5] After debating a variety of approaches that China could take to accomplish this, the group concluded that attacking the back-end hubs supporting the U.S. distributed and networked system-of-systems represented a key approach for China.[6] A group of military technology experts was then asked, "If this were a PLA goal, what capabilities might China seek to deploy?" From a catalog of expected answers, such as cyber attack, an unexpected answer emerged: the use of nonnuclear electromagnetic pulse (EMP) to disable electronic equipment.[7]

The exercise then moved into its second phase, **screen S&T activity**. This phase asks, "Are there indications in the available data that China has an outsized interest in technologies related to relevant S&T activity?" The screening phase entails several iterative, automated scans of patent and publication databases (both English- and Chinese-language) using large numbers of technical search terms that evolved from a technology palette associated with nonnuclear EMP—for example, "megagauss" or "Marx generator," in addition to the all-inclusive "electromagnetic pulse." Both expert judgment and automated NLP were employed to identify other potentially productive search terms based on the findings of each previous screening. Ultimately, this iterative process resulted in refinement of the overall concept, redirecting searches from the too broad nonnuclear EMP toward the more specific term *HPM weapons*. The process continued to iterate based on this more-tightly focused concept.[8]

Until the China-Taiwan dispute is resolved, maintaining the military capacity to subdue Taiwan will remain a core mission of the People's Liberation Army.

The results of the screening process are depicted in scorecards that provide a sense of the magnitude of technical activity in a given area, as measured by these patent and publication counts over time and compared with the overall global or U.S. research effort. Furthermore, they identify areas in which the Chinese level of effort stands out (Figure 5). The scorecards provide a quantitative summary of the technology landscape and suggest areas for further assessment in the next phase. An example element from a scorecard for nonnuclear EMP and HPM weapons is shown in Figure 5.

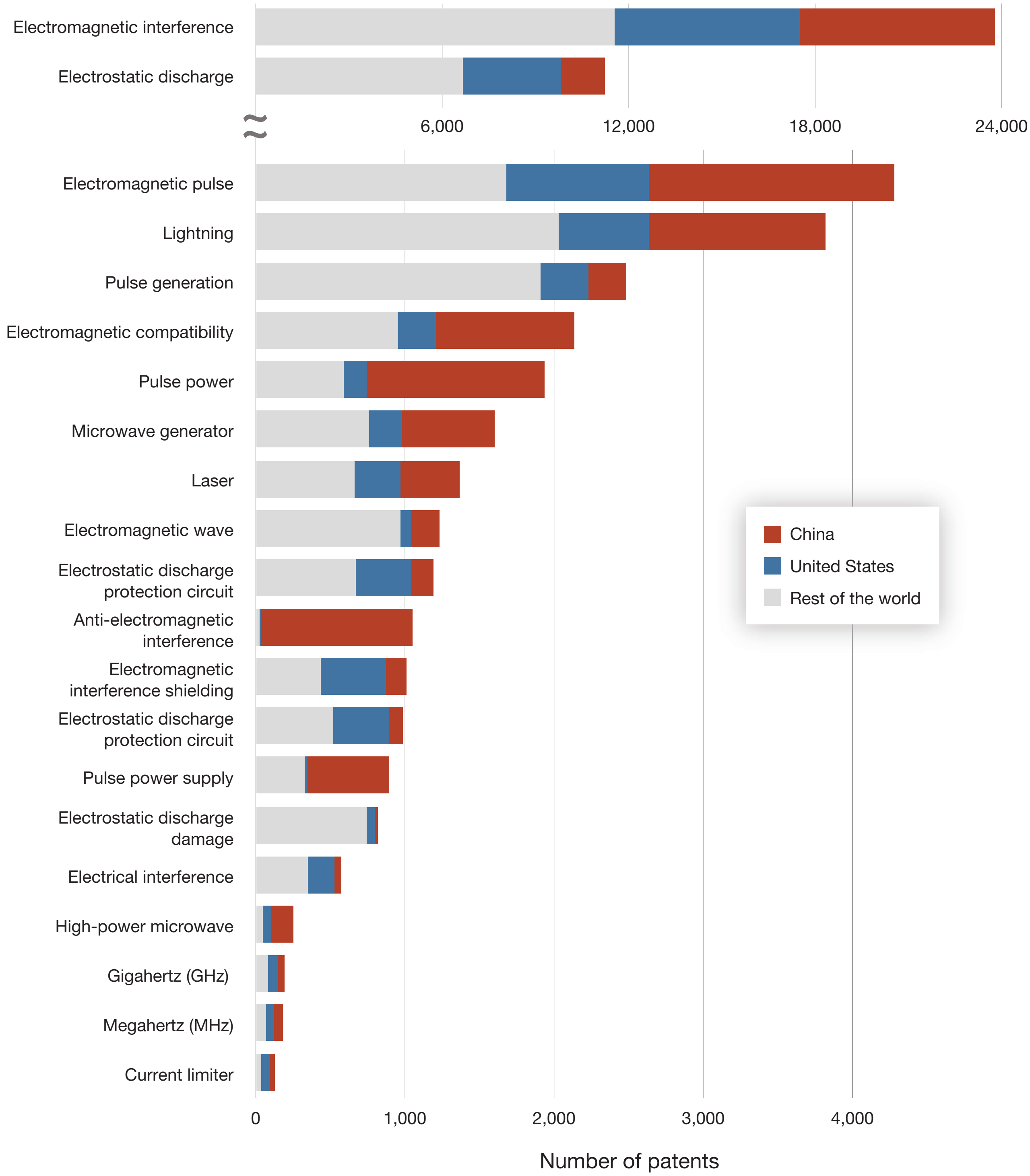
The **baselining** phase assesses the output and capacity of—as well as leadership interest in—the technical areas specified by the screening phase. The key element of this phase is developing metrics and measures of S&T progress. We identified 17 measures across the three categories of output, capacity, and leadership interest (Table 1). These metrics are combined into a report card for each S&T area.[9]

The data uncovered in the screening and baselining phases of the framework revealed that China has, in fact, been very active in S&T domains related to HPM. For example, Chinese researchers and organizations are responsible for 90 percent of the world's new HPM-related patents.[10] The analysis showed that China's HPM research has a heavily military flavor and appears to embrace both the offensive aspects of HPM and defenses against it.

Ultimately, the first three phases produce a quantity of data that is impossible for a busy senior

FIGURE 5

Patents Scorecard for Nonnuclear EMP and HPM Weapons



SOURCE: RAND analysis using data from Clarivate Analytics, "Web of Science Platform: Derwent Innovation Index." The period of analysis is 2000 to 2017.

TABLE 1
Output, Capacity, and Leadership Interest

Component	Subcomponent	Metric
S&T output	Scientific progress	1.1 International scientific publications
	Domestic scientific interest	1.2 Chinese-language publications
	Technological progress	1.3 Patent grants
	Technological maturity	1.4 Cross-domain patent classification linkages
S&T capacity	Scientific human capital	2.1 Chinese authors of scientific publications
	Scientific experts	2.2 Domestic theses published
	Scientific organizational capacity	2.3 Unique author affiliations
	Technological organizational capacity	2.4 Unique organizations listed as patent assignees
	International collaborative network reach	2.5 Average path-length ratio of the international coauthorship network
	Domestic collaborative network reach	2.6 Average path-length ratio of the domestic coauthorship network
	T&E capacity	2.7 T&E facilities
Leadership Interest	Government S&T activity	3.1 NSFC requests for proposals
	Defense research activity	3.2 Chinese publications with defense funding
	Signaled leadership commitment	3.3 *PLA Daily* and *People's Daily* mentions
	Leadership research commitment	3.4 Military university publications
	Leadership financial commitment	3.5 NSFC spending

NOTE: NSFC = National Natural Science Foundation of China.

decisionmaker to digest. The final MAST phase, **decisionmaking support**, refines these results into a form that DoD leaders can use. The dashboard condenses a report that contains numbers, graphs, and tables—which are useful to analysts who are focused on specific technologies and issues—and captures the 17 metrics and their trends over a defined period in a more compact form (Figure 6).

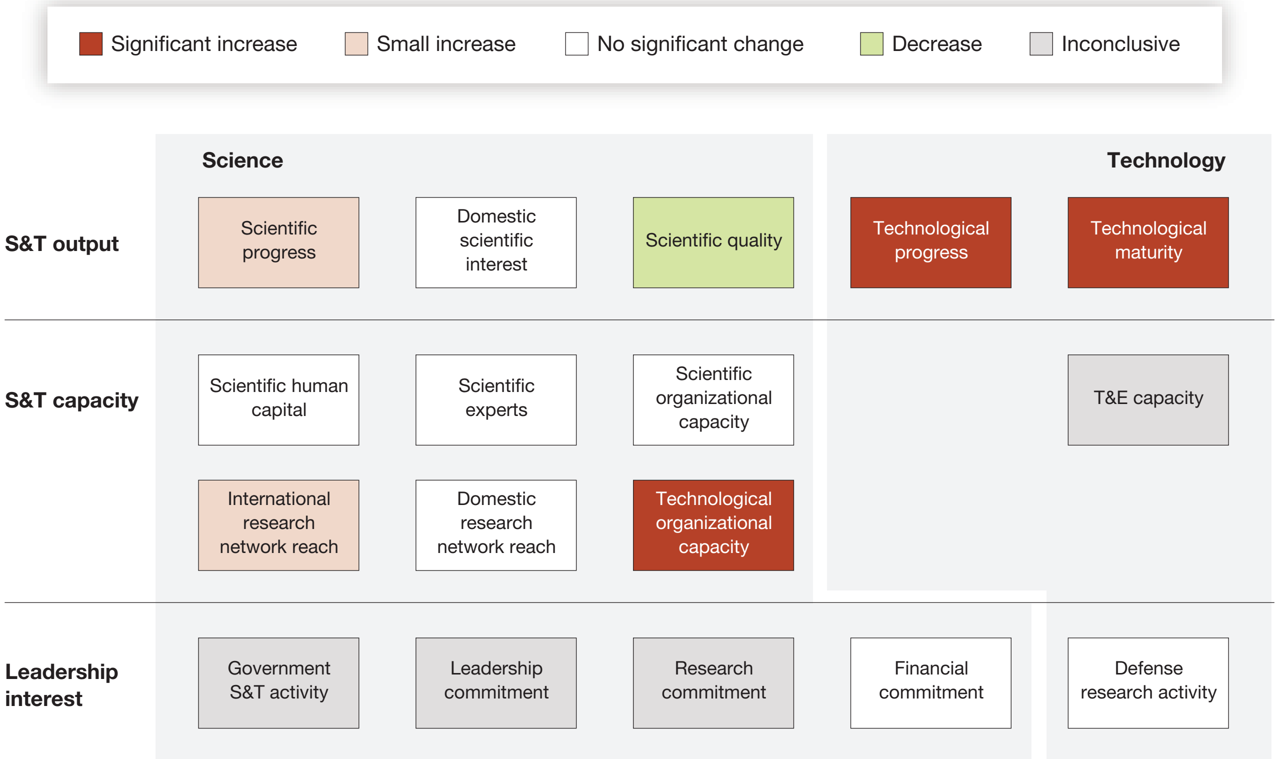
As noted earlier, the dashboard incorporates a wealth of information, including the current state of China's activity in a particular area and a four-year moving average of how Beijing's efforts are trending relative to the rest of the world. A full explication is given in another research report, but the primary message can be discerned by reviewing the overall array of colors and how they change over time (see the retrospective examination of hypersonic technology in Figure 4).

What It All Means

Traversing the framework yields a narrative about China's S&T evolution for a specific military requirement. Decisionmakers can employ this narrative in several ways. It might reinforce our understanding of areas that decisionmakers previously believed China has focused on, or it can pinpoint particular areas of effort more specifically. It also might identify new, unexpected areas of China's activity.

The complexity of the military S&T ecosystem—in which weapons are composed of subsystems that, in turn, are built from multiple components that each comprise a combination of technologies—means

FIGURE 6
China's HPM Dashboard, 2014–2017



that no single analytic framework can answer all the questions that can be asked about the relationship between a country's S&T activity and its future military capabilities. Rather, the framework teases apart aspects of this complexity in a reasonable and, most importantly, transparent and traceable way. Every step, of course, entails expert judgment.

The practical implications of MAST's careful application span DoD and the intelligence community. In the example we discussed, the dashboard indicators suggest that by 2030, China might be able to deploy weaponized technologies that are analogous to those developed in conjunction with the U.S. Counter-Electronics High Power Microwave Advanced Missile Project (CHAMP) and that could be used offensively, as envisioned by the experts involved in this elicitation effort, or defensively to "fry" the electronics in enemy unmanned aerial systems or incoming missiles. The analysis also identified two specific research organizations and two specific individuals who are deeply involved in China's HPM research. The intelligence community could use this information for further data collection aimed at answering key remaining questions about, for example, the primary focal areas of the PLA's HPM research.

Service S&T communities might wish to assess the potential influence of China's HPM S&T on U.S. warfighting capabilities and concepts to (1) ensure that they are robust against China's progress and (2) develop any necessary countermeasures. DoD might consider tasking U.S. Indo-Pacific Command with determining whether existing plans for dealing with China contingencies are viable in the face of such capabilities. CFIUS might be alerted to China's interest in these technology areas to ensure additional vigilance on any transactions that possibly touch on these areas.[11] Funders of scientific research, such as the DoD, National Science Foundation, U.S. Department of Energy, and the National Institutes of Health, might use the MAST framework to identify Chinese institutions and researchers that are involved in research to benefit the PLA.

Summary and Next Steps

The MAST framework was designed to provide a systematic and transparent means to link S&T assessments to strategic planning—an analytic capability that will grow in importance for DoD in an era of strategic competition. Three test cases demonstrate that the framework can provide early warning on China's strategically relevant R&D and, in so doing, could identify S&T progress that might warrant further intelligence community attention, focus DoD goals and modernization priorities, and potentially flag programs for which special protective measures might be appropriate. Achieving these benefits might require periodic use of the MAST framework to identify where China continuously appears to be focusing on militarily relevant S&T activities and to track those activities over time. When integrated into and made a regular part of DoD's larger analytic enterprise, the MAST framework can provide an early warning of an adversary's militarily critical S&T programs that would be useful for multiple communities.

Notes

[1] In reality, innovation does not follow a strictly linear path from basic research to fielding. Rather, the path to a fielded technology is highly varied and can include out-of-sequence breakthroughs; the incorporation of advancements made from other, once-independent, innovation efforts; and feedback loops between the various innovation activities. In Figure 1, we present the innovation activities in a recognizable pipeline diagram because this formulation is consistent with how publicly funded weapon system development and acquisition are structured within the focal countries and because the observable markers of innovation increase as development proceeds from basic research to a fielded weapon system.

[2] The framework we developed is itself generic and could be applied to any country's S&T enterprise, including the U.S. S&T enterprise. It was developed as part of a fiscal year 2021 RAND project sponsored by the DoD Office of the Undersecretary for Research and Engineering.

[3] While the technology areas identified in China's 14th Five-Year Plan are national priorities and while the DoD Critical Technology Areas represent those of a government component, we find the comparison appropriate because of the congruence between the policy priorities of the Chinese Communist Party and the PLA (Chinese Communist Party, *Proposal of the Central Committee of the Chinese Communist Party on Drawing Up the 14th Five-Year Plan for National Economic and Social Development and Long-Range Objectives for 2030*; DoD, *Command, Control, and Communications (C3) Modernization Strategy*).

[4] An important characteristic of the MAST framework is that it approaches every question from a Red (i.e., adversary) perspective. To do so, the best available expertise must be accessed so that the answers come as close as possible to what China would do and not reflect what the United States would do were it in China's position.

[5] A clumsy translation from the Chinese, *intelligentization* entails employing cutting-edge, networked, autonomous systems, including weapons, across all phases of warfare and throughout the theater.

[6] This is similar to how the PLA seeks to defeat U.S. airpower—not in a series of air-to-air encounters but instead by attacking its airbases to keep it out of the fight. Attacking the servers sustaining "intelligentized" capabilities was seen as a wholesale versus a retail way of defeating a superior U.S. capability.

[7] EMP is a short, very powerful burst of electromagnetic energy that is capable of damaging or destroying electronic equipment. EMP is normally a byproduct of a nuclear detonation, but for years, militaries have researched ways of inflicting EMP on their enemies via other means.

[8] This result highlights two important elements of the MAST framework. First, it is intrinsically iterative: At almost every step, results are subject to further refinement, with those results being fed back into the beginning of that step or, in some cases, a prior step. Second, the framework is not an autonomous answer-producing machine: At every point in employing the framework, expertise and judgment are required.

[9] Some of these metrics are inevitably fuzzy while others are at least arithmetically precise. Combining these metrics is intended to provide a sense of how much effort China might be expending in a particular area. When carefully executed, the framework is meant to produce, at best, an ordinal ranking of topics—i.e., China appears to be more interested in this than that.

[10] The sum of the patent counts displayed in Figure 5 do not constitute the full HPM dataset but rather a subset of that dataset that contained one of the listed terms in the patent title or patent abstract.

[11] The use of open-source markers of innovation activity to measure military technology development runs the risk of losing track of an initiative when that initiative goes black—i.e., is treated as a state secret and thus fails to produce public markers of activity. We acknowledge this as a limitation of the proposed methodology. However, the sudden disappearance of evidence of innovation activity might provide analysts with an early indication that a given research strand has gone black and thus indicate an area where the intelligence community should focus.

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DoD—*See* U.S. Department of Defense.

U.S. Department of Defense, *Command, Control, and Communications (C3) Modernization Strategy*, September 2020.

About This Report

RAND's National Security Research Division (NSRD) is conducting a two-year study intended to help the U.S. Department of Defense better identify and track China's critical research and development efforts from an early stage in their development. The first year was committed to developing and testing a framework—a set of step-by-step processes—that could be used for this purpose.

The full report from the first year consists of two volumes and is not available for public release. This short research report focuses specifically on the methodology developed in that project and is intended to provide an overview of the framework in a form suitable for wider distribution.

RAND National Security Research Division

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