ABSTRACT

Title of Dissertation: **SCHRODINGER'S TECHNOLOGY IS HERE AND NOT: A SOCIO-TECHNICAL EVALUATION OF QUANTUM SENSING IMPLICATIONS FOR NUCLEAR DETERRENCE**

Lindsay Elizabeth Rand, Doctor of Philosophy, 2023

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When and how could technological advances undermine nuclear deterrence? This research uses an interdisciplinary approach to explore the technical, strategic, and social factors that propagate interest in emerging technologies like quantum sensing, and to assess the likely effects on strategic stability. Recent scholarship asserts that new remote sensing technologies may soon provide the capabilities needed to detect, track, and precisely target the delivery systems that constitute a nuclear-armed state's second-strike capabilities. If true, this would have profound consequences for international security, nuclear force structure planning and arms control. Even if such predictions are not technically feasible, exaggerated expectations generated by strategic or social influences could still negatively impact acquisition and force structure decisions critical to strategic stability and arms control policy.

This dissertation proposes an integrated, socio-technical analytical framework to examine the technical, strategic, and social factors that inform U.S. decision-making on new technologies with important military implications. The framework improves upon existing research in security studies literature by integrating technical projection methods and science and technology studies theories. Before applying the framework to the contemporary case of quantum sensing, the framework's operability is demonstrated through five historical case studies: ballistic missile defense, hypersonics, satellite imagery, remote vision, and isomer weapons. These case studies illustrate the intricate interplay among technical, strategic, and social factors that has shaped prior U.S. decisions about pursuing technological innovations related to nuclear deterrence, often leading to over-investment as a strategy to hedge against technological surprise.

The quantum sensing case study begins with a technical assessment to determine the realistic advances that can be expected, and the likelihood of disruption to a core feature of stable nuclear deterrence: confidence in the survivability of retaliatory forces. It surveys experimental results to identify sensitivities of current quantum sensor prototypes and theoretical literature to evaluate the likelihood of performance gains as R&D progresses. It then estimates how much these projected capabilities could improve submarine detection and missile accuracy applications in the next 10 years. It finds that quantum sensing will afford more evolutionary, rather than revolutionary, improvements in comparison to existing capabilities.

The dissertation then surveys the types of strategic narratives and social dynamics that had important effects on prior decisions about efforts to innovate other strategically relevant technologies, highlighting how they also appear to be shaping debates and decisions about quantum sensing. By assessing competing claims about quantum sensing's impact on second-strike vulnerability, this dissertation explores how diverging deterrence theories amplify disagreements over the impact of new technologies. It also evaluates the social factors that propagate expectations for quantum sensing across the respective social worlds of technologists and capability seekers, finding that realistic assessments are further frustrated by divides between technical and non-technical literatures and classified information barriers.

Based on these findings, policymakers should anticipate continued pressure to pursue emerging technologies like quantum sensing, regardless of patent technical limitations, due to a combination of social dynamics and strategic narratives that support damage limitation deterrence postures. While a technology hedging strategy may seem like an innocuous way for policymakers to appease stakeholders with diverging viewpoints on the risks and benefits of emerging technologies, this dissertation suggests that hedging is likely to galvanize social, strategic, and technical momentum that ultimately signals innovation, fosters competition, and manifests strategic effects, regardless of the initial policy intent.

SCHRODINGER'S TECHNOLOGY IS HERE AND NOT: A SOCIO-TECHNICAL EVALUATION OF QUANTUM SENSING IMPLICATIONS FOR NUCLEAR DETERRENCE

by

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Dissertation submitted to the Faculty of the Graduate School of the University of Maryland, College Park, in partial fulfillment of the requirements for the degree of Doctor of Philosophy
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Preface

I never anticipated that this dissertation project would lead me down the path of attempting to parametrize and evaluate ambiguity and uncertainty. When I was an undergraduate student majoring in physics, I even used to joke that my capstone project would focus on the theory of error propagation. Yet, I believe that the natural progression of this research, which initially sought to identify how quantum sensing will impact nuclear deterrence, into these murky analytical domains underscores the challenges inherent in studying “emerging technologies.” There are a lot of unknowns when looking over the horizon of innovation. But this does not mean that we cannot clearly propagate our errors – or express technical uncertainty and recognize ambiguity that arises from different strategic or social perspectives – when we project the effects of new technologies. Especially as the United States begins to rely more heavily on hedging or “innovate to compete” policies, the proposed form of “error propagation” becomes even more necessary. It allows us to more accurately weight the benefits we gain by pursuing new technologies compared to the arms racing risks we introduce.

Dedication

To Bailey,

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Acknowledgements

I am grateful beyond measure to everyone who has supported me through this winding journey. I've been so fortunate to have the support of such an enormous network of people who have extended topical expertise, research advice, and moral support. They have made this process far more fruitful and enjoyable. Thank you all.

I'd first like to express my gratitude to the members of my dissertation committee. They have each helped me navigate the diverse disciplines required for this project. Nancy Gallagher, my advisor and committee chair, has supported various threads of research that have contributed to this dissertation throughout my graduate education. I am immensely thankful for the time she has taken to mentor me and the care she has taken to review my work and improve my research (as well as the various books I still need to return to her). Steve Fetter has provided generous feedback on the technical estimates, deterrence evaluations, and policy recommendations in this dissertation, and has pointed me towards a number of key historical technical analyses that exemplify the impact of unbiased technical critiques. Chris Lawrence has helped me to navigate the security studies, technical, and STS social worlds and has shown me boundary objects (he'll get the pun) that can be used to transmit theories and methods across these literatures. Charlie Harry introduced me to network theory, and taught me the value in mapping out actor ecosystems, however complex they may be. Finally, Drew Baden has provided valuable insight from a physicist's perspective.

In addition to my committee members, I've been very lucky to receive support from many technical and policy folks in the nuclear and quantum fields. James Acton, Toby Dalton, and the folks at Carnegie helped me hone my policy engagement skills and provided support for my final year of research. Teddy Parker and Rich Silberglitt at RAND Corporation gave me the opportunity to begin mapping out quantum actors and have fostered a much deeper understanding of the global quantum technology ecosystem. Ann Cox afforded me many experiences to witness the quantum policymaking process first-hand. Finally, my health physics mentor and advisor, Luis Benevides, provided me with laboratory and professional opportunities at Carderock and Georgetown that fostered my curiosity, research intuition, and methods.

The completion of this dissertation would also not have been possible without support from my family and friends. My parents, Tom and Barb, and brother, Ted, have encouraged my interdisciplinary curiosity since I was young. They have been patient throughout my many years spent in school (and have never once told me to "get a real job"). My colleagues and friends at UMD and in the broader nuclear community have made the long hours tinkering on nuclear and policy issues much more pleasant. An extended network of family and friends in the DMV area have also provided much moral sport throughout all the highs and lows; I cannot list everyone, but thank you!

Lastly, I am profoundly thankful for my partner (and soon to be wife!), Bailey. Although she is often my most critical editor, she has never doubted me at any point in this journey. Bailey, if you are reading this, I promise this is (most likely) my last degree. Although there are no more chapters to add here, we have many more in life.

Table of Contents

List of Tables

List of Figures

Chapter 1: Introduction

> "The history of hypersonics teaches that faith in, and unquestioning acceptance of, a hypersonic future is akin to belief in the Second Coming: one knows and trusts that it *will* occur, but one can't be certain *when*."
> -Richard Hallion, 1998[1]

> "The existence of thousands of nuclear weapons is the most dangerous legacy of the Cold War. No nuclear war was fought between the United States and the Soviet Union, but generations lived with the knowledge that their world could be erased in a single flash of light."
> – Barack Obama, April 5, 2009[2]

Technologies like quantum sensing, artificial intelligence, and hypersonic weapons are generating significant interest among nuclear policymakers and analysts. This is unsurprising, considering that the impact of new technologies on nuclear deterrence has been a recurring subject of debate since the advent of the nuclear era, fueled by a combination of scientific uncertainty, tensions between competing deterrence narratives and strategic perspectives, and social dynamics at the interface of technology and policy communities. However, throughout the history of nuclear

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[1] Richard Hallion, "Whither Hypersonics? A Foreword to the 1998 Edition," in *The Hypersonic Revolution: Case Studies in the History of Hypersonic Technology* (Washington, DC: U.S. Air Force History and Museums Program, 1998), 98-iii.

[2] Barack Obama, "Remarks by President Barack Obama in Prague as Delivered," (speech, Prague, April 5, 2009), available at https://obamawhitehouse.archives.gov/the-press-office/remarks-president-barack-obama-prague-delivered.

deterrence, very few technological innovations have substantially bolstered or weakened perceptions of security in a clearcut way that experts agree on. Instead, most technologies and innovations have produced mixed effects that stakeholders have interpreted variably due to differing conceptions and assumptions about deterrence, security, and technological innovation. In addition to foreign policy and strategic ideologies, stakeholder outlooks regarding the potential benefits and risks associated with new technologies are influenced by their institutional positions, involvement in epistemic communities, and other social factors.

Ambiguity over the state of technology development and uncertainty over the fundamental limits that could be achieved through future innovation are important drivers of intrigue and concern over "emerging" or new technologies that complicate debates and decisions regarding a policy response. There is no agreed definition of an "emerging" technology, but commonly referenced characteristics include a state of ambiguity regarding the development timeline and uncertainty over operational traits that should be expected of the new technology. Significant ambiguity over the state of innovation and uncertainty over feasible applications allow for interpretive flexibility, and thus exacerbate the divergence in assessments made by different stakeholders about the effects of technologies on established constructs like nuclear deterrence, and the policy responses merited.

Regardless of whether different assessments are shaped more by technical, strategic, or social considerations, they can still affect policy decisions if they gain momentum among critical stakeholders. In the context of nuclear deterrence, some policymakers may argue that certain technological disruptions require an increase in

U.S. force levels and should dissuade the pursuit of arms control or cooperative risk reduction efforts. Other policymakers who have access to the same information may perceive disruptions caused by new technologies as incentivizing arms control to reduce escalation risks. Depending on the stakeholder, strategic effects may be only one element that informs the appropriate response, in addition to other social considerations, such as interagency rivalry or domestic politics. Thus, identifying the strategic and social factors that foster heterogeneous assessments and shape policy decisions, in addition to evaluating how and when technological innovation stabilizes or disrupts deterrence, furnishes a more detailed understanding that is necessary for identifying policies that mitigate risks (and maximize benefits) of innovation.

The evolution of missile defense technologies provides a long and rich historical example of the extent to which technical uncertainty and disagreements across social and strategic perspectives fuel debates over the impact of innovation. Since the earliest stages of missile defense research, skeptics have criticized the technology, claiming that missile defense systems would never achieve a strategically significant success rate.[3] Beyond demonstrating skepticism over technical feasibility with scientific calculations, opponents voiced concerns that pursuing missile defense would produce negative signaling effects that could incite arms-racing, arguing that adversaries may perceive missile defense development and deployment as undermining their assured retaliation capabilities.[4]

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[3] For example: "Nike Zeus: The U.S. Army's First ABM," U.S. Department of Defense, Missile Defense Agency, October 20, 2009, https://www.mda.mil/global/documents/pdf/zeus.pdf.
[4] Cyrus Vance and Robert McNamara, "Memorandum for the President on the Production and Deployment of the NIKE-X", U.S. Department of Defense, December 10, 1966, https://nsarchive2.gwu.edu/nukevault/ebb281/4B.pdf.

Despite persistent concerns about technical feasibility and negative strategic effects, the United States has been pursuing missile defense for decades, almost as long as the deployment of long-range ballistic missiles. This has occurred despite ongoing performance shortcomings of missile defense systems and the exorbitant strain they have imposed on the defense budget. Extrapolating from the case of the "missile defense illusion," Joseph Cirincione observes that "history has shown that lack of proven technical capability has never prevented congressional approval of military systems."[5] However, perceptions of the legacy of missile defense are mixed. While skeptics like Cirincione contend that missile defense has had deleterious effects on strategic stability, proponents contend that missile defense capabilities enable a more flexible U.S. response strategy and have fostered other important science and technology derivatives.[6]

Indeed, in expanding the scope of analysis, missile defense is just one brushstroke on a full canvas of technologies and capabilities that have stoked fear, hope, and intrigue throughout the history of nuclear deterrence. Zeal for directed energy technology has waxed and waned, even in the wake of Ash Carter's landmark assessment of fundamental physics limitations in the application for missile defense in space.[7] Proponents of hypersonics have sustained unwavering faith, as exemplified by the quote from Richard Hallion at the beginning of this chapter, through recurring

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[5] Joseph Cirincione, "Persistence of the Missile Defense Illusion," Presentation to the Conference on Nuclear Disarmament, Carnegie Endowment for International Peace, July 3, 1998, https://carnegieendowment.org/1998/07/03/persistence-of-missile-defense-illusion-pub-134.
[6] Brad Roberts, "On the Strategic Value of Ballistic Missile Defense," IFRI Security Studies Center, June 2014, https://www.ifri.org/sites/default/files/atoms/files/pp50roberts.pdf.
[7] Ashton Carter, "Directed Energy Missile Defense in Space," U.S. Congress, Office of Technology Assessment, OTA-BP-ISC-26, April 1984, https://www.princeton.edu/~ota/disk3/1984/8410/8410.PDF.

cycles of renewed interest and resumed scrutiny over strategic rationale, starting with an early assessment in 1963 that showed limited strategic benefit and continuing intermittently until the current wave of interest resurged almost 50 years later.[8] Meanwhile, technologies on the horizon are already beginning to spark similar cycles of intrigue, such as drone swarms and autonomous weapon systems,[9] low-cost overhead persistent sensing technologies, and high-powered computing.[10] As the horizon becomes increasingly populated with frontier technologies, such as quantum sensing and artificial intelligence, the technological landscape that contextualizes nuclear deterrence will continue to evolve.

Interest in how policies are made amidst these competing and subjective assessments, concern about technologies at the frontier of innovation, and hope for opportunities to change the arms racing trajectory in this arc of innovation – an enduring feature throughout the history of nuclear deterrence – have motivated this research. In this dissertation, I evaluate one currently "emerging" technology, quantum sensing, with two key goals. First, I provide a technical analysis of the possible deterrence applications for quantum sensing and discuss how such applications may affect strategic stability. Many security policy analyses of emerging technologies are detached from scientific literature on the actual status of research and development for the technologies, and thus provide incomplete guides for

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[8] Larry Schweikart, "The Hypersonic Revolution: Case Studies in the History of Hypersonic Technology," Air Force History and Museums Program, 1998, https://media.defense.gov/2010/Sep/27/2001329809/-1/-1/0/AFD-100927-036.pdf.
[9] Jurgen Altmann and Frank Sauer, "Autonomous Weapon Systems and Strategic Stability," *Survival*, Vol. 59, No. 5 (2017), https://www.tandfonline.com/doi/abs/10.1080/00396338.2017.1375263?journalCode=tsur20.
[10] Christopher Bidwell and Bruce MacDonald, "Emerging Disruptive Technologies and Their Potential Threat to Strategic Stability and National Security," Federation of American Scientists, September 2018, https://uploads.fas.org/media/FAS-Emerging-Technologies-Report.pdf.

policymakers. Second, I identify social factors that influence conceptions of new technologies, like quantum sensing, and that shape how actors use incomplete technical assessments in policy debates about pursuing, deploying, or restraining new strategic capabilities. To do this, I propose and apply an integrated analytical framework that defines the technical characteristics and capabilities through which technologies may affect nuclear deterrence, but that also captures the agency of actors, influenced by both conceptions of deterrence and institutions, domestic politics, and other social dynamics, as participants, observers, and propagators of technology perceptions and policies.

Through this research approach, I argue that technological advances in quantum sensing will have more of an evolutionary, rather than revolutionary, effect on deterrence. Improved accuracy achieved with quantum sensing will likely advance performance of current capabilities, including limited-area submarine detection and missile navigation, but is unlikely to introduce entirely new capabilities or afford technical characteristics that would make current capabilities significantly more disruptive over the next ten years. By applying the integrated analytical framework, I also explore how the network of actors involved in the development and application of quantum sensors has harnessed innovation momentum and fostered expectations regarding the technology's capacity to disrupt nuclear deterrence that diverge from what would be recognized as feasible based on a technical assessment. Finally, by drawing comparisons to historical case studies, I highlight the enduring effects of policymakers' perceptions of new technologies, whether driven by technical, strategic, or social factors, on nuclear deterrence, force structure, and arms control.

This chapter serves as an introduction to the dissertation research and a roadmap for the various, and at times distinctly different, methodologies that are used to study the phenomena, actors, and mechanisms relating technology innovation to nuclear deterrence, force structure policy, and arms control. First, it provides a brief background on the literature fields from which this research draws to highlight the contours that define current discussions on the relevant topics and to indicate important gaps that the dissertation attempts to address. Next, it defines the research questions that frame this dissertation and provides rationale for the methodological approaches that have been taken to answer these questions as well as the analytical scope. It then provides a chapter overview laying out the organization of this dissertation. Finally, the main findings and implications of the dissertation are summarized to indicate the key contributions this research makes to broader security studies literature and nuclear policy dialogue.

Policy Problem and Literature Gaps

Policymakers' decisions to pursue certain technologies are rarely based purely on assessments of technical feasibility. Rather than wait to resolve uncertainties and ambiguity about new technologies before deciding whether to pursue development and acquisition, they more commonly choose to innovate in order to either compete or hedge against uncertainty. For example, the Biden administration has established a U.S. national imperative to compete for global leadership in quantum information science and technology, despite a lack of consensus among experts over the realistic prospects for achieving many technologies within the broad quantum category.[11] Specifically, experts remain divided on whether or not quantum computing, an important driver of quantum technology interest, will ever live up to predictions of large-scale applications that have overtaken media and policy agendas.[12] Where most experts agree is that there is still only limited clarity in predicting the true potential and timeline for development of quantum computers.[13]

Decisions to pursue U.S. leadership in a technology also often ignore or undervalue the potential negative repercussions, such as production of arms racing incentives. The prioritization of military readiness and the power distribution among actors in the institutions that comprise the military industrial complex have historically incentivized over-investing in a technology to safeguard or hedge against the possibility that it may have extraordinarily important effects, regardless of recognized uncertainty in anticipating a new technology's potential.[14] The U.S. Department of Defense (DOD) recently codified the strategy to pursue extremely advanced technologies with high degrees of uncertainty by allocating over $1 billion to establish a "hedge portfolio" in the proposed 2024 Appropriations Bill. On the definition and the strategic motivation, the proposal specifies:

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[11] U.S. Executive Office of the President, "Executive Order on Enhancing the National Quantum Initiative Advisory Committee," Presidential Action, May 4, 2022, https://www.whitehouse.gov/briefing-room/presidential-actions/2022/05/04/executive-order-on-enhancing-the-national-quantum-initiative-advisory-committee/.

[12] John Horgan, "Will Quantum Computing Ever Live Up to Its Hype?" *Scientific American*, April 20, 2021, https://www.scientificamerican.com/article/will-quantum-computing-ever-live-up-to-its-hype/.

[13] Larry Greenemeier, "How Close Are We – Really – to Building a Quantum Computer?" *Scientific American*, May 30, 2018, https://www.scientificamerican.com/article/how-close-are-we-really-to-building-a-quantum-computer/.

[14] For example, discussed in: Eugene Gholz and Harvey Sapolsky, "The defense innovation machine: Why the U.S. will remain on the cutting edge," *Journal of Strategic Studies*, Vol. 44, No. 6 (2021), pp. 854-872.

> A hedge in this sense will resource organizations capable of developing non-traditional solutions from non-traditional sources by intentionally taking calculated risks to incentivize positive, deliberate, and accelerated change. If properly executed, this hedge has the potential to create asymmetric advantage to support combatant command operational challenges and reduce the taxpayer's burden by leveraging private capital, expand America's economic advantage by accelerating emerging technology, and broaden the pool of talent supporting national defense.[15]

There are many historical examples that indicate negative, even if unintended, consequences of indiscriminate technology hedging, as well as massive investments in technologies that may be feasible, but are also destabilizing. In her account of isomer weapon research that took place in the 1990s and 2000s, Sharon Weinberger examines technology hedging motivations and effects. Specifically, she surveys when and why members of the U.S. military industrial complex, including the DOD, the Defense Advanced Research Project Agency (DARPA), national labs, and the armed forces have, at times, invested resources into long-shot technologies, despite scientific skepticism, and guided by the belief that any potential strategic advantage, however unlikely, outweighs anticipated, or unforeseeable, consequences.[16] Emphasizing negative repercussions, Weinberger persistently nods to the fact that these pursuits are often at odds with arms control, material security, and non-proliferation interests, suggesting that such policy objectives merit similar weight in acquisition decisions.

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[15] "Proposed Department of Defense Appropriations Bill, 2024," Report 118 – XXX, 118th Congress (2023), p. 4, https://docs.house.gov/meetings/AP/AP00/20230622/116151/HMKP-118-AP00-20230622-SD002.pdf.

[16] Sharon Weinberger, *Imaginary Weapons: A Journey Through the Pentagon's Scientific Underworld*, (New York: Nation Books, 2006).

Further research into the effects of hedging policies towards new technologies and on alternative approaches to treat ambiguity or uncertainty is vexed by seemingly incongruous literatures. Because of the technical, strategic, and social factors that each contribute to perceptions of new technologies, partitioning of information between fields of study on each set of dynamics has led to incomplete explanations.

In the security studies literature, nuclear policy experts have explored the risks and potential benefits of new technologies for nuclear deterrence, evaluating when and how innovation affects a delicate equilibrium referred to as "strategic stability." Although the strategic stability equilibrium is a common metric in these analyses, consensus on a definition of the term has remained elusive across the security studies community.[17] Edward Warner, a nuclear policy analyst and treaty negotiator, claimed that the narrowest definition of strategic stability specifies the lack of incentives for nuclear weapon first-use (crisis stability) and the lack of incentives to build up nuclear weapon infrastructure (arms racing stability). Warner notes, however, that the term has also been applied in a much broader sense to refer to the absence of conflict among nuclear weapon states, as well as conditions of regional or global security.[18]

Despite the subjective strategic yardstick, scholars and analysts like James Acton, Christopher Chyba, Rebecca Hersman, and Michael Mazarr have applied broad knowledge of nuclear deterrence requirements and strategic stability theory to propose general frameworks and mechanisms that support evaluation of the escalation

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[17] James Acton, "Reclaiming Strategic Stability," in *Strategic Stability: Contending Interpretations*, Ed. Elbridge Colby, Michael Gerson (2013), pp. 117-146, https://carnegieendowment.org/files/Reclaiming_Strategic_Stability.pdf.
[18] Acton, "Reclaiming Strategic Stability," pp. 117-118.

risks and strategic stability disruptions caused by new technologies and capabilities.[19] These endeavors provide useful analytical guideposts, indicating key areas of consideration across technologies, including escalation dynamics, proliferation potential, information flow, and decision-making factors.

Other analysts and policymakers in the security studies field have opted for more narrowly focused reports on implications for individual emerging technologies, such as artificial intelligence[20] and additive manufacturing.[21] The specificity that is provided by these narrower assessments, and the benefits of higher resolution evaluations for developing policy responses, demonstrates the importance of evaluating key characteristics of individual technologies.

While these contributions in the security studies literature provide valuable insights on the strategic effects of new technologies and capabilities, they sometimes suffer from deficits in empirical rigor or lack interdisciplinary methodology that could provide greater clarity on effective policy options. Analyses of specific technologies often take at face value claims made by proponents of technology development rather than providing independent technical feasibility assessments

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[19] James Acton, "Escalation through Entanglement," *International Security*, Vol. 43, No. 1 (2018), https://direct.mit.edu/isec/article-abstract/43/1/56/12199; Christopher Chyba, "New Technologies & Strategic Stability," *Daedalus*, Vol. 149, No. 2 (Spring 2020), pp. 150-170, https://www.jstor.org/stable/48591318; Rebecca Hersman, "Wormhole Escalation in the New Nuclear Age," *Texas National Security Review* (Summer 2020), pp. 90-109, https://tnsr.org/2020/07/wormhole-escalation-in-the-new-nuclear-age/; Michael Mazarr, et al., "Disrupting Deterrence: Examining the Effects of Technologies on Strategic Deterrence in the 21st Century," RAND Research Report, 2022, https://apps.dtic.mil/sti/pdfs/AD1166723.pdf.
[20] James Johnson, "Artificial Intelligence: A Threat to Strategic Stability," *Strategic Studies Quarterly* (Spring 2020), pp. 16 – 39, https://www.airuniversity.af.edu/Portals/10/SSQ/documents/Volume-14_Issue-1/Johnson.pdf.
[21] Tristan Volpe, "Dual-use distinguishability: How 3D-printing shapes the security dilemma for nuclear programs," *Journal of Strategic Studies*, Vol. 42, No. 6 (2019), https://www.tandfonline.com/doi/abs/10.1080/01402390.2019.1627210.

which could inform some of the uncertainty regarding a technology's future potential and could provide insight into what capabilities can realistically be expected. Analyses that evaluate larger patterns across emerging technologies rarely incorporate discussion of historical military innovation trends that could shed light on phenomena likely to occur with new technologies based on similar preceding technology characteristics or geopolitical and domestic policy contexts and that would strengthen the analytic power. Finally, to identify effective policy recommendations, the security studies field would benefit from more extensive research into the social and organizational actors and mechanisms that cause policymaker appraisals of new technologies to deviate from estimates established in technical assessments, or furthermore that override technical assessments in shaping policy decisions.

Scholarship in the science and technology studies (STS) field offers insight into how social phenomena shape technology innovation that could resolve some of these issues. A seminal article published by Langdon Winner in 1980 argued that decisions about even relatively mundane technological artifacts, such as the mechanical tomato harvester, produce social effects, and therefore are also political decisions.[22] A few years later, Wiebe Bijker and Trevor Pinch argued for a social constructivist approach to the study of science and technology.[23] This line of logic was further expounded when the two authors published an edited volume of essays

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[22] Langdon Winner, "Do Artifacts Have Politics?" *Daedalus*, Vol. 109, No. 1 (Winter, 1980), https://www.jstor.org/stable/pdf/20024652.pdf?refreqid=excelsior%3A7bd67b2474bd64b90aaf1c1fc7017ee8&ab_segments=&origin=&acceptTC=1.

[23] Trevor Pinch and Wiebe Bijker, "The social construction of facts and artefacts: or how the sociology of science and the sociology of technology might benefit each other," *Social Studies of Science*, Vol. 14, No. 3 (1984), https://research.utwente.nl/en/publications/the-social-construction-of-facts-and-artefacts-or-how-the-sociolo.

with Thomas Hughes titled *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology*, in which they merged methodologies and theoretical models from the fields of sociology and history of science and technology to build out a framework that is now commonly referred to as Social Construction of Technology (SCOT).[24] With respect to the noted gaps in security studies literature, SCOT and the broader STS literature base provide analytical tools for critically assessing the "blackbox" assumption of technology innovation in military settings and recognizing artifacts as not just constituting a technology, but also embodying political and social phenomena.

Although scientific literature on new technologies provides useful insight on the distance between state-of-the-art R&D and feasible applications, it is often omitted from security studies analyses for two reasons. First, is the lack of interdisciplinary knowledge among security studies experts that limits their understanding of the physical science fields related to new technologies. Conversely, most technical experts with the background needed to inform gaps in feasibility knowledge are not trained in security studies policy. Thus, there is a very small contingent of analysts with the core set of information needed to traverse the divide between the literatures.

A second, more inherent challenge is that technical research is often published in sporadic waves throughout the early R&D phases of newer technologies and research areas. This cadence makes it difficult to decipher important developments

[24] *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology*, edited by Wiebe Bijker, Thomas Hughes, and Trevor Pinch (Cambridge Massachusetts; MIT Press, 1987).

and distinguish between breakthroughs and recurring roadblocks that will impede R&D. Furthermore, technical literature may only focus on narrow subsets of the technology, and thus may not necessarily provide a comprehensive appraisal of the stage of development for the technology as a whole.

To rectify the limitations common in security studies assessments, this dissertation applies an interdisciplinary perspective to evaluate the implications of new technologies for nuclear deterrence. Specifically, this dissertation proposes integration of evidence from historical case studies in security studies literature, social phenomena theory in the STS field, and technical assessment of current quantum research progress. Together, these lenses offer complementary perspectives for evaluating assertions about new technologies and understanding the strategic and social motivations that may lead policymakers to pursue technologies and capabilities despite major technical hurdles and potentially negative strategic effects.

Research Question

This dissertation examines the potential impacts of quantum sensing technologies on nuclear deterrence doctrine, force structure, and arms control decisions. It aims to address the specific question of how quantum sensors are likely to affect these aspects of deterrence and strategic stability and explores policy options to mitigate associated risks. Through assessing the sources of concern arising over quantum technologies, this dissertation highlights technical, strategic, and social factors that have complicated emerging technology analyses in the nuclear deterrence community, currently and historically. Thus, the research also informs the broader question of how technological innovations, and the ambiguity and uncertainty inherent in new technologies, affect nuclear deterrence policymaking, and how the interplay of technical, strategic, and social factors should be managed when developing policy responses. The methodologies applied to answer the question with respect to quantum sensing demonstrate empirical approaches that can be used to better predict the disruption of other emerging technologies and to anticipate social influences that may factor into and constrain policymaking in conditions of technological uncertainty. This research also informs how strategic motivations and social factors create artificially positive feedback loops that stimulate interest in developing technologies or capabilities that may not be feasible or realistic in real-world settings.

Component questions

To answer the main research question focused on quantum sensing and to inform the overarching debate of when and how new technologies impact deterrence, this dissertation answers three supporting sets of questions:

1. <u>What factors influence policy decisions to pursue new technologies and develop responses based on their impact to nuclear deterrence?</u> To what extent do technical considerations, in addition to political and social factors, inform policymaker decisions? When are each of these elements more influential?
2. <u>What factors have historically influenced decision-making regarding technological innovation and deterrence?</u> When and how have technical, social, and strategic factors influenced decision-making in past circumstances of technological uncertainty? What were the effects of these decisions on technology development and strategic stability?

3. How could quantum sensing impact nuclear deterrence and what are the factors influencing policymaker perceptions? What are the current debates about how quantum sensing will affect nuclear deterrence, force structure requirements, and arms control? What does a fuller "socio-technical" analysis of quantum sensing innovation indicate about the types of disruption that are possible as R&D progresses? How do strategic, social, and technical features of current quantum sensing dialogue compare to those of previous technologies? Based on the similarities and differences, what are the key risks that policymakers must avoid when assessing conjectures about quantum sensing and navigating potential effects?

Why quantum sensing? Choosing an emerging technology

Before reviewing the contents of this dissertation, it is worth clarifying the decision to use quantum sensing technologies as the main contemporary case study in this analysis. Quantum sensors are a versatile set of technologies that leverage quantum physics to improve accuracy in the measurement of physical quantities, such as electric, magnetic, and gravitational field strength, temperature, time, and acceleration. The applicability of quantum sensors to a wide array of activities in both the defense and civilian sectors has earned quantum sensing a spot among most lists of emerging technologies which are of interest to security policymakers.[25] In addition to the wide versatility, a few characteristics distinguish quantum sensing as a

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[25] Chris Jay Hoofnagel and Simson Garfinkel, "Quantum Sensors – Unlike Quantum Computers – Are Already Here," *Defense One*, June 27, 2022, https://www.defenseone.com/ideas/2022/06/quantum-sensorsunlike-quantum-computersare-already-here/368634/.

particularly interesting technology to tackle with an interdisciplinary approach, including the current stage of development and the interconnection with other innovation areas.

The broader category of quantum technologies has recently attracted interest across defense and security communities, drawing varied responses from different stakeholders. Quantum technologies include technologies that apply quantum phenomena to achieve some form of operation enhancement, including improved accuracy, increased sensitivity, or faster computation. Beyond this single unifying element, quantum technologies are usually grouped into three categories: quantum sensing, quantum communication, and quantum computing. Quantum sensing, the most well-developed of the three, uses quantum science to improve the measurement of physical quantities. Quantum communication, the next most advanced, applies quantum systems to increase the speed or security of communication. Finally, quantum computing, the most nascent of the three, employs quantum principles to improve computation for purposes such as decryption. Within the past 5-10 years, major governments worldwide have signaled interest in developing and deploying quantum technologies, especially in military domains, given the substantial performance improvements promised by proponents of the new wave of technologies. Galvanized by government interest, defense and security analysts have also begun to postulate applicability to certain military and strategic operations.

Despite the increased interest in quantum technologies, significant technical uncertainties and ambiguity surrounding their specific application areas, scope of impact, and timeline for development have propagated diverging perspectives of impact and resulted in relatively undirected policy responses. The United States has established a National Quantum Initiative but still lacks specific policies and strategic objectives beyond the narrow security focus of protecting against foreign quantum decryption and the higher-level goal of attaining technological leadership.[26] Similarly, Russia and China are establishing government funding and resourcing schemes but have yet to declare their stated purposes for pursuing quantum technologies.

Given that quantum communication and quantum computing are at earlier stages of development, quantum sensing was the most sensible focus for this analysis. The quantum sensing R&D community has achieved many significant milestones, with numerous sensor prototypes already on the commercial market.[27] Furthermore, a robust industry of quantum sensing R&D firms suggests that more advanced quantum sensing technologies with increased capabilities will continue to enter the market.[28] Although the increased uncertainty enveloping quantum communication and computing research offers an opportunity to study how policymakers respond to extremely nascent technologies, such research would necessarily be highly speculative. Assessing a new technology at a somewhat later stage of R&D is advantaged by the fact that many key application areas and obstacles towards major milestones have already been identified. Finally, as will be discussed in Chapter 2,

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[26] U.S. Executive Office of the President, "Executive Order on Enhancing the National Quantum Initiative Advisory Committee," Presidential Action, May 4, 2022, https://www.whitehouse.gov/briefing-room/presidential-actions/2022/05/04/executive-order-on-enhancing-the-national-quantum-initiative-advisory-committee/.
[27] Lindsay Rand, Tucker Boyce, and Andrea Viski, "Emerging Technologies and Trade Controls: A Sectoral Composition Approach," Center for International and Security Studies at Maryland, 2020, http://www.jstor.org/stable/resrep26934.1.
[28] Lindsay Rand, "Quantum Sensing Sectoral Analysis," Center for International and Security Studies at Maryland, Working Paper, 2021.

quantum sensors encapsulate many of the characteristics and capabilities that the security studies literature has emphasized as disruptive for nuclear deterrence, including more effective targeting of second-strike capabilities.

Research Methodology and Chapter Structure

An interdisciplinary approach, guided by an integrated analytical framework, is applied to answer the research questions and to build on and contribute to the different literature fields discussed above. Research objectives and methodologies for each analytical approach taken throughout the dissertation are summarized below, with reference to the chapters in which they appear. Each chapter contributes to answering the quantum sensing-specific research question with a more interdisciplinary approach than traditional security studies analyses. Moreover, they also afford greater insight into the broader research dilemma of assessing the impact of new technologies.

Developing an integrated analytical framework

Chapters 2 and 3 specify the theoretical basis that underpins this research. This basis draws on literature from the three fields of study identified – security studies, STS, and scientific and technical research – to develop a more integrated analytical framework that serves as the conceptual backbone for this research. To develop an analytical framework that can weave together important contributions from each field, relevant variables, mechanisms, and patterns that have been proposed in existing literature to understand the means through which emerging technologies impact nuclear deterrence are distilled.

Chapter 2 surveys the existing literature to identify frameworks and theories that could be employed to understand the consequences of new technologies for nuclear deterrence. This review includes security studies, STS, and quantum science literature produced by policy, academic, and technical communities. It incorporates different scopes of evaluation, ranging from literature that focuses on the characteristics of individual technologies to literature that discusses larger trends that traverse a host of new technologies. Chapter 2 highlights contributions from the existing literature and identifies key differences between the various literatures and gaps across fields of study. Exploring these divides provides insight into why policymakers have historically struggled to develop policies around new technologies and motivates the endeavor for a more integrated approach.

The influential factors identified through the literature review are woven together in Chapter 3 to construct an integrated analytical framework that remedies gaps in existing scholarship and connects technology characteristics and sought-after military capabilities to nuclear deterrence effects. This framework incorporates important and often underestimated factors defined in STS theory, such as the role of social and political institutions and the power of certain individual actors in a socio-technical network, that influence policies on security studies topics to promote development or acquisition of new technologies.

The primary purpose of the framework is to provide a comprehensive, yet flexible analytical tool that incorporates technical characteristics, strategic and social influences, and patterns found in and across historical case studies and that has predictive power in anticipating effects on policymaking across various emerging technologies. Technology characteristics identified through this research include those that define how a technology is produced, what a technology is composed of, and how a technology operates. Potential impacts for deterrence and strategic stability include capabilities that affect crisis management, escalation dynamics/deterrence effectiveness, and nuclear governance. The specification of general technology characteristics and their connections to capabilities with certain types of effects, rather than the technology systems themselves, as the analytic focus makes the framework more adaptable to assess historical and current patterns and enables the framework to be applied more readily to different technologies and innovations.

Examining influential factors in historical cases

Chapter 4 applies the framework to five historical case studies of previous emerging technologies: ballistic missile defense, hypersonics, satellite imagery, remote (psychic) vision, and stimulated isomer energy release (in the application of isomer weapons). The historical case studies tease out two key features that are not obvious from the abstract overview of the analytical framework components in Chapter 3. First, they illustrate how the complex system of technical, strategic, and social factors interact to impact policy decisions. Second, they explore the temporal evolution of the technical, strategic, and social factors that results in different policy decisions at various points in time. Because the framework establishes a complex system of explanatory variables and mechanisms, process-tracing informs when and how particular characteristics or dynamics carry greater gravitas in policy decisions.

Additionally, through evaluating technologies that have evolved over different timescales, the multiple case study approach highlights heterogeneity in the endurance of effects across technologies.

These five case studies were selected to reflect a range of traits across the main dimensions of the analytical framework. Together, they account for an array of capabilities, technical characteristics, and social influences to explore policy responses for technologies with differing degrees of uncertainty and ambiguity.[29]

From a security studies lens, the strategic impacts of the technologies range based on their associations with offensive, defensive, and enabling capabilities. The case study on satellite imagery sheds light on decision-making regarding an enabling technology that broadly supports offensive and defensive capabilities, including improvements in reconnaissance for more accurate targeting with offensive capabilities, as well intelligence and early warning improvements for defensive capabilities. The missile defense case study provides insight into decision-making on defensive systems. Conversely, hypersonic technologies primarily enhance offensive capabilities. The case study on remote vision offers a unique perspective on how technologies (or technical methods) with high degrees of uncertainty and ambiguity, and which have little or no scientific basis, can still attract funding by feeding on hopes of achieving a capability with immense strategic impact. Finally, stimulated isomer energy release signifies a technology that neither appeared technologically

[29] Alex George and Andrew Bennett, "Phase One; Designing Case Study Research," Chapter 4 in *Case Studies and Theory Development in the Social Sciences*, p. 74.

feasible nor was linked to a strategically significant capability, but that was nevertheless pursued.

The set of five technology case studies also covers a wide array of technical characteristics. The missile defense and hypersonic case studies address the evolution of large, technically intensive kinetic systems that require immense expertise across various science and engineering disciplines. The satellite imagery and remote vision case studies tangentially inform key factors for intangible or enabling technologies (relevant for the wide suite of currently emerging digital and communication-oriented technologies). Meanwhile, the stimulated isomer energy release case study provides insight into a lab-based capability that derives from the basic research community.

For each case, the technical characteristics, proposed capabilities, actors, and social dynamics that shaped policy responses, and the resulting impacts on U.S. nuclear deterrence, force structure, and technology acquisition policy decisions are identified through process tracing. All analyses focus on important points for policy decisions in the innovation processes when there was uncertainty over the potential performance improvements to be gained from each of the technologies. While policymakers were aware that there was some degree of uncertainty over the technical opportunities for U.S. adoption or risks in the event of adoption by an adversary, their decisions on how to respond to the technologies were ultimately guided by beliefs about deterrence and various social factors, in addition to technical expectations.

One recurring pattern across case studies is that most policymakers overestimated the importance of preparing for technological change. This perspective led them to pursue new technologies to hedge for strategic advantages or to outcompete an adversary pursuing the technology in case the most extreme expectations turned out to be correct. This also means they underestimated the negative consequences of overpreparation, supporting policies of competition at the expense of cooperation.

Previous research has said little about the extent to which this preference for technological over-investment derives more from strategic considerations or institutional pressures and parochial concerns, so the interplay of these factors is a critical focus in the historical case studies. To gauge how technological, strategic, and social factors interact to produce policy outcomes, the case studies evaluate the timelines to develop (or pursue) the technologies, the policy decisions and resources required to pursue the technologies, and the eventual impact of the technologies on nuclear deterrence compared to predictions that were made at the time of consequential decision-making.

Evaluating quantum sensing suitability for applications

Chapter 5 provides a deep dive into one contemporary case study: quantum sensing. It includes a survey of emerging narratives on quantum sensing, identification of technology-specific characteristics that have implications for nuclear deterrence and force structure planning, assessment of feasible capability improvements, and comparison of projected capabilities to those predicted in the emerging narratives.

Because quantum sensing is at the frontier of new and emerging technologies, it allows for application of the framework to a technology that currently exhibits technical uncertainty and application ambiguity. Some sources claim that quantum sensing capabilities are imminent and will reshape nuclear deterrence through applications that dramatically improve capabilities to track and target second-strike capabilities, among other uses.[30] If such claims were true, from a security studies perspective, quantum sensing would fundamentally disrupt conditions of mutual vulnerability between China, the United States, and Russia, which rely on secure second-strike forces to maintain assured retaliatory capabilities with (somewhat) smaller arsenals. Yet, there is uncertainty over exactly how much of an improvement over existing methods quantum sensing can provide, how long these capabilities will take to come to fruition, which platforms (e.g., qubit types) will perform best, how operating conditions or constraints may impose limits on the performance gains they afford, and whether such improvements could be easily countered.

The quantum sensing analysis was framed by an initial literature review of current narratives on quantum sensing security implications and an evaluation of likely applications. As noted previously, the relative novelty of quantum sensing has led to a wide array of assertions about what impacts the technology can be expected to have on deterrence. Some of these assertions are based on technical evidence, while others are rooted more in strategic motivations for to project capabilities. To identify realistic application areas worth assessing in this dissertation, the initial survey also involved an analysis of state-of-the-art prototypes and interviews with industry experts to pinpoint a few key applications for which quantum sensing could

[30] David Hambling, "China's quantum submarine detector could seal South China Sea," *New Scientist*, August 22, 2017, https://www.newscientist.com/article/2144721-chinas-quantum-submarine-detector-could-seal-south-china-sea/.

feasibly improve capabilities. The initial literature and technology reviews found two key capability areas that would be suitable for quantum sensing application as the technologies continue to improve and for which a capability enhancement would have a significant strategic effect: missile navigation and submarine tracking.[31]

After identifying the major quantum sensing applications, estimates of the improvements that could be feasibly expected compared to existing technologies were produced for each capability. Focusing on improvements to missile navigation and submarine detection narrowed the broader set of quantum sensing devices into a more manageable scope and allowed for operation-specific performance considerations, such as a sensor's suitability based on the sensing target and the deployment requirements to achieve a certain strategic objective. Finally, a capability-based analysis afforded consideration of countermeasures that could negate the benefit of quantum sensor applications.

For each capability, a tiered process was used to iteratively adjust the projection for quantum sensor operability and performance improvements.[32] The first tier established the most generous estimates for advances in performance capability over the next 10 years, based on measurements for established quantum sensor systems in lab settings. The next tier of analysis reined in the optimistic projections achieved using current lab sensitivities by accounting for experimental obstacles and

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[31] For example, discussed in: Michal Krelina, "Quantum Technology for Military Applications," *EPJ Quantum Technology*, Vol. 8, No. 24 (2021), https://epjquantumtechnology.springeropen.com/articles/10.1140/epjqt/s40507-021-00113-y.

[32] For example, this process has been used in two recent articles analyzing quantum sensing impacts in other areas: S. Crawford, R. Shugayev, H. Paudel, P. Lu, M. Syamlal, P. Ohodnicki, B. Chorpening, R. Gentry, and Y. Duan, "Quantum Sensing for Energy Applications: Review and Perspective," *Advanced Quantum Technologies* (2021), DOI: 10.1002/qute.202100049. And David Farley, "Quantum Sensing and its Potential for Nuclear Safeguards," Sandia Report, October 2021, https://www.osti.gov/servlets/purl/1829781.

uncertainties. This included consideration of how factors present in the lab setting, such as measurement techniques, material acquisition, and control technologies will introduce uncertainty, and thus impose constraints on predicted performance levels. Finally, application-specific sources of uncertainty, including target variability and impacts due to mobility and operation in harsher, but more realistic, environments were considered. In real-world applications, targets may be moving, have less distinguishability, and reside at varying distances from the sensor. These characteristics introduce challenges that will either impact the sensitivity in each application, or that will increase the requirements for deployment.[33] The performance effects of potential countermeasures were also considered at this tier of analysis.

This in-depth case study analysis finds that quantum sensing may offer significant theoretical performance improvements, but experimental and application-based hurdles will circumscribe these benefits for most applications on realistic timescales. The likelihood of overcoming major R&D obstacles and achieving significant performance gains in the near-and long-term futures was also considered. Based on this analysis, it seems unlikely that the more optimistic expectations will be met, at least in the next 10 years. Significant sensitivity improvements that have not yet been achieved even in lab settings would be required to perform tasks such as high-confidence, long-distance submarine detection. Once achieved in lab settings, further research will be needed to support operability in real-world conditions. This means that many current predictions for quantum sensing, especially those based on

[33] For example: Daniel Boddice, Nicole Metje, and George Tuckwell, "Capability assessment and challenges of quantum technology gravity sensors for near surface terrestrial geophysical imaging," *Journal of Applied Geophysics*, Vol. 146 (2017).

theoretical performance gains, overestimate what should be expected and ignore known limits.

Assessing the quantum sensing deterrence impact

The historical case studies showed that exaggerated expectations and uncertainties about what new capabilities an emerging technology might yield often foster diverging assessments of strategic stability impact across different deterrence perspectives. Therefore, Chapter 6 evaluates how the technical estimates for quantum sensing applications translates to various strategic effects depending on different perceptions of security, strategic stability, and deterrence. Although the technical assessment provides estimates for quantum sensor improvements that reduce at least some of the uncertainty over the technology's future development and application, the effects of these innovations are still ambiguous, depending on the deterrence lens through which they are evaluated. Accounting for both assured destruction and damage limitation deterrence narratives, the different ways in which quantum sensing may impact strategic stability and deterrence are considered.

Because of underlying disagreements across deterrence theories, assertions about the disruption caused by new technologies like quantum sensing could exacerbate policy disputes over the vulnerability of secure second-strike capabilities whether or not those assertions are technically realistic. Specifically, Chapter 6 finds that, given the technology limitations identified in Chapter 5, quantum sensing is unlikely to change conditions of mutual vulnerability between the United States, Russia, and China through undermining submarine invulnerability. Rather, quantum sensing is more likely to heighten (or recycle) claims made by damage limitation proponents that increased missile accuracy will make low-yield nuclear or conventional weapon capabilities useful for counterforce applications that would currently require higher yield nuclear warheads, stimulating further arms racing.

Mapping the quantum sensing socio-technical ecosystem

Finally, guided by the socio-technical motivations identified in the historical case studies, Chapter 7 evaluates the social factors that have contributed to perceptions of quantum sensing and that are likely to further influence policy decisions beyond technical assessments and strategic considerations. In order to assess the various social worlds and epistemic communities that comprise the quantum sensing socio-technical ecosystem, network analysis methods were used to map out U.S. entities involved in advancing quantum sensing innovation, either through basic research, prototype development, or funding/resource provision. The dissertation then applies analytical tools from STS literature to explore social influences within technical quantum sensing communities and among policy communities seeking capabilities. The STS lens is also used to examine dynamics at the boundary between the different communities that impact information flow and result in bifurcated dialogue, and which will shape perceptions of quantum sensing and influence policy decisions.

Understanding of these social mechanisms, in addition to historical, technical, and strategic insight gained throughout the dissertation research, inform better policy recommendations for mediating dialogue over quantum sensing and new technologies and navigating technology governance decisions. Chapter 8 summarizes the findings from the entire trajectory of this research to identify policy implications. It summarizes how the quantum sensing analysis findings should inform nuclear force structure and arms control policymaking. It also discusses the implication of the findings in the context of broader hedging and innovation competition strategies, which are especially important as the United States engages in arms racing-style competition for technological leadership.

Key Findings and Research Contribution

Through applying an interdisciplinary approach, this dissertation finds that the incremental improvements to missile accuracy afforded by quantum sensing technologies are more likely to be feasible than major improvements to submarine detection. Achieving a strategically significant improvement in submarine detection capabilities, including one which would allow for near-constant tracking and sensing of an adversary's nuclear submarines (referred to as "transparent oceans"), would be both technically challenging given the low target signal strength, and operationally difficult given the vast network of sensors that would be required even under generous performance projections.

Meanwhile, given the long history of incremental innovations in positioning, navigation, and timing (PNT) technologies, and the new capabilities afforded by quantum sensing, improvements to missile navigation accuracy may be feasible and operationally achievable. For example, if quantum gravimeters – or quantum sensors that measure gravitational field strength – can be operationally deployed on missile payloads, they could improve terminal guidance capabilities and further reduce the error in missile navigation. This may afford greater assurance in precisely targeting missile silos, which could theoretically one day allow for a pre-emptive, disarming first strike with low-yield or conventional warheads, if targeted countries kept their entire nuclear force in ICBM silos. However, the net strategic benefit or risk of this development could be interpreted variably due to different deterrence logics.

From a policy perspective, these technical findings have important deterrence and strategic stability implications. Based on this assessment, it is unlikely that quantum sensing technologies will enable the capability to persistently monitor or track nuclear submarines. This finding offers a favorable outlook for the survivability of second-strike capabilities and sustained conditions of mutual vulnerability. It also reinforces that policymakers should avoid over-assuming the potential detection capabilities of quantum sensors, which could unnecessarily signal disruption to strategic stability and incentivize arms-racing. Instead, they should re-engage on debates over the strategic benefits and risks of conventional prompt strike and low-yield nuclear warheads in the current geopolitical landscape. Better missile navigation accuracy could eventually increase the appeal of counterforce strategies in ways that drive arms racing without offering an escape from mutual vulnerability. However, several technical hurdles, including natural environmental anomalies, still need to be addressed for a truly transformational improvement to accuracy, so high assurance of a nearly direct strike is unlikely to be attainable within the next 10 years.

The quantum sensing analysis, in conjunction with the analytical framework and findings from the historical case study analyses, also illuminates policies that could reduce risks of disruption (or perception of disruption). Each methodology provides added context as to how U.S. officials will decide whether to spend money to develop and deploy quantum sensors, whether to pursue specific types of capabilities, and whether to engage in bilateral or multilateral dialogues to strengthen or weaken relevant arms control constraints and norms. Specifically, the interdisciplinary context informs policies that will best ameliorate security dilemma risks not only associated with the technology itself, but with the social phenomena arising from the technology perceptions. For example, it highlights the importance of accurate signaling to adversaries *and* domestic actors through transparency-enhancing activities such as demonstrations and strategy/policy declarations, as well as the merits of practicing technological restraint for applications which would have destabilizing effects or could incentivize arms racing.

Thus, the dissertation also demonstrates the benefit of addressing emerging technologies with an interdisciplinary perspective to produce concrete and practicable policy recommendations. In realizing this objective, the research offers an improved analytical approach for predicting the implications of emerging technologies for nuclear deterrence based on technical, strategic, and social factors and multi-disciplinary evaluation. Because the findings specific to quantum sensing are discussed in the broader context of emerging technologies, nuclear deterrence, and arms control, the outputs of this research are relevant to similarly "hyped" emerging technologies with inflated expectations, including artificial intelligence and hypersonic weapons. They also inform how past debates over new technologies have led to conflicting policy decisions which have had enduring effects for deterrence postures and force structures today.

As the historical and present-day case studies show, apprehension caused by inflated expectations of new technologies and ambiguity over their applications has always been a key factor in nuclear deterrence and arms control policymaking and continues to influence policymaker assessments of deterrence requirements. These amplified assertions are driven by technical uncertainty and damage limitation strategies that make even small improvements seem significant, but they are promoted to support social institutions or political preferences. By critiquing these assumptions, this research may also help to lower the political barriers that impede efforts to pursue force structure and technology restraint and to engage more vigorously on arms control or cooperative dialogues. If countries believe that they need to fortify their nuclear arsenals to gain strategic advantage from technology innovation, or at the very least maintain hedging strategies, then they would perceive an increased cost of arms control agreements that limit freedom to pursue these capabilities and thus would be less likely to participate in cooperative efforts.

Finally, these findings are becoming increasingly timely as the United States adopts a more aggressive technology competition strategy in its broader foreign policy agenda. As rhetoric on the importance of engaging in great power competition surges, Washington must understand the domino effect that unrestrained and over-exaggerated technology development induces, leading to downstream effects across the national security domains, including for nuclear deterrence. By better parametrizing the impact of quantum sensing, and laying the foundation for more realistic assessments of other emerging technologies, the findings from this dissertation could help reduce some of these barriers to a more cooperative U.S. foreign policy as opposed to a competitive one.

Chapter 2: Identifying Gaps in the Literature

> "Of course, it isn't the job of intelligence officials, most of whom aren't scientists, to figure out if such technology was feasible, but only if the Russians were working on it. That made fears of a gamma-ray weapon – realistic or not – very important."
> -Sharon Weinberger, *Imaginary Weapons*[34]

> "Lurking in these historical questions are broad organizational issues about how scientific knowledge is created by organizations and how that knowledge is ultimately encoded in technology and organizational routine."
> -Lynn Eden, *Whole World on Fire*[35]

Given the multidisciplinary nature of the research question, this dissertation draws on a blend of political, sociological, and technical literatures. Deterrence theory is defined in the security studies and international relations/political science literature, which articulates the means and methods to successfully posture strategic forces to dissuade adversaries from attacking, as well as other techno-military factors that should guide decisions on force structure and arms control requirements. Other fields that look at the more social/organizational aspects of human-technology interaction, such as the science and technology studies (STS) field, offer insight on non-strategic factors that also shape policy decisions. Specifically, STS scholarship explores how

[34] Weinberger, *Imaginary Weapons*, p. 15.
[35] Lynn Eden, *Whole World on Fire*, Cornell University Press, Ithaca, (New York, 2004), p. 5.

these decisions and theories are influenced by a mixture of personal biases, political predilections, and parochial interests that run adjacent to, and interact with, technology innovation. Finally, and more relevant to evaluating technological change, scholarship from scientific and technical fields contextualizes R&D progress beyond the scope of nuclear deterrence and military technology. As a result, it offers insight into likely timelines for feasible technology innovations and technical roadblocks that may stunt the eventual acquisition of a new technology or capability. The partitioning of security studies literature from these other fields of study thus imposes barriers to cross-pollination that could otherwise improve analysis of key questions regarding when and how new technologies will impact nuclear deterrence.

In building bridges across different fields of study, it is important to account for the debates and divides that arise *within* each field and recognize how these divides amplify confusion that commonly occurs at the intersection of literatures. Within security studies literature, disagreements about how deterrence works (e.g., damage limitation versus assured destruction) as well as fundamentally different world views and international relations ideologies (e.g., realist, idealist, etc.) lead to divergent policy assessments of how new technologies will impact nuclear deterrence. In the STS community, internal debates rage over the degree to which technology is shaped by social institutions or vice versa (social construction of technology versus technological determinism), resulting in different theories of how to manage technological change. Lastly, although technical fields are often perceived to have objective, concrete answers, discussions in newer fields of study and over emerging technologies for which limited scientific consensus has been reached are marked by uncertainty and debate. Disputes about scientific progress are exemplified by the wide range of assertions on the feasibility of certain quantum technologies.

Such disagreements among experts are normal and should be recognized when combining various literatures to answer interdisciplinary questions. Otherwise, viewpoints of a faction of experts in one field could be cherry-picked to support an opinion being made in a different field, creating the false perception that the view represents consensus among specialists in the other field. Failure to recognize these internal community debates when evaluating topics such as the effect of new technologies on nuclear deterrence underemphasizes the degree of uncertainty or ambiguity inherent in projections and assessments.

This chapter surveys the key concepts in each of these areas of study that are used to develop the analytical framework proposed in Chapter 3. It highlights gaps in security studies frameworks that are important to address in order to answer the larger dissertation question, as well as debates and disagreements that inject uncertainty or ambiguity into such assessments. The first and largest section of this chapter surveys the security studies field to highlight strategic factors that shape deterrence theory and nuclear policymaking. It also reviews current approaches that have been developed in the security studies field to evaluate and predict the effects of emerging technologies, indicating limitations and gaps in knowledge. Because the research goal is to evaluate the implications of quantum sensing for nuclear deterrence, security studies literature serves as the core discipline to which interdisciplinary methods will be integrated. Next, this chapter provides a brief introduction to the STS field of literature, arguing that STS theories and analytical tools can better contextualize the social elements that are often ignored from emerging technology analyses in security studies literature. Finally, this chapter cautions against using scientific assessments to overcome uncertainty about emerging technologies and their strategic implications that characterize internal policy debates and international discussions. It indicates how technical consideration may be useful to guide security studies analyses, but also underscores the unavoidable uncertainty that arises in technical literature for newer areas of study by surveying disagreements arising over quantum technologies.

Security Studies Narratives on Nuclear Deterrence and Emerging Technologies

In the United States, the strategic purpose of nuclear weapons is to deter adversarial confrontation. Policymakers rely on deterrence logic to make decisions on force structure requirements that will achieve security objectives in different threat environments. However, among policymakers, there is disagreement over the means through which deterrence can be achieved.

Two main strategies govern decision-making on nuclear deterrence force structure requirements: assured destruction (AD) and damage limitation (DL). AD logic suggests that as long as states maintain force structures with survivable retaliatory nuclear forces capable of inflicting unacceptable damage, they can reliably deter nuclear attack. In contrast, DL logic suggests that states with sufficient counterforce capabilities may be able to escape vulnerability by using a combination of pre-emption and defense to deny adversaries the ability to cause unacceptable damage should they attack first or in retaliation. In light of modern geopolitics and new technologies, there has been some debate over what constitutes an AD capability and whether DL can feasibly be deployed to achieve strategically significant effects.[36] Yet, the essence of each strategy persists in debates over deterrence requirements.

Depending on which outlook they support, policymakers reach different conclusions on the best method to maintain strategic stability. Proponents of DL prioritize reducing the risk of deliberate deterrence failure by deploying forces that would minimize harm to the United States and its allies if an adversary used nuclear weapons. Under this lens, deterrence should be reinforced with any available capabilities that would minimize damage in the event of nuclear escalation, such as missile defense and counterforce systems. Conversely, proponents of AD argue that as long as countries maintain conditions of mutual vulnerability, a deliberate choice to start a nuclear war would never be rational. Therefore, the main risks are those associated with inadvertent deterrence failure, or risks that arise when states end up in a nuclear war that nobody wants due to misinterpretation, miscommunication, or internal failures of command and control. From the AD perspective, new technologies can destabilize deterrence either by disrupting conditions of mutual vulnerability or by introducing new areas for misinterpretation, mis-signaling, or command and control failures.[37]

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[36] For example, see: Charles Glaser and Steve Fetter, "Should the United States Reject MAD? Damage Limitation and the U.S. Nuclear Strategy toward China," *International Security*, Vol. 41, No. 1 (Summer 2016), pp. 49-98.
And reply to commentaries: Charles Glaser and Steve Fetter, "Correspondence: The Limits of Damage Limitation," *International Security*, Vol. 42, No. 1, (Summer 2017), pp. 201-207.
[37] Charles Glaser, *Analyzing Strategic Nuclear Policy* (Princeton University Press, 1990); and Glaser and Fetter, "Should the United States Reject MAD?"

Because these lenses lead to different perceptions on the role of technologies or technology-afforded capabilities in stabilizing or destabilizing nuclear deterrence, even in instances with established technical assessments, they also prompt disagreement over the necessity for arms control and cooperation. From the DL perspective, agreements that prevent the acquisition of capabilities to minimize damage should the nuclear escalation barrier be breached are undesirable. Meanwhile, from the vantage of the AD camp, agreements to limit the use of technologies that could be perceived as undermining assured retaliation capabilities are necessary to increase transparency and minimize the risk of escalation.

Beyond doctrinal predilection for either theory, policymaker decisions on nuclear force structure requirements are informed by a myriad of technical, political, and social factors. Uncertainty over the future capabilities a technology may provide introduces ambiguity over whether a technology could be truly destabilizing under either AD or DL assumptions. However, even under widely-accepted technical assessments, policymakers may reach different opinions on how to treat the technologies because of their unique perceptions of advantages to be gained in either international or domestic politics.[38] Additionally, their approach to the technologies may be biased by institutional incentives and organizational processes.[39]

A smaller body of literature in the security studies field has sought to connect deterrence logic to the sociology of technology theories, indicating that a contingent of scholars already have recognized the importance of understanding the social

[38] Caitlin Talmadge, "The US-China Nuclear Relationship: Why Competition is Likely to Intensify," Global China: Assessing China's Growing Role in the World, (September 2019).
[39] For example, discussed at length in: Fred Kaplan, *The Wizards of Armageddon* (Stanford University Press, 1983).

dynamics that influence nuclear decision-making. David Rosenberg argued in 1983 that Eisenhower's force structure decision-making was guided more by organizational concerns than strategic objectives.[40] In 1993, Donald MacKenzie published *Inventing Accuracy*, detailing the social and political pressures, in addition to the technical parameters, that influenced the development of strategic ballistic missile guidance. He found the former factors to be equally as influential as the latter.[41] With an even richer historical perspective, Lynn Eden wrote on the effects of social mechanisms in *Whole World on Fire*, published in 2004. Eden similarly finds that social constructions led to a systematic omission of fire damage analysis in nuclear destruction calculations, thus resulting in an inflated force structure. On the intrigue driving this series of inquiries, Eden writes: "lurking in these historical questions are broad organizational issues about how scientific knowledge is created by organizations and how that knowledge is ultimately encoded in technology and organizational routines."[42]

Yet, there remains a lack of STS consideration in security studies literature that evaluates the impact of "emerging technologies" on nuclear deterrence. Just as sociological lenses afforded deeper insight for Rosenberg, MacKenzie, and Eden, application of more recent developments in the STS field could inform social factors that are galvanizing and shaping emerging technology debates beyond strategic or technical considerations. At an even higher level, it could also expose dynamics that have led to the formation of a sub-field of study focused on emerging technologies.

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[40] David Rosenberg, "The Origins of Overkill: Nuclear Weapons and American Strategy, 1946-1960," *International Security*, Vol. 7, No. 4 (1983), pp. 3 – 71.
[41] Donald MacKenzie, *Inventing Accuracy* (MIT Press, 1993).
[42] Lynn Eden, *Whole World on Fire*.

Defining the "emerging technologies" problem

Although the idea of "emerging technologies" has become a feverish concern and a prominent pillar of nuclear policy dialogue, the concept of "emerging technologies" extends into broader policy domains. A unifying curiosity within and beyond the nuclear policy sphere is the question of what constitutes an "emerging technology." Surveying the use of the term across studies, Rotolo, Hicks, and Martins find that the term is commonly used to reference: "a radically novel and relatively fast growing technology characterized by a certain degree of coherence persisting over time and with the potential to exert a considerable impact on the socio-economic domains which is observed in terms of the composition of actors, institution, and patterns of interactions among those, along with associated knowledge production process."[43] They further emphasize that because an emerging technology's importance is predicated on anticipated capabilities and applications, its emergence is characterized by uncertainty and ambiguity.[44]

Despite definitional opacity, debates over the effects of emerging technologies on the nuclear deterrence status quo, strategic stability, crisis stability, and arms control viability rage on in the security studies community. As the Rotolo, Hicks, and Martins definition indicates, though, the conception of emerging technologies is so broad that analysts do not agree on what technologies will have the most significant effects, let alone what those effects will be. For example, a November 2021

[43] Daniele Rotolo, Diana Hicks, and Ben Martins, "What is an Emerging Technology?" *Research Policy*, Vol. 44 (2015), pp. 4, http://sro.sussex.ac.uk/id/eprint/56071/1/2015RPRotoloHicksMartinPreprint.pdf.
[44] Rotolo, Hicks, and Martins, "What is an Emerging Technology?"

Congressional Research Service brief identified artificial intelligence, lethal autonomous weapons, hypersonic weapons, directed energy weapons, biotechnology, and quantum technology as key "emerging military technologies in the United States, China, and Russia."[45] Meanwhile, a September 2018 report published by the Federation of American Scientists on emerging technologies likely to impact strategic stability across the broader international community focused on a slightly different list, including laser isotope separation technology, antineutrino detection technology, high-energy lasers, hypersonic technology, artificial intelligence, low-cost overhead persistent sensing technologies, and cybersecurity threats.[46] What these and other studies of emerging technologies and nuclear deterrence have in common is the attempt to grapple with the impact of unpredictability on nuclear weapons and predict the endurance of deterrence (or the failure to endure) in the face of technological change.

Beyond definitional challenges, another shortfall of emerging technology dialogue is that it often portrays an element of novelty in the problem of new technologies and nuclear deterrence, even though interest in the effects of technology innovation on nuclear security well predates the current fascination. (Various interesting sociological and STS theories could likely inform the origins and of this rebranding, including a self-selection bias among the experts that choose to specialize on these issues and institutional incentives to highlight the novelty of these

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[45] Kelley Sayler, "Emerging Military Technologies: Background and Issues for Congress," Congressional Research Service – R46458, November 10, 2021, https://sgp.fas.org/crs/natsec/R46458.pdf.
[46] Christopher Bidwell and Bruce MacDonald, "Emerging Disruptive Technologies and Their Potential Threat to Strategic Stability and National Security," Federation of American Scientists – Special Report, September 2018, https://uploads.fas.org/media/FAS-Emerging-Technologies-Report.pdf.

challenges.) To rectify this blind spot, and to contextualize the pervasive history of this problem, this section begins with a discussion of the evolution of emerging technology analyses, highlighting the history that predates the contemporary research surge. This is followed by a survey of current perceptions of emerging technology issues and methods used to evaluate emerging technology disruption in security studies literature. Finally, the strategic implications for these analytical approaches and misperceptions regarding technologies in shaping arms control and force structure policies are reviewed to motivate a more interdisciplinary methodology.

Not-so-hidden emerging technologies historic arc

Security studies experts have long speculated about the potential consequences of emerging technologies for nuclear weapons. Albert Wohlstetter and Bernard Brodie, early nuclear strategists, published theories in the 1960s as to how technological innovation could impact the deterrence balance. In his 1968 contribution to Adelphi Paper No. 46, Wohlstetter claimed that previous scholarship and strategy on nuclear deterrence "presumed a plateau in the arts of nuclear offence and defense," but that by the 1960s, it had become clear that military technology could destabilize nuclear strategy and that "the plateau was a mirage."[47] To Wohlstetter, innovations with the greatest disruptive potential included anti-ballistic missiles, technologies to improve adversary intelligence-gathering operations, multiple independent reentry vehicles, and technologies capable of improving accuracy and reliability of offensive systems. His reasoning was that this set of

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[47] Albert Wohlstetter, "Strength, Interest and New Technologies," in Adelphi Paper No. 46 by The Institute for Strategic Studies, 1968, p. 1.

technologies and capabilities could shift the offense-defense balance and thus provide a meaningful strategic advantage.[48] Brodie wrote on a similar set of technologies in 1969, also in the context of the offense-defense balance. However, his assessment of the disruption potential of new technologies was more conservative, partly because he did not believe that minor shifts in the offense-defense balance would change the basic conditions of mutual vulnerability.[49] Thus, even in early debates, analysts disagreed over the disruption potential of new technologies, reaching different conclusions based on competing deterrence narratives.

During the 1980s and 1990s, security studies scholars and defense analysts continued attempting to grapple with and anticipate the disruptive impacts of emerging technologies on nuclear deterrence. In 1983, Carl Builder, an analyst at The RAND Corporation, speculated that military strategy had already shifted away from a nuclear basis in favor of advanced conventional theater weapons.[50] In his research, Builder focused on a slightly newer set of technologies, including "smart" precision-guided munitions, space-based global information systems, and long-range delivery vehicles. In proposing a more dramatic shift, Builder expanded the speculation in his analysis from the offense-defense balance focus of Wohlstetter and Brodie, to include the difficulty that arms control experts and international policymakers would face in adjusting agreements and treaties to address a post-nuclear-centric military era. To do so, he additionally identified new verification challenges, potential disruption to the

[48] Wohlstetter, "Strength, Interest and New Technologies," pp. 2-4.
[49] Bernard Brodie, "The Future of Deterrence," in *The Future of Deterrence in U.S. Strategy* by the University of California – Los Angeles Security Studies Project, 1969, https://apps.dtic.mil/sti/pdfs/AD0687071.pdf. [This study was funded by the U.S. Air Force and the author claims that this had significant sway on the topics included].
[50] Carl Builder, "Strategic Conflict Without Nuclear Weapons," The Rand Corporation, April, 1983.

nuclear umbrella extended to allies of nuclear countries, and increased feasibility and likelihood for horizontal nuclear proliferation.[51]

Revived interest and recent debates

A new wave of technologies, and a rebranding of this concern under the label of "emerging technologies," has reignited concern over future risks and opportunities for nuclear deterrence. While early nuclear strategists focused on kinetic weapon innovation and space-based intelligence technologies, contemporary analyses center around digital and information technologies such as artificial intelligence and autonomous systems, computing and cyber-enabling technologies, and advanced positioning, navigation, and timing (PNT) technologies.[52] Some tangible technologies, such as drone swarms, small satellite constellations, more robust ballistic missile warning and tracking systems, and more reliable means of communication have also fostered interest, but largely in relation to improvements in intangible information and digital technologies that have augmented their capabilities.[53] Beyond new technology platforms, an added challenge frequently cited for "emerging technologies," is that such systems often have both civilian and military applications, with commercial actors playing a larger role in development, application, and diffusion than for prior military technologies.[54]

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[51] Builder, "Strategic Conflict Without Nuclear Weapons," 54-63.
[52] For example: Sayler, "Emerging Military Technologies," and Bidwell and MacDonald, "Emerging Disruptive Technologies and Their Potential Threat to Strategic Stability and National Security."
[53] Zachary Kallenborn, "A Partial Ban on Autonomous Weapons Would Make Everyone Safer," *Foreign Policy*, October 14, 2020, https://foreignpolicy.com/2020/10/14/ai-drones-swarms-killer-robots-partial-ban-on-autonomous-weapons-would-make-everyone-safer/.
[54] Alexander Montgomery, "Double or Nothing? The Effects of the Diffusion of Dual-Use Enabling Technologies on Strategic Stability," CISSM Working Paper, July 2020, http://people.reed.edu/~ahm/Projects/ProlifInnov/Montgomery2020Double.pdf.

Renewed interest around “emerging technologies” has been reinforced by U.S. government signaling. In 2014, Defense Secretary Chuck Hagel announced the Pentagon’s so-called “Offset Strategy” (which has also been referred to externally as the “Third Offset Strategy”[55]), an initiative with the goal of integrating new technologies to maintain American military supremacy against Chinese anti-access and area-denial (A2/AD) systems.[56] The 2018 U.S. National Defense Strategy more recently affirmed this strategy, declaring that America’s military focus had transitioned from counterinsurgency and counterterrorism to “the reemergence of long-term strategic competition by what the National Security Strategy classifies as revisionist powers.”[57] It highlighted the modernization of technological capabilities by China and Russia, and claimed that such efforts were intended to bolster their military strength and propagate their authoritarian ideals.

The Biden administration has similarly signaled that maintaining U.S. advantages in new technologies will remain a foreign policy focus, but that cooperation should be sought to put “guardrails” on competition. Soon after the presidential transition, the Biden administration signaled this shift in strategy with the national security strategy guidance released on March 3, 2021, which highlighted the threats associated with technological competition and called for efforts to create shared norms and agreements, suggesting that emerging technologies would remain a

[55] DOD members referred to this as the “Third Offset” to link it with previous efforts to deploy advanced American technologies as a means of “offsetting” Soviet conventional superiority. The First Offset refers to the use of tactical and strategic nuclear weapons to offset the Soviets conventional advantages in the early 1950s. The Second Offset refers to the use of advanced technologies such as precision-guided strike and stealth, to offset Soviet numerical superiority in the 1970s and 1989s. See: Gian Gentile, Michael Shurkin, Alexandra Evans, Michelle Grise, Mark Hvisda, and Rebecca Jensen, “A History of the Third Offset, 2014-2018,” RAND Corporation, 2021.
[56] Chuck Hagel, “Innovation Memo”, United States Department of Defense, OSD012411-14, 2014.
[57] 2018 National Defense Strategy of the United States of America.

prominent fixture.[58] The Biden administration has reinforced this agenda by releasing documents that establish and promote standards for safely developing and deploying new technologies, such as the "Blueprint for an AI Bill of Rights"[59] and the "National Standards Strategy for Critical and Emerging Technology."[60] But, in addition to initiating these guardrails, the Biden administration has also stated in the National Security Strategy that competing for technology leadership is a key pillar that will support the current U.S. strategy to out-innovate China and constrain Russia.[61]

Regardless of the position different administrations have taken in the spectrum between cooperation and competition, "Offset Strategy"-era policy efforts have adopted broader, interagency approaches. Beyond the defense realm, the Trump Administration initiated a government-wide transition to "Industries of the Future" by allocating direct funding pathways for R&D on artificial intelligence and quantum information technologies intended for non-defense purposes in the FY 2021 budget.[62] Biden's new "Chips and Science Act" similarly embraces an inter-agency approach that is centered around the National Science Foundation, but calls on different departments and agencies to "expand fundamental and use-inspired research."[63]

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[58] Shannon Bugos, "State Reviews Plans for New Tech Bureau," *Arms Control Today*, Arms Control Association, April 2021.
[59] "Blueprint for an AI Bill of Rights," United States Office of Science and Technology Policy, October 2022, https://www.whitehouse.gov/ostp/ai-bill-of-rights/.
[60] "United States Government National Standards Strategy for Critical and Emerging Technology," United States Executive Branch, May 2023, https://www.whitehouse.gov/wp-content/uploads/2023/05/US-Gov-National-Standards-Strategy-2023.pdf.
[61] "National Security Strategy," United States Executive Branch, October 2022, https://www.whitehouse.gov/wp-content/uploads/2022/10/Biden-Harris-Administrations-National-Security-Strategy-10.2022.pdf.
[62] "Advancing United States Leadership in the Industries of the Future," The White House, 2020.
[63] "Fact Sheet: Chips and Science Act Will Lower Costs, Create Jobs, Strengthen Supply Chain, and Counter China," United States Executive Branch, August 2022, https://www.whitehouse.gov/briefing-room/statements-releases/2022/08/09/fact-sheet-chips-and-science-act-will-lower-costs-create-jobs-strengthen-supply-chains-and-counter-china/.

These strategies appreciate the fact that, compared to earlier technology eras, most modern technology innovation is occurring outside the sphere of the traditional military industrial complex. This civil-to-military technology transfer phenomenon, labeled "spin-on" as opposed to "spin-off" (military-to-civilian), requires a policy approach that expands engagement on strategic objectives to encompass economic and dual-use technology factors and that better engages larger socio-technical networks of private sector and interagency stakeholders to constrain risks and leverage benefits in certain application areas, such as nuclear deterrence.[64]

Evaluating how emerging technologies will impact nuclear deterrence

In response to the funding and resource interest signaled by these government policies, security studies experts have been quick to jump on the theme of emerging technologies and nuclear deterrence. Some scholars and research groups have tried to fully identify the disruptions (good and bad) created by specific technologies.[65] Others have sought to formulate more comprehensive frameworks for assessing how a range of emerging technologies might affect a specific aspect of nuclear strategy, such escalation propensity,[66] extended deterrence,[67] or arms control.[68]

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[64] Maaike Verbruggen, "The Role of Civilian Innovation in the Development of Lethal Autonomous Weapon Systems," *Global Policy*, June 14, 2019.

[65] For example: James Johnson, "Artificial Intelligence in Nuclear Warfare: A Perfect Storm of Instability?" *The Washington Quarterly*, Vol. 32, No. 2 (2020).

[66] For example: Caitlin Talmadge, "Emerging Technology and Intra-War Escalation Risks: Evidence from the cold War, Implications for Today," *Security Studies*, 2019.
And: Rebecca Hersman, "Wormhole Escalation in the New Nuclear Age," *The Strategist*, 2020.
And: James Acton, "Escalation through Entanglement: How the Vulnerability of Command-And-Control Systems Raises the Risks of Inadvertent Nuclear War," *International Security*, 2018.

[67] Rupal Mehta, "Extended deterrence and assurance in an emerging technology environment," *Journal of Strategic Studies* (2019).

[68] For example: Rebecca Hersman, Heather Williams, and Suzanne Claeys, "Integrated Arms Control in an Era of Strategic Competition," CSIS Project on Nuclear Issues Report, January 2022.

Few security studies scholars or analysts have offered a comprehensive framework for assessing how different types of emerging technologies may impact the broader balance of strategic stability. Favaro, Kuhn, and Renic perform expert elicitation to evaluate the applications and technology readiness level of a set of 12 emerging technologies.[69] Despite asking participants to identify both positive and negative effects that should be expected for the technologies, the authors ultimately find that emerging technologies are likely to have a "negative multiplicity" of effects, with a combination of both first- and second-order negative effects. However, beyond the main conclusion that policymakers will face difficulty finding appropriate arms control measures due to the speed of innovation, the unclear impact of emerging technologies, and the current military technology competition, the report neither provides longer-term, deeper understanding of the socio-technical factors that influence deterrence, nor a set of practicable policy measures.

Conversely, Durkalec, Peczeli, and Radzinksy present an analytical framework that is centered around policymakers' decisions.[70] Their report seeks to answer how complex interactions of emerging and disruptive technologies impact decision-making during conflict escalation, how emerging and disruptive technologies change the context and choices available during decision-making, and which technologies will be the most relevant to nuclear-decision-making. Their

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[69] Marina Favaro, Neil Renic, and Ulrich Kuhn, "Negative Multiplicity: Forecasting the Future Impact of Emerging Technologies on International Security and Human Stability," IFSH Research Report #10, 2022.
[70] Jacek Durkalec, Anna Peczeli, and Brian Radzinsky, "Nuclear decision-making, complexity, and emerging disruptive technologies: A Comprehensive Assessment," European Leadership Network Report, February 14, 2022, https://www.europeanleadershipnetwork.org/report/nuclear-decision-making-complexity-and-emerging-and-disruptive-technologies-a-comprehensive-assessment/.

analysis does not include arms racing or arms control factors, nor does it evaluate impacts of specific technology characteristics. This reduces the flexibility to apply the model more generally to other technologies and also narrows the focus to the decision-making process of an escalation continuum, rather than considering arms control, force structure, or technology acquisition decisions.

Of the analytical frameworks proposed, Christopher Chyba's is the most flexible in applying a broad scope of strategic stability elements and allowing for application to a wide range of technologies. Chyba's framework proposes that a technology's disruption to strategic stability should be analyzed along three distinct axes: the pace and diffusion of the technology, the implications for defense and deterrence, and the technology's potential for direct impact on crisis decision-making.[71] Although Chyba's framework is broad in capturing a range of impact areas across strategic stability, it appreciates the importance of technology-specific characteristics that may impact the scope of disruption. The split between evaluating the defense and deterrence implications and the crisis decision-making disruptions also allows for evaluation along a wide horizon of strategic stability impact areas.

Because it incorporates technology characteristics and categorizes strategic stability impact areas, Chyba's framework provides a useful starting point for the research in this dissertation. However, Chyba does not include evaluation of political and social mechanisms that may influence policymaking, nor does he include reference to historical precedents. This positions the focus of Chyba's framework strictly on identifying areas of disruption and limits its ability to identify potential

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[71] Chyba, "New Technologies & Strategic Stability."

policy remediations as well as its ability to determine how novel the effects of a new technology might be.[72] Despite these limitations, the dual lenses of technical and policy perspectives, as well as the broad range of strategic effects considered, make Chyba's framework most similar to the framework proposed in Chapter 3.

Limitations of emerging technologies and strategic stability scholarship

The utility of existing security studies literature in developing concrete deterrence and technology policies has been circumscribed by three main trends in the field. First, in trying to encompass the emerging technologies in a universal categorization, treatment of the group as a whole tends to be overly generalized and ignores underlying debates between different deterrence camps.[73] The pitfall of this approach is that it fails to recognize inherent ambiguity in assessments of new technologies.[74] Second, in mapping technologies to real world implications, studies frequently omit technical analyses that would allow for realistic feasibility assessments of the technology and related capabilities that could counter inflated rhetoric and provide more directed policy recommendations.[75] Finally, the literature largely excludes insights about how policymakers have assessed the potential effects

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[72] Chyba, "New Technologies & Strategic Stability," p. 163.

[73] For example: "Emerging Technology and National Security: Findings and Recommendations to develop and deploy advanced technologies through effective partnerships that promote economic, technological, and national security competitiveness," 2018 Analytic Exchange Program, July 26, 2018, https://www.dhs.gov/sites/default/files/publications/2018_AEP_Emerging_Technology_and_National_Security.pdf.

[74] Daniele Rotolo, Diana Hicks, and Ben Martins, "What is an Emerging Technology?" *Research Policy*, Vol. 44 (2015), pp 1827 – 1834, http://sro.sussex.ac.uk/id/eprint/56071/1/2015RP_Rotolo_Hicks_Martin_Preprint.pdf.

[75] Shawn Brimley, Ben Fitzgerald, and Kelley Sayler, "Game Changers: Disruptive Technology and U.S. Defense Strategy," Center for New American Security, September 2013, https://s3.amazonaws.com/files.cnas.org/documents/CNAS_Gamechangers_BrimleyFitzGeraldSayler.pdf?mtime=20160906081305.

of earlier forms of disruptive technologies, and what those effects actually turned out to be.[76] Without historical case studies, analyses risk over-estimating the disruption potential of emerging technologies, or underemphasizing the social influences on decision-making beyond strategic and technical evaluations.

The first trend, the tendency to focus on overly broad, positivist categories, derives from attempts to develop more comprehensive analyses, but necessarily undervalues the inherent ambiguity of deterrence implications fostered by competing narratives on policy and strategy requirements. This approach is most common in analyses that discuss more theoretical, mechanism-based ideas for the nuclear-emerging technology nexus.[77] While generalization may be useful for theory generation and framework development, it can also risk constricting the study to overly vague timelines and implications, limiting the depth of resulting policy recommendations. Groups viewing the new technologies through different deterrence lenses will adopt competing narratives to perceive different implications for nuclear deterrence and force structure. Thus, any positivist approach that ignores this underlying debate would be very constricted in its evaluation if it only recognizes points of consensus across all deterrence logics.

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[76] For example: Andrew Futter, "Explaining the Nuclear Challenges Posed by Emerging and Disruptive Technology: A Primer for European Policymakers and Professionals," EU Non-Proliferation and Disarmament Consortium – Non-Proliferation and Disarmament Papers, No. 73 (March 2021), https://www.sipri.org/sites/default/files/2021-03/eunpdc_no_73_0.pdf.

[77] For example: Dominik Jankowski, "NATO and the Emerging and Disruptive Technologies Challenge," in *NATO: in the Era of Unpeace: Defending Against the Known* Unknown, 2021, pp. 81-102. (Here, the author discusses a wide set of emerging technologies, but provides policy recommendations broadly across the technologies, resulting in overly broad policy options. Additionally: Christopher Chyba, "New Technologies & Strategic Stability," *Daedalus*, Vol. 149, No. 2 (Spring 2020), https://doi.org/10.1162/DAED_a_01795. Here, Chyba presents an interesting framework to encompass the broad category of "New Technologies" but in doing so impedes his ability to extend more narrow policy recommendations.

The second trend, the tendency to omit technical details, likely stems from both a lack of technical understanding given the emerging nature of the topic and an overemphasis on strategic factors. Some members of the nuclear security community have highlighted the overly technical emphasis in the approach to arms control, and how it can obfuscate political processes.[78] While this may be true in nuclear arms control, where the technologies have been well-developed for a considerable amount of time and where research and development is no longer a key focus, it is not necessarily the case for emerging technology. Given that emerging technologies are, by nature, nascent and often developing rapidly, technical grounding is more necessary to determine practical estimates of feasible impact and realistic timelines to these developments, as well as to anticipate obstacles based on recurrent features in technical literature. Better-informed parameters are not only instrumental in predicting disruption, but also in identifying specific and effective policy options.

The third trend, the relative absence of empirical or historical information, minimizes the importance of social and political processes that influence decision-making under technological uncertainty. Speculation about the impact of emerging technologies on nuclear deterrence is rarely informed by empirical analysis of similar debates in the past, what the actual impact on nuclear deterrence turned out to be, and how those effects were the product of choices that were not based solely on accurate understanding of what was technologically feasible and what was strategically

[78] For example, a key theme in *The Politics of Verification*, by Nancy Gallagher, is the imperative of considering the politics of verification, even though verification is often discussed in solely technical terms. Also discussed in: "Technical Aspects of Nuclear Proliferation," in *Technologies Underlying Weapons of Mass Destruction*, United States Congress Office of Technology Assessment – OTA-BP-ISC-115, 1993.

possible. Even Chyba's exemplar framework lacks this element of historical depth. However, the sociological analyses conducted by scholars like Eden, Rosenberg, and MacKenzie suggest that underlying social and political phenomena will be equally as important to address as compared technical factors when identifying policy options and recommendations.

Force structure and arms control implications

The ambiguity generated by the gaps identified in the security studies emerging technology literature leaves major deterrence and arms control implications open to interpretation based on the narrative lens through which a policymaker or strategist views the issue. Analysts applying a DL logic, such as Keir Lieber and Daryl Press, posit that new technologies, through enabling significant improvements to counterforce capabilities, may critically undermine nuclear deterrence.[79] They argue that technologies which can improve accuracy or detection capabilities can provide enough of an advantage to enable a disarming first strike counterforce attack. This logic would imply that the appropriate policy response to an adversary's potential technological advantage is to bolster the nuclear forces to compensate for the loss of hardening and concealment and ensure a secure retaliatory capability.[80] Conversely, if the adversary is perceived to be disadvantaged, a robust force structure, in addition to providing technological advantage, could allow one to escape

[79] Keir Lieber and Daryl Press, "The New Era of Counterforce: Technological Change and the Future of Nuclear Deterrence," *International Security*, Vol. 41, No. 4, Spring 2017.
[80] Lieber and Press, "The New Era of Counterforce." See also: Matthew Kroenig and Bharath Gopalaswamy, "Will disruptive technology cause nuclear war?" Bulletin of the Atomic Scientists, November 12, 2018.

assured destruction. In either case, Lieber and Press find that technological change disincentivizes arms control.

Narratives rooted in the AD logic argue that emerging technologies increase the pressure for arms control, as long as countries maintain secure retaliatory capabilities. Under this logic, scholars claim that very few technologies could conceivably undermine nuclear deterrence entirely and necessitate or incentivize larger arsenals. Rather, these arguments focus on the destabilizing aspects of emerging technologies, such as the potential for unintended escalation and the reduced confidence in retaliatory capabilities, and thus find an added imperative for arms control agreements and force structure restraint.[81] Because they de-emphasize technical characteristics, though, they often fail to address inflated assertions specifically and systematically.

Science and Technology Studies: Reframing the Problem

STS literature provides theories and frameworks that could be useful for including social and organizational factors to supplement strategic factors in analyzing the decision-making process for new technologies. Chapters 3, 4, and 7 provide greater detail on the specific STS mechanisms that are incorporated in integrated analytical framework, found in the historical case studies, and observed in

[81] For instance: James Acton, "Escalation through Entanglement: How the Vulnerability of Command-And-Control Systems Raises the Risks of Inadvertent Nuclear War," *International Security* (2018). Or: Andrew Futter, "Explaining the Nuclear Challenges Posed by Emerging and Disruptive Technology: A Primer for European Policymakers and Professionals," EU Non-Proliferation and Disarmament Consortium, No. 73 (March 2021).

the quantum sensing socio-technical ecosystem. This section will provide a brief introduction on the theoretical basis and methodologies that underpin theSTS field. It outlines a key tension in approaches to understand the relation between technology and societal change that has shaped the STS field, specifies the aims and methodologies applied in STS to explore technological innovation processes, and argues for the utility of applying STS frameworks and theories to examine how new technologies, and specifically quantum sensing, affect nuclear deterrence.

Although the social studies of science field dates back to the early 1900s (and likely earlier), the STS field was not established in a unified and defined form until the 1960s and 1970s. Prior to the development of the field as formal area of study, a variety of economic, philosophical, and sociological scholars began to explore the relation between social institutions and technological change. Thorstein Veblen, a sociologist and economist, is believed to have been the first person to establish the concept of technological determinism in his seminal essay "The Place of Science in Modern Civilization."[82] In it, Veblen asserts that modern human civilization, including institutions and behaviors, has been dramatically shaped by the evolution of technologies, sciences, and machines – an idea now recognized as technological determinism. On this determinism induced by technology, Veblen writes:

> In the modern culture, industry, industrial processes, and industrial products have progressively gained upon humanity, until these creations of man's ingenuity have latterly come to take the dominant place in the cultural scheme; and it is not too much to say that they have become the chief force in shaping men's daily life, and therefore the chief factor in shaping men's habits

[82] Thorstein Veblen, "The Place of Science in Modern Civilization," *The American Journal of Sociology*, Vol. 11, No. 4 (1906), https://www.jstor.org/stable/2762805.

> of thought. Hence men have learned to think in the terms in which the technological processes act.[83]

However, in the following decades, scholars began to formally critique this view, countering the appraisal of technological change (and corresponding changes to human civilizations) as fundamentally deterministic. Since its conception, the STS field has largely been shaped by this divide between the deterministic view and the more constructivist approach – social construction of technology (SCOT). The SCOT theory was first proposed by Trevor Pinch and Wiebe Bijker in 1984, but drew upon earlier theories developed in the sociology of scientific knowledge, science-technology relationship, and technologies studies fields which asserted that social factors, such as politics, actors biases, and organizational incentives, do in fact shape technology change.[84] In their theory, Pinch and Bijker shift the agency from technologies to social institutions, asking how society impacts technology change rather than the other way around. Under SCOT, Pinch and Bijker asserted that social institutions are key factors in creating closure around the applications and impacts of new technologies, rather than the science underlying the technologies or the material objects themselves. Since Pinch and Bijker's proposal in 1984, many STS scholars have produced a continuum of theories between the deterministic and constructivist poles, analyzing case studies of historical technologies and developing frameworks,

[83] Veblen, "The Place of Science in Modern Civilization," p. 598.
[84] Trevor Pinch and Wiebe Bijker, "The Social Construction of Facts and Artefacts: or How the Sociology of Science and the Sociology of Technology might benefit each other," *Social Studies of Science*, Vol. 14, No. 3 (1984).

constructs, and mechanisms to specify key factors that explain the ways in which technology and society are interconnected.[85]

Many of the mechanisms and theories that have been formed in the STS field to analyze the reductionist-constructivist spectrum are applicable to the evaluation of technology change and nuclear deterrence, as well as other contemporary issues associated with modern innovation. For example, the process of technology closure, or the mechanism through which consensus is reached about the design and utility of a technology, can help to explain both why it is difficult to predict the impact of emerging technologies, but also why nascent technologies are most fungible to policies and social influences before their conceptions stabilize.[86] Similarly, the "technology paradigm" or the socially-manifested association of a new technology with an older technology (even if there are underlying technological differences) for the purpose of shaping a new technology, explains how historical developments can produce internal biases in humans and institutions that will dictate their response and beliefs about the new, separate technology.[87]

The benefit of applying these STS concepts is that the information they afford on the underlying people and institutions that affect policy decisions will ultimately allow for a more nuanced understanding of how new technologies have and will continue to impact nuclear deterrence. Although the STS literature does not point to a

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[85] For example: Allan Dafoe, "On Technological Determinism: A Typology, Scope Conditions, and a Mechanism," *Science, Technology, and Human Values*, Vol. 40, No. 6 (2015), https://journals.sagepub.com/doi/full/10.1177/0162243915579283.
[86] Hans Klein and Daniel Kleinman, "The Social: Construction of Technology: Structural Considerations," *Science, Technology, and Human Values*, Vol. 27, No. 1 (Winter 2002).
[87] Donald MacKenzie and Judy Wajcman, "Introduction," in *The Social Shaping of Technology*, Open University Press (1999), https://eprints.lse.ac.uk/28638/1/Introductory%20essay%20%28LSERO%29.pdf.

clear answer on whether new technologies will shape nuclear deterrence, if nuclear deterrence will shape innovations, or if they will each mutually co-evolve, it can afford the language to discuss the complex network of stakeholders and social institutions that provides insight into decisions are made about new technologies. These actors and concepts will be integrated throughout the remaining dissertation chapters. Chapter 3 provides one interpretation of an integrated analytical framework for assessing technical, strategic, and social factors at the intersection of new technologies and nuclear deterrence, Chapter 4 follows in the footsteps of STS scholars by providing assessments of historical case studies, finally Chapter 7 applies the integrated framework and assessments of the quantum sensing ecosystem to survey key actors and social dynamics in the current case study of quantum sensing.

Quantum Technology: Here and Not

Finally, it must be recognized that there is a significant degree of subjectivity and uncertainty when evaluating the readiness and capabilities of new technologies. Given the timeliness of its development and the ways in which it could impact nuclear deterrence, quantum sensing offers a valuable opportunity to examine a real-time emerging technology case study. As the pursuit to realize the practical utility of quantum technologies accelerates, sensing has the highest technology readiness level, compared to computing and communication. However, even at this later stage of development, there still is no consensus about the best applications or reasonable expectations for quantum sensing technologies.

A prominent review article by Degen, Reinhard, and Cappellaro defines the quantum sensing field as encompassing technologies that employ quantum mechanical systems to act as sensors for different physical quantities.[88] For sensors, the "central weakness" of quantum systems – their susceptibility to external perturbances – is harnessed as a tool for querying physical qualities of the environment at an extremely fine scale.[89] Proposed measurable qualities include magnetic and electric fields, gravitational fields, temperature, pressure, time, acceleration, and rotation. Yet, there is still significant uncertainty over the current technology readiness level for quantum sensing, how the technology will develop over time, and specific capability improvements that should be expected.

Quantum sensing development status

Quantum sensors have undergone significant innovation in the past 10-15 years. Although some sensor types, such as superconducting quantum interference devices (SQUIDs), have been operable since the 1990s, modern quantum information science (QIS) innovations have enabled greater mobility. One of the key requirements for SQUIDs and most atom-based sensors is an extremely cold operating temperature. Until recently, ultra-cold refrigeration devices were very large, but chip-sized refrigeration technologies are now commercially available.[90] Additionally, improved optics and laser technologies have enabled better control of quantum sensor systems,

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[88] Degan, Reinhard, Cappellaro, "Quantum sensing."
[89] Degan, Reinhard, Cappellaro, "Quantum sensing."
[90] Maria Martinez-Perez and Dieter Koelle, "NanoSQUIDs: Basic & Recent Advances," *Physical Sciences Reviews*, Vol. 2, No. 8 (August 2017).

which has led to increased sensitivity.[91] Finally, certain QIS research areas have given rise to entirely new sensing platforms and techniques, such as nitrogen vacancy (NV) center-based sensors[92] and distributed sensing.[93] Thus, although quantum sensors have been used in lab settings for more than 20 years, recent technology improvements have made quantum sensors more sensitive and mobile, and have allowed for entirely new architectures. These transformations have increased the practical utility of quantum sensors for real world applications.

Despite this progress, there is still significant uncertainty as to how quantum sensing R&D will unfold. For example, the variety in architectures that are being researched has introduced uncertainty as to what type of sensor is best for a particular application and which types will be easiest to manufacture and operate. Even within narrow categories of quantum sensor types, such as those that perform magnetometry or gravimetry, there are various architectures for sensor devices. For gravimetry, atomic interferometers represent the tried-and-true sensor platform,[94] while newer qubit research has introduced the feasibility of superconducting levitation sensors[95] or NV-center diamond sensors.[96] Meanwhile, for magnetometry, SQUIDs have long

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[91] Andreas Thoss, Markus Krutzik, and Andreas Wicht, "Quantum Technology: Quantum sensing is gaining (s)pace," *Laser Focus World*, January 2018.
[92] Diamond quantum sensors: from physics to applications on condensed matter research," *Functional Diamond*, Vol. 1, No. 1, https://doi-org.proxy-um.researchport.umd.edu/10.1080/26941112.2021.1964926.
[93] Zheshen Zhang and Quntao Zhuang, "Distributed Quantum Sensing," *Quantum Science and Technology*, Vol. 6, (2021). https://doi.org/10.1088/2058-9565/abd4c3.
[94] M. Hauth, C. Freier, V. Schkolnik, A. Peters, H. Wziontek, and M. Schilling, "Atom interferometry for absolute measurements of local gravity," in Proceedings of the International School of Physics" Enrico Fermi, Vol. 188 (2014), pp. 557–586.
[95] Johnsson, Brennen, and Twamley, "Macroscopic superpositions and gravimetry with quantum magnetomechanics," *Nature – Scientific Reports*, Vol 6, No. 37495 (2016).
[96] Xing-Yan Chen and Zhang-Qi Yin, "High-precision gravimeter based on a nano-mechanical resonator hybrid with an electron spin," *Optics Express*, Vol. 26, No. 4 (2018).

been the state of the art,[97] but are beginning to face competition from atomic optical sensor schemes[98] and NV-center diamond sensors.[99] Further, even within each of these individual platform types, variations have arisen due to research on different materials that are used, alternative quantum systems, and unique measurement protocols applied.

Due to this diversity and lack of convergence around one type of system, there is uncertainty over which sensor design will prevail for each sensing branch, complicating the process of predicting reasonable capability ranges. Scientists in the field suggest that this diversity is likely to persist, given that each platform type may find its own market niche depending on the level of noise present in each application and the sensitivity required for the target for a specific application.[100] Thus, analyses that project future sensing capabilities must identify the most suitable platforms depending on the specific application, and consider how projections may vary depending on differential speeds of development for each sensor platform.

Across the different platforms, a few key trends arising from the quantum nature of the sensors could lead to varying degrees of quantum advantage compared to classical alternatives. First, as engineering begins to catch up with theory, quantum devices are likely to have a size advantage. Smaller sensing devices increase mobility.

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[97] R. Fagaly, "Superconducting quantum interference device instruments and applications," *Review of Scientific Instruments*, Vol. 77, No. 101101 (2006), https://www.physlab.org/wp-content/uploads/2016/04/Squidcomprehensive.pdf.
[98] H. B. Dang, A. C. Maloof, and M. V. Romalis, Ultrahigh sensitivity magnetic field and magnetization measurements with an atomic magnetometer, Appl. Phys. Lett. 97, No. 151110 (2010).
[99] A. Kuwahata, T. Kitaizumi, K. Saichi, T. Sato, R. Igarashi, T. Ohshima, Y. Masuyama, T. Iwasaki, M. Hatano, F. Jelezko, M. Kusakabe, T. Yatsui, and M. Sekino, "Magnetometer with nitrogen-vacancy center in a bulk diamond for detecting magnetic nanoparticles in biomedical applications," *Nature Scientific Reports*, Vol. 10, No. 2483 (2020).
[100] Finding based on preliminary interviews with technical experts in the field.

Second, depending on what is needed for a specific application, quantum sensors can be more sensitive or more robust to noise than classical sensors. However, some scientists point out that this should not be assumed given the sensitivity of non-quantum alternatives, but rather should be based on the needs of the specific application.[101] Third, quantum sensors may continue to be improved through advanced quantum measurement techniques, such as squeezing, that allow for the sensitivity to surpass the "standard quantum limit" (SQL).[102] Finally, quantum entanglement, if reliably achieved, may enable extremely strong detection capabilities via techniques such as ghost imaging or quantum illumination.[103] However, the latter two attributes are still in the early stages of research and have not yet been demonstrated, let alone rigorously tested, in an experimental setting.

Both magnetometer and gravimeter quantum sensors are now commercially available, although necessary improvements must be met to better harness the quantum advantage. Thus far, quantum gravimetry has been enabled with atomic interferometer devices[104] and quantum magnetometry has been deployed through SQUIDs[105] and optical atom-based magnetometers.[106] For both fields, NV-center diamond devices appear to be on the horizon, backed by market interest.[107] However, at the moment, these devices only capture the first two advantages for quantum

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[101] Finding based on preliminary interviews with technical experts in the field.
[102] Degen, Reinhard, and Cappellaro, "Quantum Sensing."
[103] Zhang and Zhuang, 2021.
[104] MSquared (https://www.m2lasers.com/quantum.html) and Muquans (https://www.muquans.com/).
[105] Magnicon SQUID sensors (http://www.magnicon.com/squid-sensors/magnetometers) and Supracon sensors (http://www.supracon.com/en/magnetometer.html).
[106] Twinleaf sensors (https://twinleaf.com/scalar/OMG/) and Quspin sensors (http://quspin.com/wp-content/uploads/2016/09/QMAG-TF-Spec-Sheet.pdf).
[107] "Quantum Magnetometer Augments GPS," May 2019, https://www.insidequantumtechnology.com/news-archive/quantum-magnetometer-augments-gps/.

sensors (size and sensitivity advantages). This means that they only offer quantum advantage for certain applications, and that the extent of a given advantage is somewhat limited. If the other two benefits, and especially entanglement, can be achieved in real-world settings, then quantum sensors may yield advantages in a wider variety of applications. However, some scientists remain skeptical that the more dramatic quantum improvements will ever be attainable outside of lab settings.

Quantum sensing security implications

Compared to their classical counterparts, quantum sensing technologies enable increased sensitivity, greater mobility, and improved operability in more adverse environments (such as in space or underwater).[108] They are also capable of dead reckoning, or operating in the absence of external signals, making them more robust to spoofing, tampering, and jamming.

Given the myriad capabilities boasted, quantum sensing is associated with a broad scope of national security implications, including PNT, detection of objects or cavities underground or in water, and radiofrequency signal detection.[109] Thus, quantum sensing has the potential to affect communication,[110] automation,

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[108] Degan, Reinhard, Cappellaro, "Quantum sensing."
[109] Sarah Gamberini and Lawrence Rubin, "Quantum Sensing's Potential Impacts on Strategic Deterrence and Modern Warfare," *Orbis*, Vol. 65, No. 2 (2021).
[110] Patrick Tucker, "US Army Creates Quantum Sensor that Detects Entire Radio-Frequency Spectrum," *Defense One*, February 8, 2021, https://www.defenseone.com/technology/2021/02/army-creates-quantum-sensor-detects-entire-radio-frequency-spectrum/171939/.

navigation,[111] missile launch detection,[112] command-and-control,[113] and organizational activities. The applications with the most direct connection to nuclear deterrence are improvements to PNT capabilities, which could increase missile accuracy, and accomplishment of radar and imaging techniques, which could allow for subsurface detection of submarines or detection of mobile missile platforms.[114] Improvements in quantum sensing technologies will also pave the way for milestones in other quantum fields that seem likely to have national security and deterrence implications, including computing and communication.[115]

As was true of the broader literature on emerging technology, current work focused specifically on the security implications of quantum sensing either lacks the necessary technical depth to provide useful projections or is overly broad in identifying applications directly connected to the international security field. Non-technical literature on the topic is limited and emphasizes major actors, rather than the technology itself,[116] or is overly vague in strategic relevance.[117] Some technical

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[111] Donghui Feng, "Review of Quantum Navigation," IOP Conference Series: Earth and Environmental Science 237 (2019).
[112] "Quantum radar has been demonstrated for the first time," *MIT Technology Review*, August 2019.
[113] Peter Hayes, "Nuclear Command-and-Control in the Quantum Era," *Nautilus Institute for Security and Sustainability*, March 29, 2018, https://nautilus.org/napsnet/nuclear-command-and-control-in-the-quantum-era/.
[114] Andrew Foerch, "The Quantum Future of PNT," Trajectory, July 2018, https://trajectorymagazine.com/the-quantum-future-of-pnt/.
[115] Demille et al., "Quantum Sensors at the Intersection of Fundamental Science, Quantum Information Science and Computing," Report of the Department of Energy Roundtable held February 2016, https://www.osti.gov/servlets/purl/1358078.
And: Martin Giles, "The US and China are in a quantum arms race that will transform warfare," *MIT Technology Review*, https://www.technologyreview.com/2019/01/03/137969/us-china-quantum-arms-race/.
And: Costello, John. "Chinese Efforts in Quantum Information Science: Drivers, Milestones, and Strategic Implications." Testimony for the U.S.-China Economic and Security Review Commission. March 16, 2017. Pp. 6.
[116] For example: Elsa Kania and John Costello, "Quantum Technologies, U.S.-China Strategic Competition, and Future Dynamics of Cyber Stability," *IEEE*.
[117] For example: Gamberini and Rubin, 2021, and: Edward Parker, "Commercial and Military Applications for Quantum Technology," RAND Corporation – Research Paper, November 1, 2021.

literature identifies relevant security applications, but most technical articles briefly survey more generic applications.[118]

Beyond the broader dialogue of international security, very little seems to have been published that connects quantum sensing with nuclear deterrence. A likely source of impedance to broader discussion is the amount of technical knowledge required to understand and assess subcategories (and differences across subcategories) of quantum sensing. This is exacerbated by the relative novelty of quantum technologies and the current lack of organized dialogue and established vernacular that would normally make it easier for non-technical people to discuss highly technical issues.

Conclusion

The challenge of traversing these distinct bodies of literatures explains why current emerging technology frameworks in the security studies field are either limited in the application of social, historical, or technical context. Integrating knowledge of technical characteristics (and those specific to certain technologies of focus) and background on social institutions and historical precedents for the technology based on these traits, and applying these characteristics, concepts, and mechanisms to deterrence and arms control theories developed in the security studies field is an immensely cumbersome and interdisciplinary undertaking.

[118] For Example: Kai Bongs et al., “Taking atom interferometric quantum sensors from the laboratory to real-world applications,” *Nature Perspectives*, December 2019.

Yet, a more integrated framework will provide better insight on how a new technology will impact nuclear deterrence, factors influencing perceptions of the technology, and policies that could be used to decrease risks and leverage benefits of technology change. This chapter has introduced the main fields required to establish an integrated framework which uses interdisciplinary context to evaluate the intersection of emerging technologies and nuclear deterrence and has demonstrated the unique approaches and histories in each of these fields.

Chapter 3: Proposal of an Integrated Analytical Framework

"In the end, all it took was a used dental X-ray machine, a few die-hard supporters, some farfetched claims of a new arms race, and the Pentagon thought it was on its way to the next superbomb."
– Sharon Weinberger, 2006[119]

"Science cannot solve the ultimate mystery of nature. And that is because, in the last analysis, we ourselves are a part of the mystery that we are trying to solve."
– Max Planck, 1932[120]

How significant is the challenge of anticipating the risks or disruptions that can be expected of "emerging" technologies and what is the appropriate level of urgency in mitigating potential hazards? Stakeholders across nearly every industry are undertaking the task of answering these questions, each contributing different viewpoints and pursuing unique approaches. Generally, the parameters for this assessment in any given context are determined by three key factors: the projected timescale, the range of technologies to be considered, and the scope of application areas where the impact of new technologies will be evaluated. Moreover, it is essential to acknowledge and accept a certain level of uncertainty regarding the development timeline and ambiguity in potential impact for emerging technologies.

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[119] Weinberger, *Imaginary Weapons,* 2006, p. xxviii.
[120] Max Planck, *Where is Science Going*, Norton & Company, 1932. Max Planck was a Nobel Laureate and the father of quantum theory, see: Maria Popova, "Relativity, the Absolute, the Human Search for Truth: Nobel Laureate and Quantum Theory Originator Max Planck on Science and Mystery," *The Marginalian*, https://www.themarginalian.org/2019/06/12/max-planck-where-is-science-going/.

This imposes added difficulties from a procedural perspective for policymakers, as uncertainty and ambiguity make it difficult to establish clear assessments of technologies and consensus on evaluations of technology effects, thus complicating the task of reaching agreements on policy approaches to mitigate potential risks.

In a *Foreign Affairs* article published in Fall 2022, William MacAskill, the leading figure in the effective altruist movement, applies the broadest conceivable lens to highlight the daunting task of identifying and mitigating threats that new technologies could pose for the long-term survival and vitality of humanity.[121] The parameters for MacAskill's assessment are defined by his "longtermism" perspective, an ideology that has emerged from the effective altruism philanthropy movement, which advocates for the prioritization of projects that aim to secure humanity's long-term well-being over an extensive timescale, spanning billions of years into the future.[122] Motivating his assessment, MacAskill hypothesizes that currently the largest risk to humanity's future is the rapid development of new technologies with yet-undefined attributes that could produce entirely unpredictable risks.[123] MacAskill references a U.S. National Intelligence Council report that declares technologies that "challenge our ability to imagine and comprehend their potential scope and scale" as the greatest contemporary sources of existential risk.[124] Despite recognizing the risk of uncertainty in technology development, MacAskill argues that a better alternative

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[121] William MacAskill, "Surviving the Era of Catastrophic Risk," *Foreign Affairs* (September/October 2022).
[122] Sigal Samuel, "Effective altruism's most controversial idea," *Vox*, September 6, 2022, https://www.vox.com/future-perfect/23298870/effective-altruism-longtermism-will-macaskill-future.
[123] MacAskill, "Surviving the Era of Catastrophic Risk," p. 17.
[124] "Global Trends 2040" A Publication of the U.S. National Intelligence Council, https://www.dni.gov/index.php/gt2040-home/gt2040-structural-forces/technology.

to avoiding these risks through technology restraint is the strategy to "innovate to survive." Solidly in the category of a techno-optimist, per Danaher's typology,[125] he touts "differential technological development" as the solution, clarifying his rationale to be: "if people can't prevent destructive technology or accidents from happening in the first place, they can, with foresight and careful planning, at least attempt to develop beneficial and protective technologies first."[126]

Unfortunately, the flaw in MacAskill's plan to mitigate the risks of new technologies with "differential technological development" of even newer, less-well understood technologies was spectacularly exemplified by one of his fellow longtermism adherents. In the same month of MacAskill's publication, Futures Exchange (FTX), a cryptocurrency trading company with a philanthropy offshoot, filed for bankruptcy. Sam Bankman-Fried, FTX's leader and a self-proclaimed advocate of effective altruism and longtermism principles, claimed that amassing financial capital from rapid gains in his cryptocurrency company would give him the means to philanthropically support projects aimed at tackling existential risks posed by other emerging technologies such as "killer robots."[127] Yet, in building his cryptocurrency clientele and accruing the investments needed to help support his philanthropic aims, Bankman-Fried exploited public proclivity for techno-optimism and enthusiasm about blockchain, the emerging technology underpinning

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[125] John Danaher, "Techno-optimism: an Analysis, an Evaluation, and a Modest Defense," *Philosophy and Technology*, Vol. 35, No. 54 (2022), https://link.springer.com/article/10.1007/s13347-022-00550-2.

[126] MacAskill, "Surviving the Era of Catastrophic Risk," p. 21.

[127] Jennifer Szalai, "How Sam Bankman-Fried Put Effective Altruism on the Defensive," *The New York Times*, December 13, 2022, https://www.nytimes.com/2022/12/09/books/review/effective-altruism-sam-bankman-fried-crypto.html.

cryptocurrency. He somewhat hypocritically, if unintentionally, catalyzed the negative technology effect he claimed to be concerned about when his business became insolvent and cost millions of people their investments and savings.[128] In the case of FTX, blind faith in adopting new technologies to facilitate reduction of other risks, without a strategy or understanding of the technology's potential shortcomings, not only failed to reduce risks, such as those imposed by killer robots, but created an entirely new set of risks in the form of serious financial problems for those who invested in his cryptocurrency scheme.

Although the FTX example may seem enigmatically hypocritical, practitioners across industries who claim to be concerned about risks of emerging technologies are also often the ones to promote buildup of new technologies to counter these risks. Beyond the conscious or sub-conscious promotion of personal biases and techno-optimist ideologies, important social phenomena characteristic of emerging technology dialogue that will be explored later in this chapter, perhaps the greatest problem with MacAskill's approach is that it relies on the ability to foretell the unpredictable. MacAskill acknowledges that a critical challenge with new technologies is the degree of uncertainty over the potential short and long-term applications and impact. Yet, his strategy requires the ability to predict how different types of technological innovations could threaten or safeguard human survival thousands, millions, or billions of years from now with enough specificity and certainty to decide what technological innovations could reduce existential risks

[128] Emile Torres, "What the Sam Bankman-Fried debacle can teach us about "longtermism", *Salon*, November 20, 2022, https://www.salon.com/2022/11/20/what-the-sam-bankman-fried-debacle-can-teach-us-about-longtermism/.

without posing different, but equally serious risks of their own. The struggle to recognize this inherent uncertainty in MacAskill's approach underscores a core challenge in evaluating emerging technology impact: uncertainty must be accepted and accounted for in projections to produce realistic expectations about not only the potential impact of the technology, but also the degree to which unintended effects may continue to remain unknown, and especially in large analytical scopes.

Analysts can make the problem caused by uncertainty a bit more manageable by narrowing their parameters – i.e., focusing on one emerging technology at a time, and trying to evaluate how a few leading applications of that technology might affect one existential risk, such as nuclear deterrence, over the next decade or so. For example, by focusing on the risk of AI integration into nuclear command and control, a reasonably comprehensive list of the individual pathways through which AI integration may lead to nuclear escalation could be identified.[129] However, there remains ambiguity over the specific conditions and actions that would facilitate each of these scenarios due to uncertainty over how exactly the technology will operate and in what capacity it will be deployed. Likewise, social, strategic, and technical disagreements still arise over the best way to manage these risks. Some propose removing AI from nuclear command and control altogether to curtail AI-enabled escalation pathways,[130] while others assume the risks are unavoidable and propose

[129] For example: Mark Fitzpatrick, "Artificial Intelligence and Nuclear Command and Control," *Survival*, Vol. 61, No. 3, pp. 81-92, https://www.tandfonline.com/doi/full/10.1080/00396338.2019.1614782?journalCode=tsur20. And Edward Geist and Andrew Lohn, "How Might Artificial Intelligence Affect the Risk of Nuclear War," Security 2040, RAND, 2018, https://www.rand.org/content/dam/rand/pubs/perspectives/PE200/PE296/RAND_PE296.pdf.

[130] Ross Andersen, "Never Give Artificial Intelligence the Nuclear Codes," *The Atlantic*, May 2, 2023, https://www.theatlantic.com/magazine/archive/2023/06/ai-warfare-nuclear-weapons-strike/673780/.

that the best solution is to reduce the effects of the risks by researching methods to survive after a nuclear winter.[131] (A recently proposed U.S. bill would codify the 2022 Nuclear Posture Review requirement that: "in all cases, the United States will maintain a human 'in the loop' for all actions critical to informing and executing decisions by the President to initiate and terminate nuclear weapon employment."[132])

Numerous security studies scholars and defense analysts have made ambitious attempts to develop analytical frameworks for evaluating specific subsets of emerging technologies or a narrower range of applications compared to MacAskill. Most of them, though, have lacked a more integrated approach that would incorporate cross-disciplinary perspectives to critically appraise and, where possible, reduce uncertainty in either a technology's capabilities or its suitability for a specific application. For example, Gamberini and Rubin outline the ways in which quantum sensing could impact deterrence and warfare, but do not provide enough technical specificity to indicate what level of technology development would be needed to afford strategically disruptive capabilities.[133] Meanwhile, Parker provides a technology-oriented analysis that estimates timelines until certain quantum technologies should be expected, but with less detail on the scale of capability disruption that should be expected in applied settings.[134] Integration of strategic, social, and technical insight would further improve predictive power through establishing a clearer comprehension

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[131] David Denkenberger and Joshua Pearce, "Feeding Everyone: Solving the Food Crisis in the Event of Global Catastrophes that Kill Crops or Obscure the Sun," *Futures* Vol. 72 (2015), pp. 57-68, https://www.sciencedirect.com/science/article/abs/pii/S0016328714001931.
[132] S.L.C. BUR23348 GC1, Proposed in the 118th Congress, 1st Session, 2023, https://www.markey.senate.gov/imo/media/doc/block_nuclear_launch_by_autonomous_ai_act_-_042623pdf.pdf.
[133] Sarah Gamberini and Lawrence Rubin, "Quantum Sensing's Potential Impacts on Strategic Deterrence and Modern Warfare," Foreign Policy Research Institute (Spring 2021), pp. 354-368.
[134] Parker, "Commercial and Military Applications and Timelines for Quantum Technology."

of the boundaries of predictions when required and affording the ability to address the challenge of estimating the feasible application-oriented capabilities for new technologies. By focusing on uncertainty in both the technology's development progression and feasibility for certain applications at specific timescales, an integrated approach would satisfy each of the parameters specified earlier. But additionally, given that the uncertainty fosters ambiguity, an integrated framework must also account for the strategic and social factors that inform perception of technology change.

This dissertation proposes a more integrated, socio-technical analytical framework to fill the gaps in existing security studies approaches. First, the framework draws on the wide array of technology-focused analyses in the security studies literature to identify technical characteristics of emerging technologies that have been flagged as important for defense applications and that can be used to gain clarity through technical analysis. The framework also uses strategic studies analyses to identify capabilities, agnostic of the technologies under consideration, that could produce strategically significant disruptions for deterrence or nuclear force structure policy. Through distinguishing between the technologies and the capabilities, the framework recognizes that although they are often conflated, even among high-level and technical policymakers, technologies and capabilities are distinct but are contextualized through various social, technical, and strategic lenses that determine the ultimate policy impact of emerging technologies in general and for certain specific new technologies. Finally, the framework emphasizes the role of actors and institutions involved in the production and appraisal of emerging technologies.

Foregrounding the actors involved accounts for the social and strategic perspectives that influence assessments of technology disruption or policy response.

Proposal of an Integrated Analytical Framework

Isolating the technologies, capabilities, or the actors that inform policy when narrowing an analysis exacerbates the uncertainty in anticipating the effects of emerging technologies. By identifying the modes of interaction between technologies, capabilities, and the actors and institutions driving and responding to innovation, this dissertation better informs the implications for new technologies and the processes through which policy decisions about new technologies are made. To incorporate each of these elements, this dissertation proposes an integrated, socio-technical analytical framework.

Technical characteristics comprise the first pillar of this analytical framework. The technical characteristics that distinguish emerging technologies provide a basis for technical assessments around definable features with metrics for evaluation. A more realistic technical assessment based on these characteristics can reduce uncertainty as much as possible, indicate areas of disagreement among technical experts, and inform assumptions of the technology's development trajectory.

The strategic capabilities afforded by certain technical characteristics, which analytically function as mechanisms through which new technologies impact nuclear deterrence, comprise the second pillar of the framework. Despite the fact that "mechanisms" introduce a layer of ambiguity into the framework, and allude to a raging debate in the field of qualitative methods over the precise definition and value of a causal mechanism,[135] the application of mechanisms in this framework captures the complex, context-oriented, and evolving impact of technology characteristics on deterrence. Technology characteristics themselves do not translate to deterrence effects, rather they afford capabilities, which then produce context and perspective-specific effects for deterrence. Analytically, the specification of capabilities as mechanisms captures the complexity in evaluating deterrence effects. Rarely does achieving a new capability necessarily translate to a discrete, measurable disruption. Rather, the magnitude of the disruption is the product of the strategic stability environment, the process through which the capability was achieved, and the actors perceiving the disruption. Practically, the specification of capabilities allows for the analysis to be anchored around what is technologically feasible and what is impactful. Through this clarification, even if a technology's R&D trajectory is still unknown, a capability of concern could still be discussed, but without necessarily propagating concern over a specific type of technology that may or may not enable that capability.

The final pillar of the framework is the network of actors involved in the production, acquisition, and deployment of the technology, as well as those responsible for evaluating the impact for nuclear deterrence. Given the high degree of uncertainty for new technologies, and thus the inherent ambiguity, the distribution of actors with varying perspectives on deterrence and technology change will inform the ways in which the disruption potential of new technologies will be interpreted and acted upon. Further underscoring the importance of including the actors, from an STS

[135] On definition: Tulia Falleti and Julia Lynch, "Context and Causal Mechanisms in Political Analysis," *Comparative Political Studies*, Vol. 42, No. 9 (2009), pp. 1143-1166; On value: John Gerring, "Causal Mechanisms: Yes, But…" *Comparative Political Studies*, Vol. 43, No. 11 (2010), pp. 1499-1526.

perspective, the actors not only perceive technology change, but may also participate in and direct the technology change.

Through each of these elements, the proposed integrated analytical framework provides an argument for and attempts to assess the degree of human agency that contradicts the technological determinist perspectives that theorists like MacAskill have espoused. MacAskill argued that technological change will occur regardless of human intention, and that it is likely to have unintended consequences, but that fear of those consequences should not necessarily lead to technological restraint. Instead, policymakers should avert the negative effects through facilitating more technology innovation. A flaw in this line of reasoning is that MacAskill fails to appreciate the actors that are influential in connecting the desire for certain capabilities to the acquisition and pursuit of those technologies (and vice versa) which may drive the pace of innovation. Thus, the most significant and distinguishing trait of this integrated analytical framework is the emphasis it places on human decisions, actors, and social dynamics. Unlike technological determinism, this socio-technical lens affords insight into how policymakers can and should influence technological development trajectories with their decision-making. Furthermore, because this framework provides greater analytic power through interdisciplinary evaluation, it is both less dependent on ambiguous claims or inherently biased assertions about technology effects, but also recognizes the sources of these perceptions and the effects they in-turn produce on technology change.

Technical Characteristics

Recognizing the unique technical characteristics that indicate the development status or specify how an emerging technology is novel as compared to existing technologies provides a useful starting point for evaluating its potential impact in a given application area and for identifying policies to mitigate risks. Technical characteristics may relate to how the technology is produced, what it is composed of, and how it operates. Answering these questions informs both the social and technical elements that produce a technology system. On the technical side, characteristics may provide insight into limitations and opportunities for the technology to out-perform existing alternatives. However, because technical characteristics are also determined by social influences and choices among innovator communities, they also illuminate important social structures that facilitate technology innovation.[136] In considering the combined socio-technical factors that gives rise to the unique characteristics of a technology, valuable insight can be gained to support the eventual mapping of the actor network and the determination of effective policies to govern the technology or address disruption.[137]

A characteristic-centric, rather than technology-centric approach increases flexibility and inferential strength of the analytical framework. Each technology is a

[136] For example, influential social mechanisms are identified in: Frank Geels and Rene Kemp, "Dynamics in socio-technical systems: Typology of change processes and contrasting case studies," *Technology in Society*, Vol. 29 (2007), pp. 441-455.

[137] The idea of the socio-technical system was introduced in the 1960s for an analysis of the labor division in socio-technical systems in: F. Emery and E. Trist, "Socio-technical Systems," *Management Sciences, Models, and Techniques*, Vol. 2, London, 1996. The term has since been used to refer to the fact that innovation derives from a complex mixture of social and technical mechanisms, for example in: Jinsoo Kim, Benjamin Sovacool, Morgan Bazilian, Steve Griffiths, Junghwan Lee, Minyoung Yang, and Jordy Lee, "Decarbonizing the iron and steel industry: A systematic review of sociotechnical systems, technological innovations, and policy options," *Energy Research and Social Science*, Vol. 89 (July 2022).

unique composition of its characteristics and could simply be assessed at the individual technology level rather than the characteristic level. As Chapter 2 illuminated, this has been a popular approach taken in many analyses on the impact of emerging technologies for nuclear deterrence. However, deconstructing a technology based on its defining characteristics allows for the extrapolation of findings to other technologies that share those traits, increasing the flexibility of the framework and expanding the applicability of its findings. It also facilitates analysis of impact across a group of technologies with similar traits. This may be informative when comparing simultaneous technology developments and examining the interconnection of multiple emerging technologies. Finally, disaggregating a technology by its characteristics affords deeper inference into the technical and social elements of a technology system that may influence capability pursuit and policymaking decisions by specifying which aspects of a technology manifest certain outcomes or effects.

This section delves into each of the three constituting questions specified above to survey the broader sets of technology characteristics. The three categories of characteristics include: production requirements, technology composition, and operability characteristics. Inevitably there is some overlap in the distinguishing features across the groups of characteristics. Establishing a more comprehensive map of traits for any emerging technology would be worthy of an entire research study on its own. Thus, the characteristics highlighted in this section are chosen because they illuminate how a technology relates to a particularly important capability (in the context of nuclear deterrence) or inform the influential groups of actors that may be involved in technology development and acquisition or in policy decision-making.

This characteristic-based categorization is not intended to give a hard and fast definition of a certain technology and its uniqueness. Rather, the motivation is to use each characteristic to provide a frame of reference for deeper technical evaluation of feasible applications to achieve capabilities of significance for nuclear deterrence and social/strategic factors that inform arms control and force structure decision-making in response to emerging technologies.

Production requirements

Compared to earlier military technology systems, the production processes and requirements for currently emerging technologies exhibit a significant degree of variation. Some new technologies, such as AI, may be produced without requiring any hardware fabrication, testing, or production, provided that the computing power required falls within the capacity of existing computing systems. Other technologies, like quantum computers, may require modular, intensive production processes that involve acquisition of rare materials, refinement of lab setups, and assembly of extensive control technologies, in addition to the production of the actual quantum processor.

Understanding what it takes to make a useful product based on a new technology innovation reduces uncertainty around its development and deployment timeline, and provides crucial insights for technology policymaking, particularly with regards to policies that support technology R&D and policies that govern access to the technology. In terms of industrial policy and planning, determination of the production process specifies the baseline techniques, knowledge, and equipment needed to acquire and operate a technology. This information also diminishes some uncertainty by clarifying the timeline that can be feasibly expected for the technology's development and eventual deployment. Greater clarity on a reasonable timeline to be expected can reduce concerns over the possibility of a technological surprise by adversarial acquisition and may also highlight potential obstacles to be addressed domestically that could impede development.[138] Furthermore, it informs policymakers on the longer-term proliferation potential and acquisition accessibility of the technology by other states and actors.

From a definitional standpoint, determining how a technology is produced also forces understanding and agreement on the R&D achievements that would be required to meet a certain degree of operability for a new technology. Defining the production process necessarily separates invention from innovation and specifies the challenges of producing a technology. For example, although Julius Nieuwland theorized in 1906 that a new material made in his lab could have several useful applications (invention), the material, now known as Neoprene and a sealant famously used for binding wetsuits, was not commercially produced (innovation) until 1932.[139] The lack of standards and clear terminology for new technologies often clouds understanding of the true stage of development. For a more current example, the concept of quantum computing was proposed by physicists in the 1980s, but still remains to be actualized over 40 years later.[140] Yet, many quantum computing

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[138] For example, discussed in: "Avoiding Surprise in an Era of Global Technology Advances," National Research Council of the National Academies, National Academies Press, 2005, https://nap.nationalacademies.org/read/11286/chapter/1.
[139] Arnulf Grubler, "Technology: Concepts and Definitions," Chapter 2 in *Technology and Global Change*, pp. 25-27, https://user.iiasa.ac.at/~gruebler/Lectures/Leoben00-01/ch2%20from%20book.pdf.
[140] "40 years of quantum computing," *Nature*, Vol. 4, No. 1 (2022), https://www.nature.com/articles/s42254-021-00410-6.

processes have already been simulated, leading to statements that quantum computing can already be harnessed, despite the fact that significant production requirements continue to impede the development of truly functional quantum computers.[141]

This insight can also be useful when trying to determine how far along the iterative improvement of a new type of technology is in the R&D process, and to identify how long it will take to reach certain development milestones. In the case of quantum sensing, many different types of quantum sensors have already been produced, and different sensors can be manufactured through a variety of techniques. However, more advanced lab equipment, personnel, materials, and advanced research will enable increased sensitivity and accuracy levels compared to sensors made using simpler production methods.[142]

Characterizing the production processes used for different applications of an emerging technology also informs the proliferation potential and general acquisition accessibility of a certain technology by clarifying the skills and capabilities that would be needed for development. The barrier to entry – or the production requirements – will determine how likely it is that a technology will proliferate widely after it is initially developed; if a technology has a very high barrier to entry, then even if a few actors can develop it, other countries would not have easy access to that technology without facilitation by a country that already possesses it.

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[141] For example: Andrew Daley, Immaneul Bloch, Christian Kokail, Stuart Flannigan, Natalie Pearson, Matthias Troyer, and Peter Zoller, "Practical quantum advantage in quantum simulation," *Nature*, Vol. 607 (2022), https://www.nature.com/articles/s41586-022-04940-6.

[142] "Bringing Quantum Sensors to Fruition," A report by the subcommittee on quantum information science Committee on Science of the National Science and Technology Council, March 2022, https://www.quantum.gov/wp-content/uploads/2022/03/BringingQuantumSensorstoFruition.pdf.

Qualitative differences deriving from different production methods may also impact utility. Some technologies have low production requirements for simpler versions, but high requirements for strategically significant, high-performance variants. To continue the quantum sensor analogy, because quantum sensors with a high degree of sensitivity will require ultra-precise equipment and state-of-the-art laboratories, only countries (and companies) that have labs with these conditions will be able to develop high-sensitivity quantum sensors, even if other countries have the means to produce more basic versions with lower operability. If high precision is a requirement for a certain capability, then higher production standards are needed.

Finally, from a monitoring perspective, production processes also provides insight that is useful for tracking the development of a technology by a specific actor to further reduce uncertainty, either through assuaging concerns over technological surprise or evaluating intent of R&D. Designation of the specific processes that must be met to develop a useful product from a given technology allows for tracking of each subcomponent and requirement to better predict when the composite technology will be developed, either in the global R&D ecosystem, or by a specific country. It may also improve monitoring of other actors that seek to acquire a technology, by providing indicators that the actor is building up its capacity to develop the technology. This can help distinguish whether a country intends to produce strategically useful items using that technology, or whether they are pursuing a technological hedging strategy. In some cases, determining intent based on production indicators may be complicated if there are potential civilian applications with very similar technology requirements. The challenges of governing these technologies, referred to as dual-use technologies, are not covered in this dissertation, but has been discussed extensively in other literature.[143]

Finally, it should be noted that production characteristics are not time-invariant. In some cases, barriers to entry lower as easier, less expensive production methods are developed. For example, within the last decade or two automation or automated systems have been used to lower the barrier to entry from a physical production standpoint.[144] This means that surveys should also consider the extent to which advanced components in a new technology could be produced through automated processes or other foreseeable technology innovations. Furthermore, once production means are well-established and technologies can be commercialized, mass-production significantly reduces economic and resource requirements for adoption and deployment.

Technology composition

Beyond considering how a technology is produced, it is also necessary to understand what a technology is composed of to predict its suitability for certain applications and the likelihood that it will enable strategically significant capabilities. Technology composition also affects the actors involved and invested in its acquisition and continued deployment and requirements. For example, this may include a breakdown of the necessary hardware and software elements, as well as a

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[143] For example: *Governance of Dual-Use Technologies: Theory and Practice*, Ed. Elissa Harris, American Academy of Arts and Sciences, 2016, https://www.amacad.org/sites/default/files/publication/downloads/GNF_Dual-Use-Technology.pdf.
[144] For example: Wyatt Hoffman and Tristan Volpe, "Internet of nuclear things: Managing the proliferation risks of 3-D printing technology," *Bulletin of the Atomic Scientists*, Vol. 74, No. 2 (2018), https://doi-org.proxy-um.researchport.umd.edu/10.1080/00963402.2018.1436811.

designation of supporting infrastructure and operating systems. Similar to the production of emerging technologies, the composition is equally variable. Some technologies, such as AI, may be entirely software-based, while others, such as quantum computing may be composed of a multitude of hardware and software parts and sub-systems. The latter case engages a much wider set of actors and stakeholders compared to the former.

Analyzing the composition of an emerging technology provides insight into the advantages it may offer over its competitors, potential operational constraints, and subcomponents of the whole that themselves may serve as artifacts with their own independent politics and applications. From an STS standpoint, viewing technologies through this lens allows for analyses that extend beyond "black box" assumptions treating technologies as abstractions of their inner workings. Emphasizing the risks of overgeneralizing technologies by "bracketing them as instruments that perform certain valuable functions," without understanding the internal structure, Langdon Winner notes: "the problem is that one's grasp may be superficial, failing to do justice to the phenomena one wants to explain and interpret."[145]

This overgeneralization is exacerbated by the fact that many lists of emerging technologies include technological systems, rather than fundamental technologies or the smaller subcomponents that comprise them.[146] A handful of STS articles have

[145] Langdon Winner, "Upon Opening the Black Box and Finding it Empty: Social Constructivism and the Philosophy of Technology," *Science, Technology, and Human Values*, Vol. 18, No. 3 (Summer 1993), pp. 362 & 365, https://journals-sagepub-com.proxy-um.researchport.umd.edu/doi/pdf/10.1177/016224399301800306.

[146] For example, one list is provided by the U.S. Executive Office in: "Critical and Emerging Technologies List Update," A Report by the National Science and Technology Council, U.S. Executive Office, February 2022, https://www.whitehouse.gov/wp-content/uploads/2022/02/02-2022-Critical-and-Emerging-Technologies-List-Update.pdf.

discussed the difference between assessing technological systems as opposed to the technologies that comprise the technological systems, which will be discussed in greater detail in the social and political mechanism section.[147] Ultimately, Thomas Hughes, who first defined large technological systems, concluded that technological systems should be identified as such but should be treated as a whole to the extent that the output or input of interest relates to the technology as a whole. The benefit of treating technology systems as black boxes in these analyses is that they allow emphasis on the output – the strategic effect – without requiring in-depth technical knowledge. But for the sake of improving policymaking, understanding these components can provide valuable information. For example, a successful hypersonic missile system is not just composed of a missile and the engine required to achieve a hypersonic speed, but also includes the propellants for the engine, the heat-resistant materials that enable the system to move at higher speeds without degradation, and the systems that provide guidance and communication. Russia, China, and the United States each had to achieve all of these subcomponent systems to develop their hypersonic missiles, despite the fact that hypersonic missiles are often referred to as a singular technology.

Designation of these constituent parts also provides insight into unique capabilities, as well as potential vulnerabilities and operational requirements that may tip the balance for or against acquisition of the new technology. Clearly, in the case of hypersonic missiles, the engine or gliding mechanisms afford the sustained speed and

[147] Thomas Hughes, "The evolution of large technological systems," In *The social construction of technological systems.* Ed. By Bijker, Hughes, and Pinche (1987), pp. 51 – 82, https://bibliothek.wzb.eu/pdf/1986/p86-9.pdf.

maneuverability that many claim provide strategic benefits to hypersonic missiles. However, this gain in speed and maneuverability also increases requirements for other components. Because of their high speeds, hypersonic missiles experience immense drag and thus require heat-resistant materials. In order to develop and test these high-heat materials, additional hypersonic wind tunnel infrastructure is needed to stimulate real-world conditions.[148] Furthermore, the heat distribution across this material in-flight may increase the vulnerability of hypersonic missiles by making them more easily detected with infrared sensors.[149] Each subcomponent must be evaluated to determine net improvement in operability as well as an increase or decrease in vulnerability and production requirements even after a "new technology" is developed. Furthermore, as will be discussed in greater detail in Chapter 4, each subcomponent brings to the fore a new set of actors, social institutions, and political and strategic connotations.

Finally, decomposing a new technology by its constituent parts also provides deeper insight on the process of innovation and further rebukes the assumption that innovation occurs at a specific point in time. On breaking this assumption of a technology as a single object, or a black box, and the impact for interpreting the disruption of an innovation or "new technology," Grubler argues, "although the timing of particular historical events is indeed important, most dimensions of technological development are continuous rather than discrete."[150] In the case of

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[148] "U.S. Hypersonic Weapons and Alternatives," Congressional Budget Office, January 2023, https://www.cbo.gov/publication/58924.
[149] Cameron Tracy and David Wright, "Modeling the Performance of Hypersonic Boost-Glide Missiles," *Science and Global Security*, https://scienceandglobalsecurity.org/archive/sgs28tracy.pdf.
[150] Grubler, *Technology and Global Change* (2021), p. 25

technology systems, and with appreciation for the subcomponents that comprise them, the establishment and refinement of each subcomponent represents a gradual shift along the continuum of progression that increases the utility and impact of a new technology.

Operability characteristics

The third category of traits are those that define how a technology operates and what exactly it does. These operability characteristics provide important information about the applications that a technology could be used for and the capabilities that it could enable. In some cases, they also help to distinguish how using a new technology for a particular application would be different from alternative technologies that could also afford the same capability.

From the perspective of assessing the strategic impact of a new technology, evaluating these operability characteristics can foster more realistic expectations regarding the scale of the disruption that the technology could create. Specifically, if the technology operates in a way such that it enables an entirely new capability, then a different set of strategic implications arise as compared to a technology that operates such that it accomplishes a capability that other technologies enable but with some performance improvement. For example, as will be discussed in greater detail in Chapters 5 and 6, one of the benefits of quantum inertial sensors is that they measure an object's inertia without relying on feedback from external conditions, which means that they could allow for a new means of dead-reckoning, or navigation without GPS signal. However, strapdown navigation systems and vibrating gyroscopes can also operate in this manner, they just accumulate drift over time that requires intermittent recalibration.[151] If a thorough assessment shows that quantum inertial sensors may not outperform other non-quantum inertial navigation systems for a certain application/capability or operate in a distinctly new and better manner, then the new technology may not provide a strategic advantage.

Beyond constraining expectations, identifying how a technology operates exposes added risks or benefits that may not be noted from a purely capability perspective. Oftentimes, new technologies introduce unintended (or even unpredictable) risks that must be weighed when making decisions about whether to implement a new technology for a certain use case. For example, in the new U.S. nuclear modernization plan, many systems will now feature cyber components to enable better control and improve reliability. However, increased cyber interface also introduces new surfaces for attack that must be addressed.[152] Understanding how a technology operates can help reveal some of these risks to better evaluate the costs versus the benefits for employing a new technology over an existing system. It may also illuminate ways to reduce risks if a technology is implemented.

Additionally, defining how the technology operates may allow for assessing key obstacles or impediments to operation. The challenge of transitioning R&D prototypes from laboratory to operational settings introduces a variety of new considerations, including operability in contested/congested environments, operability while mobile, operability without communication, and performance at operational

[151] For example, drift surveyed in: Demoz Gebre-Egziabher, "Design and Performance Analysis of a Low-Cost Aided Dead Reckoning Navigator," Doctoral Dissertation, Stanford University, 2004, https://web.stanford.edu/group/scpnt/gpslab/pubs/theses/DemozGebreEgziabherThesis01.pdf.
[152] For example, surveyed in Sam Nunn and Ernest Moniz, "Nuclear Weapons in the New Cyber Age," NTI Report, September 26, 2018, https://www.nti.org/analysis/articles/nuclear-weapons-cyber-age/; and Herbert Lin, *Cyber Threats and Nuclear Weapons*, Stanford University Press, October 2021.

speeds, among other factors. Likewise, understanding real-world operational requirements could inform assessments about what types of countermeasures could be used against that capability. These operability traits are especially important to consider for new technologies, as the challenges that scientists and engineers will face when applying their technologies in real-world settings are often overlooked.

Finally, assessment of operability for specific applications and in more general enabling capabilities may inform other areas where the technology could be useful. This is especially important to consider when a large number of civilian use-cases may be identified for a new technology. Governance of dual-use technologies with wide-ranging civilian applications poses a number of pernicious challenges.[153] These challenges, and their reverberating implications for promoting the utility of military technologies in the name of non-strategic and parochial interests will also be discussed in later sections.

Capabilities and Strategic Stability Disruption

While some analyses in existing literature have assessed whether certain technologies will disrupt strategic stability, others have focused on specific capability areas and use-cases that would impact nuclear deterrence and strategic stability. As noted in Chapter 2, identifying categories of disruptive or stabilizing capabilities has been a central focus for analysts in the security studies field. However, these analyses

[153] Summarized in Elisa Harris, "Concluding Observations: Technological Characteristics and Governance Prospects," in *Governance of Dual-Use Technologies: Theory and Practice*, American Academy of Arts and Sciences (2016), pp. 158 – 170. https://www.amacad.org/sites/default/files/publication/downloads/GNF_Dual-Use-Technology.pdf.

often conflate technologies and capabilities, which reduces the flexibility and depth of their insights. The benefit of focusing on capabilities is that the analysis can be technology-agnostic, instead identifying disruption mechanisms that could be triggered by one or a combination of technologies and evaluating the impact on deterrence and strategic stability. To afford this flexibility and explore the complexity of the mechanisms, this section will survey capability disruption mechanisms from a technology-agnostic perspective. Three specific sets of capabilities will be discussed in terms of the consequences rather than the means of causation: capabilities that influence inadvertent escalation likelihood and crisis management; capabilities that influence deliberate deterrence failure likelihood and conditions of mutual vulnerability; and capabilities that influence governance of cooperative agreements between countries to reduce risks. As noted above, there is also some degree of variation to the extent that certain stakeholders weigh different capabilities based on their deterrence predilection, and in some cases capabilities that may be seen as deleterious from a DL perspective may be perceived as beneficial from an AD perspective. Thus, highlighting the divergences of viewpoints that arise when looking specifically at capabilities rather than technologies illuminates likely debates that will be raised for technologies that accomplish particularly contentious capabilities.

Treating the capabilities as disruption mechanisms captures the increased complexity and ambiguity compared to the technology traits. One area of complexity arises from the duplicitous nature of some new technologies that may simultaneously introduce stability through certain capabilities and increase risks in other capabilities. This dual phenomenon was highlighted in an expert elicitation analysis detailed in

Favaro's "Emerging Technologies and Nuclear Stability."[154] Furthermore, even with agreement on the nature of the capability mechanism, fundamental disagreements on deterrence requirements may lead to different interpretations of a net stabilizing or destabilizing effect. To the extent possible, this section will try to indicate the dual phenomena and competing interpretations as to how different capabilities may be viewed as stabilizing or destabilizing.

Unlike the technical characteristic dimension, which could be applied broadly to other sectors and industries, this section reviews only a narrow scope of capabilities determined by the fact that this dissertation is focused on nuclear deterrence and strategic stability. However, similar analyses could be performed to identify capability mechanisms in other domains to understand the wide range of impacts a new technology could have in a given field.

Crisis management and inadvertent escalation

The first set of capabilities impact a country's ability to navigate a crisis. Some emerging technologies increase communication speed and clarity to reduce risks in crises, while others increase the fog of war or speed of engagement. Speed of engagement, communication, situational awareness, and response flexibility each inform how a state responds to crisis scenarios, and thus impact the likelihood of inadvertent escalation. Some technologies may have both positive and negative effects on different aspects of crisis management, depending on which actor acquires

[154] Marina Favaro, "Emerging Technologies and Nuclear Stability," ELN Report, July 2021, https://www.europeanleadershipnetwork.org/commentary/emerging-technologies-and-nuclear-stability/.

and deploys the technology and how the technology's application is perceived by its adopter and by a counterpart in the crisis.

Speed of Engagement

The first set of capabilities are those that increase the speed of engagement. This could be achieved by physically speeding up a weapon system's travel or deployment time. It also could be caused by increasing the speed at which systems process information and perform different functions. Because of these various methods, increased speed of engagement is associated with a wide array of technologies, ranging from hypersonic weapons to automated systems. Some policymakers could perceive benefits from an increased speed of engagement, as it could allow for improved DL posture and greater flexibility. Conversely, a faster speed of engagement may also increase crisis instability by truncating decision-making time and increasing the fog of war through faster transitions. For example, autonomous weapon systems incite debates over the effect of "machine speed" on response decision-making.[155]

Crisis Communication

A second set of capabilities include those that impact communication. Improved communication in contested/congested environments and with added security are commonly cited reasons for pursuing new technologies. For example,

[155] For example: Burgess Laird, "The Risks of Autonomous Weapons Systems for Crisis Stability and Conflict Escalation in Future U.S.-Russia Confrontations," RAND Blog, June 3, 2020, https://www.rand.org/blog/2020/06/the-risks-of-autonomous-weapons-systems-for-crisis.html.

China's stated motivation for developing quantum communication is that the technology would enable internal communication with a nearly impervious degree of security, even in contested environments or crisis scenarios.[156] Better communication between counterparts in a crisis can allow for more rapid de-escalation through information dissemination. However, leveraging emerging technologies for communication can also introduce new surfaces for attack. Technologies that allow for deep fakes and signal interference, for example, would corrupt or disrupt communication.[157]

Support for robust communication infrastructure was codified in the establishment of a hotline between Moscow and Washington. Other bilateral hotlines have since been established between Russia and China, the United States and China, India and Pakistan, North Korea and South Korea, South Korea and China, India and China, Vietnam and China, and Taiwan and China.[158] Although telecommunication links are already fairly well established, growing concern that deep-fakes, or false communication methods made easier by new technologies, could be used to produce interference makes capabilities that continue to bolster hotline communication methods a strategic priority.[159]

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[156] Nanxi Zou, "Quantum Entanglement and Its Application in Quantum Communication," *Journal of Physics* Vol. 1827 (2021), https://iopscience-iop-org.proxy-um.researchport.umd.edu/article/10.1088/1742-6596/1827/1/012120/meta.

[157] For example, discussed in: James Johnson, "Artificial Intelligence A threat to Strategic Stability," *Strategic Studies Quarterly*, Vol. 14, No. 1 (2020), https://www.jstor.org/stable/resrep25355.10.

[158] Daryll Kimball, "Hotline Agreements," Arms Control Association, May 2020, https://www.armscontrol.org/factsheets/Hotlines.

[159] Daniel Byman, Chongyang Gao, Chris Meserole, and V.S. Subrahmanian, "Deepfakes and international conflict," Brookings Institute, January 2023, https://www.brookings.edu/research/deepfakes-and-international-conflict/.

Situational Awareness

A third set of capabilities are those that improve situational awareness. In addition to improved communication, sensing and detection technologies can provide policymakers with more accurate information on their own country's infrastructure and activities or that of an adversary. For example, increased computing power that processes network data much more rapidly is sometimes specified as a way to increase situational awareness and improve logistics. If a country is pursuing situational awareness for the purpose of decreasing the likelihood of inadvertent escalation, then situational awareness technologies can be beneficial. However, if one country is concerned that improvements to an adversary's situational awareness will reveal hidden vulnerabilities, disrupt the offense-defense balance, or provide some other asymmetric advantage, technologies that enable situational awareness may increase diplomatic tensions and heighten levels of distrust. Additionally, some technologies, again such as deep fakes or decoys, may *reduce* situational awareness.

Response Flexibility

The final cluster of capabilities that affect crisis management are those that alter response options. Countries do not need to respond in kind to a nuclear or conventional attack. Other forms of engagement may include cyber interference, drone swarms, signal disruption, or advanced conventional weapons. These systems may provide more flexibility in responding below the nuclear threshold under conditions of uncertainty in a crisis scenario. Likewise, technologies that could improve operations for smaller nuclear weapons may expand response options.

Increased response flexibility, though, does not necessarily facilitate crisis management or reduce escalation risks. Through allowing for lower or sub-nuclear response, alternative forms of engagement may shrink the distance between rungs in the escalation ladder and ultimately increase the likelihood of some form of conflict that could escalate to nuclear use. Thus, the net strategic effect of this set of capabilities is particularly ambiguous based on competing deterrence strategies.

Deterrence efficacy and credibility

The second set of capabilities impact the ways in which technologies affect strategic stability and deterrence efficacy and credibility. Through influencing conditions of mutual vulnerability and actor's perceptions of the credibility of their adversary's deterrent, this category of capabilities is more closely linked to deliberate deterrence failure or deliberate escalation estimations. Thus, assessments of capabilities in this category largely parallel the debate flagged in Chapter 2, with disagreements arising between security studies experts who focus on emerging technology risks through AD or a DL logic. From the AD perspective, these capabilities are significant only if they undermine conditions of mutual vulnerability – i.e., they enable one side to pre-emptively destroy or defend against enough of the other side's nuclear forces that they can "win" by sustaining less damage from the war than the other side (even if the lesser amount is still horrific). Conversely, these capabilities are significant from the DL perspective if they afford asymmetric advantages or increase the likelihood of a successful counterforce strike or deterrence by denial so that the other side cannot credibly threaten retaliation.

Targeting Accuracy

Technologies that improve targeting accuracy necessarily provide an enhanced capability for a country to hold an adversary's fixed targets at risk. To some degree, there are thresholds of accuracy that provide different degrees of strategic value. One major threshold of targeting accuracy innovation was a series of technological improvements in the 1970s that afforded 300–500-meter accuracy.[160] This provided substantiation for some U.S. strategists to favor counterforce targeting, rather than countervalue, under the argument that they might be able to efficiently destroy Soviet missile silos.[161] Another capability threshold that would be strategically significant is the ability to target nuclear silos so precisely that they could be destroyed with conventional or low-yield nuclear weapons. Attaining this capability would require much better precision than for higher-yield nuclear targeting (10 meters or less, depending on the conventional or low-yield nuclear warhead) but could theoretically allow for a counterforce attack with lower casualties.

The prevailing deterrence theory camp will likely have a dramatic influence on the extent to which technologies that impact targeting accuracy are pursued, tested, and deployed. Depending on the persuasion towards DL or AD doctrine, the effect of this capability differs drastically: AD proponents would argue that such a capability is destabilizing as it may lower the barrier to escalation, while DL proponents would contest that it allows for greater response flexibility and increases options for lower-

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[160] Kosta Tsipis, "The Accuracy of Strategic Missiles," *Scientific American*, Vol. 233, No. 1 (July 1975), pp. 14-23, https://www.jstor.org/stable/10.2307/24949839.

[161] John Baker and Robert Berman, "Evaluating Counterforce Strategy," *The New York Times*, February 22, 1974, https://www.nytimes.com/1974/02/22/archives/evaluating-counterforce-strategy.html.

casualty nuclear strikes. From an STS perspective, continual accuracy improvement is not a technologically deterministic progression that is destined to occur, but rather a product of social, political, and strategic influences. Donald MacKenzie highlights the social construction of missile accuracy research, contending that just as influential political actors who favor a DL form of deterrence support efforts to increase missile accuracy, those who prefer an AD form of deterrence may try to impede accuracy innovation through limiting access to crucial resources and testing because they perceive a negative impact on strategic stability.[162]

Stealth Capabilities

Iterative improvements to the stealth capabilities that allow for concealment of the platforms comprising a nuclear weapon state's secure second-strike is another important application area. New technologies that improve stealthy operations of mobile missiles or submarines, thus preventing tracking and reducing vulnerability, are destabilizing through the DL lens because they impede targeting assurance. However, they produce mixed effects from the AD logic because they reinforce conditions of mutual vulnerability but also make verification of numerical or operational limits more challenging. Made infamous in popular culture by "The Hunt for Red October," one of the more severe capability thresholds would be a country developing a significant, asymmetric stealth capability that would allow for unfettered and strategically significant deployment. However, realistically, stealth

[162] Donald Mackenzie, *Inventing Accuracy*.

capability improvements have historically occurred gradually over time, and often in response to counter-stealth technology innovations.[163]

Detection and Sensing Capabilities

Inextricably linked to stealth technologies, some technologies also provide the capabilities to detect, track, and target the mobile delivery systems that afford a secure second-strike. The balance for strategic stability impact due to detection and sensing capabilities is very similar, but inverse to that for stealth capabilities. The most significant disruption would arise from the achievement of a significant asymmetric advantage that would render an adversary's mobile systems as completely transparent and vulnerable. For example, in *Tides of Change*, Tong Zhao argues, "of all the aspects of China's SSBNs, their overall survivability is the most important factor in determining their impact on strategic stability," and defines survivability as a balance of the SSBN's capabilities (including stealth and supporting technologies) in comparison to antisubmarine detection capabilities.[164]

Interestingly, similar technologies and scientific bases are required for both stealth and detection capabilities. For example, quantum sensing may improve the ability to detect nuclear submarines, but knowledge of quantum sensing detection methods can also improve stealth capabilities to avoid detection by re-orienting submarine compositions and hulls, or by creating decoys. From an STS perspective,

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[163] John Correll, "History of Stealth: From Out of the Shadows," *Air & Space Forces Magazine*, September 1, 2019, https://www.airandspaceforces.com/article/history-of-stealth-from-out-of-the-shadows/; and Neil Kacena, "Stealth: An Example of Technology's Role in the American Way of War," Air War College – Air Force University, April 14, 1995.

[164] Tong Zhao, *Tides of Change*, Carnegie Endowment for International Peace, 2018, pp. 25.

this interrelation between stealth and detection capabilities and the joint politics that continue to drive them is an example of constitutive co-production.[165] Research and development in the science underlying these technologies will be pursued by some political actors to advance stealth and detection capabilities, which will force political pressures on the other side to pursue the stealth/detection counterpart technology, requiring cyclical innovation rather than technological restraint. From a security studies perspective, this forebodes enduring strategic consequences whereby the unique interaction between the science and politics will continually incentivize, or require, arms-racing dynamics with each incremental technology improvement.

Defensive Capabilities

The final major group of capabilities that affect deterrence estimates and the strategic stability equilibrium are defensive capabilities. If a country were to build up technologies to completely defend their population, industrial base, and military forces from nuclear attack, or defend to some strategically significant degree,[166] against another country's nuclear deterrent, then the equilibrium espoused by AD proponents could be significantly disrupted. However, from the DL perspective, defensive capabilities complicate an attacker's calculations, and therefore may strengthen deterrence. The most notable example that demonstrates the contested

[165] Sheila Jasanoff, "Ordering knowledge, ordering society," in *States of Knowledge: The co-production of science and social order*, Routledge Press, 2004, pp. 22-23, https://sheilajasanoff.stsprogram.org/wp-content/uploads/Jasanoff_Ordering-KnowledgeOrdering-Society.pdf.

[166] Although the iterative thresholds of improvement to achieve certain DL benefits is debated, Kroenig argues that any iterative improvement is significant. See: Matthew Kroenig, "Correspondence: The Limits of Damage Limitation," *International Security*, Vol. 42, No. 1 (Summer 2017), pp. 199-201, https://muse.jhu.edu/article/667398.

significance of this capability is the long, and deeply political, history of ballistic missile defense and anti-missile defense technology production, a case which will be explored in greater detail in Chapter 4. Continued missile defense technology development in the United States is one of the most often-cited reasons for current modernization and build-up of nuclear forces in Russia and China,[167] yet remains an element of U.S. nuclear strategy.[168]

Capabilities that impact governance

Beyond force structure and crisis stability planning, some capabilities are also sought to improve the governance of nuclear deterrence and strategic stability. These capabilities are beneficial if they can improve signaling transparency through information or verification processes. They can also enrich diplomatic and track two dialogue when their effects or disruptions are discussed multilaterally. Though, if pursued unilaterally, they may be perceived as destabilizing by giving one party an asymmetric information advantage.

Verification and Monitoring

Capabilities that provide new or improved methods to verify compliance with warhead or delivery vehicle limits, constraints in fissile material production, and other arms control commitments have sustained interest since the Cold War.

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[167] Igor Ivanov, "The Missile-Defense Mistake: Undermining Strategic Stability and the ABM Treaty," *Foreign Affairs* (September/October 2020), https://www.foreignaffairs.com/world/missile-defense-mistake-undermining-strategic-stability-and-abm-treaty.
[168] "2022 Missile Defense Review," in the "2022 National Defense Strategy of the United States of America," U.S. Department of Defense, October 2022, https://media.defense.gov/2022/Oct/27/2003103845/-1/-1/1/2022-NATIONAL-DEFENSE-STRATEGY-NPR-MDR.PDF.

Technologies that facilitate these capabilities might enable counting of warheads from afar, verifying that warheads have been decommissioned or separated from delivery vehicles, confirming that warheads are not deployed in certain locations, or monitoring fissile material production. Neutrino detection is an example of a capability that has generated interest since 1978, because it could provide greater insight on nuclear reactor operations to monitor fissile material production and diversion.[169] It also may become more feasible with new technologies, such as quantum sensing.[170] From a governance perspective, a recent International Atomic Energy Agency (IAEA) report specifies that the objective for developing technologies to support these capabilities is to aid in meeting requirements for arms control agreements or non-proliferation safeguards.[171] This means that, pursued in a multilateral forum, verification technologies could increase global stability. However, they could also be seen as destabilizing to states that seek an advantage by maintaining some capability that would otherwise be restricted through existing agreements if it were detectable; this could decrease willingness to engage in arms control agreements (though obviously would make the agreements themselves more credible).

Many technologies could also help improve infrastructure protection capabilities and safeguarding activities. The IAEA has long led analyses on the

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[169] Adam Bernstein, Nathaniel Bowden, Bethany Goldblum, Patrick Huber, Igor Jovonic, and John Mattingly, "Colloquium: Neutrino detectors as tools for nuclear security," *American Physical Society*, Vol. 92, No. 011003, May 12, 2020, https://link.aps.org/accepted/10.1103/RevModPhys.92.011003.
[170] Bernadette Cogswell, Apurva Goel, and Patrick Huber, "Passive Low-Energy Nuclear-Recoil Detection with Color Centers," *Phys. Rev. Applied*, Vol. 16, No. 064060, December 27, 2021.
[171] "Enhancing Capabilities for Nuclear Verification," IAEA Safeguards Report STR-399, January 2022, https://www.iaea.org/sites/default/files/22/02/rmp-2022.pdf.

opportunities to apply new technologies for a range of their activities, including AI and ML for surveillance of facilities.[172] Likewise, cybersecurity of nuclear infrastructure has been a growing concern for all nuclear weapon countries.[173]

Information Sharing

Information-sharing more has also become a thrust in verification, safeguards, and signaling domains. Capabilities that garner interest include the ability to share certain types of information about force structure deployment, or to share hashed information, such as through block chain or distributed ledger technologies.[174] In the post-Covid era, there has also been a push for virtual information-sharing capabilities that allow for remote fulfillment of governance activities, such as through remote inspections that are aided by digital technologies which provide more granular visual detail.[175] Better information sharing can be stabilizing if it increases transparency and reduces the possibility of misperceptions or miscommunication. Conversely, it could lead to political issues that arise from disruptions in data transmission during periods of high tension between information-sharing parties, misinterpretation through

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[172] For example: "Emerging Technologies Workshop: Insights and Actionable Ideas for Key Safeguard Challenges," IAEA Workshop Report, January 27-29, https://www.iaea.org/sites/default/files/20/06/emerging-tehnologies-workshop-290120.pdf.

[173] Herbert Lin, *Cyber Threats and Nuclear Weapons*, Stanford University Press, October 2021.

[174] William Moon, "Technical Issues and Considerations for Verifying Limits on Nonstrategic Nuclear Warheads," in *Everything Counts: Building a Control Regime for Nonstrategic Nuclear Warheads in Europe*, CNS Occasional Paper, May 2022, https://nonproliferation.org/wp-content/uploads/2022/05/op55-everything-counts.pdf.

[175] Luke Petruzzi, Bernadette Cogswell, Alexander Glaser, Malte Gottsche, Tamara Patton, and Drew Wallace, "Nuclear Inspections in the Matrix: Working with Radiation Detectors in Virtual Reality," 58th Annual INMM Meeting, 2017, https://sgs.princeton.edu/sites/default/files/2021-05/ALX-VR-INMM-2017.pdf.

streamlining analysis of more abundant data, or decentralization of data production and analysis.[176]

As can be discerned from this survey, even when looking at the specific impact area in nuclear deterrence, strategic stability, and arms control, the range of capabilities that must be considered is immense. Because the focus of this dissertation is on the impact of quantum sensing for nuclear force structure and arms control policymaking, greater focus will be given to the second group of capabilities: those that impact deterrence effectiveness. However, overlap across the categories means that the extent to which quantum sensors could satisfy capabilities in the first and third groups could also still play an important role in evaluating social and political mechanisms that may drive interest in quantum sensing in the nuclear policy domain. For example, research funding allocation by the U.S. State Department for quantum sensing verification methods may tangentially increase interest and improve talent needed for quantum sensing applications to achieve detection and tracking capabilities.[177] Similarly, the balance of potential benefits and risks of quantum sensing and new technologies, and the extent to which a benefit or risk is perceived depending on one's perspective, will also be considered in much greater detail in Chapter 6. The complicated interplay between reducing the risks of new technologies while exploiting potential benefits, and the challenges it imposes for policymakers, is

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[176] Sara Al-Sayed, "Revisiting Societal Verification for Nuclear Non-proliferation and Arms Control: The Search for Transparency," *Journal for Peace and Nuclear Disarmament*, Vol. 5, No. 2 (2022), https://www.tandfonline.com/doi/full/10.1080/25751654.2022.2133336.
[177] A U.S. State Department Key Asset Verification Grant was awarded in FY 2023 to VERTIC to evaluate quantum sensing applications in verification.

a key finding in another expert elicitation survey performed by Favaro, Renic, and Kuhn.[178]

Actor Network

Ultimately, the technologies and the capabilities are connected through a network of actors, epistemic communities, and institutions that each have their own bureaucratic, political, and social dynamics and that influence decision-making on whether technology development and acquisition will be pursued and how it will be applied. If the necessary actors align to facilitate support for a new technology, either organized around the technology's characteristics or the capabilities that it will afford, then R&D and acquisition activity may be propelled, regardless of a lack of consensus around whether the technology can realistically meet the capability needs and security objectives. Likewise, if certain actors and communities are poorly aligned, or if the gap between the technology and the capabilities desired is too significant, then the technology may not be pursued seriously. Sometimes, the gap between technologies and capabilities is flexible, changing as technologies evolve over time to allow for a more direct connection with capabilities, or if geopolitics and threat environments shift enough to motivate more vigorous attempts to achieve a capability, regardless of feasibility uncertainty.

[178] Marina Favaro, Neil Renic, and Ulrich Kuhn, "Negative Multiplicity: Forecasting the Future Impact of Emerging Technologies and International Stability and Human Security," Institute for Peace Research and Security at University of Hamburg, Research Report #10, https://ifsh.de/file/publication/Research_Report/010/Research_Report_010.pdf.

The concept of epistemic communities, proposed in 1992 by Peter Haas, is the most applicable security studies theory that explores how communities of experts inform policy decisions under conditions of uncertainty. Haas defines that epistemic communities are shaped by four unifying traits: (1) principled beliefs that "orient behavior and shape perceptions" of the group; (2) causal beliefs arising from their shared expertise and practices; (3) shared conceptions of validity based on internal criteria for expertise; and (4) a common "policy enterprise" or a shared perspective on the main problems of focus.[179] Although epistemic communities are commonly associated with technical communities and scientists, Mai'a Cross has since argued that Haas' original intention was to encompass shared professional knowledge rather than strictly technical knowledge. Cross clarifies:

> Diplomats, judges, defense experts, high-ranking military officials, bankers, and international lawyers, among others, all have just as much of a claim to authoritative knowledge as scientists…there is no reason to assume that their shared expertise is less reliable or influential. Professionalism, rather than science, is the glue that holds epistemic communities together, facilitates consensus, and enables persuasion.[180]

The broader, more inclusive definition that Cross specifies is somewhat more consistent with Actor-Network Theory (ANT), a concept in STS literature. However, ANT would offer an even more constructivist lens, asserting that the unifying factors identified are social phenomena that derive from the actor network. In STS literature,

[179] Peter Haas, "Introduction: Epistemic Communities and International Policy Coordination," in *International Organization*, Vol 46, No. 1 (1992), P. 22.
[180] Mai'a Davis Cross, "Rethinking epistemic communities twenty years later," *Review of International Studies*, Vol. 39, No. 1 (2013), pp. Pp.150-151.

ANT asserts that all social forces and phenomena arise from a network of actors and the interconnections between actors in the network. Per STS theorists like Bruno Latour, a complete network is comprised of human and non-human actors. Human actors are those that partake in the production, deployment, or some other aspect of innovation, to be discussed below. Technically, non-human actors are also included in ANT, and for example may include the technologies themselves. However, because this section is focused on social phenomena, non-human actors are not discussed extensively. Together, diverse actors in the network and their relations to each other explain the systems of beliefs and shared concepts that arise in and across epistemic communities and which influence technology development.[181] Thus, the STS perspective provides a more explanatory lens to complement the narrower epistemic community construct.

This section outlines three major sets of actors, or epistemic communities, that contribute to policy decisions on new technologies and nuclear deterrence: technologists, capability seekers, and skeptics/reviewers. In specifying these actors and communities, this section emphasizes the social, political, and bureaucratic factors that shape actor perceptions beyond simple technical appraisals. In addition to epistemic knowledge concepts, many of these insights draw from the STS literature that was surveyed in Chapter 2. Through ANT, STS has sought to systematically explore how technologies evolve and the interconnection of actors and their beliefs and principles to the real technologies underpinning innovation. In addition to

[181] Bruno Latour, "On actor-network theory: A few clarifications," *Soziale Welt*, Vol. 47, No. 4 (1996), pp. 369-381, https://www.jstor.org/stable/40878163.

epistemic communities, this section also includes consideration of the institutions as structures that organize actors and community dialogue.

Scientists and technologists

The first set of actors are the scientists and technologists that are responsible for producing or facilitating production of the technology. Regardless of setbacks that may be encountered throughout the development of the technology, this group typically supports the technology's application either because of research focus bias or because of monetary or resource incentives. Creators and innovators often promote their own science and technology developments, although they may not do so consciously or for self-serving motives. They need to define their motivation for conducting their research and garner attention to attract funding, jobs, and resources, which necessarily requires that they highlight the impact and potential application areas of their research. Even without financial or resource motivations for advertising in communication broadly, scientists that spend their careers working on narrow topics are also inevitably biased towards over-estimating the potential of their research and promoting their research for specific applications even when there may be more suitable alternatives.[182] The two can also be intertwined; research focus bias may be heightened when a scientists' prestige, livelihood, and/or resource access are impacted by whether others perceive their research area as "useful."

[182] Mariana Sa Santos, "Ethics of Hype and Bias in Science," *Nature – News and Opinions*, October 25, 2021, https://bioengineeringcommunity.nature.com/posts/ethics-of-hype-and-bias-in-science.

Recent research suggests that the prevalence of "hype", or "inappropriate exaggeration with the potential to be misleading or deceptive,"[183] has surged in science communication over the past few decades. Weingart proposes that this increases is the result of three industry trends: the integration of market mechanisms into academic incentive systems, the rise of social and mass media platforms, and political changes that treat science and technology research as a marker of innovation and economic competition.[184] Regardless of the intentions of the scientists in propagating inflated expectations, the method through which they advertise their research and its implications has become an active area of research for science and technology ethicists in recent years. Some argue that, in the long term, as hype begins to spread more easily via mass media or social media, a deterioration of trust in scientists by the public may occur.[185] Others focus on the counterproductive effects of hype on science communication[186] and evaluate efforts that have been made to temper hype among science communities.[187]

Technologists, or actors who produce technologies, are also prone to harboring and propagating inflated expectations for very similar reasons. Being somewhat removed from the lab setting and closer to the commercialization stage, technologists are compelled to generate (or at least promote) these expectations as a

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[183] Santos, "Ethics of Hype and Bias in Science,"

[184] Peter Weingart, "Is There a Hype Problem in Science? If So, How is it Addressed?" in *The Oxford Handbook of the Science of Science Communication*, June 2017, https://academic-oup-com.proxy-um.researchport.umd.edu/edited-volume/27956/chapter/211537810?login=true&token=.

[185] Zubin Master and David Resnik, "Hype and Public Trust in Science," *Science Engineering Ethics*, Vol. 19 (2013), pp. 321-335, DOI 10.1007/s11948-011-9327-6.

[186] Kristen Intemann, "Understanding the Problem of 'Hype': Exaggeration, Values, and Trust in Science," *Canadian Journal of Philosophy*, Vol. 52, No. 3 (2022).

[187] Peter Weingart, "Is There a Hype Problem in Science? If So, How Is It Addressed?" *The Oxford Handbook of Science and Science Communication*, pp 111.

way to attract attention and prestige, funding, and prospective buyers. Especially in the United States, venture capital has become a significant driver of technology hype.[188] However, Maslow's hammer, or the "law of the instrument," significantly predates venture capital forces. It is a recognized cognitive bias in favor of applying new technologies to old problems, even if they may not be the most suitable, because they are in the spotlight at the time (hence the well-known adage "when you have a hammer, everything looks like a nail").[189]

Finally, communication methods between these technical epistemic communities and non-technical technology consumer communities can create conflicting interpretations of new technologies. In some cases, the technologists tasked with attracting resources are not scientific or technical experts in the technologies that they are marketing, creating a communication barrier between technology consumers and producers. When scientists and technologists speak directly to technology consumers, they also often code-switch between technical and non-technical communities. When speaking among technical peers, scientists are often more candid about the potential drawbacks and limitations of their technologies/research than they are to potential funders or donors because they perceive a financial incentive to omit such information or because they do not know how to communicate highly technical aspects of these barriers in laymen's terms.[190] Keohane, Lane, and Oppenheimer point out that this communication is especially

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[188] Jeffrey Funk, "The Downside of Tech Hype," *Scientific American*, November 21, 2019, https://blogs.scientificamerican.com/observations/the-downside-of-tech-hype/.
[189] Jackie Fenn and Mark Raskino, *Mastering the Hype Cycle: How to Choose the Right Innovation at the Right Time*, pp. 43.
[190] From interactions in personal interviews with quantum technologists and while attending technical conferences.

challenging when there is uncertainty in the technical estimates under consideration, increasing the value of the scientists' judgements and communication principles.[191] In their analysis of the communication of sea level rise, they found that "precision and communication of uncertainty were sacrificed to a desire to avoid confusion through simplification, and a reluctance to state conclusions that did not reflect a scientific consensus."[192]

Although ambitious perceptions of technology production and the propagation of uncertainty or misleading expectations have rational origins and may seem harmless from the perspective of technologists and scientists, they can have unintended consequences. Most scientists and technologists are unlikely to consider the comprehensive and long-term political and strategic effects of the messages they communicate. Faced with funding challenges and pressures to increase citation counts or lab visibility, it is rational for scientists and technologists to adopt some degree of hype rhetoric. But it is also important that technical communities recognize the inflated expectations that they may produce when translating science and technology advances to policy audiences. This nexus has been remarkably understudied given the spotlight that emerging technologies have received (likely in-part due to technology hype) and will be scrutinized more closely with relation to the quantum sensing field in Chapter 7.

One effect of this communication gap, even under best intentions, is that it may result in actors that are more removed from the technical communities to

[191] Robert Keohane, Melissa Lane, and Michael Oppenheimer, "The ethics of scientific communication under uncertainty," *Politics, Philosophy, and Economics*, Vol. 13, No. 4 (2014), pp. 343-368.
[192] Keohane, Lane, and Oppenheimer, "The ethics of scientific communication under uncertainty," *Politics, Philosophy, and Economics*, Vol. 13, No. 4 (2014), p. 362.

perceive greater closure, consensus, and certainty around an issue than the technical actors actually involved in producing the technology. MacKenzie refers to this as the "certainty trough."[193] In his analysis of inertial guidance systems, MacKenzie finds that overconfidence is a common effect of the certainty trough, or the underemphasis of uncertainty when relating information to non-technical practitioners.[194] Other effects seen in the quantum sensing ecosystem will be explored in Chapter 7.

Capability seekers

The second important group of actors responsible for promoting or evaluating new technologies are the capability seekers. Distinct from general technology consumers, capability seekers are actors that actively pursue technologies that could fill perceived gaps in capabilities. Drawing from the survey of categories identified above, there are a wide variety of capability seekers in the nuclear community – across the U.S. interagency, in the private sector, and internationally. Depending on where they work, capability seekers may have organizational incentives to seek new technologies that could fill the need for certain capabilities, and institutional power to pursue these technology/capability gaps.

The scope of capability seekers that propel interest in a technology will likely expand dramatically for dual-use technologies. As discussed previously, dual-use technologies, or technologies that have applications in both the civilian and military spheres, are likely to gain traction faster as advocacy coalitions may form in both

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[193] Donald MacKenzie, "The Certainty Trough," in *Exploring Expertise* (London: Palgrave MacMillan, 1998).
[194] MacKenzie, pp. 325-329.

civilian and military ecosystems. However, dual-use technologies may also suffer from policy pushback if policymakers perceive a national security risk from the widespread deployment of a critical military technology. Conversely, even if a technology has limited or negative effects for strategic stability, it may end up being pursued by the private sector for civilian applications, which would still require a governance response.

The significance of capability seekers in the larger actor network and in the context of communication dilemmas and the propagation of biased or unrealistic perceptions is the extent to which they may build coalitions with science and technology epistemic communities, but do not engage in critical evaluation. When technologists and capability seekers establish connections on a common goal, either to develop a technology for a certain capability or to identify a new capability for an emerging technology, they may find mutually beneficial outcomes for pursuing R&D despite remaining questions about the extent to which a technology could meet a capability need. Furthermore, because this coalition of epistemic communities can sometimes establish a monopoly on relevant scientific or practical knowledge, either related to capability requirements or technical limitations, the alliance may spur on inflated expectations of the technology's suitability for a particular application. Importantly, by "buying in" the technologist community, this feedback loop also impedes commentary from technical experts who may be more cognizant of a technology's limitations. Circumstances in which such coalitions have formed in the past are identified in the historical case studies presented in Chapter 4.

External reviewers/policy advisors/information stewards

The third key group of actors consists of members of the technical community or policy actors which engage heavily with the technical community that have sufficient insight and credibility to review and critique assertions about new technologies. Actors from this group may be paid to perform technical analyses and critiques of technology acquisition plans or may feel a moral obligation to use their expertise in this way. For members of this group to be effective, they need very in-depth knowledge of the technology which they are critiquing, and enough credibility among community members for their views to be taken seriously. The nuclear community has benefited from the analysis of numerous highly engaged "reviewers" of technology innovation over the years. Examples of the outputs of this group include Ashton Carter's analysis that found directed energy unlikely to substantially support missile defense efforts in space[195] and Richard Garwin and Hans Bethe's reviews on the limits of anti-ballistic missile systems.[196]

While this group of actors can influence policy by providing unbiased evaluation of claims made by technologists and capability seekers, the incentive structures, constraints on resources, and barriers to information restrict the size and operability of this group. First, incentive structures that encourage scientists and technologists to promote their own area of expertise, as well as job availability, mean that most people with direct experience within a given technical focus area are likely

[195] Ashton B. Carter, "Directed Energy Missile Defense in Space," *Office of Technology Assessment*, 1984, http://www.princeton.edu/~ota/disk3/1984/8410/8410.JPG.
[196] Richard Garwin and Hans Bethe, "Anti-Ballistic-Missile Systems," *Scientific American*, Vol. 218, No. 3 (1968), https://rlg.fas.org/03%2000%201968%20Bethe-Garwin%20ABM%20Systems.pdf.

to be employed by that technology or capability sector. Although technical experts who have backgrounds in closely related fields may be able to critique claims, their background may not be as directly applicable.

For example, of the limited number of experts with technical expertise directly focused on isomer energy release, most were touting the technology's utility for at least some practical applications, either for military capabilities like gamma ray lasers or isomer bombs, or in civilian uses such as energy storage or propulsion.[197] Technical experts from related fields critically assessed claims over the feasibility of accomplishing reliable isomer energy release technologies and the utility of such devices (a case which will be discussed in greater detail in Chapter 4). However, their assessments were criticized for lacking the necessary information or experience to critique the technology because it was not their direct area of expertise or primary topical interest.[198] Furthermore, skeptics working on related technical issues often did not have direct access to the equipment or material (in the case of isomer weapons, hafnium) needed to refute inflated or ungrounded claims made on the practicality of stimulated isomer energy release. Yet, in spite of these restrictions, technical critics clearly played an important role in convincing policymakers to draw down and discontinue stimulated isomer energy release research for the purpose of developing isomer weapons.[199]

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[197] H. Roberts, "The importance of stimulated gamma release from isomers," *Hyperfine Interactions*, Vol. 107 (1997), pp. 91-97.
[198] R. Garwin, D. Hammer, W. Happer, R. Jeanloz, J. Katz, S. Koonin, P. Weinberger, and E. Williams, "High Energy Density Explosives," JASON Report – JSR -97-110, October 1997, https://irp.fas.org/agency/dod/jason/he.pdf.
[199] Sharon Weinberger, "Scary Things that Don't Exist: Separating Myth from Reality in Future WMD," Stanley Foundation Policy Analysis Brief, June 2008, https://stanleycenter.org/publications/pab/WeinbergerPAB08.pdf.

Many similar examples can be seen throughout the history of post-WWII military technology research in the United States. This prevalence across case studies makes these “skeptics” a necessary focal point for the analytical framework. Understanding where these actors emerge from, what compels them to critique claims of new technologies or capability applications, and how they establish credibility among policymakers may illuminate one of the most important methods for successfully challenging exaggerated claims about new technologies and more clearly understanding the utility and limitations of new technologies.

Institutions and organizations

Across these three categories, actors’ perspectives are shaped by their unique circumstances and the structural environment in which they are interacting. Employment connections, topical associations, political and theoretical preferences, and levels of shared technical understanding each influence the extent to which actors engage on certain technologies. In this way, individual actors serve as markers for larger trends within institutions and organizations that develop and adopt/deploy new technologies. Their structural perspectives also dictate the ways in which they engage on dialogue over new technologies. Distinct from epistemic communities, for which there are shared system of beliefs regardless of whether or not actors work for the same organizations, institutions and organizations may comprise actors from various epistemic communities but instill similar biases or bureaucratic perspectives.

The first important institutional trait influencing an actor is their resource or employment vantage point. Employment and resource availability determine how actors engage in discussions because they contribute to the actor’s credibility and platform for information distribution or the audience they engage with. Distinct from influencing personal biases, as discussed above, employment and incentive structures within an organization also dictate an actor's ability to focus on a given topic, to acquire the resources to investigate the topic, and to broadly discuss and engage actors from beyond their institution or network on the topic. Thus, these traits influence both the set of tools available for an actor to engage on a topic, as well as their level of influence by establishing (or abating) the actor's credibility.

The second institutional or organizational influence on actors is the degree to which areas of expertise are isolated or interconnected. As discussed above, and in the literature review, siloing of topical expertise in academia or professional settings often impedes engagement of actors on topics that may be tangential but not directly related to their area of expertise. For example, most quantum technologists do not consider the context of nuclear deterrence and how quantum technologies could impact strategic stability. Even if they are interested in these issues, opportunities for them to engage meaningfully with policymakers or technology users after acquisition are often very limited. Furthermore, some scientists actively prefer to avoid focusing on the applications of their technologies to military applications, a recognition that Marris, Jefferson, and Lentzos refer to as a type of "uncomfortable knowledge," or something which may be avoided in certain institutions to promote research.[200]

[200] Claire Marris, Catherine Jefferson, and Filippa Lentzos, "Negotiating the dynamics of uncomfortable knowledge: The case of dual use and synthetic biology," *BioSocieties*, Vol. 9 (2014), pp. 393-420, https://link.springer.com/article/10.1057/biosoc.2014.32; Also in: Steve Rayner, "Uncomfortable knowledge: the social construction of ignorance in science and environmental policy discourses," *Economy and Society*, Vol. 41, No. 1 (2012).

Likewise, technologists that are only loosely connected to one technology area because of how it relates to their main research focus may be biased from a co-development or co-production perspective. One example of this is the fact that the power of quantum sensing is often link with quantum computing assertions. Although the two technologies are separate fields, because of overlaps in technical design and methodology, quantum computer technologists may promote quantum sensing developments without understanding the full array of applications. Because of how expert settings are structured, each degree of removal from a narrow focus area may increase the number of experts in related fields but decreases direct topical credibility.

The final factor is the accumulation of biases through membership in different types of institutions and organizations, including their professional roles, social networks, and political affiliations that may influence an actor's perspective. Most actors have their own internal biases towards supporting specific political, strategic, or social narratives, whether consciously or subconsciously. These biases may lead them to focus on very specific aspects of technologies or capabilities, without considering consequences that may impact competing narratives/perspectives. For example, a DL-focused nuclear strategist may be interested in technologies that could afford the capability to track and target second-strike capabilities, while omitting or ignoring consideration of the impact that such capabilities may have on mutual vulnerability. Political ties are also influential, especially in the American military industrial complex, where policies of competition may lead some actors to view technology buildup as unambiguously good, without understanding the political signals such competition sends. Even if an actor does not maintain their own political or strategic biases, they may also be influenced by the social perspectives of the institution in which they are working or the communities they engage with. Similar to the workplace considerations, these institutions and organizations may similarly establish barriers to evade uncomfortable knowledge.

Operationalizing the Framework

Combined, each part of the integrated framework allows for incorporating important distinctions and perspectives that can illuminate processes of decision-making for emerging technologies. By first assessing the technology characteristics, one can understand the technical basis that constitutes the novelty of an "emerging technology" and factors that may influence R&D and deployment. Second, by considering the capabilities that the technology may afford or impact, the framework highlights an important distinction between the technology itself and the resulting applications (or would-be applications). This distinction has become especially important as the term "emerging technologies" has increasingly been used in reference to capabilities rather than technology elements. Finally, identifying the network of actors, communities, and institutions involved in the technology and capability ecosystems contextualizes the key groups that influence technology debates and decision-making and their ability to impact dialogue and perceptions based on structural designs of the ecosystems.

Compared to analyses that focus strictly on responding to technologies or capabilities, this framework also introduces opportunities for more proactive policy decision-making. Diagnosing how technology characteristics, capability impact, or actors influence assertions about the impact of a new technology equally informs ways in which to critically evaluate claims made about new technologies and their applications. This may require dedicated staffing of technical expertise in specific agencies, or larger shifts in funding strategies for science and technology research. Such policy options will be discussed in greater detail in Chapter 8. It may also provide linguistic tools for better discussing and signaling intent to develop new technologies and cultivate new capabilities. As Keohane, Lane, and Oppenheimer note, "science has plenty of associations focused on getting more money from society, but few, if any, focused on ensuring the scientific community as a whole is meeting ethical responsibilities."[201]

Some important considerations should inform operationalization of the framework. First, the framework parameters will necessarily change over time, sometimes in unpredictable ways. As a technology (or capability market) evolves over time, the threat landscape and technology state-of-the-art may shift the readiness-level of the technology or the perceived necessity of a capability. Likewise, temporality also characterizes actor, community, and institutional influences. When epistemic communities and actors expand their coalitions or suffer credibility deficits, their power to shape narratives also changes over time. Second, in addition to capabilities, which are intended outcomes for technologies, unintended consequences or use-cases may also emerge as a technology is developed and deployed. These negative connotations for technologies may ultimately sway the preference for

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[201] Keohane, Oppenheimer, and Lane, "The ethics of scientific communication under uncertainty," p. 362.

developing such technologies and the perceived benefits over costs. Finally, norms may form that can drastically shift perspectives on new technologies. As was seen in the case of autonomous weapons, international organizations may mobilize campaigns to conjure negative connotations for technologies or to push for greater oversight. These norms may not necessarily arise from capability or technology epistemic communities, but they could impact actors working in those fields as they gain more attention.

Conclusion

While the proposed framework is by no means exhaustive, it still provides a starting point for evaluating new technologies based on a set capability scope. The framework allows for a more critical lens through which to assess the flow of information on new technologies between different sets of actors and the ways in which information may be mis-applied or molded to fit the needs of technology producers and users/adopters. The framework also draws on insight from fields that are often disconnected from security studies literature, including technical fields and science and technology studies. Further academic cross-pollination could allow for deeper integration of these concepts.

The proposed framework will be leveraged in the subsequent chapter to evaluate case studies of technology development programs (and corresponding capability acquisition plans) that have shaped the post-World War II American defense enterprise. In these case studies, the key actors, communities, and institutions will be identified, and the technologies of focus and capabilities of interest defined.

The case studies will also examine how the dialogue around a technology's development changed over time, and how the complex network of actors and institutions either promoted eventual development and deployment of technology systems or impeded eventual application of the technologies.

Chapter 4: Historical Case Studies of Military Innovations

"Involvement with fraudulent experiments, publication of poor experimentation and open association with the CIA would be deleterious to the careers of the investigators and the credibility of the Institute. For this effort, we recommend a secret level contract."

-John McMahon
and Sayre Stevens, 1973[202]

"As in every innovation, technological opportunity had to be fused with demand for the application of the new technology."

-David Holloway, 1981[203]

Along with his Air Force colleagues, General Curtis LeMay, Air Force Vice Chief of Staff and former Commander of the Strategic Air Command (SAC), approached the transition from President Dwight Eisenhower to President John F. Kennedy with a skeptical but optimistic outlook. Despite President Eisenhower's substantial reallocation of military funding in favor of the Air Force, his adoption of a massive retaliation nuclear strategy as a way to reduce overall military spending was perceived by many Air Force officials as restricting to their ability to develop a

[202] John McMahon and Sayre Stevens, "Office of Research and Development and Office of Technical Service Paranormal Perception Research Project," CIA, 1973, https://www.cia.gov/readingroom/document/cia-rdp79-00999a000300100032-6.

[203] David Holloway, "Entering the Nuclear Arms Race: The Soviet Decision to Build the Atomic Bomb, 1939-45," *Social Studies of Science*, Vol. 11, No. 2 (1981), pp. 190.

flexible force structure that would be more suitable for "limited war" scenarios.[204] Although Kennedy's politics did not align with LeMay's, Kennedy criticized President Eisenhower's massive retaliation nuclear strategy during his campaign for presidency and stressed the missile gap concern, providing hope for a return to increased military expenditures and a buildup of limited war forces.[205]

Upon taking office, Kennedy tasked his Secretary of Defense, Robert McNamara, with prioritizing second-strike capabilities and expanding the range of targeting and force options.[206] Under this new strategy, a number of nascent Air Force programs focused on diversifying capabilities gained traction, including the Dyna-Soar (short for "dynamic soaring") program. Air Force personnel claimed that the proposed Dyna-Soar platform, a manned, hypersonic boost-glide vehicle, would support both bombing and reconnaissance missions. Furthermore, as the only space program solely under the jurisdiction of the Air Force, Dyna-Soar would assure U.S. military – and specifically Air Force – operability in space.[207] Under more favorable funding conditions due to President Kennedy's strategy, the Air Force was approved to move forward with the Dyna-Soar program, despite continued doubt from within the Department of Defense (DOD). Voicing skepticism that resonated throughout the DOD regarding the utility of the program beyond existing capabilities, one program review panel member claimed, "the Dyna-Soar is a vehicle looking for a mission."[208]

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[204] Franklin Houchin, "The Rise and Fall of Dyna-Soar: A History of Air Force Hypersonic R&D," Dissertation at Auburn University, 1995, p. 249, https://apps.dtic.mil/sti/pdfs/ADA303832.pdf.
[205] Fred Kaplan, *The Wizards of Armageddon*,(Simon and Schuster, 1983), pp. 248-255.
[206] Steven Reardon, "U.S. Strategic Bombardment Doctrine Since 1945," *Case Studies in Strategic Bombardment*, edited by R. Cargill Hall, U.S. Government Printing Office, 1998, pp. 420-425, https://media.defense.gov/2010/Oct/12/2001330115/-1/-1/0/AFD-101012-036.pdf.
[207] Houchin, "The Rise and Fall of Dyna-Soar," p. 201.
[208] Carl Derger, "The Air Force in Space," USAF Historical Division, 1962 (Declassified 1998), https://www.nro.gov/Portals/65/documents/foia/declass/WS117L_Records/59.PDF.

In the wake of the Cuban Missile Crisis and the Kennedy Administration's strategic shift to an AD strategy to prevent an expensive and risky arms race, McNamara grew more critical of military programs with poorly defined applications. This included the Dyna-Soar program. McNamara ordered a review to evaluate and compare the benefits of the Dyna-Soar and Gemini programs, concluding that the two together would add unnecessary redundancy in achieving low earth orbit manned flight (a new mission set that the Dyna-Soar program had adopted in a pivot to match the program with space capability needs).[209] This return to Eisenhower-era military technology scrutiny was perceived as a crisis by LeMay and his Air Force colleagues who viewed such programs as essential for getting U.S. military personnel (and especially Air Force personnel) in space, demonstrating science and technology competencies, and expanding force structure diversification.[210]

The cycle of unquestioned enthusiasm and scrutiny over the Dyna-Soar program highlights many of the factors that inform policymakers' decisions to pursue or halt certain technologies or capabilities. Facing a combination of concerns over resource constraints, uncertainty in technological feasibility, and strategic factors, McNamara argued the importance of a review and cross-program comparison before a congressional committee: "what do we have when we finish [dyna-soar]?... Do we meet a rather ill-defined military requirement better by proceeding down that track, or

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[209] "The Dorian Files Revealed: A Compendium of the NRO'S Manned Orbiting Laboratory Documents," Center for the Study of National Reconnaissance, Ed James Outzen, 2015, pp. 25-27, https://www.nro.gov/Portals/65/documents/history/csnr/programs/docs/MOL_Compendium_August_2015.pdf.
[210] Derger, "The Air Force in Space," pp. 22-23.

do we meet it better by modifying Gemini in some joint project with NASA?"[211] McNamara's predicament is not an isolated case; similar questions have been raised in response to other technological and political changes throughout the history of nuclear weapons. Speaking on the impact of new technologies in 1984, Richard Garwin echoed, "we ought to understand which [new technology] systems will benefit us, which ones will cost us, and what the balance is. We ought to improve these options; when we have an option good enough to buy, then we ought to buy it, not before."[212]

Despite the clear resonance between both McNamara's and Garwin's inquiries and those under consideration today, historical perspective is remarkably absent from most current analyses of new technologies. Drawing parallels between todays emerging technology challenges and those in the past could provide important insight on the precedents and success rates for the processes through which policymakers vet technology applicability for desired capabilities and decide whether to accelerate or halt R&D efforts. Scholars and analysts that omit historical perspective, either because they are biased by the novelty imbued by terms like "emerging" or "disruptive" technologies or because they do not see the relevant connections, forgo opportunities to empirically assess how earlier cases of decision-making under technological uncertainty have played out in the past, and to examine what the consequences have been for overly zealous or underappreciative appraisals. In addition to revealing underlying trends in the fundamental questions sparked by new

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[211] Robert McNamara, Testimony before the 88th Congress, House Committee on Armed Services, Session 1, Hearing on Military Posture, February 2, 1963.
[212] Richard Garwin, "The Impact of New Technologies," National Security Issues Symposium, 1984, https://rlg.fas.org/impact.pdf.

technologies throughout the modern U.S. military history, historical surveys also reveal remarkable similarities between the actual technologies and capabilities that were flagged as disruptive in the past and those being evaluated today; in fact, numerous technologies and capabilities currently in the spotlight were subjects of debate in the past. For example, in 1983 (before his statement on new technologies), Garwin evaluated whether antisubmarine warfare technologies would afford capabilities to render submarines vulnerable.[213] This concern is once again resurfacing in the context of new detection capabilities, such as those that may be afforded by quantum sensing.

The insights and patterns found in historical case studies can be leveraged to predict the technical, strategic, and social factors that will influence technology R&D and acquisition decisions in the present and future, avoid potential pitfalls, and improve the policymaking process. There are many social and strategic factors, beyond strictly technical considerations, that drive or quell technology innovation. Policymakers may find political or strategic motivation through cooperative agreements with countries abroad or domestic stakeholders for propelling a new technology. They may also find strategic incentives in signaling technology leadership. In the interagency and U.S. technology ecosystem, certain organizations and individual actors may have their own motivations deriving from prestige, resources, or funding needs and desires to warp their narrative on new technologies. Or they may be biased based on their own narrow perspectives. And finally, technical

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[213] Richard Garwin, "Will Strategic Submarines Be Vulnerable," *International Security*, Vol. 8, No. 2 (1983), https://rlg.fas.org/1983_Will_Strategic_Submarnes_Be_Vulnerable.pdf.

aspects may not be clearly communicated to policymakers in ways that are helpful for strategic decision-making. All of these factors, introduced in Chapter 3, will impact decisions on whether to foster and adopt new technologies in the future and how to respond to claims made about the likelihood of future disruptions. But none of these factors are new, and each can be examined in any number of historical cases.

This chapter will use the integrated analytical framework developed in Chapter 3, to evaluate specific decision points in five historical cases of military technologies and capabilities: ballistic missile defense, hypersonics, satellite imagery, psychic remote viewing, and isomer weapons. This will demonstrate the flexibility of the framework in evaluating technologies and capabilities under varying degrees of technological uncertainty, differing degrees of compatibility between technologies and capabilities, mechanisms through which capabilities influence deterrence, and the numerous social and technical factors that shape policymaker expectations. The historical case study survey will also supplement the more abstract factors defined by the analytical framework with concrete examples, as well as consideration of the outcomes for the decisions.

This survey highlights a few important dynamics that lead to misunderstandings or misperceptions about a technology or a capability, as well as risks that could arise due to these misguided expectations. Across the cases evaluated, this chapter finds that inflated expectations are commonly evoked alongside concerns about an adversary gaining an asymmetric advantage or promising a major strategic benefit from U.S. acquisition to motivate spending. Even if such allegations are cautionary, connotation with adversarial development can foster techno-optimist discourse that sustains funding. Regardless of the nature of these concerns, increased expenditures uniformly lead to long-lasting funding commitments that are very difficult to curtail after more realistic technological appraisals are available. The survey also finds that even when there is significant technological uncertainty or skepticism, sufficient motivation to acquire a capability to meet a strategic need can compel the rationalization of and decision to pursue immature technology options. Sometimes other factors will motivate the pursuit of a technology or capability for which there is no clear strategic value, including technology competition, domestic politics, institutional dynamics such as inter-service or inter-agency rivalry, and promise for future R&D breakthroughs in the long term.

The five historical case studies underscore the enduring impact of these decisions. Even at the early stage of development, when engaged epistemic communities and actor networks begin to form around particular technologies or capabilities and establish economic, social, and political forces in favor of sustained support accrue significant momentum. As these networks gain allies across different institutions, they accrue increased power to influence policy decisions. This means that early R&D decisions begin molding actors with vested interests. In more benign cases, the establishment of these long-lasting programs lead to resource consumption at the expense of more useful allocations. In the most severe cases, such programs also disrupt strategic stability and instigate arms racing dynamics. Ultimately, findings from this survey stress the importance of engaging with unbiased technology reviewers/skeptics, recognizing the long-term effects of decisions to promote technology development, and establishing clear metrics for analysis early in the consideration of emerging technologies.

Case Study Methodology

The motivation for the historical case study survey is two-fold: first, to address gaps in existing literature by adding empirical, historical context to current emerging technology analyses, and second, to expand on the complex network of factors comprising the integrated analytical framework proposed in Chapter 3. Aligned with these objectives, the historical survey includes a series of case studies that explore technology innovations and capabilities that have influenced nuclear deterrence in the past, but that provide useful context for current research on emerging technology analysis. The analytical framework proposed in Chapter 3 provides a helpful theoretical basis to map out the important technology characteristics (including how a technology is produced, what a technology is composed of, and how a technology is operated), evaluate how these characteristics produce deterrence and strategic stability effects through enabling certain capabilities, and capture the influence of actors and institutions in propagating perceptions of the technologies and capabilities. However, as discussed in Chapter 3, the capability mechanism is complex in that it imposes ambiguity into the assessment of disruption, and is a product of complicated technical, strategic, and social factors. Furthermore, because the status of technology innovation, strategic environments, and social factors are dynamic – they change over time – the framework must be recognized as temporally invariant. Historical case studies are used to complement the integrated analytical framework by providing insight on the complexity of the causal mechanisms and the dynamic nature of the effects as the technical, political/strategic, and social environments evolve.

Case selection

Cases were selected to account for the key elements of the integrated analytical framework. These include consideration of the different capabilities the technologies enable that are of importance for nuclear deterrence and strategic stability, technological characteristics they embody, and influential actors and institutions that constitute both the technology and capability epistemic communities. In the chapters that follow, the dissertation will apply findings from the historical survey, along with the integrated analytical framework, to assess how quantum sensing, a currently emerging technology that is generating interest, will impact nuclear deterrence and strategic stability. Thus, the case studies were also selected with the intention of analyzing factors that are likely to be pertinent to the quantum sensing case.

To satisfy the second objective of examining the dynamic nature, the case studies also explore different temporal durations and strategic settings. Together, the case studies cover wide spans of time; programs to pursue some of the case study innovations have already been completed or terminated, while others continue to garner support today. Importantly, for almost all cases, the technologies and capabilities were under consideration for long periods of time – on the order of decades. This not only significantly contrasts the notion that technologies "emerge" rapidly or in any surprising manner, but also provides insight into how perceptions and expectations change as technologies evolve and strategic objectives of capabilities change. Beyond these commonalities, each case study provides unique perspectives on the processes through which the technologies and capabilities garner support, incite criticism, and ultimately facilitate some degree of disruption in the larger nuclear deterrence and strategic stability environment. Interestingly, many of the case studies illustrate that these processes are cyclical – meaning that windows of analysis for the case studies must account for periods of waxing and waning interest. To focus on key turning points in these long innovation timelines, some case studies only focus on specific decision-making windows.

The case studies analyzed include ballistic missile defense, hypersonics, satellite imagery, remote viewing, and stimulated isomer energy release. Of these historical cases, ballistic missile defense has been the longest sought and most evasive capability and thus provides ample insight on deeply engrained political and economic biases and the power of well-established coalitions despite technical uncertainty. The hypersonics case also has a long and convoluted timeline because interest in ultra-fast missiles and planes arose very early in the Cold War, subsequently waned due to technology immaturity and lack of targeted missions and has recently resurged in-part because of strategic interests in prompt conventional strike and technological competition with Russia and China (who claim to be pursuing hypersonics partly to counter U.S. missile defense buildup). In contrast to these cases with long development timelines, satellite imagery, initiated in the United States under the program name Corona, demonstrates a case where a highly feasible technology with very short development timeline was initially underestimated due to lack of strategic precedent hindering predictions of capability impacts. The satellite programs offered more advanced command, control, communication, and intelligence infrastructure systems, as well as enhanced surveillance capabilities over adversaries, but the true extent of the strategic effects of these capabilities were not entirely fathomable without precedent. Despite this relative success, technical limitations of satellite imagery gave rise in to a third case in the 1970s – psychic remote viewing – that was significantly more speculative, but that provides valuable insight into the extent to which actors may go to pursue a "technology" with a high degree of uncertainty when a capability is extremely alluring The final and most recent case study—isomer weapons – also capitalized on institutional momentum established by successful programs like Corona and geopolitical concerns. It promised to use new, speculative nuclear physics methods to create a weapon with a sub-nuclear yield, which would be more destructive than conventional but less catastrophic than nuclear weapons, based on stimulated isomer energy release, despite underwhelming assessments of strategic value.

A final reason for selecting these five cases is their relevance to the technical characteristics of quantum sensing and the strategic capabilities motivating interest in that emerging technology. Missile defense and hypersonic systems raise similar questions over the utility and vulnerability of ICBMs as compared to the missile navigation application of quantum sensing. Meanwhile, satellite imagery and remote vision evoke concerns over the vulnerability of mobile delivery vehicles that are similar to those arising from the submarine detection application of quantum sensing. Meanwhile, regarding technical characteristics, isomer energy release is an area with a very narrow set of technical experts, and which is fairly inaccessible to non-technical experts; this is somewhat similar to the barriers around quantum sensing.

Other case study selections may have allowed for greater focus on alternative technical traits or capabilities relevant to nuclear deterrence that were covered in the analytical framework in Chapter 3, including enhanced decision-making speed and increased offensive potential. These cases could have examined the equally fascinating development processes for technology systems like the "dead hand" and multiple independently targetable reentry vehicles (MIRVs), which also had significant impacts on the history of nuclear deterrence. Future studies may consider expanding on these cases.

Case study design and organization

Guided by the research objectives to further explore complexity in the causal mechanisms between technology characteristics, capabilities, and deterrence effects and to evaluate the evolution of these factors along a temporal dimension, the case study design aligns best with the causal process tracing inference method. Blatter and Bloom specify that causal process tracing allows for observation of "temporal unfolding of situations, actions and events, traces of motivations (or other lower mechanisms), evidence of (complex) interactions between causal factors, and/or information about restricting/catalyzing contexts/conditions."[214] The key outcomes of interest are the processes (strategic, social, and technical) through which perceptions

[214] Joachim Blatter and Till Blume, "In Search of Co-variance, Causal Mechanisms or Congruence? Towards a Plural Understanding of Case Studies," *Swiss Political Science* Review, Vol. 14, No. 2 (2008), P. 319

are developed around new technologies and capabilities, as well as the policy effects of these perceptions. Policy effects of importance include both policymaker decisions to pursue or halt technology development, as well effects for policies that govern nuclear force structure, arms control, and strategic stability. Guided by the analytical framework, other factors that are evaluated for each case include: the technology characteristics, the capabilities that are identified in relation to the technology, and the strategic and political narratives that arise among relevant epistemic communities that mediate expectations over the technology. Finally, overarching considerations that must be accounted for despite that they are often ignored, as noted in the Chapter 2 literature review, are the evolving threat landscape and the geopolitical climate. Depending on the threat environment and geopolitical relations, military or political decision-makers may be more disposed to take risks on certain types of technologies.

Within the case studies, the main methodologies employed were process tracing and other forms of historical analysis of primary and secondary sources, including some declassified documents available in the national archives. Historical analysis was performed specifically to evaluate the evolution of narratives on technologies and capabilities among decisionmakers, as well as to specify the determinants for important policy decisions. Process tracing was also performed to empirically evaluate the mechanisms that connect key actors and policy decisions and to better inform the concepts defined in the analytical framework.

The historical analysis methodology provides a useful basis for each case study to identify key decision-makers and influencers, and to identify how they impacted the policymaking processes. It is especially informative for cases with older timelines and for cases that include previously-classified information.[215] A key focus for the historical analysis was to identify key actors and mechanisms for policy decisions and propagation of expectations, including departments and personnel, and their roles in connecting the explanatory variables to the outcome variables or effects. As a byproduct of working with a mixture of primary and secondary data sources, many of which are as informal as handwritten notes, triangulation of information is used where possible to improve internal validity of the assessments made. Additionally, the credibility of each source's assertion is considered, including the personal or institutional biases that may be influencing an assessment.

Process tracing is also used to guide the analysis, as another key research objective includes identifying *how* decisions are made about new technologies and *how* nuclear force structures change as new technologies are adopted. Although a variety of technologies are considered, the ability to extrapolate the findings to even more technologies would be limited without process tracing. This deeper look at the connection between the explanatory factors and mechanisms and policy effects ensures that the findings can be more easily applied to other technologies in different temporal contexts based on the key connecting mechanisms (through the developed analytical framework). David Collier underscores the utility of process tracing for within-case analysis, claiming, "process tracing can contribute decisively both to describing political and social phenomena and to evaluating causal claims."[216] Rather than search for definitive causality, the process tracing in this survey sought to delve

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[215] George and Bennett, "Phase One; Designing Case Study Research," pp. 75-76.
[216] David Collier, "Understanding Process Tracing," *Political Science and Politics*, Vol. 44: 4, 2011, pg. 823.

into the complex interactions of actors and mechanisms, and to evaluate temporal effects on the process of decision-making.

Succinct summaries of the cases and the key findings from the analyses are presented in this chapter, with supplementary information provided in Appendix A. First, the technical characteristics and the corresponding capabilities are identified for each case. Next, the role of various organizations and actors involved in production and decision-making of the technology, and their perceptions of the technologies and capabilities are summarized. Evaluations of whether a technology could feasibly satisfy a capability need are noted, as well as the relationships between key actors and institutions that contribute to diverging perceptions of these technical feasibility estimates. For cases that extend over considerable spans of time, the temporal evolutions of the technical bases, capability requirements, and epistemic communities are discussed. Finally, the key technological and strategic effects and policymaking influences highlighted by each case are summarized. Appendix A provides more detail for each case, including tables that summarize the programs or projects used to develop a technology or capability within a case, the organizations and actors responsible, and the constraints and attributes that determined strategic impact. A cross-case summary of trends is offered at the end of the chapter.

Case 1: Ballistic Missile Defense

The ballistic missile defense (BMD) case study examines key turning points in the evolution of a large technological system which has been subject to a high degree of technical skepticism, and which has remained politically contentious over decades of technology innovation. This lengthy endeavor has been sustained by proponents who continue to claim that each new improvement to subcomponent technologies will render the system successful. Beyond fundamental disagreements over technical feasibility, conceptions of the level of performance that BMD systems would need to operate at to be deemed "successful" capabilities also remain highly contentious as a result of diverging strategic perspectives.

Likely a product of this extended timeline and enduring debate, an immense amount of literature on the technical and social pillars that support the BMD ecosystem has been produced. One of the most voluminous government sources of information on the early internal decision-making processes for BMD developments, though also likely at least a little biased, is a two-volume, 650-page series published by the U.S. Army Center of Military History. Divided chronologically, the series details the political and technical factors that contributed to BMD adoption and development decision-making between the periods of 1945-1972.[217] For more recent analyses, various government agencies continued to publish updates on missile defense performance, spending, and strategy. Outside of government-generated literature, through historical and technical assessments of BMD debates, members of civil society and academia have sought to provide independent analyses of influential factors in decision-making and information as to what can be feasibly expected of BMD technologies and capabilities.[218] Comparing evaluations asserted across the

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[217] "History of Strategic Air and Ballistic Missile Defense: Volume I 1945-1955," 2009, https://history.army.mil/html/books/bmd/BMDV1.pdf; "History of Strategic Air Ballistic Missile Defense: Volume II 1956-1972," 2009, https://history.army.mil/html/books/bmd/BMDV2.pdf.
[218] For example, "Ballistic Missile Defense: Threats and Challenges," American Physical Society, Panel on Public Affairs, 2022, https://aps.org/policy/reports/popa-reports/upload/MissileDefense-Report-final.pdf; and Charles Glaser and Steve Fetter, "National Missile Defense and the Future of

different bodies of literature, a key theme that emerges is that perceptions of BMD effectiveness and viability differ according to political and strategic perspectives. The subjective nature of technical and strategic evaluations of missile defense has led to the topic amassing an immense network of technical and political advocates and critics.[219] Even among technical communities, there is often disagreement over the appropriate means to evaluate BMD technology innovations.[220]

From a technology standpoint, BMD systems more closely resemble large technical systems oriented around specifications dictated by a desired capability, because their structures vary depending on strategic intent and their operability relies on a unique composition of technologies and subcomponents. Due to the high variability in the underlying technology, this case study will emphasize evaluation of the strategic capability, rather than technical characteristics. BMD is an umbrella term used to define the capability to intercept and destroy a missile or its warhead at some point in its trajectory. Within this category, BMD systems are distinguished by where the interceptors are based (ground, sea, air, or space) and the phase of a missile's trajectory at which interception is attempted– either during the boost phase, midcourse phase, or terminal phase.[221] Typically, systems are designed to defend

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U.S. Nuclear Weapons Policy," *International Security*, Vol. 26, No. 1 (2001), pp. 40-92; Ashton B. Carter and David Schwartz (eds.), *Ballistic Missile Defense*, The Brookings Institute, 1984; and James Cameron, *The double game: The demise of America's first missile defense system and the rise of strategic arms limitation*, Oxford University Press (2017).

[219] For example, surveyed in, Victoria Samson, *American Missile Defense: A Guide to the Issues*, Praeger, 2010.

[220] William Broad, "Physics Body Concedes Mistakes in Study of Missile Defense," *The New York Times*, September 19, 2022, https://www.nytimes.com/2022/09/19/science/missile-defense-north-korea.html.

[221] "The Ballistic Missile Defense System," U.S. Department of Defense (2019) https://www.defense.gov/Portals/1/Interactive/2018/11-2019-Missile-Defense-Review/MDR-BMDS-Factsheet-UPDATED.pdf.

certain facilities, population centers, or regions of the U.S. homeland from long-range missiles or to defend military forces and allies against short and medium-range missiles. Although there are some variations in technical requirements based on these parameters, BMD systems are generally composed of sensor and detection systems, interceptor mechanisms, and command and control infrastructure. While the specific elements in each of these components will vary, some form of all three functions are necessary for an operational missile defense system.[222] As is customary for technological systems, most innovations throughout the BMD development timeline can be traced back to individual improvements in smaller technologies within these spheres of requirements, rather than products of larger, whole-system innovations.

As a large technological system, BMD is better categorized as a capability rather than a pure technology from the perspective of the analytical framework. This means that it has a defined task – to intercept ballistic missiles – and thus induces a complex causal mechanism based on technical feasibility, deterrence interpretation, and capability perceptions to produce strategic effects. As suggested when discussing the category of defensive capabilities in Chapter 3, beyond technical uncertainty, the strategic value of BMD is widely debated across policy and military experts. Those applying a DL perspective view even very limited forms of BMD as beneficial since they may reduce impact should a nuclear war break out. However, from an AD perspective, a highly effective BMD would be destabilizing since it would diminish the credibility of an adversary's second-strike capability and would thus reduce

[222] "Ballistic Missile Defense Technologies," Chapter 7 in U.S. Congress Office of Technology Assessment, OTA-ISC-254 (1985), https://www.princeton.edu/~ota/disk2/1985/8504/8504.PDF.

conditions of mutual vulnerability. Furthermore, and more likely, limited/imperfect BMD would be destabilizing because it would incentivize first strike strategies and could catalyze arms racing to counter defensive buildup with more robust offensive capabilities.[223] Because of the significant rift between these assessments, national policies over U.S. acquisition and deployment of BMD systems have varied widely across different political administrations.

Given the long timeline for BMD development, technical feasibility to develop a successful BMD system and the geopolitical climate and threat environment that influence desire for the capability have also evolved. Uncertainty over technical feasibility was contributing factor to tempering interest and halting early efforts on BMD. Importantly, this evolution also sheds light on the value policymakers have placed on signaling and perception of BMD.

The first wave of serious interest in ABM systems began in the 1950s, with the establishment of the U.S. Army's Nike-Zeus program, which is recognized as the first U.S. BMD program.[224] At the time, President Eisenhower, along with his scientific and strategic advisors, was skeptical of the technical feasibility of the program, and the strategic value given the likelihood that the Soviet Union would respond by increasing their ICBM arsenal.[225] However, the program received funding

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[223] "Crisis Stability, Arms Race Stability, and Arms Control Issues," Chapter 5 in U.S. Congress Office of Technology Assessment, OTA-ISC-254 (1985), https://www.princeton.edu/~ota/disk2/1985/8504/8504.PDF.
[224] Samson, *American Missile Defense*, p. 2.
[225] "Nike-Zeus, The U.S. Army's First Ballistic Missile," Missile Defense Agency, MDA-4885, 2009, p. 8. https://web.archive.org/web/20130219034349/http://www.mda.mil/global/documents/pdf/zeus.pdf.

due to congressional support arising from lobbying efforts spearheaded by the U.S. Army and allegedly out of concern about Sputnik's launch in 1957.[226]

Once President Kennedy took office, McNamara supported continued ABM funding, despite the fact that forecasts for the technology's development indicated the existence of patent technical limitations. At this time, recognizing technical limitations, McNamara reinforced strategic advantages of "deployment of a less than perfect ballistic missile defense." In a 1962 memo to President Kennedy, McNamara contended that, even though Congress disapproved of the Nike-Zeus program on the basis of these limitations, "a ballistic missile defense of limited capability would contribute to the deterrence of attacks by raising doubt about the attacker's ability to penetrate. Such a defense, even though limited, greatly complicates the design and tactics for offensive weapons."[227] However, in a matter of years, McNamara grew skeptical of these benefits based on arguments made by his systems analysts regarding the economic inefficiency of the program.[228] In a 1967 memo to President Johnson, McNamara urged against a full-scale ABM deployment on the basis that the Soviet Union would be forced to offset U.S. ABM systems with more ICBMs and therefore the strategic value would be circumscribed.[229] Instead, he urged a smaller-

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[226] "Ballistic Missile Defense Then and Now," Chapter 3 in *Ballistic Missile Defense Technologies*, U.S. Congress, Office of Technology Assessment, OTA-ISC-254, 1985, p. 45, https://www.princeton.edu/~ota/disk2/1985/8504_n.html; and "Production and Deployment of the Nike-X," Memorandum for the President, The Secretary of Defense, 1966, https://nsarchive2.gwu.edu/nukevault/ebb281/4B.pdf.

[227] Robert McNamara, Draft Memorandum to President Kennedy, November 20, 1962, https://history.state.gov/historicaldocuments/frus1961-63v08/d111.

[228] "Ballistic Missile Defense Then and Now," p. 45.

[229] "Production and Deployment of the Nike-X," Memorandum from Secretary of Defense McNamara to President Johnson, January 17, 1967, https://history.state.gov/historicaldocuments/frus1964-68v11/d173.

scale deployment to address congressional pressure, and began pushing for a limitation agreement with the Soviet Union.[230]

Following the early Nike programs, BMD continued to receive periodic interest in response to claims of Soviet research, strategic interests of military and political decisionmakers, and urges to reconsider technical feasibility with new innovations. After Eisenhower and Kennedy pursued technological hedging with basic BMD research, to appease congressional members, President Richard Nixon faced scrutiny over the location of ABM systems near cities, rather than silos.[231] Arriving at the same conclusion as McNamara on the net negative security effects, Nixon approved of deployment of the limited Safeguard Anti-Ballistic Missile system following Soviet development of its first ABM system, claiming that the Safeguard system could serve as a lever for negotiations in the Strategic Arms Limitation Talks (SALT) underway between the Soviet Union and the United States.[232]

Research continued under Jimmy Carter until President Reagan's "Star Wars" speech, which caught many security experts off guard, as the administration had previously rejected two possible missile defense systems, reportedly due to assessment of continued technical limitations.[233] Notably, it is evident from Reagan's initial speech that he foresaw such research as a long-term endeavor, claiming "it will take years, probably decades, of effort on many fronts."[234] Reagan then proceeded in

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[230] "Ballistic Missile Defense Then and Now," p. 48.
[231] "Ballistic Missile Defense Then and Now," p. 48.
[232] Joseph Cirincione, "Brief History of Ballistic Missile Defense and Current Programs in the United States," February 1, 2000, https://carnegieendowment.org/2000/02/01/brief-history-of-ballistic-missile-defense-and-current-programs-in-united-states-pub-133.
[233] Cirincione, "Brief History of Ballistic Missile Defense."
[234] Reagan, SDI speech, 1983, https://www.atomicarchive.com/resources/documents/missile-defense/sdi-speech.html.

a full-court press to develop missile defense as quickly as possible, despite significant skepticism from technological and political standpoints.[235]

Subsequent administrations began to develop alternative missile defense options, but have largely been stuck with the missile defense portfolio instituted by the Strategic Defense Initiative Organization (later BMDO and MDA). These efforts encompass advanced research on laser and space-based interceptors, as well as traditional ground and sea-based BMD systems. Although they did not actively pursue BMD as ardently as the Reagan administration, both President George H.W. Bush and President Bill Clinton pursued variants of BMD. President Bush continued legacy efforts but lacked the Soviet threat justification so pursued more limited systems like GPALS, which were intended to target rogue states and actors and deter nuclear coercion. Meanwhile, President Clinton shifted focus to a theater missile defense program to appease Republicans in congress while preserving the ABM Treaty.[236] Lastly, President George W. Bush pursued a comprehensive national missile defense system, similar to Reagan's. His program again sought a layered approach to target missiles at all stages of flight, however it was composed of a different mix of technologies compared to Reagan's and entailed a more distributed funding, resource, and task designation.[237]

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[235] Sydney Drell, Phillip Farley, and David Holloway, "Preserving the ABM Treaty: A Critique of the Reagan Strategic Defense Initiative," *International Security*, Vol. 9, No. 2 (Fall, 1984), pp. 51-91; and David Holloway, "Strategic Defense Initiative and the Soviet Union," *Daedalus*, Vol. 114, No. 3 (1985), pp. 257-278.
[236] James Acton, "U.S. National Missile Defense Policy," in *Regional Missile Defense from a Global Perspective*, Stanford University Press, 2015, pp. 33-47; and Victoria Samson, *American Missile Defense*.
[237] Philip Coyle, "Rhetoric or Reality? Missile Defense Under Bush," *Arms Control Today*, 2002, https://www.armscontrol.org/act/2002-05/features/rhetoric-reality-missile-defense-under-bush.

Appendix A outlines the series of research projects and the technical barriers faced by each program throughout the history of U.S. BMD research. Although some of the technical challenges that plagued earlier programs have since been addressed, many others have persisted throughout the history of BMD or have emerged under newer conceptions, including the prevalence of counter-BMD tactics, such as decoys and anti-satellite capabilities. Finally, similar claims to those made early on by McNamara about the psychological benefits of BMD systems, even with well-defined technical limitations and low probabilities of success, have persistently supported BMD development amidst these hurdles.[238]

Sustained BMD development has also been supported by its large network of advocates, including the technologists, capability seekers, and institutions that the coalition has accrued throughout the technology's extended duration. As the U.S. Army's historical account notes, the most significant factors that influenced early U.S. decision-making on BMD were threat perceptions of Soviet missile capabilities and the decision-making processes in place.[239] Throughout the Cold War and post-Cold War eras, these strategic and organizational influences waxed and waned as budgetary funding availability and threat perceptions shifted to create opportunities and challenges for developing, acquiring, and deploying BMD systems.

Yet, the programs weren't wholly susceptible to budgetary and economic winds. Once the BMD field amassed an expansive actor network with invested epistemic communities that relied on sustained funding, it became very politically

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[238] For example, referenced in comments by Markus Garlauskus at Atlantic Council Missile Defense Workshop, May 2023.

[239] "History of Strategic Air and ballistic Missile Defense – Volume II 1956-1972," U.S. Army, https://history.army.mil/html/books/bmd/BMDV2.pdf.

challenging to cut the development altogether or to propose decreasing allocated funding.[240] In the case of Reagan, other social mechanisms such as personal prestige also drove interest in BMD. This momentum and the sustained interest also reinforced power in BMD coalitions despite the fact that a lack of consensus among scientists on the technical feasibility of ever implementing a BMD system with a high success rate continued circulating.[241]

Finally, beyond deterrence consideration, broader strategic factors – or political hedging – incentivized sustained research on BMD, especially among democratic administrations. Both the Clinton and Obama administrations focused on theater missile defense because it was a technically easier approach, addressed a contemporary threat, and was less likely to cause problems with China and Russia. Viewed through a socio-technical lens, the core issue with political hedging is that it maintains momentum in programs and coalitions, making it easier for reinvigoration under better political winds, rather than killing them and reassigning funding to more cost-effective alternatives.

One of the more interesting takeaways illuminated by the BMD case study is that even when technologies fail to meet performance expectations required to satisfy a capability, they can still produce strategic effects. Although BMD systems never met the much-anticipated success of a reliable, credible defense that preceded early R&D decisions and that motivated sustained funding, the pursuit of a BMD capability

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[240] David Mosher, "Understanding the Extraordinary Cost of Missile Defense," RAND, 2000, https://www.rand.org/natsec_area/products/missiledefense.html.
[241] For example: George Lewis, Theodore Postol, and John Pike, "Why National Missile Defense Won't Work," *Scientific American,* Vol. 281, No. 2, 1999; and George Lewis, Lisbeth Gronlund, and David Wright, "National Missile Defense; An Indefensible System," *Foreign Policy*, No. 117, Winter 1999.

still had a significant strategic impact on adversaries and consequently U.S. force structure planning. Some policymakers and strategists claim that simply having BMD systems deployed, albeit with some degree of uncertainty or inaccuracy, influences decision-making by adversaries and may potentially disincentivize escalation due to perceived asymmetric advantage. Adopting DL perspective, DeBiaso writes, "defenses do not have to be large or perfect to inject complexity and doubt into the adversary's pre-war planning and execution of missile strikes. Even limited defenses are capable of weakening the opponent's confidence in its ability to achieve its military objectives."[242]

However, similar to the debates over the strategic effects of a theoretically successful BMD system, policymakers remain divided on the effects of BMD systems with high uncertainty and continued BMD R&D. Many claim that U.S. deployment of missile defense systems was influential in Russian and Chinese decisions to expand and modernize nuclear arsenals. Even accounting for current limitations, U.S. deployment of missile defense systems threatened that future capability improvements may eventually render their assured retaliatory capabilities obsolete. Others contend that even if Russian and Chinese officials are aware of the technical limitations, they may feel political pressure to counter U.S. BMD buildup. Skeptics of these claims contend that Russia and China merely use U.S. BMD to validate capability buildups that they would have undergone regardless.[243]

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[242] Peppi DeBiaso, "Why the U.S. must invest in homeland missile defense," *Defense News*, September 20, 2022, https://www.defensenews.com/opinion/commentary/2022/09/20/why-the-us-still-must-invest-in-homeland-missile-defense/.
[243] Debate discussed in Tong Zhao and Dimitry Stefanovich, "Missile Defense and the Strategic Relationship among the United States, Russia, and China," American Academy of Arts and Sciences,

Amidst this turbulence, BMD research continues to this day, with the support of an institutionalized U.S. Missile Defense Agency and sustained funding for missile defense deployments. Significant skepticism remains over the success of the program, however. Civil society groups and even the U.S. Government Accountability Office (GAO) have reproached institutional issues and failures for programs to meet stated objectives, budgets, and timelines.[244] Still, U.S. policymakers continue to develop force structure plans and make nuclear policy decisions that assume some degree of BMD accuracy and long-term viability, supported by competing civil society groups and defense contractors. Recently, these claims have shifted to emphasize BMD as a defense against North Korea's burgeoning ICBM arsenal, despite the instability necessary systems may inject into U.S. relations with Russia or China.[245]

Thus, the BMD case study demonstrates that even the perception of a capability, or the possibility that it could be achieved at some point in the ambiguous future with further R&D, can be impactful. If they can gain policymaker interest, coalitions can build up significant momentum to support R&D despite underwhelming feasibility assessments and strategic/political concerns. BMD strategic effects and technical feasibility have become a hallmark of nuclear deterrence debates since the 1970s, regardless of efforts by technical skeptics to quell concerns and exaggerations about what can be expected from BMD systems. Critics,

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2023, https://www.amacad.org/publication/missile-defense-and-strategic-relationship-among-united-states-russia-and-china.

[244] "Missile Defense: Annual Goals Unmet for Deliveries and Testing," GAO, May 18, 2023, https://www.gao.gov/products/gao-23-106011

[245] Summarized in: Jaganath Sankaran and Steve Fetter, "Defending the United States: Revisiting National Missile Defense against North Korea," *International Security*, Vol. 46, No. 3 (2022), pp. 51-86.

including many reputable scientists, have consistently rejected claims made for each new iteration of missile defense technologies and capabilities. Such criticism has highlighted historical technical failings, the impact of cheap countermeasures, high economic costs, and political effects that produce cyclical offense-defense buildups.[246] Additionally, critics argue that proponents of missile defense often propel the program for "reasons related as much to ideology and partisan politics as to national security."[247] Amidst disagreements over what can be expected to be feasibly achievable, advocates for BMD still claimed that the perception of a BMD system is strategically effective, and thus merits sustained R&D funding. Thus, even despite criticisms over the validity of DL-oriented strategic logic *and* technological feasibility, skeptics and strategists viewing risks from the AD perspective face the added challenge of a well-established coalition and a robust epistemic community oriented around the production and operation of BMD systems. The power that the BMD coalition continues to exert demonstrates that institutionalized momentum to support a technology and/or capability decreases the likelihood of subsequent decisions to drawdown the technology area.

Case 2: Hypersonics

The hypersonics case study illuminates similar characteristics and mechanisms to those in the BMD case study, as a large technical system with a long

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[246] Kenneth Werrell, "Hitting a Bullet with a Bullet: A History of Ballistic Missile Defense," Airpower Research Institute – Research Paper 2000-02, https://apps.dtic.mil/sti/pdfs/ADA381863.pdf.
[247] Nancy Gallagher, "Congress and Missile Defense," CISSM pre-publication, September 14, 2015, https://cissm.umd.edu/sites/default/files/2019-07/Chapter%205%20-%20Congress%20and%20Missile%20Defense.pdf.

timeline and evolving technologies and strategic objectives. While there is a lack of closure in both the BMD and hypersonic cases, ambiguity arises in different realms. In the case of BMD, lack of closure persists with respect to feasibility, and in hypersonics, lack of closure is more rooted in the failure to identify a compelling strategic incentive. Research on hypersonic platforms, or vehicles that travel at speeds greater than Mach 5, has been subject to cyclical periods of interest similar to those for BMD. Likewise, strategists viewing deterrence from AD and DL perspectives have debated the strategic logic for hypersonics restraint or development. However, compared to BMD, hypersonics represent a technology that has – to some degree – been achieved for some countries and thus has undergone some level of closure with respect to the technological feasibility for acquisition (although innovations that would improve the qualitative performance which have not yet been achieved continue to inject some uncertainty). STS literature defines closure as a process of stabilization in the perceptions of a technology's feasibility for development, design selection, operational characteristics, and suitability for certain applications.[248]

Like the BMD case study, the long development timeline for hypersonics has afforded this analysis a large body of text to draw from to evaluate the continuing closure process. This includes an immense three-volume edited series published by the U.S. Air Force History and Museums Program that organizes declassified information to trace the "hypersonic revolution" from 1924-1995. Richard Hallion, the editor of the first two volumes in the series, asserts that the story of hypersonics is

[248] Trevor Pinch and Wiebe Bijker, "The Social Construction of Facts and Artefacts: or How the Sociology of Science and the Sociology of Technology might Benefit Each Other," *Social Studies of Science*, Vol. 14, 1984, pp. 244-245.

a “particularly American one”, and that “faith in, and unquestioning acceptance of, a hypersonic future is akin to belief in the Second Coming one knows and trusts will occur, but one can’t know when.”[249]

Constituting a technological system similar to BMD, hypersonic platforms rely on a combination of technologies, including heat-resistant materials, electronics, and navigation systems, as well as high-speed propellent systems, in order to achieve speeds faster than Mach 5. Generally, platforms that travel at speeds faster than Mach 5 fit into three categories: ballistic missiles, boost-glide vehicles, and cruise missiles. However, ballistic missiles, which have been around for decades, only reach high speeds because of their rocket propulsion, and thus have more predictable and constrained trajectories than would be allowed with a tailored hypersonic propulsion method. In comparison, boost-glide and cruise missile hypersonic systems afford extended high-speed flight with greater maneuverability. Boost-glide vehicles are initially propelled by rockets, but glide at hypersonic speeds once they reenter the atmosphere. Cruise missiles use rocket boosters for initial acceleration and are then powered throughout their flight by supersonic combustion ramjet (scramjet) engines, allowing them to fly at lower altitudes.[250]

The key technical barriers to hypersonic missile development vary depending on the system, but primarily include materials to manage and endure heat distribution, air vehicle and flight control and electronics platforms, propulsion mechanisms

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[249] “The Hypersonic Revolution, Volume 2: From Scramjet to the National Aero-space Plane,” 1995.
[250] Dean Wilkening, “Hypersonic Weapons and Strategic Stability,” *Global Politics and Strategy*, Vol. 61, No. 5, 2019.

(particularly for cruise missiles), and testing, modeling, and simulation capabilities.[251] All platforms must be able to endure significant heat and friction buildup to ensure no degradation during flight, and likewise afford flight control and electronic operability at extremely high temperatures.[252] Furthermore, in the case of cruise missiles, scramjet engines must be protected enough to ensure that the combustion will remain lit even when air flows by at high speeds (a challenge that is likened to keeping "a candle lit during a hurricane that's about 10 to 15 times faster than the fastest hurricane you can imagine").[253]

The degree of strategic benefit for hypersonic capabilities has been a source of debate in decisions over whether to pursue the necessary technical means. Generally, the purported strategic benefits of hypersonic capabilities derive from their maneuverability and speed. Hypersonics proponents argue that these qualities allow hypersonic cruise missiles and boost glide vehicles to evade an adversary's detection, tracking, and defensive measures more easily than other types of missiles. These attributes may also allow for easier targeting of moving systems (such as mobile second-strike delivery vehicles) and the high speed and low detectability could force a truncated decision-making time for adversarial response, both of which could provide an asymmetric advantage in an escalation scenario.[254]

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[251] Richard Speier, George Nacouzi, Carrie Lee, and Richard Moore, "Hypersonic Missile Nonproliferation: Hindering the Spread of a New Class of Weapons," RAND Corporation Report: RR2137, 2017, Pp. 99-103.

[252] D. Sziorczak and H. Smith, "A review of design issues specific to hypersonic flight vehicles," *Progress in Aerospace Sciences*, Vol. 84 (2016).

[253] Keith Button, "Reducing the need for hypersonic tunnel testing," Aerospace America, May 2022.

[254] Kelley Sayler, "Hypersonic Weapons: Background and Issues for Congress," Congressional Research Services Report R45811, February 13, 2023, https://sgp.fas.org/crs/weapons/R45811.pdf.

Critics argue that hypersonics provide very limited strategic value, particularly for the United States, beyond existing ICBM capabilities. They contest that, evaluated in the context of a nation's comprehensive force structure and with respect to that of the country's primary adversaries, hypersonics have a much more limited set of use cases for actors who already have other asymmetric technological advantages over adversaries. Specifically, hypersonics provide very limited added value for a country with a robust ICBM capability unless against an adversary with a high-precision missile defense system (which no country currently satisfies).[255] These critics argue that, compared to modern ICBMs, hypersonics do not necessarily have improved maneuverability, nor do they have detection evasion capabilities that outpace stealth capabilities for other platforms.[256] Furthermore, beyond escalation operational characteristics, some analysts argue that continued U.S. hypersonics research could promote further arms-racing dynamics.[257]

In addition to lacking a revolutionary-scale disruption potential, hypersonics platforms are also certainly not emerging. Development of the technologies that support hypersonic systems have gained periodic funding interest since the 1950s. Hypersonics were first explored in the United States through the funding of Project Dyna-Soar, which aimed to develop a hypersonic space plane to achieve a variety of missions, including satellite maintenance and interference, aerial reconnaissance, and bombing.[258] The DOD funded the Air Force's Dyna-Soar research from 1957 to 1963

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[255] "U.S. Hypersonic Weapons and Alternatives," Congressional Budget Office, January 2023, https://www.cbo.gov/publication/58924.
[256] Cameron Tracy, "Slowing the Hypersonics Arms Race," Union of Concerned Scientists, 2021, https://www.ucsusa.org/sites/default/files/2021-04/slowing-the-hypersonic-arms-race.pdf.
[257] Tracy, 2021.
[258] "X-20 Dyna-Soar," National Reconnaissance Office, August 2011.

before concluding that the project faced too many technological obstacles and offered little strategic benefit beyond existing capabilities.[259] In 1963, with $660 million already sunk into the project and facing budgetary constraints, Robert McNamara ordered a review of whether the Air Force's Dyna-Soar program or NASA's Gemini program would provide the most technologically feasible option for space-based operability.[260] Reviewers recommended cancellation of the Dyna-Soar program, citing the limited mission scope and persisting technical hurdles. Hallion's hypersonic recount, which laments how the program was "callously treated by bureaucratic forces beyond the research and development community," refers to the Dyna-Soar program as a "strangled infant."[261]

Despite early impediments and lack of a clear mission, U.S. hypersonics research has garnered more significant support in recent years, following BMD buildup and breakthroughs achieved by NASA in related technologies as a result of space shuttle R&D. Following the termination of the Dyna-Soar program, dedicated hypersonics research in the United States was largely dormant until the 1990s and early 2000s.[262] During the interim period, as alluded to by Hallion's preface quoted at the beginning of Chapter 1, hypersonics technologists and capability seekers waited patiently in the bay for more auspicious winds, many pivoting to work on tangentially related technologies in civilian space programs until resumed DOD funding.[263]

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[259] Houchin, Roy. "The Rise and Fall of Dyna-Soar: A History of Air Force Hypersonic R&D." Dissertation for Air Force Institute of Technology, 1995.
[260] "X-20 Dyna-Soar," National Reconnaissance Office, August 2011.
[261] "Case II Strangled Infant: The Boeing X-20A Dyna-Soar," in "The Hypersonic Revolution, Volume 1: From Max Valier to Project PRIME (1924-1967)," 1998, https://apps.dtic.mil/sti/pdfs/ADA441127.pdf.
[262] "The Hypersonic Revolution: Volume II – From Scramjet to the National Aero-Space Plane (1964 - 1986)," Ed. Richard Hallion, https://apps.dtic.mil/sti/pdfs/ADA302634.pdf.
[263] Hallion, "The Hypersonic Revolution: Volume II," pp. 947-1255.

By the late 1990s and early 2000s, interest began to resurge along with strategic objectives to develop capabilities for targeting time-sensitive terrorist and proliferator infrastructure, Russian and Chinese progress towards developing operable hypersonic missiles in response to U.S. prompt global strike capabilities, as well as R&D breakthroughs in materials science that increased technological feasibility and with a new potential strategic application (conventional prompt global strike).[264] Under these conditions, hypersonics research has progressed more rapidly in the United States and abroad than early attempts, despite continued debates over true strategic benefit. As shown in Table A.2 in Appendix A, hypersonics research has proliferated immensely in recent years, with each branch of the military currently pursuing multiple hypersonic missile platforms. In addition to hypersonic missiles, the DOD has also announced the establishment of Project Mayhem, a new program tasked with developing a hypersonic platform capable of carrying an integrated payload over longer ranges that many suspect translates to a hypersonic bombing capability (which would be a resurrection of the Dyna-Soar program).[265]

Although the United States has had mixed success in successfully testing its hypersonics platforms, the completion of prototypes and purported success in Chinese and Russian tests provide considerable evidence that some degree of hypersonics capability is feasible.[266] However, the qualitative attributes of each of Russian and Chinese platforms is debated, as well as the ability to reach the degree of accuracy

[264] David Ignatius, "America led in hypersonic technology. Then other countries sped past," *The Washington Post*, February 3, 2022, https://www.washingtonpost.com/opinions/2022/02/03/america-led-hypersonic-technology-then-other-countries-sped-past/.
[265] Darren Orf, "Project Mayhem, The Air Force's Secret Hypersonic Bomber, Has Begun Cooking," *Popular Mechanics*, January 20, 2023.
[266] Sayler, "Hypersonics Weapons: Background and Issues for Congress."

that would be required for conventional weapon use, a more technically challenging approach that the United States is pursuing.[267]

From the early "strangled infant" to the futuristic Project Mayhem, the history of U.S. hypersonics research demonstrates that sustained interest in a capability and continued investment in the related R&D sphere over long timelines may eventually allow for production of the capability/technologies as long as interest can be sustained enough to maintain small programs that further R&D. Despite the long timeline of R&D trials and tribulations and the paucity of evidence in favor of a strategic benefit of hypersonics, invested actors built a sufficient coalition between technologists and capability seekers to sustain funding and policymaker interest over time. Critiquing this technology-centric evolution, James Acton argues, "the development of hypersonic weapons in the United States, in my opinion, has been largely motivated by technology, not strategy. In other words, technologists have decided to try and develop hypersonic weapons because it seems like they should be useful for something, not because there is a clearly defined mission need for them to fulfill."[268]

The hypersonics case also exemplifies the eventual successful alignment of technologists and capability seekers to amplify claims over hypersonic applications and capitalize on concern for U.S. technological weakness. While technologists highlighted improvements to underlying requirements, capability seekers and DL strategists have claimed Chinese and Russian systems as evidence of the United States losing science and technology leadership and strategic advantages, regardless

[267] Ibid.
[268] James Acton, "Hypersonic Weapons Explainer," Carnegie Endowment for International Peace, April 2, 2018, https://carnegieendowment.org/2018/04/02/hypersonic-weapons-explainer-pub-75957.

of whether there would be a unique strategic objective for hypersonics to satisfy within the broader U.S. force structure.[269] Intermittently, the coalition also found support and more favorable political and funding winds among DOD advocates interested in prompt conventional global strike capabilities, which would require increased speed to ensure sufficient target destruction despite delivering a non-nuclear warhead.[270] The cycles evident in both the BMD and hypersonic case studies suggest that sometimes this alignment is sufficient to overcome actors and arguments against full-scale development and deployment efforts, and sometimes there is counter-pressure that scales back (but never truly eliminates) acquisition pursuit. Each cycle of pro-development/deployment activity seems to create technological momentum, vested interests, and action-reaction dynamics with other countries that help sustain some degree of effort in the lean funding years. This sustainment makes it easier to ramp the program back up when another cycle of alignment occurs.

A third interesting feature of the hypersonics case study involves the interconnection and co-development of strategic technologies and capabilities. Even when there was no strategic rationale for developing hypersonic capabilities, important advances in civilian space flight were then repurposed for military uses under President Bush's campaign to develop prompt global. Compared to BMD, the hypersonics case represents a capability/technical system that did reach some degree

[269] For example: Ben Johansen, "US Lagging China, Russia on Hypersonic weapons: Lamborn," *The Hill*, October 18, 2022, https://thehill.com/policy/defense/3694954-us-lagging-china-russia-on-hypersonic-weapons-lamborn/; and Josh Rogin, "The most shocking intel leaks reveal new Chinese military advances," *The Washington Post*, April 13, 2023, https://www.washingtonpost.com/opinions/2023/04/13/china-hypersonic-missile-intelligence-leak/.
[270] James Acton, "Conventional Prompt Global Strike and Russia's Nuclear Forces," Carnegie Endowment For International Peace*,* October 4, 2013, https://carnegieendowment.org/2013/10/04/conventional-prompt-global-strike-and-russia-s-nuclear-forces-pub-53213.

of closure over technical feasibility, but for which the strategic effects remain minimal. This was less of a hedging strategy (i.e., continuing low-level research on dual-use capabilities to keep a military option open for the future) than it was an example of development intended for civilian use that kept relevant dual-use technologies alive. Finally, as other technologies, such as BMD evolved, rationale for hypersonics was also impacted.

Additionally, similar to the BMD case study, the long timeline indicates that hypersonics capabilities by no means rapidly emerged, but rather took decades to mature from a "strangled infant" to an operable capability (with further qualitative improvements still planned). Although hypersonics are treated as an emerging technology in contemporary security studies literature, the foundation for the technology has been under development for decades. It is only recently that the technology has gained interest because of Russian and Chinese advance compared to U.S. capabilities, in addition to development of early systems.

Finally, the hypersonics case study demonstrates an interesting degree of interconnection across technology innovations. The strategic value of hypersonics for Russia and China increased as U.S. BMD research and deployments became more prevalent. Furthermore, hypersonics afford different benefits to each of the main countries pursuing the capability – Russia, China, and the United States – depending on their relative achievements in other strategic capabilities. Neither Russia nor China have significant BMD systems and, facing U.S. deployment of BMD, ostensibly intend to use hypersonics to sustain mutual vulnerability and assure a retaliatory strike capability. The United States, which has superior conventional military and missile defense capabilities, receives less strategic benefit from hypersonics than Russia or China. This explains why the primary military rationale used for U.S. hypersonics development involves having a conventionally armed way to destroy time-sensitive rogue state and terrorist targets without using a ballistic missile that might be misperceived by Russia or China as nuclear-armed delivery vehicle.

Case 3: Satellite Imagery

The early satellite imagery case study exemplifies an even more advanced stage of closure than the hypersonic case study, as the desired initial capability was reasonably technologically feasible at the time of initial interest (compared to BMD and hypersonics), was developed fairly rapidly, and has had an indisputable impact on nuclear deterrence, strategic stability, and arms control verification that continues to this day. Since achieving this initial capability, further R&D has continued to provide qualitative improvements, including more frequent revision time, higher resolution imagery, and alternative imagery techniques. It has also led to commercialization and reduced costs for imagery satellites.

Upon relatively rapid completion of an initial prototype, satellite imagery capabilities provided an un-manned alternatives to stealth aircraft for reconnaissance missions. Even at the time the program was launched in the late 1950s (roughly concurrent with the initiation of Project Dyna-Soar), simultaneous R&D on ICBM rocketry made the proposition to launch satellites with cameras into space seem technologically feasible in a short timespan (an estimated six year production period until an initial satellite launch).[271] Since its ausipicious beginning, space-based imagery techniques have continued to evolve and provide an expanding array of strategically impactful capabilities. There has also been a substantial amount of information recorded on the decision-making influences that have guided the development of satellite imagery technologies and capabilities produced by the National Reconnaissance Office (NRO) and the Central Intelligence Agency (CIA), though many have only been declassified within the past ten or twenty years.[272]

The first U.S. satellite imagery capability was achieved through the Corona Program, which was largely based on the integration of existing technologies to be applied in new ways. For example, the Corona Program entailed application of rocketry that was already being developed for ICBM propulsion. With existing rocketry, the Corona satellite was designed to launch from Cooke Air Force Base, operate with a THOR booster to reach the lower trajectory stage, and then use an Agena upper-stage vehicle to achieve the final orbit.[273] Once in orbit, the Corona satellite would collect imagery using a rotating camera with 7.5 m resolution, with the images being printed on film. The film cassettes would then be ejected so that they

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[271] Robert Perry, "A History of Satellite Reconnaissance: Volume I," Prepared for the U.S. National Reconnaissance Office, 1974 (Declassified 2012), Pp. 3, https://www.nro.gov/Portals/65/documents/foia/docs/hosr/hosr-vol1.pdf.

[272] For example: Perry, "A History of Satellite Imagery,"; Kevin Ruffner, "Corona: America's First Satellite Program," CIA Cold War Records, 1995, https://www.cia.gov/static/corona.pdf; Ingard Clausen and Edward Miller, "Intelligence Revolution 1960: Retrieving the Corona Imagery that Helped Win the Cold War," Center for the Study of National Reconnaissance, 2012, https://www.nro.gov/Portals/65/documents/history/csnr/corona/Intel_Revolution_Web.pdf; Frederic Oder, "The Corona Story," Center for the Study of National Reconnaissance, September 2013, https://www.nro.gov/Portals/65/documents/history/csnr/corona/The%20CORONA%20Story.pdf?ver=BgSn5nPYz45EZ9O_ZF57Ow%3d%3d.

[273] Albert Wheelon, "Corona: The First Reconnaissance Satellites," *Physics Today*, Vol. 50, No. 2 (1997), pp 24-30, https://pubs.aip.org/physicstoday/article/50/2/24/409757/Corona-The-First-Reconnaissance-SatellitesBased-on.

could be collected at high altitudes by military aircraft.[274] Technological co-development of the Corona Program with more advanced technologies led to three independent early assessments viewing the technological feasibility propitiously.[275]

In addition to the co-development with existing technologies, the high feasibility assessments were also products of the low requirements placed on the program and prioritization for speed of development to achieve a very specific capability. The capability intent was for satellite imagery to replace the U-2 aircraft in performing certain reconnaissance missions. Although the U-2 could achieve overhead imaging without requiring space-based capabilities, the operating assumption among the intelligence and military communities was that the U-2 would have a "a relatively short operational life in overflying the Soviet Union – perhaps no more than a year or two," based on an expectation that the Soviets would quickly develop the means to track and shoot down U-2s.[276] (However, U.S. intelligence estimates had severely under-estimated Soviet radar capabilities and even the first U-2 flight was tracked fastidiously, delegating U-2 deployment to satisfy more sporadic missions rather than provide sustainable coverage and creating a severe capability gap.)[277] Given this expectation, a concurrent plan was established to develop satellite-based imagery capabilities, commencing with a feasibility assessment and production

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[274] "Corona Systems Navigation," National Reconnaissance Office, https://www.nro.gov/History-and-Studies/Center-for-the-Study-of-National-Reconnaissance/The-CORONA-Program/System-Information/.
[275] Kenneth E. Greer, "Corona," in *CIA Cold War Records: Corona*, Supplement, Spring 1973 (Declassified 1995), pp. 4, https://www.cia.gov/static/3d24f7019bf7e718fd1d2a5c57e6a646/corona.pdf; and Perry, "A History of Satellite Imagery, pp. 30-35.
[276] Greer, pp. 3.
[277] Alexander Orlov, "The U-2 Program: A Russian Officer Remembers," *Studies in Intelligence*, 1998-1999, https://www.cia.gov/static/c82cc78656a2f4e56f3b9a3305327ae1/U2-Russian-Officer-Remembers.pdf.

plan by the RAND Corporation as early as 1946. Throughout RAND's evaluation and production of a development plan, the feasibility for such a capability increased as ICBM propulsion research was catalyzed by a shift in Air Force requirements to prioritize ICBM research in response to the perceived missile gap and a de-emphasis on manned bombers. The Corona Project officially commenced in 1956.[278] At the time, the two largest perceived obstacles were the necessity to maintain secrecy and the requirement of a high-resolution imagery collection and transmission method that would allow for surveillance of strategically significant targets.[279] Despite these challenges, the objective was to get a satellite in orbit within one year (an extension beyond the initial, brisk 19-week period). The priority for speed to achieve immediate area-search photographic reconnaissance capability needs meant the satellite was not expected to serve as a long-term fixture.[280]

Although the Corona Program was deemed more technologically feasible than other long-shot programs like BMD systems and hypersonics, criticism arose from political concerns surrounding satellite imagery. First, Eisenhower's "space for peace" movement (as it was referred to by members of the CIA and in reference to "atoms for peace"[281]) established momentum around the avoidance of an arms race in outer space and thus created political resistance to proposals for increased funding and pursuit of satellite imagery technology development.[282] Efforts to preserve space

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[278] Greer, pp. 4.
[279] Clausen and Miller, "Intelligence Revolution 1960," pp 20-50; "The Corona Story," p.32.
[280] Greer, pp. 9.
[281] "The Corona Story," National Reconnaissance Office, 1988 (Declassified 2013), pp. 5 https://www.nro.gov/Portals/65/documents/history/csnr/corona/The%20CORONA%20Story.pdf?ver=BgSn5nPYz45EZ9O_ZF57Ow%3d%3d.
[282] Jeremy Grunert, "The 'Peaceful Use' of Outer Space?" *War on the Rocks*, June 22, 2021, https://warontherocks.com/2021/06/outer-space-the-peaceful-use-of-a-warfighting-domain/.

for peaceful purposes persisted even in the immediate aftermath of the Sputnik launch, with Henry Cabot Lodge, President Eisenhower's UN representative, beseeching an agreement to restrict military activities in space and even offering unilateral U.S. acceptance of such a treaty.[283] The second political criticism centered around issues with the consumption of limited resources in a period of budgetary constraints, and especially when the funding of military activities during a period "peaceful" space policy was incongruent with the national strategy.[284]

Political opposition to military activities in space waned quickly in the wake of Sputnik, amidst the Soviet Union's expressed disinterest in demilitarizing space and mounting U.S. domestic political pressure to engage with the Soviets in an apparent space race.[285] The U.S. National Security Council issued a revised "U.S. Policy On Outer Space," stating that while efforts were being made to mitigate the risks of arms racing in space, Sputnik's successful launch underscored military implications of space programs.[286]

This convoluted foreign and domestic political backdrop led to a complicated overlap between public and classified programs. Before the program was fully classified, it was masked by the R&D under the "Discoverer" program. The Discoverer program was publicized as an effort to develop a satellite that would afford scientific and engineering research in space. While the Discoverer was ostensibly intended for civilian applications, the underlying technical foundation also

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[283] Grunert, "The 'Peaceful Use' of Outer Space?" 2021.
[284] "The Corona Story," National Reconnaissance Office, 1988 (Declassified 2013), pp. 6.
[285] Rodger Payne, "Public Opinion and Foreign Threats: Eisenhower's Response to Sputnik," *Armed Forces & Society*, Vol. 21, No. 1 (Fall 1994), pp. 89-112.
[286] "U.S. Policy on Outer Space," National Security Council – NSC 5918, 1959, Declassified in 1991, https://aerospace.csis.org/wp-content/uploads/2019/02/NSC-5918-US-Policy-on-Outer-Space.pdf.

progressed Corona R&D. Concealing that some aspects of the program were intended for military satellite imagery applications appeased some of the political concern over militarization of space.[287]

With respect to perception, the 1958 decision to convert the project to a covert status limited – to a degree – the capability's expectations and strategic impact for technology signaling. Beyond provoking arms racing in space, it was recognized that overhead imagery would have an immense effect on nuclear deterrence and strategic stability, providing better situational awareness, asymmetrical information, and potentially better information for eventually targeting ICBMs. These concurrent developments made satellite imagery an important milestone to acquiring counterforce over countervalue capabilities, and furthermore make satellite imagery an important precursor to quantum sensing and contemporary apprehensions over the ability detect and target second-strike delivery vehicles.[288] (Although, while satellite imagery could give the United States a pretty good idea of how many ICBMs the Soviets had, and could provide some early warning of large troop movements, more real-time and frequent data would be needed to directly improve targeting accuracy.) Despite some realization of the strategic impact, classification of the program and a more modest outlook at the outset minimized the propagation of inflated expectations. Very few people were aware of the program, and those that did knew that the Corona satellite was only intended to last a couple of years before being replaced.

[287] John Sislin and Joseph Caddell, "From U-2 to Corona: How Intelligence Collection Norms Evolve," *War on the Rocks*, May 31, 2017, https://warontherocks.com/2017/05/from-u-2-to-corona-how-intelligence-collection-norms-evolve/.
[288] Keir Lieber and Daryl Press, "The New Era of Counterforce," *International Security*, Vol. 41, No. 4 (Spring 2017), pp. 34.

Despite the low expectations, the Corona satellite entered orbit in 1960 and sustained a 12-year operational period until 1972. In retrospect, the Corona Program and its successors achieved a truly new capability that likely surpassed the modest expectations established at the program's outset. From a feasibility perspective, narrow, defined capability objectives helped establish a manageable goal for the program, which was also molded around existing or near-existing technologies to afford greater speed and reduced costs. The latter suggests that, although the capability seemed to emerge quickly, it had longer technological roots than are normally associated with the program and may not have been as much of an "emerging technology" as some claim in hindsight. Classification of research on satellite imagery also limited propagation of unrealistic expectations among the general public or members of Congress and thus did not entail significant signaling threats or induce major political barriers that should otherwise be expected.

Despite classification of the program, the strategic effect of satellite imagery has been well feted. Satellite imagery capabilities that derived from the Corona Program and which afforded tracking of Chinese and Soviet weapons deployments and development are regarded by some as a decisive factor in ending Cold War[289] by assuaging concerns about a missile gap.[290] They also eventually contributed to a more effective counterforce strategy with better ICBM targeting accuracy. In 1995,

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[289] Ingard Clausen, "Afterword: Reflections on Corona, Winning the Cold War and Beyond," in *Intelligence Revolution 1960: Retrieving the Corona Imagery that Helped Win the Cold War*, Center for the Study of National Reconnaissance, April 2012, https://www.nro.gov/Portals/65/documents/history/csnr/corona/Intel_Revolution_Web.pdf.

[290] Robert McDonald, "Introduction," in *Intelligence Revolution 1960: Retrieving the Corona Imagery that Helped Win the Cold War*, Center for the Study of National Reconnaissance, April 2012. *Intelligence Revolution 1960: Retrieving the Corona Imagery that Helped Win the Cold War*, Center for the Study of National Reconnaissance, April 2012, https://www.nro.gov/Portals/65/documents/history/csnr/corona/Intel_Revolution_Web.pdf.

Admiral William Studeman, then Acting Director of Central Intelligence, reflected, "[The Corona program] allowed us to base our national security strategy – and spending – on facts rather than fear, on information rather than imagination."[291] From a technology standpoint, the initial satellite imagery development under the Corona Program has also led to a long line of satellite R&D, including new types of imagery, better resolution, more persistent monitoring capabilities, and public accessibility via private satellite companies.

Case 4: Psychic Remote Viewing

If the case of satellite imagery's inception with the Corona Program illustrates an unusual example of a classified technology program that builds on existing technologies, exceeds expectations, and satisfies a capability need in a relatively short period of time, then the historical case of psychic remote viewing serves as a striking example of the opposite. Intrigue in the application of psychic remote viewing to further expand the asymmetric information divide between the Soviet Union and the United States came at the heels of the Corona Program in the 1970s. Relative to the Corona Program's outcome, remote viewing demonstrates a departure from capability acquisition strategies supported by technological feasibility.

Compared to the previous case studies, there is significantly less publicly available information on remote viewing. Declassified information about the history of remote viewing research and activities sponsored by the U.S. government has only

[291] "Early Satellites in US Intelligence," Remarks by William Studeman, ADCI Speech, February 24, 1995, https://irp.fas.org/cia/product/dci_speech_22495.html.

surfaced in the last five years due to a large, CIA-wide declassification effort in response to a freedom of information lawsuit filed by MuckRock, which led to the release of 13 million documents.[292] Per the timeline established in the declassified CIA documents, psychic remote viewing held a remarkable 25-year funding tenure before it was allegedly discontinued in 1995.[293]

Unlike the other case studies, psychic remote viewing does not have any solid technological basis. Although the specific "methodology" employed varied across programs and personnel, the task of remote viewing generally entailed a person leveraging psychic abilities to view a remote location, determine the coordinates of an object, or infiltrate another person's thoughts to ascertain key information.[294] The CIA used the term "parapsychology" as a "catch-all label to denote the study of unexplained and seemingly inexplicable (hence paranormal) activities and phenomena."[295] The lack of a scientific and technological basis upon which to evaluate the rigor of parapsychology methods and programs, reproduce or explain findings, or establish regulations and standards for experimental protocols was often referenced as a challenge by project managers tasked with overseeing remote vision programs.[296] (Coincidentally, the inability to definitively disprove the methods or

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[292] Liat Clark, "From UFOs to its psychic Stargate tests, the CIA just dumped 13 million declassified pages online," WIRED Magazine, January 18, 2017, https://www.wired.co.uk/article/the-cia-just-dumped-13-million-declassified-pages-online.
[293] Project Stargate, the last declassified program that entailed remote viewing, was terminated in 1995. It is possible that remote viewing continued after 1995 but has not since been declassified.
[294] John Pike, "STAR GATE [Controlled Remote Viewing]", Federation of American Scientists, 2005, https://irp.fas.org/program/collect/stargate.htm.
[295] Thomas Hamilton, "Soviet and East European Parapsychology Research," CIA SI 77-10012, 1977 (De-classified in 2011), https://www.cia.gov/readingroom/docs/NSA-RDP96X00790R000100010041-2.pdf.
[296] Kenneth Kress, "Parapsychology in Intelligence: A Personal Review and Conclusions," Central Intelligence Agency, Vol. 21, No. 4, 1977, https://www.cia.gov/readingroom/docs/CIA-RDP96-00791R000200030040-0.pdf.

results through repeatable experiments was also probably a factor that shielded the program from more rigorous evaluation.)

Rather than being motivated by promising technological advancements, early programmatic interest in remote viewing stemmed from a capability requirement to improve situational awareness of Soviet asset positioning and strategic intention. Tasks for remote viewing included: penetration of inaccessible targets, acquisition of science and technology information, cuing for other intel collection methods, anticipation of imminent hostilities, discrimination between nuclear and non-nuclear targets, and human intelligence collection.[297]

Efforts to achieve reliable remote viewing capabilities were also fueled by concerns regarding Soviet activities. U.S. government-sponsored remote viewing research began in the early 1970s. It was galvanized by claims from the intelligence community that the Soviet Union was conducting research into psychotronics, based on the identification in 1969 of a new Soviet facility to investigate "black magic."[298] Assessments produced by the CIA and Defense Intelligence Agency (DIA) concluded that "the Soviets will continue their attempts to develop paranormal abilities of gifted subjects to the point that these abilities can be used successfully in applied tasks," including remote viewing, telepathy, and mind control.[299] Likely due to limited knowledge about parapsychology within the intelligence institutions at the time, the

[297] "Project Sun Streak," Defense Intelligence Agency, https://nsaarchive2.gwu.edu/NSAEBB/NSAEBB534-DIA-Declassified-Sourcebook/documents/DIA-21.pdf.
[298] Hamilton, "Soviet and East European Parapsychology Research."
[299] Hamilton, "Soviet and East European Parapsychology Research." and John LaMothe, "Controlled Offensive Behavior – USSR," Defense Intelligence Agency – T72-01-14, July 1972, https://www.cia.gov/readingroom/docs/CIA-RDP96-00788R001300010001-7.pdf.

suspected Soviet ambitions were then projected onto U.S. capability interests and were used to sculpt U.S. acquisition plans, particularly for remote viewing.

Estimates of Soviet research launched a long series of U.S. parapsychology programs across intelligence and defense agencies. The CIA initiated parapsychology research with Project SCANATE in 1972. It quickly discontinued the program in 1977 when one of its main remote viewers, Patrick H. Price, died. In addition to the loss of a core pillar of talent, the majority of the CIA program's research portfolio was also reportedly transitioned to the DIA and Army INSCOM due to an internal scandal. The CIA program that formerly handled parapsychology research had to be disbanded due to controversy related to other activities. A DIA report notes, "this program was the same one that was alleged to have planned assassination plots" although also continues with, "DIA postulates that CIA will be conducting an 'official' collection program in the future when the political climate is better."[300]

Following SCANATE, the DIA and the Army provided sustained funding to parapsychology efforts through a series of projects aimed at defining underlying methodological approaches and developing talent acquisition strategies. This series of parapsychology projects, discussed in greater detail in Table A.4, were together referred to as STARGATE. STARGATE concluded in 1995 when the American Institutes for Research completed a government-sponsored evaluation of remote viewing research techniques and operational utility for intelligence activities.[301] The

[300] Frederick Atwater, "Gondola Wish," Letter to Chief OPSEC, 1978, https://www.cia.gov/readingroom/docs/CIA-RDP96-00788R002000160011-2.pdf.
[301] Michael Mumford, Andrew Rose, and David Goslin, "An Evaluation of Remote Viewing: Research and Applications," Prepared by The American Institutes for Research, September 29, 1995, https://www.cia.gov/readingroom/docs/CIA-RDP96-00791R000200180006-4.pdf.

evaluation concluded that: “it remains unclear whether the existence of a paranormal, remote viewing has been demonstrated,” and, “further, even if it could be demonstrated unequivocally that a paranormal phenomenon occurs under the conditions present in the laboratory paradigm, these conditions have limited applicability and utility for intelligence gathering activities.”[302]

Throughout the 25-year tenure of government-facilitated parapsychology research and well before the 1995 cancellation, internal and external skepticism was voiced frequently. Even in the 1970s, around the time of STARGATE’s inception, external skeptics argued that remote viewing was unreliable and untestable from a methodological standpoint, and that the existence of parapsychology had yet to be proven from a feasibility standpoint.[303] This skepticism was substantiated by an internal review of the program conducted by the CIA in 1975, in which a remote viewer was tasked with viewing and providing information about the Soviet Semipalatinsk test site (at the time referred to in the CIA as URDF-3). Following the test, the CIA program manager concluded, “the experiment to determine the validity of Pat Price’s remote viewing of URDF-3 appears to be a failure,” noting that the psychic had evaded answering several key questions and provided numerous wrong answers. Furthermore, the reviewer concluded that operationalizing the practice would be not only challenging, but also risky as CIA personnel could be sent on operations with entirely incorrect information. In the final sentence of his report, the reviewer suggests the possibility of intentional cheating by the remote viewer under

[302] Mumford, Rose, and Goslin, 1995, pp. E4.
[303] For example: “The Magician and the Think Tank,” *Science*, March 12, 1973, https://www.cia.gov/readingroom/docs/CIA-RDP96-00787R000400100023-4.pdf;

evaluation, recommending, "I am not competent to judge the reliability of the PSE [psychological stress evaluator] as an aid to lie detection, but I think the tapes should be subjected to such a test."[304]

Despite criticism and poor performance evaluations, remote viewing programs continued to receive funding for 25 years, shielded by the classification of the research, and supported on the basis that the research was deemed as passive, inexpensive, and having no known countermeasures.[305] Similar to the case of the Corona Program, parapsychology research was classified in early R&D stages. However, unlike Corona, classification of parapsychology research was justified out of concerns that the programs would *negatively* impact the credibility of the CIA and the researchers involved. John McMahon, Director of the Office of Technical Service and Sayre Stevens, Director of the Office of Research and Development at the CIA urged: "Involvement with fraudulent experiments, publication of poor experimentation and open association with CIA would be deleterious to the careers of the investigators and the credibility of the Institute. For this effort, we recommend a secret level contract…"[306] Despite the fact that the program sparked concern over institutional prestige, in addition to questions over methodological rigor, the government decided to continue funding remote viewing programs, reasoning that such research was a low risk, high reward endeavor. One report claimed that eventual

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[304] "An Analysis of a Remote-Viewing Experiment of URDF-3," Central Intelligence Agency – RDP96, 1975, https://www.cia.gov/readingroom/docs/CIA-RDP96-00791R000200240001-0.pdf.
[305] "PSI Operational Capability," Central Intelligence Agency – RDP-96, https://www.cia.gov/readingroom/docs/CIA-RDP96-00788R001100110007-2.pdf.
[306] John McMahon and Sayre Stevens, "Office of Research and Development and Office of Technical Service Paranormal Perception Research Project," CIA, 1973, https://www.cia.gov/readingroom/document/cia-rdp79-00999a000300100032-6.

remote viewing capabilities could afford a variety of benefits, including: passivity – it could be conducted without detection; low-cost – just the salary of the psychics; and lack of a known defense – neither time, distance, target, size, nor degree of difficulty had apparent effects on remote viewing success/validity, which was unascertainable or low under any circumstance.[307]

With all these factors combined, the remote viewing program provides a fascinating example of a null case study, in which a capability is sought despite complete lack of scientific basis or technical foundation. It offers a distinct contrast to the positive role of classification in the satellite imagery: instead of constraining expectations and external scrutiny long enough to acquire the desired capability, classification allowed secret parapsychology programs to continue without independent assessment long after internal evaluation found them to be useless and potentially dangerous.

Unlike BMD and hypersonics, which also encountered significant skepticism due to technical hurdles and strategic/political consequences, but which still yielded some capability results after decades of research and had significant, even if unintended, strategic effects due to Russian and Chinese reactions to U.S. development efforts, remote viewing had no technological basis to produce effects from application or signaling that the capability was being pursued. Also, unlike the BMD and hypersonics case studies, the parapsychology field does not have a sizeable community of technologists in academia, industry, or civil society, and lacks clout in

[307] CIA- RDP96-00789R003300210002, https://www.cia.gov/readingroom/docs/CIA-RDP96-00789R003300210002-1.pdf.

Congress, which inhibited the development of a successful coalition. Although remote viewers were obviously interested in sustained funding and support, the community never surpassed a handful of viewers nationwide. Furthermore, while classifying satellite imagery research helped the CIA to restrain technological propaganda until a successful prototype was launched, publications continued to rebuke the application of parapsychological research being conducted for defense purposes. In addition to failing to mitigate external discussion about the capability, classifying work on remote viewing actively increased the challenge of exercising institutional scrutiny and oversight that could have been used to restrain and halt investment in remote viewing research at much earlier stages.

Case 5: Isomer Weapon (Stimulated Isomer Energy Release)

Like the remote viewing case study, the isomer (or hafnium) weapon case study also involves the pursuit of a capability that was never attained. Although the isomer weapon concept had more technical basis than remote vision ever did, it had arguably less strategic rationale. Although there is little published information on the strategic rationale for developing an isomer weapon, motivation was organized around the potential to release large amounts of energy without fission or fusion. Theoretically, this could afford a weapon with high-energy gamma rays and an explosive yield more powerful than conventional weapons, but with a lower yield and markedly less fallout than nuclear weapons.[308]

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[308] David Hambling, "Gamma-ray weapons could trigger next arms race," *NewScientist*, August 2003, https://www.newscientist.com/article/dn4049-gamma-ray-weapons-could-trigger-next-arms-race/.

Skepticism over the feasibility of developing such a weapon centered around challenges with reliably stimulating isomer energy release even in a laboratory setting, and doing so safely in an operational setting. From a physics perspective, there was limited certainty over the ability to induce triggering; from a deployment perspective, concern revolved around issues in harnessing the technology for safe use. Despite skepticism from well-respected physicists in and out of the government, research funding supported stimulated isomer energy release research for decades, starting at least as early as the late 1970s and continuing through the early 2000s (see Table A.5 in Appendix A). Once again, a key motivation was to prevent technological surprise as the Soviet Union simultaneously pursued isomer weapons, underscoring the power of technological hedging claims in guaranteeing resource allocations for a new technology or capability program.

Isomer weapons are a capability that rely on a technical process called Stimulated Isomer Energy Release (SIER), a more technical term which is often used in government documents to discuss isomer or hafnium weapons (the latter term is a reference to the hafnium material that is deemed most suitable for isomer weapons). Nuclear isomers are atoms with metastable nuclei. When isomers decay to their ground states, they release energy in the form of electromagnetic radiation, with energy levels that vary depending on the specific isomer.[309] One element that particularly enticed physicists was the hafnium-178 isomer, which has a half-life of 31 years and releases 2.5 MeV of energy, mostly in the form of gamma rays, when it

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[309] Philip Walker and James Carroll, "Ups and Downs of Nuclear Isomers," *Physics Today*, Vol. 58, No. 6 (2005), pp. 39, https://physicstoday.scitation.org/doi/10.1063/1.1996473.

decays. [310] (This is a significant amount of energy compared to other metastable atoms, although less than the 200 MeV released by uranium-235 and plutonium-239 fission processes). Whether it is theoretically *and* experimentally possible to artificially trigger the decay process and stimulate isomer energy release is a question that is pervasive to all SIER research, raising skepticism over feasibility.

Believing the answer to this question to be yes, isomer proponents generally converged on arguments that SIER research would lead to new energy production methods and weapon capabilities, though some claimed potential applications could extend much further. In an application for funding, one of the leading isomer researchers, Hill Roberts, claimed the utility for isomers to be wide-ranging, from energy storage devices with “far greater energy densities than conventional devices” to countering bioweapon threats, space propulsion, oncology treatments, and gamma ray lasers.[311] From the perspective of strategic utility, isomer weapons garnered the most interest of all applications. Despite the scant technical depth of isomer weapon information, the argument was that they theoretically would have introduced a challenging gray space between conventional and nuclear weapons, generating a debate over whether isomer weapons should be classified as nuclear weapons (sometimes referred to as “micro nukes”).[312]

The strategic significance of this ambiguity was a main driver for SIER research programs. DL proponents viewed isomer weapons as allowing for greater deterrence flexibility, while AD proponents were concerned that isomer weapons may

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[310] Andy Oppenheimer, “Mini-Nukes: Boom or bust?” *Bulletin of the Atomic Scientists*, Vol. 60, No. 5 (September/October 2004), pp. 12-14, https://journals.sagepub.com/doi/pdf/10.2968/060005004.
[311] SBIR Application: https://www.sbir.gov/sbirsearch/detail/316695.
[312] Hambling, 2003.

make the escalation to nuclear weapon use more likely by providing a more usable intermediate option. Another strategic consideration fleetingly entertained among a few capability seekers and policymakers was whether isomer weapon testing would permit testing below the threshold defined in the text of the Comprehensive Test Ban Treaty, a question which generated some interest at the State Department.[313]

These debates were all theoretical and took place among the very small circle of people aware of isomer research. The government's interest in isomer technologies were never publicly defined, likely due to the lack of substantiated evidence for technical feasibility and strategic rationale for weapons applications Further, because isomer weapons never really bridged the credibility gap to establish a feasible future strategic application, there is very little evidence that technological hedging of the capabilities even produced a strategic impact. Some articles reference a "new arms race" when discussing isomer research, though these references are scant, and such concerns never really took off. [314]

Even in early narratives, the idea that operable isomer weapons could ever be successfully developed was approached with skepticism. The inception of the idea for isomer weapons and SIER methodology dates back to vague references amidst an intense research period on gamma ray engineering that took place in the 1960s. Following the 1960s, serious isomer research went dormant due to lack of technical progress until the late 1980s, at which point renewed interest in gamma ray lasers introduced a new Pentagon funding stream. At that time, physicist Carl Collins, who

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[313] Oppenheimer, "Mini-Nukes: Boom or bust?" 2004.

[314] Discussed in Peter Zimmerman, "The Strange Tale of the Hafnium Bomb: A Personal Narrative," APS News Vol. 16, No. 4, June 2007, https://www.aps.org/publications/apsnews/200706/backpage.cfm.

had spent the majority of his physics career researching SIER, began to accrue renewed interest in isomer weapons and SIER, promising that 50 researchers worldwide were committed to furthering gamma ray laser research.[315] Yet, even in this early narrative, articles on the surging interest over gamma ray lasers also were paired with skeptical commentary from members of national institutions, such as national laboratories.[316] Nearly concurrent with Collins' initial publication, a JASON report concluded that isomer research "had no rational nor credible analysis" to prove that the resulting capability could be feasibly produced.[317]

Because of the coupling of isomer research with other nuclear physics research, a steady contingent of stalwarts grew, many of whom benefitted from direct or tangential R&D resource allocations from SIER projects. The initial spark that began to pique the government's renewed interest in an isomer weapon was a series of reports that suggested production of the underlying technology may be more feasible than previously predicted. In 1999, an article published in *Physical Review Letters*, a reputable peer-reviewed journal, summarized the methodology and results of an experiment that claimed to have induced gamma ray emissions from a hafnium source through irradiation with a used dental x-ray machine.[318] A steady flow of additional technical publications claiming greater feasibility than expressed in the

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[315] D. E. Thomsen, "Pumping Up Hope for a Gamma Ray Laser," *Science News*, Vol. 130, No. 18 (1986), p. 276, https://www.jstor.org/stable/pdf/3970900.pdf?refreqid=excelsior%3A7c0625b882ee3907ff99a0135340e69c&ab_segments=&origin=&initiator=&acceptTC=1.
[316] Thomsen, "Pumping Up Hope for a Gamma Ray Laser," p. 276.
[317] "High Energy Density Explosives," JASON and The MITRE Corporation, JSR-97-110, October 1997, https://irp.fas.org/agency/dod/jason/he.pdf.
[318] Carl Collins, F. Davanloo, M. C. Iosif, R. Dussart, and J. M. Hicks, "Accelerated Emission of Gamma Rays from the 31-yr Isomer of ^{178}Hf Induced by X-Ray Irradiation," *Physical Review Letters*, January 25, Vol. 82, No. 4 (1999), https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.82.695.

JASON report led isomer weapon SIER research proponents to receive more funding from the Bush administration through 2006, at which point a tri-laboratory report published by Argonne, Lawrence Livermore, and Los Alamos National Labs concluded that isomer research was not substantiated (the Bush administration also faced significant pressure to decrease military spending after 2006 due to the war in Iraq and Democrats taking both houses of Congress).[319]

Despite technical skepticism, isomer weapon research received funding for years, even as the technology was further rebuked by respected physicists and engineers within and outside of the government. In *Imaginary Weapons*, Sharon Weinberger recounts the history of the isomer weapon's progression through the defense industrial complex. She highlights how DARPA continued to fund isomer research despite the fact that Carl Collins' findings could never be replicated (much like remote vision research) and were even proven to be highly unlikely. But she also dissects how DARPA's failure to provide internal oversight arose due to social and parochial interests, financial and otherwise, within the agency and the funding processes.[320] In the early 2000s, internal financial constraints required that DARPA cut funding for isomer research down from $30 million to $7 million. But procedurally, DARPA was allowed to specify which aspects of the program would be cut. It decided to discontinue the research of a scientist who was supposed to verify repeatability of isomer experiments – and who had only yielded null results in attempting to duplicate Collins's triggering experiments – which meant that the

[319] A. Hazi, "Testing the Physics of Nuclear Isomers," Lawrence Livermore National Laboratory, January 27, 2006, https://www.osti.gov/servlets/purl/883612; And: https://www.llnl.gov/news/physicists-challenge-reports-accelerated-decay-nuclear-excited-state.
[320] Sharon Weinberger, *Imaginary Weapons*, 2006.

program dismissed a critical oversight mechanism in its internal review process.[321] DARPA programs were also shielded from scrutiny by national labs and respected scientists because of the institutional objective to both prevent technological surprise from an adversary *and* seek technological advantages for the United States. At the time, Tony Tether, DARPA director, qualified continued isomer research:

> We know that there are other countries, such as the Former Soviet Union, interested in Isomer weapons. Our research effort will help us answer the question of whether this is a threat we need to worry about. On the other hand, having the capability ourselves would give the U.S. a capability that would truly be revolutionary given our ability to deliver small munitions with incredible precision... The U.S. could use this capability as a deterrent.[322]

Even after Weinberger's exposé on isomer weapons, isomer loyalists continued to affirm the merit of isomer research. They claimed that Weinberger's findings and argument misconstrued the research progress and motivation. Upon his retirement in 2009, Tony Tether vaguely referenced some derivative research gains after the publication of *Imaginary Weapons* to rebuke Weinberger's portrayal. He argued that the importance of funding programs like the isomer bomb research is that they push DARPA's research to the brink:

> One program that really got a lot of press was this program we had on isomers – hafnium – the golf ball that could be a big bomb and stuff like that. And a woman wrote a book. I forget what she called it. It was something along the lines of *Weird Science*, or, you know, *Fake*

[321] Weinberger, *Imaginary Weapons*, pp. 196.
[322] Weinberger, *Imaginary Weapons*, pp. 193-194.

> *Science*, or something like that. She argued that we should have known that this couldn't be done. Well it turns out that she's wrong, and over time we've shown that it does work. It doesn't work the way we thought it would work, but it does work, and that led us to other situations.[323]

Key takeaway from the isomer weapon saga include the resilience of long-shot technology projects for the sake of technology hedging, and the importance of having both internal and external review of technology development efforts. Only after significant external review by the JASON committee and national labs, lack of progress with dedicated resources, and conditions of budgetary constraint did the isomer research community suffer its fatal blow (at least in public records). The factors that permitted isomer research to continue despite skepticism include: DARPA's institutional structure and mission, propaganda by physicists biased toward their own research, and hedging due to Soviet research perceptions. Both Tether and Weinberger's accounts illuminate the effects of DARPA's mission to seek out and support long-shot research, with Tether applauding it and Weinberger cautioning that it creates an institutional landing spot for energetic scientists. In the isomer weapon case, the key technical boosters included a small, but powerful coalition of scientists who had powerful ties to politicians and research institutions that afforded them better access to funding sources. Finally, and likely the initial and underlying impetus for the isomer research, was the consistent referral to Soviet research on the subject.

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[323] "Interview with Dr. Tony Tether," February 13, 2009, p. 409, https://www.esd.whs.mil/Portals/54/Documents/FOID/Reading%20Room/DARPA/15-F-0751_DARPA_Director_Tony_Tether.pdf.

Hedging against technological surprise with an adversary created an added incentive for research even if technical progress seemed unlikely. On hedging, Weinberger reflected after writing her book: "Is it worthwhile to invest in defenses against these technological surprises? What do we mean by 'surprise'? And what can we reasonably expect such defenses to do?"[324]

Summary of Findings

Together, the case studies shed light on the myriad of social, strategic, and technical factors that contribute to acquisition and funding decisions that can be analyzed using the integrated analytical framework developed in Chapter 3. Across the board, case studies illustrate how long innovation timelines are, even for so called "emerging technologies." Throughout these timelines case studies also highlight the long lag time in decisions once momentum is established for a specific technology or capability, the importance of a sufficient actor coalition in favor of developing a certain technology, institutional mechanisms that support information flow (or impede it), and oversight mechanisms that ultimately contribute to the halting of a technology that fails to yield progress. However, another higher-level finding from the historical survey at large was that each evolution of research on individual technologies/capabilities was unique, suggesting that there really is no "one size fits all" process – or hype cycle[325] – that can be neatly applied to all technologies.

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[324] Sharon Weinberger, "Scary Things That Don't Exist: Separating Myth from Reality in Future WMD," The Stanly Foundation Policy Analysis Brief, June 2008, https://stanleycenter.org/publications/pab/WeinbergerPAB08.pdf.

[325] For example, this is proposed by the Gartner Hype Cycle: https://www.gartner.com/en/chat/gartner-hype-cycle.

First, in order for R&D on a technology or capability to commence, sufficient support from both the technology and capability communities must be established. Interest in a new capability may arise when a technology innovation allows for a capability that was previously viewed as unattainable. The case study of satellite imagery illuminated this phenomenon when research on ballistic missile technology innovation increased the feasibility of launching satellites to achieve overhead imagery. Likewise, in the case of hypersonics, rocketry research catalyzed interest in developing hypersonic platforms, resulting in the technical and ally coalition seeking out missions for the technologies so they could connect to capability seekers that might be interested in supporting the research.

Sometimes interest in a capability – or perceptions that a capability could someday be feasible– can arise absent of a proven technology innovation. As the cases of remote viewing and isomer weapons indicate, this can occur when adversaries are suspected to be pursuing a technology innovation (or capability). In the cases of remote viewing and isomer weapons, some strategic appeal was associated with capabilities, at least among small but well-connected groups. However, the more significant catalyst for funding and research initiation was the threat that Soviets were also funding psychic and isomer weapon research. Because of the perceived competition, skepticism that did arise was overridden among decision-makers by the compromise to pursue technological hedging (and avoid technological surprise). In these cases, there are also often barriers in information flow that prevent wider access to necessary information that skeptics or oversight stakeholders could use to critically appraise the viability of the capability.

Once government R&D commences, funding is likely to continue for a very long time, even if the technology is failing to satisfy capability needs. As was seen in the case of BMD, hypersonics, and remote viewing, technical skepticism was raised early on, but was overlooked for the sake of capability interest and under the conditions of limited R&D funding. Many of the institutional mechanism that facilitate this research momentum are discussed in the analytical framework presented in Chapter 3. A key factor noted throughout the case studies that facilitated longer gestation periods was the classification or segmentation of information.

In *Imaginary Weapons*, Weinberger argues that classification of military programs related to advanced science produces two deleterious effects: reduced quality of science through lack of peer-review and "conspiracy theories" – or inflated expectations – arising from incomplete information provided to the public on the technologies and capabilities being tested.[326] With respect to the actor network, incomplete information flow can afford greater power to actors and institutions directly connected to, and invested in, technology production. Often the actors responsible for providing oversight do not have sufficient information to completely override policy decisions made about a certain technology. In the case of isomer weapons and remote viewing research, classification of information was directly cited as a way to allow for unfettered technology development despite opposition from well-respected scientists who viewed classification of information as prolonging interest and funding for programs that would not be able to meet established expectations.

[326] Weinberger, *Imaginary Weapons*, p. 171.

Beyond classification, segmentation of information among epistemic communities can also result in capability seekers not being aware of technical issues and technologists not being aware of the mission requirements that would be needed to satisfy a capability gap. In the case of isomer weapons, most policymakers were unable to go to labs to evaluate the methods or tests; likewise, isomer technologists failed to consider operational requirements for isomer bombs that would make it nearly impossible for detonation without accepting casualty of the operator. (Some of the scientists refused to consider military applications entirely). These dynamics are evaluated in much more detail in the quantum sensing analysis.

R&D investments can further be amplified and elongated through coalition-building among the actor networks. When technologies sustain adequate coalitions of support, or when support is expressly codified, then decisions to halt technological development become even more politicized. In the case of isomer weapons, scientists looked towards various support avenues, including those impacted by the CTBT, beneficiaries of isomer production, and even foreign scientists to establish a coalition. Likewise, the BMD community accrued an enormous coalition of support over its long timeline through engaging diverse science, engineering, and policy communities, and ultimately gained immense, and likely irreversible institutional power through the establishment of the Missile Defense Agency.

Often the best method to check these processes is through credible, influential technical experts who are independent of the institutions advocating for technology advancement to achieve some new military capability. Unfortunately, this group of actors faces a lot of institutional challenges, as discussed in Chapter 3. Because scientists who work on an issue are often biased to inflate expectations for funding incentives, there are typically fewer scientists who have the training to deflate unrealistic expectations that will not be incentivized to overlook issues. Scientists attempting to provide more realistic, unbiased expectations are also often working outside of the projects and are therefore not privy to certain information on political elements, classified technology developments, or capability-based requirements – a fact often used to refute their technical analyses. Finally, even when technical people highlight limitations of technologies, the objectivity of their analyses may be questioned, and their findings politicized, as was seen in the BMD case.

Given the network of actors with vested interest that is easily established, how can oversight be acted upon to reverse technology decisions? Ultimately, the case studies show that many factors must align to objectively evaluate the motivations and viability for military technology programs. First, budgetary constraints must impact organizations responsible for funding R&D – this could either occur due to overall budgetary shrinking or reallocation to other more valuable technology areas. Second, external and internal reviews must be conducted and critically evaluated in order to ascertain that skeptics are accurate, and establish consensus that a technology could not be leveraged by an adversary (or the United States) – deflating the technology hedging mechanism.

But additionally, closure of a program may be hastened if a net strategic deficit from the research is identified. One example common for new technologies is the incentivization of arms racing. The legitimacy of these effects are not universally agreed upon though, and thus are reliant on the strategic perspectives of policy members that are in office at a given time. This was exemplified in the BMD case study in the 1960s and 1970s as well as the termination of remote viewing activities in the 1990s. It is also important to note, however, that even when funding lulls occur, coalitions may wait in the wings to resurface under more auspicious budgetary circumstances or in more favorable political circumstances. Taken together, these findings suggest that once pandora's technology box opens, it changes the research community and strategic environment in ways that makes it very difficult to close the box completely.

Conclusion

By illuminating the processes through which the U.S. government evaluates R&D opportunities and the effects of these decisions, these cases provide insight into that could help the U.S. government avoid responding to inflated expectations and resulting strategic effects. First, program reviewers and policymakers rarely evaluate or formally recognize possible incentives an actor may have for promoting propaganda on a given technology. Implicit biases of individual scientists may be manipulated to support certain strategic postures or political groups.

Second, unbiased scientists that can provide oversight that is necessary to establish realistic expectations for a technology. Scientist groups like JASON, the national labs, and the American Academy of Arts and Scientists (AAAS) have each featured prominently in the case studies (either with direct in-text reference or reference in Appendix A), providing important reviews to facilitate oversight on technology and capability programs. The historical case studies indicate that these reviews should be mandated at various intervals for all technologies and capability systems that receive significant funding or that are under consideration for large funding proposals. Intermittent reviews on over-the-horizon technologies could also provide certainty that the government will not encounter down-stream technological surprise scenarios as innovation progresses in related topics, which would assuage these concerns without requiring that the technology or capability be hedged.

These factors also highlight the importance of rigorous pre-emptive analyses before funding certain types of research. In the case of satellite imagery, RAND conducted a multi-year assessment that was also required to develop a project plan, ensuring that all potential feasibility issues were resolved before commencing development. Once research begins, coalitions and actor networks naturally form and can create artificially positive feedback loops in favor of a technology's production. Similarly concerning, these feedback loops can stimulate research by other countries, and potentially among adversaries, on the technology or a countermeasure. Thus, early research should not be treated through hedging, because even hedging still may produce strategic effects. These effects must be recognized in order to facilitate much heavier scrutiny early on in research.

Ultimately, these findings raise a number of questions for programs like DARPA, which are intended to fund "high risk, high reward" projects. On one hand, these funding avenues can provide important resources for technologies that may not be supported by private or mainstream research funding mechanisms. But on the other hand, such programs can also facilitate outsized assertions for the science and technology areas that are most prone to coalition-building because they are connected to high rewards with less oversight. Others have highlighted this risk, such as Weinberger, and so more scrutiny should be given to evaluate the net positive value that these programs have provided throughout their tenures, and to specify where they have erred.

Finally, given the long development timelines, the case studies indicate that technologies rarely “emerge” rapidly. Forgoing the impulse to perceive threats of a “surprise” affords more time to define and assess key developmental indicators. Most of the technologies and capabilities surveyed here have had decades-long innovation periods before possibly achieving a significant strategic advantage. Thus, if claims are made about an adversary developing a disruptive capability, the government can look back in time for indicators to determine whether progress made is meaningful and likely to be strategically significant.

The long timelines evaluated in this survey also indicate a significant degree of interconnection between different technology and capability areas. As research progresses on one technology, such as ICBM rocketry, it may lead to advances in related capabilities, such as BMD, hypersonics, and satellite imagery. Thus, greater attention to interconnections between related research communities can provide valuable indicators of certain innovations that may trigger cascades of critical capabilities which can be monitored.

The findings from these historical case studies highlight the degree of scrutiny that should be given to current claims made about the technological feasibility and strategic effects of quantum sensing technologies. Chapters 5 will evaluate the technological feasibility of developing certain types of quantum sensors and the corresponding capabilities, while Chapter 6 will assess competing claims about strategic effects. Chapter 7 will then combine findings from Chapters 3 and 4 and Chapters 5 and 6 to evaluate the socio-technical factors likely to form acquisition interest and expectations around quantum sensing capabilities and apply STS literature theories to identify underlying mechanisms. Finally, Chapter 8 will identify policy options that could improve rational evaluation of technical potential and treatment of new technologies like quantum sensing.

Chapter 5: Quantum Sensing Technical Assessment

"I think I can safely say that nobody really understands quantum mechanics."
-Richard Feynman[327]

"Knowledge is indeed a network wherein different kinds of test are performed against differently constructed backgrounds, with no one test – not even 'use' – and no one background being accepted by all as the ultimate arbiter."
-Donald Mackenzie[328]

Quantum sensing is a branch of emerging technologies that is rapidly capturing interest and creating concern in nuclear deterrence and strategic stability dialogue. Sensing technologies are a subset of the larger category of quantum technologies, which also includes quantum communication and computing technologies. Quantum sensors use quantum phenomena to improve measurement of physical properties, such as magnetic field strength, electric field strength, gravitational field strength, acceleration, time, rotation, etc. While quantum computing and quantum communication, which rely on larger and more intricate hardware infrastructure as well as more advanced techniques, are still at fairly early stages of research and development, quantum sensing technologies have already

[327] Sean Carroll, "Even Physicists Don't Understand Quantum Mechanics," *The New York Times*, September 7, 2019, available at https://www.nytimes.com/2019/09/07/opinion/sunday/quantum-physics.html.
[328] Donald MacKenzie, *Inventing accuracy: an historical sociology of nuclear missile guidance*," MIT Press (Cambridge, MA 1990), pp. 378.

entered the stage of commercialization and early deployment.[329] Because they are at a more advanced stage of development, their application for defense and security use-cases, and thus the implications they will impose in these domains, are more imminent, compared to communication or computing. Furthermore, given that there has been much more closure around quantum sensing and possible application areas and scopes of expected impact than for either quantum computing or communication, there is also better basis for reasonably predicting feasibility and limitations of their applications.[330]

Although quantum sensing has had a longer research timeline than quantum computing or quantum communication, major research milestones in the broader fields of quantum information science and quantum engineering have accelerated quantum sensing development recently, igniting policymaker interest. Technically, quantum physics has been employed for decades to achieve an array of sensing and measurement feats, including nuclear magnetic resonance (NMR) and scanning tunnelling microscopy.[331] However, newer techniques and materials have given rise to sensors with more acute precision, increased operability outside of lab settings, and

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[329] "Bringing Quantum Sensors to Fruition," United States Executive Office - A Report by the Subcommittee of Quantum Information Science of the National Science And Technology Council (March 2022), pp. 9, available at https://www.quantum.gov/wp-content/uploads/2022/03/BringingQuantumSensorstoFruition.pdf.

[330] It is harder to get a clear idea of the scope of impact that quantum communication and quantum computers will have given that the potential extent of their capabilities is not well determined yet. This process of development and closure around a technology as it evolves is most often linked to the Gartner Hype Cycle. See A. Linden and J. Fenn, "Understanding Gartner's Hype Cycles," Gartner R-20-1971 (2003), available at http://ask-force.org/web/Discourse/Linden-HypeCycle-2003.pdf. It is also addressed in broader science and technology studies literature, including Andy Stirling, "'Opening Up' and 'Closing Down': Power, Participation, and Pluralism in the Appraisal of Technology," *Science, Technology, and Human Values*, Vol. 32, No. 2 (2007).

[331] Iulia Georgescu and Franco Nori, "Quantum technologies: an old new story," *Physics World*, Vol. 25: No. 5 (2012), available at https://iopscience.iop.org/article/10.1088/2058-7058/25/05/28/pdf.

better size, weight, power, and cost (SWaP-C) parameters. Because these changes have increased the utility and availability of quantum sensors, policymakers and analysts have grown interested in identifying potential applications that could satisfy national security capability needs. A few existing analyses have highlighted implications of advances in quantum sensing for nuclear deterrence. One prevailing narrative is that quantum sensing, and other emerging technologies, could undermine secure second-strike capabilities through affording increased detection and targeting capabilities.[332]

There is a gap in existing literature with respect to technical feasibility and projected timelines for deployment in use-cases relevant for nuclear deterrence that has impeded thoughtful policy analysis of how much improvement quantum sensing is likely to provide over existing detection and targeting methods, how soon such advanced capabilities are likely to be in the hands of the United States and/or its strategic rivals, and what the United States should do now to minimize negative effects on strategic stability. As a recent publication by the RAND Corporation highlights, there is continued uncertainty over quantum technology development, even with a thorough knowledge of the industrial base.[333] The RAND report surveys both the U.S. and the Chinese quantum industrial bases to identify key actors, the

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332 For example, discussed both in: Rose Gottemoeller, "The Case Against a New Arms Race: Nuclear Weapons Are Not the Future," *Foreign Policy* (August 9, 2022), available at https://www.foreignaffairs.com/world/case-against-new-arms-race.
And in: Rose Gottemoeller, "The Standstill Conundrum: The Advent of Second-Strike Vulnerability and Options to Address It," *Texas National Security Review*, Vol. 4, No. 4 (Fall 2021), available at https://repositories.lib.utexas.edu/bitstream/handle/2152/90577/TNSRVol4Issue4Gottemoeller.pdf?sequence=2&isAllowed=y.

333 Edward Parker, Daniel Gonzales, Ajay Kochhar Sydney Litterer, Kathryn O'Connor, Jon Schmid, Keller Scholl, Richard Silberglitt, Joan Chang, Christopher Eusebi, and Scott Harold, "An Assessment of the U.S. and Chinese Industrial Bases in Quantum Technology," RAND - Research Report (2022), available at https://www.rand.org/pubs/research_reports/RRA869-1.html.

technology focus of each actor, and the resources that are supporting actors in each sector.[334] Despite this expansive network of information, the authors conclude that there is too much uncertainty in the timeline for development to seriously consider export controls or other governance mechanisms.[335] While these technology-oriented reports are useful for elevating the issue of quantum technologies, ultimately through omitting even reasonable timeline or estimates for specific capabilities of concern, they fuel the ambiguity and uncertainty regarding policy implications, and thus enable deviations in interpretations stemming from competing deterrence narratives or institutional/organizational biases.

This chapter provides a capability-driven technical assessment of feasible quantum sensing improvements to inform and critique assertions on the impact of quantum sensing for nuclear deterrence. First, this chapter surveys key developments in quantum sensing, including types of quantum sensing platforms and quantum logic units. Next, this chapter identifies the main foreseeable use cases for quantum sensors that could disrupt nuclear deterrence through undermining secure second-strike capabilities by facilitating detection of nuclear-armed submarines at sea or targeting of land-based missiles in hardened silos or mobile basing modes. For these two use cases, this chapter calculates feasible near-term improvements in sensitivity that could be achieved through quantum sensing based on estimates from recently published research literature. Finally, it considers possible long-term improvements by evaluating known theoretical limits, as well as various experimental and

[334] Parker, et al., "An Assessment of the U.S. and Chinese Industrial Bases in Quantum Technology."
[335] Parker, et al., "An Assessment of the U.S. and Chinese Industrial Bases in Quantum Technology."

operational constraints that are likely to hinder achievement of this full performance gain in the near- and long-term futures.

Technology Background

Introduction to quantum technologies

Although the definition is somewhat debated, the term "quantum technologies" generally refers to any technology that harnesses quantum phenomena in its operation.[336] Newer quantum technologies that harness superposition and entanglement are most often associated with the term, despite the fact that older quantum technologies have relied upon spin and tunnelling quantum phenomena for decades.[337] Across newer and older iterations, the exploitation of quantum principles allows for improved performance in one or more dimensions, including speed, power, sensitivity, or mobility depending on how quantum phenomena are applied.

The advantages of newer quantum technologies are enabled by the probabilistic nature of quantum systems. Quantum mechanics is the study of small systems, typically sub-atomic particles. For example, quantum mechanics may apply to photons, electrons, atoms, or even molecules, which serve as the bases for newer quantum technologies.[338] At these small scales, the tenets of classical mechanics, including discrete entities with definitive positions and momentums, can no longer be assumed. Instead, characteristics of these systems must be described with

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[336] Georgescu and Nori, 2012, "Quantum technologies: an old new story," pp. 16.
[337] Georgescu and Nori, "Quantum technologies: an old new story," p. 17.
[338] "Introduction to Quantum Physics," Quantum Flagship – European Union, available at https://qt.eu/discover-quantum/introduction-to-quantum-physics/.

probabilities. This is commonly referred to as the "wave-particle" duality, where a subatomic particle may at times operate as a particle, for instance when it is directly measured (a process referred to as "measurement collapse"), but also often exists in a wave-like state that is best described as the sum of the probabilities for each possible state the object could assume.[339]

In addition to measurement collapse, the wave-particle duality of quantum systems induces two key phenomena that have come to represent the newer set of quantum technologies. First, quantum objects may exist simultaneously in multiple states. This is referred to as superposition, where the sum of each state defines the object, rather than its singular position. Second, quantum objects may be intrinsically correlated, through a process referred to as entanglement (dubbed by Albert Einstein as "spooky action at a distance"). The fact that quantum objects can be correlated means that knowledge about one entangled object may provide information about its counterpart, even when the counterpart is physically separated and has not been observed.[340]

To resolve disagreements over the definition of quantum technologies, and the fact that quantum phenomena are employed in many everyday items, including LED lightbulbs and semiconductors,[341] the current wave of quantum technologies has been

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[339] A. C. Phillips, *Introduction to Quantum Mechanics*, John Wiley and Sons (2003), p. 1.
[340] Ben Brubacker, "How Bell's Theorem Proved 'Spooky Action at a Distance' is Real," *Quanta* (July 20, 2021), available at https://www.quantamagazine.org/how-bells-theorem-proved-spooky-action-at-a-distance-is-real-20210720/#:~:text=The%20%E2%80%9Cspooky%20action%E2%80%9D%20that%20bothered,distinct%20entities%20lose%20their%20independence.
[341] "How Are Quantum Phenomena Used in Technology Today?" CalTech Science Exchange, available at https://scienceexchange.caltech.edu/topics/quantum-science-explained/quantum-technology.

referred to by experts as the "second quantum revolution."[342] In distinguishing newer quantum applications from earlier applications, the second quantum revolution is characterized by the ability to control individual quantum objects. While operationalization of quantum mechanics has been well understood at the aggregate level, scientists have only recently been able to initialize, manipulate, and measure individual quantum objects consistently. The ability to manipulate quantum objects has been afforded by improvements in experimental techniques, such as precision laser and microwave manipulation, as well as breakthroughs in the deeper theoretical understanding of quantum systems.[343] Following the innovations that allowed them to be controlled as discrete units of information, these objects have been referred to as qubits, and they serve as the building blocks for modern quantum technologies.[344]

Qubits are analogous to bits in classical computers. Just as the bit is the smallest unit of information for a classical computer, a qubit is the smallest unit of information in a quantum computer. However, qubits can hold significantly more information than classical bits due to their quantum properties. Mathematically, a qubit is a vector that represents the superposition of the two physical states the object could occupy. Thus, while bits only exist in one of two states (as bits are binary, these states are referred to as 0 and 1), a qubit can be in a superposition state where it has

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[342] Jonathan Dowling and Gerard Milburn, "Quantum technology: the second quantum revolution," *The Royal Society*, (June 2003).
[343] Daniel Garisto, "The second quantum revolution," *Symmetry* (January 12, 2022), available at https://www.symmetrymagazine.org/article/the-second-quantum-revolution.
[344] Martin Giles, "Explainer; What is a quantum computer?" MIT Technology Review (January 29, 2019), available at https://www.technologyreview.com/2019/01/29/66141/what-is-quantum-computing/.

some combination of non-zero probabilities for occupying both physical states. This quantum state, ψ, is mathematically expressed in Dirac (or bra-ket) notation as:

$$|\psi> = \alpha|0> \ +\beta|1>, \qquad (5.1)$$

where α and β are probability coefficients for each state that are normalized such that:

$$|\alpha|^2 + |\beta|^2 = 1.$$

In this definition, α and β indicate the probabilities that the qubit is in the 1 and 0 state. In a normalized equation (meaning the object's entire probabilistic scope is defined) the sum of both α and β squared must equal 1, to ensure that the sum of all defined states constitutes a full probability horizon.

The probabilistic nature of a qubit's superposition state gives rise to a few unique operational advantages. First, a qubit-based system can hold 2^n times more information than an *n*-bit system, as it can simultaneously occupy all possible combinations of the bits.[345] For example, a two-bit system can only store information in one of four possible combinations: 10, 11, 01, or 00. Conversely, a two-qubit system can store information in all four possible combinations if each state has a non-zero probability (2^2 times more information). This also allows for quantum systems to process data at significantly faster speeds.[346] Because each possible combinations can be maintained at once, a quantum computer can be optimized to run complex calculations, processing all possible combinations concurrently, instead of running

[345] John Preskill, "Quantum Computing and the Entanglement Frontier," WSPC – Proceedings (November 13, 2012), available at https://arxiv.org/pdf/1203.5813.pdf.
[346] John Preskill, "Lecture Notes for Physics 229: Quantum Information and Computation," California Institute of Technology, September 1998, Pp. 13.

through each individual combination iteratively. This advantage is magnified as the quantum system scales up to larger numbers of qubits, with a 2^n exponential increase.

Additionally, quantum systems may be able to perform more complex processes through entanglement and higher dimensional qubits, referred to as qudits.[347] While qubit dynamics primarily pertain to two-state quantum systems, it is worth noting that quantum systems may have larger operational spaces, referred to as Hilbert spaces, that incorporate more than two dimensions. Thus, qudits (or quantum digits) expand the operational space to "any (integer) number of states greater than 1."[348] However, notably, these systems *must* sustain their quantum superposition and entanglement states throughout the specific measurements, calculations, or operations to achieve these advantages, which can be challenging practically as quantum systems are extremely sensitive to environmental perturbations.[349]

The three categories of quantum technologies that constitute the second quantum revolution are quantum computing, quantum communication, and quantum sensing. Quantum computing harnesses quantum superposition and quantum entanglement to outpace the speed and complexity power of conventional

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[347] For quantum communication: Daniele Cozzolino, Beatrice Da Lio, Davide Bacco, Leif Katsuo Oxenlowe, "High-Dimensional Quantum Communication: Benefits, Progress, and Future Challenges," *Advanced Quantum Technologies*, Vol. 2, No. 12 (2019).
For quantum computing: Yulin Chi, et al., "A programmable qudit-based quantum processor," *Nature*, Vol. 13, No. 1166 (2022).
For quantum sensing: M. Kristen et al, "Amplitude and frequency sensing of microwave field with a superconducting transmon qudit," *Nature Quantum Information* (June 2020), available at https://www-nature-com.proxy-um.researchport.umd.edu/articles/s41534-020-00287-w.

[348] Andrew Greentree, S. G. Schirmer, F. Green, Lloyd Hollenberg, A Hamilton, and R. Clark, "Maximizing the Hilbert space for a finite number of distinguishable quantum states," *Physics Review Letters*, Vol. 5, No. 92 (2004), pp. 1.

[349] Greentree et al., "Maximizing the Hilbert space for a finite number of distinguishable quantum states," pp. 4.

computing.[350] With a somewhat narrower range of applications, quantum communication relies on quantum correlation and entanglement to bolster security of communication.[351] Finally, quantum sensing operationalizes the sensitivity of quantum systems to environmental perturbations, a trait which is considered to be a constraint in the other two quantum technology branches, to measure physical properties with increased sensitivity over conventional alternatives.[352]

While each branch has surpassed major milestones over the last ten years, quantum sensing has reached the most advanced stage of development. Basic and applied research has yielded useful information and techniques required to initialize, measure, and manipulate quantum systems. For quantum computers to be realized, further research is needed to identify methods to scale up the number of qubits in a system's processor to a requisite amount for useful operation, without severely impacting the fidelity and operation of each of the individual qubits.[353] Basic quantum communication capabilities have already been achieved, such as for limited communication between major cities, using satellites as relays.[354] Yet, limitations on the duration and fidelity of entanglement capabilities will likely continue to hinder efforts to increase data transmission distances and volume capacities, at least for the

[350] Martin Giles, "Explainer: What is a quantum computer?" MIT Technology Review (January 29, 2019), available at https://www.technologyreview.com/2019/01/29/66141/what-is-quantum-computing/.
[351] Martin Giles, "Explainer: What is quantum communication?" MIT Technology Review (February 14, 2019), available at https://www.technologyreview.com/2019/02/14/103409/what-is-quantum-communications/.
[352] Degen, Reinhard, and Cappellaro, "Quantum sensing."
[353] Francesco Bova, Avi Goldfarb, and Roger Melko, "Commercial applications of quantum computing," *EPJ Quantum Technology*, Vol 8, No. 2 (2021).
[354] Mahdi Chehimi and Walid Saad, "Physics-Informed Quantum Communication Networks: A Vision Towards the Quantum Internet," arXiv:2204.09233vv1 (2022), available at https://arxiv.org/pdf/2204.09233.pdf.

next ten years.[355] Comparatively, quantum sensors are already commercially available. Although R&D achievements could further increase operability and sensitivity of quantum sensors, basic devices are now available for limited use for basic timekeeping, surveying, and navigation activities.[356]

Quantum communication and quantum computing may impact nuclear deterrence and strategic stability once they reach more advanced stages of development, however assessing the impact of quantum sensors is a higher priority for policymakers in the near-term given the comparatively advanced technology readiness level. Although quantum computing and quantum communication have also been identified as having nuclear security and strategic stability-relevant applications,[357] their nascent stage of development makes these assertions more tenuous and harder to assess. Thus, this chapter focuses exclusively on quantum sensing technologies. However, because of the interconnection of research and development across the three branches of quantum technologies due to commonalities in the basic science and techniques, findings from this analysis may be relevant to and/or have impacts for policymaking on the other two quantum technologies (this form of technology R&D coupling across quantum technologies is discussed in greater detail in Chapter 7).

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[355] Chehimi and Saad, "Physics-Informed Quantum Communication Networks: A Vision Towards the Quantum Internet."
[356] "Quantum Sensing Use Cases: Prospects and Priorities for Emerging Quantum Sensors," QED-C, September 2022, https://quantumconsortium.org/sensing22/. And Susan Curtis, "Converting quantum promises into commercial realities," *Physics World* (May 30, 2021), available at https://physicsworld.com/a/converting-quantum-promises-into-commercial-realities/.
[357] Michal Krelina, "Quantum technology for military applications," *EPJ Quantum Technology*, Vol 8, No. 24 (2021), available at https://epjquantumtechnology.springeropen.com/articles/10.1140/epjqt/s40507-021-00113-y#:~:text=Quantum%20warfare%20(QW)%20is%20warfare,as%20well%20as%20ethics%20issues..

Given this assessment, the remainder of this section is dedicated to surveying quantum sensing technology developments, and specifically those technologies most relevant to the capability use-case analysis that is presented in subsequent sections. First, a background on the requirements for all quantum sensors is provided. To evaluate current quantum sensing technologies, this section then surveys the different quantum sensor platform types that are already being developed, distinguished based on the targets they are measuring and the physical basis for their operation (the qubit type).

Quantum sensing overview

Quantum sensors leverage the sensitivity of quantum systems to environmental perturbations to measure physical properties. By varying the composition of a quantum platform's material and selecting a suitable quantum object within it, a quantum sensor can be precisely tuned to detect and measure a broad range of external conditions. When quantum systems are used for quantum computing or quantum communication, sensitivity to ambient environmental signals can lead to the decoherence or dephasing of qubit states, meaning that the probability distribution no longer reflects what would be expected in ideal conditions. This decoherence and dephasing accumulates unless it is corrected, which degrades the quality of performance over time. However, through measuring the degree of decoherence or dephasing of quantum systems when exposed to various environmental conditions, quantum sensors can determine the magnitude of environmental condition they are exposed to. For example, they may be used to measure electric or magnetic field strength, gravitational field strength or gradients across areas, time durations, or rotation and acceleration.[358] In addition to these main quantum sensing targets, which have received the greatest amount of research interest thus far, other measurable properties, such as radiation exposure, are still being identified through research across the quantum technology sphere.[359] Thus, it is possible that new areas of quantum sensing will continue to emerge.

Although there are various types of quantum sensing platforms, all quantum sensors follow a similar general protocol: [360]

1. First, the quantum sensor must be initialized into a well-known, observable basis state. As presented in Equation 5.1, above, this would mean the qubit is entirely in either the |0> or |1> states.
2. Second, the sensor must be transformed to a known quantum state, $|\psi_0\rangle$, which is usually a superposition of the |1> and |0> states.
3. Third, the quantum sensor must be allowed to precess under some signal, H, for a known time, t, which will evolve the quantum state to $|\psi(t)\rangle$.
4. Fourth, the sensor must be transformed back into a superposition of observable readout states.
5. Fifth, the final state must be read out, collapsing the quantum state to one of the two basis states.

[358] Degen, Reinhard, and Cappellaro, "Quantum Sensing."
[359] For example, research on the impacts of radiation on quantum computation may lead to eventual radiation quantum sensors: A. P. Vepsalainen, "Impact of ionizing radiation on superconducting qubit coherence," *Nature*, (2020), available at https://www.nature.com/articles/s41586-020-2619-8.
[360] Degen, Reinhard, and Cappellaro, pp. 10-11.

6. And sixth, this must be repeated many times to estimate the different probabilities of each basis in the quantum state with statistical significance.

This generic process is commonly described using a Hamiltonian equation which can be mathematically fit to best represent each specific initialization, precession, and readout processes for a given quantum sensing measurement. [361] The basic quantum sensing Hamiltonian, *H(t)*, is often expressed as a sum of the internal Hamiltonian for the sensor in the absence of a signal, H_0, the change in the sensor Hamiltonian as a response to the external stimulus being measured, $H_v(t)$, and the expected change in the Hamiltonian in response to control manipulations and procedures, $H_{control}(t)$, such that:

$$H(t) = H_0 + H_V(t) + H_{Control}(t).^{362} \qquad (5.2)$$

These generalizations form a set of criteria that all quantum sensor systems must satisfy. The criteria are structured to be analogous to a famous set of requirements for quantum computing platforms, proposed by theoretical physicist David DiVincenzo and aptly referred to as the DiVincenzo criteria.[363] For quantum sensing, this set of criteria define that the quantum system has discrete, resolvable energy levels that can be measured/observed; that the quantum system can be

[361] A Hamiltonian expression for a quantum system defines the total system energy, which determines the possible range of outcome states. See: Michael O'Keefe, "Hamiltonian engineering with constrained optimization for quantum sensing and control," *New Journal of Physics*, Vol. 21 (2019, https://doi.org/10.1088/1367-2630/ab00be.
[362] Degen, Reinhard, and Cappellaro, "Quantum Sensing," p. 9.
[363] Degen, Reinhard, and Cappellaro, "Quantum Sensing," p. 3.

initialized to a known state; that the quantum system can be manipulated; and that the quantum state has some defined reaction to the physical property being measured, through relation V(t). Beyond this set of criteria, and the definition that the quantum sensor uses quantum objects, quantum coherence, or quantum entanglement, there are very few constraints to clearly define what can and cannot be considered a quantum sensor. This open-ended definition has led to the proliferation of a wide variety of quantum sensing platforms.

The subsequent sections detail the various types of quantum sensing platforms, organized both by the type of target they measure and by the physical basis of the platform. As with the broader quantum technology field, there are a wide variety of quantum sensors under development. That quantum sensors can be grouped based on either the target of measurement or the qubit platform used has been a source of confusion for policymakers and non-technical audiences. Non-technical audiences typically differentiate the sensor platforms based on the type of target measured (a closer reference to application/capability), while scientists and engineers prefer the specificity of distinguishing sensors based on the types of quantum systems, or the qubits, that they harness (a closer reference to the technical foundation). Further confusion stems from fact that different types of qubits can be used to measure the same target, and conversely one type of qubit can be operated in different ways to measure different targets.[364]

[364] Lindsay Rand, "Quantum Technology: A Primer on National Security and Policy Implications," LLNL CGSR Report (2021), https://cgsr.llnl.gov/content/assets/docs/Quantum-Primer_CGSR_LR_Jul18.pdf.

Types of quantum sensors

For less technical users, the most practical way to distinguish the types of quantum sensors is with respect to the physical properties they measure, including electric fields, magnetic fields, gravitational fields, acceleration, or time. Depending on what the target of measurement is, various types of qubit platforms may be used, and some qubits can measure multiple physical properties through different techniques. For many types of qubits, the physical property that is being measured is determined based on the aspect of the qubit that is being monitored in the precession period, as well as the method of analysis. For example, when a trapped ion is being used to measure a magnetic field, the spin is being read, while the energy level is used to measure electric field variations. Although there are a variety of measurement targets that distinguish sets of quantum sensors, only a few are discussed in detail in this chapter, as guided by the deterrence-relevant use cases identified in the subsequent section. These include: magnetometers, inertial sensors, and gravimeters.

Magnetometers

Magnetometers are used to measure magnetic field strength or magnetic field gradient. Thus, the requirement for a platform to accomplish magnetometry is that it must contain some element that responds with a corresponding or relative magnitude to different strengths of magnetic fields. In atomic systems, this is typically accomplished by analyzing spins, which could either be positioned in an up or down state depending on the ambient magnetic field.[365] Earlier magnetometry systems were based on classical mechanics or aggregate quantum techniques. Second quantum

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[365] John Kitching, "Chip-scale atomic devices," *Applied Physics Reviews*, Vol. 5, No. 031302, 2018.

revolution magnetometers that measure changes in individual qubits promise increased sensitivity, especially with the application of entanglement regimes.[366]

Although magnetometers have been used for surveying, detection, and navigation applications for over a century, quantum and other advanced technologies have dramatically increased the sensitivities, and thus the detection range, of magnetometers in the last 50 years. The first known magnetometer was created by Carl Gauss in 1833 to measure the Earth's magnetic field.[367] The next major breakthrough was the development of the fluxgate magnetometer in 1936, which was motivated as a method to detect submarines. The fluxgate magnetometer relies on a ferromagnetic core wrapped in a wire coil to calculate a magnetically-induced voltage.[368] Although variants of the fluxgate magnetometer remain in use today, alternatives have been developed that rely on different areas of physics and engineering, including platforms based on optics, microelectromechanical systems, and superconductors. Quantum physics is also being used to continue this line of magnetometry innovations, which is discussed later in this chapter.[369]

Knowledge of local magnetic field strengths or gradients can allow for a variety of innovative applications in the military and security sphere. For example, magnetometers may be used for navigation, by measuring the magnetic field strength in a certain location and comparing it to a map of known magnetic field strength

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366 M. Auszinsh, D. Budker, D. F. Kimball, S. M. Rochester, J. E. Stalnaker, A. O. Sushkov, and V. V. Yashchuk, "Can a quantum nondemolition measurement improve the sensitivity of an atomic magnetometer," July 24, 2004, https://arxiv.org/pdf/physics/0403097.pdf.
367 Carl Friedrich Gauss, "The Intensity of the Earth's Magnetic Force Reduced to Absolute Measurement," (1832), available at http://21sci-tech.com/translations/gaussMagnetic.pdf.
368 F. Primdahl, "The fluxgate magnetometer," *Journal of Physics: Scientific Instruments*, 1979, Vol. 12, No. 241, 1979, available at: https://iopscience.iop.org/article/10.1088/0022-3735/12/4/001.
369 Alan Edelstein, "Advances in magnetometry," *Journal of Physics*, Condensed Matter, Vol. 19, No. 165217, 2007, https://iopscience.iop.org/article/10.1088/0953-8984/19/16/165217/pdf.

distributions.[370] Magnetic field gradients may also be used to detect objects that introduce significant magnetic gradient anomalies compared to the ambient environment, such as ferromagnetic submarines in oceans or underground storage tanks.[371] Finally, magnetometers may be used to determine the shape or material composition of an object, a trait which has led to their application in medical imaging and screening for decades.[372]

Inertial Sensors

Inertial sensors are used to measure the acceleration and direction of movement of an object. Inertial sensors generally include combinations of gyroscopes and accelerometers to measure an object's angular velocity, which allows its position to be determined, assuming requisite knowledge about its initial location.[373] This means that inertial sensors can determine an object's location without external signal/communication.

Because of the strategic advantages this capability affords in adverse environments, governments have explored inertial navigation systems for decades. By the 1940s and 1950s, significant effort was underway to develop inertial guidance systems that could be used for military purposes, such as for navigation of submarines, missiles, and airplanes.[374] Early mechanical systems relied on pendulous

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[370] A. Greentree, X. Wang, W. Li, B. Gibson, W. Moran, L. Hall, D. Simpson, and A. Kealy, "Quantum diamond magnetometry for navigation in GNSS denied environments," Symposium of IAG Commission, Potsdam, Germany, 2022, https://doi.org/10.5194/iag-comm4-2022-32.
[371] Sarah Hussain, "Application of quantum magnetometers to security and defense screening," Dissertation – University College London, 2018, pp. 91-105, https://core.ac.uk/download/pdf/158170317.pdf.
[372] Hussain, 2018, pp. 31.
[373] Manon Kok, Jeroen Hol and Thomas Schon, "Using Inertial Sensors for Position and Orientation Estimation," https://arxiv.org/pdf/1704.06053.pdf.
[374] Daniel Tazartes, "An Historical Perspective of Inertial Navigation Systems," *IEEE*, 2014, https://ieeexplore-ieee-org.proxy-um.researchport.umd.edu/stamp/stamp.jsp?tp=&arnumber=6782505.

masses to measure speed and rotation, including spinning mass gyroscopes and jewel-and-pivot accelerometers. These early systems had high control requirements: there had to be fluid in which the mass could move and the fluid had to be heated to a certain temperature.[375] By the 1970s, some of these challenges had been resolved, allowing for strapdown navigation systems. Strapdown systems can measure a higher degree of axes without the use of fluid due to better technologies and microprocessor capabilities allowing for more complex analysis algorithms. They are still widely used for inertial navigation in commercial and military applications, but with innovative methods applied. An important innovation that initially allowed for strapdown navigation was the development of optical gyroscope methods in the 1960s, which evaluated acceleration and rotation based on fluctuations in light propagation.[376] Light could be measured as it passed from lasers through a cavity (ring laser gyroscope) or in fiber optic cables (fiber optic gyroscope).[377] Notably, these systems often included GPS receivers to help correct their readings over time and reduce error. Microelectrical mechanical systems (MEMs) have also been studied. They are subject to extreme drift over time, so never overtook the optical gyroscopes in military-grade applications.[378]

Quantum platforms for inertial sensing rely on interferometry techniques and nuclear magnetic resonance. Interferometry, or the measurement and comparison of superimposed waves which have travelled different paths and thus have been subject

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[375] Tazartes, "An Historical Perspective of Inertial Navigation Systems."
[376] Paul Savage, "Blazing Gyros: The Evolution of Strapdown Inertial Navigation Technology for Aircraft," Aerospace Research Central, Vol. 36, No. 3 (2013).
[377] Tazartes, "An Historical Perspective of Inertial Navigation Systems."
[378] Tazartes, "An Historical Perspective of Inertial Navigation Systems."

to different degrees of exposure to a physical phenomenon, is commonly employed in the use case of cold atoms.[379] Nuclear magnetic resonance measures spin transitions in nuclei as some frame of reference cell accelerates and rotates with the moving reference frame. Although nuclear magnetic resonance was considered in the 1960s, it was not pursued as seriously as ring laser gyroscopes because of technical design issues at the time. Advances in measurement techniques and miniaturization of NMR capabilities brought about by the second quantum revolution have made nuclear magnetic resonance seem more feasible now.[380]

The use of interferometry or nuclear spin techniques rather than mechanical operation means that quantum inertial sensors are unlikely to suffer the same weakness as MEMs – degradation due to mechanical wear over time. Without this constraint, scientists and engineers are hopeful that quantum inertial sensors will be operational for much longer periods of time without requiring correction or losing accuracy.[381] The major application commonly understood for inertial sensors is positioning and dead reckoning. However, they can also be used to track and interpret smaller scale movement such as for robotics manipulation or biomechanical analysis.[382] In either application, the expansion of operability time could allow for long-term continuous observation.

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[379] B. Barrett, A. Bertoldi, and P. Bouyer, "Inertial quantum sensors using light and matter," March 10, 2016, https://arxiv.org/pdf/1603.03246.pdf.

[380] A. K. Vershovskii, Yu A. Litmanovich, A. S. Pazgalev, and V. G. Peshekhonov, "Nuclear Magnetic Resonance Gyro: Ultimate Parameters," *Gyroscopy and Navigation*, Vol. 9, No. 3, 2018.

[381] Phillippe Bouyer, "Quantum technology for a new generation of inertial sensors," *International Society for Optics and Photonics*, March 1, 2016, https://spie.org/news/6312-quantum-technology-for-a-new-generation-of-inertial-sensors.

[382] Bouyer, "Quantum technology for a new generation of inertial sensors."

Gravimeters

Gravimeters are sensors that measure gravitational field strength. The gravitational acceleration at any position in space reflects a unique set of localized components due to the relationship between the Earth, the Sun, the Moon, and other celestial bodies. Ultra-precise instruments allow for highly sensitive, time-variable measurements of gravity smaller than 10^{-9}.[383] A few different measurement schemes can be used with quantum sensor platforms to perform gravimetry. One platform that has been used for decades now is the free-fall gravimeter, which adopts cold atoms as test masses to measure gravitational acceleration.[384] Recently, various research groups have applied new quantum control equipment, such as precision lasers and smaller control systems, to increase portability and operability of quantum gravimeters, which increases the use cases to which they could be applied.[385] Similar to magnetometry, the typical applications associated with gravimeters include dead reckoning and object detection/characterization, as well as basic research.[386]

Other types of quantum sensor

Other types of quantum sensors grouped based on the measurement target are worth mentioning, but not discussing in detail here because they are not relevant to

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[383] Michel Van Camp, Olivier de Viron, Arnaud Watlet, Bruno Meurers, Olivier Francis, and Corentin Caudron, "Geophysics from Terrestrial Time-Variable Gravity Measurements," *American Geophysical Union*, 2017, https://doi.org/10.1002/2017RG000566.
[384] M. K. Zhou, X. C. Duan, L. L. Chen, Q. Luo, Y. Y. Xu, Z. K. Hu, "Micro-Gal level gravity measurements with cold atom interferometry," *Chinese Physics B*, Vol. 24, No. 5, 050401, https://doi.org/10.1088/1674-1056/24/5/050401.
[385] Vincent Menoret, Pierre Vermeulen, Nicolas Le Moigne, Sylvain Bonvalot, Philippe Bouyer, Arunaud Landragin, and Bruno Desruelle, "Gravity measurements below 10^-9 g with a transportable absolute quantum gravimeter," *Nature*, February 2018, DOI:10.1038/s41598-018-30608-1.
[386] Jiaqi Zhong, Biao Tang, XI Chen, and Lin Zhou, "Quantum gravimetry going toward real applications," *Innovation*, Vol. 3, No. 3 (2022), https://www-ncbi-nlm-nih-gov.proxy-um.researchport.umd.edu/pmc/articles/PMC8983424/.

the key use cases considered in this dissertation. Quantum electrometry, or the measurement of electric field strength, which is largely based on Rydberg atoms, can be used for radiofrequency sensing and signal interception.[387] Quantum metrology, which allows for precision timekeeping, could be useful for satellite, swarm, and signal synchronization.[388] And finally, quantum thermometry, which allows for the measurement of nanoscale changes in temperature, could be used for signal interception or materials innovations.[389] While achievements in each of these applications could impact strategic stability in some way, their implications to-date are less clearly linked to deterrence or defense disruptions than quantum magnetometers, inertial sensors, and gravimeters.

In some cases, the same platforms can be used to measure multiple target types, creating a crossover of technologies within each of the measurement-focused category delineations. For example, the same underlying technologies that measure the acceleration of quantum objects can be used for gravimetry or inertial sensing. The distinction lies in the set-up of the platform and whether it is designed to measure extremely small acceleration changes due to gravitational field anomalies or to measure larger and more rapidly changing acceleration anomalies to track object movement. Likewise, the measurement of time, (e.g., quantum metrology) is required

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[387] Adrien Facon, Eva-Katharina Dietsche, Dorian Grosso, Serge Haroche, Jean-Michel Raimond, Michel Brune, and Sebastien Gleyzes, "A sensitive electrometer based on a Rydberg atom in a Schrodinger-cat state," *Nature*, Vol. 535 (2016), https://www.nature.com/articles/nature18327.
[388] Vittorio Giovannetti, Seth Lloyd, and Lorenzo Maccone, "Advances in quantum metrology," *Nature Photonics*, Vol. 5 (2011), https://www.nature.com/articles/nphoton.2011.35.
[389] Masazumi Fujiwara and Yutaka Shikano, "Diamond quantum thermometry: from foundations to applications," *Nanotechnology*, Vol. 32 (2021), https://iopscience.iop.org/article/10.1088/1361-6528/ac1fb1.

for many different types of quantum sensors, such as inertial sensing (to integrate acceleration over time).

Types of qubits

An alternative classification approach differentiates quantum sensor platforms based on the type of qubit used to perform a measurement, rather than the target to be measured. This section compares five different types of qubit platforms that can be used for magnetometry: (1) superconducting qubits, (2) atomic vapor neutral atom qubits, (3) cold neutral atom qubits, (4) trapped ion qubits, and (5) defect qubits. (These and other qubit platforms may be more or less relevant for other types of sensor targets.) In this simplistic comparison, magnetic field measurement quality is assessed based on sensitivity, which is typically provided in the smallest degree of measurable magnetic field strength resolution (in the units of Tesla) over a range of √Hz analyzed. Though, certainly, in evaluating the applicability of a specific type of qubit for a use-case, other factors such as those included in the SWaP-C parameters would be important to consider as well.[390]

Superconducting qubits, or artificial qubits made from macroscopic circuits, have been studied for decades. This category includes one of the oldest forms of quantum sensors, the superconducting quantum interference device (SQUID). SQUIDs are interferometry-based sensors that measure the interference imposed by measurement targets as flux induced in superconducting circuit loops. Despite

[390] For example, in space-based applications particularly, SWaP-C parameters may be equally, if not more important that sensitivity gains. Discussed in: J. Cortes and J. Karburn, "Low Size, Weight, and Power (SWaP) Space-Based Imaging System," Lawrence Livermore National Lab – Technology Report 814352, August 2020, https://www.osti.gov/servlets/purl/1659399.

predating more contemporary forms of quantum sensors by decades, SQUIDS have retained their position as one of the most sensitive platforms, capable of detecting extremely small magnetic fields, with sensitivities on the order of fT/√Hz (or 10^{-15} T/√Hz).[391] However, as quantum techniques have advanced methods to measure individual quantum objects, other types of superconducting qubit-based platforms are now being pursued as alternatives to SQUIDs for superconducting quantum sensors. In these platforms, the qubits may represent a number of circuit parameters, including the flux in the circulating currents (flux qubits) or the charge distribution in the circuit (charge qubits).[392] Experiments using flux qubits have achieved sensitivities on the order of magnitude of pT/√Hz (or 10^{-12} T/√Hz – 3 orders of magnitude less sensitive than 10^{-15} T/√Hz).[393] Transmon qubits have also received significant research interest as they are one of the leading platforms for quantum computing processors. Transmon magnetometers are still not quite as sensitive as SQUIDs or flux qubits, but have achieved experimentally observed resolutions as low as 10pT/√Hz (or 10^{-11} T/√Hz).[394] Furthermore, scholars are now proposing methods to exceed the standard

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391 S. Danilin and M. Weides, "Quantum sensing with superconducting circuits," arXiv:2103.11022v1 – quantum physics, March 19, 2021, https://www.researchgate.net/publication/350311944_Quantum_sensing_with_superconducting_circuits/link/60595ed992851cd8ce5e5fb5/download; and M. Buchner, K. Hofler, B. Henne, V. Ney, and A. Ney, "Tutorial: Basic principles, limits of detection, and pitfalls of highly sensitive SQUID magnetometry for nonmagnetism and spintronics," *Journal of Applied Physics*, Vol. 124, No. 161101 (2018), https://pubs.aip.org/aip/jap/article/124/16/161101/1030088/Tutorial-Basic-principles-limits-of-detection-and.

392 Morten Kjaergaard, Mollie Schwartz, Jochen Braumuller, Philip Krantz, Joel I-J Wang, Simon Gustavsson, and William Oliver," Superconducting Qubits: Current State of Play," *Annual Review of Condensed Matter Physics*, Vol. 11 (2020).

393 Rangga Budoyo, Kosuke Kakuyanagi, Hiraku Toida, Yichiro Matsuzaki, and Shiro Saito, "Electron spin resonance with up to 20 spin sensitivity measured using a superconducting flux qubit," *Applied Physics Letter*, Vol. 116, No. 194001 (2020).

394 S. Danilin, A. V. Lebedev, A. Vepsalainen, G. B. Lesovik, G. Blatter, and G. S. Paraoanu, "Quantum-enhanced magnetometry by phase estimation algorithms with a single artificial atom," Vol. 29, *Nature Quantum Information*, 2018, https://doi-org.proxy-um.researchport.umd.edu/10.1038/s41534-018-0078-y.

quantum limit with superconducting qubits by increasing the speed of phase accumulation or through using entangled pairs, feats which are not as feasible for older SQUID systems.[395]

Neutral atom platforms are another branch of quantum sensors with a fairly long history. Alkali atoms are used for neutral atom qubits because they satisfy the criteria for quantum sensor platforms in that they are sensitive to a wide range of physical properties and can be measured and manipulated with existing technologies and techniques.[396] As the technological means to control neutral atoms have improved, several different methods to manifest neutral atom sensing have emerged. First, thermal vapors (or "atomic vapors") may be used at room temperature for magnetic field sensing with high sensitivities, achieving resolutions in the range of .10 fT/√Hz (or 10^{-16} T/√Hz), partly enabled by long coherence times (and thus increased measurement times).[397] These platforms are most commonly referred to as spin exchange relaxation-free (SERF) sensors due to the measurement of the spin precession. Vapor cell/SERF sensors continue to present promise, as their size has been successfully scaled down and current research efforts have demonstrated the ability to apply entanglement enhancement techniques.[398]

As modern laser technology and cryogenic techniques have been refined, the ability to cool and optically manipulate atoms has also improved. This has enabled a

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[395] Danilin and Weides, "Quantum-enhanced magnetometry by phase estimation algorithms with a single artificial atom."
[396] Degen, Reinhard, and Cappellaro, "Quantum Sensing."
[397] Degen, Reinhard, and Cappellaro, "Quantum Sensing," and Jundi Li, Wei Quan, Binquan Zhou, Zhuo Wang, Jixi Lu, Zhaohui Hu, Gang Liu, and Jiancheng Fang, "SERF Atomic Magnetometer – Recent Advances and Applications: A Review," *IEEE Sensors Journal*, Vol. 18, No. 20 (2018).
[398] Degen, Reinhard, and Cappellaro, "Quantum Sensing."

second type of neutral atom platform: cold atom sensors. By significantly reducing ambient temperatures, thereby lowering the velocities of atoms in a cold environment, longer manipulation/ interrogation times can be achieved for individual atoms.[399] Scientists believe that longer interrogation times will afford increased sensitivity, despite the added requirement of cryogenic techniques to maintain cold temperatures. Research on cold atom magnetometers have achieved resolutions around 10-100 pT/√Hz (or 10^{-11} to 10^{-10} T/√Hz), dependent on the control system requirements.[400] In addition to enabling magnetometry, cold atom platforms have facilitated the development of free-falling atom-based sensors, which can be used for gravimetry by measuring acceleration as cold atoms fall.[401] Researchers working on cold atom platforms have demonstrated entanglement enhancement feasibility. They have also found evidence that sensitivity could be improved beyond the shot-noise-limit through manipulation of entanglement with spin-squeezing.[402] Finally, other cold atom magnetometry research seeks to reduce systems control requirements, which would drastically increase operability, by using polar-gradient cooling and magneto-optical trapping instead of cryogenics to cool the atoms to ultra-low temperatures.[403]

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399 Degen, Reinhard, and Cappellaro, "Quantum Sensing."

400 Yuval Cohen, Krishna Jadeja, Sindi Sula, Michela Venturelli, Cameron Deans, Luca Marmugi, and Ferruccio Renzoni, "A cold atom radio-frequency magnetometer," *Applied Physics* Letters, Vol. 114, No. 073505 (2019); and Michela Venturelli, "Ultra-cold atomic magnetometry: realization and test of a ^{87}Rb BEC for high-sensitivity magnetic field measurements," Dissertation submitted to University College London, August, 2018, https://discovery.ucl.ac.uk/id/eprint/10055887/1/Michela%20Venturelli%20Thesis.pdf.

401 M. Kasevich and S. Chu, "Measurement of gravitational acceleration of an atom with a light-pulse atom interferometer," *Applied Physics* B, Vol. 54, No. 231, 1992, https://link.springer.com/article/10.1007/BF00325375.

402 P. Sewell and M. Koschorreck, M. Napolitano, B. Dubost, N. Behbood, and M. Mitchell, "Magnetic Sensitivity Beyond the Projection Noise Limit by Spin Squeezing," *Physical Review Letters*, Vol. 109, No. 253605, 2012, https://doi.org/10.1103/PhysRevLett.109.253605.

403 Eileen Nugent, "Novel Traps for Bose-Einstein Condensates," University of Oxford Dissertation, 2009, https://www2.physics.ox.ac.uk/sites/default/files/2013-01-19/eileen_pdf_95059.pdf.

While many of these quantum sensing platforms have been researched for long periods of time, others have arisen recently during the "second quantum revolution." Trapped ion qubits are the one of the newer types of qubits used for quantum sensing.[404] Trapped ion qubits are formed by trapping ions in a vacuum using electric or magnetic fields. They have historically been used for electrometry, or the measurement of electric fields, with predicted sensitivities on the order of 500 nV/m/√Hz or 1 yN/√ Hz, depending on whether the electric field strength or force magnitude, respectively, is being measured.[405] However, recent research has demonstrated that, by measuring different aspects of trapped ions (such as the ground state of spin sublevels), these qubits can also measure magnetic fields,[406] with resolutions in the range of 100 pT/√Hz (or 10^{-10} T/√Hz).[407] Although trapped ion sensors have not yet achieved sensitivity levels on par with neutral atom platforms, preliminary research finds promise in trapped ions allowing for smaller platform sizes due to their operability at room temperatures and because they enable greater dynamic ranges of operation.[408]

Quantum sensing platforms based on defects in diamonds are another new qubit type that has fostered interest in recent years. These defects are formed by nitrogen vacancies, and thus are often referred to as NV-centers. NV-center-based

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[404] Note: Although Rydberg atoms have been demonstrated to have critical interception promise, they are not included because that was not a nuclear-deterrent relevant application. Though, it may tangentially impact intelligence, surveillance, and reconnaissance efforts.
[405] Degen, Cappellaro, and Reinhard, "Quantum Sensing."
[406] W. C. Campbell and P. Hamilton, "Rotation sensing with trapped ions," *Journal of Physics B: Atomic, Molecular and Optical Physics*, Vol. 50, No. 064002, 2017, https://iopscience.iop.org/article/10.1088/1361-6455/aa5a8f.
[407] Ethan Potter, "Development and demonstration of a high bandwidth, ultra sensitive trapped ion magnetometer," Dissertation submitted to University of Sussex, 2019, https://ethos.bl.uk/OrderDetails.do?uin=uk.bl.ethos.793568.
[408] Campbell and Hamilton, "Rotation sensing with trapped ions."

qubits are relatively easy to operate, as they only require lasers to tune, initialize, and read.[409] Furthermore, NV-center qubits are relatively stable over longer periods of time, while still maintaining sensitivity to key physical properties that are targeted in quantum sensing. Recent research has demonstrated that NV-center magnetometers are able to achieve sensitivities in the pT/√Hz (or 10^{-12} T/√Hz) range.[410] NV-centers have been popularized by their applications as magnetometers for small-scale magnetic field gradients.[411] They also may be applied for spectrum analysis via NMR techniques. Finally, one research team has proposed their use for velocimetry, but this application has not yet been widely studied.[412]

This basic overview of the qualitative and performance differences across types of quantum magnetometers is necessarily oversimplified. Because these sensitivities are measured in experimental lab settings, the equipment setup, testing parameters, and environmental background are unique for each experimental design. Furthermore, as research progresses, the current sensitivities will improve at varying paces for each sensor type. Thus, these ranges of sensitivities should be taken as a glimpse at the current state of the art, with recognition that they are likely to change, and that they will vary in different testing and environmental conditions.

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409 Degen, Reinhard, and Cappellaro, 2017.
410 John Barry, Jennifer Schloss, Erik Bauch, Matthew Turner, Connor Hart, Linh Pham, and Ronald Walsworth, "Sensitivity Optimization for NV-Diamond Magnetometry," *Reviews of Modern Physics*, Vol. 92 (2020).
410 Barry et al., 2020; and Jixing Zhang, Lisia Xu, Guodong Bian, Pengcheng Fan, Mingxin Li, Wuming Liu, and Heng Yuan, "Diamond Nitrogen-Vacancy Center Magnetometry: Advances and Challenges," (2020), available eat https://arxiv.org/pdf/2010.10231.pdf.
411 Kin On Ho, Yang Shen, Yiu Yung Pang, Wai Kuen Leung, Nan Zhao and Sen Yang, "Diamond quantum sensors: from physics to applications on condensed matter research." *Functional Diamond*, Vol. 1, No. 1, 2021.
412 Daniel Cohen, Ramil Nigmatullin, et al, "Utilizing NV based quantum sensing for velocimetry at the nanoscale," *Nature Scientific Reports*, Vol 10, No. 5298.

Nuclear Deterrence-Relevant Use-Case Identification

Depending on whether a user is interested in a specific application area or a qubit platform, there is often a lot of overlap across the different types of quantum sensors. Perhaps the most directly relevant way of grouping and comparing quantum sensors is by the use-case to which they will be applied. Quantum sensors have been considered for a wide range of use-cases, including more robust positioning, navigation, and timing (PNT), geological surveying, subsurface imaging, and basic research. For example, of the platforms considered above, improvements in navigation/targeting could be achieved using better sensing of gravitational field strength, magnetic field strength, or inertia, depending on the preferred characteristics. Each of these capabilities could also be attained using an array of qubit types depending on the performance characteristics preferred, such as mobility, cost, or sensitivity.

Several authors have identified potential applications that could impact nuclear deterrence or strategic stability. Krelina provided a high-level primer on quantum technology use-cases across all military applications. In discussing quantum sensing applications, Krelina identified PNT for military activities, Earth surface and underground surveillance, submarine detection, and general quantum radar for surveillance and tracking.[413] Likewise, Gamberini and Rubin conducted a survey on the implications for strategic deterrence and warfare, identifying quantum radar and

[413] Michal Krelina, "Quantum technology for military applications," *EPJ Quantum Technology*, Vol 8, No. 24 (2021).

sensing to detect and monitor stealth aircraft and submarines as potentially disruptive applications.[414] They highlight concerns over Chinese efforts to develop capabilities that could in theory provide an asymmetric strategic advantage in detecting American stealth bombers and submarines,[415] a concern which has been amplified by defense media outlets.[416] Finally, Kubiak focused on submarine second-strike vulnerability, including use-cases that could help detect submarines and/or improve operation of submarines to bolster stealth capabilities.[417]

These analyses have included remarkably little technical assessment to provide a realistic estimate of the extent to which quantum sensors could allow truly revolutionary or disruptive capabilities, and in what realistic timelines. To help fill this gap and to decrease uncertainty over the evolution of quantum sensing applications, this dissertation chapter explores two use cases that could have significant impacts on nuclear deterrence and strategic stability. First, as Krelina notes, quantum sensors offer a number of strategic benefits over existing PNT platforms, some of which could improve missile accuracy to the extent that low-yield nuclear weapons or perhaps even conventional weapons could destroy hardened missile silos. If ICBMs were to become more invulnerable, then the second-strike capabilities would rely more heavily on mobile platforms such as nuclear-armed

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[414] Sarah Gamberini and Lawrence Rubin, "Quantum Sensing's Potential Impacts on Strategic Deterrence and Modern Warfare," *Orbis*, Vol. 65, No. 2 (2021).
[415] Gamberini and Rubin, "Quantum Sensing's Potential Impacts on Strategic Deterrence and Modern Warfare."
[416] For example: Sebastien Roblin, "Can China's Quantum Radar Detect Any Submarine?" *National Interest* (December 2021), available at https://nationalinterest.org/blog/reboot/can-chinas-quantum-radar-detect-any-submarine-198560.
[417] Katarzyna Kubiak, "Quantum Technology and Submarine Near-Invulnerability," European Leadership Network – Global Security Policy Brief (2020), available at https://www.europeanleadershipnetwork.org/wp-content/uploads/2020/12/Quantum-report.pdf.

submarines and mobile missiles. But, as discussed by Gamberini and Rubin, as well as Kubiak, quantum sensors could also afford better detection capabilities, allowing for the tracking and targeting of nuclear submarines (or for circumventing other anti-stealth capabilities). From a strategic perspective, if a country was able to increase the vulnerability of its adversary's second-strike capabilities through quantum sensing technologies, it might gain an asymmetric advantage that would allow it to launch a disarming first strike.

Although several other important applications could impact nuclear deterrence as well, including radiofrequency detection for improved intelligence, surveillance, and reconnaissance (ISR) missions, mobile ballistic missile launcher tracking, or PNT for swarming systems, this dissertation narrowly analyzes the two use cases of submarine tracking and missile accuracy, and extrapolates findings to discuss quantum sensing implications and feasibility of operation more broadly. Chapter 6 reassesses concerns over the strategic implications of quantum sensing based on the technical assessment provided in this chapter.

Methodology for Technical Assessment

Although the wide range of platforms and specialized (if not esoteric) nature of quantum technologies impose significant obstacles to accessing and interpreting the technical research literature that would be insightful for use-case analyses, two published studies have successfully bridged this divide. A study commissioned by the U.S. Department of Energy's Fossil Energy Crosscutting Technology Research Program performed a reasonably comprehensive technical analysis of quantum sensing research and development to identify suitable applications in the energy industry.[418] Another analysis conducted by Sandia National Labs used a similar methodology to explore the feasibility of quantum sensing applications in nuclear safeguards activities.[419] While these studies examined use-cases that differ from those evaluated in this chapter, they provide valuable examples of methodologies that can also be used to conduct technologically-grounded feasibility assessments for quantum sensing platforms.

Both studies connect application-oriented concerns with findings in the technical literature on quantum sensing R&D to provide clear analyses and comprehensive policy recommendations. They are both divided into three main sections: an overview of quantum sensing applications in the field of focus (energy or safeguards); an overview of quantum sensing technologies available and the different ways in which they contribute to the surveyed use cases; and a survey of key obstacles and opportunities for application.[420] The only shortcomings of this methodology is that neither article uses existing technical literature to estimate the potential performance benefits from new quantum sensing technologies compared to technologies currently in-place, nor do they operationalize theory to identify upper limits in the improvements that can feasibly be expected.

This dissertation expands the methodology described above to address those two shortcomings in its analysis of use cases identified as relevant for nuclear

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[418] Scott Crawford, Roman Shugayev, Hari Paudel, Ping Lu, Madhava Syamlal, Paul Ohodnicki, Benjamin Chorpening, Randall Gentry, and Yuhua Duan, "Quantum Sensing for Energy Applications: Review and Perspective," *Advanced Quantum Technologies*, Vol. 4, No. 8 (2021).
[419] David Farley, "Quantum Sensing and its Potential for Nuclear Safeguards," Sandia Report – SAND2021-13677, October 2021, https://www.osti.gov/servlets/purl/1829781.
[420] Farley, "Quantum Sensing and its Potential for Nuclear Safeguards."

deterrence: submarine tracking and missile navigation. Because this is a tighter list of applications than those surveyed in the energy industry and nuclear safeguards analyses, a narrower cross section of quantum sensing technologies is evaluated. However, like the exemplar analyses, this chapter discusses the myriad of quantum sensing platforms that could be used to accomplish each application.

First, to assess and project the feasible improvements that quantum sensing could provide in both applications, the following sections survey the state of the art for non-quantum technologies. Next, the analyses highlight the types of quantum sensing platforms that may conceivably be used to expand operability in these use cases and evaluates recent research publications on the relevant quantum sensing platforms. To establish reasonable estimates on the extent to which quantum sensing could improve operability under continued R&D, the analyses estimate best-case performance improvements and likely obstacles to maximizing quantum sensing potential. The analyses use theoretical limits to approximate the highest levels of achievement that could be expected, then parametrize these expectations with identification of challenges and operational constraints. Finally, potential countermeasures that would negate the quantum benefits are also considered for both application areas. The goal of this extended methodology is to give a range of feasible expectations for quantum sensors in a narrower set of use cases, digging deeper into existing findings than the exemplar analyses for the sake of providing greater clarity on feasibility and timeliness of disruption.

Submarine Detection Technical Assessment

Evolution of submarine detection methods

Various submarine detection methods have been deployed throughout the history of submarine warfare, with each new approach tracking different signals emitted from undersea vessels. Acoustic sensing, one of the earliest methods, involves tracking submarines based on the sounds they emit as they move and operate underwater. Because water has a higher density (for example, compared to air), it is an efficient medium for transmitting noise.[421] Any significant noise produced by the propeller blades or other machinery can be detected from distances of between 100 and 1000 km depending on the conditions (water depth, background noise, etc.).[422] Sound Navigation and Ranging (SONAR), the sensing technique used to detect these underwater noises, can be operated in an active or passive method. Active SONAR allows for more directed probing through the use of energy pulses that are sent out and, if reflected off an object, return to denote detection; however, active SONAR also risks disclosing the searcher's location.[423] Passive SONAR is more discrete, but is also more subject to background noise. It cannot easily be directed, as it only involves receivers that "listen" for sound waves that naturally travel to the SONAR

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[421] Sabine De Brabandere, "What Do You Hear Underwater?" *Scientific American* (June 27, 2019), https://www.scientificamerican.com/article/what-do-you-hear-underwater/.
[422] William Dixon and Ray Rollins, "Very Low Frequency Acoustic Detection of Submarines," *Naval Research Laboratory*, Washington DC, 1977, https://apps.dtic.mil/sti/pdfs/ADC010105.pdf.
And: E. V. Miasnikov, Appendix B in"The Future of Russia's Strategic Nuclear Forces: Discussions and Arguments," Moscow Institute of Physics and Technology, 1995, https://spp.fas.org/eprint/snf0322.htm.
[423] Tom Stefanick, "The Nonacoustic Detection of Submarines," *Scientific American*, Vol. 258, No. 3 (1988).

receivers.[424] In addition to SONAR, optical satellite imagery and RADAR are two more methods that have traditionally been used to detect submarines when they surface or when their periscopes are raised.[425]

At the same time that new capabilities have emerged for tracking submarines, so have countermeasures to evade detection. For example, SONAR detection techniques are no longer as successful as they once were because countries with nuclear-powered and stealth submarines have developed highly effective countermeasures to reduce the noise emitted by the vessels. Such efforts include sound-damping mechanisms, rubber tile coatings, propeller screw designs, and precision computer numerical control (CNC) manufacturing capabilities that are able to produce higher quality components.[426] As nations continue to modernize their submarine fleets, such as in the case of the current U.S. transition from Ohio to Columbia class submarines, more significant advances in noise reduction techniques can be anticipated.[427] Thus, operable SONAR ranges are now much smaller than they previously were and will likely continue to shrink as noise signatures are attenuated. Furthermore, optical imagery and RADAR are only useful part of the time, when submarines have their periscopes raised or are surfaced and visible. Thus, these

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[424] Tom Stefanick, "The Nonacoustic Detection of Submarines."
[425] "Submarine Detection and Monitoring: Open-Source Technologies," Nuclear Threat Initiative – Submarine Proliferation Resource Collection, September 24, 2021, https://www.nti.org/analysis/articles/submarine-detection-and-monitoring-open-source-tools-and-technologies/; and Jeffrey Ousborne, Dale Griffith, and Rebecca Yuan, "Periscope Detection Radar," Johns Hopkins APL Technical Digest, Vol. 18, No. 1 (1997).
[426] Kyle Mizokami, "What Makes Submarines So Quiet?" *Popular Mechanics*, August 15, 2017, https://www.popularmechanics.com/military/navy-ships/news/a27768/what-makes-submarines-so-quiet/.
[427] Matt Korda, "ICBM Advocates Say U.S. Missile Subs Are Vulnerable. It Isn't True," *Defense One*, December 10, 2020, https://www.defenseone.com/ideas/2020/12/icbm-advocates-say-us-missile-subs-are-vulnerable-it-isnt-true/170677/.

capabilities are restricted when adversaries adjust their behaviors and tactics to avoid such exposure.

This race to increase signal-to-noise detection capabilities and to reduce signature emissions has also given rise to other methods for submarine detection, including magnetic anomaly detection (MAD). Because the steel hulls of submarines are composed of ferromagnetic material, they create detectable anomalies in the Earth's known, local magnetic fields. These signature anomalies mean that devices capable of measuring local magnetic fields or magnetic field gradients, and with a priori knowledge about the magnetic field in a specific location, can determine if a vessel is likely to be in the area based on anomalies present in the measurements.[428]

The concept of MAD has been around for decades but has gradually improved with the advent of new sensing technologies.[429] MAD devices rely on a variety of magnetometers to sense magnetic field signatures. The first magnetometer used for MAD was a fluxgate sensor, which calculates fluctuations in the alternate and direct current (AC and DC) fields around a magnetic core to determine changes in the magnetic field.[430] Recent efforts to improve MAD capabilities and circumvent the short detection range of fluxgate sensors include laser-pumped helium magnetometers, which are 20-30 times more sensitive than fluxgate sensors.[431]

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[428] Tom Stefanick, "The Nonacoustic Detection of Submarines."
[429] Yue Zhao, Junhai Zhang, Jiahui Li, Shuangqiang Liu, Peixian Miao, Yanchao Shi, and Enming Zhao, "A brief review of magnetic anomaly detection," *Measurement Science Technology*, Vol. 32 (2021); Evan Lisman, "Non-acoustic Submarine Detection," CSIS – On the Radar, 2019, https://ontheradar.csis.org/issue-briefs/non-acoustic-submarine-detection/.
[430] Pavel Ripka and Michal Janosek, "Advances in Magnetic Field Sensors," *IEEE*, 2010, https://core.ac.uk/download/pdf/47168751.pdf.
[431] Lisman, "Non-Acoustic Submarine Detection."

Superconducting quantum interference devices (SQUIDs) have been considered, and in some cases used, for MAD detection. However, they are limited in their field operability because they require cryogenic temperatures (and thus larger and more technology-intensive operating systems). Another drawback is that their high sensitivity makes SQUIDs susceptible to background noise.[432] One idea to increase the capacity of these older, more sensitive systems is through the networking of MAD sensors, in which a fleet of multiple, interconnected sensors is dispersed across a region.[433] While a sensor network can increase overall detection sensitivity by reducing background noise through triangulation across the sensors, it comes at the cost of higher operability requirements. Finally, although MAD technologies have improved, so have countermeasures that reduce the magnetic signature of submarines. MAD countermeasures, or magnetic silencing techniques, range from construction design choices that limit the amount of magnetic materials, operational protocol that limit the production of eddy currents induced by electronics operating on the vessel, and degaussing of the ship's hull to remove residual magnetism.[434]

Synthetic aperture radar (SAR) techniques have also introduced a new avenue for submarine detection, leveraging advanced imaging technologies to identify the discrete wakes that submarines create on the surface of the water above them as they travel. As submarines move, depending on the speed and depth at which they are travelling, they may create small wakes on the surface of the ocean, called Bernoulli

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432 Lisman, "Non-Acoustic Submarine Detection."
433 Yuqin Chen and Jiansheng Yuan, "Methods of Differential Submarine Detection Based on Magnetic Anomaly and Technology of Probes Arrangement," 2nd International Workshop on Materials Engineering and Computer Sciences (2015), https://www.atlantis-press.com/article/25840634.pdf.
434 "Magnetic Silencing," Chapter 475 in Naval Ships' Technical Manual S9086-QN-010, U.S. Navy, 1992, https://man.fas.org/dod-101/sys/ship/nstm/475r1.pdf.

humps (near wakes) and Kelvin wakes (far wakes).[435] Some analysts have suggested that advanced satellite imagery techniques, which rely on microwave pulses to detect otherwise unobservable surface patterns, could be used to identify and track signature submarine wakes. SAR techniques have already been used successfully in other, somewhat similar settings. For example, SAR has been used to identify locations of nuclear weapon tests based on the detection of slight depressions in the ground surrounding a test location.[436] However, in the case of submarine detection, SAR is challenging as wake formation depends on the tactics employed by submarine operators. Wake detection could be countered or evaded by decreasing speed or increasing operating depth, particularly when surface conditions are calm.

Quantum sensing and submarine detection

New quantum sensors offer potential innovations to both the MAD and SAR techniques. In the case of MAD, newer quantum magnetometers may increase the sensitivity of detection over those for traditional, non-quantum magnetometers. Likewise, for SAR detection methods, some analysts have proposed that quantum technologies could also be used to increase sensitivity of detection of the wakes through improvements in the high-noise, low-brightness regime, increasing analytic capabilities to detect lower signal-to-noise ratios at the surface of the ocean.[437] Finally, quantum sensors may also enable gravimetry detection of submarines.

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[435] Lisman, "Non-Acoustic Submarine Detection."
[436] Tom Stefanick, "The Nonacoustic Detection of Submarines."
[437] Marco Lanzagorta, Oliverio Jitrik, Jeffrey Uhlmann, Salvador Venegas-Andraca, "Quantum synthetic aperture radar," *SPIE Defense and Security* conference presentation, 2017, https://www.spiedigitallibrary.org/conference-proceedings-of-spie/10188/101880F/Quantum-synthetic-aperture-radar/10.1117/12.2262645.short?SSO=1.

Gravimetry has been considered as a theoretical option for detecting submarines since the 1990s, but it was never seriously pursued due to lack of adequate instrumentation.[438] By increasing the ability to measure local gravity field strength (gravimetry) or changes in gravitational fields (gravity gradiometry), quantum sensors could conceivably resurface debates over the viability of detecting submarines through recognizing patterns and signatures in gravitational fields. Similar to MAD, gravity-based detection methods would identify submarines by the changes they impart on local gravitational fields, and thus would compare measured values to local gravity field maps to identify anomalies that may indicate the presence of a submerged vessel.

While the increased sensitivity of newer quantum devices may allow for better detection, there are limitations based on known quantum technology operational parameters, and the nascent stage of development for many of the quantum sensor types. The following sections survey relevant research findings for the three relevant types of quantum applications to examine suitability of quantum sensor platforms and identify limitations. Of the three, quantum magnetometry has received the greatest research to-date and would thus be the most likely to be impactful in the near-term.

Quantum magnetometry

Modern magnetometers have wide ranges in sensitivity, between 10^{-10} T and 10^{-15} T depending on their operating principles. There are two key variants of magnetometers based on the measurement principles applied: vector and scalar

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[438] P. M. Moser, "Gravitational Detection of Submarines," Pacific-Sierra Research Corporation PSR Note 984, 1989, https://apps.dtic.mil/sti/pdfs/AD1012150.pdf.

magnetometers. Vector magnetometers measure the flux density in a three-dimensional space (including directional information). Scalar magnetometers measure the magnitude of the magnetic vector, without providing any information on directionality. Modern quantum magnetometers are typically scalar magnetometers, while older systems, such as SQUIDs and non-quantum alternatives may perform vector magnetometry.[439] Although some vector quantum magnetometers have also been achieved.[440] The magnetic flux density measured by magnetometers, B, is expressed in units T (tesla).[441] A single magnetometer sensor will measure magnetic flux density in its direct vicinity, with the magnetic field distortion generated by a magnetic object dropping in intensity at the rate of distance cubed (proportional to approximately $1/d^3$). This means that the maximum detection range for a given sensor is proportional to the cube root ($s^{1/3}$) of its sensitivity (or the lowest resolution that it is capable of detecting), so a thousand-fold increase in sensitivity only increases detection range by a factor of ten.[442] This puts practical limits on the extent to which detection range can be increased as sensitivity is improved.

As discussed in the previous section, a few different types of quantum magnetometers could be suitable for MAD application. Generally, quantum magnetometers rely on spin transitions of subatomic particles, including valence (unpaired) electrons and nuclei, to measure magnetic fields. Neutral atom quantum sensors rely on atomic spins to measure magnetic fields; and, as discussed previously,

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439 Hrvoic and Hollyer, "Brief review of quantum magnetometers," GEM Advanced Magnetometers, http://www.gemsys.ca/pdf/MM3_GEM_Brief_Review_of_Quantum_Magnetometers.pdf.
440 See Twinleaf TMR Vector Magnetometer: https://twinleaf.com.
441 Hrvoic and Hollyer, "Brief review of quantum magnetometers."
442 Hrvoic and Hollyer, "Brief review of quantum magnetometers."

they either adopt atomic vapors or cold atom clouds as the sensor basis.[443] Meanwhile, solid state spin quantum sensors, including those based on silicon, quantum dots, or NV-centers in diamonds, rely on electron spins to detect magnetic fields.[444] And finally, SQUID and transmon qubit-based magnetometers use currents to measure magnetic field strength. Other types of quantum sensors could also theoretically be used to perform magnetometry, including those based on elementary particles (such as muons and neutrons), as well as phonon optomechanics. But given that considerably less research has been done on these sensor types, there is no clear way to estimate the operability of these devices outside of lab settings.[445] Thus, the three major branches identified above will be the top platforms considered.

Generally, there are three key qualities to account for when comparing magnetometers. First, as discussed, the sensitivity of quantum magnetometers indicates the lowest signal-to noise-ratio that the sensor can resolve. The lowest detectable field gradient, ΔB, is based on the constant of proportionality, k, the spectral line width, Γ, the gyromagnetic constant, γ_n, and the signal-to-noise ratio, S_n. The relation is given as:

$$\Delta B = k\Gamma / \gamma_n S_n \, . \qquad (5.3)$$

Thus, to some extent, regardless of how precise a sensor is, there will always be a limit imposed by noise, both from the environment and from the sensor itself.[446]

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443 Degan and Cappellaro, "Quantum Sensing."
444 Degan and Cappellaro, "Quantum Sensing."
445 Degan and Cappellaro, "Quantum Sensing."
446 Hrvoic and Hollyer, "Brief review of quantum magnetometers."

The second quality is the bandwidth, which describes the "fastest appearing feature that you can observe with an instrument."[447] This corresponds to the number of samples a magnetometer can take per second. Because the physical spins and currents themselves will freely respond to changes in the ambient precession signal, the bandwidth for quantum magnetometers is largely a derivative of the sensor electronics used to capture measurements.[448]

The final quality is the dynamic range, also measured in T, which defines the range of magnetic field strengths that the magnetometer can measure. The dynamic range is determined by the physical system, or qubit, used and estimates the point at which it can no longer resolve change (the lower bound) as well as the point of saturation, where any added magnetic field strength is unable to be captured (the upper bound).[449]

To determine the technical suitability of each type of sensor for submarine detection, the magnetic fields involved must also be approximated. Two key magnetic fields should be accounted for when surveying the ocean for a submarine signature. First, is the background marine magnetic field, which includes the geomagnetic field (40-60 μT), or the Earth's magnetic field, and the ambient induced magnetic field, which is some changing component around 1-100 nT that is determined by varying

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[447] Hrvoic and Hollyer, "Brief review of quantum magnetometers."
[448] Hrvoic and Hollyer, "Brief review of quantum magnetometers."
[449] James Bennett et al., "Precision Magnetometers for Aerospace Applications: A Review," MDPI - *Sensors*, Vol 21, No. 5568, https://doi.org/10.3390/s21165568.

tidal factors.[450] This composite magnetic field represents the "noise" which the sensors must be able to filter out.

The second magnetic field is the submarine's induced magnetic field, which is also the target signal for detection. It is hard to ascribe a precise value to the submarine's induced magnetic field since certain countermeasures can be used to silence submarines by attenuating the signature's magnitude, as previously discussed. However, the induced magnetic component of the submarine's magnetic field can generally be estimated based on the size and magnetic properties of a submarine hull. As Chen and Yuan approximate, a submarine that is roughly 100 m in length and 10 m in width will have a magnetic moment of around 10^7 A^2m, with the induced magnetic flux density of around 1.65 nT at 1 km (which decreases as the distance between the submarine and the sensor increases at a rate of $1/d^{3)}$.[451]

A single sensor can only identify a submarine from within a distance at which the submarine's signature flux is greater than the background noise. However sensitive a detector may be, as the distance between the submarine and the detector increases, the signal will decrease until it is lower than the background noise. At this point, a single sensor cannot detect the signal, even if the signal strength is still within the operating range of the detector. Background noise can be further minimized, to some extent, by using networked sensors to reduce the background noise to roughly

[450] Yuqin Chen and Jiansheng Yuan, "Methods of Differential Submarine Detection Based on Magnetic Anomaly and Technology of Probes Arrangement," 2nd International Workshop on Materials Engineering and Computer Sciences, 2015.
[451] Chen and Yuan, "Methods of Differential Submarine."

match the differential between the background picked up by two sensors.[452] Thus, a system of n sensors can reduce the background noise through the relation:

$$\Delta B_t = \sqrt{\frac{\sum_{i \neq j}(B_{ti} - B_{tj})^2}{n-1}}. \qquad (5.4)$$

Even within some reasonable detection range, determining the feasibility for a sensor (or a sensor network) to successfully identify and track a submarine is a feat of complex, non-linear mathematical estimation due to the challenging operational environment. Sithiravel et al. demonstrate that Bayesian modeling can be used to approximate the detection success in different scenarios.[453] Li et al. use a cell-averaging greatest-of-constant false alarm rate test method to determine the detection range of a sensor prototype at some specified "false alarm" rate.[454] Zhoe et al. explore various improvements to detection algorithms that could be used to address non-linear noise components.[455] Thus, beyond sensitivity, detection success rate would also have to be considered to define the probability of success in consistently detecting and tracking a submarine in any environment based on the specific sensor's unique operability constraints. However, for the purpose of this analysis, the general sensing parameters will be imputed into a single, simplified detection approximation to estimate order-of-magnitude level improvements that could be expected with

[452] Chen and Yuan, "Methods of Differential Submarine."
[453] Rajiv Sithiravel, Bhashyam Balaji, Bradley Nelson, Michael McDonald, Ratnasingham Tharmarasa, and Thiagalingam Kirubarajan, "Airborne Maritime Surveillance Using Magnetic Anomaly Detection Signature," *IEEE Transactions on Aerospace and Electronic Systems*, Vol. 56, No. 5, October 2020.
[454] Chengjing Li, Shucai Huang, Daozhi Wei, Yu Zhong, and K. Y. Gong, "Detection Range of Airborne Magnetometers in Magnetic Anomaly Detection," *Journal of Engineering Science and Technology Review*, Vol. 8, No. 4, 2015.
[455] Yue Zhao, Junhai Zhang, Jiahui Li, Shuangqiang Liu, Peixian Miao, Yanchao Shi, and Enming Zhaoe, "A brief review of magnetic anomaly detection," *Measurement Science and Technology*, Vol 32, No. 042002, 2021, https://doi.org/10.1088/1361-6501/abd055.

quantum technologies. If even greater assurance against "transparent oceans" or a more granular estimation of the requirements for persistent monitoring is desired, then these non-linear mathematical assessments should be considered.

Given these detection parameters, there are two major areas in which quantum sensors could offer some improvement over existing capabilities. First, quantum sensors could achieve increased sensitivities for detecting smaller signal-to-noise ratios. Sensors with increased signal-to-noise ratios could probe slightly greater distances, evade certain countermeasures aimed at decreasing the signal-to-noise ratio, and operate in noisier environments. Second, quantum sensors could be distributed using entanglement methods to lower the background noise further than existing networked signals. For example, Ciurana et al. find that entanglement of cold atom interferometry sensors could lead to a reduction in background noise by around 25%.[456]

Two primary commercial sensors have cornered the market in MAD submarine detection systems, one is developed by Bartington Instruments and the other by CAE. Although the Bartington Instruments Ltd Mag03 prototype had previously been used extensively for submarine detection,[457] the U.S. Department of Defense has recently transitioned to CAE as its main supplier of MAD sensors.[458]

[456] Martin Ciurana, G. Colangelo, L. Slodicka, R. J. Sewell, and M. W. Mitchell, "Entanglement-Enhanced Radio-Frequency Field Detection and Waveform Sensing," *Physical Review Letters,* Vol. 119, No. 043603, 2017, https://link.aps.org/doi/10.1103/PhysRevLett.119.043603.

[457] Andrew Bond and Leighton Brown, "UDT 2019- The Suitability of Quantum Magnetometers for Defense Applications," UDT Global, 2019, https://www.udt-global.com/__media/libraries/platform-design/74---Andrew-Bond-Paper.pdf.

[458] "Lochkeed Martin Awards CAE Contract to Provide MAD-XR for U.S. Navy Helicopters," *Aviation Pros*, November 19, 2020, https://www.aviationpros.com/aircraft/defense/press-release/21163509/cae-lockheed-martin-awards-cae-contract-to-provide-madxr-for-us-navy-mh60r-helicopters.

CAE also supports a large portion of the global MAD market, having past experience contracting out to various militaries, including the Japanese Ministry of Defense, the Canadian Forces, the Indian Navy, the Australian government, and the Chilean Navy. Newer customers include the Turkish Navy and the Republic of Korea Navy.[459] Given this broad consumer base, the CAE device will serve as the main comparison point for this analysis.

Citing this expansive global market, CAE touts itself as the "world leader in the design, manufacture, and integration of digital MAD systems."[460] Its most recent MAD detection system is the CAE MAD Extended Role (MAD-XR), which the company claims is small enough to be deployed on unmanned aerial systems, helicopters, and small fixed-wing aircraft, and is capable of detecting anomalies within a range of 1,200 meters (although the magnitude of the assumed anomaly and the operating conditions are unspecified).[461] CAE has provided very little public information on the design of its sensor, but commercial magnetometers based on optically pumped helium, such as the CAE model, typically achieve sensitivities in the range of 0.3-1.0 pT/√Hz.[462]

In comparison, various quantum magnetometers with newer designs have already achieved comparable sensitivities, although performance improvements are somewhat hard to estimate given the unique operational constraints for different

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[459] CAE MAD-XR explainer, 2020, https://www.cae.com/media/documents/DM044_MAD-XR-_EN_Feb2020.pdf.
[460] CAE MADXR explainer, 2020.
[461] CAE MAD-XR explainer, 2020.
[462] D. C. Hovde, M. D. Prouty, I. Hrvoic, and R. E. Slocum, "Commercial Magnetometers and Their Applications," in *Optical Magnetometry*, 2013, https://webtest.gemsys.ca/wp-content/uploads/2013/10/Commercial-magnetometers-and-their-application.pdf.

quantum systems. The first column in Table 5.1, below, provides the sensitivities that have been achieved in lab settings with different types of magnetometers. As such, they should be considered optimistic estimates for what could be achieved in operational environments. The second column extrapolates the expected detection distance for the type of sensor based on the indicated sensitivity, and the known relation between sensitivity and detection range (discussed below). As Hovde, Prouty, Hrvoic, and Slocum note, this is a notoriously difficult field to perform direct comparisons, since each type of sensor will also have operational challenges either arising from noise, detection range, or practical deployment challenges.[463] Thus, the final column in Table 5.1 notes expected operability and deployment constraints.

Table 5.1: Magnetometer Evaluation

Sensor Type	Resolution with Earth background (T/√Hz)	Estimated detection Range (m) for Columbia Class Sub with 99% suppression	Operability and Deployment Constraints
Optically Pumped Helium[464] [CAE]	10^{-12}	200	Dependent on field orientation in relation to Earth's magnetic field (would impact operability motion)
NV-Center Diamond[465]	10^{-12}	200	Requires better diamond fabrication and characterization techniques; decreasing the size (and diamond

[463] D. C. Hovde, M. D. Prouty, I. Hrvoic, and R. E. Slocum, "Commercial Magnetometers and Their Applications."
[464] Francis Lortie, "Magnetic Sensor System," U.S. Patent No. 9,864,019 B2 (January 9, 2018), available at https://patentimages.storage.googleapis.com/6c/2e/7e/033b1b891daa32/US9864019.pdf. Jeffrey Schweiger, "Evaluation of Geomagnetic Activity in the MAD Frequency Band (0.04 to 0.6 Hz)," Naval Postgraduate School Thesis (1982), https://apps.dtic.mil/sti/pdfs/ADA125641.pdf. Gregor Oelsner, Volkmar Schultze, Rob Jesselsteijn, and Ronny Stolz, "Performance analysis of an optically pumped magnetometer in Earth's magnetic field," *EPJ Quantum Technology*, Vol, 6, No. 6, 2019, https://doi.org/10.1140/epjqt/s40507-019-0076-9.
[465] Jixing Zhang, Lixia Xu, guodong Bian, Pengcheng Fan, Mingxin Li, Quming Liu, and Heng Yuan, "Diamond Nitrogen-Vacancy Center Magnetometry: Advances and Challenges," Arxiv, 2020,

			volume) to increase mobility could decrease sensitivity
SQUID[466]	10^{-15}	1800	Most systems require some cryogenic capability; susceptible to motion noise (less sensitive when moving)
Cold Atom[467]	10^{-10}	40	Very nascent technique; requires cryogenics
SERF[468]	10^{-16}	3800	Very limited bandwidth and operational range; requires temperature control
Transmon Superconducting Qubit[469]	10^{-12}	180	Requires cryogenics; operability not defined in mobile setting
Flux Superconducting Qubit	10^{-11}	80	Requires cryogenics; operability not defined in mobile setting

As Clem notes,[470] the sensitivity determines the operational range based on the signal that is being targeted and the correlated magnetic field. Fortunately, significant work has already been done to estimate the magnetic moments and magnetic field anomalies associated with submarines. Treating a submarine as a

https://arxiv.org/pdf/2010.10231.pdf; John Barry, Jennifer Schloss, Erik Bauch, Matthew Turner, Connor Hart, Linh Pham, and Ronald Walsworth, "Sensitivity Optimization for NV-Diamond Magnetometry," arxiv, 2019, https://arxiv.org/pdf/1903.08176.pdf; Ryoto Katsumi, Masaki Sekino, and Takashi Yatsui, "Design of an ultra-sensitive and miniaturized diamond NV magnetometer based on a nanocavity structure," *Journal of Applied Physics*, Vol. 61, No. 82004 (2022), https://arxiv.org/pdf/2010.10231.pdf.

466 M Buchner, K. Hofler, B. Henne, et al., "Tutorial: Basic principles, limits of detection, and pitfalls of highly sensitive SQUID magnetometry for nanomagnetism and spintronics," *Journal of Applied Physics*, Vol. 124, No. 161101, 2018, https://doi.org/10.1063/1.5045299; Z. Song, H. Dai, L. Rong, et al., "Compensation of a Mobile LTS SQUID Planar Gradiometer for Aeromagnetic Detection," *IEEE*, Vol. 29, No. 8 (2019).

467 Venturelli, "A cold atom radio-frequency magnetometer."

468 Jundi Li, Wei Quan, Bingquan Zhou, Zhuo Wang, Jixi Lu, Zhaohui Hu, Gang Liu, and Jiancheng Fang, "SERF Atomic Magnetometer – Recent Advances and Applications: A Review," *IEEE Sensors Journal*, Vol. 18, No. 20, October, 2018.

469 Danilin and Weides, 2021. N. Gusarov, M. R. Perelschtein, P. J. Hakonen, and G. S. Paraoanu, "Optimized emulation of quantum magnetometry via superconducting qubits," *Physical Review A*, Vol. 107, No. 052609 (2023); Andre Schneider, "Quantum Sensing Experiments with Superconducting Qubits," *Experimental Condensed Matter Physics*, 2021.

470 T. R. Clem, "Superconducting Magnetic Gradiometers for Underwater Target Detection," *Naval Engineers Journal*, January 1998.

magnetic dipole, the magnetic induction, B, for a point magnetic dipole with magnetic moment, m, at distance, d, is determined through the magnetic induction relation:

$$\boldsymbol{B} = \frac{3(\boldsymbol{m}\cdot\boldsymbol{r})\boldsymbol{r}}{\boldsymbol{d}^5} - \frac{\boldsymbol{m}}{d^3}. \qquad (5.5)$$

However, because the sensor is assumed to be at a distance, r, from the submarine that is much greater than the length of the submarine, Equation 5.5 is often simplified to $B = m/d^3$ in MAD detection range estimations.[471] Zhou, Chen, and Shan assess that the anomaly caused by a submarine is at around the order of a few nT (1nT = 1,000 pT),[472] in comparison to the geomagnetic background field of about 50,000 nT (50,000,0000 pT).[473] Therefore, the magnetometer would at least require a sensitivity within the fT to pT range (10^{-15} to 10^{-12} T) to discern the anomaly signal from the ambient geophysical signal at a standard operating distance.

As can be seen from Table 5.1, most proposed quantum magnetometers fall at or near the cusp of this sensitivity range, even at the early stages of R&D, suggesting a wide array of feasible future technology options. To distinguish the degree of detection improvement for each sensor, enhancements in detection range afforded by the varying sensitivity levels, as well as operability considerations, must be evaluated.

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[471] P. M. Moser, "Magnetic Signatures of Submarines," Pacific-Sierra Research Corporation, June 1994, https://apps.dtic.mil/sti/pdfs/AD1012958.pdf.

[472] Jiaxin Zhou, Jianyong Chen, and Zhichao Shan, "Spatial Signature Analysis of Submarine Magnetic Anomaly at Low Altitude," *IEEE Transactions on Magnetics*, Vol. 53, No. 12, December 2017, https://www.researchgate.net/publication/318891707_Spatial_Signature_Analysis_of_Submarine_Magnetic_Anomaly_at_Low_Altitude/link/5aa7cea145851539b3a2de37/download.

[473] Zhou, Chen, and Shan, "Spatial Signature Analysis of Submarine Magnetic Anomaly at Low Altitude."

In comparing the operational feasibility, a basic order-of-magnitude estimate for the detection range is likely the best approximation approach with available data. As discussed previously, many scholars have highlighted the near impossibility of accurately estimating the detection range of a MAD sensor in submarine detection, given the unpredictable time-varying and operational deviations, such as the operational depth of the submarine, changes in background noise, and variations in materials/suppression technologies built into different types of submarines. Therefore, given these constraints and the intent to use estimates to evaluate relative feasibility, this research attempts order-of-magnitude accuracy with the following approximation model.

Detection range approximation method

The first step is to approximate the geometry of the submarine's magnetic flux density. Technically, the magnetic moment for a submarine is a combination of vector components that indicate directional magnetic moments based on the shape of the submarine. Because the submarine is a cylindrical shape, there would be one significant magnetic moment along the horizontal axis of the submarine and another along the vertical axis of the submarine. However, because operational MAD would occur at a distance from the submarine that is significantly greater than the submarine length, a dipole is assumed, reducing the directional consideration to either the radial or the axial dimension.[474] Under this assumption, the magnetic flux density, B, at any point along these axes is calculated as a product of the magnetic moment of the

[474] P. M. Moser, "Magnetic Signatures of Submarines," Pacific-Sierra Research Corporation, June 1994, https://apps.dtic.mil/sti/pdfs/AD1012958.pdf.

object, m, the permeability of empty space, μ_0, and the inverse of distance along the axis, d, cubed, written as either:

$$B_{axial} = \frac{m*\mu_0}{2*d_y^3}, \text{ or} \qquad (5.6)$$

$$B_{radial} = \frac{m*\mu_0}{d_x^3}.$$

The magnetic flux density generated by the submarine can then be calculated by substituting the current loop magnetic moment assumption. In this assumption, the loop current, I_{loop}, corresponds to the magnetic moment through the relation, $m = I_{loop} * A_{loop}$, where the loop area, A_{loop}, is calculated using the submarine's hull radius, r_{sub}, and length, L. The flux density generation, based on current loop assumption and the Biot-Savart law, is then calculated as:

$$B_{axial} = \frac{I_{loop} * r_{sub}^2 * \mu_0}{2*(r_{sub +} d_y^2)^{3/2}}.^{475} \qquad (5.7)$$

Next, the B_{axial} relation can be used to determine the magnetic moment for the submarine. The interface between the submarine and the water is where the flux created by the magnetic moment of the submarine propagates. At this point, flux density is expressed as a relation between the magnetic field of the Earth, B_{Earth}, and the difference between the magnetic susceptibility of the submarine, $\chi_{submarine}$, and the susceptibility of the water, χ_{water}. The flux density change at the interface is determined as $B_{Earth} * (\chi_{submarine} - \chi_{water})$, where susceptibility indicates the degree of

[475] "MEA Magnetometer Detection Range," INTREL Service Company, 2014, http://www.intrel.com/mea/mag/mea_app_mag_rng_sum.pdf.

magnetization of a material (in this case, the susceptibility of the water or the submarine hull). Then, assuming that the above equation for B_{axial} is rearranged to calculate the magnetic moment, m, equal to the product of the area and the loop current, m can be written as:

$$m = I_{loop}Area_{loop} = \frac{B_{axial}*2*(r_{sub+}\ d_y^2)^{3/2}}{r_{sub}^2*\mu_0} *\ \pi * r_{sub}^2. \qquad (5.8)$$

With the new B_{axial} value and at a distance of half the length of the sub, to account for the radial distance, m simplifies to:

$$m = \frac{B_{Earth}(\chi_{sub}-\chi_{water})*2*\pi*(r_{sub}^2+(L/2)^2)^{3/2}}{\mu_0}. \quad (5.9)$$

Using this estimation, the magnetic flux density at varying distances can be determined by plugging the magnetic moment back into the initial magnetic flux density equations:

$$B_{axial} = \frac{m*\mu_0}{2*d_y^3} = \frac{B_{Earth}(\chi_{sub}-\chi_{water})*\pi*(r_{sub}^2+(L/2)^2)^{3/2}}{d_y^3}, \text{ and } \quad (5.10)$$

$$B_{radial} = \frac{m*\mu_0}{d_x^3} = \frac{B_{Earth}(\chi_{sub}-\chi_{water})*2*\pi*(r_{sub}^2+(L/2)^2)^{3/2}}{d_x^3}.$$

Finally, the detection range can be calculated by solving the above equations for the distance, using the sensitivity of the magnetometer as the upper limit for the magnetic flux to estimate the maximum detection distance. Yet, as was discussed above, in submarine detection (as well as in general sensing) estimation, a practical false alarm rate is often assumed. Thus, to minimize false alarms, the maximum field should be a factor of 10 times greater to ensure *reliable* detection.[476] This means that rather than being the equivalent of the magnetic flux parameter, the estimate is a product of 10 times the sensor sensitivity. Under these assumptions, the maximum distance in either the radial or axial range can be determined using relations:

$$d_x = \frac{B_{Earth}{}^{1/3}(\chi_{sub}-\chi_{water})^{1/3} * \pi^{1/3} * (4r_{sub}^2+(L)^2)^{1/2}}{4^{1/3} * equiv.mag.flux^{1/3}} \text{ and,} \qquad (5.11)$$

$$d_y = \frac{B_{Earth}{}^{1/3}(\chi_{sub}-\chi_{water})^{1/3} * \pi^{1/3} * (4r_{sub}^2+(L)^2)^{1/2}}{2 * equiv.mag.flux^{1/3}}.$$

Thus, the third column in Table 5.1, above, reflects the maximum detection range as estimated using Equation 5.11 to solve for d_x, with a range of assumptions regarding the submarine being detected, the sensor applied, and the environment.

Figure 5.1, below, depicts the relation between the magnetometer sensitivity and the detection range based on the approximation method. First, the submarine parameters are estimated using those of the new U.S. Columbia Class submarine, with hull length L = 171 meters, hull radius r_{sub} = 6.5 meters, and submarine mass = $2.11*10^7$ Kg (used to estimate the $\chi_{submarine}$).[477] (This estimation would thus differ to some degree for submarines with different dimensions.) Next, for each sensor, the best achieved sensitivity to-date is used, although in practical operation, this sensitivity is likely to be lower due to operational constraints (as will be detailed below). Finally, the background Earth magnetic field assumed is approximated at 58

[476] "MEA Magnetometer Detection Range," INTREL Service Company, 2014, http://www.intrel.com/mea/mag/mea_app_mag_rng_sum.pdf.
[477] "Navy Columbia (SSBN-826) Class Ballistic Missile Submarine Program: Background and Issues for Congress," Congressional Research Services, Updated July 18, 2022, https://sgp.fas.org/crs/weapons/R41129.pdf.

μT. Additionally, because every nuclear submarine in operation employs efficient signature suppression techniques,[478] a 99% field suppression success rate is assumed (meaning that the attenuated, detectable signal is assumed to be 1% of the signature that would otherwise be estimated based on the submarine's physical parameters).[479]

Figure 5.1: Detection Range Based on Sensitivity

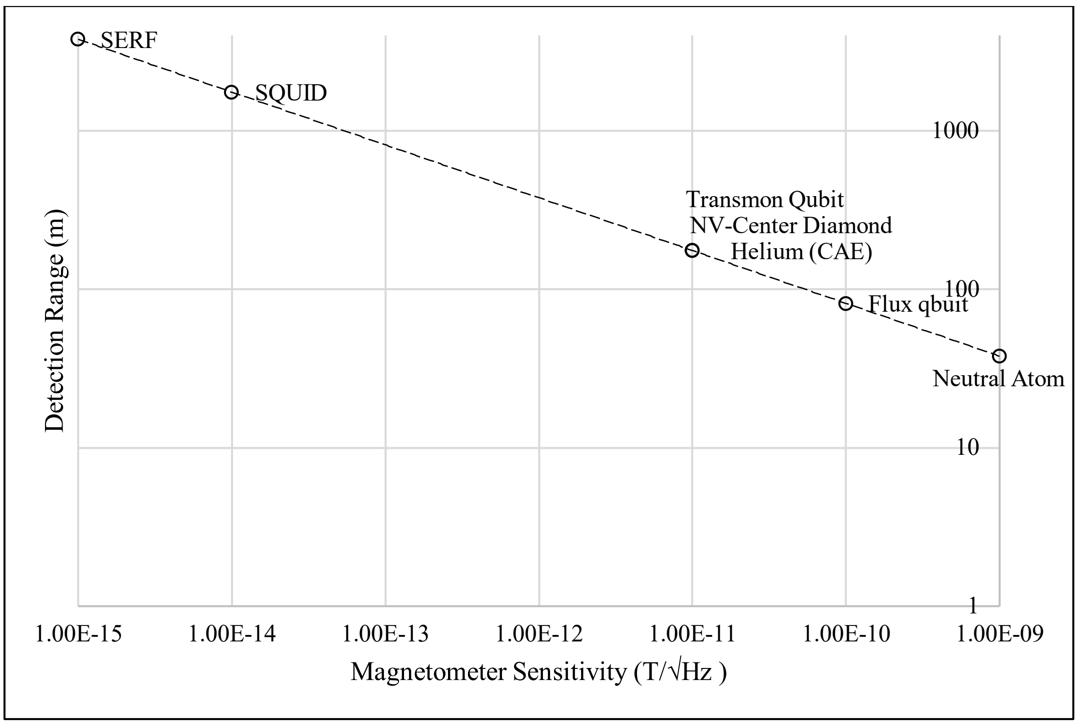

Figure 5.1 shows the sensitivity-detection range relation based on Equation 5.11 and the detection ranges for the different sensor types in Table 5.1 based on assumption of Columbia-class submarine parameters with assumed 99% stealth suppression capabilities.

[478] The exact value for degaussing suppression is not released by any country. However, reports of degaussing processes or demagnetization facilities suggest that all countries with nuclear submarine fleets utilize magnetic signature suppression techniques.
[479] "MEA Magnetometer Detection Range," INTREL Service Company, 2014, http://www.intrel.com/mea/mag/mea_app_mag_rng_sum.pdf.

As Figure 5.1 indicates, the maximum detection range that can be expected for MAD-based submarine detection is around 10,000 meters. However, this detection range is based on favorable sensitivity estimates from lab-based experiments. Furthermore, as can be seen in Figure 5.1, the sensitivities and detection ranges for quantum sensors lag compared to older sensor platforms like SQUID and SERF (although, as Table 5.1 showed, they may afford some improved operability parameters).

One of the largest and most challenging assumptions of the estimation has to do with the stealth capabilities that are employed for nuclear-armed submarines and the impact that this could have on the detection range. There is very little information in open-source literature on the stealth capabilities that are used and the relative effectiveness for suppression of magnetic signatures. Based on publicly available literature, the main method for suppression is degaussing while the submarine is at port.[480] Thus, there is a chance that throughout the duration of a submarine's patrol it loses some degree of stealth that could increase vulnerability.[481] Additionally, certain countries are known to have better stealth capabilities than others (which is discussed more extensively in Chapter 6). To account for these variations in stealth capabilities, Figure 5.2 provides estimates of the detection ranges that can be expected for different levels of stealth suppression, between 99.99% and 90%. As can be seen, as the stealth capability decreases, the detection range increases accordingly.

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[480] "Magnetic Silencing," DOD Report S0986-QN-STM-010 (1992), https://man.fas.org/dod-101/sys/ship/nstm/475r1.pdf.

[481] Jianming Fan, Wenchun Zhao, Shengdao Liu, and Zhen Zhu, "Summary of ship comprehensive degaussing," *Journal of Physics*, Vol. 1827 (2021), https://iopscience.iop.org/article/10.1088/1742-6596/1827/1/012014/pdf.

Figure 5.2: Detection Ranges Under Varying Stealth Suppression Capabilities

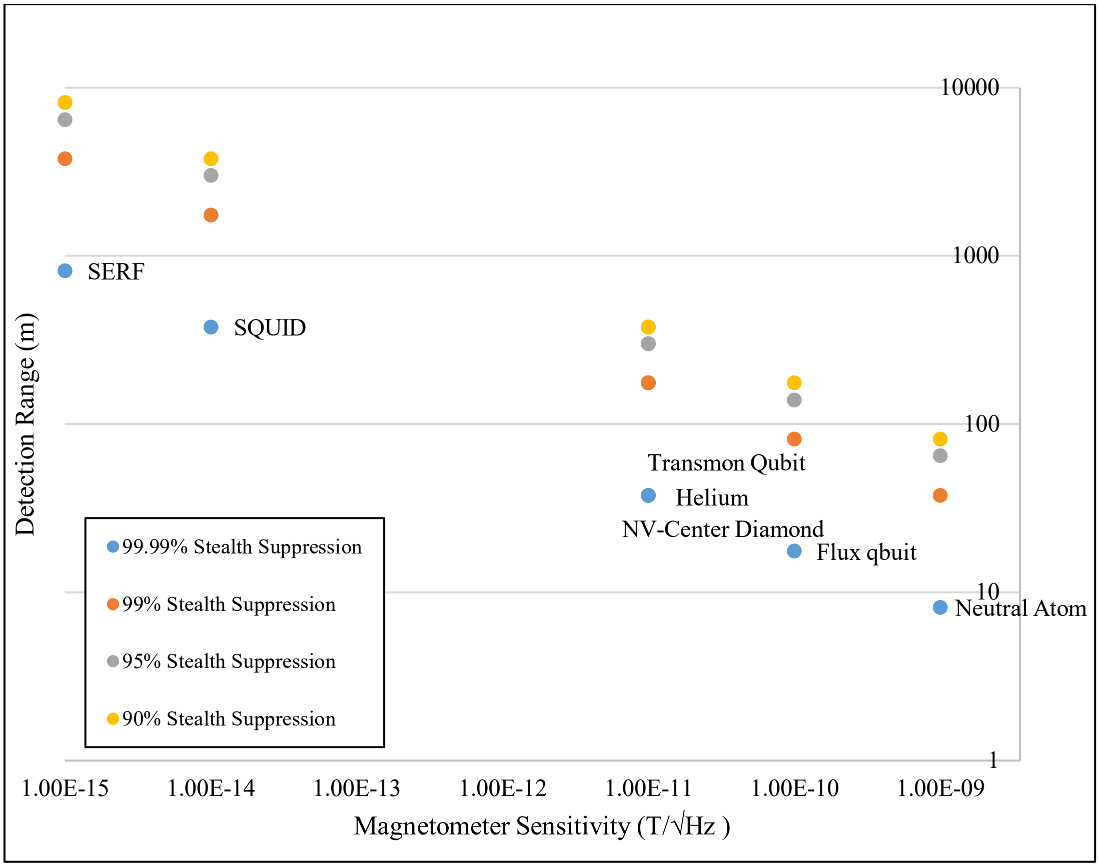

Figure 5.2 shows how detection ranges differ depending on assumptions about the stealth capability deployed to reduce magnetic signature.

MAD search problem

Deployment requirements to achieve strategically significant improvements in tracking or persistent observation capabilities based on estimated detection ranges must also be considered. The most ambitious goal for submarine monitoring would be persistent observation, a feat referred to as “transparent oceans.” Achieving this capability would require deploying an extensive network of sensors across all areas of the ocean in which submarines might operate to provide continuous awareness of their movements. A more modest objective would involve wide-area tracking and regional monitoring in ocean regions of particular strategic importance. The technological feasibility of satisfying deployment requirements for persistent global observation, regional monitoring, or tracking is assessed in this section.

Achieving the high ambition of persistent ocean monitoring in the next 10 years would be very challenging, according to open-source information about submarine operation and the magnetometer sensitivity levels presented in the previous section. The total area of global ocean coverage is approximately 300 million km^2. Even assuming a maximum predictable detection range of 10,000 meters and relatively low magnetic signature suppression capabilities, a network of ~ 1 million floating buoys would be needed to consistently monitor all global ocean coverage.[482] Beyond deployment, the task of maintaining and securing this network would be enormous. Even under ideal conditions, the magnetometers would have to be repaired, updated, or recalibrated periodically. Floating buoys would be susceptible to attacks, as well as natural interference from marine life or weather, which would require further upkeep or replacement. Alternatively, unmanned drone swarms, either on the ocean surface, in air, or underwater, could also be deployed. As mobile systems, they may be able to cover wider patrol areas through elegant search techniques but would still be limited by their battery lifetimes. Operating unmanned drone swarms would also impose significant systems engineering requirements for continual command and control.

[482] Assuming a 300 million km^2 area of global ocean coverage.

These deployment challenges in achieving a transparent ocean capability suggest that tracking may be a more attainable capability, where *a priori* information about submarine's location is used for targeted, local surveillance. In this scenario, sensors do not have to continually observe the whole ocean. They just need to be deployed locally to track submarines after they leave ports or known locations and follow the vessels throughout their patrols. However, because of the speed at which nuclear-armed submarines travel (with a maximum speed of at least 20 knots – or 23 miles per hour), this would require a network of high-speed drone swarms just to follow each submarine, a network of swarms dedicated to patrol certain areas, or a large enough fleet of dedicated nuclear-powered general-purpose submarines (SSNs) equipped with external MAD detectors on the perimeter of their hulls to track every foreign submarine of interest. Similar to the ocean-wide network deployment scenario, tracking techniques are also susceptible to countermeasures and evasive maneuvers. In contrast to the ocean-wide network deployment case, if a tracking network loses a submarine, it may be very hard to find it again.

Thus, even if advanced quantum sensors provided a ten-fold increase in detection range over the currently deployed MAD sensors, there would still be major operational challenges that would have to be met to accomplish persistent monitoring or tracking. Because of drone battery constraints and swarming system engineering challenges, it would be technically difficult, expensive, and risky to attempt either persistent monitoring or tracking. However, any increase in detection range does increase the feasibility of deploying such systems, especially if there were only a limited time window for which knowledge of submarine locations would be needed. Chapter 6 provides further discussion of strategic implications for these findings.

Quantum gravimetry alternative

In addition to magnetometry, quantum sensors using gravimetry and SAR have also been proposed for enhanced submarine detection. Lanzagorta, Ulhmann, and Venegas-Andraca et al. demonstrate that a new type of quantum gravity anomaly detection (GAD) sensor, referred to as Wigner gravimeters based on the type of spin rotations they measure, could feasibly detect submarines through GAD.[483] In their approximation analysis, the authors find that a 100-qubit quantum Wigner gravimeter, which would be considerable in size, could detect a submarine from a distance of about 200 meters. While this may be shorter than some MAD detection ranges, GAD would be more difficult to counter given that the hull mass can only be minimally manipulated to evade detection. However, constrained by this range, a quantum gravimeter would likely need to be located on a very low-flying plane, an unmanned aerial vehicle (UAV), or a surface ship.[484] And even then, coverage would not be guaranteed as the publicly declared maximum operating depth for U.S. nuclear submarines is around 240 meters (with unofficial claims of operability at 300 meters or deeper).[485] Such gravimeters would not be suitable for persistent, long-range surveillance, detection, or tracking, but could be used for highly localized monitoring in shallower waters. Finally, current research indicates that gravimetry would be challenging for detecting meter-length and mobile objects, given that longer

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483 Marco Lanzagorta, Jeffrey Uhlmann, Salvador Venegas-Andraca, "Quantum Sensing in the Maritime Environment." *IEEE Oceans*, 2015.
484 Lanzagorta, Uhlmann, and Andraca, "Quantum Sensing in the Maritime Environment."
485 Dorian Archus, "How deep can a submarine dive?" *Naval Post*, April 26, 2021.

measurement times would be needed.[486] However, there is promise that more prolonged research on quantum gravimeters and gravity gradiometers could yield major improvements that could make future application worthwhile.

Quantum synthetic aperture alternative

Quantum application to SAR for submarine tracking has also been considered.[487] In this application, quantum electric-field-sensing probes, such as the Rydberg atom sensor previously discussed, could be used to increase the resolution of existing SAR techniques. Additionally, quantum application could allow SAR sensors to leverage entanglement for enhanced signal distinguishability in low signal-to-noise-ratio environments, which could likewise increase the detection range of SAR sensors.[488] In these entanglement schemes, sometimes referred to as quantum illumination, entanglement would be applied by transmitting one entangled photon as the detection signal and retaining one entangled photon at the receiver in idle mode. Although the entanglement is lost throughout the signal photon's trip to the target and back to the receiver, the high correlation between the two allows for reduction of background when comparing measurements upon the signal photon's return.[489] This could theoretically allow for better detection of the signature waves formed as

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[486] Ben Stray, Andrew Lamb, Aisha Kaushik, et al., "Quantum sensing for gravity cartography," *Nature* Vol. 602 (2022), https://www.nature.com/articles/s41586-021-04315-3.
[487] Marco Lanzagorta, Oliverio Jitrik, Jeffrey Uhlmann, Salvador Venegas-Andraca, "Quantum synthetic aperture radar," *SPIE Defense and Security* conference presentation, 2017, https://www.spiedigitallibrary.org/conference-proceedings-of-spie/10188/101880F/Quantum-synthetic-aperture-radar/10.1117/12.2262645.short?SSO=1.
[488] Peter Vouras, Kumar Mishra, Alexandra Artusio Glimpse et al., "An Overview of Advances in Signal Processing Techniques for Classical and Quantum Wideband Synthetic Aperture," Arxiv, May 2022, https://arxiv.org/pdf/2205.05602.pdf.
[489] S. Barzanjeh, S. Pirandola, et al., "Microwave quantum illumination using a digital receiver," *Science Advances*, Vol. 6, No. 19, 2020, available at https://www.science.org/doi/10.1126/sciadv.abb0451.

submarines navigate underwater, which are too discrete to be consistently detected with current SAR techniques. However, recent studies conclude that, although quantum electrometers could eventually allow for a significant resolution gain, the technology is still at too nascent of a stage in R&D to even evaluate the resolution level that could be expected, or to anticipate the performance requirements that would have to be met.[490]

Countermeasure considerations

The last aspect that must be considered in predicting the utility of these different detection approaches is the likelihood that countermeasures will be developed that could negate the capability improvement. As was discussed previously, technologies and behavioral tactics that have been used to silence submarines have significantly reduced the utility of passive SONAR, especially for U.S. submarines. Countermeasures to subvert each new quantum submarine detection technique would require different approaches, and would vary in effectiveness, but are likely to be considered given the history of submarine detection and countermeasure developments.

Beyond existing magnetic silencing techniques, there are a few conceivable countermeasures to evade MAD that should be anticipated. As discussed previously, degaussing is already used to significantly reduce magnetic signatures and thus shorten the detection range for sensors. If a more extensive network of MAD sensors were deployed, additional decoy or jammer tactics could be developed. For example,

[490] Vouras, et al., "An Overview of Advances in Signal Processing Techniques for Classical and Quantum Wideband Synthetic Aperture."

magnetic pulse emitting devices could be deployed on underwater drones or submarines to overwhelm MAD detectors and to lure attention away from stealth submarines.

For GAD, countermeasures are expected to be more difficult. While engineers could attempt to rearrange the hull mass distribution to achieve a somewhat more subtle gradient, there will always be a significant gradient at the interface between the hull and the water. This presents a significant limit in the degree of camouflage that is attainable to prevent GAD detection. However, if GAD were ever to become truly operable, it is possible that altering submarine maneuvering tactics could decrease GAD imaging quality, given that gravimetry currently requires longer measurement times than magnetometry does; but, it is unclear what level or type of mobility this would entail.

Finally, sufficient SAR countermeasures could be achieved nearly entirely through changes in operational practices. Although moving submarines will always risk producing surface waves, operational practices could be adjusted to reduce the distinguishability of these waves, such as enforcing operational speed and depth changes or employing evasion techniques when weather patterns create turbulence and higher background noise on the ocean's surface to mask characteristic submarine waves. For shallow water regions which are particularly prone to submarine wave detection, vibrational devices could be employed to temporarily induce wave patterns that create sufficient background noise to conceal signature waves.

Beyond countermeasures geared specifically towards each of the detection methods, quantum application in nuclear submarine command, control, and communication may also allow for improved stealth capabilities. Quantum communication may enable submarines to receive communication from command-and-control centers without having to surface or approach the surface. Additionally, quantum sensors may be used to increase dead reckoning navigation capabilities for the submarines, which would allow for the submarines to navigate for longer periods of time without external signals. Thus, a variety of quantum applications may allow submarines to engage in less risky behavior, which would increase the difficulty of detection and tracking.

Missile Navigation Technical Assessment

A second potential quantum sensing application area which could have significant implications for nuclear deterrence is missile navigation. As a missile travels along its trajectory, a certain amount of error is assumed to accumulate, expressed as uncertainty in the accuracy estimation for the missile.[491] As discussed previously, one of the main sources of interest around quantum sensors is their potential to improve navigation through allowing dead reckoning, or navigation without external signals, and improved precision in PNT activities. The application of quantum-enhanced navigation techniques could thus lower the uncertainty in missile accuracy by allowing for higher precision and dead reckoning at key stages of the warhead's trajectory. If the error is lowered substantially, the capability improvement would have serious consequences for the survivability (or perceived survivability) of

[491] Matthew Bunn and Kosta Tsipis, "Ballistic Missile Guidance and Technical Uncertainties of Countersilo Attacks," Massachusetts Institute of Technology – Report 9, 1983.

nuclear forces, and thus would be impactful for nuclear doctrine, force structure, and arms control policymaking.

The United States, Russia, and China each have immense arsenals of ICBM-based nuclear weapons that are secured in underground silos hardened to withstand air blasts and ground shocks. While it is possible that a first strike could destroy a significant fraction of the hardened missile silos, some number of hardened silos are likely to survive a first strike. This enhanced survivability was a major impetus for the U.S. decision to overhaul silo designs to increase protection against Soviet missile strikes in the 1980s, despite concern that greater silo protection could induce arms-racing.[492]

Under current accuracy assumptions, it is usually assumed that two warheads would be needed to achieve a high probability of destroying each silo. For U.S. ICBMs armed with a single warhead, Russia may need to use two warheads to destroy one U.S. warhead. Thus, even a perfectly successful Russian strike would result in more surviving U.S. than Russian warheads. However, improvements in accuracy could allow for high probability of destruction with one-on-one attacks. Additionally, launching a disarming first strike would require many high-yield nuclear weapons to maintain a degree of certainty that the missiles will hit close enough to destroy the silos. These high-yield weapons would create a significant amount of fallout and casualties, increasing the likelihood of a retaliatory response.

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[492] Walter Pincus, "New Silo Hardening Tests Could Reopen Missile Basing Debate," *Washington Post* (May 11, 1984), available at https://www.washingtonpost.com/archive/politics/1984/05/11/new-silo-hardening-tests-could-reopen-missile-basing-debate/861520be-89e7-4508-b35c-8d96d87ce02a/.

Whether these effects would be stabilizing or destabilizing depends on the deterrence logic used, and will be addressed in the next chapter.

The magnitude of navigation-specific improvement that would be necessary to lower the required warhead yield by a given amount is unclear, as are the limits on targeting accuracy that can be achieved with quantum sensors. The degree to which a reentry vehicle can correct its trajectory after the boost stage is still limited by on-board maneuvering devices. This means that even if navigation became feasible in reentry, maneuvering would still be constrained under current reentry vehicle designs (and thus the warhead could only course-correct to account for a certain range of error). Moreover, the kill probability (or the likelihood that a warhead will effectively destroy the launch capability of a silo) will never reach 100% due to random variations across the weapons, missiles, and targets.[493] Therefore, improved navigation accuracy could only address a few of the factors that determine the yield or number of warheads needed to guarantee a successful, disarming first strike.

This section examines the ways in which quantum sensing may improve missile accuracy and assesses whether such applications could substantially increase the likelihood of a successful disarming first strike. First, this section examines the evolution of missile accuracies over the last few decades and highlights the innovations which have supported this progression, as well as the determinants of modern missile accuracy. Next, this section evaluates the likelihood of using various types of quantum sensors and feasible effects in reducing different sources of

[493] Bruce Bennett, "How to Assess the Survivability of ICBMs: Appendixes," RAND Report R-2578-FF, June 1980, pp. 1-5, https://www.rand.org/content/dam/rand/pubs/reports/2006/R2578.pdf.

navigation error to achieve further accuracy improvements. As it does for the submarine vulnerability analysis, Chapter 6 then evaluates whether these improvements would effectively impact perceptions of a feasible first-strike success or other strategic considerations, and thus would disrupt current secure second-strike and deterrence assumptions.

Determinants and evolution of missile accuracy

Intercontinental Ballistic Missiles (ICBMs) are composed of three main elements: rocket boosters, guidance systems, and payloads/warheads. They also have launch, post-boost, and reentry vehicles that integrate these components. The rocket boosters launch the ICBM during the boost phase, after which the boosters detach. During the midcourse phase, the post-boost vehicle (or payload bus), which includes the navigation system, maneuvers the missile to readjust targeting and eventually releases the reentry vehicle with the payload/warhead. After ejection from the post-boost vehicle, the reentry vehicle's trajectory is entirely ballistic.[494] Thus, the navigation systems for current ICBMs guide the missile's trajectory until just before the reentry phase. While it is possible that satellite navigation systems could be used to aid ICBM targeting in ideal environments (limited plasma and within the range of GPS signals), inertial guidance systems have been the prevailing form of navigation since very early on in ICBM development and deployment due to concerns about

[494] Matthew Bunn and Kosta Tsipis, "Ballistic Missile Guidance and Technical Uncertainties of Countersilo Attacks," Massachusetts Institute of Technology – Report 9, 1983, p. 6, https://scholar.harvard.edu/files/bunn_and_tsipis_ballistic_missile_guidance_and_technical_uncertainties_of_countersilo_attacks.pdf.

satellite susceptibility to countermeasures such as jamming.[495] With GPS-based systems, such countermeasures could effectively block navigation methods.

Throughout the history of ICBM improvements, various innovations have facilitated better guidance systems and thus have increased missile navigation accuracy. Very early navigation systems developed in the 1950s relied on massive strap-down inertial navigation platforms that were operated with pre-programmed analog computation and control systems.[496] Digital computers were developed soon after and allowed for faster and improved trajectory calculations that could incorporate data from on-board sensors. At the same time, somewhat smaller and more accurate inertial navigation systems were also developed.[497] Another innovation complementary to inertial navigation was the stellar sensor, which employed celestial navigation (or the viewing of star orientations) to determine the attitude of the warhead as it exited boost stage without requiring external communication, and which corrected a major source of error in early systems.[498]

With each of these developments, the goal has been to reduce various sources of error in missile navigation. Because the error in the accuracy of missile systems accumulates due to a variety of factors throughout the total trajectory of a missile, it is calculated cumulatively, with the total missile accuracy expressed as the circular error

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495 Bunn and Tsipis, "Ballistic Missile Guidance and Technical Uncertainties of Countersilo Attacks," p. 8.

496 Robert Braun, Zachary Putnam, Bradley Steinfeldt, "Advances in Inertial Guidance Technology for Aerospace Systems," AIAA Guidance, Navigation, and Control Conference (2013), Pp. 8, https://engineering.purdue.edu/RDSL/aiaa-guidance-navigation.pdf.

497 Braun, Putnam, and Steinfeldt, "Advances in Inertial Guidance Technology for Aerospace Systems," p. 8.

498 Stephen Rounds and George Marmar, "Stellar-Inertial Guidance Capabilities for Advanced ICBM" American Institute of Aeronautics and Astronautics, 1983, https://arc.aiaa.org/doi/abs/10.2514/6.1983-2297.

probable (CEP). Conceptually, the CEP value specifies the radius of a circle centered around the target within which 50% of missiles are expected to land.[499] Iterative improvements have sought to minimize certain contributions to this error budget. As smaller component errors accumulate, a guidance system that would be able to operate and correct such errors in the reentry and terminal phases could play a critical role in decreasing the CEP of a missile by negating the errors that accumulate throughout flight.

Throughout the evolution of ICBM technologies since the 1960s, and as inertial navigation sensitivity and computing power have improved, the CEPs for U.S., Russian, and Chinese silo-based ICBMs have shrunk significantly, as shown in Figure 5.3. Smaller CEPs in all three countries have facilitated counterforce strategies by enabling more effective targeting of hardened military and leadership targets, not just population centers, economic infrastructure, and soft military targets like bases. The first major improvement in ICBM accuracies, largely resulting from the transition to digital navigation computer systems, which the United States achieved in the 1960s, had enabled the shift to smaller warheads with lower yields. Together, improved navigation and smaller warheads paved the way for the eventual deployment of missiles with multiple independent reentry vehicles (MIRVs). The adoption of MIRVs has increased the feasibility of a disarming – or near-disarming – first strike and at a lower missile requirement.[500]

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[499] James Moran, "Probable Circular Error (CEP) of Ballistic Missiles," Utah State University Graduate Dissertation, 1966, pp. 1, available at https://core.ac.uk/download/pdf/127678696.pdf.
[500] "Case Study 3: The Origin of MIRV," https://minutemanmissile.com/documents/TheOriginOfMIRV.pdf.

Figure 5.3: Silo-Based ICBM CEP Reduction Over Time

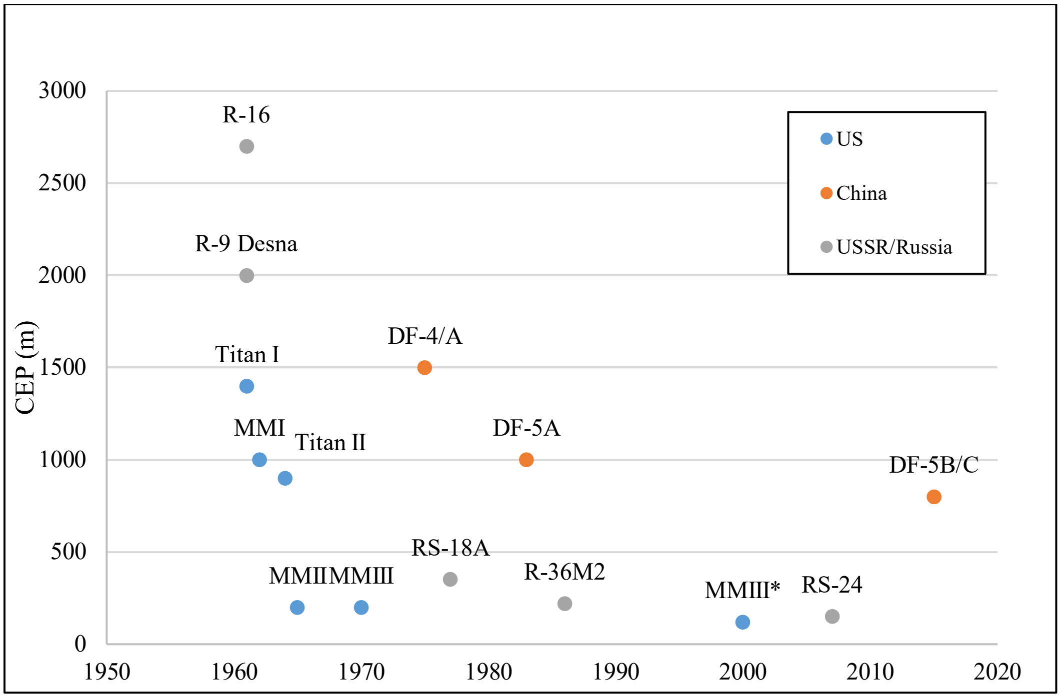

Figure 5.3 shows the progress in reducing CEPs for silo-based ICBMs. MMIII* indicates an upgrade for the MMIII missile system.[501]

If the CEPs for U.S. ICBMs could be significantly reduced again, more dramatic counterforce improvements are conceivable. With greater accuracy, lower yield warheads could be used to achieve the same lethality of strikes, and if the CEPs were shrink to below 10 meters then successful conventional strikes against hardened silos may also become feasible (or below 20 meters for soft, mobile launchers).[502] This section reviews the determinants of CEP estimates to assess the ways in which

[501] CEP values from: https://missilethreat.csis.org/missile/.
[502] Based on estimates from: Lauren Caston, Robert Leonard, Christopher Mouton, Chard Ohlandt, Craig Moore, Raymond Conley, and Glenn Buchan, "The Future of the U.S. Intercontinental Ballistic Missile Force," RAND Monograph 1210, 2014, pp. 75, https://www.rand.org/content/dam/rand/pubs/monographs/MG1200/MG1210/RAND_MG1210.pdf.

quantum sensing may improve missile CEPs. Strategic implications of the potential to reduce missile CEPs are discussed in Chapter 6.

To evaluate the impact that quantum sensors could have in further reducing CEP, it is important to understand the determinants of a missile's CEP. Mathematically, the CEP is calculated based on the probability that missiles will land within a certain range of a target.[503] The probability estimation for the missile distribution based on a given radius is calculated by integrating the distribution of missiles within the range of a target with an assumed standard deviation, σ, based on a Gaussian distribution and at all circles of radius, *r*, where *r* lies between 0 and maximum radius, R. The cumulative probability that the missile will land within a distance, R, from the target is expressed as:

$$P(0 \leq r \leq R) = \int_0^R \frac{r}{\sigma^2} e^{-\frac{1}{2}(\frac{r}{\sigma})^2} dr = 1 - e^{-\frac{R^2}{2\sigma^2}}. \qquad (5.12)$$

Because the CEP is defined as the radius at which P = 50%, the equation above can then be used to solve for R as the CEP radius.[504] This simplifies to the well-known expression:

$$CEP = 1.774\sigma. \qquad (5.13)$$

The sources of error that contribute to σ, and thus the cumulative CEP, arise from a variety of environmental and mechanical factors. Because CEP represents the

[503] John St. Ledger, "Nuclear Targeting Terms for Engineers and Scientists," LANL Report UR-17-20752, 2017, pp. 4, https://permalink.lanl.gov/object/tr?what=info:lanl-repo/lareport/LA-UR-17-20752.
[504] Moran, "Probable Circular Error (CEP) of Ballistic Missiles."

accumulation of these errors throughout the entire trajectory of a missile, an elaborate error propagation is required to fully parametrize the CEP, including the estimation of each individual contribution through a series of mixed stochastic and deterministic partial differential equations. Advanced modeling methods, such as the Monte Carlo simulation technique, have allowed analysts to attempt to evaluate and express the differential rates at which each source of error accumulates during different phases throughout the duration of a missile's trajectory.[505] These methods require precise values for numerous variables, many of which are classified or not publicly-available, to yield reliable, quantifiable estimates.

Given the high degree of uncertainty that still prevents clear, quantifiable estimation of quantum improvements, a more generalized method like that performed by Bunn and Tsipis can be used to conceptualize the contributions of different sources of error to the CEP value.[506] Bunn and Tsipis estimate each error source contribution individually, then express the standard deviation as the root-sum-square of the various error contributions:

$$\sigma = \sqrt{\sigma_{Init}^2 + \sigma_{Acc}^2 + \sigma_{Gyro}^2 + \sigma_{Comp}^2 + \sigma_{Thrust}^2 + \sigma_{Gravity+}^2 \sigma_{Reentry}^2 + \sigma_{Fusing}^2}\ . \qquad (5.13)$$

[505] For example, see George Siouris, "Chapter 6: Strategic Missiles," Chapter 6 in *Missile Guidance and Control Systems*, Springer, 2004, available at https://ftp.idu.ac.id/wp-content/uploads/ebook/tdg/MILITARY%20PLATFORM%20DESIGN/Missile%20Guidance%20And%20Control%20Systems.pdf; and Salem Abd El-Hakem Hegazi, Ahmed Kamel, Ibrahim Arafa, Yehia Elhalwagy, "INS Stochastic Noise Impact on Circular Error Probability of Ballistic Missiles," *Navigation*, Vol. 69, No. 2, 2021, available at https://navi.ion.org/content/navi/69/2/navi.523.full.pdf.
[506] Bunn and Tsipis, "Ballistic Missile Guidance and Technical Uncertainties of Countersilo Attacks," p. 49.

Table 5.2 defines each of these error sources, then summarizes an assessment of the likelihood for quantum sensing applications to reducing those error sources that is provided in the following section(s).

Table 5.2 Error Contributions to Missile CEP[507]

CEP Contribution	Error Source	Description	Quantum-Feasible Application?
σ_{Init}	Initiation sequencing	Initial error from positioning	Unlikely – pre-launch errors unlikely to be impacted
σ_{Acc}	Accelerometer	Error from accelerometer bias and scale factor	Likely – quantum accelerometers could reduce bias from drift and could be naturally calibrated (or calibrated with lower uncertainty
σ_{Gyro}	Gyroscope	Error from gyroscope bias drift and acceleration-sensitive drift	Likely – quantum gyros are likely to experience less drift over time and drift may be less susceptible to acceleration sensitivity
σ_{Comp}	Guidance computation	Error in guidance computer accuracy	Potentially – likely has already improved significantly with modern computers, but may be improved slightly with improvements from quantum navigation in readout
σ_{Thrust}	Thrust	Error from unpredictability of thrust termination	Unlikely - unless negated by post-thrust recalibration enabled through quantum sensing
$\sigma_{Gravity}$	Gravity	Error from gravitational variations; dependent on whether missile has a gravimetric system	Potentially – could be improved through more sensitive gravimetry sensors and through more accurate gravity surveys afforded by quantum sensors
$\sigma_{Reentry}$	Reentry	Error from asymmetries in reentry vehicles that create unexpected aerodynamic effects	Potentially – cannot impede error accumulation, but could correct if quantum sensing allows post-reentry navigation
σ_{Fusing}	Fusing	Error from fusing timing for detonation; Dependent on fuse quality and timing from navigation system	Potentially – partially dependent on navigation to determine fuse timing, which may be improved with quantum sensors

507 Bunn and Tsipis, "Ballistic Missile Guidance and Technical Uncertainties of Countersilo Attacks," pp. 30-49.

Quantum sensing applications to improve missile accuracy

Many scientists believe that quantum sensors will offer a host of unique benefits for guidance purposes compared to classical counterparts. Even without various operational sources of error, non-quantum inertial systems are inherently prone to drift over time due to small biases that accumulate in the process of dead reckoning, as well as mechanical wear in the sensors that causes alignment issues. Because of their high sensitivity, quantum inertial navigation sensors experience significantly less drift over time, which would incorporate a lower error volume into the CEP of the missile.[508] Additionally, as was previously discussed, absolute gravimeters or magnetometers could also be used, with prior mapping, to establish absolute positions and re-calibrate inertial sensors on warheads, or at the very least could be applied in parallel to inertial systems to allow for triangulation between the two guidance methods.

If these capabilities are achieved, then warheads could continue to navigate in the post-boost and terminal phases to strike targets with much greater accuracy. Motivated by a national directive to pursue conventional prompt global strike capabilities, both the Air Force and Navy researched methods to enable navigation in the reentry phase in the early 2000s.[509] Resulting tests of a Trident missile enhanced with a GPS-enabled reentry vehicle demonstrated the significance of this capability, finding that navigation in the reentry phase could afford accuracy within 10 meters.[510]

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[508] Michael Wright, Luke Anastassiou, Chnmaya Mishra, James Davies, Alexander Phillips, Simon Maskell, and Jason Ralph, "Cold atom inertial sensors for navigation applications," *Frontiers in Physics*, October 3, 2022.
[509] Amy Woolf, "Conventional Prompt Global Strike and Long-Range Ballistic Missiles: Background and Issues," Congressional Research Service – R41464, pp.8-9.
[510] Woolf, "Conventional Prompt Global Strike," p. 18.

However, achieving these advances would be no small feat, even with quantum sensing. Leveraging this degree of quantum application would require small-scale quantum sensors that are able to fit within the reentry vehicle and withstand reentry conditions. Significant R&D is needed to approach the necessary sizing milestones, and to ensure that small quantum systems are robust enough to withstand the extreme environmental strains placed on missile systems during reentry phase (as well as earlier phases). However, a recent influx of investment from both the Air Force and the Department of Energy demonstrates government interest in pursuing reentry navigation capabilities, indicating that R&D will likely progress, despite limited certainty in improvement for the foreseeable future.[511]

Much like other quantum technology research areas, there are a variety of different approaches being taken to achieve quantum inertial navigation. As discussed previously, quantum inertial navigation systems have four main parts: a three-dimensional atomic gyro, an accelerometer, an atomic clock, and a signal processing module.[512] Any number of technology types could be used to satisfy each requirement.

One category of quantum inertial sensors is based on atomic spin gyroscopes. The main approach has been to use the electron spins of alkali metal atoms to measure total angular momentum.[513] In recent years, as NV-center qubits have increased in popularity, diamond nuclear spin gyroscopes have also begun to

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[511] Parker, 2021.
[512] Donghui Feng, "Review of quantum navigation," *IOP Conference Series: Earth and Environmental Science*, Vol. 237, No. 032027, available at https://iopscience.iop.org/article/10.1088/1755-1315/237/3/032027/pdf.
[513] Jiancheng Fang, Shuangai Wan, and Heng Yuan, "Dynamics of an all-optical atomic spin gyroscope," *Applied Optics*, Vol. 52, No. 30, October 2013.

emerge.[514] While NMR gyroscope research dates to the 1950s, R&D in the field was recently reinvigorated due to quantum breakthroughs. NMR-based gyroscopes are now approaching the sensitivities seen in fiber optic gyroscopes (non-quantum state-of-the-art systems), but can be produced in much smaller sizes, making them suitable for use on missiles, and particularly reentry vehicles.[515] Boeing, which plans to conduct the first all-quantum navigation flight test in 2023, has pursued the NMR quantum gyroscope approach, a particularly promising variant of the atomic spin gyroscope;[516] Northrop Grumman has also indicated that it is developing NMR gyroscopes.[517]

Another quantum approach is based on atomic interferometry. Atomic interferometry gyroscopes that operate with cold atoms measure and compare different characteristics of atoms as they travel along diverging pathways, estimating the rotation of the system by calculating the difference between the two atoms. Sandia appears to be pursuing chip-scale cold-atom inertial sensors based on interferometry methods. Sandia researchers assert that quantum inertial sensors could increase missile accuracy by 1000 times.[518] However, they note that the biggest challenge will be making quantum systems, which have notoriously high control equipment

[514] Andrew Jarmola, Sean Louretta, Victor M. Acosta, Glen Birdwell, Peter Blumler, Dmitry Budker, Tony Ivanov, and Vladimir Malinovsky, "Demonstration of diamond nuclear spin gyroscope," *Science Advances*, Vol. 7, 2021.
[515] Meyer and Larsen, 2013.
[516] Interview with Jay Lowell, Boeing, November 29, 2022
[517] D. Meyer and M. Larsen, "Nuclear Magnetic Resonance Gyro for Inertial Navigation," *Gyroscopy and Navigation*, Vol. 5, No. 2, 2015.
[518] Matt Swayne, "'Rugged' Quantum Sensors Could Guide Vehicles without Satellites," Quantum Insider, October 25, 2022, https://thequantuminsider.com/2022/10/25/rugged-quantum-sensors-could-guide-vehicles-without-satellites/

requirements, small and rugged enough to be operational outside of lab settings.[519] To rectify these issues, the Sandia researchers have focused on the use of chip-scale photonics in quantum inertial sensors. In a recent research publication, they discuss the preliminary findings of a chip-scale compatible quantum inertial sensor.[520]

Finally, it is possible that fiber optic gyroscopes (FOGs), one of the non-quantum state-of-the-art platforms, could be augmented with quantum entanglement to surpass classically imposed noise limits. While better entanglement methods than those available today would be required, some researchers have already conducted preliminary analyses on such applications. Fink et al. demonstrate that, through applying non-classical states of light, the standard shot-noise limit that bounds current FOG systems can be exceeded to improve resolution and phase sensitivity.[521] However, the researchers ultimately conclude that, given current limitations in entanglement feasibility, such systems are still out-performed by traditional FOG systems.[522]

Table 5.3, below, provides a comparison of the different gyroscope platforms under consideration in terms of their sensitivities in measuring rotation (specified as °/s√Hz**)**, their bias stabilities throughout operation (°/s), and operability requirements.

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[519] M. Travagnin, "Cold atom interferometry for inertial navigation sensors," European Commission - JRC Technical Reports, 2020.

[520] Jongmin Lee, Roger Ding, Justin Christensen, Randy Rosenthal et. al., "A compact cold-atom interferometer with a high data-rate grating magneto-optical trap and a photonic-integrated-circuit-compatible laser system," *Nature Communications*, Vol. 13, No. 5131, 2022, https://www.nature.com/articles/s41467-022-31410-4.

[521] Matthias Fink, Fabian Steinlechner, Johannes Handsteiner, Jonathan Dowling, Thomas Scheidl, and Rupert Ursin, "Entanglement-enhanced optical gyroscope," *New Journal of Physics*, Vol. 21, (2019), https://iopscience.iop.org/article/10.1088/1367-2630/ab1bb2/pdf.

[522] Fink, Steinlechner, Handsteiner, Dowling, Scheidl, and Ursin, "Entanglement-enhanced optical gyroscope." And "Guide to comparing Gyro IMU technologies – micro-electro-mechanical systems and fiber optic gyros," KVH White Paper, 2016, https://caclase.co.uk/wp-content/uploads/2016/11/Guide-to-Comparing-Gyros-0914.pdf.

The values in Table 5.3 are based on observations and results achieved in experimental settings and published in open-source literature. It should be noted that, particularly as many quantum sensing platforms are being pursued for military use, it is possible that defense contractors, private companies, or military/government research groups have already achieved platforms that outperform the unclassified values specified in Table 5.3. Though this information is not available to the public. Additionally, very little research has been done to indicate how rugged quantum gryoscopes may be compared to non-quantum sensors, but this would clearly be an important consideration for application to reentry vehicles.

Table 5.3. Gyroscope Evaluation

Gyroscope Sensor Type	Sensitivity (°/s√Hz)	Bias stability (°/s)	Deployment Constraints
Diamond nuclear spin gyro[523]	10^{-5}	0.4	Accumulates bias quickly; will require magnetic shielding to reduce bias
NMRG spin[524]	10^{-6}-10^{-7}	10	Harder to entangle given characteristic defect differences
Cold atom interferometer[525]	10^{-7}-10^{-10}	10^{-8}-10^{-10}	Large equipment requirement; low operating frequency
Ring laser gyro (non-quantum)[526]	10^{-7}-10-[11]	10^{-9}-10^{-13}	Bulkier size
MEMs (non-quantum)[527]	10^{-7}	10^{-13}	Mechanical wear over time causes drift

[523] Jarmola et al., "Demonstration of diamond nuclear spin gyroscope.".
[524] Ke Zhang, Nan Zhao, and Yan-Hua Wang, "Closed-Loop Nuclear Magnetic Resonance Gyroscope Based on Rb-Xe," *Nature*, Vol. 10, No. 2258, 2020, https://www.nature.com/articles/s41598-020-59088-y.
[525] Carlos Alzar, "Compact chip-scale guided cold atom gyrometers for inertial navigation: Enabling technologies and design study," AVS Quqnatum Science*,* Vol. 1, No. 0144702.
[526]Scott Bezick, Alan Pue, and Charles Patzelt, "Inertial Navigation for Guided Missile Systems," *Johns Hopkins Applied Technical Digest*, Vol. 28, No. 4, 2010, https://secwww.jhuapl.edu/techdigest/Content/techdigest/pdf/V28-N04/28-04-Bezick.pdf
[527] Bezick, Pue, and Patzelt, "Inertial Navigation for Guided Missile Systems."

An additional application that could further reduce the composite CEP is the application of gravimeters and magnetometers for navigation and surveying based on absolute gravitational and magnetic field measurements. This process is colloquially referred to as map-matching, and entails the use of a precise gravimeter, gradiometer, or magnetometer in addition to a high-resolution gravitational or magnetic field map to estimate a position by comparing the absolute measurement in a location to a known field distribution.

As was indicated above, naturally occurring gravitational field anomalies inject an inherent uncertainty into the CEP because they cannot be easily predicted; they also limit the ability to perform high-precision map-matching navigation. However, if quantum gravimeters could be deployed on satellites to provide more frequent maps to account for time-variant uncertainties, either left of launch or while in-flight, then positioning using gravimeters could be used to recalibrate the missile navigation without needing GPS signals. Surveys and better knowledge of gravitational anomalies could also reduce the gravitational anomaly contribution to CEP.[528] Likewise, it is possible that magnetometers could achieve a similar effect through measuring and mapping Earth's magnetic field, as some quantum sensing platforms will significantly enhance magnetometry precision. There is, however, less evidence to support that this could feasible as compared to that for gravimetry.[529]

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[528] For example, discussed in Anthony DeGregoria, "Gravity Gradiometry and Map Matching; An Aid to Aircraft Inertial Navigation Systems," Air Force Institute of Technology – Thesis, 2010, https://core.ac.uk/download/pdf/277529181.pdf.
[529] Xuezhi Wang, Wenchao Li, et. al., "Quantum diamond magnetometry for navigation in GNSS denied environments," 2023, available at https://arxiv.org/abs/2203.16932.

On the feasibility of gravitational field-mapping, satellite gravimetry has already dramatically improved estimations for Earth's static gravitational field. GOCE and GRACE, satellite missions funded by the European Space Agency and NASA, respectively, have provided high-resolution and high-accuracy models of Earth's gravitational field, along with much better insight regarding sources of temporal variations.[530] This information is useful for a variety of things, including tracking climate change, ice melt, and geodynamics. It also demonstrates that further improvements could be achieved with better gravimeters.

Accurate maps of the Earth's static gravity field can also be used to improve navigation using gravitational field measurement. A recent quantum gravity cartography experiment was able to achieve 0.5-meter resolution,[531] which would be more than sufficient for calculating missile navigation with gravimetry. However, this experiment was performed on-land and with large instrumentation, raising questions about how long it would take and how much it would cost to map the Earth's static gravity field in every region of interest. As these methods improve, it may become feasible to conduct high-resolution surveys of gravitational or magnetic fields using small instruments deployed on satellites with broader terrestrial coverage. This would be necessary for augmenting missile navigation across territory controlled by unfriendly countries and across contested territory, both of which would contain important missile targets and be largely inaccessible to U.S. ground or air-mobile gravitational mapping systems.

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[530] Federica Migliaccio, Mirko Reguzzoni, et. al., "The MOCAST+ Study on a Quantum Gradiometry Satellite Mission with Atomic Clocks," *Surveys in Geophysics*, Vol. 44, 2023, pp. 666.
[531] Ben Stray, "Quantum sensing for gravity cartography,' *Nature Article*, Vol 602, February 2022, https://www.nature.com/articles/s41586-021-04315-3.

Countermeasure considerations and lower uncertainty limits

Predicting whether quantum technologies alone could help lower current CEP values by a full order of magnitude and whether that would be sufficient to ensure target destruction with conventional or low-yield nuclear weapons is complicated by several other uncertainties. First, in addition to errors encompassed by the CEP, there are persistent uncertainties in the kill dynamics. In other words, even if a missile achieves a near-direct hit, several other factors could influence whether that strike damaged the silo sufficiently to prevent a post-impact retaliatory launch. These kill dynamics are not discussed here, but have been explored by other analysts.[532] Importantly, these added layers of random (or systematic) error introduce further elements of uncertainty beyond errors that strictly affect CEP, and which could also impact confidence in one's ability to conduct a successful strike. The more targets that must be destroyed for a mission to succeed, the lower the overall probability of success would be.

There are fewer countermeasure opportunities for quantum navigation applications as compared to submarine detection and tracking because silos are by-nature immobile. Still, countries could use several methods to maintain a secure retaliatory ICBM capability as CEPs decrease. First, countries could construct decoy silos to increase the number of possible targets. Second, countries could set up point defenses near silos or install cages or pebble beds over silos to lower the kill probabilities; because conventional or very low-yield strikes would require near direct hits, anything that could diffuse or redistribute the missile's impact, even slightly,

[532] For example: Caston et al., "The Future of the U.S. Intercontinental Ballistic Missile Force."

could reduce its lethality significantly. Finally, to counter targeted, low-yield nuclear strikes, countries may be able to design their silo fields such that fratricide – or the inadvertent destruction of an incoming warhead by a preceding warhead detonation in close proximity – would reduce the certainty that a large number of ICBMs launched in a disarming first-strike attack would successfully destroy all of the targeted silos before a counterattack. Fratricide was a major concern when the United States planned to launch multiple high-yield warheads against each ICBM silo it hoped to destroy.[533] Less is known about how many highly accurate missiles would be assigned per target, and what the likelihood of fratricide would be if very-low-yield warheads were used.

Evaluating the Stage of R&D and Anticipating Obstacles

One reason there is limited discussion of technical feasibility for quantum sensor applications is that it is difficult to convert early R&D evaluations to real-world scenarios and to consider evolution of the technology over longer time periods. This analysis has used sensitivities and performance evaluations for quantum sensors in lab settings to anticipate upper limits in what can be reasonably expected for quantum sensing applications in the near term (less than ten years). Theoretical limits can be used to calculate the highest possible performance improvement for quantum sensors that could be achieved with sufficient resources and skill over the longer term. When surveying the potential future benefits of quantum sensors, though,

[533] Bunn and Tsipis, "The Uncertainties of a Preemptive Nuclear Attack," pp. 42-44.

practical limitations should also be considered. Experimental obstacles that constrain sensor operability in lab settings are already being identified. Another series of restrictions will arise when transitioning sensors to real-world environments.

Theoretical limitations

Theoretical limits help set the ceiling for all possible capability improvements that could be expected over time. They define the extent to which quantum applications could theoretically exceed the boundaries of possibility over non-quantum alternatives. Findings about the outermost limits of what might someday become possible have been the main drivers of interest and inflated expectations over quantum technologies because they suggest quantum systems should significantly outperform non-quantum alternatives. Three ways of expressing quantum theoretical limits include: Standard Quantum Limit (SQL), Quantum Fisher Information (QFI), and Quantum Cramer-Rao Bound (QCRB).

SQL establishes the theoretical prediction for noise, defining the minimum noise level for a sensor scheme *without* entanglement.[534] The less noise there is, the more sensitive the signal measurement can be. In a sensor system where qubits are not entangled, the SQL scales at rate of $\sqrt{N}$, where the greater number of qubits decreases the noise by a square root relation.[535] However, upon entanglement, the relation set by SQL theoretically changes to reflect the Heisenberg limit, which

[534] Standard Quantum Limit, Entry in *Photonics Encyclopedia*, https://www.rp-photonics.com/standard_quantum_limit.html.
[535] Jonathan Jones, Steven Karlen, Joseph Fitzsimons, Arzhang Ardavan, Simon Benjamin, Andrew Briggs, and John Morton," *Science*, Vol. 324, May 2009, https://www.ucl.ac.uk/quantum-spins/sites/quantum-spins/files/paper22.pdf.

dictates that as the number of entangled qubits, N, increases, the sensitivity scales at N rate.[536]

In contrast to the noise estimation given by SQL, QFI and the QCRB relate to the precision of estimation for a measurement. Quantum sensors use the precession of qubits to different quantum states to measure physical phenomena. Thus, to some extent, the information related to this precession is encoded in the quantum system. QFI quantifies the fidelity between the true state and the error state of the measured system, and thus the ability to measure a change in the state. Beckey et al. write that "A true state with a high QFI will be very distinguishable from the error state, making it easier to estimate the parameter via measurement."[537] The precision limit for estimating this value is given by the QCRB, which is the inverse of the QFI.[538]

Mathematically, the relation between the QCRB, θ, and QFI, F_Q, is given by:

$$(\Delta\theta)^2 \geq \frac{1}{mF_Q[\rho,H]}, \qquad (5.12)$$

where *m* defines the number of measurements, ρ is the state of the system, and H is the Hamiltonian that describes the precession of the system. The QFI defines the discernability between two states via their eigenvalues, λ_k and λ_l, and their eigenvectors, |k> and |l>, as well as the Hamiltonian:

$$F_Q[\rho,H] = 2\sum_{k,l}\frac{(\lambda_k-\lambda_l)^2}{(\lambda_k+\lambda_l)}|< k|A|l >|^2. \quad (5.13)$$

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[536] Jones, Karlen, Fitzimons, Ardavan, Benjamin, Briggs, and Morton, 2009.
[537] Jacob Beckey, M. Cerenzo, Akira Sone, and Patrick Coles, "Variational quantum algorithm for estimating the quantum Fisher information," *Physical Review Research*, Vol. 4, No. 013083, 2022.
[538] Changhao Li, MO Chen, and Paola Cappellaro, "A geometric perspective: experimental evaluation of the quantum Cramer-Rao bound,"Arxiv, April 2022, https://arxiv.org/pdf/2204.13777.pdf.

The improvement gained for each of the applications surveyed in this chapter would be dependent on the extent to which quantum mechanics is harnessed by the devices. Quantum sensors that achieve superposition phenomena could enable some performance improvement in sensitivity. But truly groundbreaking improvements would require the use of entanglement. Entanglement between multiple quantum sensors would increase the confidence of detection measurements, as a network of sensors would be able to compare anomalies from sensor to sensor in local settings. Entanglement could also allow for surpassing the SQL.

Experimental limitations

While the theoretical limits are useful for determining the upper-level sensitivity for quantum systems, it is widely understood that achieving these values, even in controlled laboratory settings, will never be feasible. Barriers to attaining theoretical sensitivity levels arise from various uncertainty sources in the laboratory setting, including uncertainties associated with laser control for manipulation and readout, as well as noise from instrumentation required for maintaining necessary conditions (dilution refrigerators, i.e.). Materials fabrication processes may also impart uncertainties within the quantum system. Together, these uncertainties imply that there will be some difference between what is achievable in an experimental setting and the performance gains that may be predicted through theoretical analysis alone. As many scientists have noted, this is likely to vary depending on the quantum systems used, because of variations in the materials and the control equipment required.[539] Due to the lower requirements for ambient environmental isolation, researchers have found saturation of the QCRB to be most feasible in solid-state quantum systems.[540]

The values in Tables 5.1 and 5.3, specifying the sensitivities of various magnetometers and gyroscopes, most accurately reflect what has been demonstrated under current experimental conditions. These are values that have been achieved in fairly early stages (although with some variation in R&D stage across qubit types) of R&D. Some further sensitivity improvement could be achieved by addressing these experimental sources of uncertainty, but they cannot be erased completely. Additionally, it is worth noting that because of the varying stages of R&D some sensors, such as solid-state sensors, may currently be at lower sensitivity levels, but may eventually be able to surpass other types of sensors if they have lower experimental noise limits.

Operation-based limitations

The final area for consideration is the extent to which operational conditions will further limit achievable bounds in sensitivity. The extent to which operational conditions will impact quantum technology sensitivity is not clear, as very few researchers have tested their devices outside of the lab setting. However, it is expected that increased uncertainty will be imposed due to greater environmental

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[539] Tanyue Xie, Zhiyuan Zhao, Xi Kong, Wenchao Ma, et. al., "Beating the standard quantum limit under ambient conditions with solid-state spins," *Science Advances*, Vol 7, No. 32, 2021.
[540] Min Yu, Yu Liu, Pengcheng Yang, Musang Gong, Qingyun Cao, Shaoliang Zhang, Haibin Liu, Markus Heyl, Tomoki Ozawa, Nathan Goldman, Jianming Cai, "Quantum Fisher information measurement and verification of the quantum Cramer-Rao bound in a solid-state qubit," *Nature Quantum Information*, Vol. 8, No. 56, 2022.

noise, mobility of devices, and target-related uncertainties. Environmental noise may include noise from other electronics, noise from space, etc. Mobility is also likely to decrease resolution, as the time of a measurement contributes to the sensitivity, and mobility requires shorter precession time. Finally, target-related uncertainties are highly likely given that many strategic targets, such as submarines, may themselves be moving or may employ countermeasures to complicate detection.

Due to the fact that operation in these settings has not yet fully been tested, values in Tables 5.1 and 5.3 do not account for these barriers. Thus, expectations for improvements from quantum sensors based on experimental results should be further adjusted to account for expected operational uncertainty. Finally, similar to the experimental uncertainties, different types of quantum platforms are likely to be more or less robust to operational uncertainties due to varying degrees of noise susceptibility or system control requirements.

Conclusion

This review has evaluated the advances that have already been achieved with quantum sensing technologies and explored ongoing progress in quantum sensing R&D. This analysis has also shed light on the complex nature of identifying and analyzing emerging technologies. Three important points about the overall trajectory of quantum sensing technology development have emerged. First, quantum sensing is not new; sensing technologies that rely on quantum phenomena extend at least as far back as the 1950s with the emergence of SQUID detectors. Second, this deeper history raises questions about the current practice of referring to the possible use of second quantum revolution methodologies for sensing and other purposes as "quantum technologies," while alternative methods that are already available are not recognized as "quantum technologies" but sometimes use quantum phenomena, too. And third, quantum sensing, in the sense that the term refers to sensing technologies that apply *new* quantum platforms or methodologies, will be evolutionary in comparison to their predecessors, rather than revolutionary.

Based on analyzing current quantum sensing technologies that could be considered as potentially applicable to submarine detection and missile navigation use cases, revolutionary disruptions are unlikely to occur in the next ten years. Quantum sensors that have exhibited performance enhancements over previous and contemporary non-quantum technologies are still largely restricted to use in labs or conditional settings, with very few prototypes having been tested in real-world environments. Further, many novel quantum technologies still lag behind current state-of-the-art technologies in either sensitivity or operability. Thus, loss of submarine invulnerability due to dramatic increases in detection capabilities is unlikely. Prospects for such a dramatic development are further reduced because some new quantum technologies could also facilitate improved countermeasures against new sensing efforts. Missile accuracy will continue to improve, but, because most quantum navigation technologies are still in the R&D stage, a significant reduction to CEP is unlikely to transpire in the next ten years, if not longer. Furthermore, underlying uncertainties in missile navigation and strike success rate cannot be addressed through improved guidance capabilities alone, if at all.

Because the newer generation of quantum technologies are more likely to be able to support entanglement once practicable networking methods are developed in the long-term future, they could eventually improve significantly beyond what would be feasible with non-quantum alternatives. It is far too early to say with confidence whether using entanglement for quantum detection or navigation systems could impact submarine invulnerability or reduce missile CEPs anywhere close to 10 m. This makes monitoring the development of more transformational quantum techniques an important thrust for maintaining awareness of breakthrough capability potential (discussed more in Chapter 7).

An added finding from this analysis has been the complex nature of monitoring a set of emerging technologies for certain use-cases, especially while the technologies are still in the R&D stage. First, comparing across technologies that operate in fundamentally different ways makes it challenging to definitively determine which technology would be more advantageous. Second, unanticipated challenges are likely to arise when converting each technology from a lab setting to an operational environment. Finally, particularly in defense applications, a significant amount of information that would be useful to determine thresholds and parameters for evaluating security-relevant applications is classified, and thus not available for open-source analysis. Some of these parameters, such as the stealth suppression level for submarines or the hardware within missile navigation systems, would be incredibly useful for establishing baseline capabilities and evaluating the potential disruption from new technologies. Executive branch agencies involved in decisions about deterrence strategy, force structures, and arms control, and Congressional staff for committees that make budget decisions and exercise oversight need their own technical experts with clearances who can compare their own assessments of what is technologically feasible with the claims being made by proponents of technology development and capability acquisition.

In attempting to separate technologies from capabilities, according to the analytical framework presented in Chapter 3, this chapter has analyzed the technologies underlying quantum sensing applications. Chapter 6 extends these findings to assess capability impacts relevant to nuclear deterrence and strategic stability. It anticipates debates about the broader implications for nuclear doctrine, force structure, and arms control that should be expected as quantum sensing technologies continue to develop. Chapter 7 then incorporates these assessments and, building on the complexity issues, evaluates the socio-technical issues emerging in the quantum sensing ecosystem that could contribute to inflated assertions or shape expectations of quantum technologies.

Chapter 6: Debating Quantum Sensing Implications for Nuclear Deterrence

"Without a doubt. Improved accuracy and lower yield is a desired military capability. Without a question."
-General Norton Schwartz, 2014[541]

"Well, I will just say throughout my career, people have been trying to tell me that the seas are going to be transparent. I have done a lot of ASW [anti-submarine warfare] in my years of service, and ASW is hard…It is not a trivial business, and I don't see in the foreseeable future the oceans becoming translucent."
-Admiral Cecil Haney, 2016[542]

Oftentimes the disruptive effects created by new technologies are only partially generated by the actual technical attributes of the system, and additionally arise from the political perceptions and strategic narratives around the innovations and the capabilities to which they are applied. This is especially true when uncertainty over a technology's development timeline or performance prospects fosters ambiguity over the technology and its impacts among actors with underlying political and strategic disagreements over deterrence and strategic stability requirements.

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[541] Hans Kristensen, "General Confirms Enhanced Targeting Capabilities of B61-12 Nuclear Bomb," Federation of American Scientists, January 23, 2014, https://fas.org/publication/b61capability/.
[542] "President Obama's Nuclear Deterrent Modernization Plans and Budgets: The Military Requirements," Hearing Before the Subcommittee on Strategic Forces of the Committee on Armed Services, House of Representatives, 114th Congress, 2nd Session, July 14, 2016, https://www.govinfo.gov/content/pkg/CHRG-114hhrg20822/html/CHRG-114hhrg20822.htm.

Chapter 5's technical assessment of how advances in quantum sensing could improve detection and targeting did not encompass the complete set of explanatory factors that inform policymakers' decisions when responding to new technologies. As outlined in the integrated analytical framework proposed in Chapter 3, strategic narratives, as well as social factors arising from the institutions and actors involved, also influence how policymakers perceive the impact of new technologies when deciding whether to pursue acquisition or bolster certain nuclear force structure elements.

Chapter 4's historical case study analysis further substantiated that strategic and social factors have influenced policy decisions in past cases of emerging technologies. In some cases, such as remote viewing and isomer weapons, despite recognition of limitations on what could be expected and technical assessments that confirmed these limitations, policymakers and members of the U.S. defense enterprise continued to pursue new technologies or capabilities. The fact that technical feasibility alone cannot explain these decisions indicates that there is a more complex interplay between technical assessments like those performed in Chapter 5 and the strategic narratives and institutional dynamics around new technologies and nuclear deterrence that ultimately influence policy decisions. These strategic and social factors must also be considered in analyzing the case of quantum sensing.

This chapter explores how strategic factors, particularly competing AD and DL logics for deterrence, influence perceptions about how significant the improvements in detection and targeting offered by quantum sensing are likely to be, and how such advances would impact mutual vulnerability, secure second strike, and pre-emptive first strike dynamics. Contrasts between current claims about what quantum sensing will be able to do in the next decade and the findings in Chapter 5's technical analysis suggest that the discourse surrounding quantum sensing is evolving in a manner similar to the early dialogue that preceded many technologies in Chapter 4's historical case studies. Initially, quantum sensors garnered interest from government and private sector funders, which then catalyzed concern about potential implications for nuclear deterrence, as well as other domains. In applications relevant for deterrence, quantum sensing prospects were used to press existing debates, driven by underlying disagreements on nuclear deterrence strategy. As a result, recognized technical progress and policymaker interest have reinforced further propagation of expectations that quantum sensing technologies will have potentially disruptive applications. This is despite barriers to unambiguously disruptive quantum sensing capabilities, such as those afforded by entanglement, that are unlikely to be overcome in the near or medium term-future, even with significant R&D.

This chapter analyzes the strategic and political elements of the integrated analytical framework, focusing more closely on the capabilities than the technologies. This chapter begins by providing a concise overview of the competing theories related to secure second-strike, mutual vulnerability, and deterrence doctrine, and discusses the ways in which ambiguity around new technologies galvanizes debates over these topics. It then uses the technical assessments from Chapter 5 to reduce some of the uncertainty and inform different perspectives in these debates to assess the extent to which quantum sensing could fundamentally disrupt the strategic stability status quo, including conditions of mutual vulnerability and reduced first-strike incentives. However, it also evaluates how remaining technical uncertainty fosters ambiguous perceptions of technologies that are malleable enough to reinforce existing narratives on vulnerability, deterrence, and strategic stability requirements. It shows how diverging appraisals of capabilities that would be needed to disrupt strategic stability, arising from competing deterrence logics, lead groups to treat uncertainty in technical assessments differently. It also considers how larger debates, such as over the future of nuclear deterrence amid technological change, could be invoked in quantum sensing dialogue.

Secure Second Strike, Mutual Vulnerability, and Deterrence Theory

Secure second strike and mutual vulnerability are key concepts that underpin deterrence. Secure second strike, assured second strike, assured retaliation, and similar terms are used to denote that a country has a high degree of certainty that it could retaliate for any type of nuclear attack, with sufficient surviving forces to ensure that adversaries will be deterred from ever attacking. If a country does not have a secure second-strike capability, or is not perceived to have one, then it cannot credibly communicate that its adversary is vulnerable to nuclear retaliation, and thus may not have an effective deterrent.

The balance of second-strike capabilities and mutual vulnerability also impact first-strike instability. Starting a nuclear war of choice could be rational for a country that believes it could launch a disarming first strike and not suffer any consequences from a second strike. Additionally, it could make countries more willing to use nuclear weapons pre-emptively if there is a high perceived probability that the other side intends to attack, making a pre-emptive first strike seem like a rational option to reduce overall nuclear damage, even if it assumes some smaller second strike would survive.[543]

Revisiting a common debate during the Cold War era, scholars, analysts, and policymakers have recently re-engaged on the question of whether to continue pursuing damage limitation or embrace mutual vulnerability as a way to increase strategic stability with lower costs and risks. The U.S. debate about mutual vulnerability for the sake of increased strategic stability has a deep history in the context of the Soviet Union (and now Russia). The desire to use BMD systems to protect U.S. population centers and ICBMs from as many Soviet missiles as possible, as noted in the case study in Chapter 4, and the controversy ignited over whether to agree to an anti-ballistic missile treaty to prevent similar Soviet BMD developments and thereby accept mutual vulnerability exemplifies this history.[544] More recently, some experts have argued that publicly accepting mutual vulnerability with China would enhance strategic stability, given China's nuclear arsenal expansion efforts and assessments that Chinese technologies and capabilities are reaching that of a "near-peer."[545] It would also reduce financial commitments to deterrence that would otherwise be needed to pursue DL strategies.

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[543] Glenn Kent and David Thaler, "First-Strike Stability: A Methodology for Evaluating Strategic Forces," RAND Report 3765-AF, 1989, https://www.rand.org/content/dam/rand/pubs/reports/2008/R3765.pdf.

[544] For example, surveyed in: Charles Glaser, "Nuclear Policy without an Adversary: U.S. Planning for the Post Soviet Era," *International Security*, Vol. 16, No. 4 (Spring 1992), pp. 34-78, https://muse.jhu.edu/article/447295/summary.

[545] For example: Charles Glaser and Steve Fetter, "Should the United States Reject MAD? Damage Limitation and U.S. Nuclear Strategy toward China," *International Security*, Vol. 41, No. 1 (Summer 2016), pp. 49-98; and George Perkovich, "Engaging China on Mutual Vulnerability," Carnegie Endowment for International Peace, Research Paper (October 12, 2022),

Typically, these discussions resurge as new technologies emerge, and as certain countries gain new capabilities that allow them to break away from or reassert conditions of mutual vulnerability. As discussed in Chapter 2, the conditions for mutual vulnerability and the strategic effects of accepting mutual vulnerability vary under different deterrence lenses. However, generally, in the former case, strategic parity in a dyadic relationship may be lost if one country has an asymmetric lead in a new technology that could allow for an overwhelming offensive or defensive advantage. The question as to what would be truly overwhelming is where disagreement arises across deterrence camps. In the latter case, strategic parity may be gained when one country uses technology innovations to achieve a state of strategic equivalence with another. Again, however, parity differs depending on the deterrence logic applied; in AD logic, it means that both sides have secure retaliatory capabilities even if one side has many more or better nuclear weapons, while in DL it means a rough quantitative and qualitative equivalence.

Ultimately, arguments in favor of maintaining mutual vulnerability assert that accepting an equilibrium condition provides stability by limiting risks of arms racing and crisis escalation. Allowing an adversary to maintain an uncontested assured retaliation capability is beneficial because it prevents risky arms racing and competition dynamics that may ensue if two countries feel that leadership in a given technology could render a significant asymmetric advantage. Mutual vulnerability arguments, therefore, are inextricably linked with AD logic, as espoused by

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https://carnegieendowment.org/2022/10/12/engaging-china-on-strategic-stability-and-mutual-vulnerability-pub-88142.

McNamara following his shift away from counterforce in the mid-1960s (reviewed in Chapter 4).[546] More recently, Renic has labelled this narrative as being guided by the allure of seeking peace through balance, where stability is achieved when balance is stalemated and peace between nuclear powers is thus fortified.[547]

To extend the BMD example, the treaty between the United States and Soviet Union on the limitation of anti-ballistic missile systems provides a clear example of two governments formally accepting mutual vulnerability and codifying it through limitations on testing and deployment. In 1972, in conjunction with interim limits on offensive nuclear weapons in the Strategic Arms Limitation Talks (SALT) between the United States and the Soviet Union, the two countries also established the Anti-Ballistic Missile (ABM) Treaty. It restricted the number of defensive ABM systems that each country could deploy, and thus disincentivized an arms-racing spiral that many anticipated would otherwise ensue as the two countries iteratively competed over offensive and defensive technology developments. In its stated narrative on the ABM Treaty, the U.S. Department of State Bureau of Arms Control indicated that the primary objective was: "to decrease the pressure of technological change and its unsettling impact on the strategic balance."[548] Supporters have feted the ABM Treaty as providing critical stability in the U.S.-Soviet deterrence and arms control

[546] David Yost, "Strategic Stability in the Cold War: Lessons for Continuing Challenges," *Proliferation Papers*, No. 36 (2011), pp. 16-19, https://www.ifri.org/sites/default/files/atoms/files/pp36yost.pdf.
[547] Neil Renic, "Superweapons and the myth of technological peace," *European Journal of International Relations*, Vol. 29, No. 1 (2022), pp. 5, https://doi.org/10.1177/13540661221136764.
[548] "Treaty Between the United States of America and the Union of Soviet Socialist Republics on the Limitation of Anti-Ballistic Missile Systems," Undersecretary for Arms Control and International Security – United States Department of State, May 26, 1972, https://2009-2017.state.gov/t/isn/trty/16332.htm.

relationship for decades, despite the fact that the United States eventually withdrew in 2002.[549]

From the perspective of those who prefer a DL approach to deterrence, acceptance of mutual vulnerability involves significant strategic and political risks. Strategists applying a DL logic assert that it is strategically advantageous for the United States to do whatever it can to reduce its relative vulnerability to any type of nuclear attack. DL advocates place a high premium on flexibility in response options and urge that any small effort to increase strategic advantage should be pursued, assuring that doing so does not decrease stability. For example, Matt Kroenig argues that the value of DL efforts cannot be quantified, claiming that even the use of "arbitrary" thresholds to assess the degrees of DL that are achievable undervalues each smaller, iterative effort to reduce the impact of a nuclear attack.[550]

Kroenig further asserts that recent literature finds that "a U.S. damage-limitation capability bolsters deterrence and extended deterrence," and that one state having nuclear superiority does not fundamentally undermine the other state's deterrent capability.[551] Rather, Kroenig and that support escaping mutual vulnerability in favor of nuclear superiority to reduce the strategic value of a nuclear deterrent against the United States argue that peace is most attainable by having one

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549 James Lindsay and Michael O'Hanlon, "Missile Defense after the ABM Treaty," *The Washington Quarterly*, Vol. 25, No. 3 (Summer 2002), pp. 163-176, https://www.tandfonline.com/doi/pdf/10.1162/01636600260046316.
And Lisbeth Gronlund, George Lewis, Theodore Postol, and David Wright, "Highly Capable Theater Missile Defense and the ABM Treaty," *Arms Control Today*, Vol. 24, No. 3 (April 1994), pp. 3, https://www.proquest.com/scholarly-journals/highly-capable-theater-missile-defenses-abm/docview/211199829/se-2.

550 Matthew Kroenig, "Correspondence: The Limits of Damage Limitation," *International Security*, Vol. 42, No. 1 (Summer 2017), pp. 199-201, https://muse.jhu.edu/article/667398.

551 Kroenig, "Correspondence: The Limits of Damage Limitation," pp. 200.

country with a clear nuclear lead (so long as that country is the United States).[552] They believe that even if nuclear superiority does not necessarily ensure that pre-emption and missile defense can be used to keep nuclear damage to zero, it still reduces a deterrent's power against the United States.

As this debate over mutual vulnerability reemerges under new conditions, it raises questions over the strategic effects of new technologies and resulting capability improvements. China's expanding nuclear arsenal undermines a U.S. DL strategy.[553] New technologies and capabilities, such as those that enable cyber domain engagement, highlight questions over the longevity of AD and strategic stability based on the sheer destructive power of nuclear weapons.[554]

While a debate deriving from disagreements in political approaches to deterrence is nearly unavoidable regardless of what information technical analyses provide on the impact of new technologies, greater insight on technical expectations can at least help to set reasonable bounds over the limits for the debate. The decision to accept mutual vulnerability has been debated since the Soviet Union developed its own nuclear weapon and is unlikely to fade away soon; for many, deterrence narratives reflect deeper worldviews, theories on international relations, and perspective on the U.S. role in global governance. However, a clear technical analysis can help to minimize the degree of interpretive flexibility in claims made by

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552 Matthew Kroenig, *The Logic of American Nuclear Supremacy: Why Strategic Superiority Matters*, Oxford University Press (2018).
553 Perkovich, "Engaging China on Mutual Vulnerability."
554 Renic, "Superweapons and the myth of technological peace," pp. 129-152; And Keir Lieber and Daryl Press, "The New Era of Counterforce: Technological Change and the Future of Nuclear Deterrence," *International Security*, Vol. 41, No. 4 (Spring 2017), pp. 9-49, https://direct.mit.edu/isec/article/41/4/9/12158/The-New-Era-of-Counterforce-Technological-Change.

advocates on either side of the debate and thus can bound the parameters for the discussion. To that end, the following section applies Chapter 5's assessment of quantum sensing technologies to address uncertainty and speculation in assertions about the deterrence effects of improved sensing capabilities and thus attempts to evaluate the extent to which political and strategic subjectivity contributes to decisions regarding new technologies.

Finally, a newer, smaller debate over whether the preemptive or second-strike capabilities in deterrence dynamics need to be comprised strictly of nuclear forces, has emerged in part due to emerging technologies that is also worth noting. Relatively recent scholarship has argued that advanced technologies may enable conventional deterrence and conventional counterforce capabilities, and thus suggests that mutual vulnerability may not have to be rooted in nuclear weapons at all.[555] Although there are deeper social dynamics that would impact any foreseeable adoption of conventional strategic capabilities (such as the perceived prestige of nuclear weapons[556]), this section also assesses the likelihood that quantum sensing could improve technical feasibility of advanced conventional attacks, evaluates resulting deterrence and strategic stability consequences, and surveys competing strategic and political narratives that contribute to disagreements on conventional counterforce regardless of technical assessments.

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[555] "Conventional Strategic Strike," Presentation by Scott Kemp at Stanford CISAC, November 11, 2021; And Tong Zhao, "Conventional Counterforce Strike: An Option for Damage Limitation in Conflicts with Nuclear-Armed Adversaries?" *Science & Global Security*, Vol. 19, No. 3 (2011), pp. 195-222, https://scienceandglobalsecurity.org/archive/sgs19tongzhao.pdf.
[556] Scott Sagan, "Why Do States Build Nuclear Weapons?: Three Models in Search of a Bomb," *International Security*, Vol. 21, No. 3 (Winter, 1996-1997), pp. 54-86, https://www.jstor.org/stable/2539273.

Quantum Sensing-Enabled Capabilities and Nuclear Deterrence

In the context of this overarching debate, articles that contest the assurance of a second-strike capability fundamentally question the sustainability of a mutual vulnerability equilibrium as a feasible logic for deterrence or an avenue to strategic stability. Therefore, arguments that hint at some future demise of a secure second strike, such as "The Standstill Conundrum" by Rose Gottemoeller,[557] "Stalking the Secure Second Strike" by Austin Long and Brendan Rittenhouse Green,[558] and "The New Era of Counterforce" by Keir Lieber and Daryl Press[559] uniformly generate a remarkable amount of concern, regardless of the different policy conclusions they may arrive at.

These arguments focus on a few key pathways for sustaining a reliable retaliatory capability, including mobility and concealment of delivery vehicles, hardening of delivery vehicles, and the number (or redundancy) of delivery vehicles and warheads.[560] If a retaliatory capability is sufficiently assured, then counterforce strikes (or disabling first strikes, either for a war of choice or in pre-emption) are perceived as infeasible and thus disincentivized. Each of the pillars that bolster survivability are briefly discussed in this section, and the impact of quantum sensing

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[557] Rose Gottemoeller, "The Standstill Conundrum: The Advent of Second-Strike Vulnerability and Options to Address It," *Texas National Security Review*, Vol. 4, No. 4 (Fall 2021), pp. 115-124, https://tnsr.org/2021/10/the-standstill-conundrum-the-advent-of-second-strike-vulnerability-and-options-to-address-it/.
[558] Austin Long and Brendan Rittenhouse Green, "Stalking the Secure Second Strike: Intelligence, Counterforce, and Nuclear Strategy," *Journal of Strategic Studies*, Vol. 38, No. 1-2, pp. 38-73, https://doi.org/10.1080/01402390.2014.958150.
[559] Lieber and Press, "The New Era of Counterforce," pp. 9-49.
[560] Lieber and Press, "The New Era of Counterforce," p. 16.

on the counterforce/disabling first strike feasibility is subsequently analyzed based on these pillars. Importantly, the three pillars are not insulated from one another in nuclear force structure decision-making, and consequences for one avenue necessarily impact requirements in the other two. For example, if new technologies affect a country' ability to ensure hardened and concealed delivery vehicles, they could also incentivize a larger arsenal size in order to assure a similarly effective deterrent (as argued by Lieber and Press).[561]

The first approach, concealment or mobility, defines the difficulty of targeting a delivery vehicle in an arsenal. Concealment and mobility impose an added strike challenge and decrease the probability of a disarming first strike. These platforms are often viewed as the primary assured second-strike platforms because, in theory, they are untraceable or else are extremely difficult to track. This approach includes road-mobile missiles, which Russia, China, and North Korea deploy, as well as submarine-based nuclear weapon delivery systems, which the United States, Russia, China, France, the United Kingdom, and India all deploy.[562]

Road-mobile missiles and nuclear-armed submarines are instrumental in maintaining mutual vulnerability, though their assured concealment has come under question with improved tracking and monitoring capabilities afforded by new technologies. For example, in the case of road-mobile missiles, proponents of mutual vulnerability have grown concerned that satellite imagery, aided with artificial intelligence and machine learning, may afford an assured tracking capability.[563]

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[561] Lieber and Press, "The New Era of Counterforce," p. 11.
[562] Gottemoeller, "The Standstill Conundrum," pp. 115-124.
[563] Thomas MacDonald, "Hide and Seek: Remote Sensing and Strategic Stability," Massachusetts Institute of Technology Dissertation, June 2021,

Apprehension has also been generated by claims that advanced tracking technologies could allow for the monitoring and tracking of nuclear-armed submarines.[564] Either scenario would increase the requirements for mutual vulnerability, and thus would have a significant effect on strategic stability. However, these claims are not entirely new; likely because of the heavy reliance on concealment and mobility for assured second-strike capabilities, the vulnerability of nuclear-armed submarines and road-mobile missiles has been a significant source of concern since the systems were first deployed,[565] leading to an equally long history in the development of concealment tactics and stealth technologies.[566]

The second approach, hardening, defines the extent to which a force structure protects delivery vehicles from attack. ICBM silos represent the gold standard for hardening, as they are designed to survive a nearby nuclear explosion. As alluded to in Chapter 5, when the U.S. military undertook efforts to harden missile silos, some policymakers and deterrence experts voiced concerns that hardened silos could incentivize arms racing pursuits of larger and more accurate missile systems.[567] Despite this debate, and even in light of the high costs and long timelines for

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https://dspace.mit.edu/bitstream/handle/1721.1/139559/macdonald-tdmacd-phd-nse-2021-thesis.pdf?sequence=1&isAllowed=y.

564 Tytti Erasto, "Revisiting 'Minimal Nuclear Deterrence': Laying the Ground for Multilateral Nuclear Disarmament," SIPRI Insights on Peace and Security (June 2022), https://www.sipri.org/sites/default/files/2022-06/sipriinsight2206_minimal_nuclear_deterrence_1.pdf.

565 For example, evaluated in: Richard Garwin, "Will Strategic Submarines Be Vulnerable?" *International Security*, Vol. 8: No. 2 (Fall 1983), pp. 52-67, https://muse.jhu.edu/article/446029/summary.

566 Owen Cote, "The Third Battle: Innovation in the U.S. Navy's Silent Cold War Struggle with Soviet Submarines," Naval War College, Newport Papers (2003), available at: https://apps.dtic.mil/sti/pdfs/ADA421957.pdf.

567 Walter Pincus, "New Silo Hardening Tests Could Reopon Missile Basing Debate," *The Washington Post*, May 11, 1984, https://www.washingtonpost.com/archive/politics/1984/05/11/new-silo-hardening-tests-could-reopen-missile-basing-debate/861520be-89e7-4508-b35c-8d96d87ce02a/.

reconstructing silos, both the United States and the Soviet Union quickly began to harden their silos to bolster assured retaliation.[568]

Hardening efforts have only moderately improved since the Cold War, but ICBMs have remained a core fixture of the U.S. nuclear triad. While some analysts have argued that ICBMs are redundant in comparison to other components of the U.S. nuclear triad, others counter that they serve as a nuclear "sponge," meaning that they would absorb a significant amount of an adversary's firepower if the adversary were to attempt a counterforce attack.[569] Maintaining the hardening of a nuclear missile also necessarily constrains the ability to increase concealment/mobility; the more done to reinforce a facility, the less mobile and easier to find the protected delivery vehicle will be. This tradeoff, and the complexity that using mobility to protect some delivery vehicles and hardening others add to an adversary's targeting calculus, is one of the main arguments in favor of a redundant but complementary nuclear triad.[570]

The final approach is the number of weapons in a country's arsenal. If concealment and hardening cannot satisfactorily ensure a retaliatory nuclear capability, then a country's next best option is to increase the size of its arsenal.[571] Thus, the extent to which a country perceives its concealment and hardening to be successful (or not) will impact the resulting decisions over force structure and arsenal

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568 Brendan Green and Austin Long, "The MAD Who Wasn't There: Soviet Reactions to the Late Cold War Nuclear Balance," *Security Studies*, Vol. 26, No. 4 (2017), pp. 606-641, https://doi.org/10.1080/09636412.2017.1331639.
569 Steve Fetter and Kingtson Reif, "A Cheaper Nuclear Sponge," *War on the Rocks*, October 18, 2019, https://warontherocks.com/2019/10/a-cheaper-nuclear-sponge/.
570 Frank Klotz and Alexandra Evans, "Modernizing the U.S. Nuclear Triad: The Rationale for a New Intercontinental Ballistic Missile," RAND Perspective, 2022, https://www.rand.org/content/dam/rand/pubs/perspectives/PEA1400/PEA1434-1/RAND_PEA1434-1.pdf.
571 Lieber and Press, "The New Era of Counterforce," pp. 9-49.

size requirements (assuming that sustaining a secure second strike is factored into the decision-making). Although missile defense systems did not strictly impact concealment or hardening, the fact that they undermined an assured second-strike capability was a key rationale for developing multiple independently targetable reentry vehicles (MIRVs) for missiles.[572]

The quantum sensing analysis conducted in Chapter 5 challenges assertions that technological change will undermine concealment and hardening. As quantum sensors represent the frontier for accuracy and detection technologies, they make an excellent proxy for probing the longevity of infrastructure that relies on evading such capabilities in long-term scenarios. First, the analysis in the previous chapter found that quantum sensing will not easily allow for persistent detection or tracking of nuclear submarines. Second, the quantum sensing analysis identified ways in which sensors may allow for improved accuracy. In terms of nuclear deterrence, the two findings suggest that (1) submarine invulnerability is likely to endure, even with new technologies, and (2) increased accuracy may allow for lower yield nuclear weapons to destroy hardened silos. However, on the latter finding, there are fundamental challenges that would still make launching a disarming low-yield nuclear strikes technically difficult and politically undesirable from the perspective of many experts; furthermore, increased accuracy may also allow for use of conventional deterrence. The perceived deterrence effects for these findings and the ways in which they relate to larger debates over secure second strike and strategic stability are discussed below.

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[572] Herbert York, "ABM, MIRV, and the Arms Race," Science, Vol. 169, No. 3942, pp. 257-260 (1970), https://www.science.org/doi/10.1126/science.169.3942.257.

Submarine vulnerability

Although the detection capability threshold at which nuclear-armed submarines would become vulnerable is somewhat debatable, it is commonly assumed that achieving a reliable, consistent ability to track and target another country's submarines throughout the duration of their patrols would render them vulnerable. As discussed in Chapter 5, achieving the capability to monitor all navigable territories, referred to as "transparent oceans," would require a network of hundreds of thousands, if not a million, sensors that could persistently monitor oceans and provide constant, real-time information about the location of the sea-based delivery vehicles. Because a capability that affords transparent oceans would allow for the targeting of nuclear submarines at any point in time (and thus greater strike flexibility), it would be the gold standard for a strategically significant innovation that unambiguously undermines submarine invulnerability. However, a lower threshold that could still destabilize submarine invulnerability to some degree would be the ability to track nuclear-armed submarines. This would entail maintaining continual knowledge about the local positioning of submarines by targeting their location at one point in time (likely when they leave port) and persistently tracking them throughout their operations. Submarine tracking occupies a gray area on the scale of strategic significance, because tracking activities would be more prone to evasion, and thus could create windows of time with lower assurance of targeting potential.

Surpassing either of these thresholds would require enormous technological and support infrastructure. As was determined in Chapter 5, sizeable detection ranges would be required for monitoring or tracking, either to feasibly deploy a network of sensors or to allow detection of submarines from a reasonable distance such that the submarine is not able to detect and counter or evade the tracker.[573] Achieving the necessary detection range is complicated by the fact that countries have continued to innovate more powerful submarine stealth technologies that suppress characteristic submarine signals. Furthermore, the task of submarine detection varies depending on the country of focus. Each country's submarine fleet has different degrees of stealth capability to reduce the signatures emitted, which was considered in the analysis conducted in Chapter 5 by estimating detection ranges under various assumptions of suppression capabilities. Each country also has differing procedures for submarine patrol lengths, but generally they can last up to two months at a time. This extended duration exacerbates the strain on tracking efforts and increases the probability that trackers will lose submarines at some point in their patrols. Since each nuclear weapon country has multiple submarines in their fleets, tracking and targeting multiple vessels concurrently would be required to ensure a single, disarming first strike. While actively preparing submarine stealth capabilities and tactics was a priority during periods of war and strategic threat, Cote notes that the continued innovations by major countries during peacetime underscores the importance of submarine technology development as an indicator of assured military status.[574]

Given this significance, there is an equally long history of analysts and policymakers estimating the relative invulnerability of nuclear submarines over the course of technology innovations to evaluate the sustained contribution to deterrence

[573] Owen Cote, "The Third Battle: innovation in the U.S. Navy's Silent Cold War Struggle with Soviet Submarines," Naval War College (Newport, Rhode Island, 2003), https://apps.dtic.mil/sti/pdfs/ADA421957.pdf.
[574] Cote, "The Third Battle," pp. 89-90.

credibility. In the 1980s, Richard Garwin found that, given the size of the ocean and the technologies available, a large network of short-range detection devices would be needed to consistently track submarines. He also noted that long-range detection devices could easily be countered through the use of decoys, evasive tactics, or signal jamming. Thus, at the time he argued that nuclear-armed submarines would remain effective deterrents against preemptive strikes.[575] But these evaluations rarely had long half-lives, because new detection technologies continued to emerge and cast doubts over previous assessments. Throughout the 1980s and 1990s, the Department of Defense solicited multiple reports to evaluate nuclear submarines signatures compared to the signal-to-noise detection probability for various detection techniques, and ultimately reached similar conclusions to those of Garwin years prior.[576]

While this cyclical trend of invulnerability skepticism persists today, the enduring deterrent value of nuclear-armed submarines seems unlikely to change over the foreseeable technology horizon. As was the motivation for this evaluation, scholars and policymakers have voiced concerns very recently over whether nuclear submarines will continue to remain invulnerable.[577] Accounting for advanced quantum sensing technologies that have not even yet been achieved, Chapter 5's analysis found that detection ranges for submarines are unlikely to exceed 10 km over the next 10 years at least, and likely longer. Given how vast the ocean is (361 million

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[575] Garwin, 1983, pp. 67.
[576] For example: Paul Moser, "Magnetic Signatures of Submarines I," Pacific Sierra Research Corporation, 1994, available at: https://apps.dtic.mil/sti/citations/AD1012958; and Paul Moser, "Magnetic Signatures of Submarines II," Pacific-Sierra Research Corporation, 1996, available at: https://apps.dtic.mil/sti/citations/AD1012961.
[577] Kubiak, "Quantum Technology and Submarine Near-Invulnerability,"; Gottemoeller, "The Standstill Conundrum," pp. 115-124.; Lieber and Press, "The New Era of Counterforce," pp. 9-49.

km^2), a network of hundreds of thousands, if not millions, of sensors would still be required to constantly surveil the ocean and provide timely data on submarine locations within targetable ranges. To accomplish this would entail an enormous fleet of advanced drones or buoys, which would also require a complex analytic capability to provide continual monitoring and deployment control. Since submarine patrols extend for months, significant maintenance of the network would also be required to replace and repair drones as they experience wear-and-tear or deplete their batteries. Accomplishing these tasks could be even more challenging when accounting for the fact that the submarines that would be of targeting interest are likely to be operated predominantly in contested areas of the ocean, introducing major accessibility issues, as well as potential escalation risks for conducting tracking activities.

Furthermore, the technical analysis did not account for the ways in which quantum sensing could also be used to increase the stealth capabilities and tactics of submarines. For example, dead reckoning with quantum sensors could allow for submarines to remain submerged, without communication for longer periods of time.[578] This could reduce the number of risky maneuvers required to establish situational awareness in crisis or conflict scenarios, and thus would exacerbate the challenge of tracking submarines. Quantum communication may also decrease reliance on port or surface rendezvous by allowing for better communication while submerged, with research already suggesting that quantum key distribution could afford communication with submarines at depths between 50 and 110 m (although

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[578] Feng, "Review of Quantum navigation," pp. 1-10.

this is still quite shallow compared to the 200 m operating depth).[579] Finally, quantum sensing may provide submarines with better technologies for counter-detection activities, such as enabling the ability to identify a sensor near the vessel. More prompt identification could then alert the submarine of tracking activities nearby and would warn the crew to perform evasive tactics to lose the tracker and hide.

The impact of these assessments on the limits of quantum sensing for submarine targeting are significant. By evaluating the outer limit for detection capabilities, and determining that there is no near-term vulnerability, this analysis makes a meaningful contribution to the debate over the extent to which nuclear submarines, long heralded as the most assured leg of the triad, will become vulnerable. Therefore, the findings provide useful insights to inform deterrence debates, but also practical implications for force structure decision-making.

One important caveat in this analysis is that not all nuclear submarines are equal. As noted above, each country with nuclear submarines has qualitative differences in stealth technology performance, varying degrees of port accessibility, and fluctuating submarine and crewman availability that impact how easily submarine fleets can be tracked. The United States maintains 14 Ohio-class ballistic missile submarines which operate in the Atlantic Ocean via the Kings Bay, Georgia port and in the Pacific Ocean, via the Bangor, Washington port.[580] Russia's fleet includes 10 nuclear-powered, ballistic missile submarines (SSBNs), with the majority based in

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[579] Marco Lanzagorta and Jeffrey Uhlmann, "Assessing Feasibility of Secure Quantum Communications Involving Underwater Assets," *IEEE Journal of Oceanic Engineering*, Vol. 45, No. 3 (July 2020), https://ieeexplore.ieee.org/document/8667364.
[580] Hans Kristensen and Matt Korda, "United States nuclear weapons, 2021," *Bulletin of the Atomic Scientists*, Vol. 77, No. 1 (2021), pp. 51, https://doi.org/10.1080/00963402.2020.1859865.

Yagelnaya Bay in the Kola Peninsula.[581] China has six SSBNs, based in the Longposan naval base on Hainan Island.[582] The United Kingdom and France each have four SSBNs. And outside of NPT-recognized nuclear weapon states, India and North Korea have begun expanding their delivery vehicle infrastructure to include ballistic missile submarines.[583] Beyond the number of submarines in a country's fleets, there are also different standards that dictate how many submarines a country has on patrol at a given time.

Both China and Russia also deploy road-mobile missiles, which means that they rely less on their SSBNs as the sole means of mobile/concealed nuclear delivery vehicles than the United States does. However, this reliance has meant that the United States has gone to much greater lengths to ensure that its submarines remain invulnerable. U.S. SSNBs are widely recognized as the quietest of the nuclear submarines. Conversely, Chinese, and Russian submarines are known to be noisier, though there is limited publicly available information indicating the order of magnitude in these differences. Tong Zhao writes:

> There is very limited information available today about how quietly Chinese SSBNs operate, but international and Chinese experts generally agree that China's 094-class SSBN is relatively noisy…. Wu Riqiang, a Chinese scholar at Renmin University, has used open sources to estimate an answer. He found that low frequency noise level (100 hertz) – a widely used indicator of submarine quietness – attributed to China's 094-class SSBN is

[581] Hans Kristensen and Matt Korda, "Russian nuclear weapons, 2022," *Bulletin of the Atomic Scientists*, Vol. 78, No. 2 (2022), pp. 107, https://doi.org/10.1080/00963402.2022.2038907.
[582] Hans Kristensen and Matt Korda, "Chinese nuclear weapons, 2021," *Bulletin of the Atomic Scientists*, Vol. 77, No. 6 (2022), p. 329, https://doi.org/10.1080/00963402.2021.1989208.
[583] Dimitrios Mitsopoulos, "Nuclear Missile Submarines in the World in One Chart," *Popular Mechanics*, June 8, 2018, https://www.popularmechanics.com/military/navy-ships/a21204892/nuclear-missile-submarines-chart/.

> significantly higher than that of Russia's Delta IV SSBN. For the time being, at least, the Delta IV forms the backbone of Russia's SSBN fleet and is noisier than the United States' current generation of Ohio-class SSBNs.[584]

These variations mean that there would be some degree of strategic difference in force structure impact depending on which countries would achieve ocean transparency or a strategically significant tracking capability. Because of the United States' reliance on submarines as a secure second-strike guarantor, Chinese or Russian attainment of assured tracking or monitoring capabilities would have more detrimental impacts on U.S. survivability. Conversely, because Chinese and Russian reliance on SSBNs is offset by road-mobile missiles, U.S. ability to track or monitor submarine movements would have a somewhat lower impact. However, the feasibility of China or Russia developing the capability to track U.S. submarines is also lower given the more robust stealth capabilities and larger fleet to contend with. Meanwhile, despite the fact that U.S. efforts to track Russian and Chinese submarines may have fewer obstacles, a successful first strike would also require the ability to track and target road-mobile missile platforms in tandem with submarine tracking to guarantee a reliable first-strike window.

In terms of deterrence debates, assuring continued submarine invulnerability has consequences for both AD and DL advocates. As AD logic rests on the ability to ensure a retaliatory response, submarine invulnerability ensures prolonged reliability of AD. Conversely, for countries seeking to maximize DL and counterforce

[584] Tong Zhao, "Tides of Change: China's Nuclear Ballistic Missile Submarines and Strategic Stability," Carnegie Endowment for International Peace, 2018, pp. 26, https://carnegieendowment.org/files/Zhao_SSBN_final.pdf.

capabilities, submarine invulnerability would mean that conducting successful splendid first strikes capable of destroying an adversary's entire retaliatory infrastructure would be extremely challenging. Even if some level of improved tracking was achieved, counterforce windows would be very slim depending on when submarines are launched and how long trackers are able to maintain close enough proximity to all submarines in an adversary's fleet to ensure successful targeting. Furthermore, these windows are unlikely to be predictable or reliable, especially in crisis scenarios when adversaries would increase evasive maneuvering.

However, even with greater technical understanding, AD and DL proponents will deal with remaining uncertainty over quantum sensing R&D and ambiguity over detection capabilities differently. Both AD and DL would accept that in the near term, quantum sensing might marginally improve local tracking of individual subs after they leave port, although even this would lead to debates over the strategic advantage of limited tracking abilities. AD logic establishes high threshold for disruption – quantum sensors would have to enable an assured disarming first strike capability to fundamentally undermine mutual vulnerability. Therefore, AD proponents are likely to accept that the remaining technical uncertainty over quantum sensing means that transparent oceans are unlikely to be feasible soon, if at all. Conversely, DL logic establishes a lower disruption threshold. DL proponents view any small amount of technological improvement as providing more flexibility, even with uncertainty, and furthermore argue that long-term R&D could still afford major breakthroughs.

In terms of force structure, these findings suggest that DL-driven arguments to hedge submarine vulnerability with other delivery systems may be misguided, or at the very least biased. As Fetter and Reif identify, one argument from the defense enterprise in favor of ICBMs is that they hedge against a future where submarines become vulnerable, making a sponge more necessary. Chapter 5's analysis refutes this possibility, at least within the next few decades, and therefore undermines the validity of this substantiation for ICBMs (and ICBM modernization efforts). This is also a timely issue as the current U.S. modernization plan calls for drastic improvements to ICBMs that will cost exorbitant amounts of money and require ICBM maintenance and inclusion in the U.S. force structure for at least the next 50 years (the lifespan for the new Sentinel ICBM systems).[585] Furthermore, from an AD perspective, significant improvements to ICBM capabilities could also be destabilizing if they are perceived as undermining other countries' deterrents.

Targeting accuracy and nuclear deterrence

The second capability evaluated was missile navigation and targeting accuracy. Because one of the main use cases considered for quantum sensing technology is position, navigation, and timing (PNT), it is highly likely that quantum sensors will be used to augment missile navigation and improve targeting accuracy, as was explored in the analysis in Chapter 5. The steady improvement in these capabilities that could be expected as quantum sensing innovations are deployed produces an interesting mix of implications for strategic stability through impacting both counterforce and assured destruction feasibility. Like the submarine

[585] Steve Fetter and Kingson Reif, "A Cheaper Nuclear Sponge," *War on the Rocks*, October 18, 2019, https://warontherocks.com/2019/10/a-cheaper-nuclear-sponge/.

vulnerability assessment, this could yield important findings for nuclear deterrence strategy, force structure, and arms control policymaking.

Over time, changes in deterrence theory and technological advancements that have improved accuracy have precipitated shifts in the strategy behind nuclear weapon targeting decisions. When nuclear weapons were first invented, urban centers (or cities) were the primary targets considered, partly due to limited targeting accuracy, either via bombing or with missiles after the late 1950s, that would have made it difficult to effectively strike smaller or more distributed transportation or military infrastructure.[586] Eventually, Bernard Brodie argued for formally adopting a more counterforce-centered strategy based on gradual improvements to missile and targeting capabilities.[587] Following Brodie's argument for counterforce, or the targeting of strictly military assets, researchers at RAND devised a delineation of three types of deterrence strategies: Type 1 – countervalue or urban targets only; Type II – a mix of counterforce and countervalue; and Type III – counterforce/no-cities. Countervalue, referred to as Type I deterrence, asserts that nuclear use would be threatened against large metropolitan areas.[588] Some analysts argued that Type I and Type II strategies had larger deterrent value because of the inclusion of urban targets. However, more modern nuclear strategy has generally conformed to a counterforce deterrence strategy, under the assumption that focusing on targets that have greater military significance and produce lower casualties make nuclear

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[586] David Rosenberg, "The Origins of Overkill: Nuclear Weapons and American Strategy, 1945-1960," *International Security*, Vol. 7, No. 4 (1983), Pp. 15, https://www.jstor.org/stable/2626731.
[587] Fred Kaplan, "Chapter 13: Counterforce" in *Wizards of Armageddon*, Stanford University Press (1983).
[588] Fred Kaplan, "Chapter 15: The Real Rivalry" in *Wizards of Armageddon*.

weapons more usable, thus increasing the deterrence value.[589] Further arguments have been made that nuclear targeting should conform to the Law of Armed Conflict, which would prioritize counterforce strategies.[590]

Despite the stated goal of Type III deterrence, however, targeting strictly military infrastructure would still produce a significant amount of fallout and civilian impact. This is in part due to accuracy limitations associated with targeting and destroying hardened military infrastructure, which require larger-yield or higher numbers of warheads. This is exacerbated by the sheer number of ICBMs that would need to be targeted. Because of their arsenal sizes, launching a strike against U.S., Chinese, or Russian ICBM forces would still generate an undeniably large amount of radioactive fallout casualties.[591] On the impact of a counterforce strike against U.S. silos, Kristensen and McKinzie argue:

> If there were to be an attack on all 450 Minutemen III ICBM silos in the United States, a pure counterforce attack that did not target civilians directly, this would cause intense radioactive fallout over large parts of the north-central United States and southern Canada and kill millions of civilians.[592]

For this reason, increased accuracy could theoretically minimize the casualty count by lowering the nuclear weapon yield and reducing the number of warheads

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[589] Fred Kaplan, "Chapter 15: The Real Rivalry" in *Wizards of Armageddon*.
[590] For example: Scott Sagan and Allen Weiner, "The Rule of Law and the Role of strategy in U.S. Nuclear Doctrine," *International Security*, Vol. 45, No. 4 (2021). And debate discussed in: Steve Fetter and Charles Glaser, "Legal, but Lethal; The Law of Armed Conflict and U.S. Nuclear Strategy," *The Washington Quarterly*, Vol. 45, No. 1 (2022).
[591] For example, this is modeled in: Sebastien Philippe and Ivan Stepanov, "Radioactive Fallout and Potential Fatalities from Nuclear Attacks on China's New Missile Silo Fields," *Science and Global Security*, (May 2023), https://www.tandfonline.com/doi/full/10.1080/08929882.2023.2215590.
[592] Hans Kristensen and Matthew McKinzie, "Nuclear arsenals: Current developments, trends, and capabilities," *International Review of the Red Cross,* Vol. 97: No. 899, (2015), pp. 596, https://international-review.icrc.org/sites/default/files/irc97_6.pdf.

needed to achieve a high kill probability (i.e. – if 2:1 targeting is no longer necessary) to strike destroy a hardened missile silo. By lowering the circular error probable (CEP) of a missile, as reviewed in Chapter 5, increased accuracy may enable warheads with lower yields to reliably destroy missile silos or reduce the number of warheads needed. A Johns Hopkins Applied Physics lab reported that missile accuracy is the most important factor in determining the survivability of a silo in a counterforce strike, with the warhead explosive yield (within reason) and the hardness of the ICBM silo serving as secondary factors.[593] In their analysis, the Johns Hopkins report found a threshold of around 200 feet (60 meters) as the point at which survivability begins to dramatically decrease when the warhead yield is in the range of hundreds of kilotons.[594] As the CEP shrinks, a similar kill probability can still be sustained even as the explosive yield of the nuclear weapon decreases.

Based on the analysis in Chapter 5, it is possible that quantum sensors may increase the feasibility of a counterforce attack with lower yield nuclear weapons and thus fewer casualties. If improved accuracy can lower the yield needed to strike and destroy an ICBM silo, then the casualties from the counterforce strike scenario described by Kristensen and McKinzie may also be reduced to a lower number. The most likely avenue through which quantum sensors would improve accuracy would be by enabling navigation and maneuvering after the post-boost phase, which is where the majority of the error is accumulated throughout the flight of an ICBM. As

[593] Dennis Evans and Jonathan Schwalbe, "Intercontinental Ballistic Missiles and Their Role in Future Nuclear Forces," *Air & Space Power Journal* (Summer 2018), p. 43, https://www.airuniversity.af.edu/Portals/10/ASPJ/journals/Volume-32_Issue-2/F-Evans_Schwalbe.pdf.
[594] Evans and Schwalbe, "Intercontinental Ballistic Missiles and Their Role in Future Nuclear Forces," pp. 6.

discussed in Chapter 5, quantum sensors could allow for dead reckoning and increased precision at smaller sizes than current navigation systems. Currently, ICBMs have CEPs of around 90-100 meters. If quantum sensing could shrink the ICBM CEP to around 10 meters (a factor of 10), warhead yields could be reduced by a factor of 1000. Based on current warhead yields of 300 kilotons, this would translate to a modified warhead with a yield of around 0.3 kilotons, a reduction which could produce less fallout and a smaller lethal dose radius.[595]

While such high accuracies might someday be possible, many technical challenges would need to be overcome. First, to achieve these improvements would require that quantum sensing technology continues to operate, and thus permit navigation after the boost phase of an ICBM launch. Extreme heat, turbulence/speed, and plasma buildup encountered throughout the flight of an ICBM could damage the sensitivity of the quantum instruments. Second, in leveraging the improved accuracy, especially if it is used to navigate in the reentry phase, some degree of reentry maneuverability could be needed to course-correct the trajectory. Current ICBM reentry vehicles can only maneuver very slightly. However, research conducted throughout the 1980s, 1990s, and early 2000s on maneuvering reentry vehicles was fairly successful (although required external GPS signals to navigate).[596] Similar augmentations could be applied in the future if quantum sensors were able to sufficiently replace the GPS receivers, though would require budgetary allocation and further modifications to existing reentry vehicles. And third, as the warhead yield

[595] Correspondence with Steve Fetter on forthcoming publication, 2023. Based on relation: P_{kill} = Yield/CEP^3.
[596] Caston et al., pp. 67-73.

shrinks below the sub-kiloton range, uncertainty in the kill probability for destroying a missile silo could increase for a near-surface airburst, even with high precision.[597] While a near-surface air burst produces comparable overpressure to a ground burst, it does not trigger a ground shock to transmit additional energy into the ground. As nuclear warhead yields shrink below 1 kiloton, there is uncertainty in the kill probability of an airburst against a silo. And if a ground burst was required for a lower yield warhead, then fallout would still be produced[598]

If terminal-phase navigation can be achieved with quantum sensing and ground bursts are either unnecessary for an application or the tradeoff of a lower-yield ground burst is deemed beneficial, the implications for nuclear deterrence and strategic stability would be substantial for both advocates of AD and DL, though each lens would view uncertainty differently. For DL proponents, low yield counterforce capabilities would increase the usability and flexibility of nuclear weapons and could conceivably allow for a more permissible first strike capability. However, for AD proponents, a fleet of lower yield nuclear warheads could introduce significant challenges and instability, as lowering collateral damage to populations and infrastructure would decrease the deterrence factor guaranteed with larger nuclear weapons that carry greater casualty risks, or in the long run could incentivize an

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[597] Andrew Facini, "Low-yield nuclear warhead: A dangerous weapon based on bad strategic thinking," *Bulletin of the Atomic Scientist* (January 28, 2020), https://thebulletin.org/2020/01/the-low-yield-nuclear-warhead-a-dangerous-weapon-based-on-bad-strategic-thinking/

[598] William Daugherty, Barbara Levi, and Frank Von Hippel, "Casualties Due to the Blast, Heat, and Radioactive Fallout from Various Hypothetical Nuclear Attacks in the United States," *The Medical Implications of Nuclear War*, 1986, https://www-ncbi-nlm-nih-gov.proxy-um.researchport.umd.edu/books/NBK219165/;
And: Robert Nelson, "Low-Yield Earth-Penetrating Nuclear Weapons," *Science and Global Security*, Vol. 10, No. 1 (2002), https://www-tandfonline-com.proxy-um.researchport.umd.edu/doi/abs/10.1080/08929880212326.

increased reliance on mobile platforms rather than fixed targets. Likewise, AD proponents would again see a higher threshold for disruption, as there would need to be high confidence that a fleet of low-yield nuclear weapons could achieve a simultaneous disarming first strike to undermine retaliatory forces. Thus, the AD proponent would again perceive uncertainty as meaning that strategically significant accuracy gains are much less likely than DL proponents, who view assume lower disruption thresholds, suggest.

An ongoing debate on the policy of low-yield nuclear weapons, which is driven more by political differences than technical factors, indicates substantial disagreement among policymakers on the strategic effects. Low yield nuclear weapons were heavily debated during the Bush, Obama, and Trump administrations. Proponents argued that lower yield nuclear weapons would increase the ability to respond "in kind" with nuclear forces.[599] Opponents argued that this necessarily decreased the deterrence value of nuclear weapons and also introduced dangerous escalation incentives.[600] Increased dialogue among U.S. analysts and policymakers also evoked skepticism over U.S. commitment to avoid nuclear escalation and hostility from adversaries, including Russia.[601] Any effort to promote a transition to low-yield, high-precision nuclear weapons would thus have to re-engage the U.S. defense enterprise in this debate, while also navigating relations with allies and

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[599] U.S. Department of Defense, "2018 Nuclear Posture Review," https://media.defense.gov/2018/Feb/02/2001872886/-1/-1/1/2018-NUCLEAR-POSTURE-REVIEW-FINAL-REPORT.PDF.
[600] For example: Facini, 2020; and Cheryl Rofer, "Low Yield Nuclear Weapons are a Danger, Not a Deterrent," *Foreign Policy*, (February 11, 2020), https://foreignpolicy.com/2020/02/11/deterrence-nuclear-war-low-yield-nukes-danger-not-deterrent/.
[601] Vladimir Isachenkov, "Russia slams US arguments for low-yield nukes," *Associated Press* (April 29, 2020), https://apnews.com/article/europe-moscow-us-news-ap-top-news-nuclear-weapons-e62b5976451bb42a47c1f15ba536484d.

adversaries. Proponents of low-yield nuclear weapons think that U.S. deterrence threats will be more credible if there are options to respond in kind to Russian or Chinese low-yield nuclear weapons, as a form of proportionate response. If increased accuracy shifts enables more effective low-yield nuclear weapons for counterforce, then the low-yield proponents could gain greater traction than they have in the past.

This may also be complicated by politics regarding U.S. modernization efforts. The United States is currently undergoing a major modernization process to update various force structure elements, including ICBMs and warheads. The timing and finances that have been committed to modernization may create added resistance to downstream doctrinal changes. Although, if a subsequent decision was made in favor of low-yield warheads, it is also conceivable that the newer, modernized warheads could be downgraded to low yield weapons fairly easily by removing the boost gas components and converting the warheads to one-stage fission weapons. While a boosted primary yield surpasses the necessary explosive energy to trigger a secondary yield, resulting in a total 300 kT yield, an unboosted primary yield, which may be less than 1kT, would not be sufficient to produce a secondary yield.[602]

Targeting accuracy and conventional deterrence

Given the policy constraints and deterrence concerns surrounding low-yield nuclear warheads, another significant implication would be the increased feasibility of using highly accurate conventional weapons to achieve similarly effective

[602] Hans Kristensen, Robert Norris, and Ivan Oelrich, "The Minimal Deterrence Stockpile," in From Counterforce to Minimal Deterrence, 2009, pp.42-44, https://www.jstor.org/stable/pdf/resrep18937.17.pdf.

counterforce and deterrence objectives. When nuclear weapons were developed, their immense explosive yields offered an incomparable deterrence advantage over conventional weapons because they could still ensure destruction of a reasonably-sized target with limited accuracy. As accuracy improves, and the power of conventional weapons and non-nuclear attack methods increase with new technologies, it is reasonable to assume that new technologies like quantum sensing could generate interest in and increase the rationale for a conventional deterrent and a conventional counterforce strategy.

Within the past few decades, the topic of conventional counterforce consideration has received consideration in security studies literature due to hypersonic technology developments (which were in part spurred by conventional counterforce interest) and interest in conventional prompt global strike capabilities. Building on the shift initiated under George W. Bush in favor of precision conventional weapons, the 2010 U.S. Nuclear Posture Review hinted at U.S. consideration of a preemptive attack with conventional strike capabilities.[603] This was roughly concurrent with the release of a 2009 Defense Science Board report on the feasibility of a conventional strike on mobile ICBMs.[604] However, at the time, scholars determined that conventional strike would be insufficient to effectively target and destroy ICBM silos.[605] Summarizing the issues with conventional counterforce at

[603] "Nuclear Posture Review Report," United States Department of Defense (2010).
[604] Ronald Kerber and Robert Stein, "Time Critical Conventional Strike from Strategic Standoff," Report of the Defense Science Board Task Force, United States Department of Defense (2009), https://dsb.cto.mil/reports/2000s/ADA498403.pdf.
[605] Tong Zhao, "Conventional Counterforce Strike: An Option for Damage Limitation in Conflicts with Nuclear-Armed Adversaries," *Science and Global Security*, Vol. 19 (2011), pp. 195-222, https://scienceandglobalsecurity.org/archive/sgs19tongzhao.pdf;

the time, Christopher Ford argued that conventional weapons were insufficient for countervalue attacks, and expensive counterforce capabilities in comparison to nuclear weapons.[606]

In these discussions, the assumed key requirements for conventional deterrence capabilities were rooted in the traditional countervalue and counterforce deterrence strategies. For countervalue attacks, conventional capabilities would need to ensure sufficient "destruction" to disincentivize adversaries from escalating to nuclear use. (This is considered despite the fact that countervalue has not been a legitimate deterrence strategy for decades.) In satisfying this strategic objective, accuracy would have a minimal role unless considering targeted attacks on critical infrastructure, such as power grids, which may result in comparable levels of destruction.[607] For counterforce attacks, conventional capabilities would not only need to be able to target and strike mobile missiles and warheads, but they would also need to be able to destroy hardened and deeply buried targets, like missile silos.

While technological feasibility may have seemed insufficient when the topic emerged in 2010, more recent estimates suggest that with increased accuracy, and hypersonic missile capabilities, penetration of these more secure infrastructure elements could become feasible.[608] Perceptions on the extent to which these proposed

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and Michael Gerson, "Conventional Deterrence in the Second Nuclear Age," *Parameters* (Autumn 2009), https://mca-marines.org/wp-content/uploads/Conventional-Deterrence-in-the-2nd-Nuclear-Age-by-Gerson-090901.pdf.

606 Christopher Ford, "Conventional 'Replacement' of Nuclear Weapons? "Commentary at Conventional Deterrence in the Second Nuclear Age, Carnegie Endowment for International Peace (2010), https://www.hudson.org/national-security-defense/conventional-replacement-of-nuclear-weapons-.

607 Calculation performed by Scott Kemp to determine the impact of targeting key grid elements in U.S. cities. Correspondence in 2021.

608 Calculation performed by Scott Kemp to determine the feasibility of penetrating hardened silos with conventional strike. Correspondence in 2021.

conventional deterrence strategies could actually assure mutual vulnerability vary, but there is a case to be made that conventional counterforce could assure mutual vulnerability to satisfy certain aspects of strategic stability. From the perspective of arms racing, mutual vulnerability of counterforce elements can help disincentivize buildup. From the perspective of crisis instability, mutual vulnerability in the AD logic bolsters the barrier to escalation. In either case, a key tenet for conventional deterrence is an improvement in targeting accuracy. For countervalue targets, conventional strike accuracy would need to be within or below a few meters to ensure a successful strike on a critical power grid element (although even 10 meters could be sufficient given that multiple weapons could be used).[609] Likewise, for counterforce targets, conventional strike accuracy would likely need to be within a meter or two to ensure that conventional warheads directly strike silos, since the blast power is significantly reduced (again, 10 meters could also be operable with a higher number of weapons).

Even with high accuracy, there is still some additional research that is needed to evaluate the penetration potential depending on the blast characteristics (and the different pressure distributions) of conventional versus nuclear warheads to determine the effect of conventional strikes on hardened ICBM silos. This was considered in the dialogue ignited by the conventional prompt strike dialogue referenced above. Based on his analysis, Acton finds that CPGS-delivered weapons could "plausibly penetrate to a depth of 30 or 40 m in concrete."[610] This means that a direct hit would likely

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[609] This is a target proposed by Kemp et al.
[610] James Acton, "Conventional Prompt Global Strike and Russia's Nuclear Forces," Carnegie Endowment for International Peace – Independent Military Review,

penetrate the silo doors and destroy an ICBM, but the value of these effects would deteriorate much more rapidly as the accuracy decreases compared to a nuclear warhead.[611] Acton ultimately concludes that a CPGS-delivered penetrator would require an accuracy of around 3 meters in order to have a 90% probability of destroying a ICBM target.[612] And as Acton pointed out, at the time this would have been unachievable if GPS signals were jammed. [613] However, a dead reckoning capability could conceivably yield a strategically significant improvement.

From a force structure perspective, feasible conventional deterrence capabilities could dramatically reduce reliance on nuclear weapons while still maintaining a deterrence strategy. If all the necessary capabilities were able to be met, or even only a partial set of them, then conventional weapons could be used to eventually reduce reliance on a robust nuclear force structure. Despite the kinetic targeting tactics, there is a growing argument that nuclear weapons are becoming more irrelevant as foreign relations and activities move to other domains, such as cyber[614] and economic statecraft.[615] At the same time, new technologies are also increasing vulnerability of nuclear forces.[616] But feasible conventional counterforce

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https://carnegieendowment.org/2013/10/04/conventional-prompt-global-strike-and-russia-s-nuclear-forces-pub-53213.

[611] Acton, "Conventional Prompt Global Strike and Russia's Nuclear Forces."

[612] Acton, "Conventional Prompt Global Strike and Russia's Nuclear Forces."

[613] Acton, "Conventional Prompt Global Strike and Russia's Nuclear Forces."

[614] Stephen Cimbala, "Nuclear Deterrence in Cyber-ia: Challenges and Controversies," *Air and Space Power Journal* (Fall 2016), https://www.airuniversity.af.edu/Portals/10/ASPJ/journals/Volume-30_Issue-3/V-Cimbala.pdf.

[615] David McCormick, Charles Luftig, and James Cunningham, "Economic Might, National Security, and the Future of American Statecraft," *Texas National Security Review* (2020), https://www.atlanticcouncil.org/wp-content/uploads/2020/06/Economic-Might-National-Security-and-the-Future-of-American-Statecraft.pdf.

[616] Page Stoutland and Samantha Pitts-Kiefer, "Understanding the Cyber Threat to Nuclear Weapons and Related Systems," *Nuclear Weapons in the New Cyber Age* (Nuclear Threat Initiative, 2018), https://www.jstor.org/stable/pdf/resrep19983.6.pdf.

strike capabilities would have a much more direct impact in decreasing the relevance of ICBMs as "nuclear sponges," since adversaries could conceivably target and strike ICBMs without nuclear weapons.

As indicated in the first iteration of these debates in 2010, the topic of conventional deterrence inevitably raises some important strategic and political considerations. First, there are important strategic stability effects of shifting to conventional pre-emptive and deterrence strike capabilities. One of the stabilizing features of nuclear deterrence is the decades of norms against nuclear use that have been established. As Nina Tannenwald writes: "The taboo helps to define a category of unacceptable 'weapons of mass destruction,' distinguished from unproblematic 'conventional' weapons that are, in contrast, viewed as legitimate and usable."[617] Thus, even though conventional weapon implementation may decrease reliance on nuclear weapons, it could have the unintended impact of increasing escalation likelihood. There is new research emerging (as well as a deep history of research) on the contrary, though, which critiques the arguments that weapons of mass destruction are a necessary means to ensure peace, claiming nuclear weapons policy based on such logic to be self-inducing.[618] Beyond strategic rationale, nuclear weapons also confer political power domestically and internationally. Sagan famously notes, "nuclear weapons, like other weapons, are more than tools of national security; they are political objects of considerable importance in domestic debates and internal

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[617] Nina Tannenwald, "The Nuclear Taboo: The United States and the Normative Basis of Nuclear Non-Use," *International Organizations*, Vol. 53, No. 3 (Summer 1999), pp. 433-468, https://www.cambridge.org/core/services/aop-cambridge-core/content/view/EA04E0104A42C12FC785A70F301197CC/S0020818399440779a.pdf/nuclear_taboo_the_united_states_and_the_normative_basis_of_nuclear_nonuse.pdf.
[618] Renic, "Superweapons and the myth of technological peace," pp. 129-152.

bureaucratic struggles and can also serve as international normative symbols of modernity and identity."[619]

Yet, despite potential effects in lowering the escalation barrier or impacting political sway, there are a few reasons why policymakers may seriously consider reducing nuclear weapon reliance if conventional weapons could fulfill the nuclear deterrence requirements. Unilaterally, a nuclear weapon drawdown would decrease costs that have long burdened the U.S. military and that have constrained the government's ability to resource other technology areas. And from an international relations perspective, moving away from nuclear weapons, and even with initial cuts to ICBM forces, would help to signify good will towards members of the Nonproliferation Treaty that are non-nuclear weapon states. As the failure for nuclear weapon states to meaningfully disarm has served as a continual subject of contempt across the regime, consideration of alternatives could absolve some tension. Lastly, a reduction in nuclear weapons stockpiles could contribute to ongoing efforts to mitigate the existential risks posed by weapons of mass destruction.

Conclusion

Given Chapter 5's assessment of the feasibility of various quantum sensing applications, and this chapter's analysis of deterrence and strategic stability implications, there are a few important conclusions and policy implications. First, as shown through this analysis, even a reasonably thorough technical analysis cannot

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[619] Sagan, "Why Do States Build Nuclear Weapons?" pp. 55.

rectify disagreements between different deterrence logics. Debates rating across AD and DL proponents on the requirements for deterrence lead to different perceived thresholds that define a disruptive innovation. Because these thresholds vary, with AD perceiving high thresholds to disruption and DL perceiving low thresholds, the two groups will also treat uncertainty over new technologies differently. This means that new technologies should not be injected into dialogue on arms control, deterrence, and force structure for the sake of alleviating tension, as the inclusion of such ambiguous topics is more likely to exacerbate underlying disagreements. Despite this divide, this chapters has indicated a few key policy implications. Because submarine survivability is unlikely to be contested, regardless of AD or DL biases, policymakers should focus on efforts to improve signaling of intent for quantum sensing and submarine detection research. However, because of the expected accuracy improvement for missile guidance, policymakers, strategists, and analysts should expand dialogues on the implications of low-yield nuclear weapons and conventional deterrence. These policy implications will be discussed in greater detail in Chapter 8, alongside policy implications from other components of the dissertation.

Finally, the analyses in this and the previous chapter and have raised numerous questions about the role that perceptions and narratives around new technologies play in the military industrial base that also merits greater consideration. Given that these analyses have shown that quantum sensing alone will not fundamentally alter nuclear deterrence, and on the contrary that over-signaling could lead to strategic instability, why do exaggerations in technical feasibility persist? The next chapter explores the social factors that have contributed to such assertions.

Chapter 7: Evaluating the Quantum Sensing Socio-Technical Ecosystem

> "The layman is awed by the laboratory set-up, and rightly so. There are not many places under the sun where so many and such hard resources are gathered in great numbers, sedimented in so many layers, capitalized on such a large scale… confronted by laboratories we are simply and literally impressed. We are left without power, that is, without resources to contest, to reopen the black boxes, to generate new objects to dispute the spokesmen's authority."
>
> -Bruno Latour, 1987[620]

> "It has become increasingly clear that a new kind of quantum technology is emerging. We can see the laureates' work with entangled states is of great importance, even beyond the fundamental questions about the interpretation of quantum mechanics."
>
> -Anders Irback, 2022[621]

Despite the technical limitations and policymaker apprehension identified in Chapters 5 and 6, interest in quantum sensing and quantum technologies more broadly continues to surge. Investments in quantum technology companies rose to

[620] Bruno Latour, *Science in Action*: *How to Follow Scientists and Engineers Through Society* (Harvard University Press, 1987), p. 93.
[621] "The Nobel Prize in Physics 2022," The Royal Swedish Academy of Sciences – Press Release, October 4, 2022, https://www.nobelprize.org/uploads/2022/10/press-physicsprize2022-2.pdf.

$2.35 billion in 2022, exceeding the $2.33 billion invested in 2021, indicating a significant, but stable increase from previous annual investment flows, which hovered around $400 million pre-2019.[622] Further underscoring the significance of contemporary quantum technology research, three scientists were awarded the 2022 Nobel Prize in Physics for their research on entangled photons and their contributions to the study of the fundamental principles that underpin quantum mechanics and quantum information sciences.[623] Policymakers worldwide have echoed this recognition of societal importance by establishing ambitious plans to bolster quantum technology R&D, particularly as it is applicable to defense and security applications.[624] In the United States, policymakers have crafted strategies to promote quantum innovation, with the stated objective of securing U.S. leadership in quantum technologies, and partially through enhancing engagement with allies on quantum research.[625] Amidst all of these endeavors, quantum sensing remains as the forefront quantum technology and is likely to have the most imminent transition to production and deployment. As a result, it is expected to establish funding and application precedents for subsequent technologies like quantum computing and quantum communication.

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622 Michael Bobowicz, Rodney Zemmel, Scarlet Gao, Mateusz Masiowski, Niko Mohr, and Henning Soller, "Quantum technology sees record investments, progress on talent gap," McKinsey Digital Article, April 24, 2023, https://www.mckinsey.com/capabilities/mckinsey-digital/our-insights/quantum-technology-sees-record-investments-progress-on-talent-gap#/.

623 Lee Billings, "Explorers of Quantum Entanglement Win 2022 Nobel Peace in Physics," *Scientific American*, October 4, 2022, https://www.scientificamerican.com/article/explorers-of-quantum-entanglement-win-2022-nobel-prize-in-physics1/.

624 "Quantum initiatives worldwide," QURECA, updated 2023, https://qureca.com/quantum-initiatives-worldwide-update-2023/.

625 "National Quantum Initiative Supplement to the President's FY2023 Budget," A report by the Subcommittee on Quantum Information Science, Committee on Science of the National Science and Technology Council, January 2023, https://www.quantum.gov/wp-content/uploads/2023/01/NQI-Annual-Report-FY2023.pdf.

Based on the analytical, historical, technical, and strategic contexts established throughout this dissertation, what specific factors are facilitating this surge of interest and contributing to current perceptions and expectations around quantum sensing? How can policymakers anticipate and mediate these rapidly evolving expectations to improve governance strategies, both for directing the evolution of the quantum sensing innovation ecosystem and for crafting appropriate responses in fields that may be impacted by quantum sensing? And, particularly given the focus of this dissertation research agenda, how should policymakers adjust nuclear doctrine, force structure, and arms control policies given perceptions of quantum sensing?

This chapter explores the actors and institutions that comprise the quantum sensing ecosystem and the mechanisms through which they drive interest in and shape expectations of the technology, using the analytical framework developed in Chapter 3. The technical feasibility analysis conducted in Chapter 5 provided an overview of the technical state-of-the-art in quantum sensing, and an estimate of what can feasibly be expected of the technology, while Chapter 6 explored the strategic and political rationale that could impact policymaker responses to quantum sensing. To complement and expand on these findings, this chapter evaluates the social factors contributing to quantum sensing interest, including the array of actors and institutions that constitute the socio-technical ecosystem. By highlighting these factors, the chapter is able to dispel the threat frequently asserted by DL proponents that technological evolution is inevitable (an assumption of technological determinism). Rather, appreciating the socio-technical ecosystem for a given technology can inform social constraints on how quickly a country or actor could acquire a technology or capability, as well as how actors (including government stakeholders) within a network achieve power to influence the technology development.

Through examining the socio-technical quantum sensing ecosystem in the United States, this chapter identifies policy options to guide the evolution of quantum sensing technologies and the associated perceptions. Specifically, this chapter evaluates the quantum sensing ecosystem from the social construction of technology (SCOT) perspective, a prominent feature of the science and technology studies (STS) literature. This chapter begins by foregrounding the people and institutions that compose the quantum sensing ecosystem to identifies the underlying human-centered drivers of technology perceptions and expectations that have contributed to the co-development of quantum sensing technologies and related acquisition and deployment policies. Next, through adopting a more human-centered analytical approach, this then chapter considers the role of human agency in shaping the evolution of science and the production of technologies. Through doing this, it informs policy implications presented in Chapter 8 that can guide policymakers' decisions on how to respond to, and in turn guide, the development of new technologies like quantum sensing.

SCOT and Mapping the Quantum Sensing Socio-Technical Ecosystem

Advocates of Pinch and Bijker's SCOT conceptual framework, which was discussed in Chapter 2, generally agree that there are inherent induction mechanisms between human actions and technology innovation. In contrast to technological determinism, a reductionist theory which asserts that technology progresses at some internal pace regardless of human intervention,[626] SCOT stresses the influence that human actions, including policies, research methodologies, and applications, have on technology innovation. Although SCOT adherents with different interpretations of the underlying social constructivist mechanisms responsible for this induction propose competing hypotheses of the method of connectivity between humans and technology, they are united in their opposition to the idea that technologies and innovation necessarily dictate human activities, as asserted by technological determinists.[627] In fostering and debating the various strains of SCOT proposed over the past few decades, the STS community has generated immense insight on the various interaction modalities. For example, SCOT literature has expanded on the interactions between technology and actors,[628] emphasized the role of institutions,[629] and evaluated the evolutionary phases of technology innovation.[630]

Across these diverse studies, SCOT theorists have provided a variety of analytical tools to evaluate the drivers of technology change through structural analysis of the technical systems or ecosystems from which they derive. The "socio-technical system" analytical method was proposed by Emery and Trist in 1960 as a way to comprehensively evaluate the technology, humans, and environmental aspects

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[626] Sally Wyatt, "Technological determinism is dead; long live technological determinism," *The handbook of science and technology studies*, Vol. 3 (2008).

[627] Allan Dafoe, "On Technological Determinism: A Typology, Scope Conditions, and a Mechanism," *Science, Technology, and Human Values,* Vol. 40, No. 6 (April 2015).

[628] Trevor Pinch and Wiebe Bijker, "The Social Construction of Facts and Artefacts: or How the Sociology of Science and the Sociology of Technology might Benefit Each Other," *Social Studies of* Science, Vol. 14, No. 3, August 1984, pp. 421-423, https://www.jstor.org/stable/285355?seq=1&cid=pdf-reference#references_tab_contents.

[629] Hans Klein and Daniel Kleiman, "The Social Construction of Technologies: Structural Considerations," *Science, Technology, and Human Values*, Vol. 27, No. 1 (Winter 2002), pp. 28-52.

[630] Lee Humphreys, "Reframing Social Groups, Closure, and Stabilization in the Social Construction of Technology," *Social Epistemology*, Vol. 19, No. 2-3 (April – September 2005), pp. 231-253.

that should inform design, labor, and production decisions.[631] Broadening the analytic lens, they argued the importance of considering the individual work systems/research groups, institutions and organizations, and macrosocial systems that each contribute to the innovation and manufacturing of technologies.[632] The socio-technical system construct has since been applied in a variety of fields, especially among engineering and manufacturing communities who view the tool as an opportunity to incorporate both social and technical considerations into a technology design at the early stage of development.[633] In contemporary STS literature, the term socio-technical *ecosystems* is sometimes used to refer to a broader, more diverse stakeholder network, including technology developers, contributors, and users.[634]

This section leverages SCOT and socio-technical ecosystem analytical tools to evaluate the complex network of actors, institutions, and mechanisms driving innovation and producing social and political effects in the quantum sensing ecosystem. With roots in both the well-evolved remote sensing and metrology science and technology ecosystem and the more esoteric but rapidly expanding quantum technology ecosystem, the U.S. quantum sensing ecosystem is an expansive network

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[631] F. E. Emery, E. L. Trist, "Socio-technical systems," in Management Science Models and Techniques, Vol. 2 (Pergamon, Oxford, 1960), pp. 83-97.
[632] Eric Trist, "The evolution of socio-technical systems: a conceptual framework and a research agenda," Ontario Ministry of Labor – Occasional Paper No. 2 (June 1981), p. 11, http://sistemas-humano-computacionais.wdfiles.com/local--files/capitulo%3Aredes-socio-tecnicas/Evolution_of_socio_technical_systems.pdf.
[633] For example, Gordon Baxter and Ian Sommerville, "Socio-technical systems: From design methods to systems engineering," *Interacting with Computers*, Vol. 23 (2011), pp. 4-17.
[634] For example: Mariarosaria Taddeo, Paul Jones, Roba Abas, Kathleen Vogel, and Katina Michael, "Socio-Technical Ecosystem Considerations: An Emergent Research Agenda for AI in Cybersecurity," *IEEE Transactions on Technology and Society*, Vol. 4, No. 2 (2023), pp. 112-118. Jim Herbsleb, "Socio-Technical Ecosystems," Institute for Software Research - Presentation, October 2010, https://herbsleb.org/web-pres/slides/IFIP2.9-2-10-2010-dist.pdf.

of developers, contributors, and users.[635] The network of developers and funders/users is shown below in Figure 7.1, and a catalog of producers is provided in Appendix B.

Figure 7.1. Quantum Sensing Socio-Technical Ecosystem

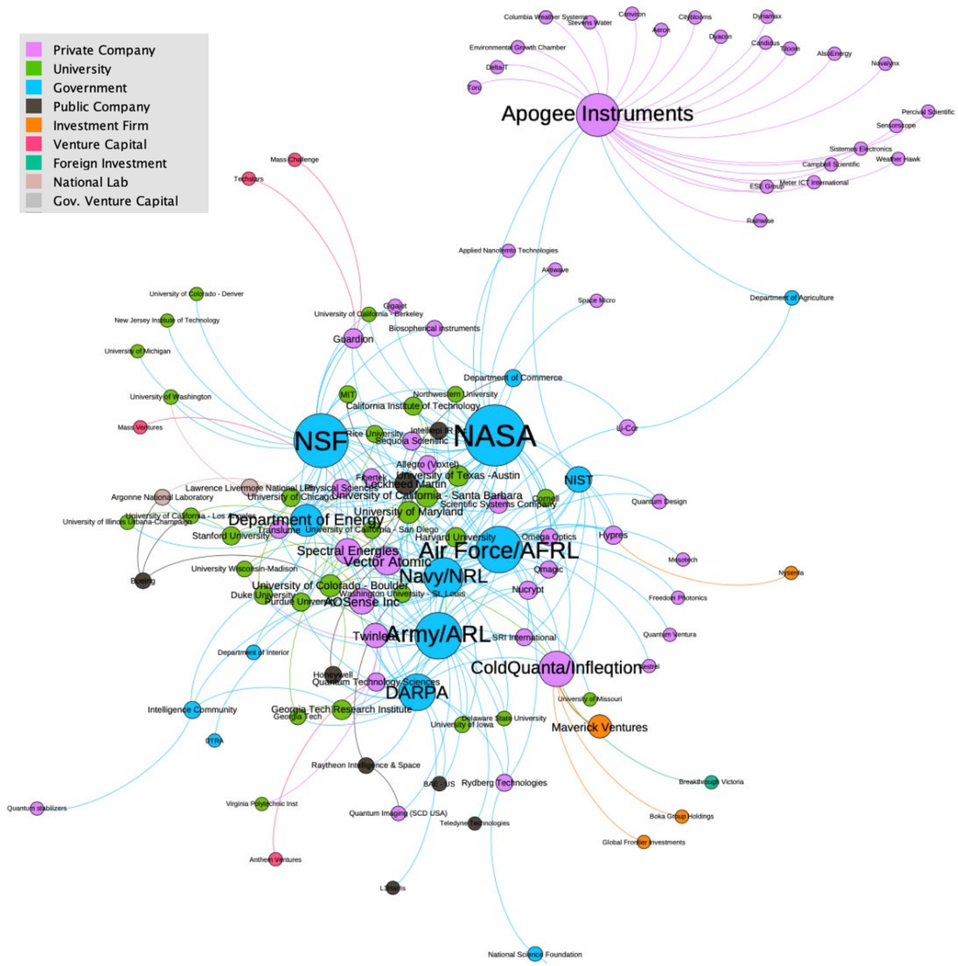

Figure 7.1 shows the U.S. quantum sensing socio-technical ecosystem. Colors of the nodes represent the type of entity. The edges for the network indicate the funding and collaboration connections between the entities (with the color of the edge indicating the source). Node sizes reflect degree centrality. Data collected to create the network diagram are included in Appendix B.

[635] Neil Savage, "Quantum Computers compete for Supremacy," *Scientific American,* July 5, 2017, https://www.scientificamerican.com/article/quantum-computers-compete-for-supremacy/.

In Figure 7.1, network theory is applied to visualize the connectivity of the actor in the ecosystem. The nodes, or circles, represent the ecosystem actors. The edges, or lines, represent the connectivity between the different groups. The colors indicate the types of actors engaged in the ecosystem. The network theory visualization indicates that the ecosystem is characterized by a complex blend of cooperative and competitive relationships.

Among technologists, or actor producing the technology, competition arises due to the lack of closure as to what constitutes a true “quantum” sensor or which type of qubit or quantum platform will be most suitable for certain applications. In their interconnectivity with users, scientists and technologists have quickly established relations with capability seekers and research funders, demonstrating the malleability of their research to fit different use-cases. Despite competition over technology designs between developers, there has been a coordinated and collaborative effort to translate the importance of quantum sensing, and quantum technologies more broadly, for practical applications to garner recognition and financial support from private industry and government consumers and funders.

On their end, many capability-seekers view integration of quantum technologies as an opportunity to demonstrate their technology awareness and to prevent potential technological surprise scenarios despite continued uncertainty over quantum sensing performance benefits and timelines to development. However, the limited information flow across technologists and capability seekers or funders, marred by the prevailing uncertainty around quantum sensing due to lack of closure, has led to flexible interpretations and diverging perspectives of the technology’s functionality in different applications. Private sector funding dynamics, barriers to technical information, and a broader, shifting geopolitical climate in favor of science and technology competition are also key mediators of quantum sensing narratives.

This section reviews each of these features in the quantum sensing socio-technical ecosystem, and leverages STS literature and SCOT theory to illuminate the effects these phenomena impart on the technology development and acquisition process, as well as the perceptions of quantum sensing. It highlights the most influential patterns in the ecosystem for each of the three structural elements of the analytical framework presented in Chapter 3. These focus areas include: (1) the technology characteristics and the developer community; (2) the nuclear deterrence-relevant capabilities and the user community; and (3) the institutional factors that connect actors across the technology and capability domains.

Technology characteristics and the developer community

As per the categories delineating technology characteristics in the analytical framework proposed in Chapter 3, this section assesses the technical aspects of quantum sensing that shape the developer community and contribute to the defining features of the quantum sensing socio-technical ecosystem. These categories include specifications about: (1) how a technology is produced; (2) what a technology is composed of; (3) and how a technology is operated. Across each of these areas, the main social trends include the lack of closure around a singular design type, the coupling between quantum sensing and other quantum technology ecosystems, and the extremely technical, tacit knowledge-intensive technology code and language.

Lack of closure is a significant feature that has shaped the quantum sensing, and broader quantum technology, ecosystem. In SCOT literature, closure refers to the process through which consensus is achieved regarding the design of a specific platform. Klein and Kleinman find that the mechanisms through which closure is reached are dependent on the different social groups involved in the innovation process, their interpretations of the technology, and the applications with which they associate the technology in the early R&D stages.[636] By this definition, lack of closure is an inherent fixture of emerging technologies. It portends a degree of "interpretive flexibility" around the technologies, fosters uncertainty over the potential applications, and increases the degree to which perceptions of the technology are susceptible to the biases of capability seekers.[637] Furthermore, lack of closure incites competition among scientists and technologists, with each distinct research group pursuing their own image of the ideal artifact design.[638]

One factor complicating the pursuit for closure is the lack of a clear, agreed-upon definition to specify what constitutes a "quantum" sensor, resulting in subjective interpretations applied by different stakeholders. As Chapter 5 indicated, under a loose interpretation of the definition, quantum sensors have been around for decades. However, the term is more commonly used in contemporary dialogue to refer to sensors, or technologies, that manipulate individual quantum systems (qubits), rather than quantum phenomena in aggregate quantities. This modern definition implies a

[636] Klein and Kleinman, "The Social Construction of Technology," p. 30.
[637] Trevor Pinch and Wiebe Bijker, "The Social Construction of Facts and Artefacts: or How the Sociology of Science and the Sociology of Technology might Benefit Each Other," *Social Studies of* Science, Vol. 14, No. 3, August 1984, pp. 421-423, https://www.jstor.org/stable/285355?seq=1&cid=pdf-reference#references_tab_contents.
[638] Klein and Kleinman, "The Social Construction of Technology," p. 30.

significantly more dynamic utilization of quantum phenomena.[639] Practically, this ambiguity leads to an inflated ecosystem beyond scientists and technologists developing quantum sensors that harness qubit-level sensitivity, and thus increases uncertainty in the estimation of quantum sensing development timelines and feasibility.

Interpretive flexibility at the pre-closure stage of R&D for quantum sensing means that there is also limited clarity as to when and how a more uniform technology production process will stabilize. A wide variety of qubits are currently being considered in the production of quantum sensors, including silicon spin/quantum dots, photonics, neutral atoms, trapped ions, and superconducting circuits.[640] Each platform exhibits unique strengths and weaknesses depending on the specific application, as reviewed in Chapter 5. To date no single platform appears to universally outperform the others in such a way that closure around a particular design type is conceivable over the next few years. Furthermore, as technologists and scientists evaluate platform types based on different metrics and are informed by their own research biases discussed in Chapter 3, agreement on a singular, objective ranking of the sensing platforms is unlikely. This simultaneous investigation of different design pathways and the conflicting assertions about different qubit types increases the complexity of dialogue and the degree of uncertainty around what is implied by "quantum sensors." It also imposes a barrier in information flow between technical experts and non-technical experts who may not understand the nuances

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[639] Daniel Garisto, "The second quantum revolution," *Symmetry*, January 12, 2022, https://www.symmetrymagazine.org/article/the-second-quantum-revolution?language_content_entity=und.
[640] For example, surveyed in Degen et. al. 2017.

across the qubits. Finally, lack of closure fosters competition among producers of different types of platforms/qubits to demonstrate applicability and establish funding merit.[641]

From the SCOT perspective, qubits can serve as touch points between research areas to allow for collaboration in the absence of closure, until sub-ecosystems based on variants emerge. Despite the lack of design closure and competition due to the various types of qubits under consideration, producers in the quantum sensing community have also collaborated to communicate with user communities through using qubits as "boundary objects." Star and Greisemer define boundary objects as materials and processes that exist across heterogeneous social worlds under more flexible, vaguer identities to facilitate collaboration and communication despite a lack of consensus or closure.[642] Greisemer notes that the initial motivation for defining boundary objects was to provide an alternative explanation of cooperation across heterogeneous groups that have not yet reached consensus. Boundary objects also facilitate transfer of ideas across the "boundary" between different social worlds, where the social worlds framework in STS literature is used to define how groups of actors that are connected by shared actions and objects establish meaning.[643]

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[641] For example, discussed in Joseph Harmon, "The quest for an ideal quantum bit," University of Chicago News, May 4, 2022, https://pme.uchicago.edu/news/quest-ideal-quantum-bit; and Davide Castelvecchi, "Underdog technologies gain ground in quantum-computing race," *Nature News*, February 6, 2023, https://www.nature.com/articles/d41586-023-00278-9.

[642] Susan Leigh Star and James Greisemer, "Institutional Ecology, 'Translations' and Boundary Objects: Amateurs and Professionals in Berkeley's Museum of Vertebrate Zoology, 1907-39," *Social Studies of Science*, Vol. 19 (1989), p. 393.

[643] Adele Clarke and Susan Leigh Star, "The Social Worlds Framework: A Theory/Methods Package," Chapter 5 in *The Handbook of Science and Technology Studies – 3rd Ed.* (MIT Press, 2008).

The transmission of information with qubits occurs both across different social worlds within the quantum community, as well as across technologist and consumer social worlds. In the case of quantum technologies (including sensing, computing, and communication ecosystems), the qubit is used to convey the power of contemporary quantum technologies despite the lack of consensus as to how the objects should be produced or composed.[644] This explains the success that scientists have had in communicating the importance of quantum technologies despite competition among themselves. For such scenarios, Greisemer also notes that it is likely that each design will eventually be matched with its own unique set of applications and social constructions, producing robust spin-off ecosystems.[645]

The lack of closure also contributes to uncertainty regarding the composition requirements that should be expected for quantum sensor production and facilitates coupling with other ecosystems to support particular qubit types. All quantum sensors will require high-precision and well-fabricated physical components and control systems to successfully manipulate and measure individual qubits. However, depending on the qubit type, drastically different subcomponents could be required, ranging from niche lasers to dilution refrigeration and other cryogenic techniques. The dependency that a particular qubit has on certain production requirements produces coupling between the quantum sensing ecosystem and ecosystems for required subcomponent technologies. Likewise, quantum sensing technologies share many subcomponent requirements with the quantum computing and quantum

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[644] "Susan Leigh Star, "This is Not a Boundary Object: Reflections on the origin of a Concept," *Science, Technology, and Human Values*, Vol. 35, No. 5 (2010), p. 604.
[645] Star, "This is Not a Boundary Object," p. 615.

communication socio-technical ecosystems. This coupling means that closure around one qubit design for quantum sensing could impact actors across the ecosystems. As a result, technologist/scientist communities in other related ecosystems are invested in and contribute their own biases and perspectives to quantum sensing perspectives and dialogue.

The operation requirements, the final set of technical characteristics in the framework, also remain partially undefined due to lack of closure, yet are shaped by socio-technical expectations for quantum sensors. Despite lack of qubit design closure, agreed upon paradigms at the qubit boundary object level, such as the DiVincenzo sensing criteria (adapted from the DiVincenzo quantum computing criteria),[646] are used to produce conceptualizations of the operational advantages of quantum sensors over non-quantum alternatives to orient ecosystem actors. Such generalizations lead to assertions that quantum sensors will reduce size, weight, and power parameters as compared to their non-quantum alternatives, and that they will require less external signaling and control.[647] However, considering that quantum sensors are still in an early stage of development, these over-generalized claims merit greater scrutiny. There is significant uncertainty in assuming that a technology for which a design has not even been established yet could encompass all imagined operating characteristics. Yet, due to the conception of these operability characteristics and their widespread association with quantum sensors that harness qubits, they can be expected to continue driving the advancement of the technology.

[646] For example, see: Degen et. al, "Quantum Sensing."
[647] For example: "Quantum Sensing Use Cases: Prospects and Priorities for Emerging Quantum Sensors," QEDC Report, September 2022, https://quantumconsortium.org/sensing22/.

Consequently, these socially-constructed technological expectations also produce high benchmarks that scientists and technologists must meet, and which may in-turn shape the overall design choices and prolong the total development timeline.

Together, these technical characteristics contribute to the formation of a large, diverse group of technologists and scientists within the quantum sensing socio-technical ecosystem. Technical experts in the ecosystem not only include those that work on specific types of quantum sensors, but also those that work on accompanying software that enables readout, as well as on basic science that supports sensor development, on materials science that provides the sensing basis, and finally on support technologies that facilitate operation. For the most part, technologists and scientists for quantum technologies are concentrated in government and academic labs and research centers, because of the early stage of development.[648] However, this ecosystem is not static, and as quantum sensing begins to reach commercialization, the ecosystem will likely grow to encompass more technology producers from private companies.

Finally, in discussing the technical actors in the ecosystem, it should be noted that human talent will play an important role broadly across production, construction, and operation of quantum sensors. Especially due to the lack of closure and the broad array of design types, many quantum sensors are being developed in lab settings, where construction of individual sensing platforms is a boutique process achieved with tacit knowledge, or knowledge that is learned through experience and which is

[648] "Bringing Quantum Sensors to Fruition," A Report by the Subcommittee on Quantum Information Science Committee on Science of the National Science and Technology Council, March 2022, https://www.quantum.gov/wp-content/uploads/2022/03/BringingQuantumSensorstoFruition.pdf.

not easily reproduced or transferred, that has accumulated over long periods of time.[649] The consequence of this actor-oriented development process is that individual actors themselves will be key mechanisms in progressing certain sensing designs.

Recognition of this emphasis on human talent has led to a number of research studies on the mechanisms through which talent and talent flow contribute to or impede innovation, as well as policies to support the retainment and optimization of actors within ecosystems that rely on tacit knowledge.[650] For instance, collaboration across research groups to distribute knowledge of key personnel has been a major policy focal point and could lead to a more collaborative technology base and a more interdisciplinary and distributed technology design.[651] At the same time, localized knowledge among few researchers could also lead to oversight issues, creating gaps in knowledge between those working on a specific technology area and those not.

The resulting asymmetry in information and technology access would make it especially difficult for unbiased observers to evaluate and critique technology assertions, even if they have technical backgrounds in tangentially related fields. In relation to the proposed analytical framework, this could make it difficult to establish a group of technical skeptics or reviewers to provide independent, unbiased assessments of assertions made about quantum sensing potential.

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[649] Jacqueline Senker, "The Contribution of Tacit Knowledge to Innovation," *Cognition, Communication, and Interaction* (2008), pp. 376 – 392. https://link.springer.com/chapter/10.1007/978-1-84628-927-9_20.
[650] For example, discussed in Franziska Greinert, Rainer Muller, Philipp Bitzenbauer, Malte Ubben, and Kim-Alessandro Weber," *Physical Review Physics Education Research*, Vol. 19, No. 010137 (June 2023), https://journals.aps.org/prper/abstract/10.1103/PhysRevPhysEducRes.19.010137.
[651] For example, at collaboration is especially discussed at the international level: Edward Parker, "Promoting Strong International Collaboration in Quantum Technology Research and Development," RAND Research Perspective, 2023, https://www.rand.org/pubs/perspectives/PEA1874-1.html.

Deterrence capabilities and the would-be user community

In order for a new type of technology like quantum sensing to produce societal effects and gain the resources needed to sustain further innovation, it must be adopted and propagated by a sufficient coalition of users. Because of their versatile nature, quantum sensors will eventually afford a variety of capabilities across diverse application areas. However, to reach this stage of commercialization and broader distribution, further innovation is needed to improve quantum sensing protypes, reduce their size weight, power, and cost parameters, and match devices with suitable user coalitions. To sustain funding and resources needed to support this innovation, the quantum sensing technologist communities must connect with other social worlds that have relevant application areas and which also have long-established political institutions that view technology production as a means to achieve their objectives, as well as the resources necessary to support technology development. Especially at this early stage of development, when establishing connections with other social worlds that may form the user communities, technologists may present overly optimistic views of a technology to support particular applications; however, conversely, at this stage of production, the technologies are also most susceptible to being shaped by the narrower applications and related user communities and funders.[652]

This section surveys the characteristics of the social worlds in the defense and security communities which form the main quantum sensing user communities. Although quantum sensing will have broader applications that will allow for more

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[652] Nelly Oudshoorn and Trevor Pinch, "Introduction," in *How Users Matter: The Co-Construction of Users and Technology* (MIT Press, 2003).

widespread commercialization, it is more likely to be dependent on and shaped by very narrow applications and capability interests, like submarine detection and missile navigation, in the meantime.

The wide array of possible applications for quantum sensing places it in the category of "general purpose technologies" (GPTs), which has been a topic of focus in more recent STS and technology literature. As a GPT, quantum sensing will eventually find a variety of applications and user communities across the civilian and military sectors, which increases the uncertainty in estimating the technology's long-term development pathway once it begins to commercialize. It also leads to more technological deterministic views that the technology will inevitably evolve, given the widespread applicability. Ding and Dafoe assert that GPTs are defined by their characteristics of having (1) a great potential for continual improvement; (2) an element of pervasiveness; and (3) strong technological complementarities, or entanglement with related technologies.[653] In their assessment of GPTs, Ding and Dafoe posit that, although a narrow set of illustrative use-cases will draw attention to a technology at the earlier stage of development, eventual applications in broader, support-oriented domains will likely have more significant impacts on the technology's development over the long-term. Relatedly, many experts and policymakers believe that quantum sensing will be influential in broad civilian and military activities which are harder to anticipate at the present but could be more widely impactful than in any narrow use-case.[654]

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[653] Jeffrey Ding and Allan Dafoe, "Engines of power: Electricity, AI, and general-purpose, military transformations," *European Journal of International Security* (2023), p. 3.
[654] Jon Harper, Pentagon Trying to Manage Quantum Science Hype, *National Defense,* December 10, 2010, https://www.nationaldefensemagazine.org/articles/2020/12/10/pentagon-trying-to-manage-

Although expectations of broad applications have begun generating interest around quantum sensing, Ding and Dafoe caution the limits of anticipating technology effects or socio-technical ecosystem characteristics for broader applications given the high degree of uncertainty in the early stage of development. They find that there is likely to be a longer "period of gestation" between a technology's invention and the point at which it reaches a suitable stage for deployment, designation for broader applications, and eventual wide-spread impact.[655] Based on this long lag time that should be expected for broader quantum sensing applications, policymakers should treat assertions about imminent, universal application, and tangential deterministic assumptions, with speculation given that these effects, and the timeline to achieving them, are more challenging to anticipate.

Despite this uncertainty over broad GPT applications, greater certainty at the early stage of development can be gleaned from evaluating influential social worlds, or capability seekers per the framework proposed in Chapter 3, focused on singular, socially and politically motivated applications. While the long-term evolution of GPTs may be hard to anticipate, the shape of the innovation trajectory is likely to be formed in part by the perspectives of capability seekers funding and acquiring the technology at earlier stages of development. These actors are motivated by political or strategic debates and sociotechnical expectations related to the capabilities that a technology could enable. As was shown in Chapter 6, the extent to which a technology contributes to a capability deemed as instrumental in the satisfaction of a

quantum-science-hype; and personal interview with a university-based quantum sensing scientist, July 2021.

[655] Ding and Dafoe, "Engines of Power," p. 17.

political or strategic debate significantly increases the desirability of its acquisition. But additionally, capability seekers may be motivated if the technology is deemed as a naturally feasible or a socially necessary constituent of a shared sociotechnical vision. This shared vision is sometimes referred to as a sociotechnical imaginary in the STS community, defined by Jasanoff as "collectively held, institutionally stabilized, and publicly performed visions of desirable futures, animated by shared understandings of forms of social life and social order attainable through, and supportive of, advances in science and technology."[656] (However, obviously in the broader deterrence community a shared visions are likely divided along DL and AD lines.) Finally, in addition to motivation from political or social rationale, capability seekers must have some degree of relative power and persuasion among the institutions in an ecosystem to effectively support and influence a technology's development.

The influence of the capability seekers when these characteristics are aligned is exemplified in the case of the military's innovation and acquisition of artificial intelligence (AI) for autonomous weapon capabilities. In their analysis, Ding and Dafoe note that despite the broader and potentially more impactful consequences of AI in more generalized applications, as a GPT, significant intrigue was generated and mobilized by emphasizing its potential application to autonomous weapon capabilities.[657] On the motivation and operationalization of military interest in AI for autonomous weapon capabilities, Bachle and Bareis identify various sociotechnical

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[656] Sheila Jasanoff, "Future Imperfect: Science, Technology, and the Imaginations of Modernity," in *Dreamscapes of Modernity*, (University of Chicago Press, 2015), pp. 4.
[657] Ding and Dafoe, "Engines of Power," p. 19.

imaginaries that contributed to technology interest, such as technological innovation as a national security safeguard or technological leadership as a means to guide regulation, which asserted deterministic views on the technology's development process to increase the imperative for policies favoring innovation. Relatedly, they find that these sociotechnical imaginaries fostered politicization of AI-enabled autonomous weapon capabilities, which inflated expectations and perceptions of the effects of the technology and the importance of pursuing the capability and driving innovation.[658] Lastly, both articles note that capability seekers must have access to power and resources in the broader socio-technical ecosystem and industrial base to support the technology innovation, making government and military actors particularly common early-stage social world connections for technologists (although signs that this trend is beginning to change will be discussed in the next section).[659]

Based on the analysis of deterrence-relevant applications conducted in this dissertation, it is evident that early linkages have already been established between quantum sensing technology communities and at least two important capability communities that could motivate further innovation. Although Chapter 5 concluded that quantum sensing is likely to be less revolutionary and more evolutionary over the next ten years in both submarine detection and missile navigation applications, the strategic stability significance found in Chapter 6 suggests that the technology will continue to garner interest and support due relevant strategic and political debates as

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[658] Thomas Christian Bachle and Jascha Bareis, "'Autonomous weapons' as a geopolitical signifier in a national power play: analyzing AI imaginaries in Chinese and U.S. military policies," *European Journal of Futures Research*, Vol. 10, No. 20 (2022), https://onlinelibrary.wiley.com/doi/abs/10.1111/jcms.13197.
[659] Ding and Dafoe, "Engines of Power," pp. 7-10.

well as existing sociotechnical imaginaries among capability seekers. In turn, and due to the outsized influence, the interests motivating these capability seekers will shape the technology's production and contribute to perceptions regarding the technology's development timeline and operability.

The alignment of political and social motivations as well as power and resource access among a community of capability seekers has been well-documented in the case of missile navigation technologies and capabilities by Donald MacKenzie in *Inventing Accuracy*. Within the missile navigation social world, MacKenzie finds a heightened state of co-production between politics, sociotechnical imaginaries, and technologies, evidenced by a series of historical cases of self-induced capability needs and technology requirements. In evaluating the process of identifying missile navigation capability gaps and pursing technologies to satisfy them (or vice versa) MacKenzie finds that technical feasibility is only one element of consideration for pursuing a technology, noting that technological change is also a product of economic, political, organizational, cultural, and legal considerations.[660]

MacKenzie highlights key socio-technical features of this community by detailing the processes that led to the acquisition of various navigation systems throughout the history of nuclear missile production in the United States and the Soviet Union. Specifically, he maps policymaker decisions and technology evolution to illuminate how capability needs and technologies were co-produced across the missile navigation communities due to the role navigation technologies served as boundary objects in political debates about missile targeting and force structure, as

[660] MacKenzie, *Inventing Accuracy,* p. 9.

well as their compatibility with sociotechnical imaginaries of missile navigation technology. For example, in the case of an early inertial navigation system, once a black-box (strap-down) navigator was deemed viable through limited technical evaluation, the means to pursue it on the part of the inventors was guaranteed. Regardless of practicality or necessity, MacKenzie argued that the technology was pursued more for the sake of the impact it would have on political debates over counterforce and as a result of the established sociotechnical imaginary (or, in MacKenzie's words, perceptions of a "technological trajectory")[661] of an ever-increasing missile guidance system accuracy that in turn shaped the evolution of targeting strategies and impacted technology requirements.[662] Summarizing the influence of the missile navigation community on inertial navigation technology innovation, MacKenzie notes, "One might say that the [technology] needs are created simultaneously with the means of fulfilling them."[663]

Despite the absence of a substantial structural evaluation of the submarine detection epistemic communities and social worlds in the STS literature, the extensive and well-documented historical record of submarine detection technologies suggest that the community is constituted and driven by political debates and sociotechnical imaginaries similar to the missile navigation communities. As indicated in Chapter 5, interest in leveraging science and technology innovations for application in submarine detection has resulted in a variety of technological breakthroughs, including the

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661 MacKenzie, *Inventing Accuracy*, p. 237.
662 MacKenzie, *Inventing Accuracy*, p. 93.
663 MacKenzie, *Inventing Accuracy*, p. 93.

development of fluxgate magnetometers[664] and sonobuoys[665] during the 1940s in response to enemy submarine threats. In terms of influence, the continuous flow of innovations demonstrates that capability seekers in the submarine detection community have effectively asserted their influence in the past to support and compel the development of technologies. However, this power distribution structure is reliant on the sustainability of nuclear submarine invulnerability and its fulfillment of a critical secure second-strike capability. This implies a co-production relationship between submarine detection (and stealth) technologies and the SSBN epistemic communities and social worlds, in which continued improvements in the sponsored technologies facilitate the power of the community, which in-turn can be used to provide the resources needed to propel more technology innovation.[666] Practically, this form of co-production results in a deeply embedded, self-inducing socio-technical ecosystem that could be especially prone to arms-racing and other self-propagating sociotechnical imaginaries of perceived future technology innovations and capability needs.

Based on historic examples of techno-political co-production seen in Chapter 4, as well as those noted above in the submarine and missile navigation communities, over-assertion of technology readiness or inflated perceptions of what is technologically feasible are very likely to arise from political debates and sociotechnical imaginaries within the early user communities identified through the

[664] Hovde, Prouty, Hrvoic and Slocum, 2013, p. 398.
[665] Roger Holler, "The Evolution of the Sonobuoy from World War II to the Cold War," *U.S. Navy Journal of Underwater Acoustics*, January 2014, https://apps.dtic.mil/sti/pdfs/ADA597432.pdf
[666] Sheila Jasanoff, "The idiom of co-production," Chapter 1 in *States of Knowledge*, Routledge (2004).

network analysis. Across the historical case studies in Chapter 4 and the quantum sensing case study, new technologies have fostered, and therefore become instrumental to, debates between DL and AD advocates, who view the technologies as inherently stabilizing or destabilizing. A variety of military sociotechnical imaginaries in favor of technology production are also exemplified, including the military imperative to develop technology to avoid technological surprise at the expense of inducing risks through arms racing. This is especially important given that most of the interest in quantum sensing currently derives from military capability seekers, making the evolution of the technology more likely to favor capability seeker-led interests. These political and social traits of early user communities, as well as assertions made by technical communities to build linkages with other social worlds, further contribute to the exaggeration or manipulation of perceptions of a technology in early stages of development.

Institutional and macrosocial community effects

Finally, in addition to dynamics among technologists and users/capability seekers that are likely to drive inflated expectations of quantum sensing impact, a few institutional and macrosocial trends will also impede information flow or obstruct mechanisms that would otherwise produce more critical appraisals of technology effects. In applying knowledge of the distribution of actors in the socio-technical ecosystem to anticipate the drivers of perceptions for new technologies, consideration of the institutions that support the actor network, organizational biases at the institutional level, and the interconnections between the scientists and capability seekers facilitated by the institutions in the network is also important. At the institution level, biases and characteristics of communication across technologist institutions obstruct the flow of information; similarly, classification of information among capability seekers impedes critical oversight and evaluation of the technology's suitability for an application. Lastly, economic and political macrosocial trends, such as venture capital (VC) funding and technology competition strategies further complicate efforts to establish more realistic perceptions and expectations for quantum sensing technologies.

Institutions play powerful roles in establishing the norms, objectives, and resources that a set of actors may have at their disposal and thus can impart on the technology production process. While each individual actor is influenced by their own personal biases, their perceptions are also products of the larger institutions in which they serve or with which they interact. In this way, institutions influence technology development in more macroscopic ways. On the role of institutions and social groups, Klein and Kleinman write, "social groups interpret artifacts differently and seek to shape them according to their different systems of meaning."[667] Particularly for military-driven technologies, as opposed to dual-use technologies produced in the private sector, government institutions have outsized effects on technology development. Klein and Kleinman note, "Where there is no market beyond state demand for the artifact under development, the state may be in a more powerful position than the contracting firm to shape the character of the technology. To the extent there are alternative consumers for this artifact, the position of the

[667] Klein and Kleinman, "The Social Construction of Technology," p. 38.

developing firm is strengthened."[668] As was discussed above in the survey of the technologists and capability-seekers, and in the network analysis, most current quantum sensing research is being performed for and funded by military/security communities in the government. Compared to other emerging technologies like quantum computing or artificial intelligence, which are being driven more by private industry, the reliance on government investments, as shown in Figure 7.1, increases the weight that policies in these communities will have in shaping quantum sensing research and adoption practices.

Among technology producers, there is significant institutional pressure to ensure that quantum technologies continue to garner this requisite government interest through selecting and facilitating key applications. At two major events held by quantum technologist communities, the Quantum Economic Development Consortium (QEDC)[669] and the Quantum World Congress,[670] a common discussion theme among quantum experts was the identification of use-cases to sustain policy interest and ensure practical applications are identified for quantum technologies. This push to establish connections is also seen in the various publications that attempt to map out use-cases for quantum sensing.[671]

Simultaneously, the structure of these institutions makes it hard for technologists to establish clear, realistic communication of expectations with capability seekers. Under pressure to express the importance of their research in

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[668] Klein and Kleinman, "The Social Construction of Technology," p. 39.
[669] QEDC 2021 meeting, convened at the Santa Clara Convention Center, November 2021.
[670] Quantum World Congress 2022, convened at the Ronald Reagan Convention Center, December 2022.
[671] For example: "Quantum Sensing Use Cases," QEDC, 2022, https://quantumconsortium.org/sensing22/.

compelling manners, technical experts may either use overly simplistic explanations, such as through boundary objects like qubits, that do not provide enough nuance to allow for debate; or else they may use technical jargon that is inaccessible to those outside of the technical epistemic community and especially to policymakers not familiar with the technology or the R&D community. The inaccessibility of technical terminology is particularly exacerbated in the case of quantum sensing by the abstract nature of quantum physics, making it harder to conceptualize and discuss, even among scientists, engineers, and mathematicians.[672]

Among capability-seeker institutions, requirements to classify information will be influential in authorizing quantum technology development and shaping perceptions. Because much of the research is funded by government actors focused on requirements for military and security applications, classification is likely to be more widespread compared to other emerging technologies. Segmentation of relevant capability information due to classification can severely limit the ability of an external reviewer to evaluate a technology's suitability for a particular application. Such oversight could be particularly useful in cases where technologies have high degrees of uncertainty and skepticism but are pursued regardless based on technological hedging strategies. Classification of information played an important facilitation role in many of the historic case studies evaluated in Chapter 4 and was most starkly exemplified in the case of remote vision. This was also demonstrated in Chapter 5's technical evaluation of submarine detection feasibility, which was constrained by the classification of information on operating procedures and stealth

[672] "Even Physicists Don't Understand Quantum Mechanics," *The New York Times.*

capabilities, and thus had to rely on assumptions and estimates to evaluate feasibility. Beyond simply impacting information flow, insulation from external criticism for actors with security clearances is also bolstered due to cultural norms among members with security clearances that perceive information gaps in assessments performed outside of the classified environment, regardless of whether the classified information itself is important in performing basic technological feasibility assessments. Lawrence argues that the boundary between classified and unclassified analysts establishes distinct social worlds across epistemic communities and provides a "profound source of identity and lived experience for actors within its vicinity."[673]

A new economic macrosocial trend that is also affecting perceptions of quantum technologies, including sensing, is the rise of VC funding. The broader quantum socio-technical ecosystem, including quantum communication and computing, has received significant support from VC funding, a new type of funding institution that did not have a significant presence for the historical case study technologies, but that has dramatically impacted science and technology innovation since the 1990s.[674] While VC firms have devoted significant resources to cutting edge technologies, Lerner and Nanda find that the uptick of influence for VC firms introduces three key effects in modern innovation ecosystems: VC funding prioritizes a very narrow set of technologies; VC funding disproportionately represents the whims of "a few deep-pocketed investors"; and VC funding has led to a decline in governance over appropriate start-up requirements in favor of high-risk high-reward

[673] Christopher Lawrence, "Heralds of global transparency, Remote sensing, nuclear fuel-cycle facilities, and the modularity of imagination," *Social Studies of Science*, Vol. 50, No. 4, 2019.
[674] Elizabeth Gibney, "Quantum gold rush: the private funding pouring into quantum start-ups," *Nature*, October 2, 2019, https://www.nature.com/articles/d41586-019-02935-4.

investments.[675] Faced with pressure to engage in high-risk, high-reward technology funding rounds in order to exemplify adaptability and impress investors, VC funders differentiate themselves by supporting niche but ostensibly promising areas like quantum technologies.[676] However, if these institutional interests in a particular technology push for funding an early-stage technology, like quantum sensing, especially with low governance requirements, inflated interest could be perceived as confidence in a technology despite lack of proven technical feasibility.

And finally, the context of renewed great power competition is beginning to exert a political macrosocial effect across all institutions that will likely further increase techno-optimism, incentivize engagement on high-risk, high-reward technologies, and manifest changes across the different technology ecosystems. As the Biden quantum initiatives signify, there is a codified U.S. strategic initiative to pursue quantum technologies for the sake of gaining U.S. leadership. This is part of a broader science and technology initiative to compete for technological leadership, with the achievement of technological supremacy justified as a strategic objective in-and-of itself. This national policy reinforces a collective imaginary that has long existed in the United States which fetes new technologies and U.S. innovation as guarantors of national security, and which is often reinvigorated in periods of threat

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[675] Josh Lerner and Ramana Nanda, "Venture Capital's Role in Financing Innovation: What We Know and How Much We Still Need to Learn," Harvard Business School, Working Paper 20-131, https://www.hbs.edu/ris/Publication%20Files/20-131_fc73af76-3719-4b5f-abfc-1084df90747d.pdf.
[676] Paul Gompers and Josh Lerner, "What Drives Venture Capital Fundraising?" Brookings Institution, https://www.brookings.edu/wp-content/uploads/1998/01/1998_bpeamicro_gompers.pdf; and Biz Carson, "Investors tell us why they're pouring millions into quantum computing," Protocol, May 4, 2020, https://www.protocol.com/manuals/quantum-computing/vc-investments-bullish-quantum-computing-coronavirus.

inflation.[677] Across capability-seeker institutions, reinforcement of this imaginary incentivizes and urges that capability seekers incorporate new technologies into their activities to the extent possible as a way to demonstrate competency and to support the national agenda. A report by the National Academies on the imperative claims, "U.S. leadership in technology innovation is central to our nation's interests, including its security, economic prosperity, and quality of life. Our nation has created a science and technology ecosystem that fosters innovation, risk taking, and the discovery of new ideas that lead to new technologies..."[678]

Beyond the impact on capability seeker institutions, geopolitics, and the resulting rationale for R&D at a given point in time, also produce long-term impacts on technology institutions, shifting the focus areas, technical codes, and talent pools in academic research communities. Slaughter and Rhoades trace shifts in U.S. competitiveness policies since the Cold War, detailing the long-term impacts of policies on different technical communities through highlighting the resulting trends in funding for particular fields and sub-fields, patent volumes, and numbers of students receiving degrees in different fields.[679] These longer term trends suggest that current policies establishing quantum as the frontier of science will produce long-term effects on the U.S technical workforce, which could incidentally increase long-term quantum bias, and may also impact competency in other fields.

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[677] Frank L. Smith, "Quantum technology hype and national security," *Security Dialogue*, Vol. 5, No. 1, 2020, https://journals.sagepub.com/doi/pdf/10.1177/0967010620904922.
[678] "Protecting U.S. Technological Advantage," National Academies, 2022, https://nap.nationalacademies.org/catalog/26647/protecting-us-technological-advantage.
[679] Sheila Slaughter and Gary Rhoades, "The Emergence of a Competitiveness Research and Development Policy Coalition and the Commercialization of Academic Science and Technology," *Science, Technology, and Human Values*, Vol. 21, No. 3 (Summer 1996),

Given these dynamics, it is expected that quantum sensing will continue to sustain high interest and funding from hopeful military capability seekers. Under pressure to maintain resource and funding volumes, technologists will continue to promote the benefits of quantum sensing. This messaging will be heightened as the broader quantum ecosystem leverages quantum sensing as a near-term application that could lead to sustained funding for quantum computing and quantum communication technologies. Military capability seekers who have historically wielded influential power over technology innovations through funding have also already asserted interest in quantum sensing, viewing the technology as natural progressions of their research portfolios. Many of these capability seekers also operate in the classified environment, creating a barrier to external review. Furthermore, these institutions will face increased pressure to pursue new technologies and demonstrate technology awareness in the geopolitical context of a great power competition, heightening their will and resources to seek out new capabilities. Given these ecosystem dynamics, policymakers should anticipate high interest and inflated perceptions on the impacts and timeliness of quantum sensing. Quantum sensing has a number of socio-technical attributes that favor heavier investment and higher expectations of impact than should be feasibly expected based on the technical analysis conducted in Chapter 5.

Effects and Consequences for Quantum Sensing Perceptions

The next important consideration is the extent to which heterogenous perceptions or expectations of a technology produce certain strategic and technological effects. Beyond impacting individual decisions to pursue, support, acquire, or refute a technology, perceptions of a technology's impact may also affect national policies and strategic stability. Additionally, the propagation of inflated expectations and interest can have a variety of effects on the socio-technical ecosystem itself. This section briefly reviews these effects.

First, as concluded in Chapter 6, unrealistic expectations of a technology produce a variety of consequences in deterrence. In the context of submarine detection and submarine vulnerability, perceptions that quantum sensing will allow better detection and tracking capabilities than is realistically feasible could impact domestic policymakers' doctrinal and force structure decisions, as well as those of adversarial and other countries. If a country's leaders believes that the country has a credible way to maintain continuous awareness of another countries' nuclear-armed submarines, they could be more willing to engage in riskier behavior or rely on pre-emptive or prevent strikes.[680] However, if a country's leaders perceive that the adversary may currently have, or could achieve in the future, the means to detect and monitor their submarines, they could feel pressure to increase their arsenal size to off-set the loss of a key second-strike capability (hedging against possible technological surprise).

These perceptions also then influence policies on related topics, such as willingness to engage in arms control and cooperative risk reduction dialogue with adversaries as opposed to competing for technological superiority. If countries

[680] Although this is less likely, President Donald Trump commonly referenced technological capabilities with assertions that were incorrect; Likewise, Vladimir Putin has asserted Russian hypersonic capabilities that have since been proven to be insufficient.

believe that new technologies carry the potential to rapidly disrupt their deterrence postures and doctrines, then they are less likely pursue or consider any form of arms control or cooperation that could impose opportunity costs on their ability to develop and acquire new technologies or sustain certain force structure elements. This underlying apprehension over technological surprise has had enormous effects on arms control since the Cold War, and is particularly heightened during periods of competition.

Finally, inflated expectations and perceptions also have important consequences for the technical communities they derive from, and thus produce downstream innovation-related implications if they impact the longevity and vitality of research in a particular field. Geels and Smit argue that some degree of "hype," or inflated promise of the socio-cultural impacts of technologies, should be expected. They stress that establishing simplistic, forward-looking connotations are important for engaging non-technical professionals responsible for funding decisions, and assert that, "for this mobilizing purpose, the advocates cannot do without some societal blinkers."[681] In this sense, hype, or techno-optimist outlook, has a positive effect in that it can be used to provide non-technical folks with conceivable "technology futures" that are easier to understand than by simply specifying each iterative R&D evolution. (However, it could also attract unmerited interest or funding that could lead to net negative effects on security.) Beyond securing resources, Roberson argues that hype may also allow for anticipatory governance by inviting debate on imagined

[681] Frank Geels and Wim Smit, "Failed technology futures: pitfalls and lessons from a historical survey," *Futures,* Vol. 32, 2000, p. 882.

technology futures that are crafted to be understandable to the public and policymakers, specifying, "a framework of anticipatory governance applied to hype suggests that rather than using hype to bring people along to a predefined agenda, hype might be used to draw attention to imagined outcomes and the assumptions that inform them."[682]

Others caution that hype can lead to mistrust in the science community, and that inaccurate predictions or exaggerations based on little to no facts may lead to intense initial responses, and eventually resulting in skepticism in the long-term that could ultimately dampen research.[683] Galitski, a condensed matter physicist at University of Maryland, urges: "I am getting more and more concerned that this recent quantum computing commotion is a self-perpetuating 'intellectual' Ponzi scheme, a bubble, which may sooner or later crash and take legitimate research and innovation efforts with it."[684]

However, defining when hype is a negative influence is challenging given the subjective nature. In assessing when hype is "inappropriate," Intemann offers one such designation, specifying that two dimensions must be considered: the goals of the communication in a particular context, and the degree to which evidence is sufficient to warrant particular claims or inferences.[685] But even this definition is complicated

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[682] Tara Roberson, "Can hype be a force for good?: Inviting unexpected engagement with science and technology futures," *Public Understanding of Science*, Vol. 29, No. 5, 2020, https://journals.sagepub.com/doi/epub/10.1177/0963662520923109.
[683] For example: Zubin Master and David Resnik, "Hype and Public Trust in Science," *Science and Engineering Ethics*, Vol. 19 (2013), https://link.springer.com/article/10.1007/s11948-011-9327-6.
[684] Victor Galitski, "Quantum Computing Hype is Bad for Science," Linkedin Pulse, July 16, 2021, https://www.linkedin.com/pulse/quantum-computing-hype-bad-science-victor-galitski-1c/.
[685] Kristen Intemann, "Understanding the Problem of "Hype": Exaggeration, Values and Trust in Science," *Canadian Journal of Philosophy*, Vol. 52, No. 3 (2022), p. 286.

by the fact that communicators can have multiple goals when messaging interest and based on the emphasis on uncertainty that Chapter 5 found for emerging technologies.

Skepticism resulting from inappropriate hype, or intentionally inflated assertions, produces strategic effects if it prevents continued interest and innovation in a security-relevant technology. For example, in response to a congressional mandate that requires government agencies to assess post-quantum cryptography capability needs and invest in requisite technologies, companies that pitch themselves as post-quantum cryptography providers are making inflated promises about their products to attract the newly established funding stream.[686] While this is not directly harmful, it could eventually produce negative consequences if actors begin to grow skeptical of the benefits of post-quantum cryptography or perceive that they have better capabilities than they actually do.

Conclusion

This chapter has expanded on the insights gained from the previous chapters in evaluating the nuclear deterrence effects of quantum sensing by identifying the drivers of perceptions and expectations over quantum sensing based on consideration of the socio-technical ecosystem. It surveyed sources of inflated expectations across technologist, capability-seeker, and oversight communities, and predicted strategic and technological effects that overly-optimistic expectations could produce.

[686] Lennart Baumgartner, Benjamin Klein, Niko Mohr, Anika Pflanzer, and Henning Soller, "When – and how- to prepare for post-quantum cryptography," McKinsey Report, May 4, 2022, https://www.mckinsey.com/capabilities/mckinsey-digital/our-insights/when-and-how-to-prepare-for-post-quantum-cryptography.

In evaluating the broad innovation ecosystem based on the technical and capability-oriented communities and social worlds, this chapter found that exaggerated expectations of quantum sensing will likely be fostered by a communication gap across technical and non-technical actors, an information barrier arising from classification of capability-relevant information, and a heterogeneous quantum sensing ecosystem that also overlaps with a much broader, general quantum technology ecosystem. Furthermore, macrosocial and institutional trends within the ecosystem favor technology competition and ambitious innovation agendas as opposed to more cooperative or restrained approaches to technology development.

By foregrounding actors, the findings can be used identify options for policymakers to anticipate new technologies (and uncertainty), engage in dialogue, and build institutional knowledge and flexibility to better navigate quantum sensing and emerging technology disruptions. This chapter applied STS perspectives to emphasize human agency in shaping technology development and innovation pathways. Through having a clearer assessment of the stage of development, policymakers can increase their oversight of the production process. Better institutional knowledge of the practical aspects of quantum technology development could alleviate the deleterious effects of the communication barriers between technical and non-technical audiences, as well as between technologist and capability-seeker communities. Finally, although new technologies, especially those as widely applicable and security-relevant as quantum sensing, are bound to generate interest, expectations could at least be used to facilitate dialogue on long-standing controversies in the nuclear policy and security studies spheres.

Thus, this chapter provides a starting point for recentering human agency in guiding and mediating technology innovations and contests that the effects of quantum sensing and perceptions of quantum sensing development are deterministic. Through careful, meaningful policies, governments can increase their oversight of technology development and ultimately improve the suitability and stability of the technologies produced. These policy implications will be discussed in much greater detail in Chapter 8, along with policy implications based on the technical and strategic assessments.

Chapter 8: Conclusion

"The Americans decided to make atomic weapons if they could, and they succeeded. Both in 1945 and after, the primary attention of both participants and observers has been given to the extraordinary process by which success was achieved. Much less attention has been paid to the events that led to the basic decision, in 1941, to go ahead. Yet of all the political decisions of the nuclear age this one is the first, not only in time, but quite possibly in importance."

-McGeorge Bundy, 1988[687]

"Yet the inventors of accuracy have a problem. They possess all these resources. But, as we have seen, there is a sense in which they still require the world as their laboratory. And the world has yet to be persuaded that it should be so used. Acting wisely, we can prevent it ever being so."

-Donald Mackenzie, 1990[688]

While the Pentagon's foray into parapsychology phenomena during the 1970s and 1980s undeniably exemplifies an overreaction to a "technology" (or technical method) that had no scientific basis, the successful American endeavor to develop

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[687] McGeorge Bundy, *Danger and Survival: Choices About the Bomb in the First Fifty Years*, Random House Press, New York, 1988, pp. 29.
[688] Donald Mackenzie, *Inventing Accuracy: A Historical Sociology of Nuclear Missile Guidance,* The MIT Press, London, England, 1990, pp. 423.

nuclear weapons in the 1940s represents one of the most productive outcomes that could be anticipated for when pursuing a new technology. The Manhattan Project led to the rapid invention of the atomic bomb in 1945, followed by the hydrogen bomb just seven years later.

These achievements marked a turning point not only for American national security, but also for the ethos of American innovation that persists today. In September of 1945, a few weeks after the atom bomb was used on Hiroshima and Nagasaki, Dwight Macdonald posited, "atomic bombs are the natural product of the kind of society we have created. They are as easy, normal and unforced an expression of the American Standard of Living as electric iceboxes."[689] The collective memory of the triumphant nuclear weapon pursuit continues to shape institutional ideals and objectives for technology acquisition processes, including the prioritization of science and technology discovery to sustain U.S. leadership, and particularly through pursuing high-risk, high-reward technologies. In contemporary parlance, nuclear historian Alex Wellerstein observes that "it has become increasingly common to invoke the Manhattan Project as a general exemplar of applied science."[690]

Even as these technical accomplishments continue to shape sociotechnical imaginaries of U.S. technology pre-eminence, the history of nuclear deterrence has also been shaped by a persistent preoccupation with the next technological turning point, animated by near obsession over emerging, disruptive technologies. As this

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[689] Quoted in James Farrell, "American Atomic Culture," *American Quarterly*, Vol. 43, No. 1 (1991), https://www.jstor.org/stable/2712975.

[690] Alex Wellerstein, "We Don't Need Another Manhattan Project," Federation of American Scientists, November 14, 2013, https://fas.org/publication/dont-need-another-manhattan-project/. Another collective memory that animates American R&D ethos is the moon landing, which gave rise to the term "moonshot."

dissertation has shown, apprehension over the potential for technological innovation to disrupt nuclear deterrence extends nearly as far back as the Manhattan Project. In recent years, the topic of "emerging technologies" continues to generate an enormous amount of literature and dialogue among nuclear deterrence and security studies experts and practitioners.

This surging interest can be accredited to a variety of technical, social, and strategic factors. Technical traits that characterize modern innovations, including automation, precision, and speed give rise to concerns that second-strike capabilities will become vulnerable.[691] Flaring tensions between the United States, China, and Russia have renewed great power competition rhetoric, underscoring technology leadership as a means to avoid technological surprise and shape the rules of the road on new technologies in both civilian and defense applications.[692] Finally, new technologies are enmeshed in a larger, more connected network of actors and social institutions vying for resources to maintain prominence at the frontier of innovation.

Concerned, and at times eager, about these vectors of change, analysts, policymakers, and academics have applied a variety of methods to evaluate the impacts of various new technologies on nuclear deterrence (and other policy domains/impact areas). A common goal across the literature is to anticipate the risks and opportunities of new technologies before they emerge, and so, in a sense, to

[691] For example, discussed in Andrew Futter, "The Risks Posed by Emerging Technologies to Nuclear Deterrence," in Perspectives on Nuclear Deterrence in the 21st Century (April 2020), https://www.chathamhouse.org/sites/default/files/2020-04-20-nuclear-deterrence-unal-et-al.pdf.
[692] U.S. Executive Branch, "National Security Strategy," October 2022, https://www.whitehouse.gov/wp-content/uploads/2022/10/Biden-Harris-Administrations-National-Security-Strategy-10.2022.pdf.

predict the unpredictable. Yet, most do not try to incorporate historical trends and consideration of socio-technical characteristics of new technologies.

One technology at the forefront of the emerging technology landscape is quantum sensing. Quantum sensing leverages quantum phenomena to improve the precision and sensitivity in the measurement of physical properties and to increase operability in adverse conditions. Given the wide scope of applications for quantum sensing, a surge of interest has animated policymakers over the potential deterrence and defense implications. While quantum sensing is not nearly as nascent as quantum computing and quantum communication, two other fields that apply advanced quantum techniques, there is still significant uncertainty around what sorts of capabilities can be expected of the technology, especially when operated in complex, real-world environments. With its extensive range of applications and recent progress in innovation, quantum sensing offers an opportunity to examine the formation of perceptions around new technologies and the contribution of these perceptions to policy decisions made under conditions of technological uncertainty.

This dissertation used the case study of quantum sensing to explore ways to estimate the technically feasible disruption that can be expected of new technologies, to untangle how strategic beliefs shape what policy implications are drawn from technical estimates and remaining uncertainties, and to understand the social dynamics that shape expectations and decisions about innovation. The findings lay the groundwork for a more structural evaluation of new technologies by developing an interdisciplinary, integrated analytical framework. It has reinforced approaches in security studies literature with technical and STS scholarship. It then applied that framework to five historical case studies to examine complexity across technical, strategic, and social dynamics, and to improve understanding of temporal effects not captured by the proposed framework. The framework was then used to evaluate the technical viability of quantum sensing applications, divergent strategic and policy implications driving debates about the technology, and the socio-technical ecosystem dynamics generating interest in and forming perceptions of the technology.

This final chapter situates the findings from this research in the broader context of security studies literature and nuclear policy dialogue and leverages these findings to identify key policy implications. This chapter summarizes the methodological contributions of this research, which are especially poignant as interest in emerging technologies surges. This chapter explains the contribution of this research to existing theoretical frameworks, particularly in its attempt to bridge gaps across existing security studies, technical, and science and technology studies literatures. Finally, this chapter highlights the policy insights gained by conducting the dissertation analysis, which can inform deterrence and strategic stability responses merited by quantum sensing, as well as opportunities to improve broader technology evaluation, acquisition, and engagement strategies.

Methodological Contribution

This dissertation has demonstrated the utility of a more integrated socio-technical analytical framework for examining the mixed technical, strategic, and social factors that shape perceptions of new technologies and their influence on nuclear deterrence. The analytical framework specifies the difference between technology innovations and the strategic capabilities to which they could feasibly be applied. In the context of nuclear deterrence, this allows for a distinction between baseline technology innovations and the capability improvements that innovations could afford that would disrupt current deterrence and strategic stability balances. By distinguishing between the underlying technologies and the capabilities that are more often debated in the context of nuclear deterrence, the framework critiques certain assumptions that innovations will inevitably produce strategically significant disruptions by emphasizing the uncertainty in leveraging a technology to achieve a particular capability. It further emphasizes the ambiguity in interpreting the effects of innovations based on different strategic perspectives. The framework also uses the separation of technologies and capabilities to delineate the different epistemic communities and social worlds, including the actors and institutions that comprise the socio-technical ecosystem for a particular innovation and which produce perceptions around the technology.

Through the historical case study analysis, the dissertation exemplifies the analytical framework and shows the merit of considering patterns throughout historical cases of technology innovation when evaluating new technologies. Although emerging technologies are perceived as being novel (and are labelled as such), remarkably similar features can be found in historical case studies. Many of the characteristics that new technologies embody or the capabilities to which they are applied have already been manifested in historical innovations; additionally, some of the actors and institutions involved in historical technology case studies still participate in today’s R&D communities.

Likewise, evaluating the contemporary quantum technology case study further demonstrated the importance of considering the mixed technical, strategic/political, and social factors that drive technology innovation and related expectations. The technical analysis illuminated a few capability improvements relevant to nuclear deterrence and strategic stability that can be expected of quantum sensing, including more accurate missile navigation and better submarine tracking methods. But the analysis also highlighted uncertainty over the development and deployment timelines based on current R&D progress and operability requirements that will limit the extent to which quantum sensing will disrupt deterrence or strategic stability, at least for the foreseeable future. Based on these technical estimates and the limitations identified, the strategic evaluation then explored how the feasible improvements, as well as perceptions of possible improvements, could impact nuclear deterrence and strategic stability, and how assessments of these effects diverge when viewed through different strategic perspectives (AD and DL, for example). Finally, surveying the socio-technical quantum ecosystem illuminated the network of actors and institutions that have facilitated overly optimistic outlooks for quantum sensing, and that could impact decisions about the technology's development regardless of technical feasibility or strategic implication estimates.

By integrating technical, strategic, and social factors, this analysis provides one bridge across the diverse literatures identified in Chapter 2. While robust scholarship exists for quantum sensing R&D, security studies, and science and technology studies, the literatures are remarkably isolated from one another. This dissertation demonstrated how each field of study contributes unique and valuable insight to address the challenges and uncertainties that are common when anticipating the impact of new technologies on nuclear deterrence. Fostering greater cross-pollination among these fields would sharpen the analytical tools used in this research and increase awareness among researchers in each field of the broader applicability of their work.

Policy Insight

Beyond establishing new methodological approaches, the research in this dissertation also offers insight that is directly useful for crafting effective policy responses. First, the research informs policy implications for nuclear deterrence, force structure, and arms control as a result of quantum sensing. But also, given that this research demonstrates how influential perceptions of new technologies are, regardless of how much they diverge from assessments based on technical feasibility, the dissertation also highlights policy implications for mediating hype and expectations around new technologies and offers insight on how to govern military innovation ecosystems.

Nuclear Policy Implications for Quantum Sensing

While this dissertation provided methodological and theoretical contributions to existing scholarship, it also identified findings relevant for policymakers responsible for governing new technologies, and quantum sensing specifically, or tasked with managing the impact of new technologies on nuclear deterrence.

The technical analysis suggests that quantum sensors will constitute a more evolutionary, rather than revolutionary, disruption to nuclear deterrence over the next ten years, if not longer. Based on R&D progress reviewed, quantum sensors will begin to move out of the lab, starting with deployment and operability testing in real-world settings. Yet, given some of the operability constraints already identified for quantum sensors, they will likely only meet or slightly exceed the performance of non-quantum alternatives until more significant innovations in entanglement and system control technologies enable better sensitivity or greater mobility, which could take decades to achieve. In submarine detection, quantum sensors may result in a slight increase in detection range, or new methods for detecting submarines, but will not afford transparent oceans or persistent tracking capabilities that would undermine a country's assured second strike due to the enormous deployment requirements that could not be addressed through quantum sensing alone. In missile navigation, quantum sensors may improve navigation accuracy, but it will still take years before systems that could afford strategically significant improvements reach the stage of deployment. Furthermore, underlying uncertainties over potential countermeasures or doctrines that could be employed by adversaries will continue to plague counterforce strategies regardless of any conceivable improvement in submarine detection or missile navigation accuracy.

Together, these findings indicate that policymakers should not let claims of increasingly vulnerable second strike-capabilities influence nuclear doctrine or force structure decisions that favor more robust arsenals. Such claims derive from DL proponents who view any incremental improvement to offensive or defensive capabilities as potentially impactful, and thus underestimate uncertainty over new technologies. Instead, through applying AD lens which establishes a higher disruption threshold, policymakers should focus on the stabilization of stealth techniques and invulnerability of the secure second strike, which could become more important as improved missile navigation may increase ICBM vulnerability over the long-term. This assessment indicates three key areas of policy implications.

First, policymakers should clearly communicate and signal the limitations of quantum sensing for detection and tracking of submarines. The easiest way to send a clear signal of a policy based around assured mutual vulnerability would be if the government stopped investing in quantum sensing technologies for submarine detection. However, this is extremely unlikely given the fact that most quantum sensors are dual-use and have many civilian and other military applications that would be impacted if the government discontinued funding for quantum sensing. Furthermore, quantum sensing research is heavily linked to quantum computing, which the U.S. government has already announced is a focus in the competition over technological leadership with China.[693]

Improved signaling and clearer communication could be achieved both through force structure and acquisition decisions, as well as better information sharing. Information sharing could be achieved through establishing Track-2 or intergovernmental dialogue with China and Russia to discuss options for ensuring a

[693] "National Security Memorandum on Promoting United States Leadership in Quantum Computing While Mitigating Risks to Vulnerable Cryptographic Systems," U.S. Executive Office, May 4, 2022, https://www.whitehouse.gov/briefing-room/statements-releases/2022/05/04/national-security-memorandum-on-promoting-united-states-leadership-in-quantum-computing-while-mitigating-risks-to-vulnerable-cryptographic-systems/.

minimum level of mutual vulnerability regardless of the detection and tracking technologies each country might employ. To ameliorate concerns over pre-emptive first strike feasibility, arms control agreements that require separation of warheads and delivery vehicles could be negotiated, or such measures could be adopted unilaterally to clearly signal that the United States is not pursuing pre-emptive first-strike capabilities. However, if the history of missile defense is any indication, Russia and China are unlikely to find this compelling if the United States is simultaneously unrestrained in its ability to pursue and deploy quantum sensors. One alternative would be to conduct joint exercises to clearly demonstrate the limitations of quantum sensors for detection and to reinforce confidence of submarine invulnerability. Unilaterally, the United States could acknowledge invulnerability through doctrinal decisions and force structure manifestations, which could send the clearest signal. For example, instead of researching and testing more intrusive sensing network technologies, policymakers could incentivize funding for counterforce capabilities that reduce vulnerability to new detection methods.

Second, given the navigation accuracy improvement that could be achievable and the impact on targeting precision, policymakers and academics in the nuclear field should re-open debates over the various implications for low-yield and conventional counterforce strategies. Both force structure transition options have ignited significant debates across nuclear policymakers, practitioners, and academics in the past few decades, with little closure about the strategic impact. These debates are fueled by conflicting perspectives on damage limitation, deterrence, and disarmament ideals, and have receded in recent years. But, given impending accuracy improvements, a more robust dialogue should be ignited to further explore the effects of these two force structure options with emphasis on the ability for these avenues to impact strategic stability and disarmament potential, or alter cost and resource considerations. This question is also likely to resurface as a result of geopolitical tensions with Russia and China, and a growing belief that mutual vulnerability constrains U.S. ability to deter non-nuclear aggression. Furthering these debates at the international governance and bilateral levels could help increase transparency of the considerations, but also may invite too many perspectives. First and foremost, the U.S. nuclear community should consider the necessities for its own force structure and convince actors in the stakeholder network of these assessments to get robust support one way or another. New technologies cannot be expected to fundamentally resolve these longer-running debates.

If, after multi-stakeholder engagement, there is still a consensus that low-yield nuclear weapons and conventional precision strike capabilities are deleterious to strategic stability, then the U.S. government may want to pursue arms control or limitation agreements on these technologies. However, verification would be a necessary component of any agreement, and it is not clear whether or how this would be possible. Multilateral or bilateral agreements, or unilateral self-restraint, have been proposed for both low-yield nuclear weapons[694] and conventional precision strike

[694] For example: Erik Gartzke, "Why, in nuclear weapons policy, sometimes fewer options are better," *Bulletin of the Atomic Scientists*, June 18, 2020, https://thebulletin.org/2020/06/why-in-nuclear-weapons-policy-sometimes-fewer-options-are-better/#post-heading; Kingston Reif, "When less is not more," *Bulletin of the Atomic Scientists*, March 12, 2012, https://thebulletin.org/2012/03/when-less-is-not-more/#post-heading.

capabilities[695] in the past but were never seriously pursued due to lack of political will and urgency. If there is a reasonable case to be made that related force structure alterations would significantly undermine mutual vulnerability and that strategic stability would be harmed to the extent of incentivizing arms racing or crisis escalation, arms control may be the best policy option. However, this could also critically undermine efforts to pursue forms of disarmament in the near and medium terms, which is why a robust round of research and dialogue must pre-empt such agreements.

Finally, with respect to decisions to pursue quantum sensing capabilities, interest in quantum sensing is expected to rise, suggesting that continued assertions regarding the potential impacts of quantum sensing on nuclear deterrence can be anticipated. This interest and dialogue on disruption (which is often prone to overly optimistic expectations) derives from the technology's suitability for security applications, the diverse and competitive network of technologists seeking research funding and recognition, and the community of capability seekers facing institutional pressures to demonstrate technological adaptability in the face of a looming great power competition. Policymakers should evaluate each of these motivations when assessing claims about the potential utility of quantum sensors, or other emerging technologies in deterrence activities. Approaches to navigating these perceptions are discussed below.

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[695] Amy Woolf, "Conventional Prompt Global Strike and Long-Range Ballistic Missiles: Background and Issues," Congressional Research Service – Report R41464 (Updated July 16, 2021), pp. 44-46, https://sgp.fas.org/crs/nuke/R41464.pdf.

Policy Implications for Mediating Hype and Managing Expectations

If the assessments of the current quantum socio-technical ecosystem and evaluations of science and technology trends at large are correct, and some degree of inflated interests and perceptions should be expected to permeate the idea of quantum sensing, then how can policy dialogue on the realistic effects and development timeline for the technology be mediated? Particularly, how can policymakers navigate potential pitfalls to ensure that their decisions are made on the basis of reasonable technical expectations and support these evaluations with appropriate funding and defense posture responses? Furthermore, as a new era of science and technology competition looms, how can policymakers better equip themselves to navigate exaggerated assertions like those evaluated in this dissertation?

One of the benefits of applying various STS perspectives to evaluate these issues is the recentering of technology and innovation to encompass socio-technical drivers, foregrounding human agency. Under a more simplistic, technological deterministic view, the prognosis for policy intervention or mediation would be bleak (or perhaps would resemble MacAskill's differential technology development argument previously discussed). This section presents policymaker-specific recommendations for navigating technology expectations, with emphasis on the implications for managing strategic stability dynamics and leveraging human agency to guide innovation through knowledge of the socio-technical ecosystem. These recommendations are built around three core pillars: anticipating realistic technology futures, leveraging these assessments and the uncertainty therein to debate core policy tenets and objectives *to the extent possible*, and building capacity to continue managing socio-technical uncertainty dilemmas.

Anticipating technology futures

Beyond maintaining awareness of the various perceptions and conjectures about technology futures, policymakers and practitioners should facilitate robust, empirical methods to monitor R&D progress for new technologies, project timelines to realistic technology futures and identify opportunities for anticipatory governance. In their assessment, Geels and Smit urge, "policy makers then should not go along too easily with promises of very high future impacts. Instead, they should have an eye for the pitfalls…"[696] Common pitfalls that Geels and Smit define include: (1) the production of expectations through cultural biases; (2) predisposition to focus on current technological trajectories rather than alternative future innovation models; (3) phrasing new technology as substitutions of an old technology; (4) assuming unchanging geopolitical and social contexts; (5) functional thinking and siloing of projections in certain applications; (6) overestimation of speed of societal adoption; and (7) initial technology futures expectations that are too high.[697] The occurrences and effects of these pitfalls have already been surveyed throughout the course of this research, either through the technical analysis, capability assessment, or socio-technical ecosystem evaluation, demonstrating the importance of opportunities to critically appraise and monitor technologies.

[696] Geels and Smit, "Failed Technology Futures," p. 882.
[697] Geels and Smit, "Failed Technology Futures," p. 880.

This dissertation has provided one such methodological approach for the development of testing and evaluation methodologies that can satisfactorily avoid each of Geels and Smit's pitfalls; depending on the agency involved or the focus area, the government may prefer to evaluate broader or more narrow areas than the quantum sensing and nuclear deterrence scope evaluated here. Although there is flexibility in how the technical assessments could be performed, each approach should seek to reduce the uncertainty as much as possible in both the technology assessment and the capability evaluation. Assessments by oversight agencies and sponsors should focus on investigating the boundary objects, either rooted in technologies or capabilities, that facilitate dialogue and expectations. Technical assessments can be used to establish the current degree of development, while independent capability assessments can be used to establish thresholds at which significant disruptions would be achieved. In some cases, technical assessments may form the main analytic focus, such as for broader societal evaluations with undefined applications; whereas in other cases, evaluations should be oriented around use-cases to determine whether a particular application is feasible with a variety of technology options and in what timeline.

Furthermore, technology assessments may also reveal additional requirements and socio-technical factors that will be necessary to implement a technology beyond the black box or boundary object requirements and that could create a lag in deployment if unanticipated, or else could prevent access to certain types of user groups in general. For example, although many assessments have speculated over the timeline until a quantum computer could achieve sufficient computing power to perform decryption, few have considered the resource requirements that would be necessary to operate such a computer. In their assessment, Parker and Vermeer demonstrate that this sort of feasibility assessment can provide insight into broader socio-technical factors that will guide technology development. In calculating the power requirements, they find that, due to the high energy consumption expected, nation-states and large organizations are likely to be the only actors capable of achieving a cryptographically relevant quantum computer for a significant period of time.[698]

To the extent possible, methodological approaches should be complemented with appropriate metrics for evaluation. Again, metrics may be categorized based on their relevance to either the technology itself or its applications. In quantum computing, for example, some metrics are used to describe the operability of the qubit, including the coherence, speed, and fidelity. However, more practically, producers of quantum computing platforms often attempt to convey their stage of development in terms of computation power metrics – such as quantum volume, algorithmic qubits, or logical qubits.[699] Applying metrics of application functionality at early stages of development may not allow for encompassing all potential assets and limitations of different technology components, though. In the case of quantum computing, some believe the technology is too nascent to begin establishing hard

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[698] Edward Parker and Michael Vermeer, “Estimating the Energy Requirements to Operate a Cryptographically Relevant Quantum Computer,” RAND Working Paper WR-A2427-3, April 2023, https://arxiv.org/pdf/2304.14344.pdf.

[699] Robin Blume-Kohout and Kevin Young, “Metrics and benchmarks for Quantum Processors: State of Play,” Sandia National Lab 0963R, 2019, https://www.osti.gov/servlets/purl/1493362; Junchao Wang, Guopin Guo, and Zheng Shan, “SoK: Benchmarking the Performance of a Quantum Computer,” *Entropy*, Vol. 24, No. 10 (2022).

metrics, and that each metric proposed so far is in some way biased in favor of a particular qubit type. To the extent possible, measurable metrics should be discussed to identify relevant parameters by which to evaluate a technology.

Until technologies are developed, continual monitoring should be performed by government sponsors and capability communities to maintain awareness of the realistic stage of innovation. This requires a dedicated focus and commitment to monitoring a technology, which is not well integrated into the existing producer-user based socio-technical ecosystem, but particularly in the area of defense technologies can alleviate the risks and requirements associated with technology hedging strategies. By offering an alternative means to prevent technological surprise, monitoring could alleviate some of the pressure that leads government agencies to resort to hedging. If executed carefully, in avoiding fully investing in the technology to capability transition, monitoring efforts also avoid establishing new self-inducing socio-technical ecosystems and sending complicated and potentially provocative signals to adversaries about intent for pursing a capability. Smit refers to this as "nonprovocative defense" and declares the strategy to be a "dynamic concept, which has to be made operational again and again in the view of ever-changing circumstances."[700] Furthermore, Smit cautions that multiple independent evaluations should be conducted, if possible, to remove the degree of objectivity around interpreting effects of disruptions.[701]

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[700] Wim Smit, "Steering the process of military technology innovation," *Defense Analysis*, Vol. 7, No. 4 (1991), p. 409.
[701] Smit, "Steering the process of military technology innovation," p. 410.

Once technologies are developed and deployed, testing and evaluation should continue to be conducted to estimate the performance constraints on the system. Such tests should focus on illuminating the limits of performance for the technology. By clearly demonstrating functionality constraints in operability settings, these tests would reduce uncertainty over the innovation as the technology continues to develop. Importantly, the potential benefits and risks or publishing the results of these assessments in open source should be considered. At the international level, providing open information on the performance of a system can increase clarity and may mitigate arms-racing risks if sufficient limitations demonstrate that the technology will not be revolutionary; however, such demonstrations may also be seen as provocative if they convey willingness to use the technology or commitment to continue pursuing the technology. For domestic stakeholders, clarity from technology assessments ensures that domestic policymakers are making posture and doctrinal decisions based on a realistic understanding of the technology and resulting capabilities. For example, it would be better to ensure that force structure and arms control decisions based on missile defense are clearly guided by an understanding of the operability constraints that should be assumed for missile defense systems, rather than in response to inflated expectations which may increase risk acceptance. Otherwise, capability gaps may arise or performance failures in the absence of the presumed capability could significantly decrease a country's technology and capability credibility.

Finally, to monitor technology development outside of the United States, policymakers must also recognize the heterogeneity of science and technology ecosystems across countries. While the findings from this research highlight characteristics of the U.S. science and technology ecosystem, other countries are likely to have their own unique patterns, as dictated by the co-production of state policies, security environments, and technology requirements and perspectives. For example, in contrast to the U.S. innovation ecosystem, Gu argues that China's science and technology ecosystem is defined by (1) officialism, or the assertion of official power and authority as a key pillar, (2) utilitarianism, or the pragmatic attitude of science, and (3) the foregrounding of politics and the emphasis on compliance and deference to authority.[702] For policymakers, these differences mean that known drivers of U.S. science and technology policy cannot be projected onto other countries when determining motives for or design of innovation; rather, policymakers should maintain awareness for distinctions across ecosystems.

Building institutional capacity

Especially amidst a technology competition over a wide set of technologies and given the user-producer ecosystem identified in Chapter 7, assuring continuous monitoring and evaluation capacity for various technologies would require significant government resources. This could be achieved through supporting expanded organizational capacity for technology-focused groups like the JASON committee and the National Academies of Science, Engineering, and Medicine and by re-examining the socio-technical ecosystem effects of exploratory long-shot research groups like DARPA. Beyond institutional capacity for organizations centered around

[702] Chao Gu, "The co-production of normal science: A social history of high-temperature superconductivity research in China," *Social Studies of Science,* Vol. 53, No. 1, https://journals.sagepub.com/doi/full/10.1177/03063127221119215.

technology review, greater resources and policy impetus should be given to individual agencies that sponsor acquisition to continually monitor technology developments specifically relevant to their capability areas. Finally, it could also be beneficial for offices that perform routine assessments to inform policymakers, such as the Congressional Research Services (CRS) or the Congressional Budget Office (CBO), to improve their in-house technical knowledge. One alternative to institutionalizing technical attaches at CRS and CBO and expanding their missions could also be reviving the Office of Technology Assessment, which was defunded in 1995.[703]

In either type of assessment communities, establishment of a "core-set" of knowledge needed to critique technology assessments and evaluations is required. On the role of individuals with a "core-set" of knowledge needed to resolve disputes over technology evaluation and production, Collins specifies, "the core-set of scientists are those who are actively involved in experimentation or observation, or making contributions to the theory of the phenomenon, or of the experiment, such that they have an effect on the outcome of the controversy."[704] However, as Collins notes, specification of what constitutes a core set is context-specific, and thus is to some degree objective. Though, importantly, Collins specifies that actors with core-set knowledge *must* have access to all relevant information needed to perform the evaluation, including tacit, technical understanding, and application-oriented

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[703] Darrell West, "It is time to restore the U.S. Office of Technology Assessment, Brookings Institute, February 10, 2021, https://www.brookings.edu/articles/it-is-time-to-restore-the-us-office-of-technology-assessment/.
[704] H. M. Collins, "The Pace of the 'Core-Set' in Modern Science: Social Contingency with Methodological Propriety in Science," *Hist. Sci*. Vol. 29 (1981),

knowledge to determine appropriate metrics.[705] In the case of quantum sensing and nuclear deterrence applications, this would require some working knowledge of quantum sensing physics and operation, as well as knowledge of parameters for operation in submarine detection or missile navigation. This implies that, although some members with core-set knowledge could exist in the open-source communities, legitimate core-set appraisals, particularly for areas with classified information, should also come from within the government.

Importantly, expanding the community of actors with core-set knowledge will require increasing acceptance of interdisciplinary skill sets that incorporate information from both technical and user/capability background. Concern over the "educational breadth of scientists and engineers" was an early topic of discussion in the STS literature and remains an important thrust to ensure that the divide between technical and non-technical actors is limited to the extent possible;[706] but educational breadth for policymakers is equally important. Especially as the pace of science and technology innovation increases and imposes complex moral, ethical, and practical questions about how technology should be integrated into certain areas of human life, a shift towards interdisciplinary skill sets, or at least appreciation for the methodologies and approaches of other disciplines, could address many of the barriers exemplified in this dissertation. In this case, the STS lens provided in Chapter 7 provides insight into some of the issues that are likely obstructing interdisciplinary

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[705] H. M. Collins, "Public Experiments and Displays of Virtuosity: The Core-Set Revisited," *Social Studies of Science*, Vol. 18 (1988), pp. 725 – 748.
[706] Stephen Cutcliffe, "A Hitchhiker's Guide to STS," *Technology and Culture*, Vol. 36, No. 4, October 1995, p. 1015.

skill sets, including institutional and administrative as well as interpersonal and emotional factors, and offers insight into means to reduce these barriers.

Beyond establishing hiring practices and incentives for individuals to transcend barriers between research disciplines, the government could also reinforce the establishment of communities with core-set knowledge through increased engagement with technical communities. Experiential learning and engagement opportunities provide significantly greater knowledge and intuition than that which could be conveyed in words. Attainment of some level of tacit knowledge would provide better insight on requirements, practices, and obstacles in basic research and engineering required for a new technology that could provide government workers with the ability to better anticipate innovation trajectories. Furthermore, increased interconnectivity between the research community and the government may alleviate some of the information barriers identified throughout the dissertation, which could prove beneficial in creating clearer expectations of new technologies and improving overall designs of technologies. Some research has been conducted to evaluate methods for transferring tacit knowledge across communities, which could be useful in developing pathways for policymakers to gain exposure to technical experiences that would be both realistically manageable and practically useful.[707]

Re-examining deterrence divides

[707] For example: Meric Gertler, "Tacit knowledge and the economic geography of context, the undefinable tacitness of being (there)," *Journal of Economic Geography*, Vol. 3, No. 1, January 2003; and Tua Haldin-Herrgard, "Difficulties in diffusion of tacit knowledge in organizations," *Journal of Intellectual Capital,* Vol.1, No. 4, 2000.

Through investigating deterrence and strategic stability implications for quantum sensing, the research also examined underlying concerns, interests, and politics regarding broader, technology-agnostic capabilities like tracking and targeting of hard-to-find second-strike forces and low-casualty counterforce. This has highlighted features of nuclear deterrence that continue to foster disagreement across different political, strategic, and social perspectives. As more emerging technologies contribute to strategic dialogue, debates over the disruptions caused by technologies like quantum sensing, that afford precision, automation, and transparency, will invoke recurring re-evaluation and deliberation over the key nuclear deterrence and strategic stability requirements in a modern technology environment.

One metric that features prominently in discussions on nuclear doctrine and force structure but that merits significantly more research is the concept of "vulnerability." This research demonstrates that vulnerability can be better understood as a socio-technical phenomenon rather than an objective measure of stability or security of nuclear deterrence infrastructure. For example, in the case of submarine detection, vulnerability is often used as the threshold to designate disruption, yet the specification of an operational level at which detection or tracking capabilities would constitute a vulnerable second strike remain undefined. Any improvement in foreign countries' detection capabilities is often assumed to increase the vulnerability of the U.S. secure second-strike capabilities, and thus rendered destabilizing, without considering other factors that influence whether the adversary could find and destroy all U.S. submarines in a short period or whether they would even be likely to attack.

Moreover, the perception of vulnerability appears to have changed over time and across different epistemic communities (such as AD and DL). Thus, like each of the technology and capability areas evaluated in this dissertation, many epistemic communities and social worlds recognize vulnerability differently and their definitions have evolved and propagated various conceptions of vulnerability within the defense enterprise. Given that vulnerability is still a commonly used metric to evaluate technology disruption, significantly more work is merited to understand the production of vulnerability, the perceived requirements of vulnerability, and the consequences of this continually changing palimpsest to define vulnerability.

Similarly, this research underscores the importance of re-examining the purpose and effect of arms control and cooperative threat reduction policies. The technological determinism perspective, which asserts that technologies will emerge regardless of any human action or due to underlying human nature that favors innovation (such as competition) and urges that policymakers focus on responding to technology change, portrays a bleak outlook on the utility of efforts to engage with adversaries to establish arms control and cooperative threat reduction agreements as new technologies emerge. From the deterministic perspective, such agreements constrain a country's ability to respond to the continual cycle of technology production that will occur regardless of U.S. facilitation.

However, the foregrounding of human influence on technology afforded by the social constructivist perspective contends that there is a more complex relationship between policies and technology development that may increase favorability of technological restraint. Specifically, it asserts that such policies could impact technology development through limiting the formation of epistemic communities and social worlds that are entirely dependent on and biased towards a technology by shifting institutional incentives away from the technology competition ethos that promotes unfettered technology development and deployment. Therefore, the constructivist view offers a much more favorable assessment of arms control and cooperation-oriented policies, viewing them as avenues to meaningfully affect the technologies ultimately developed, while also disincentivizing risky arms-racing behavior. This re-appraisal under a constructivist lens could provide a much-needed silver lining to reanimate arms control dialogue.

Prospects for Future Research

In many ways, this research was just as much an exploratory endeavor to expand the analytical methods for evaluating new technologies as it was a direct analysis of nuclear deterrence policy implications from quantum sensing. Future research should seek to refine the components and operability of the integrated analytical framework to increase the internal validity by expanding the analysis of influential mechanisms and actors, and the external validity by increasing flexibility of the framework to adapt to different policy domains or technologies. Future research could further test the analytical framework through application to other technologies or other capability domains. The framework could also be used to illuminate innovation processes in other countries and distinguish country-level characteristics, including the technical, political, and social factors that comprise distinct research and development ecosystems for certain countries. Finally, future research should seek to better analyze the effects of macrosocial trends, such as the evolution of science and technology knowledge and larger policy shifts that arise from domestic and international political tensions (for example, shifts catalyzed by policies like the Biden Administration's CHIPs and Science Act[708]).

Beyond methodological improvements to the analytical framework, future research should also focus on further defining the quantum sensing socio-technical ecosystem and monitoring its evolution. Given all the technical, strategic/political, and socio-technical factors identified in Chapters 5, 6, and 7, quantum technologies in general will likely continue garnering interest and intrigue. Sensing is only a small piece of the much broader quantum technology socio-technical ecosystem. As quantum computing and quantum communication begin to emerge more earnestly, they will further amplify interest and expectations (more than they already have). To anticipate and proactively address future challenges from the emergence of quantum technologies, policymakers should treat quantum sensing as a test case to begin establishing governance strategies, assessment methods, and institutional competence that will be useful for decades to come.

Conclusion: Role of the Human Observer

This research raises a vexing question regarding the decision to ramp up technological hedging efforts that was outlined in the 2024 NDAA, as discussed in Chapter 1. Do the risks of technological surprise that are inherent (though

[708] "H.R.4346 – 117th Congress (2021-2022): Chips and Science Act," Congress.gov, Library of Congress, August 9, 2022, https://www.congress.gov/bill/117th-congress/house-bill/4346.

manageable) in technological restraint policies exceed the risks generated by hedging through modest pursuit of high-risk, high-reward capabilities?

In quantum mechanics, the measurement problem creates a host of experimental and theoretical issues. The measurement problem, famously exemplified by the Schrodinger cat thought experiment, asserts that the act of taking a measurement necessarily impacts a quantum system by causing the wave function to collapse, forcing the system into a single, definite state. Experimentally, the measurement problem upends the gold standard of reproducibility and prevents the ability to continually monitor and observe quantum evolutions. In theoretical analysis, the measurement problem injects immense debate over the interpretation of quantum mechanics. These issues are further complicated by the institutional design of scientific research, which aims to increase objectivity by removing perspective and human influence. Solid state physicist, N. David Mermin, observes:

> The language of science scrupulously avoids mentioning the subject – the user of science. So does much of the ordinary language we have learned to use to talk about the external world. The puzzles and paradoxes of quantum mechanics arise from such omissions. Putting the scientist back into the story requires us to expand into human terms all of the impersonal constructions that we have become used to and generally rely upon to make concise speech possible… Why have we kept fooling ourselves about such metaphysical issues for so many years?... It can be hard to acknowledge that it is humanity all the way down, in all fields – even physical science. There was no need to acknowledge it until quantum mechanics refused to make sense for almost a century.[709]

[709] N. David Mermin, "Making better sense of quantum mechanics," *Reports on Progress in Physics*, Vol. 82, No. 012002 (2019), p. 15.

Just as the quantum measurement principle asserts that human observers impact quantum systems through measurement, so too does the social constructivist theory assert that actors impact technology ecosystems, even when they may only intend to observe or hedge the development of a technology. Thus, as one of the more technical fields of physics begins to grapple with the role of the human observer, so too must policymakers seeking to improve policymaking on emerging technologies. Progress in science and technology studies literature has provided many other tools that can be used to impute the human influence on innovation and grapple with the co-production of technologies and politics through social mechanisms and institutions. Many of these insights have yet to trickle down into security studies analyses of emerging technology effects and policy imperatives for strategic stability.

While the human factor increases the degree of uncertainty and complicates the search for objectivity, it also inserts an opportunity for change. If technologies are realized as being in part produced by, and not just deterministically affecting, certain aspects of human social and political life, then opportunities for proactive, rather than reactive, policies emerge. As this research shows, incorporating socio-technical analysis not only allows for better anticipation of the effects of emerging technologies, but provides insight into the evolution of the technologies themselves and how such trajectories can be affected by policy changes on topics like nuclear doctrine, force structure, and arms control, even if only in a hedging strategy.

Appendix A: Selected Historical Case Study Timelines

Table A.1 Selected Ballistic Missile Defense Programs in the United States[710]

Project Name	Years	Technical characteristics	Technical Challenges & Skeptics	Motivation for Project	Government Stakeholders
Projects Thumper and Wizard	1946-1959	Early program with conventional interceptor; later program considered to employ nuclear interceptor	Technologies deemed to be far too nascent; less cost-effective than building more ICBMs	Intercept short and medium-range (V-2 style) missiles	Air Force
Army Theater ABM System (Plato and Patriot I)	Late 1940s-1950s	Theater ballistic missile defense to provide limited field protection	Issues intercepting missile at supersonic speeds – aerodynamic and thermodynamic concerns	Provides protection to field units	Army
Nike-Zeus ABM	1955s-1963	Advanced radar for tracking incoming missiles, with Zeus nuclear interceptor	Prone to decoys	Congressional interest; defend against Soviet ICBM attack	Army
Nike X	1961-1967	Nike-Zeus system more layered attack and waits until missiles are at 30km altitude to discern decoys; faster Spartan nuclear interceptor	Smaller window for interception; large requirement on computing power; high-power radar and fast missiles	Continued congressional interest; defend against Soviet attack	Army
Sentinel	1968-1969	Spartan nuclear interceptor; 700 needed to defend US cities	Animosity over placement in urban areas	Protect cities against Chinese or limited Soviet attacks	Army
Safeguard	1969-1975	Spartan nuclear interceptor	Still prone to decoys; continued concerns over accuracy	Protect ICBM silos against Chinese or limited Soviet attacks	Army

710 "Missile Defense Timeline," Missile Defense Agency, https://www.mda.mil/news/timeline.html#!.

Strategic Defense Initiative (SDI)	1980s	Broad program to develop advanced technologies; includes hit-to-kill transition, directed energy, etc.	APS Study;[711] Ashton Carter Report;	Protect against all ICBM threats (large-scale attacks included)	SDIO
Brilliant Pebbles (late SDI)[712]	1987 - 1993	Small satellite network armed with missiles	Technology immaturity and ease of countermeasures (JASON review of brilliant pebbles[713])	Defend against large scale attacks	Air Force; SDIO
Global Protection Against Limited Strike (GPALs)[714]	1990	Brilliant pebbles in space; ground-based missile systems for CONUS; ground and sea-based systems abroad; and command and control system	Continued limitations of brilliant pebbles; threats also not justifiable	Defend against limited strike	BMDO
National Missile Defense (NMD)	1990s	Glide phase interceptors; ground-based interceptor missiles; Aegis ballistic missile defense; Terminal high-altitude area defense; airborne systems; shorter range systems;	any country able to deploy ICBMs could also deploy counters (Union of Concerned Scientists)	Preventing coercion by rogue states and actors	BMDO; MDA

[711] N. Bloembergen and C. Patel, "Report to the American Physical Society of the study group on science and technology of directed energy weapons," *Reviews of Modern Physics*, Vol. 59, No. 3 (July1987).
[712] Donald Baucom, "The Rise and Fall of Brilliant Pebbles," *The Journal of Social, Political and Economic Studies*, Vol. 29, No. 2 (2004).
[713] "Review of Brilliant Pebbles," JASON Report JSR-1989, September 1989.
[714] John Pike and Christopher Bolkcom, "Global protection against limited strikes: An unnecessary and unworkable system," *Space Policy*, Vol. 7, No. 3 (August 1991), pp. 179-183.

Table A.2 Selected Hypersonic Missile Programs in the United States[715]

Project Name	Years	Technical Basis	Technical limitations	Motivation for Project	Government Stakeholders
Dyna-Soar (X-20)	1957-1963	Manned hypersonic plane	Uncertainty over appropriate booster	Intelligence; bombing; satellite interference	Air Force
[Hypersonic Hiatus][716] -MaRV -Space Shuttle -Project Prime	1970s-1980s	Hypersonic weapon platforms not directly researched – but MaRV and space shuttle testing provided useful technical innovations	All projects in this era were focused on lifting re-entry; scramjets remained a major challenge	Motivated by other objectives. Space shuttle motivated by space exploration; MaRV motivated by missile defense	NASA; Air Force
SWERVE[717]	1975-2010	Missile glide body	Limited speed and range	To continue research on missile glide body.	Sandia
X-51 WaveRider[718]	1990s-Present	Unmanned, scramjet-powered aircraft	Test issues at boost-phase. Lost aerodynamic control due to fin degradation	To improve scramjet technologies for long-duration flight	Air Force
Force Application and Launch from Continental United States (FALCON)	2003-2011	Test vehicle	Coating material wore down due to hypersonic speed	To study technologies to extend reach of U.S. missiles launched from CONUS	DARPA; Air Force
Advanced Hypersonic Weapon	2010s	Hypersonic glide vehicle	Testing issues at boost stage of flight	Developed as part of conventional prompt global strike	Army
Hypersonic Airbreathing Weapon Jet (HAWC)	2021	Cruise missile technology	Unspecified	To develop a smaller vehicle that could launch from a variety of platforms	DARPA; Air Force

715 "U.S. Hypersonic Weapons and Alternatives," CBO Report, January 2023.
716 Hypersonic Case Studies
717 "U.S. Conventional Prompt Global Strike: Issues for 2008 and Beyond," National Academies of Science, Engineering, and Medicine, Pp. 133-134.
718 Michael Belfiore, "The X51A Hypersonic Plane: What Went Wrong," *Popular Mechanics*, October 26, 2012.

Tactical Boost Glide (TBG)[719]	~2015-2020	Glide body prototype for ARRW	Unspecified, but had to fix design after testing	To develop and demonstrate technologies that enable air-launched, tactical-range hypersonic boost glide systems	DARPA; Air Force
Long-Range Hypersonic Weapon (LRHW)[720]	~2020-present	Ground-launched boost-glide missile	Testing failure and delay; reason unspecified	Strategic attack weapon to counter A2/AD	Army
Air-Launched Rapid Response Weapon (ARRW)[721]	2018-2023	Air-launched boost-glide missile	Many testing issues with launch (reasons unspecified); Issues shrinking size of long-range HGVs	Decrease size of long-range gliders to allow for tactical use	Air Force
Hypersonic Attack Cruise Missile (HACM)	~2020-Present	Air-launched cruise missile	Unspecified	Tactical flexibility to employ fighters and mark high-value, time-sensitive targets	Air Force
Operational Fires (OpFires)	~2020-Present	Ground-based launcher for HGVs	Unspecified	To develop and demonstrate a ground-launched HGV capable of penetrating air defenses	DARPA; Army
Intermediate-Range Conventional Prompt Strike (IR-CPS)	~2020-Present	Sea-launched boost-glide missile	Unspecified	To strike high-value, heavily defended and dime-sensitive targets	Navy; Army
Hypersonic Air-Launched Offensive Antisurface Warfare (HALO)[722]	2023-Present	Air-launched cruise missile	Anticipated challenge: Operating and controlling in a contested environment	To provide an anti-ship hypersonic weapon	Navy

[719] Peter Erbland, "Tactical Boost Glide," DARPA.
[720] Andrew Feickert, "The U.S. Army's Long-Range Hypersonic Weapon," Congressional Research Service, March 31, 2023.
[721] Patrick Tucker, "What's Next in US Hypersonic Efforts as Air Force Shelves ARRW," *Defense One*, March 30, 2023.
[722] Justin Katz, "Hypersonic ship-killer: Navy taps Lockheed, Raytheon to start developing HALO missile," *Breaking Defense*, March 29, 2023.

Table A.3 Selected Reconnaissance Satellite Imagery Programs in the United States

Project Name	Years	Technical Basis	Technical limitations	Motivation for Project	Government Stakeholders
SAMOS (WS-117L)[723]	1956-1961	Launched on Atlas-Agena booster; equipped with camera and scanning and transmission equipment	Image transmission was infeasible; numerous failed launches	Satellite image reconnaissance	US Air Force ARPA
Project Vanguard[724]	1956-1959	Three-stage rocket designed to launch satellites; with civilian development of booster and satellite	Failed launches due to rushed test	Develop a rocket to establish a satellite presence in orbit for R&D purposes (tracking and scientific experiments)	Navy NSF (Funder)
Explorers Program[725]	1958-Present	Very basic sensor equipment on early satellites (radiation sensors, thermometers, microphone, and cosmic ray chamber)	Sporadic communication; signal collection was inconsistent; some launch failures	"Civilian" satellite program for R&D purposes	Army NASA
Corona Program (KH-1 to KH-6)	1959-1972	Launched on Thor-Agena booster; camera with film canister ejection mechanism	Very low reliability; issues collecting film	Satellite image reconnaissance	Air Force CIA

[723] Robert Perry, "A History of Satellite Reconnaissance: Volume IIA – SAMOS," NRO, 1972, https://forum.nasaspaceflight.com/index.php?topic=20232.0.
[724] Constance Green and Milton Lomask, *Vanguard: A History*, NASA, 1970, https://history.nasa.gov/SP-4202.pdf.
[725] David Devorkin, "The Missing History of the Explorer 1 Satellite," Smithsonian Air and Space Museum, January 26, 2018, https://airandspace.si.edu/stories/editorial/missing-history-explorer-1-satellite.

Table A. 4 Selected Remote Viewing Programs in the United States[726]

Project Name	Year	Technical Basis	Technical limitations	Motivation for Project	Government Stakeholders
SCANATE[727] (scan by co-ordinate)	1970	Viewers describe what they see when provided a map coordinate; initially focused on a small group of viewers	Overly dependent on individual viewers; program terminated when viewer died; cannot test reliably	Offensive intelligence collection	Army CIA
Gondola Wish[728]	1977	Viewers included civilians and soldiers	Cannot test reliably	Offensive intelligence collection; "to evaluate potential adversary applications of remote viewing"	Army/ INSCOM
Grill Flame[729]	1978	External contracting with SRI, as well as some in-house talent; emphasis on training more talent	Cannot test reliably; Negative assessment by National Academy of Science	Study to evaluate the capabilities and vulnerabilities associated with paranormal phenomena	Army/ DIA/ INSCOM
Sun Streak[730]	1985	Viewers to be trained, tested, and reviewed; operating through "extended remote viewing"; and "coordinate remote viewing"	Cannot test reliably	"To undertake operational intelligence applications using an aspect of psychoenergetics known as remote viewing"; tasking for: penetration of inaccessible targets; science and technology information; cuing of other intelligence systems; imminent	DIA

[726] John Pike, "STAR GATE" Federation of American Scientists, 2005.
[727] "Project SCANATE: Exploratory Research in Remote Viewing," CIA-RDP96, https://www.cia.gov/readingroom/docs/CIA-RDP96-00791R000100480002-4.pdf.
[728] Frederick Atwater, "Gondola Wish," Letter to Chief OPSEC, 1978, https://www.cia.gov/readingroom/docs/CIA-RDP96-00788R002000160011-2.pdf.
[729] "Project Grill Flame," August 20, 1981, https://www.cia.gov/readingroom/docs/CIA-RDP96-00788R001100210002-6.pdf.
[730] "Project Sun Streak," Defense Intelligence Agency, https://nsaarchive2.gwu.edu/NSAEBB/NSAEBB534-DIA-Declassified-Sourcebook/documents/DIA-21.pdf.

				hostilities; determination of nuclear from non-nuclear targets; human source assessments; accurate personality profiles	
STARGATE[731]	1991 - 1995	Extended Remote Viewing; Coordinate remote viewing; written remote viewing; secondary methodologies – dowsing, psychometry, and clairvoyance	Testing found that it was never useful for intelligence activities; collected irrelevant or erroneous data	"To provide an overview on remote viewing focusing on definitions, operations, management, participation, benefits, primary and secondary methodologies, categories of tasking, types of targets, and operational methodology."	DIA

[731] "Project STAR GATE," Defense Intelligence Agency, https://cia.gov/readingroom/docs/CIA-RDP96-00789R002600360002-3.pdf.

Table A.5 Selected Stimulated Isomer Energy Release Programs in the United States

Project Name	Years	Technical Basis	Technical limitations	Motivation for Project	Government Stakeholders
Gamma Ray Laser Project – Phase 1[732]	1987-1988	Test feasibility of optically pumping isomer candidates	Difficulty of stimulating and measuring resonances	Proof of technical feasibility of coherent and incoherent schemes for pumping laser	Naval Research Lab
Gamma Ray Laser Project – Phase 2[733]	1988-1996	Study identified Hafnium-178 as the best candidate	Difficulty of stimulating and measuring resonances	Study to identify gamma ray laser candidates and development of production cycle	DOD; Naval Research Lab; Ballistic Missile Defense Organization
Gamma Ray Laser Project – Phase 3[734]	2001-2005	Evaluation of use of synchrotron radiation sources for x-rays	Paucity of SR sources; challenge of triggering	Continue development of gamma ray laser for potential use in missile defense	AFRL
SIER (Stimulated isomer energy release)[735]	2004-2007	Trigger isomer energy release for metastable nuclei	No consistent tests to confirm 1998 triggering results; significant scientific skepticism	Goal is to develop a technique to control the release of isomer energy for a weapon yield between conventional and nuclear (hafnium weapon)	DARPA; DOD; USAFRL

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[732] Carl Collins, "Proof of the Feasibility of Coherent and Incoherent Schemes for Pumping up a Gamma-Ray Laser," Annual Technical Report GRL/8705, 1988, https://apps.dtic.mil/sti/pdfs/ADA199327.pdf.

[733] Carl Collins, "Progress in the Production of Samples of Gamma Ray Laser Candidate Materials," GCT/9601, April 15, 1996, https://apps.dtic.mil/sti/pdfs/ADA307242.pdf.

[734] Carl Collins, "Renewal of Research on Triggering Nuclear Spin Isomers," F49620-02-1-0141, 2005, https://apps.dtic.mil/sti/pdfs/ADA441411.pdf.

[735] "Research, Development, Test and Evaluation, Defense-Wide," Volume 1 – DARPA in Department of Defense Fiscal Year 2007 Budget Estimates, U.S. Department of Defense, February 2006, https://www.darpa.mil/attachments/(2G10)%20Global%20Nav%20-%20About%20Us%20-%20Budget%20-%20Budget%20Entries%20-%20FY2007%20(Approved).pdf; Edward Hartouni, Mau Chen, Marie-Anne Descalle, Jutta Escher, Alex Loshak, Petr Navratil, W. Ormand, Jason Pruet, Ian Thompson, and Tszu-Fang Wang, "Theoretical Assessment of $^{178m2}Hf$ De-Excitation," Lawrence Livermore National Lab – LLNL-TR-407631, October 9, 2008, https://www.osti.gov/servlets/purl/945547.
Sharon Weinberger, "Scary Things Come in Small Packages," *Washington Post*, March 28, 2004, https://www.washingtonpost.com/archive/lifestyle/magazine/2004/03/28/scary-things-come-in-small-packages/10d88640-038b-4afb-b25b-003026a8e5f5/; Carl Collins, "Use of L and M Shell Electrons to Trigger Nuclear Spin Isomers," F49620-03-1-0196, 2007, https://apps.dtic.mil/sti/pdfs/ADA474483.pdf.

Appendix B: U.S. Quantum Sensing Ecosystem

Table B.1. Quantum Sensing Ecosystem Innovators and Developers

Entity Name	Entity Type	Year Founded (companies)	Headquarters Location	Quantum Sensing Platform Type (If specified)	Application (If specified)	Industry (If specified)
Lockheed Martin	Public Company	1995	Bethesda, Maryland	NV center diamond	Magnetometer	Navigation; Aerospace; Defense
Argonne National Laboratory	National Lab	1946	Lemont, Illinois	Superconducting circuit; Defect qubit; Trapped ion	Magnetometer; Gravimeter	Unspecified
Li-Cor	Private Company	1971	Lincoln, Nebraska	Photon sensor	Spectrometer	Agriculture; Environmental Science
Apogee Instruments	Private Company	1996	Logan, Utah	Atom optical sensor; Photon flux	Spectrometer	Agriculture; Environmental Science
AOSense Inc	Private Company	2004	Sunnyvale, California	Optical atomic interferometry	Accelerometer; Inertial sensor; Gravimeter; Gravity gradiometer; Quantum clock; Spectrometer	Military; Aerospace; Industry
ColdQuanta/ Infleqtion	Private Company	2007	Boulder, Colorado	Cold atom; Atom interferometer; Trapped ion	Quantum clock; Accelerometer; Gyroscope	Aerospace; Manufacturing; Logistics
Rydberg Technologies	Private Company	2015	Ann Arbor, Michigan	Atomic vapor interferometry	Magnetometer; Spectrometer; RF sensor	Unspecified
Quantum SensoriX	Private Company	2020	Austin, Texas	NV center diamond spin-based	Magnetometer; RF sensor; Inertial sensor	Aerospace; Manufacturing; Logistics; Defense
Raytheon Intelligence & Space	Public Company	2020	Arlington, VA	Superconducting; Photon sensor	Unspecified	Defense; Aerospace
Boeing	Public Company	1916	Arlington, VA	NMR Gyroscope	Unspecified	Unspecified

Twinleaf	Private Company	2007	Plainsboro, New Jersey	Optical atomic spin; SERF	Magnetometer	Academia; Government; Industry
Northrop Grumman	Private Company	1994	Denver Colorado	NMR spin; electron spin; synchronous pumping	Magnetometer; Gyro	Defense; Aerospace
Biospherical instruments	Private Company	1977	San Diego, California	Photon sensor	Spectrometer	Environmental Monitoring
Stanford University	University	N/A	Palo Alto, CA	Atom interferometer; superconducting	Gravimeter; Magnetometer	Unspecified
Nucrypt	Private Company	2003	Park Ridge, Illinois	Photon sensor	Lidar; Photon detection; QKD	Basic research; Industry; Communication
Gigajot	Private Company	2017	Pasadena, California	Photon sensor	Spectrometer; Photon detection	Unspecified
BAE - US	Public Company	1999	Falls Church, Virginia	Cold atom	Inertial sensing; Gravimeter; Magnetometer; RF sensing; Quantum radar	Defense; Industry; Basic research
Vector Atomic	Private Company	2018	Pleasanton, California	Atomic interferometry	Inertial sensing; Gravimeter; Quantum clock	Defense; Industry; Communication; Transportation; Energy
Teledyne Technologies	Public Company	1960	Los Angeles, California	Cold atom interferometry	Gravimeter; Quantum clock	Space; Basic research; Industry
Lawrence Livermore National Lab	National Lab	N/A	Livermore, California	Cold atom interferometry; Superconducting	Gravimeter; Magnetometer; Quantum clock; Photon detector	Computing; Defense
Physical Sciences	Private Company	1973	Andover, MA	Quantum cascade laser	Spectrometer	Environmental monitoring
Fibertek	Private Company	1983	Herndon, Virginia	Spectrometry	Lidar; Synthetic aperture radar	Space; Defense
Vescent Photonics	Private Company	2003	Golden, Colorado	Cold atom	Gravimetry; Magnetometer; Inertial sensing	GPS; Communication
Scientific Systems Company	Private Company	1976	Woburn, Massachusetts	Unspecified	Inertial navigation	GPS; Aerospace; Defense
Mesotech	Private Company	1992	Sacramento, California	Unspecified	Temperature	Meteorology

Honeywell	Public Company	1906	Charlotte, North Carolina	Trapped ion	Spectrometer	Energy; Pharmacy; Basic research; Aerospace; Defense; Communication; Industry
L3Harris	Public Company	2019	Melbourne, Florida	Unspecified	Inertial navigation; Detection; Quantum clock; Imaging; Metrology	Aerospace; Defense; Communication
SRI International	Private Company	1946	Menlo Park, California	Cold-atom; Rydberg	Magnetometry; Electrometry; Gyroscope;	Healthcare
Hypres	Private Company	1983	Elmsford, New York	SQUID; Superconducting qubit	Quantum clock; Electrometer	Unspecified
Quantum Technology Sciences	Private Company	1991	Melbourne, Florida	Unspecified	SONAR	Energy; Geophysics
Translume	Private Company	Unspecified	Ann Arbor, Michigan	Trapped ion	Unspecified	Unspecified
Georgia Tech	University	N/A	Atlanta, Georgia	Neutral atom	inertial sensor; gyro; magnetometer	Unspecified
University of Missouri	University	N/A	Columbia, Missouri	Unspecified	Radar	Unspecified
Intelliepi IR Inc	Public Company	1999	Richardson, Texas	Spin qubit; Quantum dot; GaAs	IR Sensor; Spectrometry	Space; Defense
Qmagic	Private Company	2003	Nashua, New Hampshire	Quantum dot	Spectrometer; Infrared sensing	Space; Defense; Environmental Surveying
Allegro (Voxtel)	Private Company	1999	Beaverton, Oregon	Unspecified	Lidar; Photon detection; Spectrometry	Space; Defense; Industry
Spectral Energies	Private Company	2006	Unspecified	Unspecified	Unspecified	Unspecified
Applied Quantum Materials	Private Company	Unspecified	Unspecified	Silicon quantum dot	Unspecified	Unspecified
Quantum Imaging (SCD USA)	Private Company	2007	Colorado Springs, Colorado	Unspecified	Lidar; Spectrometry	Space; Defense
Sequoia Scientific	Private Company	1995	Bellevue, Washington	Unspecified	Spectrometer	Environmental monitoring
Virginia Polytechnic Inst	University	N/A	Blacksburg, Virginia	Unspecified	Quantum clock	Military; Aerospace; Industry

University of Maryland	University	N/A	College Park, Maryland	Nv-center diamond	Unspecified	Unspecified
Space Micro	Private Company	2002	San Diego, California	Unspecified	Spectrometer	Military; Aerospace; Industry
Omega Optics	Private Company	2001	Austin, Texas	Photonic; Silicon	Spectrometer; Lidar	Unspecified
Quantum Ventura	Private Company	Unspecified	Palo Alto, CA	Unspecified	Unspecified	Unspecified
Guardion	Private Company	Unspecified	Burlington, Massachusetts	Unspecified	Radiation detection; Spectrometry	Aerospace; Defense; Communication
Aktiwave	Private Company	Unspecified	Henrietta, New York	Unspecified	Unspecified	Unspecified
University of Texas - Austin	University	Unspecified	Austin, Texas	Unspecified	Unspecified	Unspecified
Applied Nanofemto Technologies	Private Company	Unspecified	Unspecified	Unspecified	Spectrometer; Photon detection	Unspecified
Freedom Photonics	Private Company	Unspecified	Santa Barbara, California	Silicon; Photonic	Spectrometer	Unspecified
Kestrel	Private Company	1993	Albuquerque	Unspecified	Unspecified	Unspecified
Quantum Design	Private Company	1982	San Diego, California	SQUID; Superconducting qubit	Magnetometer	Unspecified
Quantum stabilizers	Private Company	Unspecified	Fort Lauderdale, Florida	Unspecified	Unspecified	Unspecified
MIT	University	N/A	Cambridge, Massachusetts	Cold atom; defect; NV-center	Quantum clock; Gyro; Magnetometer	Unspecified
Cornell	University	N/A	Ithaca, New York	Superconducting qubit	Magnetometer; Electrometer; Quantum clock	Unspecified
University of Illinois Urbana-Champaign	University	N/A	Champaign, Illinois	Superconducting qubit	Magnetometer; Electrometer; Spectroscopy	Unspecified
University of Chicago	University	N/A	Chicago, Illinois	NV-center diamond	Magnetometer; Temperature; Electrometer	Unspecified
University Wisconsin-Madison	University	N/A	Madison, Wisconsin	Defect; NV-center; Atom interferometer	Magnetometer; Quantum clock; Electrometer	Unspecified
Delaware State University	University	N/A	Dover, Delaware	Spin; Cold atom interferometry	Clocks; Magnetometers	Unspecified
Northwestern University	University	N/A	Chicago, Illinois	Unspecified	Unspecified	Unspecified

Harvard University	University	N/A	Cambridge, Massachusetts	NV-center diamond	NMR	Unspecified
University of Colorado - Boulder	University	N/A	Boulder, Colorado	Unspecified	Unspecified	Unspecified
New Jersey Institute of Technology	University	N/A	Newark, New Jersey	Unspecified	Unspecified	Unspecified
University of Iowa	University	N/A	Iowa City, Iowa	NV-center diamond	Magnetometer; Electrometer; Temperature	Unspecified
Washington University - St. Louis	University	N/A	St. Louis, MO	Solid state spin defect	Spectrometer; Magnetometer	Unspecified
Purdue University	University	N/A	Lafayette, Indiana	Spin defect	Magnetometer; Electrometer; Temperature	Unspecified
University of Michigan	University	N/A	Ann Arbor, Michigan	Topological qubit; Solid state qubit	Spectrometry; Temperature	Unspecified
University of California - Berkeley	University	N/A	Berkeley, California	Silicon qubit; Superconducting qubit	Gyroscope	Space; Basic research
California Institute of Technology	University	N/A	Pasadena, California	Unspecified	Unspecified	Unspecified
University of California - San Diego	University	N/A	San Diego, California	NV center diamond	Unspecified	Unspecified
University of Colorado - Denver	University	N/A	Denver Colorado	Unspecified	Unspecified	Pharmacy; Basic research
University of California - Los Angeles	University	N/A	Los Angeles, California	Atom interferometer	Navigation	Unspecified
Rice University	University	N/A	Houston, Texas	Silicon qubit	Unspecified	Unspecified
Duke University	University	N/A	Durham, North Carolina	Trapped ion	Unspecified	Unspecified
University of Washington	University	N/A	Seattle, Washington	Trapped ion; SQUID	Magnetometer	Space; Basic research

University of California - Santa Barbara	University	N/A	Santa Barbara, California	Atom interferometry	Gravimeter; Magnetometer	Space; Basic research
Georgia Tech Research Institute	University	1934	Atlanta, Georgia	Trapped ion; Cold atom; Rydberg	Magnetometer; Gyroscope; Quantum clock	Unspecified

Table B.2. Quantum Sensing Ecosystem Funders/Supporters

Entity Name	Entity Type
Canadian Government	Foreign Investment
Breakthrough Victoria	Foreign Investment
Innovate UK	Foreign Investment
In-Q-Tel	Gov. Venture Capital
NIST	Government
Air Force/AFRL	Government
Army/ARL	Government
Navy/NRL	Government
NASA	Government
National Science Foundation	Government
Department of Commerce	Government
DARPA	Government
NSF	Government
DTRA	Government
Intelligence Community	Government
Department of Energy	Government
Department of Agriculture	Government
Department of Interior	Government
Nyserda	Investment Firm
Maverick Ventures	Investment Firm
Boka Group Holdings	Investment Firm
Global Frontier Investments	Investment Firm
LCP Quantum	Investment Firm

Solomon Partners	Investment Firm
Lennox Capital	Investment Firm
Foundry Group	Investment Firm
Toro	Private Company
Weather Hawk	Private Company
Tiloom	Private Company
Sistemes Electronics	Private Company
Stevens Water	Private Company
Sensorscope	Private Company
Percival Scientific	Private Company
Rainwise	Private Company
Meter ICT International	Private Company
Novalynx	Private Company
ESE Group	Private Company
Dynamax	Private Company
Environmental Growth Chamber	Private Company
Conviron	Private Company
Delta-T	Private Company
Dyacon	Private Company
Candidus	Private Company
Cityblooms	Private Company
Columbia Weather Systems	Private Company
Aeron	Private Company
AlsoEnergy	Private Company
Campbell Scientific	Private Company
Techstars	Venture Capital
Mass Challenge	Venture Capital
Forma Prime	Venture Capital
Caruso Ventures	Venture Capital
Mass Ventures	Venture Capital
Anthem Ventures	Venture Capital

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