



# Future Directions at the Intersection of Management Science and Information Science

*A Workshop on the Emerging Sciences and Their  
Applicability to DoD R&D Management Challenges*

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## **Future Directions Workshop series**

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## A Note from the Basic Research Office

Over the past century, science and technology have brought remarkable new capabilities to all sectors of the economy; from telecommunications, energy, and electronics to medicine, transportation and defense. Key to this technological progress is the capacity of the global basic research community to create new knowledge. Understanding the trajectories of fundamental research empowers stakeholders to identify and seize potential opportunities. The Future Directions Workshop series, sponsored by the Basic Research Office in the Office of the Under Secretary of Defense for Research and Engineering, seeks to examine such emerging research areas to uncover new phenomena and generate new knowledge that are most likely to transform future capabilities.

These workshops gather distinguished academic and industry researchers from around the globe to engage in an interactive dialogue about the promises and challenges of each emerging basic research area and how they could impact future capabilities. Chaired by leaders in the field, these workshops encourage unfettered consideration of the prospects of fundamental science areas from the most talented minds in the research community. These discussions are not intended to be focused on defense applications, but rather enable the exchange of ideas between academia, industry, and the government. Reports from the Future Direction Workshop series capture these discussions and therefore play a vital role in the discussion of basic research priorities.

This report is the product of a workshop held October 23–24, 2018 at the Basic Research Innovation Collaboration Center in Arlington, VA on the Intersection of Management Sciences and Information Science research. This workshop differed from previous future directions workshops in that it was focused on the Department of Defense (DoD) enterprise. Held in collaboration with C3, Cyber and Business Systems (DASD(C3CB)) of the Under Secretary of Defense for Acquisition and Sustainment (OUSD(A&S)), the goal was to open a dialogue with the academic community on the applicability of these emerging sciences to addressing the DoD research and development (R&D) management challenges. The themes and scope of this workshop do not necessarily reflect a position of the Department nor avenues of current focus, but rather provided a forum for experts and operators to discuss how insights from management and information sciences could inform DoD operations and processes. This report is intended to guide future discussions between the DoD operator and research community and also to inform the broader federal funding community, federal laboratories, domestic industrial base, and academia.

**Innovation is the key  
to the future, but basic  
research is the key to  
future innovation.**

—Jerome Isaac Friedman,  
*Nobel Prize Recipient (1990)*

## Executive Summary

Accelerating changes in technology and society pose fundamental challenges to the management of complex, hierarchical organizations like the U.S. Department of Defense (DoD). For the DoD, the stakes are especially high, as the security of the nation depends on our success in tackling these complex challenges, like managing asymmetric warfare, anticipating digital attacks, coordinating complex acquisition processes, optimizing global supply chains, and rethinking scientific and technological superiority. The DoD needs ways to understand and meet these new, forward-facing challenges. The intersection of management sciences and information sciences offers a set of principles and practices to provide guidance.

The management the DoD's research and development (R&D) is especially key to the security of the nation as advances and supremacy in R&D have been a bulwark for many decades, and the country has invested accordingly. But just investing more funds in R&D alone will not achieve the needed gains in security. R&D advances need to be accompanied by a culture of innovation, which, in turn, requires advances at the frontiers of management science and information science. The accelerating rates of change associated with the current digital era require equally rapidly evolving capabilities for organizations and institutions, yet most of the military-industrial complex has only been advancing in small, incremental ways.

In order to understand and meet the DoD's challenges in R&D management, a workshop was convened on October 23-24, 2019 in Arlington, VA to discuss emerging research at the intersection of management sciences and information sciences with the following goals:

- **Identify management, information, and operations challenges that the DoD is likely to face over the next two decades**
- **Identify future trajectories in management science and information science that are likely to be relevant to these future DoD challenges**
- **Develop an integrated roadmap for research in management science that can inform future efforts to improve the Department's technology management processes**

This Future Directions workshop gathered distinguished researchers from the nation's top business and management schools together with industry personnel and DoD R&D practitioners to engage in an interactive dialogue about these challenges and opportunities.

Among the considerable challenges in the DoD's R&D ecosystem, discussions focuses on five domains where inputs are needed from management and information science:

- **Budget and Programming:** The DoD manages a complex landscape of separate silos with challenges for coordination and integration. Long-established concepts, such as the distinction between basic and applied research, may impede rather than advance innovation.
- **Joint Integration:** Emerging threats seldom fit structures designed to handle current threats. Moreover, future threats are likely to become a greater challenge.
- **R&D Acquisition:** DoD's highly structured approach to acquisition constrains future choices. The frontiers of science and technology are advanced through rapid prototyping and option/portfolio-based approaches. R&D acquisition can benefit by incorporating "fail-fast" approaches that are now too often seen as too risky.
- **Supply Chain Risk Mitigation:** DoD supply chains face long-standing and new threats of disruption, with particular challenges arising from low frequency, high consequence events.
- **R&D Leadership:** This source of United States competitive advantage is at risk due to expanding capabilities of China and other nations.

The workshop participants agreed that success in meeting each of these challenges will require an ability to accomplish current missions concurrently transforming strategies, structures, processes, and cultures. They identified three fundamental tensions that underlie these challenges that are common across all large, established organizations. The tension between:

1. Horizontal and vertical functions (centralized strategy and R&D vs distributed services)
2. Learning and doing (research organization vs a complex fighting force)
3. The need for 'the best' and the need for just having competitive advantage (state-of-the-art vs better-than-our-enemies)

Underlying these challenges is the logic of digital technologies. Historically, organizations and institutions have lagged advances in technology. The present era has the potential to be an exception in the historical record, based on our understanding of the underlying logic of modularity. Digital systems of bits, bytes, and packets are assembled and disassembled with error correction, which is an important enabler of change. But this logic is also being reflected in a fragmentation of organizational and institu-

tional arrangements. **The future directions challenge centers on transforming existing organizations and institutions, as well as launching new ones, that can co-evolve (rather than lag) advances in science and technology—harnessing digital modularity rather than being captive to it.**

Discussions on emerging research at the intersection of management science and information science explored ways to link advanced digital capabilities with new organizational and institutional models for DoD R&D management. Workshop participants agreed that this intersectional research is still in development (research on digital technologies is too often separate from work on organizations and institutions), and neither field has been oriented toward DoD needs. As future directions, the participants identified seven research areas to address the DoD R&D management challenges:

- **Large-scale Systems Change Management:** Models are needed that go beyond traditional top-down and bottom-up change, accommodating accelerating change in the context of complex and dynamic combinations of stakeholders. This requires better understanding of change management and ecosystem considerations.
- **R&D/Innovation Management:** Moving rapid prototyping and agile development into large bureaucratic organizations is challenging for DoD culture(s). New workforce management strategies and methods require participation driven more by knowledge than rank or title.
- **Cyber Infrastructure and Data Analytics:** Open data exchange and stakeholder voice enabled by digital technologies, combined with distributed governance, is needed to support innovation in R&D.
- **Stakeholder Alignment in Complex Systems:** New forms of stakeholder alignment are needed within the DoD, across supply chains, and in programs and initiatives that span public, private, national and multinational efforts.
- **Social Psychology of Culture, Identity, and Conflict:** Lessons from social psychology are needed to guide a rethinking of core operating assumptions within the DoD.
- **The Science of Science Teams and Institutions:** The National Science Foundation's term, the science of science teams, points to further future directions of R&D involving the science of science institutions.
- **Supply Chain Resilience:** DoD should foster resilient supply chains as essential for security and as an element of needed organizational and institutional capability.

This report describes all of these and other related future directions using the language of advanced (lean) production methods: "Demand-Pull" and "Research-Push." From the perspective of the DoD, "Demand-Pull" refers to problems identified within the Department and in need of solutions or mitigation strategies. Thus, DoD "demand" signals are a call for help from the management and information science research communities in order to fulfill its mission in more agile and effective ways. "Research-Push" in this report refers to new insights generated in information science or management science that are highly relevant to R&D management but not yet linked to clear problems within DoD. Aligning

the demand signals with the flow of research would result in a highly generative ecosystem essential for the nation's defense.

The roadmap for future directions at the intersection of management science and information science can be described as a series of "From → To" challenges.

**Hierarchies → Networks → Ecosystems**  
**Alignment within organizations → Alignment across stakeholders**  
**Entrepreneurs → Intrapreneurs → Ecosystem architects**  
**Bilateral → Multilateral → Multilayered interactions**  
**Cost control → Balanced scorecard → Ecosystem metrics**  
**Risk management/mitigation → Adaptive response capability**  
**Top down → Bottom up → Middle out**  
**Agile teams → Agile organizations → Agile institutions**

Advanced expertise in ecosystems is needed to add to the well-developed literatures on hierarchies and networks. Our knowledge of mechanisms for alignment within organizations need to be extended to include alignment across stakeholders with relevant checks and balances, information sharing, collective action, and mutual gains. Knowledge about entrepreneurs and internal innovators, called intrapreneurs, needs to expand to include ecosystem architects. We need to extend knowledge on bilateral and multilateral interactions to understand these interactions in the context of multi-layered systems (a theme highlighted in the 2016 Future Directions report on Network Science and reinforced here). Building on the balanced scorecard, there is now the further challenge of lateral metrics that reach across ecosystems. Tools for risk management and risk mitigation need to encompass adaptive, resilient response capabilities. Middle-out change tools and methods need to be added to what we know about top-down and bottom-up change. Agile teams and agile organizations need to be joined by agile institutions in society. It is these many future directions that guide this report.

Finally, the workshop participants envisioned a path for establishing an effective military-academic knowledge ecosystem where advances in management and information science enable military organizations and institutions to anticipate and address DoD R&D-management challenges. This first involves increased situational awareness of R&D ecosystems, including points of alignment and misalignment among key stakeholders. With such awareness organizational and institutional innovations are possible, for example integrated program teams could be created that are comprised of professionals from the science, technology, acquisition, contracting, finance, legal, and social science domains—staying with the program across its lifecycle—from technology development through delivery and sustainment. A virtual network of supporting scholars in university management and information science programs, along with military colleges, could link theory development and practical application in new ways. The co-evolution of the social and the technical would be a fundamental break from the historical record where organizations and institutions have consistently lagged technological innovation—at considerable cost to society. Socio-technical co-evolution is advanced in this report as an essential capability given the complex and accelerating threats that we all face.

Since the industrial revolution, organizations and institutions have lagged advances in science and technology—at considerable cost to society. In the present era, when science and technology are advancing at accelerating rates, the costs and risks of lagging organizations and institutions are also accelerating. **This Future Directions report represents a challenge both to organizational and institutional scholars and to leaders in the public and private sector. They must work together to close the gap—so that social systems can effectively coevolve with technical ones.** Such advances are not just important for competitive advantages in the commercial sector and bridging digital divides in the social sector—the capability for institutional and organizational innovation to join effectively with science and technology innovation is essential for the current and future security of our nation.

# 1.0 The Intersection of Management Sciences and Information Sciences

Management science emerged more than two centuries ago and took on its modern form in the early part of the 20th century in response to the military and industrial challenges of increased concentration of capital and human resources, along with the growing global scale of operations. Information science emerged in the later part of the 20th century in response to digital revolutions in communication and computation, along with the growing importance of data in society. Just as economics has the market at its core and psychology has the human psyche at its core, management science centers on the hierarchical organizational form and information science is centered on network structures. In both cases, the dominant trend has been toward more micro aspects of each domain—problems that can be addressed by single investigators and small teams. Macro challenges facing organizations and institutions that require thinking beyond hierarchies or networks by large interdisciplinary groups are not studied as often, but are the primary focus in this Future Directions report.

Within management science, specialized branches exist (e.g. organization behavior, organizational development) and the same is true within information sciences (e.g. information systems, data science). In this report we refer to the domains as management science and information science and focus primarily at their intersection. This intersection is an important space because this is where new, digitally enabled arrangements can be identified that are neither just hierarchies nor just networks, as illustrated in Figure 1.0a. Layered ecosystems and digital enablers are examples of new organizational and institutional arrangements that sit at this intersection. Continued innovation at this intersection promises to offer insights into the organizational and institutional arrangements needed for the 21st century, both in terms of basic science and for practical applications in the commercial, academic, public, and non-profit sectors—all of which has deep implications for the military sector.

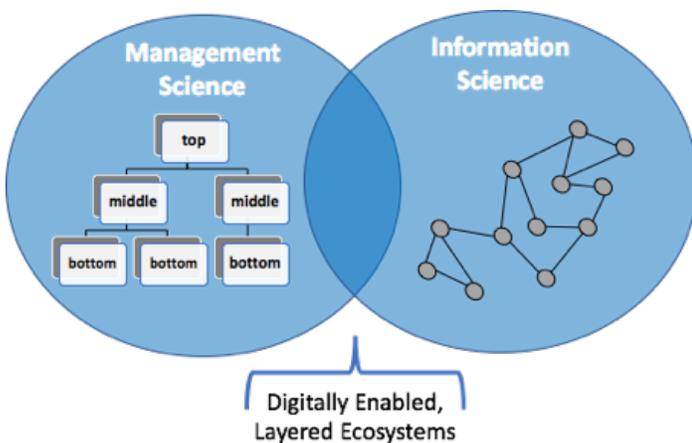


Figure 1.0a: The Intersection of Management Science and Information Science

Underlying the intersection of management science and information science is the logic of digital science. Digital communication and computation involves modular bits, bytes, and packets that can be disassembled and assembled with governing rules such as TCP/IP, and enabling principles such as error correction. Since organizational and institutional structures have always co-evolved with the dominant technologies of the time, this Future Directions workshop is motivated by the challenge of understanding the emerging organizational and institutional forms in the context of a succession of digital revolutions (Gershenfeld, Cutcher-Gershenfeld, and Gershenfeld, 2017).

Although the fields of management science and information science have much to offer in addressing DoD challenges, they are mostly advancing independently, with little connection to DoD applications. This is unfortunate both because there is a risk of inefficient or inappropriate decisions and actions on the part of the defense establishment and because needed advances in basic science in these domains would benefit from defense investments and applications.

## 1.1 Scale and Scope of Management and Information Sciences

Although foundational research in nearly all of the more technical aspects of information science was launched with DoD investments, for decades the social sciences have been largely disconnected from DoD investments and applications. Recently, however, DARPA has indicated interest in Next Generation Social Science (NGS2) and the Basic Research Office in the Office of the Secretary of Defense has a very successful Minerva Initiative to improve DoD’s basic understanding of the social, cultural, behavioral, and political forces that shape regions of the world of strategic importance to the U.S. Within the social sciences, management science and information science are among the more applied domains, though each is vast, spanning many subfields and domains. This Future Directions workshop has focused on the intersection of the two domains, spanning issues of large-scale systems change, multi-stakeholder collaboration, accelerating rates of change, data analytics, science and technology management, identity in digital media, and other related matters. Before turning to these issues, the full scale and scope of management science and information science need to be signaled since not every aspect of these fields can be covered in a Future Directions workshop. It is as important to know what is not covered as it is to know what is covered.

Within management science, the Academy of Management (AoM) was founded in 1936 and now features 25 divisions and interest groups. Additionally, there are dozens of other relevant professional associations such as the Institute for Operations Research and the Management Sciences (INFORMS), which also includes an active military community of practice; the Labor and Employment Relations Association (LERA); the Society for Indus-

trial and Organizational Psychology (SIOP); and many others. Most of the basic science and applied research in these domains is oriented around the private sector, with some work focused on the non-profit and public sectors—though very little in the context of the defense establishment.

Within information science there are many dozens of professional societies, some with roots in library science, some with roots in computer science, and some coming from other domains. Examples include the American Library Association (ALS), the Association for Computing Machinery (ACM), the Association for Information Systems (AIS), the Association for Information Science and Technology (ASIS&T), the Institute of Museum and Library Services (ILMS), the International Association for Computer Information Systems (IACIS), and the International Organization for Standardization (ISO). While these and numerous other professional associations have disparate roots, all are grappling with accelerating advances in digital technologies in which data and information are taking on ever broader roles in society.

### 1.2 A Demand-Pull and Research-Push Defining Future Directions

Given that this Future Directions workshop is designed to build bridges across communities in which there have been relatively limited interactions in recent decades, it is not just focused on projecting the future directions of the basic sciences. It also features the identification of DoD problems and challenges that can serve as motivation for Future Directions in research.

In Section 2.0, we present the “demand pull” problems, building on the principles of lean production and the concept of aligning operations to respond to a pull in the marketplace.

Historically, the challenge has been this: the best, innovative organizations create knowledge, and then mobilize that knowledge into applications to create strategic advantage. In this model, the challenges are clear. Acquire the best people to make the best knowledge, turn those innovations into actionable applications. Today, the constellation of complexities around digital and connected knowledge has changed how knowledge is created, shared, transformed into innovations; but it is now in conflict (or at least disharmony) with organizational forms optimized around the historical model. At the same time, some organizations (startups, VC-backed agile orgs, digital-native firms) are either experimenting or organically organizing around these new realities. These foundational tensions are filtering into the military via the above five interconnected areas: budget, joint integration, acquisition, supply chain, leadership. But addressing these individual areas require grappling with the broader institutional transformation.

Underlying the formal problem statements are management cultural challenges, which workshop participants described as an industrial and innovation base that is no longer oriented around the DoD, with inadequate tools for modeling policy and regulation. Stated more bluntly, DoD was described as too often captive to silver-bullet solutions from consultants and Silicon Valley, shiny-object driven chaos, new offices on top of old programs that could still be useful, perceptual reorganization, and excessive risk

aversion. Whether the operations and culture of social science can be oriented to respond effectively to these challenges remains an open question that is addressed in this workshop report.

In Section 3.0 we present the “research push” from the management and information sciences. In general, a “pull” approach is preferable to a “push” approach in a market, but the current reality is that the relevant social science research is pushing ahead without DoD applications in mind. Bearing in mind that management and information research is distinct from management and information consulting, a central focus of this report is on the longstanding and emerging advances that are in the management and information sciences in order to identify where opportunities may lie.

The concluding section (Section 4.0) applies emerging social science understandings on ecosystem management to consider what a future co-evolution might look like, connecting the “pull” with the “push” in constructive ways. The vast majority of the people and technology that will be in place in 2030 is already in the system and are part of current programming. Given how dramatically threats may shift by 2030, the challenge lies in agile and adaptable organizations and institutional arrangements.

This Future Directions report is not specific about particular projects or agendas, but rather a conceptual framework for collective action with illustrated next step action implications. Elements of this framework are summarized as a set of “From → To” Future Directions challenges in the next section.

### 1.3 “From → To” Future Directions

The intersection of management science and information science represents the space in which new organizational and institutional arrangements co-evolve with new digital technologies. Today, as the “demand-pull” and “research-push” examples suggest, the sciences of management and information are at an inflection point. This involves a series of what can be termed “from → to” challenges (also listed in the executive summary) that together begin to indicate the Future Directions needed for basic science and practical applications.

#### From → To Future Directions at the Intersection of Management and Information Sciences

**Hierarchies → Networks → Ecosystems**

**Alignment within organizations → Alignment across stakeholders**

**Entrepreneurs → Intrapreneurs → Ecosystem architects**

**Bilateral → Multilateral → Multilayered interactions**

**Cost control → Balanced scorecard → Ecosystem metrics**

**Risk management/mitigation → Adaptive response capability**

**Top down → Bottom up → Middle out**

**Agile teams → Agile organizations → Agile institutions**

The term “ecosystems” appears in a number of cases, which is broadly defined as a set of interacting elements in a shared context with common governing principles. The term takes on particular meaning in the current era where the relevant domains are larger than organizations, but have social meaning the parallels the role that organizations have traditionally played in peoples’ lives.

**Hierarchies → Networks → Ecosystems.** The classic management science focus is the hierarchical structure, which is paired in the report with a focus on networks as a classic information science structure. Hierarchies and networks are combining and evolving into layered ecosystems. As noted above, ecosystems have many interacting elements within defined boundaries and underlying principles that govern their interactions. For hierarchies and networks, ecosystems seem emergent and unpredictable. In fact, management and leadership are possible, but require new directions in management and information science centered on tools and methods for architecting and cultivating ecosystems.

**Alignment within organizations → Alignment across stakeholders.** Advances in management science have enabled alignment among diverse functions and interests within organizations. Increasingly, however, the needed alignment crosses organizational boundaries and involves diverse stakeholders some of which are well defined and some of which are emergent and evolving. A key future directions challenge involves advancing the tools and methods for achieving sufficient alignment among diverse stakeholders so that they can accomplish together what they can’t accomplish separately.

**Entrepreneurs → Intrapreneurs → Ecosystem architects.** Much of the innovation in the latter parts of the 20th century has been led by entrepreneurs who have formed dynamic new organizations. In the first part of the 21st century, the focus expanded to include pioneering individuals launching new products, services, and initiatives within organizations—what are termed intrapreneurs. What is emerging as a challenge for the management and information sciences is a new class of innovators who are architecting and cultivating entirely new ecosystems—changing the very institutional arrangements within which they are operating.

**Bilateral → Multilateral → Multilayered interactions.** The micro literatures in management and information science have evolved from the study of bilateral to multilateral interactions involving negotiations, communications, and coordination. Increasingly, however, the challenge is to appreciate the multi-layered structures within which these actions take place. This goes beyond hierarchies in management science and the “stack” in an information system to include complex multi-layer systems of interactions, such as local, regional, national, and transnational layers in geo-political systems where independent action can happen at any layer with implications for all of the others. This theme was highlighted in the 2016 Future Directions report on Network Science and is reinforced here.

**Cost control → Balanced scorecard → Ecosystem metrics.** The shift from a traditional cost-control to a balanced scorecard approach within management science marked an explicit

recognition that organizational success is multi-dimensional and requires a dynamic balance across functions and interests. The challenge looking ahead is to bring that same functional capability to the complex ecosystems level where the interplay is not just between functions in a hierarchy but among diverse and emergent stakeholders.

**Risk management/mitigation → Adaptive response capability.** In any large-scale project, there are well-developed tools for allocating and mitigating risk. These function well when the external context is operating with linear rates of change. When the rates of change are exponential and highly variable, however, adaptive response capabilities are needed in addition to traditional risk management methods. Leading research on supply chains is embracing these challenges. The implications reach into virtually all aspects of management and information science and challenge deeply embedded assumptions around what can and can’t be managed in a traditional sense. In the military sector relevant innovations include how the marines prepare for leadership transitions in battle, as well as how the DoD addresses cyber-security issues.

**Top down → Bottom up → Middle out.** There are many change models that are designed to guide top-down and bottom-up change, all of which implicitly assume a hierarchical organization as the context and relatively stable rates of change. Increasingly, however, models of change are needed where there is no overarching hierarchy and the rates of change are either accelerating or dynamic in other ways. In these cases, a new class of change models—middle-out models—are needed that operate laterally among diverse stakeholders and connect various top-down and bottom-up initiatives.

**Agile teams → Agile organizations → Agile institutions.** In software development and lean production, the concept of agility has emerged as an essential capability for teams and organizations. Increasingly, however, the agility that is needed is at the level of the rules of the game governing entire systems. For management and information science this involves pioneering theory and methods for addressing agility at the institutional level of analysis.

Thinking at the level of institutions involves the ability to examine and adjust these rules of the game. As a result, advancing these “From → To” capabilities doesn’t just promise to enhance military capabilities. It is possible that it will offer ways to rethink and transform conflict itself. Indeed, it may be possible to organize defense capabilities better to achieve interventions that respect differences and that prevent conflicts from escalating out of control. At stake is a holistic appreciation for social systems at the level of an entire ecosystem such that the rules of engagement are both effective and constructive—potentially enabling civil societies to utilize targeted interventions and deterrence to effectively address seemingly intractable differences.

## 2.0 Demand-Pull from the Military Establishment

After the Vietnam War, the U.S. military undertook a major effort to establish and extend its technological advantages relative to the far more numerous Soviet and Warsaw Pact forces that it was preparing to fight in a potential European war. Since that time, technological superiority has, along with realistic training, formed the foundation of the U.S. military's competitive advantage. Simply put, U.S. military superiority relies extensively on research and development capabilities both in and out of the U.S. government. There is a direct line between the effective resourcing and management of research and development (R&D) and the performance of U.S. military forces on modern battlefields. Victory begins not only on the rifle range but also in the lab. High-performing R&D management is an essential part of a successful Department of Defense.

The first half of the workshop focused on identifying the DoD's need for management science and information science insight into R&D challenges across these topics:

- 2.1 Budget and Programming
- 2.2 Joint Integration
- 2.3 R&D Acquisition
- 2.4 Supply Chain Risk Mitigation
- 2.5 R&D Leadership

The dialogue involved a mix of academics and DoD practitioners. Participants were encouraged to focus more on problem identification than on connecting those problems to management research and theory, which is the focus of section 3.0 of this report.

### 2.1 Budget and Programming<sup>2</sup>

#### Motivating research questions:

- How can budgeting and financial management policies be tailored to match the speed needed to counter emerging threats and utilize new technological opportunities?
- How useful is the current distinction between basic and applied research? What types of innovations are best suited for combining basic and applied approaches in an integrated, iterative development process?
- What policies and practices can be developed that maximize the DoD's flexibility in funding, while preserving openness and transparency to Congress and the public?
- Would allowing "mini skunkworks" enable adaptive responses to emerging threats?
- What models of financing and budgeting would optimize efforts to maintain world class researcher infrastructure within the DoD labs and test ranges?
- How should DoD analyze its overall Science and Technology budget across the Services and agencies to ensure an optimal portfolio, balanced between disciplines and risk levels?

These questions are connected to four key budget and program areas that would benefit from management science insight:

- **The tension between applied and basic research**
- **The tension between centralized and decentralized control and coordination**
- **Stakeholder misalignment**
- **Imperfect information: funding decisions and research outcomes**

#### 2.1.1 The Tension between Applied and Basic Research

The Department of Defense funds both applied research and basic research. But what gets funded, and how do we know that we are funding the right thing? Furthermore, how useful and appropriate is pga the "basic" versus "applied" label? Basic research poses a more significant managerial challenge than applied research, because it lacks a connection to a specific operational problem. Basic research may not necessarily end up discovering the thing that it seeks to discover and may involve spending a lot of money to determine if an idea even makes sense. It therefore incurs greater risk from an efficiency standpoint.

Department-wide, in FY2017 the DoD spent just over two billion dollars on basic research, and just over five billion dollars on applied research. (See figures 2.1.1a, b, and c below.) In the long-term, DoD has demonstrated a sustained commitment to supporting both basic and applied research. However, its overall share of federally-funded research continues to decline, and basic research has remained stagnant. Furthermore, Chinese defense-oriented research and development funding has increased

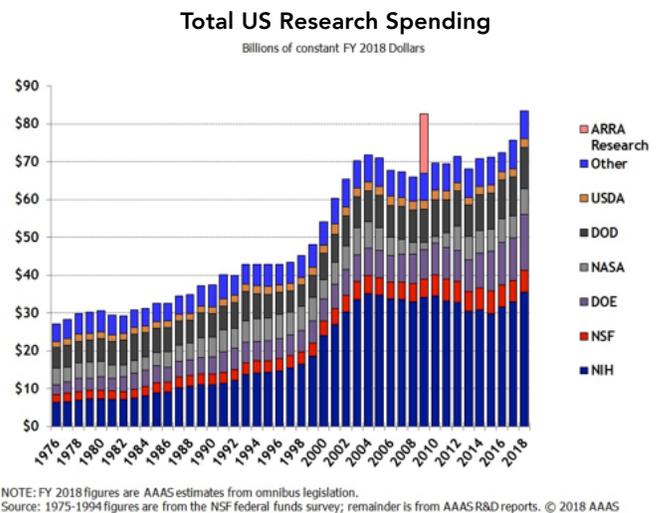
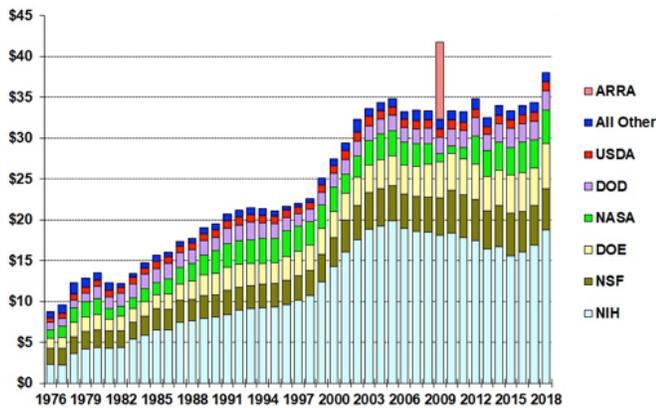


Figure 2.1.1a Spending on Total US Research, by Government Agency, FY 1976- 2018. (in Billions of constant FY 2018 Dollars). <https://www.aaas.org/page/historical-trends-federal-rd>

2. Portions of this section are excerpted from Army War College study "Marginal Costs of Marginal Requirements" (2015), by Thomas Hickey, Anthony Juarez, and Julie Stabile, written under the supervision of Andrew Hill.

## Basic Research Spending

in billions of constant FY 2018 dollars



NOTE: FY 2018 figures are AAAS estimates from omnibus legislation.  
Source: AAASReport: Research & Development series. © 2018 AAAS

Figure 2.1.1b Spending on Basic Research, by Government Agency, FY 1976- 2018. (in Billions of constant FY 2018 Dollars).

<https://www.aaas.org/page/historical-trends-federal-rd>

significantly in recent decades and is likely to exceed U.S. spending soon.<sup>3</sup> This suggests that there may be a need to strengthen basic research funding in the DoD.

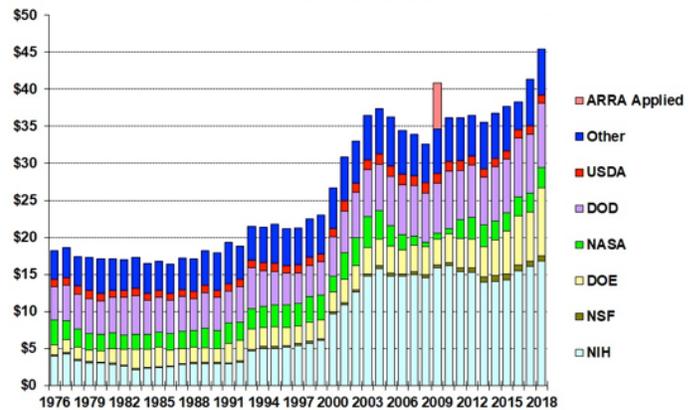
In this context, the dichotomy between basic and applied research needs to be reconsidered. In "Pasteur's Quadrant," a term coined by Donald Stokes in his book of the same title (1997), the author argues that the basic/applied taxonomy of research is counterproductive—if not outright wrong. In its stead, Stokes proposes evaluating research in terms of its developmental maturity (how much do we understand about it at the start) and its potential utility. "Pasteur's Quadrant" represents research that significantly advances our basic understanding and is tremendously useful—meeting the definition of both basic and applied research.

Related to the applied versus basic research challenge is the continual tension between current operational needs and the future goals of the organization. Military organizations must remain capable of engaging in current operations while simultaneously building a future force that may or may not incorporate discontinuous technologies, that is, technologies that have no current analog. For example, the first military aircraft posed fundamental conceptual and training challenges to the military organizations that adopted them. Current military demand for research usually falls into the "applied" category and can crowd out significant investment in fundamental research that is more likely to yield paradigmatic shifts in capabilities. Furthermore, such streams are typically uncoordinated and therefore unable to construct a coherent narrative describing their utility. (For more on this, see the subsection 2.1.2 and section 2.2.) **A fundamental challenge for the military is how to develop and use effective management systems that appropriately weigh the future value of inherently uncertain research investments against alternative investments that seem to meet current operational requirements.**

3. <https://chinapower.csis.org/china-research-and-development-rnd/>

## Applied Research Spending

in billions of constant FY 2018 dollars



NOTE: FY 2018 figures are AAAS estimates from omnibus legislation.  
Source: AAASReport: Research & Development series. © 2018 AAAS

Figure 2.1.1c Spending on Applied Research, by Government Agency, FY 1976- 2018. (in Billions of constant FY 2018 Dollars).

<https://www.aaas.org/page/historical-trends-federal-rd>

### 2.1.2 The Tension between Centralized or Decentralized Control and Coordination

The proper way to establish research programs, set budgets, and administer funds presents a second set of challenges requiring management science insight. Centralizing efforts is efficient in budget terms. There are areas of commonality in funding (e.g., materials, cyber risk, weapons development), providing opportunities to consolidate programs.) Yet such central coordination has potential costs in effectiveness and adaptive capability.

DoD and the military services seldom know exactly what is going to be needed in future operations. Independent, potentially redundant research efforts are more likely to produce a wider variety of future options than a single, centrally controlled research program. Right now, the DoD invests broadly to try to get it mostly right (or at least, not very wrong). Consider, for example, autonomous systems or directed energy: the Army, Navy, and Air Force are all looking at these things. Individually, they are not allocating all the money they may like to. In the aggregate, they could more fully fund key research areas. Yet such consolidation would remove alternate paths to future technological capabilities. Dilemmas such as this are common for organizations and institutions without simple resolution, but better and worse ways of addressing the challenge.

**DoD needs more sophisticated approaches to investing in R&D that simultaneously involve distributed innovation and central coordination.** Exploration and exploitation activities are both essential to effective R&D management. The challenge is to know when to stop exploring a less successful area and focus on exploiting a more successful area. Different research groups may "not need to know what others are doing," during the early stages of research. However, as research matures, such mutual ignorance becomes more costly. We are not the first to observe that the lack of information sharing across the DoD research com-

munity is problematic. There is still no central repository or set of mechanisms to communicate around the state of the art. Research may be competitive or cooperative, or both at different stages. Management science can offer useful insights on the structures and processes needed for research communities and teams.

This (again) reveals a false dichotomy: either centralized or decentralized control. The organization can dynamically allocate funds throughout the life-cycle of research, in the same way that venture capital firms compete for rounds of funding. Early-stage research can be decentralized, using multiple lines of effort to improve the chances of finding something significant. Even there, however, mechanisms for awareness across services around the types of motivating problems can be beneficial. **Moreover, once one research program produces promising results, redundant programs should be subject to greater scrutiny and increased coordination, and stakeholders should consider consolidating their efforts.** A major question is how to structure this dynamic budgeting process, which requires systematic reviews, hard choices, and significant mid-course changes. At present, too many research programs “limp along,” in the words of one participant.

### 2.1.3 Stakeholder Misalignment

The R&D research community in DoD is diverse, with many different objectives. In simple terms, researchers fall into two categories: product line developers vs. research lab scientists. While this distinction echoes the basic vs. applied tension discussed above, it is not the same. This difference has less to do with the specific purpose of a research program and more to do with the values of a professional community. For example, basic research conducted at a university may be motivated by different values than basic research conducted at a DoD lab. As one workshop participant observed, “Multiple stakeholders wanting different things is at the root of all this.” Specifically, advancing scientific understanding and improving national security are not always or necessarily complementary objectives. Merging these two philosophies may not be possible or beneficial.

**Incentive and evaluative structures (e.g., criteria for starting or continuing funding) need to accept the inherent diversity in objectives across the DoD, rather than taking a one-size-fits-all approach.** The challenge for R&D is to support, in the words of another participant, “communities that are meaningful at the sub-community level, as well as at the community level.” That is, DoD must enable diverse research communities, yet retain the ability to coordinate and unite their activities when necessary.

### 2.1.4 Imperfect Information: Funding Decisions and Research Outcomes

Finally, research funding decisions pose inherent informational challenges. What makes a good research program? The answer depends on whether “good” means that the program will get funded, or that it will produce actionable results. One participant commented that it is, “easy to get money for the next clever idea (‘shiny objectism’),” but that this does not lend itself to long-term coherence in research. There is little consensus regarding what makes a research finding good. As a result, researchers assume that they need to go after the next clever idea.

Research outcomes cannot be captured near the funding decision point, so you need a proximal (near-term) outcome palatable to everyone in order to evaluate a research program. Proximal outcomes usually focus on some combination of resource-intensiveness, resource oversight, and “shiny objectism” (i.e., a compelling narrative for the research effort). While each of these criteria has some merit, it is unclear that DoD applies them in an appropriately holistic manner. Missing from this analytical approach is a broader sense of research’s potential impact, or how it may interact positively or negatively with other R&D activities.

The language of scientific research does not necessarily lend itself to communicating expectations in a way that resonates with national security leaders. For example, research on GPS was first framed within the DoD in narrow terms (e.g. assisting submarine guidance at the North Pole) without full consideration of its military or commercial potential. Scientists learn early in their careers to be circumspect in their expectations regarding research outcomes. They speak in probabilities, not certainties. In this sense, they sometimes struggle to be effective advocates for their research agenda.

### 2.1.5 Concluding Observations, Programming and Budgeting

DoD R&D activities have an illustrious record of producing tremendous public goods, such as the semiconductor community, GPS, and the Internet. In each case, however, the process by which these innovations emerged was measured in decades and marked by a lack of coordination. **Better processes are possible and may be essential. It is certainly the case that DoD research budget proposals should include significant, broader goals such as dual-use in civilian applications. This would contrast with the ways that corporations manage research and development (i.e., simple portfolio analysis).** New mechanisms and underlying principles are needed for the management of R&D in the DoD.

## 2.2 Joint Integration

### Motivating research questions:

- How can the DoD maintain the current structure and process needed for addressing current operational challenges, while concurrently experimenting with developing alternative structures and processes needed for emerging operational challenges?
- How can the DoD pursue research on innovations that do not fit into existing concepts of war and that represent alternative (and possibly superior) ways of fighting – e.g. disruptive innovations.
- What data are needed to actively manage the joint R&D portfolio? How can this information be collected in a continuous and non-burdensome way?
- How can the DoD utilize emerging “middle-across” approaches to R&D operations in order to bridge across central, top-down coordination and emergent, bottom-up innovation in the services and facilities?

All research should result in identifiable improvements in U.S. military capabilities or in lessons learned that inform future research. While military acquisition communities handle the de-

velopment of materiel solutions, they are not responsible for telling the research community what technological problems are important, or for developing the military contexts in which those materiel solutions are used. The services (Army, Navy/Marine Corps, and Air Force) develop military forces based on service and Joint operation concepts. In an ideal case, the services do two things: 1) they use concepts to provide a demand signal for S&T research, and 2) they effectively integrate valuable capabilities into the force. **The services and Joint communities are therefore crucially important at the beginning and at the end of the R&D process, as well as providing inputs throughout.**

For example, when the U.S. Army led the development of the Air/Land Battle concept in the 1970s, the fundamental premise of the concept—"fight outnumbered and win"—produced clear demand signals for research. If you are going to fight outnumbered and win, you need to have some combination of the following competitive advantages:

- Hit the enemy more often than he hits you (precision strike, plus protection advantages)
- See the enemy before he sees you (stealth, night vision, long-range or space-based ISR)
- Hit the enemy before he can hit you (extended range delivery systems, rifle and gun range advantages)
- Mass forces to create local, temporary numerical advantages (advanced Command and Control, improved mobility)

The defense R&D community met the challenges presented by Air/Land Battle, helping the U.S. field systems that established the U.S. as the world's great military power. Crucially, many of those systems incorporated technologies that had already been in development prior to the Air/Land Battle concept. These capabilities co-evolved between the concept development and research communities. This type of coevolution will be needed in the future, with faster rates of change required.

The U.S. military fights as a Joint force. **An effective demand signal for research is one that is generated with Joint-ness in mind, anticipating how U.S. forces fight together, and allowing the military to accept risk in some areas when that risk is effectively offset in other areas.** For example, U.S. ground forces operating with close-air support may be willing to operate without extensive ground-based indirect fire support. Effective R&D investment should therefore reflect a portfolio-based approach to capabilities development, one that manages risk across (and not just within) the services. This is a challenge for traditional mechanisms for risk management, where multiple concurrent risks are effectively managed at a system level. Successful research advances must be integrated into the Joint force in a way that exploits those successes, even when that proves disruptive to pre-existing force concepts and structures.

So how is the military doing with respect to sending demand signals for needed capabilities to the research community, and integrating their outputs into the military? Where does it need help?

**We identified three major challenges in the demand signal area, and one major challenge in the integration area. The communication of a clear, coherent demand signal is challenged by: 1) the power of the services and the relative weakness of the Joint staff in concept development; 2) ongoing tension between current and future operational requirements; and 3) inherent uncertainty about the future operating environment.** Effective integration is challenged by the power of existing concepts of warfare, and the relatively rigid alignment of organizational structures around those concepts.

### *2.2.1. The Power of the Services in Demanding R&D Activity*

The demand signal for research activity is relatively coherent at the service level, but there is little coordination at the Joint level. Although the Joint force is the fighting force, and Joint staff support is required to approve major requirements for improved capabilities, the services still control force development, and military concepts are developed primarily by the services, with coordination across services, not through the Joint staff. This is a strange organizational setup. The U.S. military periodically undergoes major redesigns and improved "Joint-ness" is a persistent theme in these efforts, yet we are not aware of any efforts that have explored redesigning the control of conceptual development to bring it more in line with the Joint control of the operating force. It may be the case that the current system is the best we can do as long as we have domain-centric services, and a meaningful improvement may require a much more fundamental reimagining of the structure of the U.S. military. Whatever the case, DoD and the services need a robust understanding of the key aspects of organizational design and would benefit from a strong connection to research in this area. As developed in part 3.0 of this report we should explore mechanisms for "middle-out" stakeholder alignment tools and methods, and other mechanisms for enabling both lateral alignment and independent action by interdependent stakeholders.

### *2.2.2. The Tension between Current and Future Operations*

A second challenge to an effective demand signal from the services to the R&D community is the tension between current and future operations. We have already discussed aspects of this problem in the preceding section on budget challenges. Warfighters are seeing new challenges every day and seeing things that need to be addressed right now. Those signals are taken very seriously by DoD, but research takes time to spin up, and we seldom consider whether a problem is likely to still be around by the time research produces a solution. Yet political considerations, especially in the area of force protection, drive resources and attention to current problems, often at the expense of significant progress in areas of more enduring relevance. If you do not get the money you need, you cannot start the work. DoD is not alone in trying to manage this kind of tension. Competitive continuity (similarity between current and future competition) makes this problem a bit easier, but there is general agreement in the U.S. military that current operations bear little resemblance to the future environment. The military needs to develop better mechanisms for identifying current signals that will have increasing importance in the future as compared to those that will be of more limited impact, then allocate resources accordingly.

### 2.2.3. *Uncertainty about the Character of Future Wars*

The final challenge to the effective communication of research needs to the R&D community is the inherent uncertainty regarding the future operating environment. How well can we predict the character of war 20 years from now? The record of military prediction throughout history is poor. But even by that low historical standard, the U.S. military seems now to be in a state of profound uncertainty about the character of future war. Yet the existing approach to force development has not changed to account for this uncertainty. You are unlikely to get an accurate, definitive requirement for the future operations environment, but what you can do is construct a set of characteristics you need to use to define a research agenda and what you want to fund now. This is a different approach to managing risk, and complementary to the real options approach proposed in the acquisition section (see 2.3 below).

### 2.2.4. *Summary Observation: The Power of Current Concepts*

In terms of integration, the U.S. military is effective at using research outputs that fit into pre-existing military concepts, but much less effective at integrating advances that require higher-level changes to concepts. This reflects the challenge of existing infrastructure, established practices and procedures, and, most of all, deeply embedded operating assumptions.

The aircraft was initially integrated into the U.S. Navy as an improvement to the surveillance and fire control systems needed by the battleship-centric concept of naval warfare. It took the harsh experience of war to bring the Navy around to seeing that the aircraft opened the possibility of an entirely different way of fighting at sea, one in which planes could be used not just to find the enemy, but also to destroy it. That said, under the direction of Admiral William Moffett and others, the Navy had done just enough in the interwar period to create a robust community of naval aviators who understood and valued naval warfare, and surface warfare officers who were open to the possibilities of air power at sea.

Major research innovations often create tremendous uncertainty regarding their significance in military application. It is therefore very hard if you do not have the answer to say how you are going to get to the answer, or what the answer will mean when you get it. What seems essential to integrating R&D outputs is an understanding of a specific, current problem that the output solves. Aircraft came into the Navy because they improved the Navy's approach to surveillance and fire control. This was by no means the highest expression of the airplane's potential, but it was enough to gain a foothold in the service's force development system.

DoD leaders must forecast and consider the integrational risk factor as the net impact of the solution to doctrine, organization, training, materiel, leadership, personnel, and facilities (DOTMLPF). Emergent military solutions can inadvertently outmode other DOTMLPF aspects. For instance, the Gatling gun and its successor, the machine gun, were technically revolutionary before they were able to change the battlefield. These rapid-fire weapons were initially misused as they undermined existing military frameworks, requiring changes to several other sub-fac-

tors of this risk subset. Leadership needed to adjust in conjunction with doctrine, training, and organization to account for the new lethality on the battlefield. Changes to DOTMLPF can be resource and time intensive. Such changes are comparable to how embedded infrastructure constrains innovation in the private sector.

**Research on disruptive innovation can identify ways in which the military can more effectively explore the possibilities inherent in significant new technologies.** This is especially important in integrating technologies such as autonomous systems and artificially intelligent command and control platforms, which raise entirely new options for how we fight at the operational level.

## 2.3 Research & Development Acquisition

### Motivating research questions:

- What approaches can enable the DoD to identify fair pricing in acquisition circumstances where there is only one prime contractor and only one customer? What are the best models to establish a fair price in the absence of a true market?
- How can we more effectively conduct multivariate optimization during requirements generation, particularly around effectively assessing the marginal costs of incremental changes in requirements that involve new doctrines, processes and technologies?
- What are the range of possible applications of "real options" methods to R&D acquisition?
- What are the most streamlined ways of measuring the technical feasibility and providing accurate cost estimates for proposed requirements?
- How can the life cycle costs of systems be accurately forecast? What can be learned from historical cases?
- What methods can be used to determine the IP rights the DoD should be purchasing from contractors?
- How can the DoD optimize its ability to negotiate with vendors?
- How can the DoD improve its ability to reengineer its business processes in order to make more effective use of commercial enterprise software systems?
- How can the DoD anonymize data, create synthetic data sets, and create trusted data sharing partnerships so that it can experiment with and model alternative policies or business practices?
- How can the DoD model the impacts of changing acquisition regulations, practices, and policies?
- How does the DoD now balance security and academic openness in university research and how should it?
- How should the DoD handle foreign nationals working on research programs, balancing security and innovation?
- How can the DoD experiment with strict peer review, collaborative agreements, and portfolio approaches in order to best be aligned mission needs?

The interface between the DoD research communities and associated acquisition communities is large, complex, and beginning to show signs of failure (Brooks, Dunlap, Kappelmann, and Hill, 2017). U.S. military dominance has been underwritten by a dynamic domestic economy and massive defense budget.

To ensure proper fiduciary control, the DoD has developed an acquisition system centered around a strict requirements generation process. Over time these complex acquisitions procedures combined with the defense industry consolidation has led to a de-facto condition that favored large, multi-year, technologically reaching programs (Elman, Hunter, McCormick, Sanders, Johnson, and Coil, 2015). Additionally, "success" for acquisition programs often means reaching a full rate of production, exiting the acquisition system, and entering sustainment. These are important goals, but other ways of defining success would allow for a more complete approach to portfolio management.

There is a long history of major acquisition programs that fell short of their potential, such as the World Wide Military Command and Control System, launched after the Cuban Missile crisis, and the DoD high-level programming language Ada, launched in the 1990s. More recently, a prime example of modernization programs is the Joint Strike Fighter (JSF) Program. The design for the JSF exposed the DoD to unsystematic risk in that its futuristic design requirements had to meet requirements from U.S. Air Force, Navy, and Marine stakeholders in addition to a range of international partners. This large scope made it costly and prone to delays while also making the program too big to fail (Insinna, 2017). The concept of an integrated, cross-service program is important, but the structure of the acquisition process pointed to a piling on of requirements (and cost) rather than alternative approaches to integration. The JSF is not alone. A 2017 Government Accountability Office (GAO) report found that even with proposed increases in defense spending, the acquisition process remains a high risk to the Department and the nation (GAO, 2017: 269). The report found that DoD programs "fall short of cost, schedule, and performance expectations, meaning DoD pays more than anticipated, can buy less than expected, and, in some cases, delivers less capability to the warfighter."

The acquisition process is optimized to support large, multi-year programs. As of February 2017, the GAO found that the DoD plans to invest the \$1.4 trillion to develop its 79 largest acquisition programs and those costs are expected to increase. Meanwhile, Defense research and development (R&D) funding has fallen by nearly 20% since 2010 to \$78.9 billion in 2017 (AAAS, 2016). While \$80 billion is a significant investment, the specific division of that \$80 billion is essential. Roughly \$2 billion of that figure is spent on basic research, while less than \$14 billion is spent on prototyping and advanced component development. In addition, the barrier between R&D funded technologies and those funded by larger programs remains difficult to traverse (Defense Business Board, 2015). **If the DoD cannot be more flexible with its acquisition and development of military technologies, the U.S. may be unable to innovate quickly enough to counter future threats. In lieu of its program centric approach to defense acquisition, DoD needs to be able to invest more widely in developing technology.**

4. Portions of this section are excerpted from the Army War College Study, "Marginal Costs of Marginal Requirements" (2015), by Thomas Hickey, Anthony Juarez, and Julie Stabile, written under the supervision of Andrew Hill.

There exists an important relationship between DoD's R&D and Acquisitions communities in that they collaborate to implement material acquisition programs. Ideally, communication between R&D and Acquisitions would be seamless and free flowing with R&D personnel informing those in Acquisitions of a technology's maturity level and development risks while Acquisitions helps R&D understand the significance of individual requirements and areas in which added development risk may be acceptable.

The reality is much messier than this, through the fault of no individual or specific group. In discussing dysfunctions and challenges in the acquisition system, with particular attention to R&D, participants identified five main problems:

1. **The Acquisition Pricing Problem**
2. **Risk Mismanagement Challenges**
3. **Barriers to Experimentation: The Problem of the "Program of Record"**
4. **Time and Upgradeability: Buying Flexibility, Preserving Future Choice**
5. **Limited Information: Improving the World of the Program Manager**

Each is addressed in turn below.

#### 2.3.1 *The Acquisition Pricing Problem*<sup>4</sup>

At its core, defense acquisitions is a market. Buyers, or the warfighter as represented by the services, demand a good: a weapon systems that fulfills a needed capability. Suppliers, or the acquisitions community working with defense contractors, provide that weapon system to the buyer. Yet the pricing mechanism in this market is highly idiosyncratic due to rampant market inefficiencies.

Perfectly competitive and efficient markets are rare, but the weapons acquisitions market is particularly distorted; the assumptions that must be satisfied for perfect competition are not met. Understanding where the market for weapons falls short of the perfectly competitive model will allow us to better understand how to move it back towards the ideal.

Key assumptions for a perfectly competitive market do not hold in the market for weapon systems. The departures from a perfectly competitive market include:

- **High transaction costs.** Uncovering required information, like the technical feasibility of a given weapon, is not a trivial endeavor, and oftentimes leads to extraordinary cost growth when the information generated is incorrect. Additionally, specifying and enforcing contracts for the extraordinarily complex modern day weapon system can be extremely difficult.
- **Heterogeneous products.** In the world of weapons acquisitions, not all products are created equally. Some firms produce better products than others.
- **High market power/barriers to entry and exit.** Because the US government is the only buyer, it very clearly has market power (this may not always be a negative characteristic).

Additionally, there are relatively few defense contractors compared to other markets, and once a contract is awarded, the contractor is essentially locked in. As a result, there are barriers to entering the weapons acquisitions market, and buyers and sellers in the market can exert market power.

- **Imperfect information.** The complexity of weapons systems prevents this requirement from being satisfied.
- **Irrational actors.** The complexity of weapons systems and the time frame of acquisitions may lead to bounded rationality because it is impossible to know everything that could impact the effectiveness of a decision; the actors involved simply cannot act in a truly rational manner, as that would require unrealistic predictive abilities.
- **Political motivations.** Defense spending represents new jobs and there is considerable political pressure for those jobs to be widely distributed across the United States and (through what are termed “offsets”) in other countries that are purchasing weapons systems, regardless of whether that is the best structure for development and production.
- **Significant externalities.** In weapons acquisitions, DoD is making decisions with taxpayers dollars. If legislators continue to spend exorbitant amounts of money on national defense, there are far reaching externalities relating to the lack of services the government could have provided. Moreover, the constantly changing actions and intentions of adversaries greatly impact weapon acquisition decisions.

There is no clear and consistent account of how price signals are generated and communicated between buyers (the warfighter, represented by the services) and sellers (the acquisitions community).

Sellers do not always know the true cost of additional units of capability, especially in the case of less mature technologies. While some problems in acquiring cost estimates are inherent to purchasing cutting-edge capabilities, others are due to inadequate techniques for uncovering and communicating prices. **The acquisition system lacks a method for attaching prices to individual marginal units of capabilities, and for communicating those prices to buyers and other stakeholders before requirements are validated and locked in.**

The services (the buyer) are primarily concerned with maintaining a margin of capability over potential adversaries, regardless of cost. The buyer in the market, then, communicates an essentially infinite willingness to pay for marginal capability. The seller, receiving this signal, will produce the additional unit of capability despite exorbitant costs. The buyer, who lacks accurate estimates of the price of additional units of capability (typically underestimates), demands more units of capability than would be optimal in an efficient market. The seller, lacking accurate information about the buyer’s willingness to pay (usually overestimates), supplies more units of capability than would be optimal in an efficient market.

An important consideration here is that given the importance of maintaining a competitive edge, marginal units of requirements may often be necessary and worth the high costs. However, this assumption is violated when marginal units of requirements drive costs so high that they threaten the viability of the entire system.

Certainly, we would prefer having a system that performs at 100% of its potential to not having a system designed to perform at 110% of its potential. Unless costs go so high that they put the entire system at risk, there is no reliable way to discover whether or not marginal units of requirements are worth their high costs.

Recent acquisitions procedures attempt to ameliorate this problem by ensuring that all appropriate trade-offs between capability and cost are made. Despite these efforts, there remain breakdowns in communication that prevent stakeholders in the requirements generation and acquisition process from being fully cognizant of all relevant information regarding the benefits of a unit of capability and its cost.

There is a disconnect between “requirements people” and “acquisitions people” that can be broadly attributed to the transaction costs inherent in communicating with professionals in different locations and with different goals. Given the high transaction costs associated with communicating information between requirements generators and the acquisitions workforce, price signals become distorted and information becomes highly asymmetric. The demand signal, amongst acquisition professionals, often takes the shape of the statement, “If the warfighter says she needs it, she does.” This is just one example of how relevant demand information—in which nuance is rather important—becomes washed out in the absence of a market that sets and communicates prices. The supply signal is generated in consultation with industry during technology development, as contractors discover, for example, the per unit cost of adding one knot of speed to a marine vehicle. However, when the services generate their requirements, they do not have access to this cost information—in other words, they demand a quantity of capability without knowing the price.

Aggravating these problems are the decreasing numbers of consumers and suppliers of certain defense systems. Prime contractors are increasingly specialized, such that certain platforms (aircraft carriers, for example) are produced by just one firm (Huntington Ingalls, in this case), while others (rotary wing aviation) are produced by two (Boeing and United Technologies). For many of these systems, the U.S. military is the only consumer. Thus, defense systems are acquired in a context bearing no resemblance to the efficient market described above.

**The result of these inefficiencies is a system in which PMs seek to meet program requirements without completely understanding the relative value of those requirements; how much risk they should accept in meeting those requirements; and therefore, little sense of how much the Department should be willing to pay for them.** Thus, we have a system in which the DoD loses bargaining power in pursuit of “gold-plated” requirements for weapons systems.

Management science can help the DoD understand how to price more effectively both acquisition systems in the aggregate, and individual system requirements. This can be through alternative game-theoretic models, different organizational structures, improved integration mechanisms, and other organizational and institutional innovations.

### 2.3.2 Risk Mismanagement Challenges

War is a resource intensive occupation and U.S. dominance has been underpinned by its economic might. This paradigm is now challenged by lower barriers to entry in the new frontiers of warfare. While the U.S. must remain ready for its current and near future operations, the DoD must maintain its technological advantage. The future of warfare is hard to predict and as such, the DoD needs to ensure that it has the ability to adapt its force to counter future threats with a portfolio of responses. Acquisition risk arises from four sources: requirements, resources, technology, and integration.

**Requirement Risk.** The first and foremost risk factor to consider deals with requirement fidelity: is the problem statement correct and will it be in the future? Once the requirement is accepted, the focus shifts to the solution. The solution is evaluated via metrics of cost, schedule, and performance against the requirement statement, not against the actual need.

One strategy for managing requirements risk is to wait until a requirement is understood with greater fidelity. In an ideal, frictionless world, necessary capabilities would be readily available when needed and developed according to well-specified, operational requirements. Assuming a “frictionless surface” of rapid development, production, and fielding, investments ahead of time would not be necessary, since forces could be created on-demand. Indeed, there are significant advantages to delaying the production of technology. A shorter period from requirement-identification to production will lower costs as development-costs drop by using existing technology and reducing requirements creep (<https://dap.dau.mil/glossary/Pages/2568.aspx>). The P-51 Mustang is an example of the benefits of this approach. Developed in only 117 days using a new approach to aircraft design, the highly successful P-51 development shows the advantage of developing new technologies immediately after the requirement is identified (Haggerty and Wood, 2010).

Alas, this frictionless surface seldom reflects reality. Just as there is friction in combat, there is friction in capabilities development. We now turn to three sources of friction: resource risk, technological risk, and integrational risk.

**Resource Risk.** Resource risk is a combination of finite assets that include national resources, political will, manufacturing capability, and budget. While national resources and political will are fairly straight forward, manufacturing capability risk is a bit more nuanced. Weapons systems and platforms may require exacting and unique manufacturing processes, skills, and competencies. In the process of evaluating this risk factor, managers should consider if required manufacturing capabilities are already in existence, their fungibility, as well as the challenges of sustaining the required industrial base. Budgetary concerns are simply the intersection of price estimates and long-term funding availability. Other risk factors, especially technological risk, can dramatically alter price estimates and can compound budgetary risk.

**Technology Risk.** Technology risk is the likelihood that science may be insufficiently advanced to satisfy requirements. The first

aspect of this factor is already assessed through the military’s Technology Readiness Level (TRL). TRL is the method of estimating the technological maturity of a proposal during the acquisition process. TRL are rated on a scale of 1-9 with 9 indicating that the technology is proven and is capable of supporting the highest level of operational readiness. Established processes like TRL explain and quantify technological risk, but they do not allow managers to avoid risk. Advanced technical requirements occasionally warrant and require managers to push the frontier of science and capabilities and thus incur additional technological risk. The space race, particularly of the 1950s and 60s, is a prime example of how this risk is both precarious and necessary. New technology can also be hard to integrate.

**Integration Risk.** We discussed integration challenges in the preceding section on Joint Integration. That problem extends to acquisition. New applied technology and capabilities can drastically alter pre-existing strategic doctrine, organization, training regimens, and leadership practices. The success of any program depends as much upon how it is integrated into the larger force as it does its technical capability.

The DoD’s fixation on mammoth programs may be a limitation in the face of technological disruption as it lends itself to betting on certain technologies while sequestering others. Simply put, in the face of technological progress, DoD needs to be able to diversify its investments in research and development and act quickly on opportunities (Carberry, 2016). **DoD doesn’t need more program managers and program executive officers, it needs more robust portfolio management.**

Modern portfolio theory has long been an essential tool for mitigating unsystematic financial risk. Instead of investing in a few instruments, portfolio theory recommends investing in a wide array of financial instruments. This allows for the reduction of unsystematic risk while maintaining profitability (McLure, 2017). The analogue between unsystematic risk and military investment is clear: over-reliance on high returns from relatively few platforms or systems is dangerous. The failure of one military investment will have an outsized effect on operational performance. Instead of investing in a few large programs, DoD could mitigate this risk by investing in a wider array of platforms and systems with some redundant effects but uncorrelated risks. For example, the risk of the failure of an armored system could be offset through a strong system of drones providing targeting information to missile-launched, loitering munitions. In addition to seeking a wider portfolio approach to modernization investments, DoD would also benefit from the real options framework.

It is difficult to predict the future value of technological investments. As such, the DoD should consider examining a real options-based approach to the research, development, prototyping, and fielding of new technologies. A real option is an arrangement where an organization purchases the right to make a choice at a later, more opportune time. In the business world, real options allow firms to quickly alter their physical (or real) properties to change, increase, or decrease capabilities to meet the demands of their market (Investopedia, 2017). For a fee, real

options allow for firms to limit the exposure of immediate full investment, while maintaining the ability to increase investment at a discounted rate later (Damordaran, 2008).

**A real options framework would allow DoD to explore multiple areas of technological developments through increased research and engineering funding, while limiting the downside of larger program failure.** Applied to DoD, a real options framework would entail research and development contracts, as well as contingency production contracts with defense and private sector firms. In exchange for funding, these firms would plan the next generation of military technology and virtually test it. The DoD, would retain the option for ordering that technology into further physical development or production. DoD would also establish contingency contracts with firms, so that it could access increased productivity if required.

Bayesian and other modern forecasting models may also have useful applications for DoD in managing acquisition risk. To our knowledge, no such models are used in the acquisition system. Pair optimization models seek to achieve improved outcomes in which the user seeks multiple outcomes that involve trade offs across them. Such models can also help DoD improve its risk management.

Management research doubtless has much insight to contribute in helping DoD experiment with real options, and explore modern forecasting and optimization models in managing risk in acquisition.

### **2.3.3 Barriers to Experimentation: The Problem of the "Program of Record"**

Given the inherent uncertainties in preparing for war, one would expect the DoD acquisitions system to encourage experimental approaches. This is not the case. The acquisition system was not designed to support programs that conclude in just a blueprint, or a prototype, or even with limited fielding of a new system. The military preference for uniformity and efficiency means that it does not appreciate maintaining multiple, similar systems. The acquisition system exists to shepherd a Program of Record through the acquisitions process to achieve full fielding. While the workshop participants understood this structure, several observed that it severely limits experimental approaches. Fully fielded systems are inevitably costlier than systems with only limited fielding, all other things being equal. This crowds out opportunities for acquiring and experimenting with a wider variety of systems. Full fielding also increases technology risk, since it reduces the diversity of a portfolio.

Research and engineering efforts should be incentivized and funded to prototype future options for the military services. Prototyping of this nature could be virtual. Research and engineering efforts should be closely linked with acquisition in order to provide program managers the greatest visibility of options available. For example, DoD could recognize that some Acquisition programs should end at milestone B (the point at which a blueprinted or prototyped system enters materiel development). The current challenge is that a substantial portion of prototyping occurs today after milestone B due to the requirement to have a

Program of Record (POR) and a wedge in the Program Objective Memorandum (POM) to secure the funding in order to prototype. This is a model that the DoD would have to break.

**To facilitate experimentation, the DoD should evaluate success at the portfolio level instead of the program level.** Portfolio level analysis would naturally drift towards being grouped either categorically or by capability. The analytics for success, integration into the joint fight, and the development of real options would all be better enabled at the portfolio level. Active portfolio managers would monitor options and look "for ways to influence the underlying variables that determine option value and, ultimately, outcomes" (Luehrman, 1998).

### **2.3.4 Time and Upgradeability: Buying Flexibility, Preserving Future Choice**

Extending the theme of risk management, time plays a key role in the R&D/Acquisitions interface. The most successful (in terms of meeting requirements on time and at or below projected cost) acquisition programs are often short in duration. Longer duration programs are challenged by unstable funding, technological change, test and evaluation, personalities, changes in leadership, and world events. The longer a program, the more it is likely to suffer from "requirements creep" and fielding mismatch.

**Requirements creep** refers to the process by which an acquisition program experiences regular increases in requirements due to changing risks in the operational environment. Predictably, it is a problem that is directly proportional to the duration of the program. Not that requirements creep is not entirely bad. It can be a positive part of development of requirements, materiel solution analysis, technology maturation, and risk reduction. The problem is exacerbated at Milestone B decision, where it becomes a program of record (POR) and a wedge in the program objective memorandum (POM) is introduced. Requirements creep from that point through to the achievement of operational capability is detrimental—leading to delays, cost overruns, and potentially negatively impacting the original requirement of the program.

**Fielding mismatch** refers to the risk that a system we acquire is no longer needed by the time it is fielded. Timothy Luehrman points out "while we're waiting, the world can change" (Luehrman, 1998: 90). This could not be more applicable to defense modernization. **One of the greatest risks we face is going down a multi-decade road, costing billions of dollars, only to find out that the system we acquired is now obsolete due to changing technology, advances of our adversaries, or our own developments or that of our sister services within that same domain.** As Luehrman puts it, "If there is value associated with deferring, why would we ever do otherwise (Luehrman, 1998, 93)?" Yet the DoD prefers not to defer acquiring defense systems.

The DoD's commitment to getting as much capability baked into a system at the start of the program creates tremendous rigidity at a very high cost. There are alternatives. What can DoD learn from management science about developing systems that have some of the following qualities: intentionally short life-spans, developmental operational effectiveness, or upgradeability.

“DevOps” in software offers an interesting model for the seamless integration of operations and development, with gradual increases in capability. Additionally, combining these new management science approaches with systems of systems engineering and modern enterprise architecture concepts would emphasize bundling smaller sets of capabilities into systems designed to interoperate, rather than building monolithic systems. For example, most modern software architectures place the authentication, access, and monitoring and logging systems as separate components that interact with many types of systems. In a monolithic system design, each application duplicates these functions, making it very difficult to respond to changing security and evolving technology requirements. In a system of system approach, each module can be upgraded and replaced independent of the supported applications. Such an approach challenges the DoD security regimes in place, that would require separate security assessments for each system, as well as examination of the systems’ interactions; these structures make transitioning to more flexible models in use in industry unlikely without updating of models to match information and computer science current state of practice.

Finally, it may be useful for DoD to examine the “minimum viable product” approach to materiel development. This involves accepting some risk on the front end, but it allows organizations to produce operational products rapidly, with built-in upgradability.

### 2.3.5 Limited Information:

#### *Improving the World of the Program Manager*

In the preceding sections, we alluded to the incentives of acquisition Program Managers. They seek to get a program out of the acquisition system and into the sustainment system, having achieved the full rate of production. Crucially, they want to do this close to the program’s projected cost, on schedule, and at or above the stated requirements. The problem is that they often lack good information regarding technological readiness or the value of a marginal capability (both discussed above).

**Workshop participants suggested that management research on running cross-functional teams or distributed teams would be useful in improving communication between the R&D community and acquisition PMs, or between PMs and the operational community that generates requirements.** Additionally, any change in the management of acquisition risk must be embraced and supported by acquisition professionals. This is not simply a matter of promulgating new guidance. It is cultural change, and it must go beyond the R&D and acquisition communities. Management science has much to contribute in this regard. How do they think about risk? It is hard to maintain focus on readiness but also take some risk. The broader culture of risk in DoD needs to change.

## 2.4 Supply Chain Risk Mitigation

### Motivating research questions:

- How can we anticipate and address the erosion or complete collapse of sub-tier capability in the supply chain?
- In what ways can distributed digital fabrication and automation capabilities reduce reliance on complex supply chains and increase local adaptive capabilities?
- What safety and security arrangements are needed in ecosystems where there are distributed fabrication capabilities?

Military supply chains have always been complex, including the combination of diverse technologies and the overlay of political interests (such as locating production in as many Congressional districts as possible). These challenges now have the added challenge of many new forms for physical and virtual disruptions, driving a need for adaptive capabilities on a global scale. In this context, workshop participants identified three challenges:

1. **Constraints Imposed by the Current Supply Chain**
2. **Risks and Benefits of R&D Design Capabilities Lower in the Supply Chain**
3. **R&D Investments for a More Agile Supply Chain**

While lessons from the private sector are relevant to the management of DoD supply chains, they are incomplete given the DoD’s warfighting mission.

### 2.4.1 Constraints Imposed by the Current Supply Chain

The DoD supply chain is organized around separate programs, resulting in countless “stovepipes” operating independently. Opportunities for coordination, integration, and simplification are hard to see since the relevant information flows up and down the stovepipes rather than across. Similarly, risk management for the supply chain is not shared across the stovepipes. Overall, the supply chain is given relatively little attention. **Workshop participants characterized it as understaffed, underfunded, rigid, complex, and opaque. They observed that, without needed investments, the DoD supply chain will continue to fall short of its potential.**

Entry into the DoD supply chain is difficult. Prime contractors must pass through numerous hurdles and they then inherit numerous constraints on their suppliers. Constraints that serve national security are necessary, but there are many additional constraints that can’t be justified on security grounds. Foremost among these constraints are what participants described as “byzantine business practices.”

A sensitive aspect of the DoD supply chain involves political pressures that shape supply decisions. These are reflected in achieving support for new programs by locating supply contracts in complex combinations of Congressional districts. Similarly, offset agreements negotiated with international customers for military systems make for increased complexity. It is understandable why these stakeholders would push for these arrangements, but the results are often inefficiencies in the supply chain.

In comparison, some of the world's leading private sector companies, such as Amazon, Dell, and Walmart, have achieved competitive advantage through their skillful management of domestic and global supply chains. Major DoD suppliers, such as aerospace and auto OEMs, have used lean and six sigma methods to transform their internal supply chains, but lessons learned do not extend sufficiently to the DoD. Technological advances, such as the use of Radio Frequency ID (RFID) chips provide real-time situational awareness on the location of material in the supply chain. Blockchain technologies hold promise for end-to-end digital ledgers for traceability. But these and other technology opportunities are not sufficiently diffused throughout the DoD supply chain.

#### 2.4.2 Risks and Benefits of R&D Design Capabilities Lower in the Supply Chain

Many commercial companies have achieved considerable supply chain gains by leveraging lower tier suppliers, but such extensive multi-tier supply chains involve risks, usually hidden, as well as potential gains. For example, Boeing's 787 Dreamliner research and development group delegated extensive design, engineering, and procurement processes down to its Tier-1 suppliers. The goal was to achieve efficiency gains and accountability for development and production costs by these suppliers and to tap into their own local expertise, as well as their multi-tier suppliers, to design and produce subsystems for which they now became prime contractors. Most of Boeing's Tier-1 suppliers, however, had never managed this degree of autonomy or accountability before. Not surprisingly, the Dreamliner project ran into multi-year delays and cost overruns for many of its subsystems and Boeing encountered its own major delays and cost overruns when attempting to assemble and integrate the subsystems in the airplane.

Beginning nearly two decades ago, the auto industry also sought to benefit from innovative product design and production expertise by contracting for engineering and design work with its suppliers. This yielded considerable cost savings and some useful innovations. Unfortunately, there were also complications. Costs increased in some cases as OEM's engineering and design employees switched employers to advance their careers, leaving the OEMs less able to oversee the work. Also, the OEMs' procurement offices lacked expertise to contract with and manage supplier performance. This led to significant warranty claims based on sub-standard work by the lower tier suppliers. Also, as OEMs continued to use contracting with tier-1 suppliers to lower costs through short-term competitive contracts, suppliers became less willing and less able to serve as relationship partners with the OEMs for critical engineering and design decisions. Recently, automotive OEMs have reversed this policy and are performing more design and engineering work internally and offering longer-term relationship contracts with their major suppliers (Helper and Sako, 2010).

**Apart from higher costs and delayed development projects, a high reliance on multi-tier supply chains introduces risks in operations and supply chains that can be completely hidden from the lead contractor.** For example, in 2012, production in the automotive industry was severely disrupted by an explosion in the factory of a tier-5 German supplier of a

specialty resin used in fuel tanks, brakes, and seat fabrics, who none of the OEMs had identified as a major or critical supplier. The experience led Ford Motor Company to identify all of its suppliers at all levels of its complex supply chain of more than 15,000 companies around the world. For each supplier, it measured the total volume of purchases, as well as the potential loss in production and sales volumes were the supplier to shut down for an extended period of time. They plotted purchasing volume vs. potential loss as shown in Figure 2.4.2a.

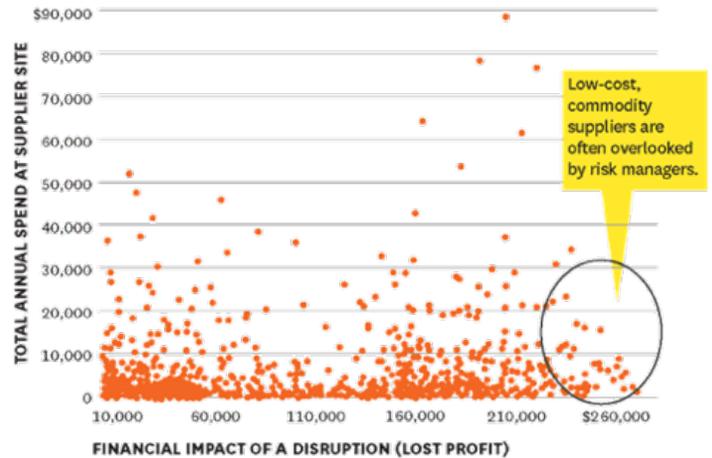


Figure 2.4.2a: Site Spending and Performance Impacts in Supply Chains  
Source: D. Simchi-Levi, W. Schmidt, Y. Wei (2014) "From Superstorms to Factory Fires: Managing Unpredictable Supply Chain Disruptions," Harvard Business Review (January-February).

The analysis helped them classify suppliers into three categories, and developed procurement and risk management policies for each category:

**I. Low Risk:** low total spend and low financial impact (lower left hand portion of figure)

Suppliers with low total spend and low financial impact can be managed by holding extra inventory (the low demands for these products makes this an inexpensive approach) and negotiation long-term competitive contracts that include penalties for sub-standard performance. If the supplier defaults, the contractor can seek alternative sources of supply.

**II. Obvious High Risk:** high total spend and high financial impact (upper right portion of figure)

These high-volume and high-risk suppliers have been the traditional focus of supplier management. These are the 20% of suppliers that account for 80% of the contractor's purchasing expenditures. For these suppliers, the contractor enters into long-term strategic partnerships that involve multi-site production capabilities for the component and risk-sharing and penalty clauses. The contractor's purchasing personnel actively monitor supplier performance and work with the supplier to mitigate the potential losses from business interruptions.

**III. Hidden High Risk:** low total spend but high financial impact (lower right sector of figure)

Low-volume suppliers, often of a commodity product (such as the resin produced by Ford's German supplier but occasionally a specialty critical component). Purchasing people often overlook low-volume suppliers since their apparent contribution to the final product seems trivial in comparison to the sub-assemblies produced by tier-1 suppliers. Once such hidden risk suppliers have been identified, the contractor has several options to mitigate high-cost supply interruptions. These options include redesigning the product to reduce reliance on the component, contracting with multiple suppliers for the component, or just purchasing multi-year supplies of the component, and storing them for use as needed. While seemingly a wasteful, high-cost option, the multi-year inventory stocking level will usually be far less expensive than bearing the extremely high cost of production interruptions should the single-source supplier lose its production capabilities (or in defense contracting, deciding to deny access to the material or component as part of a larger geopolitical strategy).

A typical automobile has approximately 10,000 parts, while an aircraft is an order of magnitude more complex at around 100,000 parts. **Given the vast complexity of the supply chains associated with the broad array of DoD programs, the challenge of identifying and addressing "hidden high risks" is considerable. It would likely require the integrated use of distributed knowledge at all levels of the many associated organizations, rather than a simple top-down assessment.**

#### 2.4.3 R&D Investments for a More Agile Supply Chain

The DoD's R&D enterprise has the potential to make unique contributions to the DoD supply chain management systems. This includes innovations that are relatively standard, such as improved information sharing systems, better alignment in material flow, and efficiency improvements (cutting cost and lead time). These types of innovation do not require new R&D investments, but rather the systematic application of known, advanced tools and methods.

More advanced investments are possible with a number of new technologies. For example, the use of real time data from RFID tags and other IoT (Internet of Things) sources makes possible visualizations that make it easier to anticipate disruptions and respond rapidly when they occur. Similarly, digital fabrication and rapid prototyping capabilities allow for cutting complex supply chains, generating spare parts and customized designs close to the source, and innovating in new ways. Battlefield fabrication capabilities are one aspect of R&D capability in this regard, as well as distributed societal production capabilities. As with any new technologies there are also risks associated with distributed fabrication capabilities in the hands of enemies. So far, the track record with community digital fabrication is that it is highly valued by communities, with strong norms against misuse (Gershenfeld, Cutcher-Gershenfeld, and Gershenfeld, 2017). Robust institutional mechanisms to mitigate such risks will be needed as the technology advances and becomes more widely available since community norms will not be sufficient to protect against misuse and, at the same time, the ability to generate more sophisticated threats (such as weapons with personalized fab or viruses with biofab) will increase.

## 2.5 Research and Development Leadership

### Motivating research questions:

- How can we better prepare the DoD workforce for new technology and rapid changes in operations?
- How can DoD leaders foster partnerships with social scientists that result in robust communities of practice that are identifying and advancing research questions relevant to DoD operations?
- Are there new ways to think about the process of awarding security clearances that are more streamlined, while still ensuring security?
- What are the best ways to promote flow of personnel between the academic, industry, and government sectors – balancing ethics, limitations on compensation and traditional reluctance of organizations to give up their best people?
- How can we eliminate or mitigate the organizational and institutional barriers to DoD achieving a clean audit as quickly as possible?
- How can reporting to Congress be made more efficient and streamlined, while still provide the desired information?

Leadership challenges in R&D management begin with questions around how R&D leaders can more effectively manage innovative processes. This challenge spans the following six areas:

1. **The Leader's Role in Anticipating and Exploiting Disruptive Technologies**
2. **Minimizing the Cognitive Biases of Leaders**
3. **Balancing Top-Down vs Bottom-Up Emergent Approaches**
4. **Seeking Opportunities to Support Complementary Research, I.E., Research That Takes Advantage of and Builds on Progress in Other Research Communities, such as Industry**
5. **Managing Innovative Groups and Organizations**
6. **Developing Behavioral and Social Science Research Communities**

Innovation poses a fundamental challenge to all organizational leaders. Organizations formalize and routinize activities, values, and beliefs that have worked in the past. Innovation often challenges these routines. The history of business suggests that the most frequent path to organizational innovation involves the destruction of old forms and their replacement with new ones. DoD probably does not want to pursue this path. So how can R&D leaders more effectively encourage innovation in their organizations? The insights of behavioral and organizational science are immensely relevant to this area.

#### 2.5.1 The Leader's Role in Anticipating and Exploiting Disruptive Technologies

Ever since the 1997 publication of Clayton Christensen's the Innovator's Dilemma, the concept of "disruptive innovation" and their effects on leading firms has assumed a central place in theories of innovation in competitive systems. What makes Christensen's work particularly significant to DoD is its special application to leading (or "dominant") firms. In the realm of military technology, DoD is dominant. Christensen describes how leading firms become captured by their existing customers, and as a result are unable to

build business around new ways of providing goods or services. Disruptive innovations are especially troubling because their triumph over the previous way of doing business tends to be both sudden and decisive. There is no gradual diminishment of a competitive position. Externally, it looks as though a firm is a leader one year and out of business the next. Typically the actual development story is more complex, with significant work preceding the disruption over many years, including failed initiatives within the dominant firm. There are also cases where dominant firms have dramatically shifted their strategies, such as IBM's journeys from hardware to software to services. The key is that new advances are inflection points and failure to adapt can pose existential risks for dominant organizations.

How can leaders in R&D management create an organizational context that encourages discovery, development and effective engagement with disruptive innovations? Crucially, disruptive innovation requires a deep and effective connection between R&D and the operational force. The significance of a technology is not apparent simply in its inherent characteristics. The degree to which any technology is disruptive can only be understood and observed in a competitive context.

### **2.5.2 Minimizing the Cognitive Biases of Leaders**

Several workshop participants noted the importance of cultivating R&D leaders who have open, unbiased minds. Cognitive biases can cause leaders to miss key opportunities. These biases can distort leaders' assessments of personnel, of methods or goals, of team processes, of organizational partners, and of several other factors. Participants noted that there is no single, best way to do effective research, but leaders may be biased toward a single approach. A leader who encourages (or at least tolerates) a diversity of approaches and styles is more likely to foster real innovation. This is especially important in pursuing interdisciplinary research, which is increasingly important. Leaders need to understand how to introduce diversity into the research context. This may require accepting more than one paradigm in a given research program, or developing different incentive structures that meet the needs of different research team members. Finally, leaders need to be learners. Subject mastery is not the goal of effective R&D leaders, because it simply is not feasible. Instead, incessant curiosity is a more valuable guiding principle.

Management science research on leading diverse teams, on critical thinking, and practicing open-mindedness and curiosity will help in developing more effective R&D leaders. The relationship between diversity and performance is complex and not always linear. First, many dimensions of diversity are relevant and research on the subject has evolved toward increasingly nuanced approaches (Roberson, Ryan, and Rains, 2017). In a study of diversity of experience on Formula 1 development teams, an inverse "U" curve was identified, with increased diversity increasing performance to a point and then declining as very high levels of diversity impaired communications and other processes (Hoisl, Gruber, and Conti, 2017). We recommend exploring how leaders in a wide mix of research enterprises outside of the DoD approach similar challenges. It would be useful to have a better understanding of the variety of research "ecosystems" in industry and academia.

### **2.5.3 Balancing Top-down and Bottom-up (or Lateral) Approaches**

Historically, the industrial approach to managing research has been to run closed research environments with internally managed personnel using internally allocated budgets, usually in pursuit of an agreed-upon objective. This has been effective in exploitation-focused research. However, in each of four key variables—research environment boundaries, personnel, money, and objectives—recent organizational developments have shown that a much wider variety of possibilities exist. The role of an effective leader in R&D has changed, and effective exploration-focused research especially requires more openness to alternative organizational models. Developments in information technology have made organizational boundaries more permeable, and made possible the involvement of large numbers of people in research (e.g., DARPA challenges or other crowd-sourced research).

Where possible, leaders need to encourage emergent approaches to innovation. Leaders who cultivate open innovation communities can do so at very low cost. Crowd-sourcing and user innovation are other examples of emergent innovation management strategies. Granted, these may not be appropriate for already classified defense research programs, yet even in classified settings leaders may have opportunities to give greater freedom and control to front-line researchers. It seems clear that DoD would benefit from exploring a wider variety of managerial approaches to innovation. This requires educating leaders in good models for bottom-up or lateral (collaborative or partnership-based) innovation management.

Research on venture capital or asset management may also be useful in helping R&D leaders more effectively manage portfolios of research activities, especially those that including programs with different risk profiles.

### **2.5.4 Taking Advantage of Complementary Research in Other Communities.**

For decades, DoD led the way in research, producing technology that was years (if not decades) ahead of similar technology in civilian applications. In some areas (materials or propulsion, for example), this remains largely true. Yet in fields such as robotics and artificial intelligence, the private sector has pulled ahead of DoD. It was never true that the state of the art in all key military technologies came exclusively from the DoD research community, but it is certainly less true now than ever. "Dual use" benefits used to flow mainly from DoD to industry. This challenges old models of security where risk could be mitigated by keeping technologies secret or classified. Now the benefits flow in both directions. R&D leaders need to build ties to other research communities, recognizing opportunities for military applications in technologies that may not have been intended for them, while evolving security models to include technologies that originated from outside the DoD.

**The repurposing of civilian technology to solve military problems requires that three things happen: 1) someone inside the DoD becomes aware of the external technology; 2) some-**

one recognizes its potential military application; and 3) the technology is acquired and modified as necessary to explore its application. Leaders can affect the probability that any one of these events occurs. “Not invented here” syndrome is a common problem in the military, which prides itself on the utter uniqueness of its operational environment, sometimes to the detriment of its ability to learn useful things from other competitive settings. R&D leaders must resist this tendency. Management science can help DoD understand how to structure R&D so that it is more likely to recognize and explore the utility of research from other communities.

### *2.5.5 Managing Innovative Groups and Organizations*

It is essential that R&D leaders understand how to be effective managers of research teams and organizations. DoD needs help understanding how to manage a mixed workforce. It needs to be innovative about bringing in outside researchers on an interim basis, allowing people to flow more freely in and out of the DoD research “ecosystem”. One participant suggested that DoD explore developing a “reserve” cadre of researchers who work part-time in DoD research settings, facilitating more sharing of good ideas between different communities. Another approach would be to create an innovation or leadership academy with a curriculum selected based on priorities and models described in this report, e.g. fostering innovation, mixing of top-down and bottom-up strategies, advances in supply chain management, Agile methods, etc. Such a program was enacted at University of California (UC), a system of ten universities and additional large research labs. While universities themselves are sources of great innovation in thought and innovation, the higher education apparatus that sustains them, including its own information management, is not regarded as agile and share many similar challenges with the DoD as identified in this report.

In the case of UC, the system wide CIO partnered with the Haas School of Business at UC Berkeley to create a curriculum meant to enable more innovation and entrepreneurship within the systems IT leaders.<sup>5</sup> This program, which includes several of the concepts mentioned, runs annually with only a few slots offered to each location. Participants attend two, one week sessions to ensure rapport is created between students and guest speakers (leaders) and attention is given to the topic. In addition to training a new cadre of leaders, the academy brings in top ranking university officials who give candid leadership advice, and engage in Q&A. The groups have regular opportunities to meet regionally and are the target of new training and scholarship opportunities. Over the longer term, the program has created a network of individuals known to be change agents and amenable to new ideas, giving participants a way to explore and sometimes enact cross-institutional programs and changes.

### *2.5.6 Developing Behavioral and Social Science Research Communities*

The behavioral and social sciences have a new, significant place in DoD’s research portfolio. Historically, DoD research has focused on the life and physical sciences. During the Cold War, important DoD research initiatives in the behavioral sciences explored phenomena such as POW brainwashing, leaderless teams, and learning curves, but the culture supporting such research is weaker now. Looking to the future, DoD needs to understand how to influence individuals and populations in a digital era. Yet the methods, goals, and reliability of behavioral and social science research differ significantly from those of the “physical” sciences. R&D leaders may need to develop new management sensitivities and approaches to accommodate these differences.

DoD invests heavily in developing military officers who are better prepared for strategic roles, but the department is much less consistent in its development of civilian leaders. Effective R&D leadership requires investing intelligently in aspiring leaders.

5. <https://www.ucop.edu/information-technology-services/initiatives/itlc/uc-it-leadership-academy.html>

## 3.0 Research-Push from Management Science and information Science

The second half of the workshop examined the research domains at the intersection of management science and information science that are relevant to the DoD problem sets. These are as follows:

- 3.1 Large-Scale Systems Change Management
- 3.2 R&D/Innovation Management
- 3.3 Cyberinfrastructure and Data Analytics Management
- 3.4 Stakeholder Alignment in Complex Systems
- 3.5 Social Psychology of Culture, Identity, and Conflict
- 3.6 The Science of Science Teams and Institutions
- 3.7 Supply Chain Resilience

Note that some are more micro in focus, such as issues of identity in a digital age, and some are more macro, such as stakeholder alignment in complex systems. In each case, the basic science is advancing based on issues and challenges that are largely independent of the defense establishment—though all are highly relevant to the defense of our nation.

### 3.1 Large-scale Systems Change Management

Motivating research questions:

- How can we best mitigate risk aversion in complex, bureaucratic organizations such as the DoD?
- What change models take into account a larger context, including accelerating technological change, complex combinations of stakeholders, and no overarching authority?
- What is the relevant mix of “middle-across” change models that can be added to top-down and bottom-up change models?
- In addition to the well-developed role of a change agent, how can we build skills and recognition for two emerging roles—that of a sustaining agent and an ecosystem architect?
- How do you effectively scale well-intentioned policies and practices over an enterprise the size and complexity of the DoD?



Figure 3.1a: Leading Change Model for Change Initiated by Leaders  
Source: Retrieved from <https://www.kotterinc.com/8-steps-process-for-leading-change/>

There are many well-established models for change management, some of which are top-down models and some of which are bottom-up. Though it is rarely explicit, all assume the existence of a hierarchical structure and a larger context that is changing, if at all, in predictable ways. Workshop participants observed that “most change models are designed to make a difference in degree, not a difference in kind.” Given that many change challenges involve major shifts, not just incremental adjustments, this limits the utility of many existing models.

For example, a common top-down model is John Kotter’s eight step model for leading change, shown in Figure 3.1a. This model builds on his 1995 article on why transformation efforts fail (Kotter, 1995). Initially presented as steps in a process, it is now depicted as a cycle. Still, it is a top-down model in that it begins with leaders creating a sense of urgency, building a guiding coalition, and forming a strategic vision. It expands to include volunteers and addresses barriers, but at the core it is a model for change in service of priorities set by leaders. Unstated, but implied is a hierarchy as context and an assumption that external changes can be handled within the scope of the model.

A common bottom-up model is W. Edwards Deming’s PDCA model, which stands for a process of continuous improvement, involving Planning, Doing, Checking, and Acting or Adjusting as is illustrated in Figure 3.1b. Although the model can be applied in a wide variety of change situations, it is most commonly utilized with front-line teams in a hierarchical organization where the continuous improvement is relative to goals and metrics in a relatively stable context.

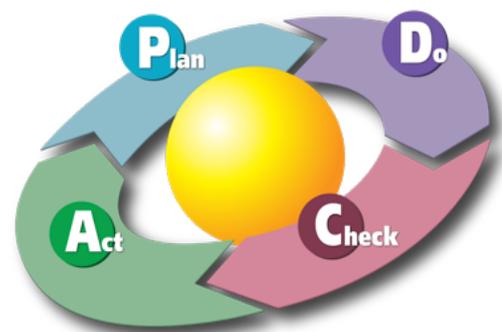


Figure 3.1b: PDCA Cycle for Continuous Change  
Source: retrieved from <https://en.wikipedia.org/wiki/PDCA>

There are also various models focused on how people deal with unexpected change, such as William Bridges model for managing transitions (Bridges, 1991) shown in Figure 3.1c. Above horizontal dotted line are more positive responses to change and below the dotted line are responses that indicate greater difficulty with change. The bold curved line represents the journey of a person from endings to new beginnings. The key to this model is a recognition that people have to let go of the old and undergo a transition before they are ready to accept the new. While this can be applied to many changes, much like the PDCA model, it is commonly used in the context of organizational change to adjust leaders' expectations to take into account predictable reservation, confusion, frustration, and denial. Implicit in the model is, however, the notion of a singular change with a relatively stable context otherwise.

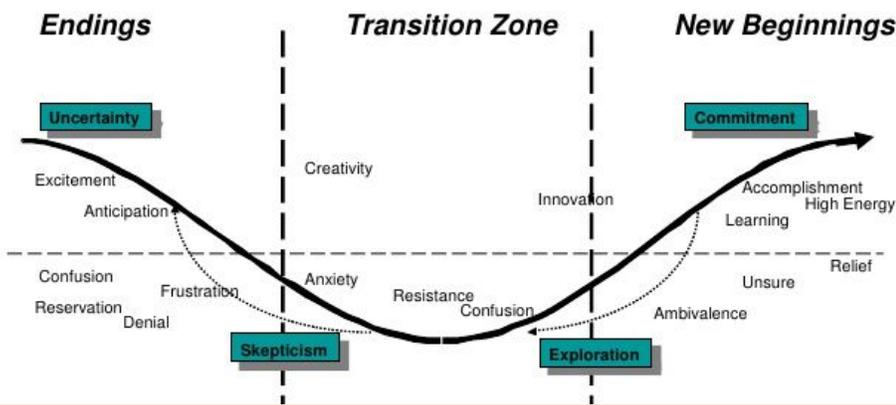


Figure 3.1c: Managing Transitions  
 Source: Adapted from William Bridges' *Managing Transitions* by Motorola University

**The Future Directions challenge for management science and information science involves developing models that take into account the following additional considerations:**

- A growing need for strategy formulation, not just strategy execution
- Multiple stakeholders to any change challenge, without any single overarching hierarchy
- Multiple interests or issues that are "at stake" in any prospective change
- Accelerating and highly variable rates of change in technology and society
- No single shared vision of success serving as "true North" to guide change
- Rules of the game that incentivize narrow self-interests over broader shared interests
- The need to architect entire new ecosystems as a "systems of systems" change challenge

It is unlikely that a single new model will incorporate all elements of existing change models, but a menu of modular options represents a promising approach to managing change. Aside from combining new models, even greater awareness of change models, and their complex relationship with battlefield command structures, could be beneficial. Workshop participants observed that the "customer" for advances in change models are particularly mid-level science and technology managers. Participants

also noted a bias in the DoD system in favor of change agents over a role that is rarely valued equally, which is that of a sustaining agent—someone who takes a change introduced by someone else and helps to sustain the innovations. The primacy given to change agents and the lack of sufficient numbers of sustaining agents leads to "change fatigue" as each new leader introduces a new "flavor of the month," with predictable frustration and cynicism. The two-year cycles for leadership assignments do build cross-functional capability for leaders, but reinforces the "change fatigue" dynamic.

In thinking in new ways about change, one workshop participant shared the example of the need for salmon recovery in Washington State. There was no overarching hierarchy to take responsibility for the problem and each stakeholder was approaching it from their own specific interests. The breakthrough in thinking about the problem came by approaching from the point of view of the salmon. In many complex challenges facing the DoD, there may be value in approaching the problems from non-traditional perspectives.

With respect to designing and building new ecosystems, workshop participants posed the question, "What are the problems for which ecosystems are the solution?" In response, it was observed that ecosystems in conflict settings may need to be reconstructed, as may ecosystems for innovation throughout the science and technology enterprise. One participant observed that

"the challenge of leadership and management in an ecosystem is that it is a context where full control is not an option, but action is needed." In this context, this person asked "What is a management model that works when you don't have control?" This further highlights the need for change models that don't depend on an underlying hierarchy.

Finally, Ed Schein's model of culture change gets to the core challenge facing the DoD. It identifies three layers to an organizational culture: the layer of visible artifacts; the layer of stated policies, procedures, and values; and the underlying layer of deeply embedded, often unstated, assumptions (Schein, 1980). **Workshop participants observed that a deeply embedded, often unstated, assumption in the case of the DoD science and technology enterprise is the assumption that the United States can always prevail through science and technology leadership.** This is problematic in two ways: First, damage has been inflicted on the United States in low tech ways by terrorists or by increasingly available advanced technologies. Second, other nations, particularly China (see figure 3.2f below) are challenging U.S. leadership in science and technology in various ways. For example, China has surpassed the US in quantum technologies since 2013, such as quantum communications, quantum radar, quantum encryption (Giles, 2019).

Just as code-breaking and radar helped change the course of

World War II, Giles (2019) states that quantum encryption and quantum radar could be similarly game changing. However, as he observes, a systems approach coordinating public and private efforts, cultivating close working relationships between government research institutes, universities, and companies, is needed to make the potentials of these new technologies fully realized for national security. While these international developments are well known, the change management challenge is that many aspects of the DoD science and technology enterprise feature cultures that are rooted in the assumption that we possess science and technology leadership, and that this will always lead to success. **A key “future directions” challenge involves wrestling with this and other embedded assumptions that are likely to still be useful in some respects and limiting in others.** The concluding “co-evolving ecosystem” section of this report highlights a number of embedded assumptions in the DoD culture that need attention.

### 3.2 R&D/Innovation Management

#### Motivating research questions:

- How can the DoD establish optimal public-private partnerships to improve DoD research lab effectiveness?
- What are the relevant options for governance structures in DoD research labs?
- How have linear R&D cultures and processes shifted to rapid prototyping/fail-fast approaches? What additional approaches are relevant?
- How can the DoD lower organizational and institutional barriers to rapid prototyping/fail-fast approaches?
- What are relevant options for the DoD to best make use of foreign national talent?
- How can the DoD best expose and exploit the IP in its research labs for commercialization or use in military systems?

There is a fundamental tension between the logic of research and development (R&D) innovation management and the hierarchical structure of most organizations (including the military). R&D emphasizes rapid prototyping in order to “fail fast,” learn and adjust. Most hierarchical organizations seek stable plans, subject to top-down oversight and control. Additionally, failures in hierarchical organizations are to be avoided or at least contained as long as possible. As one workshop participant commented, “You can’t study failures if you aren’t willing to admit you have them.” This challenge is compounded in the public sector where failure also involves the failed use of public taxpayer dollars. Thus, management science recognizes a long-standing tension between learning and risk, on the one hand, and stability and control, on the other.

Many of today’s leading project management practices are justified based on their roots in military research projects. In a study of these roots, it was noted that the Manhattan Project and others like it started out with missions that were beyond what was currently possible and solutions had to emerge over time. It was found that “[t]hey succeeded by a combination of parallel trials (from which the best would then be selected) and trial-and-error iteration (allowing for the modification of solutions pursued over a period of time).” These practices “fly in the face of accepted professional

standards [for project management], making managers uncomfortable when they are encountered.” The authors conclude that “[t]he discipline of project management should be broadened in order to create greater value for organizations whose portfolios include novel and uncertain projects” (Lenfle and Loch, 2010).

Further complicating the inherent tensions associated with R&D is the inevitable transition from a focus on innovation in the development of a new product or service to a focus on process innovation in the production and delivery of that product or service. This is illustrated in Figure 3.2a.

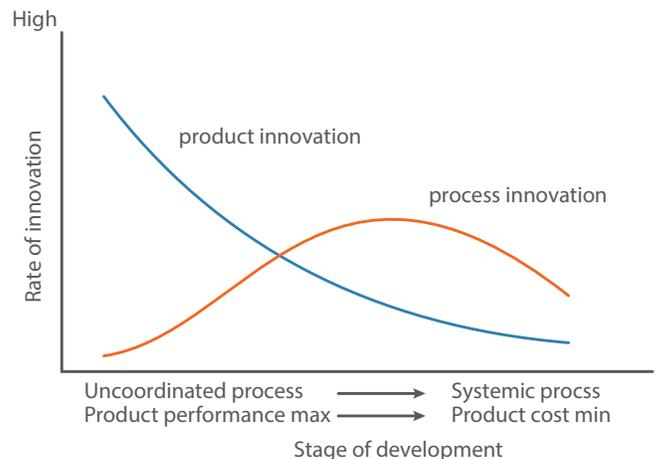


Figure 3.2a: Product and Process innovation

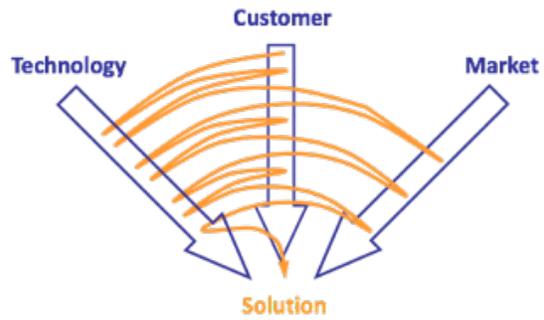
Source: Abernathy W. J. and Utterback, James M. 1978. *Patterns of industrial innovation. Technology Review, Vol. 80 (June-July).*

The management of innovation in development of new products and services emphasizes creativity and break-through ideas. In contrast, the management of innovation in process improvement emphasizes standardization and incremental improvements. Each involves different forms of oversight, coordination, and support. A classic managerial dilemma arises at the inflection point where process innovation exceeds in importance the development of new products and services.

**Some workshop participants had organizational guidance for the DoD going forward. For example, one participant commented that, “In government, acknowledging failure is very difficult (e.g., wasted tax dollars). Can this be reinterpreted as pivoting, which does not have the same stigma?” Another recommended a portfolio approach, including some risky projects. A third participant called for more sophisticated metrics that tracked both risk and reward so as to be able to identify the optimal balance or mix.** The comment was that “we need to better understand the beta on risk.” The Abernathy and Utterback model and these participant comments operate at the organizational or enterprise level of analysis. Other aspects of the R&D and innovation literatures are more micro, at the individual level of analysis, and more macro, at industry or national levels of analysis.

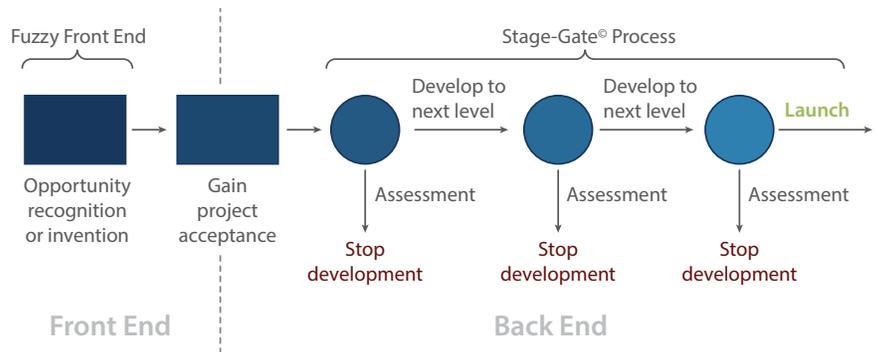
At the micro level, attention is given to individual innovators, such as winners of Lemelson awards, which have been one of the premier forms of recognition for innovators for over twenty years. At

the tenth anniversary of the awards, a study was commissioned to examine the educational strategies of past awardees (Sheppard, Cutcher-Gershenfeld, and Magee, 2004). It was found that most had generated innovations that involved expertise well beyond their formal education and training. In contrast to traditional models of education and training, which emphasize building depth of expertise in a domain, they reported being problem driven and, if a problem required chemistry, they would learn just enough chemistry, if it involved physics, they would learn just enough physics, and so on. This model works well for individual innovators who are pursuing new ideas on their own. For hierarchical organizations, with defined domains that correspond to markets or functional areas, it is more challenging to support innovators who are pursuing a problem that crosses organizational boundaries.



**Figure 3.2b: Iterative Innovation Process**  
 Source: Griffin, A., R.L. Price, and B. Vojack, 2004, *Serial Innovators: How Individuals Create and Deliver Breakthrough Innovations in Mature Firms*.

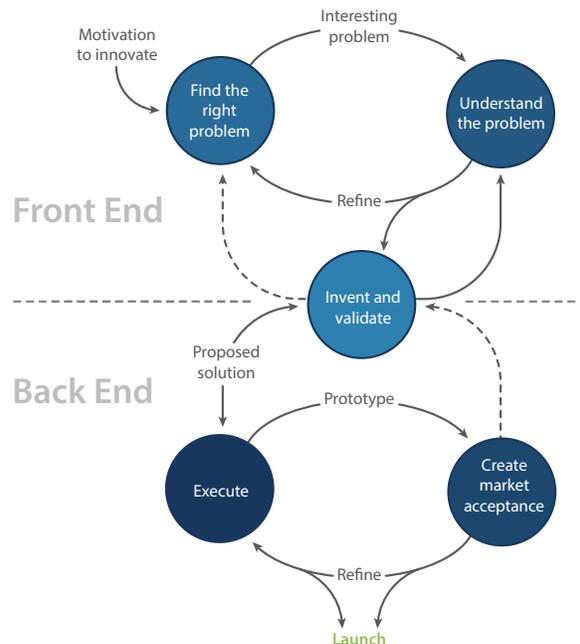
An emerging focus of the R&D innovation literature are serial entrepreneurs who operate within established organizations. These individuals are sometimes referred to as the most famous people you have never heard of, since they are often legendary within their firms, but unknown in the broader society (Griffin, A., R.L. Price, and B. Vojack, 2004). Like any innovators, they succeed through an iterative process combining an interrogation of technology, customers and markets, such as is illustrated in Figure 3.2b.



**Figure 3.2c: Classic Stage Gate Process**  
 Source: Griffin, A., R.L. Price, and B. Vojack, 2004, *Serial Innovators: How Individuals Create and Deliver Breakthrough Innovations in Mature Firms*.

What is distinctive about these internal serial entrepreneurs is they also bridge well-established organizational functions in non-linear ways. Figure 3.2c shows a traditional technology development process in which an innovation takes shape, gains acceptance, and then travels through a series of stage-gates. This allows the larger hierarchical organization to retain oversight and control.

By contrast, the successful serial entrepreneur follows a more iterative path in defining the problem, understanding the market, and advancing the new idea (Figure 3.2d). In the process he or she is doing the work of multiple distinct functions, including marketing, engineering, and finance—not just R&D. The result is a better match between the innovations and needs, but a lack of clear stage-gates at which go/no-go decisions can easily (though sometimes incorrectly) be made.



**Figure 3.2d: Serial Innovation Process**  
 Source: Griffin, A., R.L. Price, and B. Vojack, 2004, *Serial Innovators: How Individuals Create and Deliver Breakthrough Innovations in Mature Firms*.

There is strong interest among management science scholars in the role of “routines” in organizations, which reflect deeply embedded operating assumptions around how best to accomplish work and other considerations. In some cases, there are routines that facilitate risk taking and in other cases there are routines that reinforce risk aversion. Workshop participants noted that an example of risk facilitation at the micro level is the role of tenure in universities, which allows for experimentation and failure with lower risk. The use of “young investigator awards” was also highlighted as allowing next generation scholars to pursue innovative topics in an open way. The routines in DoD science labs and related settings would be appropriate for such study looking at enablers and barriers to innovation, which involves risk.

The same way that intrapreneurs innovated in integrated rather than sequential ways is also reflected in workforce management. A recent report on “Engaging the Workforce in Digital Transformation,” commissioned by Oliver Wyman and Mercer in collaboration with MIT’s Thomas Kochan, illustrates the contrast:

The interrelated approach for workforce development is interactive rather than sequential. This suggests that the HR function, civil service, and worker representatives need to be entrepreneurial in ways comparable to the technology development process so that they can be integral to free development of the technology.

## DESIGNING THE WORKFORCE FOR THE FUTURE

Exhibit 1: Moving from a sequential workforce strategy development process to a circular integrated process

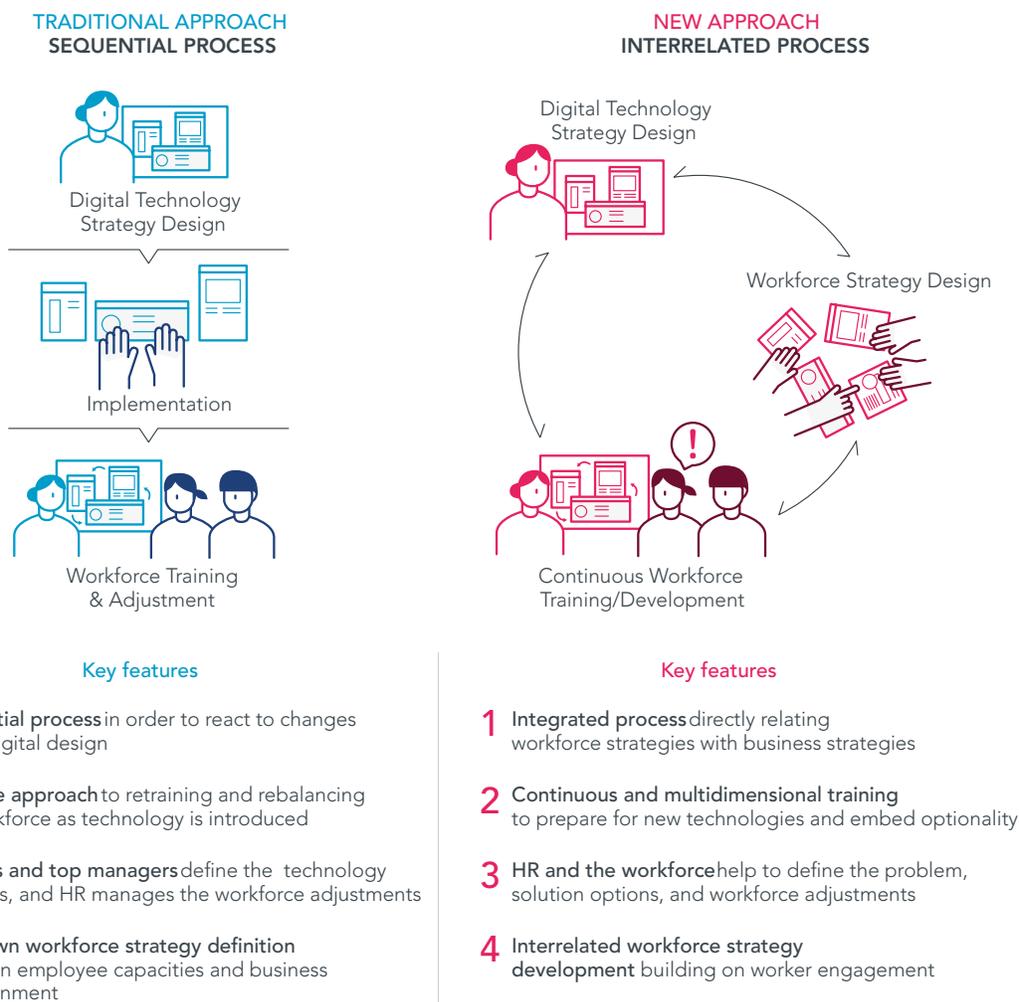


Figure 3.2e: Designing the Workforce for the Future

Source: Antonis Christidis, A., A. Miller, T. Kochan (2018), *Engaging the Workforce in Digital Transformation*, retrieved from: <https://www.oliver-wyman.com/content/dam/oliver-wyman/v2/publications/2018/april/Engaging-The-Workforce-In-Digital-Transformation.pdf>

At the macro level of analysis there are important distinctions made between levels of investment and rates of change. Two charts illustrating the two approaches are included. The first chart (Figure 3.2f) plots the public and private R&D expenditures and the size of the R&D workforce in a number of nations. The US and China stand out in terms of overall expenditures, with China having substantial room to grow in terms of the number of researchers relative to the overall full-time working population.

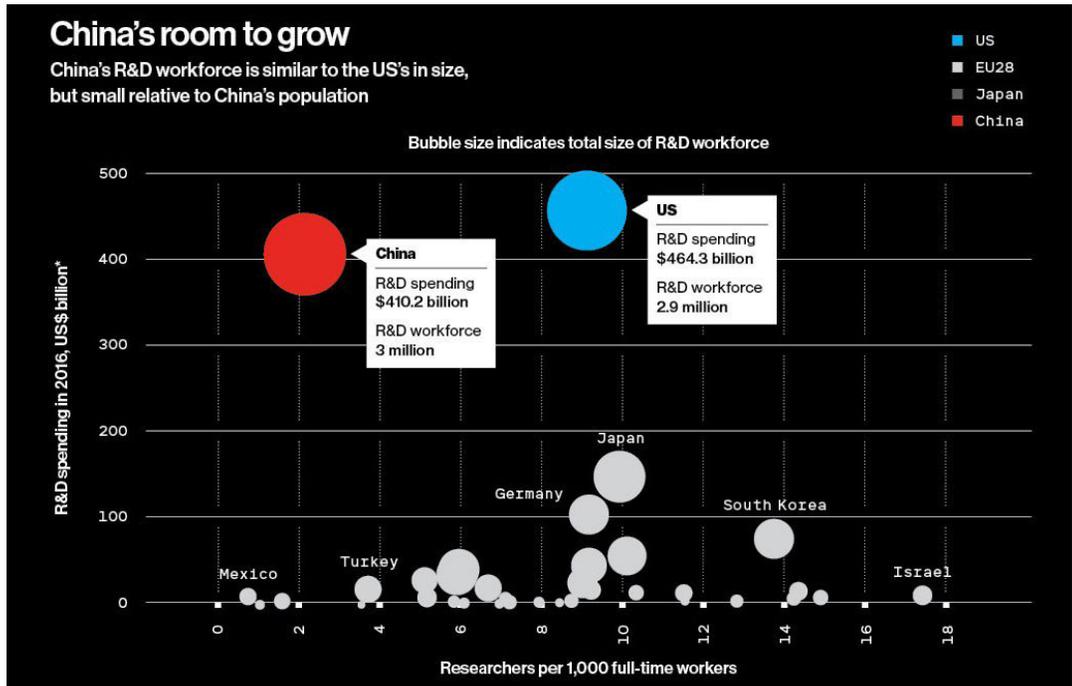


Figure 3.2f: R&D Expenditures and R&D Workforce

Source: World Bank OECD data, cited in: Mara Hvistendahl (2018), "China's tech giants want to go global. Just one thing might stand in their way," MIT Technology Review (December 19, 2018) (retrieved from: <https://www.technologyreview.com/s/612598/chinas-tech-giants-want-to-go-global-just-one-thing-might-stand-in-their-way/>)

More striking, the chart shown in Figure 3.2g presents rates of growth in R&D expenditures, pointing to China as showing accelerating rates of growth.

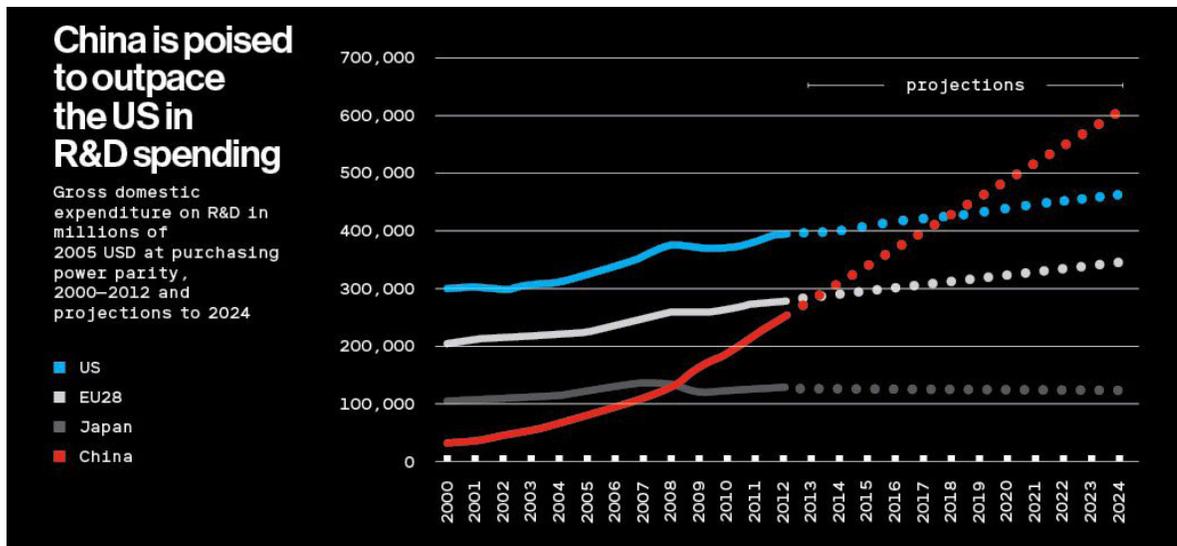


Figure 3.2g: China is poised to outpace the US in R&D spending

Source: World Bank OECD data, cited in: Mara Hvistendahl (2018), "China's tech giants want to go global. Just one thing might stand in their way," MIT Technology Review (December 19, 2018) (retrieved from: <https://www.technologyreview.com/s/612598/chinas-tech-giants-want-to-go-global-just-one-thing-might-stand-in-their-way/>)

At the macro level, a key research question centers on the implications of R&D shifting from a relatively small number of premier government and industry labs, to a large array of public and private innovation facilities, to a much broader array of distributed innovation nodes that are mostly individuals and small groups of individuals. In this context, workshop participants noted the challenges of annual budget cycles for federal investments in innovation, much of which involves longer time frames. Also, workshop participants discussed the need to better understand what types of innovations are best advanced with a competitive model and what ones are best advanced with more directive or collaborative models. Ultimately, the strong need to advance what can be termed the science of science innovation was identified.

### 3.3 Cyberinfrastructure and Data Analytics Management

#### Motivating research questions:

- If the logic of digital science involves modular elements that can be assembled and disassembled (with error correction), what organizational and institutional arrangements might best co-evolve with these technologies?
- How can the DoD make data and data sources available (through contracts, enclaves, competitions, or other means) in order to advance the frontiers of data science, while also generating new insights from the data?
- What are mechanisms to build legitimacy, trust and input into black-box algorithmic models?
- How can we measure the technological maturity of software that is in continuous agile development and production – in order to optimize use of the software and meet DoD oversight requirements?

Data is being celebrated as the new source of value in markets and data-driven business models now dominate the economy. The book *Moneyball* (Lewis, 2003) documented how data analytics not only provided a competitive advantage on the baseball diamond but also symbolized similar, advanced uses of data in a wide range of industries. Today, data analytics are seen as at the heart of a management revolution (McAfee and Brynjolfsson, 2012; Chen, Chiang, and Storey, 2012). With the increasing importance of data has come new risks, including cyber attacks, weaponized social media, impenetrable algorithms, and more. Less visible, but essential to the increased dependence on data is the enabling cyberinfrastructure. Our focus here is on future directions in the cyberinfrastructure and data analytics for science and technology. The principles are far broader in scope and implications, with science and technology at the leading edge of some challenges and lagging in other cases.

**With respect to data analytics, workshop participants observed that the DoD has within its purview vast data sets that could be de-identified and scrubbed of classified content.** Then, contests could be held to select scholars with the requisite skills to mine the data—advancing scholarship and generating what are likely to be practical insights. The example of competitions hosted by Professor Peter Fader in the Marketing Department at the University of Pennsylvania was identified as an illustration of the controlled, productive matching of researchers with commercial data.

Beyond prompting the broader use of DoD data to advance understanding of data analytics are workforce pipeline issues around the DoD being able to attract and retain the needed talent with data analytics and other aspects of data work. This is a challenge that is also being experienced in universities where data professionals are developed internally and then hired away by the commercial sector that has an insatiable appetite for data-related talent. **Workshop participants posed the question of whether a data talent ecosystem could be co-architected by universities and the DoD so that they could both better meet their staffing needs.** New programs such as those funded by the National Science Foundation's Data Science Corps<sup>6</sup>, may provide opportunities for such DoD and university collaborations.

Most of the infrastructure supporting science and technology centers on generating publications and scholarly citations, which itself is a "creaky system" (Buckland, 2017). Much more challenging, however, is the infrastructure associated with data, which is still emerging (Borgman, 2015). The array of associated models and data sources in the weather and climate sciences has been termed a "vast machine" of individuals, organizations, and institutions (Edwards, 2013). However, it doesn't function in a fully coordinated way and other parts of the science and technology enterprise vary considerably in the capabilities of the cyberinfrastructure. Indeed, there are considerable structural and cultural barriers to the needed collaboration and sharing of data in science.

Structurally, much of the funding of cyberinfrastructure and broader aspects of science is rooted in underlying competitive assumptions. While competition can often be an engine of innovation, there are aspects of infrastructure in which competition can also be inefficient and destabilizing. Moreover, cyberinfrastructure is a common pool resource that is at risk of tragedies of the commons (Hardin, 1968) where everyone depends on it, but doesn't dedicate the needed resources to support it (a market failure). Further, there are research questions best advanced through collaboration rather than competition.

In 1962, Thomas Kuhn documented a historic conservative tendency in the structure and operation of science, where new ideas are too often rejected until so much evidence builds up that there is a revolutionary overthrow of the old ideas. The incentives associated with promotion and tenure in universities reinforce these conservative tendencies, giving priority to work that is within disciplines, rather than across, and that is incremental vs. revolutionary. Further, higher value is placed on the original generation of new data, rather than the inventive reuse of existing data. Even data that was generated with public funds is too often allowed to be treated as proprietary—closely held by the researchers rather than shared (after an appropriate embargo period to reflect a scientist's investment in generating that data). It is true that not all data can or should be shared, but much more can be shared especially when key advances in science hang in the balance.

In contrast to the individual, organizational, and institutional dynamics that limit investments in cyberinfrastructure and that constrain open sharing of data, most leading science funders

6. [https://www.nsf.gov/funding/pgm\\_summ.jsp?pims\\_id=505536](https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=505536)

such as the NSF and the NIH now require data management plans as part of all research proposals. Even if there is some variation in the enforcement of these plans, it does place data management on the radar screens for most researchers seeking federal funding. Further, scientific publishers are increasingly insisting on the submission of reusable data with articles entering the publications review process. While scientific collaboration is as old as science itself, it has historically been secondary to the competitive dynamics. Within the past decade, however, there has been an upsurge of multi-stakeholder initiatives promoting collaboration and more open data in science (Stakeholder Alignment Collaborative, 2018). More than sixty such collaborations have been launched in this past decade, which is a multi-fold increase relative to prior decades. Most of these initiatives have been in the biomedical sciences, as well as ecology and the geosciences, with less activity in other fields and disciplines. There are also fields and disciplines where data sharing is well established, such as high energy physics, so new multi-stakeholder arrangements are not needed. A future directions question relevant to the DoD is whether there are domains where data sharing would be mutually beneficial and where there are either barriers or enablers for multi-stakeholder collaboration.

A particular risk with cyberinfrastructure is that many key stakeholders operate independently and so there isn't a command and control structure to compel more constructive behaviors. In a 2015-16 stakeholder survey of over 1,500 geoscientists and cyberinfrastructure experts working in the geosciences, the researchers asked both about the degree to which they had organizational and institutional support for interdisciplinary scholarship, as well as whether they were actively involved in the NSF-funded "EarthCube" initiative designed to advance open sharing of data and interdisciplinary science in the geosciences. The table in Figure 3.3a presents the baseline results in a two-way grid, which reveals very high levels of support and engagement by cyber infrastructure professionals and then progressively lower levels of engagement across various geoscience fields and disciplines. This posed the risk of a classic "build it but they don't come" failure mode for the cyberinfrastructure investments.

**Looking ahead, the fields of cyberinfrastructure and data analytics in science and technology will need to pioneer ways to maintain dynamic alignment among end users and the developers of advanced tools, methods, and infrastructure.** When well-aligned, the power of digital revolutions can be accelerated; when poorly aligned, there are the risks of wasted investments, lost alternative opportunities, and increased cynicism and disengagement across communities.

Lessons from open digital platforms that propagate on a global scale, such as Wikipedia, R, Minecraft, Linux, and others, need to be better understood for the insights that they offer around architecting eco-systems (a theme in other workshop sessions), and for the DoD's own needs to develop, launch, and sustain digital platforms. For example, the founders and distributed users of the global scale platforms are well known, but less visible is what social impact that video game developer Alan Gershenfeld terms the "empowered and empowering middle"—the editors of Wikipedia, the "modders" of Minecraft, the module developers of R, and others. These are key force multipliers and their role would be a key Future Directions topic of study.

**Workshop participants observed that career advancement in the DoD comes more strongly from fighting wars than from building data and cyberinfrastructure capabilities, highlighting a disconnect between incentives and functional need.** Yet, history teaches us that organizations and institutions co-evolve with the dominant technologies. As digital technologies become ubiquitous, aspects of these technologies, such as modular assembly and disassembly (with underlying principles of error correction) will increasingly co-evolve with the way or-

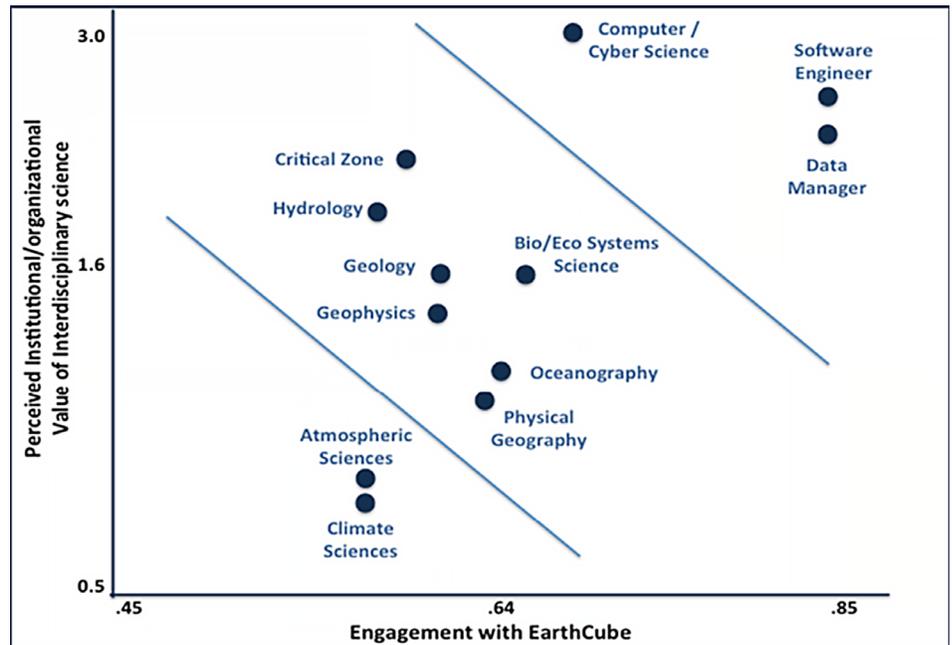


Figure 3.3a: Support for Interdisciplinary Science and Engagement with the NSF Earth-Cube Initiative  
 Source: Stakeholder Alignment Collaborative (2016) "Build It, But Will They Come? A Geoscience Cyberinfrastructure Baseline Analysis," *Data Science Journal* (15:8). DOI: <http://doi.org/10.5334/dsj-2016-008>

ganizations and institutions function. As a result, military leaders with expertise in leading digital innovation will have crucial insights and capabilities into the structure, process, and culture of the future DoD.

### 3.4 Stakeholder Alignment in Complex Systems

#### Motivating research questions:

- How can the DoD accelerate alignment with R&D stakeholders, while also pivoting from unproductive partnerships?
- How can we best visualize and apply analytics to the dynamics of alignment among diverse stakeholders in complex systems?
- What can be learned from past efforts by the DoD to foster communities of interest and multi-stakeholder consortia with various scholarly, industrial, and other groups?
- What can be learned from the experiences with launching and sustaining emerging institutional arrangements that represent new “rules of the game” for multiple stakeholders?
- How can we construct what are termed “stakeholder maps” among competitive stakeholders, where information on the relevant stakeholders is not openly shared?

The concept of alignment within organizations was advanced by Robert Kaplan and David Norton in 2006 through the use of the balanced scorecard (Kaplan and Norton, 2006). It suggested that internal alignment within a hierarchy is a dynamic process that involves simultaneous optimization along multiple dimensions, reflecting the diverse functions and priorities within any organization. Today, virtually all public and private organizations have some form of balanced scorecard as a key enabler to align multiple business units and staff departments to corporate strategy.

**A crucial future direction that is a focus of this report is the challenge of inter-organizational alignment among diverse stakeholders without a dominant authority.** A number of concepts and models from organizational theory can be applied in this setting, including the long-standing concepts of a boundary spanner and a boundary object. Boundary spanners are individuals who sit at the intersection of two different organizations, commu-

nities or cultures (Tushman, 1977). They face common dilemmas of not forgetting where they came from (such as going “native” in the new setting) while also still learning to appreciate and value what is new about the different setting to which they are bridging. At their best, they serve as translators in both directions. Boundary objects were first identified in a study of a vertebrate zoology museum fundraising campaign that served as a bridge across diverse communities who might not otherwise talk with each other (Star and Griesemer, 1989). The campaign became a focus of work practices and was imbued with meaning beyond the event itself. Now, many events, work products, and facilities act as boundary objects that help to bridge across communities. These can bridge across organizations, cultures, and communities, but they don’t fully define a new institutional or organization form or a form that is less hierarchical.

One model of change designed to bridge across stakeholders is the “collective impact” model advanced by the Stanford Social Innovation Review (2013). As the illustration of the model (Figure 3.4a) indicates, it has the advantage of providing a structure that can span multiple stakeholders. A limitation of the model, however, is that it is, in effect, creating a new virtual hierarchy with a backbone organization, a common agenda, common progress measures, and the rest.

The importance of entirely new forms of stakeholder alignment was illustrated recently in Fortune Magazine’s list of the top fifty leaders in the world for 2018. Along with the many recognizable individuals, the list included collectives and movement such as the Students, Marjory Stoneman Douglas and other schools; the #MeToo Movement; the Gymnasts and Their Allies; and the West Virginia Teachers. The list might have also included #blacklivesmatter; #bluelivesmatter; and the 350 mayors who indicated that they were still in the Paris Climate Accord a month and a half after President Trump pulled out. These are lateral connections among stakeholders, using digital media and accomplishing together what they can’t do separately. Lateral connections among stakeholders are not new, but digital media accelerate the ability to make these connections and, as a result, their impact. Sadly and importantly, terrorist organizations also operate according to these principles and achieve some of the same multiplier effects.

#### The Five Conditions of Collective Impact

<b>Common Agenda</b>	All participants have a shared vision for change including a common understanding of the problem and a joint approach to solving it through agreed upon actions.
<b>Shared Measurement</b>	Collecting data and measuring results consistently across all participants ensures efforts remain aligned and participants hold each other accountable.
<b>Mutually Reinforcing Activities</b>	Participant activities must be differentiated while still being coordinated through a mutually reinforcing plan of action.
<b>Continuous Communication</b>	Consistent and open communication is needed across the many players to build trust, assure mutual objectives, and create common motivation.
<b>Backbone Support</b>	Creating and managing collective impact requires a separate organization(s) with staff and a specific set of skills to serve as the backbone for the entire initiative and coordinate participating organizations and agencies.

Figure 3.4a: Collective Impact Model

Source: J. Kania, and M. Kramer, 2013. “Embracing Emergence: How Collective Impact Addresses Complexity,” *Stanford Social Innovation Review*, (4), 1. [https://ssir.org/articles/entry/social\\_progress\\_through\\_collective\\_impact](https://ssir.org/articles/entry/social_progress_through_collective_impact)

The term “stakeholder alignment” is relatively new (Stakeholder Alignment Collaborative, 2016) and contrasts with “stakeholder management” and “stakeholder engagement.” Stakeholder management refers to tools and methods for mitigating the risks associated with stakeholders who might interfere with or block projects or initiatives. Stakeholder

engagement generally refers to tools and methods for appreciating and including stakeholders whose inputs and support are desired for a given project or initiative. In both cases, relatively narrow, stereotypical assumptions are made about the interests of stakeholders as being either opposed or supportive. **In fact, most complex systems involve stakeholders with a mix of common and competing interests, requiring dynamic and continuing processes of alignment.** Specifically, stakeholder alignment has been defined as: “individuals and groups with common and competing interests orienting and connecting to accomplish together what they can’t accomplish separately.” It is a continual accomplishment rather than a one-time occurrence.

Research on stakeholder alignment begins with two core building blocks: (1) specification of key stakeholder categories or types and (2) identification of key interests that are “at stake.” This allows for conceptualization of any complex system as featuring a matrix with stakeholders on one side and interests on the other, as is illustrated here:

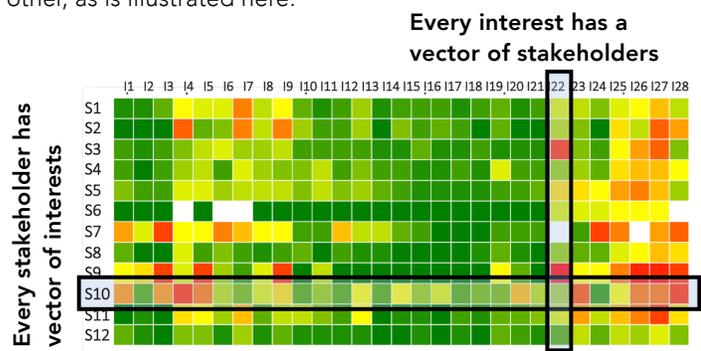


Figure 3.4b: Stakeholder and interest Matrix  
Source: WayMark Analytics

Conceptualized in this way, every stakeholder has a vector of interests around which they are more or less aligned and every interest has a vector of stakeholders with some more or less aligned on that interest. In the visualization, shades of green signal positive views, yellow neutral, and red negative.

Among efforts to document and understand stakeholder alignment in complex systems, two models are emerging which can be characterized broadly as a relatively bounded systems approach and as a relatively open systems approach. The relatively bounded systems approach is well-illustrated by Robert S. Kaplan, George Serafeim, and Eduardo Tugendhat who document new strategies for alleviating poverty through mutually beneficial restructuring of relations among rural farmers, communities, local intermediaries, NGOs and multinational corporations (Kaplan, Serafeim, Tugendhat, 2018). Similarly bounded forms of alignment can be seen in public-private partnerships in biomedicine, such as the BioMarkers Consortium (Knight, Cutcher-Gershenfeld, and Mittleman, 2015). In these and other cases, the set of relevant stakeholders is relatively well defined and the interests (what is “at stake”) is also relatively well known.

More challenging are efforts at stakeholder alignment that are not so tightly bounded, such as the efforts by many science fund-

ing agencies, science publishers, science data facilities, and professional societies to foster more open sharing of data, models, physical samples, and research software in science (The Stakeholder Collaborative, 2017). Here a new normal is sought but it is a much more dynamic and complex mix of stakeholders and interests. **The formation of new multi-stakeholder initiatives reflects gaps in the long-standing institutional arrangements and raising many questions on how these arrangements will interact with one-another and be sustained in the years to come.**

More work is needed to identify the different types of bounded and more open alignment situations, as well as the mechanisms for forming and sustaining these new organizational and institutional arrangements.

### 3.5 Social Psychology of Culture, Identity, and Conflict

#### Motivating research questions:

- What is the role of digital technologies in accelerating or moderating conflicts around identity (race, religion, gender, ethnicity, tribes, etc.)?
- In what ways can diversity contribute to innovation in R&D operations?

Culture and identity have emerged in the 21st Century as powerful forces for and against social change. Identities that were long suppressed are being given legitimacy in ways that counteracts centuries of oppression; some of the associated interests are being advanced through violence in the form of terrorism and seemingly intractable conflicts. Clearly future directions of research are needed to better understand the nexus between identity and conflict in society.

One key concept that is poorly understood is “intersectionality” (Crenshaw, 1989). People are a blend of multiple identities and there are key research questions centered on factors leading some identities to be more salient and those that drive polarization in how others’ identities are treated. Within the military, intersectional identities represent an antidote to polarizing debates on race, gender, sexual identity, and other personal characteristics. Forms of social contagion—both constructive and destructive—are of great interest in this context. Contagion builds on some identities and suppresses others. New research on social “nudges” were highlighted in the recent Nobel Prize in economics, with great implications for shifting counterproductive behaviors.

A key new frontier that connects management and information science to social psychology are expressions of culture and identity that are filtered through digital media and that take on new organizational forms. Here digital technologies and new organizational forms can serve as accelerators or amplifiers of social dynamics. In the session on stakeholder alignment (see section 3.4 above), digitally enabled lateral alignment was highlighted as an emergent change model that needs to be better understood. Here it takes on additional relevance when the alignment is based on social identity.

**Workshop participants observed that, underlying the issues of culture, identity and conflict, are deep philosophical questions around who we are and why we do what we do.** Beyond traditional positivist (explaining phenomena based on natural logic) views, there are important developments from a constructivist perspective holding that what we observe is socially constructed. This is a powerful shift in perspective since it also suggests that things need not stay the way they are—they can be reconstructed.

A broad array of social science methods are relevant in this context, including appreciative inquiry methods, network methods, deep learning with artificial intelligence around social pattern recognition, cognitive science, geospatial analysis, economic analysis, anthropological methods, and others. The issues need to be understood at the individual, small group, large group, organizational, and institutional levels of analysis.

**The dialogue on culture, identity, and conflict extended into dialogue on the social psychology of risk.** Military leaders understand that war is inherently risky, so they work hard to reduce all other risks that can be controlled. The result can be unintended consequences. For example, weaponized drones were embraced as reducing the risk to soldiers on the battlefield, but they had the unintended consequence of producing deeper levels of antagonism among civilian populations at risk of collateral damage and hardening opposition by those who viewed the technology as alien and frightening. Reducing one form of risk generates unexpected new forms of risk. Ultimately this aspect of the workshop highlights the need for new ways to think about risk, through the lenses of culture and identity.

### 3.6 The Science of Science Teams and Institutions

#### Motivating research questions:

- How can team science findings from the commercial and academic sectors be adapted for science and technology teams in the DoD?
- How can DoD codify its experience with cross-functional teams and integrated product and process teams to enable more continuous improvement across the DoD?
- In what ways can the DoD partner with the National Academies to advance the science of science institutions?
- What institutional models are best matched to managing technologies that are rapidly changing?

When that U.S. National Academies sponsored a series of workshops on the “science of science teams,” a mix of social scientists were joined together with domain scientists. Key insights from field research on workplace teams in industry directly translated into the structure and operation of research teams, including issues of team leadership, team size, team communications, team decision making, team diversity, team turnover, and other such topics (Hall, et. al., 2018). These connections are directly relevant to the use of teams in the DoD’s science and technology operations, as is indicated by these research questions posed by the National Academies in launching the initiative:<sup>7</sup>

- How do individual factors (e.g., openness to divergent ideas), influence team dynamics (e.g., cohesion), and how, in turn, do both individual factors and team dynamics influence the effectiveness and productivity of science teams?
- What factors at the team, center, or institute level (e.g., team size, team membership, geographic dispersion) influence the effectiveness of science teams?
- How do different management approaches and leadership styles influence the effectiveness of science teams? For example, different approaches to establishing work roles and routines and to the division of labor may influence team effectiveness.
- How do current tenure and promotion policies acknowledge and provide incentives to academic researchers who engage in team science?
- What factors influence the productivity and effectiveness of research organizations that conduct and support team and collaborative science, such as research centers and institutes? How do such organizational factors as human resource policies and practices and cyberinfrastructure affect team and collaborative science?
- What types of organizational structures, policies, practices and resources are needed to promote effective team science, in academic institutions, research centers, industry, and other settings?

Additional areas of research are also relevant in this context. For example, we know from early research on virtual teams that they need to be together on a face-to-face basis at least every six months or social relations begin to fray. New research questions arise when virtual teams have available to them immersive technologies, such as VR (Gilson, et. al., 2015). Similarly, research on relational coordination has consistently demonstrated that improved organizational outcomes are achieved when organizational functions communicate, share information, engage in problem-solving, share goals, have mutual respect, and are otherwise taking into account each other’s work (Gittell, 2016). This relational coordination approach works at the team level and at higher levels in organizations. **A key future directions challenge centers on how relational coordination can still function in settings where communications and coordination is highly fragmented, such as happens during the fog of war.**

One theme surfaced by the workshop discussions that has not been fully explored by the science of science teams initiative are macro issues around the context in which teams function. This is a key future direction for research on the science of science teams. **Indeed, a parallel body of research is possible around what can be termed the science of science institutions.** As states reduce their support for higher education and U.S. K-12 educational achievement continues to lag especially in STEM areas, the academic R&D infrastructure that the DoD relies on is rapidly changing. What is not clear is what organizational structures, policies, practices and resources are needed to maintain the nation’s basic and applied research capabilities. This has broad implications for DoD’s R&D management, as well as enabling transformational advances in the civilian science enterprise.

7. Retrieved from [http://sites.nationalacademies.org/dbasse/bbcss/currentprojects/dbasse\\_080231](http://sites.nationalacademies.org/dbasse/bbcss/currentprojects/dbasse_080231)

### 3.7 Supply Chain Resilience

#### Motivating research questions:

- How can we build supply chain resilience to handle low frequency, high consequence disruptions?
- How can supply chain resilience models take into account the demands of acquisition complexity and national security?
- In what ways can lessons from resilient supply chains inform other needed increases in organizational and institutional resilience?

Disruption and complications in supply chains are a central concern for all enterprises, posing particularly consequential risks for the DoD. Supply chain challenges were highlighted in section 2.4 of this Future Directions report. Additional inputs on supply chain resilience are provided here, considering the many ways in which supply chains can be disrupted or complicated, including “bullwhip” effects associated with responses to variation (or perceived variation) in demand, shorter product life cycles, increasing product variety, supply variability, capacity constraints, component quality variability, spatial dimensions of mutually dependent supply chain decisions, and disruptive events that are natural and human-caused. This goes beyond the workshop discussions and presents increasing attention that is given to reducing the likelihood of disruptions and increasing the capacity to bounce back from disruption (Sheffi, 2015).

Resilience strategies include advanced inventory management systems, increased knowledge backup capabilities, increased shipment visibility, improved collaboration with suppliers, risk pooling among suppliers and OEMs, public-private partnerships, clarified security roles and responsibilities, and direct emergency assistance. These strategies are relevant at different stages of a disruptive event. Figure 3.7.1.a illustrates how performance impacts lag disruptive events and, by the time the full effects are felt, mitigation options are more limited.

What happens to supply chain performance during an unforeseen event?

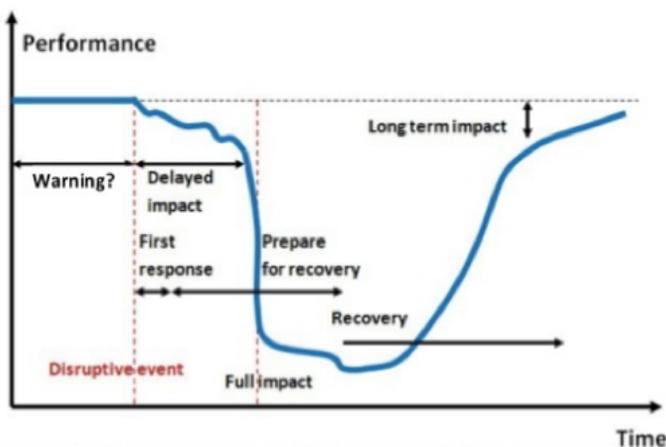


Figure 3.7.1a: Performance Impacts Over Time Following Disruptive Events in Supply Chains  
Source: Sheffi, Y., & Rice Jr, J. B. (2005). A supply chain view of the resilient enterprise. MIT Sloan Management Review, 47(1), 41.

When anticipating possible disruptions in supply chains, most of the focus is on either low frequency, low consequence events or high frequency, high consequence events. Each of these two combinations has its associated policies, practices, and metrics. As Figure 3.7.1b indicates, there are also low frequency, high consequence events that are possible and these are often not well addressed in supply chains. In discussing this aspect of supply chain risk mitigation, a workshop participant observed that a “Chief Worry Officer” might be worth considering for low-likelihood, high consequence events. As was suggested, “only the paranoid survive” and **the challenge**

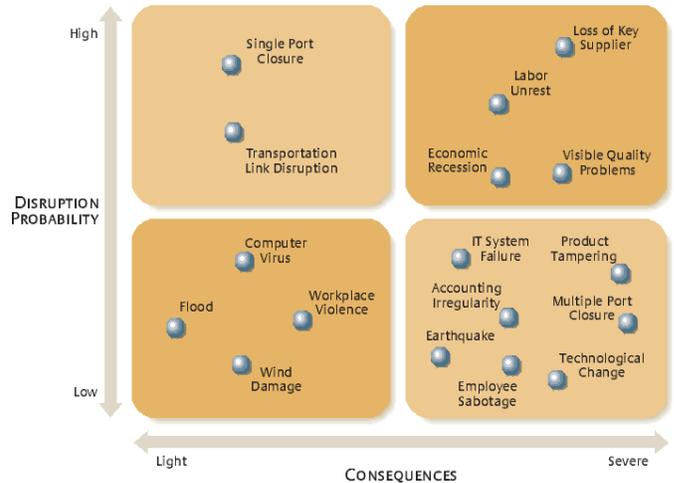


Figure 3.7.1b: Disruption Probability and Consequences in Supply Chains  
Source: Sheffi, Y., & Rice Jr, J. B. (2005). A supply chain view of the resilient enterprise. MIT Sloan Management Review, 47(1), 41.

for the DoD is to bring this thinking about low frequency, high consequence events to the management of supply chains. Further research by Yossi Sheffi adds a third dimension to the analysis, which is the detection lead time, as illustrated in Figure 3.7.1c.

The research on resilience has implications that go beyond supply chain management. It calls for new organizational capabilities, metrics, and practices. Further, there are institutional implications for what information is shared across multiple supply chains and other enabling infrastructure. Detection lead time is best managed through multi-stakeholder arrangements and new forms of ecosystem management.

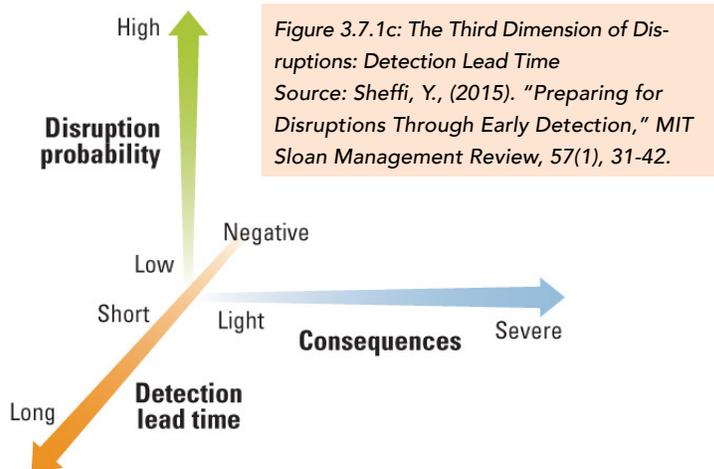


Figure 3.7.1c: The Third Dimension of Disruptions: Detection Lead Time  
Source: Sheffi, Y., (2015). “Preparing for Disruptions Through Early Detection,” MIT Sloan Management Review, 57(1), 31-42.

## 4.0 Towards an Effective Military-Academic Knowledge Ecosystem

Imagine a world where advances in management and information science enable military organizations and institutions to anticipate and address conflict through a combination of deterrence and micro-interventions that prevent escalation and reinforce constructive social systems. Conflict is inevitable and often an expression of legitimate competing interests. Too often, however, conflict is managed in ways that exacerbate the tensions and destabilize needed elements of society.

Advances in management and information science have largely been focused on commercial aims, with some additional focus on the public and non-profit sectors. Minimal focus has centered on the challenges associated with military missions that grapple with some of the most intractable conflicts on the planet. **This Future Directions report points to worthy challenges for management and information sciences in the military sector, with needed changes in the culture and operations of both the social sciences and the military sector to achieve the full potential for a constructive knowledge ecosystem.** Thus, the ecosystem encompasses: DoD (services, labs, and other elements); Congress; universities; commercial organizations (as contractors, R&D leaders, and exemplars of organizational innovation); allies (which may feature alternative organizational and institutional models); distributed communities of practice; and others.

In contrast with military investments in the physical sciences, investments in the social sciences raise moral and ethical issues that are compelling at the outset. In fact, these moral and ethical issues should also be raised throughout the development processes in the case of the physical sciences, which is one of many important research questions for the management and information sciences. So an important challenge for the management and information sciences is to attend to moral and ethical issues associated when working with the military establishment.

### 4.1 Elements of New Management and Information Sciences for DoD R&D Management

Elements of a constructive knowledge ecosystem connecting the military establishment with the management and information sciences would include the following:

**Ecosystem science.** The development of a new domain that might be termed ecosystem science would build on foundational theories rooted in hierarchies and networks, while also taking into account the unique features and properties of ecosystems, including complexity, emergence, interdependence, and fragility.

**Alignment across stakeholders.** Advances in understanding and enabling alignment across stakeholders builds on foundational knowledge on alignment within organizations while also taking into account complex and dynamic arrays of stakeholders and interests.

**Ecosystem architects.** The launch of countless popular ecosystems such as Wikipedia, Linux, Minecraft, and others involves a role for founding architects that builds on a foundational literature on entrepreneurs and intrapreneurs. Importantly, these architectures have properties that engage people on a vast scale in ways that incorporate markets that also are empowering in ways that markets are not.

**Multilayered interactions.** Beyond foundational research on bilateral and multilateral interactions, there is a need to advance theory and methods around the study of multilayered interactions in complex systems. Think of 3D, multi-party chess as a metaphor.

**Ecosystem metrics.** Building on a foundation of traditional cost control methods, advanced in the form of the balanced scorecard, there is a need for metrics and feedback systems at the level of ecosystems that take into account temporal issues.

**Adaptive response capability.** Foundational research on risk management, risk allocation, and risk mitigation is necessary, but not sufficient. Advances are also needed around adaptive response capabilities, building on lessons from leading supply chain research and some military models such as how Marine units prepare for leadership transitions in battle.

**Middle-out change.** Building on top-down and bottom-up change models, there is a need for new models and methods for enabling lateral change—connecting top-down and bottom-up actors, resources, and processes, as well as for achieving lateral alignment.

**Agile institutions.** Research on agile teams and agile organizations needs to be extended to understand and enable agile institutions in society. At a time when technology is changing exponentially, incremental linear rates of change in institutions is not sufficient. Stability is still needed, posing deep challenges to combine stability with agility.

### 4.2 Needed Cultural Changes

Within the military establishment there is deep discomfort with the work of social engineering and, in many ways, such work is beyond scope for the military. Within the management and information sciences there is deep discomfort with the destructive and collateral impacts of war. **Deeply embedded operating assumptions in each of these contexts reinforce the deep discomforts, resulting in cultural barriers to communication, shared learning, and collaboration.**

Among the deeply embedded assumptions in the military culture that are relevant to the Future Directions identified in this report are the following, along with additional related assumptions:

- The assumption that the United States can prevail in any conflict through a combination of greater resources and technological superiority.
  - » The related assumption that the United States will always have scientific and technological superiority.
- The assumption that leaders are defined by the new initiatives and programs that they introduce.
  - » The related assumption that career advancement is not achieved by sustaining programs launched by your predecessors.
- The assumption that private-sector management models, IT tools, and related methods can be applied “off the shelf” in the military.
  - » The related assumption that there is not the internal capacity in the military to pioneer innovative new management and administrative models, tools, and methods.
- The assumption that the structure and operation of the Department of Defense should be oriented around sustaining the capacity of large, prime contractors.
  - » The related assumption that the Department of Defense doesn’t need to have mastery of how to architect and sustain productive ecosystems.
- The assumption that each service has unique cultures and administrative challenges when it comes to science and technology.
  - » The related assumption that science and technology investments can’t be co-managed across services and functions.
- The assumption that military is the most important customer to the private sector for technology investments and acquisition decisions.
  - » The related assumption that the military technology investments and supply chain can be shaped by political priorities without any implications for capability and readiness.
  - » All of these embedded assumptions were once functional, but are now in various ways, problematic.

At the core of this Future Directions report is a view that new learning about ecosystems and complex arrays of stakeholders can and should be applied to the very parties advancing knowledge on these matters. Whether the full potential from such collaboration can be achieved is an open question. Workshop participants observed that 95% of the joint force that will be present in 2030 has already been bought or programmed. Similarly, the vast majority of the future leaders in 2030 are already in the force now. So the challenges created by change begin with creative adaptation of the vast aspects of both the social and technical capabilities that are already in the system. Further, it is certain that there will be unintended consequences—positive and problematic—from such efforts. **The best hope for progress comes if all communities adapt to the digital age by recognizing the future directions needed for operating at the intersection of management science and information science—in order to be consistent with its principles, one of which is to learn actively in the process.**

### 4.3 Action Implications

The military needs ways to understand and meet new, forward-facing challenges in a changing world. The intersection of management sciences and information sciences holds great promise in helping to meet these challenges. Ultimately, it will be a massive undertaking, requiring changes in strategy, structure, process, and culture across the R&D enterprise in the DoD. What is listed here are illustrative action implications, with many more next steps possible.

There is substantial archival data within the DoD that would support future directions research on each of the five “demand-pull” domains highlighted in section 2.0 of this report. Here are a few examples of relevant research questions that are drawn from the beginning of each of the 2.0 sub-sections:

- **Budget/Programming Challenges**
  - » How can budgeting and financial management policies be tailored to match the speed needed to counter emerging threats and utilize new technological opportunities?
  - » How useful is the current distinction between basic and applied research? What types of research innovations are best suited for combining basic and applied approaches in an integrated, iterative development process?
  - » What policies and practices can be developed that maximize the DoD’s flexibility in funding, while preserving openness and transparency to Congress and the public?
  - » Would allowing “mini skunkworks” enable adaptive responses to emerging threats?
  - » What models of financing and budgeting would optimize efforts to maintain world class researcher infrastructure within the DoD labs and test ranges?
  - » How should DoD analyze its overall Science and Technology budget across the Services and agencies to ensure an optimal portfolio, balanced between disciplines and risk levels?
- **Joint Integration Challenges**
  - » How can the DoD maintain the current structure and process needed for addressing current operational challenges, while concurrently experimenting with developing alternative structures and processes needed for emerging operational challenges?
  - » How can the DoD pursue research on innovations that do not fit into existing concepts of war and that represent alternative (and possibly superior) ways of fighting – e.g. disruptive innovations.
  - » What data are needed to actively manage the joint R&D portfolio? How can this information be collected in a continuous and non-burdensome way?
  - » How can the DoD utilize emerging “middle-across” approaches to R&D operations in order to bridge across central, top-down coordination and emergent, bottom-up innovation in the services and facilities?

- **Research and Development Acquisition Challenges**

- » What approaches can enable the DoD to identify fair pricing in acquisition circumstances where there is only one prime contractor and only one customer? What are the best models to establish a fair price in the absence of a true market?
- » How can we more effectively conduct multivariate optimization during requirements generation, particularly around effectively assessing the marginal costs of incremental changes in requirements that involve new doctrines, processes and technologies?
- » What are the range of possible applications of “real options” methods to R&D acquisition?
- » What are the most streamlined ways of measuring the technical feasibility and providing accurate cost estimates for proposed requirements?
- » How can the life cycle costs of systems be accurately forecast? What can be learned from historical cases?
- » What methods can be used to determine the IP rights the DoD should be purchasing from contractors?
- » How can the DoD optimize its ability to negotiate with vendors?
- » How can the DoD improve its ability to reengineer its business processes in order to make more effective use of commercial enterprise software systems?
- » How can the DoD anonymize data, create synthetic data sets, and create trusted data sharing partnerships so that it can experiment with and model alternative policies or business practices?
- » How can the DoD model the impacts of changing acquisition regulations, practices, and policies?
- » How does the DoD now balance security and academic openness in university research and how should it?
- » How should the DoD handle foreign nationals working on research programs, balancing security and innovation?
- » How can the DoD experiment with strict peer review, collaborative agreements, and portfolio approaches in order to best be aligned mission needs?

- **Supply Chain Risk Mitigation Challenges**

- » How can we anticipate and address the erosion or complete collapse of sub-tier capability in the supply chain?
- » In what ways can distributed digital fabrication and automation capabilities reduce reliance on complex supply chains and increase local adaptive capabilities?
- » What safety and security arrangements are needed in ecosystems where there are distributed fabrication capabilities?

- **Research and Development Leadership Challenges**

- » How can we better prepare the DoD workforce for new technology and rapid changes in operations?
- » How can DoD leaders foster partnerships with social scientists that result in robust communities of practice that are identifying and advancing research questions relevant to DoD operations?
- » Are there new ways to think about the process of awarding security clearances that are more streamlined, while still ensuring security?

- » What are the best ways to promote flow of personnel between the academic, industry, and government sectors – balancing ethics, limitations on compensation and traditional reluctance of organizations to give up their best people?
- » How can we eliminate or mitigate the organizational and institutional barriers to DOD achieving a clean audit as quickly as possible?
- » How can reporting to Congress be made more efficient and streamlined, while still provide the desired information?

Additionally, each of the “research-push” domains in section 3.0 has pressing research questions that are relevant to the above questions, including the following which are drawn from the beginnings of each of the 3.0 sub-sections:

- **Large-Scale Systems Change Management**

- » How can we best mitigate risk aversion in complex, bureaucratic organizations such as the DoD?
- » What change models take into account a larger context, including accelerating technological change, complex combinations of stakeholders, and no overarching authority?
- » What is the relevant mix of “middle-across” change models that can be added to top-down and bottom-up change models?
- » In addition to the well-developed role of a change agent, how can we build skills and recognition for two emerging roles – that of a sustaining agent and an ecosystem architect?
- » How do you effectively scale well-intentioned policies and practices over an enterprise the size and complexity of the DOD?

- **R&D/Innovation Management**

- » How can the DoD establish optimal public-private partnerships to improve DoD research lab effectiveness?
- » What are the relevant options for governance structures in DoD research labs?
- » How have linear R&D cultures and processes shifted to rapid prototyping/fail-fast approaches? What additional approaches are relevant?
- » How can the DoD lower organizational and institutional barriers to rapid prototyping/fail-fast approaches?
- » What are relevant options for the DoD to best make use of foreign national talent?
- » How can the DoD best expose and exploit the IP in its research labs for commercialization or use in military systems?

- **Cyberinfrastructure and Data Analytics Management**

- » If the logic of digital science involves modular elements that can be assembled and disassembled (with error correction), what organizational and institutional arrangements might best co-evolve with these technologies?
- » How can the DoD make data and data sources available (through contracts, enclaves, competitions, or other means) in order to advance the frontiers of data science,

while also generating new insights from the data?

- » What are mechanisms to build legitimacy, trust and input into black-box algorithmic models?
- » How can we measure the technological maturity of software that is in continuous agile development and production – in order to optimize use of the software and meet DoD oversight requirements?

- **Stakeholder Alignment in Complex Systems**

- » How can the DoD accelerate alignment with R&D stakeholders, while also pivoting from unproductive partnerships?
- » How can we best visualize and apply analytics to the dynamics of alignment among diverse stakeholders in complex systems?
- » What can be learned from past efforts by the DoD to foster communities of interest and multi-stakeholder consortia with various scholarly, industrial, and other groups?
- » What can be learned from the experiences with launching and sustaining emerging institutional arrangements that represent new “rules of the game” for multiple stakeholders?
- » How can we construct what are termed “stakeholder maps” among competitive stakeholders, where information on the relevant stakeholders is not openly shared?

- **Social Psychology of Culture, Identity, and Conflict**

- » What is the role of digital technologies in accelerating or moderating conflicts around identity (race, religion, gender, ethnicity, tribes, etc.)?
- » In what ways can diversity contribute to innovation in R&D operations?

- **The Science of Science Teams and Institutions**

- » How can team science findings from the commercial and academic sectors be adapted for science and technology teams in the DoD?
- » How can DoD codify its experience with cross-functional teams and integrated product and process teams to enable more continuous improvement across the DoD?
- » In what ways can the DoD partner with the National Academies to advance the science of science institutions?
- » What institutional models are best matched to managing technologies that are rapidly changing?

- **Supply Chain Resilience**

- » How can we build supply chain resilience to handle low frequency, high consequence disruptions?
- » How can supply chain resilience models take into account the demands of acquisition complexity and national security?
- » In what ways can lessons from resilient supply chains inform other needed increases in organizational and institutional resilience?

Normally, a set of university-based research centers would be appropriate to advance the above research questions. In this case, **a collaborative network for management and information science, consistent with the recommendations in this report, can be advanced, linking experts in management and information**

**schools, as well as military colleges, research labs, and industry.** This would support both the needed theory development and action partnerships, such as the above example. This virtual organization could house leadership academies as described in 2.5.5. The focus would not be just basic management and information science in isolated centers, but a shared learning ecosystem in which movement from underlying principles to practical applications and back to underlying principles is a continuously developing process capability.

Additionally, **DoD should consider developing an enduring, internal management and information science research entity that would identify emerging research needs (“demand pull”), invite external researchers to pursue work in those areas, organize research teams, and facilitate access to data pertinent to research questions, while maintaining appropriate data protections.** While DoD has well-developed organizations, systems, processes for collaborating with civilian researchers in pursuing sensitive research in the physical and life sciences, it has no equivalent or appropriate system for doing so in areas such as organizational behavior, social psychology, and other areas relevant to the questions examined in this report. Obtaining access to undertake management research in DoD currently depends on the persistence of individual researchers and their ability to create trust with local unit leaders. This is no way to manage a more comprehensive, department-wide research program.

In building out the supporting community of researchers to pursue the above questions, increased situational awareness is needed regarding R&D ecosystems and other relevant parts of the DoD. This involves first identifying the ecosystems and assessing the current points of stakeholder alignment and misalignment (specifying who the stakeholders are, knowing what interests are “at stake,” and mapping the landscape). Then, it is likely that key underlying operating assumptions—the rules of the game—such as those identified in this Future Directions report will need various forms of what is termed “assumptions wrangling” and change management initiatives to simultaneously deliver on current priorities and anticipate future challenges. **The overarching aim is to foster a culture of innovation around organizational and institutional arrangements that co-evolve with today’s substantive R&D innovation.**

An example of an applied experiment would be **restructuring an ecosystem to ensure co-evolution of capabilities by creating program teams that are comprised of professionals from the science, technology, acquisition, contracting, finance, legal, and social science domains.** Such a program team could stay with the program from “cradle to grave”—from technology development through delivery to the warfighter. There could be co-PMs wherein the primary responsibility transfers from the R&D professional to the acquisition professional as the capability matures. Career paths are typically defined by multiple moves across programs or initiatives rather than by this type of long-term engagement. This kind of long-term responsibility could be enhanced with additional cross-program advisors or other targeted roles to foster breadth, as well as depth for the programs and the people involved.

Following crisis events associated with DoD acquisition and other program areas, new checks are typically placed in the system to prevent recurrence. The result is a cumbersome set of hurdles and gateways that stifle innovation. An alternative would be to **allow program managers and other relevant leaders an increased ability to fund pilot demonstration programs or projects—mini-skunkworks—with guiding principles and reduced amounts of oversight.** This would involve accepting some increased risk of early failures in exchange for valuable lessons learned from both successful and failed projects and a broader array of innovations.

**A DoD champion or office could be responsible for executing the action implications of this report, developing an integrated roadmap for research in management and information sciences, and tracking progress in addressing the deeply embedded “From → To” assumptions that limit innovation and capability.** This would not only involve reporting back to Congress, but also interacting with Congress around its roles in enabling needed culture change.

Throughout human history, innovations in organizations and institutions have lagged advances in science and technology—with enormous costs to society. Given the ways that digital technologies are contributing to accelerating advances, the risks of lags in social systems are ever more consequential. Although there are few historical precedents, it is possible and essential that we pioneer new ways for organizations and institutions to co-evolve with advances in science and technology.

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# Appendix I - Workshop Agenda

DAY 1—TUESDAY, OCTOBER 23, 2018

Time	Title
8:00—8:30	Check-in and Continental Breakfast
8:30—9:00	<b>Welcome, Overview, Introductions and Expectations</b> Dr. Joel Cutcher-Gershenfeld, Brandeis University
9:00—10:15	DoD Panel: Demand-Pull for DoD Management, Information, and Operations Challenges in 2025-2035
9:30—9:45	Keynote Address—Ms. Lisa W. Hershman, Deputy Chief Management Officer, Department of Defense
10:15—10:30	<b>BREAK</b> (move to breakout rooms)
10:30—11:30	<b>Working Groups I: Demand-Pull for DoD Management, Information, and Operations Challenges in 2025-2035</b> <i>Small group discussion to identify a) DoD challenges, b) approaches currently used to address, c) theory frameworks and management methods will likely be relevant, and d) roadblocks to implementation</i> Group A: Budget / Programming Group B: Joint Integration Group C: Science and Technology Acquisition Group D: Supply Chain Risk Mitigation Group E: Research and Development Leadership
11:30—12:00	Working Group I Outbriefing
12:00—1:00	<b>LUNCH</b>
1:00—2:30	<b>Working Group II: Management Science and Information Sciences Research Opportunities in 2025-2035 (Round 1)</b> <i>Small group discussions to identify a) promising trajectories, b) worrisome trajectories; c) elements of a success vision</i> Group A: Large-scale Systems Change Management & Stakeholder Alignment in Complex Systems Group B: R&D / Innovation Management & the Science of Science Teams Group C: Cyberinfrastructure and Data Analytics Management Group D: Social Psychology of Culture, Identity, and Conflict
2:30—2:45	<b>BREAK</b>

DAY 1—TUESDAY, OCTOBER 23, 2018

Time	Title
2:45—4:00	<p><b>Working Group II: Management Science and Information Sciences Research Opportunities in 2025-2035 (Round 2)</b></p> <p><i>Small group discussions to identify a) promising trajectories, b) worrisome trajectories; c) elements of a success vision</i></p> <p><i>Group A: Large-scale Systems Change Management &amp; Stakeholder Alignment in Complex Systems</i></p> <p><i>Group B: R&amp;D / Innovation Management &amp; the Science of Science Teams</i></p> <p><i>Group C: Cyberinfrastructure and Data Analytics Management</i></p> <p><i>Group D: Social Psychology of Culture, Identity, and Conflict</i></p>
4:00—4:15	<b>BREAK</b> (move to main room)
4:15—5:00	Working Group II Outbriefing
5:00—5:15	<p><b>Session Observations</b></p> <p>Dr. Arun Seraphin, US Senate Armed Services Committee</p> <p>Ms. Gwyneth Woolwine, US Senate Armed Services Committee</p>
5:15—5:30	Summary of the Day
5:30	<b>MEETING ADJOURNED FOR THE DAY</b>

DAY 2—WEDNESDAY, OCTOBER 24, 2018

Time	Title
8:00—8:30	Check-in and Continental Breakfast
8:30—9:30	<b>Welcome and Day 1 Recap</b> Dr. Joel Cutcher-Gershenfeld, Brandeis University
9:30—9:40	<b>BREAK</b> (move to breakout rooms)
9:40—10:30	<b>Working Group IV: Integrated Roadmaps Gap Analysis</b> <i>Small group discussion to identify a) desirable milestones/ needed advances; b) indicators/measures of success; c) illustrative capability investments; d) relevant underlying assumptions</i> Group A: 2020-2025 Group B: 2025-2035 Group C: 2035 and beyond
10:30—10:45	<b>BREAK</b> (move to main room)
10:45—11:15	Working Group IV Outbriefing
11:15—12:00	Discussion and Implications
12:00—12:30	Concluding Remarks
12:30	<b>MEETING ADJOURNED FOR THE DAY</b>

## Appendix II - Concluding Words by Participants

All participants were asked to use 1-3 words as a concluding signal on their thoughts regarding the Future Directions workshop—a taking of the pulse on people’s affective feelings and observations. Here are the comments:

### Concluding Comments from Participants (1-3 words)

- Intrigued
- Conflict and consensus
- New age
- Feel better informed
- Doubtful
- Skeptical
- Would like a map
- Encouraged
- Puzzled and curious
- Informed
- Complex
- To be continued
- DoD works by direction
- Culture consumes strategy
- Chaos management
- Inspired
- Curious
- Optimistic
- It’ll be alright
- Follow-up important
- Collaboration
- Frustrating, just starting
- Deep dive required
- Hungry (not lunch)
- Useful data
- Too many questions
- Right mission
- Follow up required
- Impending Congressional mandate

## Appendix III - Workshop Attendees

### Workshop Co-chairs

Joel Cutcher-Gershenfeld	Brandeis University
Andrew Hill	Army War College

### Workshop Participants

Michelle Atchison	University of Texas System
Nick Berente	University of Notre Dame
Sheri Briggs	US Army AL&T
Jean-Luc	AFOSR
Pat Canavan	Motorola (retired)
Jason (JP) Clark	US Army War College
Dan Druckman	George Mason University
Terence Emmert	US Department of Navy, OCMO
Colonel Michelle Ewy	USAF S&T (Mil Asst to USAF Chief Scientist)
Maryann Feldman	University of North Carolina
Mary Harper	US Army Research Laboratory
Robert Kaplan	Harvard Business School
John Leslie King	University of Michigan
Christine Kirkpatrick	San Diego Supercomputer Center, UC San Diego
Jytte Klausen	Brandeis University
Chris Lawson	Aerospace Corporation
Chris Lenhardt	University of North Carolina at Chapel Hill
Peter Levin	Intel
Spencer Lewis	Draper Labs
Kalle Lyytinen	Case Western Reserve University
Barbara Mittleman	NIH (retired) / MedStar Health
Jennifer Morgan	US Air Force Research Laboratory
Namchul Shin	Pace University
Michael Stewart	US Navy, OCMO Business Reform
Susan Winter	University of Maryland
Louis Yuengert	Army War College (Army G8)

### Workshop Observers

Joan Cleveland	Office of Naval Research
Jody Cox	ODASD (Logistics)
Jason Day	DOD/Basic Research Office
Charles Day	Charles F. Day & Associates
Scott Hawkins	ODASD (Logistics)
Col Brent Hyden	US Air Force, DoD Reform
Chris Marchefsky	Office of Naval Research
Caitlyn Mebrutre	DOD/Basic Research Office
Bindu Nair	OUSD(R&E)
Melissa Naroski Merker	DoD, Senior Program Analyst
Vanessa Pena	IDA/STPI
Matthew Poe	Office of Naval Research
Joye Purser	DoD Cost Assessment and Program Evaluation (CAPE, formerly OMB)
Arun Seraphin	Armed Services Committee
Gwyneth Woolwine	U.S. Senate Committee on Armed Services

### Workshop Report Commentators

Sallie Keller	Virginia Polytechnic Institute and State University
Kathy Harger	STAM21
Allison Lazarus	Belfer Center for Science and International Affairs, Harvard University

### Workshop Rapporteurs

Lindsay Anderson	Virginia Tech Applied Research Corporation
Karen Baker	University of Illinois
Mike Haberman	University of Illinois
Charlie McElroy	California Institute of Technology
Lynne Ostrer	Virginia Tech Applied Research Corporation

### Workshop Organizers

Kate Klemic	Virginia Tech Applied Research Corporation
Nick Kosmidis	Booz Allen
Esha Mathew	OUSD(R&E)
Bob Ramsey	OUSD(A&S)