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Lessons from Modular Design, Occupational Surprise, and Commercial Research and Development Processes

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Preface

We performed this research for the Advanced Systems and Technologies (AS&T) Directorate at the National Reconnaissance Office (NRO). Today, the NRO faces an operational environment that is faster paced, more uncertain, and filled with more variables than it was even ten years ago. One of the biggest challenges now facing the Intelligence Community (IC) is that it must confront unknown threats that continue to emerge from unexpected directions.

To address these challenges, the NRO asked RAND to research ways that AS&T and the NRO could be become more responsive toward an ever-changing environment. To do this, RAND researched three different topics, each designed to address a different component within the NRO: the hardware, the people, and the organization's processes. For the hardware, we researched the benefits of modularity and developed a list of factors to help determine whether the NRO's space hardware was a good candidate for a modular architecture. For the people, we looked at how other occupations respond to unexpected events (i.e., surprise), with the goal of identifying a set of practices that could be employed by people who work in uncertain environments. To do this, we spoke with ambassadors, chief executive officers, military personnel, and health care professionals, and we report on some common methods and techniques that they use to prepare for and respond to surprise. Finally, we took a preliminary look at the organizational methods used inside other established organizations and made some observations about the motives behind their innovative processes.

The findings from this research will therefore be useful for NRO strategists as they make plans to shape their future hardware architectures, workforce, and organizational structures. The research on modularity and surprise has broader applications beyond the NRO and the IC and will therefore be useful for individuals working on hardware development and within uncertain environments, respectively.

This research was conducted within the Intelligence Policy Center of the RAND National Security Research Division (NSRD). NSRD conducts research and analysis on defense and national security topics for the U.S. and allied defense, foreign policy, homeland security, and intelligence communities and foundations and other nongovernmental organizations that support defense and national security analysis.

For more information on the Intelligence Policy Center, see http://www.rand.org/nsrd/ndri/centers/intel.html or contact the director (contact information is provided on the web page).

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Summary

The U.S. Intelligence Community (IC) is now facing a larger number of unknown threats than at any other time in its history. During the Cold War, the IC faced one primary, well-identified threat, along with a few second-order concerns. Today, the biggest surprises facing the IC are likely to come from places of which the community may not even be aware.

To help address these challenges, the Advanced Systems and Technology (AS&T) Directorate at the National Reconnaissance Office (NRO) asked RAND to perform research to help it develop strategic plans that will yield insights on becoming more flexible and adaptable. We settled on three research questions, specifically designed to target three different aspects of the NRO enterprise:

- How can the NRO build more-flexible hardware?
- How can NRO personnel become better prepared to deal with uncertainty?
- How can the NRO's organizational structures be used to promote innovation and creative thought?

How Can the NRO Build More-Flexible Hardware?

To investigate this question, we first hypothesized that there are two ways to build more-flexible hardware: (1) by building in excess capability and (2) by using a modular architecture. Excess capability gives operators the freedom to develop new tactics, techniques, and procedures as needs change. However, it can be challenging to convince decisionmakers to support excess capability when budgets and resources are becoming increasingly constrained. Therefore, for this project, we investigated the suitability of implementing a modular architecture for the NRO's space systems.

Modularity Provides Flexibility, But at a Cost

Modularity is the engineering equivalent of a financial option: Like a financial option, modularity permits a product designer to invoke some flexibility in the future in exchange for a cost premium that is paid up front. For space systems, this premium is

paid in the form of additional systems engineering that is needed to plan and design a set of standardized interfaces. These interfaces must be designed in their final form at the onset of the project so that the modules are ready for future use, providing the potential for added flexibility and responsiveness.

However, modular systems do not provide all this flexibility for free. Typically, a modular system will not perform each function as well as the equivalent individual (singular) systems. For example, a Swiss Army knife allows the user to carry a number of tools around in one small package. However, this flexibility comes at a price: The tools in the Swiss Army knife will never perform as well as a dedicated knife, corkscrew, or pair of scissors.

Different Classes of Systems Provide Different Levels of Functionality and Benefit

We researched several examples of modular systems and found that different classes of systems provide different levels of functionality and benefits. For example, dry-cell AA batteries and carpet are designed to be readily scaled based on user needs, but the primary functions of each never change. In contrast, an electronics breadboard with resistors, capacitors, and transistors offers nearly infinite functional possibilities to the user.

However, we observed that, while modular systems that offer changes in function are certainly more flexible, they also place greater responsibility on the user. For example, in order to use a breadboard kit to build an electronic device, the user needs a high degree of knowledge and experience. This is an important factor that designers should weigh when considering a modular architecture: The use of more-flexible systems often requires more-knowledgeable users.

NRO Space Systems Do Not Appear to Be Strong Candidates for Modularization

Our findings suggest that some systems might be better suited for modularity than others. To apply this knowledge about modular systems to the NRO, we developed a list of factors to help system designers determine if a system is a good candidate for modularity.

When we applied our factors to the NRO's space-based collection systems, we reached an inconclusive result: While some factors seem to encourage modularization, others seem to discourage it or are neutral. On one hand, the NRO faces uncertain future user needs, along with a customer base that desires a highly flexible product. Both of these factors encourage a modular architecture. On the other hand, the NRO relies on cutting-edge, state-of-the-art technologies in its systems, and these technologies do not lend themselves well to modularity. This is because rapid changes in technology can quickly outgrow the static interfaces in a modular architecture, rendering the entire system useless.

The NRO Needs to Be Able to Quantify the Value of Its Intelligence-Gathering Systems

So what can be done to move forward and make progress toward a more satisfying solution? What is really needed to provide a satisfying answer is a mathematical relationship that relates desired flexibility with the likelihood of investment gain or loss. To gain some perspective, we looked at how this calculation is done in another industry: parking garage design. The parking garage designer can easily quantify the balance between flexibility and investment risk. Revenue (in dollars) is a measure of value, and an interest rate is used to determine the change in value over time.

However, there is an important difference between commercial systems and the NRO's intelligence systems: It is very difficult to evaluate the *value* of intelligence systems and how that value *changes over time*. This observation leads to a key conclusion: It is not possible to find the optimum "knee in the curve" for implementing modularity if one is not able to assess the value of the intelligence resulting from the subject system.

How Can NRO Personnel Become Better Prepared to Deal with Uncertainty?

To investigate our second question, we started by thinking about other professionals who are regularly surrounded by uncertainty: stock traders; U.S. Navy Sea, Air, Land (SEAL) teams; and emergency room (ER) doctors. Practitioners of all three occupations must be comfortable dealing with surprise, and this idea yielded the two research questions that we sought to address in this work:

- Can people become more adept at planning for an uncertain future by studying surprise?
- Are there lessons for the IC in how different professionals respond to surprise?

To research this topic, we designed a framework to classify different professions based on the following two factors: (1) how quickly they typically have to respond to surprise and (2) the complexity of their work environment. We then conducted discussions with several professionals across a variety of fields to test our hypotheses.

We Identified Two Broad Categories of Responses to Surprise Among Different Professions

We found that most professionals who have to respond to surprises within seconds or minutes are usually skilled in touch labor—i.e., they work with their hands. This category includes surgeons, Navy SEALs, test pilots, and professional athletes. Practitioners in this category usually must control feelings of fear and anxiety when they encounter unexpected events, and they all have mental and physical rituals to help them manage these emotions.

Professionals who typically have more time to respond to surprises (e.g., hours, days, or weeks) are usually valued for their knowledge capital. This category includes chief executive officers (CEOs), ambassadors, military officers, and engineers. When encountering surprise, these practitioners must control ego, anger, and overreaction, and the most successful and agile practitioners in this category have typically developed mental rituals to help them manage these specific emotions.

The Level of Chaos in the Environment Also Affects People's Response to Surprise

We found that the level of chaos in the environment has a big effect on how people prepare for surprise. For example, those working in the most controlled environments, such as an athletic stadium, often have the luxury of being able to prepare a "what if" plan for every possible unexpected scenario because the range of possibilities is discrete and manageable. We found that professionals working in moderately chaotic environments tend to develop "what if" plans for the most likely scenarios, along with any scenario that represents an existential threat. When a professional of this sort encounters something in the environment that was not planned for, he or she relies on experience or training.

The Most Complex and Chaotic Situations Are Caused by Other Humans, Rather Than Something in the Environment

Regarding those working in the most complex environments, we arrived at an unexpected observation: All the individuals working in the most complex environments face surprises that are generated by other humans. A CEO, an ambassador, a Special Weapons and Tactics (SWAT) team captain, a Navy SEAL, and military general officers all fall within this category. We found that all of these professions face such complex operating environments—with an infinite number of things that can go wrong—that it does not make sense to develop comprehensive "what if" plans. Instead, the successful members of this group develop generalized frameworks that they can use to deal with surprise, regardless of the specifics of the surprise.

The Biggest Surprises Tend to Come from Third Parties

The final key finding from our research on surprise is that the biggest surprises are most likely to come from third parties—i.e., people and effects outside the immediate field of view. A Navy SEAL was the first to make this point to us, but nearly everyone else made the same observation.

The intuitive reason for this is that practitioners often spend a lot of time thinking about their adversaries, competitors, or key challenges and therefore develop a good understanding of how these forces are likely to behave. One way to address the threat of the unexpected third party is to conduct exercises to widen the organization's field of view and highlight potential alternative possibilities.

How Can the NRO's Organizational Processes Be Used to Promote Responsiveness and Creative Thought?

Our research on this final topic was motivated by the following objective: How did some organizations that have taken steps to become more responsive in promoting innovation and creative thought achieve this?

We looked at three companies suggested to us by NRO/AS&T: Pfizer, IBM, and Caterpillar. These companies have all been recently recognized in the media as having gone through transformations in order to better respond to pressures in the marketplace. However, each company reached a very different end state: Pfizer become more centralized, IBM started selling a completely different product, and Caterpillar became more decentralized. With all three companies looking to innovate, why did they take such different approaches?

Innovation Occurs for Many Reasons, Each Requiring a Different Approach

We found that innovation occurs for many reasons, and every situation requires a different approach. For example, one company might innovate to become more efficient (make better use of resources), another to become more effective (enhance current capabilities), and a third to become more agile (quickly adopt new technology). The reason for the innovation will help determine the approach taken.

As an example, we found that Pfizer decided to concentrate on anticancer and Alzheimer's drugs. To do this, it sold off and divested all of its unrelated properties so that it could concentrate on this high-risk, high-reward goal. In the process, it centralized its organization and processes to pursue a single mission.

By contrast, Caterpillar was interested in becoming more responsive to its customers' needs. To do this, the company decentralized and set up fully contained Caterpillar offices around the country, each containing everything needed to run the business: product experts, sales and maintenance teams, and finance and accounting personnel. In doing this, Caterpillar was able to customize its service to the local market, but this end goal required a different approach than that taken by Pfizer.

Conclusions

We conclude our research by noting that, even though all three topics appear to be very different, we observed three common lessons.

Modularity and Innovation Are Not Goals in Themselves

The first observation is that modularity and innovative methods are not goals by themselves—they are tools for meeting a particular goal. Instead of saying that the organization "needs to innovate" or "needs to implement a modular architecture," strategists should first set the priorities and the mission objectives. Then their organization will be in a position to determine what mechanisms should be used to meet the priorities.

Strategic Planning Would Be Beneficial for All Three Areas Discussed

The second observation is that success in modularity, innovation, and reacting to surprise all benefit from at least a partial ability to predict the future. Therefore, we conclude that any investments in developing strategic plans or visions, along with exercises designed to probe the future, can advance all three topics.

Solutions in All Three Areas Require Not Just Hardware, But Also People and Organizational Structures

Modularity, surprise, and innovative processes yield ways to evolve hardware, people, and corporate structures, respectively. Merely developing flexible hardware will not suffice because the hardware will require an equally flexible staff and organizational structure to design, implement, and operate it.

Acknowledgments

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We are also very thankful for several colleagues both inside and outside of the RAND Corporation. At the very beginning, Steve Rast contributed some key insights that eventually led us to our surprise framework. Bill Welser IV kept us on track by participating in the discussions that generated and refined our initial framework. Tim Webb and Scott Savitz provided careful reviews of an early draft, and their comments helped make this report stronger and easier to understand. Amy McGranahan worked hard at assembling the initial manuscript, and we are grateful to have such capable assistance. Finally, we appreciate the efforts of our editing team: Nora Spiering, Matt Byrd, and Steve Kistler all worked hard to ensure that this piece was properly edited, proofread, and typeset.

The observations and conclusions made within this document are solely those of the authors, as are any errors or omissions, and do not represent the official views or policies of the U.S. Intelligence Community or of the RAND Corporation.

Abbreviations

AC	alternating current
AS&T	Advanced Systems and Technology
ASW	antisubmarine warfare
CD	compact disc
CEO	chief executive officer
DoD	Department of Defense
ER	emergency room
FOV	field of view
HRO	high-reliability organization
IC	Intelligence Community
I/O	input/output
LCS	littoral combat ship
MCM	mine countermeasures
NFL	National Football League
NGO	nongovernmental organization
NPV	net present value
NRO	National Reconnaissance Office
R&D	research and development
RPD	recognition-primed decision model

SEAL	Sea, Air, Land
SLR	single-lens reflex
SUW	surface warfare
SWAT	Special Weapons and Tactics
USB	Universal Serial Bus

CHAPTER ONE

Introduction

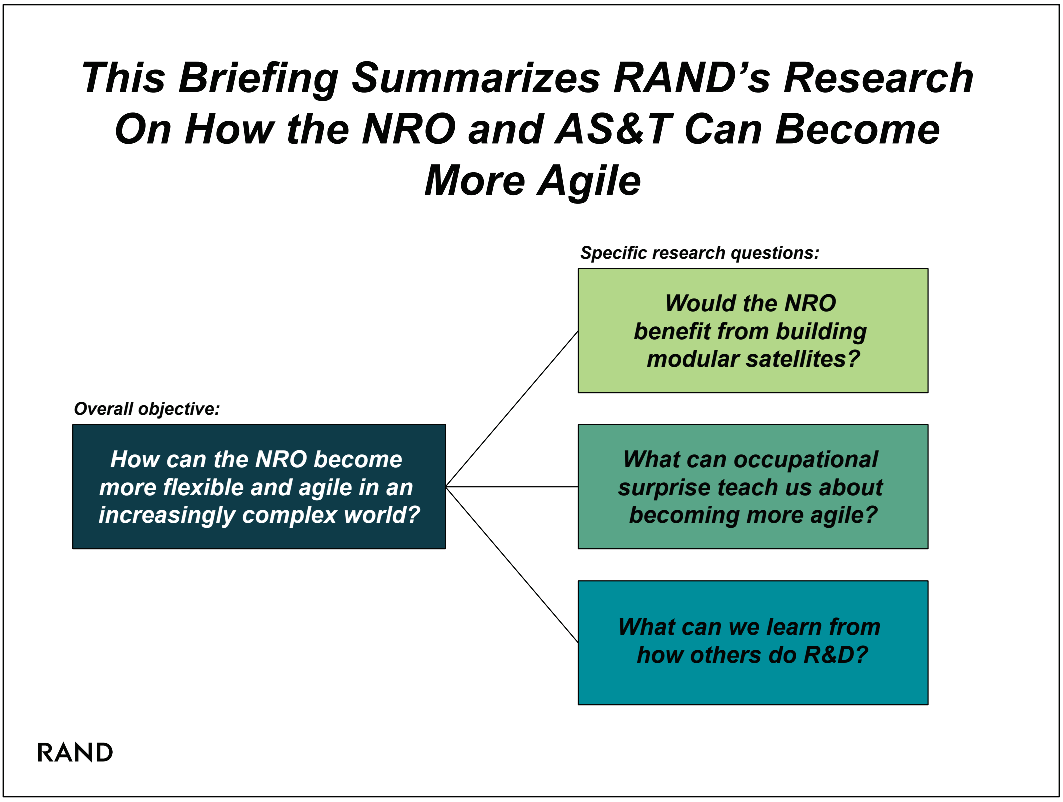
RAND NATIONAL SECURITY RESEARCH DIVISION

Increasing Flexibility & Agility: Lessons from Modular Design, Occupational Surprise, and Commercial Research and Development Processes

The National Reconnaissance Office (NRO)—indeed, the entire U.S. Intelligence Community (IC)—faces an operational environment that is faster paced, more uncertain, and filled with more variables than it was even ten years ago. One of the biggest challenges facing the IC today is that it must confront unknown threats that continue to emerge from unexpected directions. This represents a dramatic contrast to the environment that the IC faced during the Cold War, where the challenges were (relatively speaking) less dynamic and better understood. As one way of addressing this problem, the NRO's Advanced Systems and Technology (AS&T) Directorate asked RAND to perform research on ways that the NRO could become more responsive.

To begin, RAND conducted discussions with thought leaders throughout the NRO, and together RAND and the NRO developed a list of 30 research topics for further study. AS&T then reviewed this list and picked three topics that RAND was to research in further detail: assessing whether a modular architecture was suitable for the NRO, investigating how other occupations respond to unexpected events (and what the NRO could learn from these professions), and performing preliminary research on how other (nongovernment) organizations have become more responsive to their customer base.

This report therefore summarizes the work that RAND performed for AS&T. The report is divided into three sections, one for each of the topics that are mentioned above. Each section serves as a self-contained module in which we outline the research objective, method, and key findings. At the conclusion of this report, we note some observations on what all of these topics have in common, along with proposing some new ideas for continued research.



Our report summarizes RAND's research on how the NRO and AS&T can become more agile in an increasingly complex world. To address this overall objective, we researched two topics in detail:

- Would the NRO benefit from building modular satellites?
- What can be learned about becoming more responsive by looking at how different occupations (e.g., test pilots, surgeons, chief executive officers [CEOs]) respond to surprise?

For the third topic, we spent time doing pilot research on what the NRO could learn from how private-sector companies have become more responsive. We will discuss the findings of this pilot research in the third portion of this report.

CHAPTER TWO

Investigating the Suitability of Modularity Toward National Reconnaissance Office Space Systems

Our Objective Was to Determine if Modularity Was Suitable for NRO Space Systems

- **We started by reviewing the academic literature and talking to subject matter experts in modularity:**
  - **What is modularity?**
  - **Why do it?**
  - **What are the ingredients of a modular architecture?**
- **We developed a list of criteria to evaluate whether systems are good candidates for modularization**
  - **We tested the list on the littoral combat ship (LCS)**
- **How do NRO space systems rate using these criteria?**
- **What questions does the NRO need to address to move forward?**

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We will begin by looking at the first topic: modularity. We studied modularity because it represents one approach for creating systems that can adapt to change. This slide describes our research objective and method.

As we will show, implementing a modular architecture provides the user with a system that is more easily modified to respond to external changes, but the ability to make these changes often comes at a cost of additional up-front systems engineering.

The goal for our analysis was to take a first-order look at whether NRO systems are good candidates for modularity.

To address this question, we started by examining the academic literature and consulting with subject matter experts on modularity. We then used our findings to form a clear definition of what modularity is and how it can make a system more easily adaptable to change. After researching how systems can adapt to change using modularity, we formed an outline of the elements that are necessary for a successful modular architecture.

Next, we developed a list of first-order factors for evaluating whether or not a system is a good candidate for modularization. To test our factors, we applied them to the missions addressed by the littoral combat ship (LCS), which is widely recognized as being a modular system (Alkire et al., 2007, p. 6; O'Rourke, 2012, p. 1). We then applied our factors to NRO space systems to determine if they might benefit from a modular architecture.

This section concludes with recommended actions that the NRO can take to further determine how to incorporate modularity into its systems.

Modular Systems Are Easily Modified to Address Future Needs

Modularity is the engineering equivalent of a financial option: pay a premium *today* to exercise an option *in the future*.

Modularity can provide flexibility functions by adding components to a common base, but that system will never yield the best performance

Modularity allows easier ability to dynamically meet customer demand

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Knife image credit: iStockphoto/Thinkstock
Train image credit: Hemera/Thinkstock

Before looking explicitly at NRO systems, we started by researching the basic principles of modularity to understand the best practices of operation. This slide and the following two slides summarize some of the background information that we used to inform our analysis. We present this information to provide necessary context for our later analysis of NRO space systems.

Modularity combines like elements or components into independent modules. By doing this, the modules can be modified separately, and in this way a modular system can quickly adapt to changing requirements and new technology (Baldwin and Clark, 2000; Lau et al., 2011; Sanchez and Mahoney, 1996; Schilling, 2001; and Tassey, 2000).

One useful way to think about modularity is as the engineering equivalent of a financial option. A financial option is a monetary instrument that gives the investor the option to pay an up-front cost to exercise an option to buy or sell in the future.[1] A financial option provides value through its ability to provide choices instead of forcing a commitment. Similarly, in engineering, modularity provides an option (but not an obligation) to allow for change in the future (Baldwin and Clark, 2006).

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[1] For financial options, this up-front cost may be in the form of increased monetary value or, alternatively, increased risk.

In practice, modularity can manifest itself in three different ways (Baldwin and Clark, 2000):

- *Modularity of design* refers to modular theory that is used during the design and fabrication phase, in which components are developed separately and in parallel by independent designers. Most space systems are designed this way; for example, the sensing package (payload) is designed separately from the propulsion or navigation systems. Systems that have modularity of design may or may not end up being modular for the end user, as we will discuss below.
- *Modularity of production* refers to an approach in which all of the functional components are manufactured separately. In the literature that we reviewed, the most common example of modularity of production was an assembly line, where subcomponents (often sourced from different suppliers) are brought together and assembled into a larger product. Systems that have modularity of design often have modularity of production because modular designs often can be built using modular production methods.
- *Modularity of use* is likely what most people think of when considering modular systems. Systems that have modularity of use allow the end user to exercise the options of flexibility that we discussed earlier. An example of a system that provides modularity of use would be a reconfigurable messenger bag in which the user can remove or reposition fabric partitions with hook and loop fasteners to resize internal compartments.

To demonstrate the basic benefits and challenges of modularity, along with providing some concrete examples of the differences between modularity of design, consider the following two examples of modular systems: a Swiss Army knife and a train.

The Swiss Army knife incorporates a large number of tools into one device, and this gives the user an increased level of flexibility for responding to future events. All of these tools mean that the Swiss Army knife has many purposes, which increases its usefulness to the end user. However, while a Swiss Army knife provides a variety of serviceable instruments and tools simultaneously, none of these tools will perform as well as an equivalent singular system, such as a dedicated chef's knife, corkscrew, or pair of scissors. The Swiss Army knife therefore highlights an important trade-off that is often made when implementing a modular architecture: increased flexibility in exchange for nonoptimal performance.

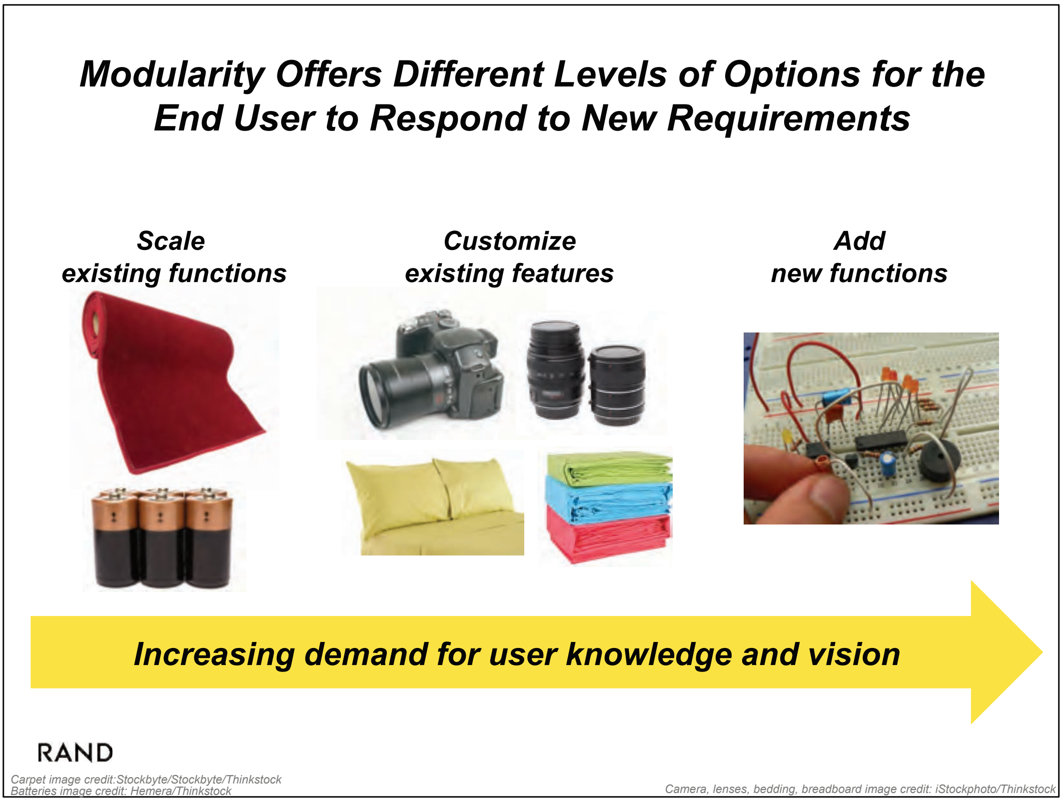
The Swiss Army knife is an example of modularity of design and production, but it is *not* an example of modularity of use. All of the tools within the knife operate independently of one another, so the designers (and fabricators) of the knife design each piece separately, optimizing each tool for the volumetric constraints put in place by the knife's chassis. This approach represents modularity in design. In fabrication, all of the tools are likely made on separate assembly lines and are combined into a single device on an assembly line. This is modularity of production. When the knife reaches the end user, the customer is not able to (easily) add new tools if he or she desires new functions or if one of the existing tools should become worn or fail. In short, the customer is stuck with the same tools that came with the knife. Because the Swiss Army knife does not have modularity of use, it is therefore a good example of an object that can be modular through the design and fabrication process yet *not* modular for the end user.

A train is a second example of a modular system because the cars can be attached or detached easily to meet dynamic rider demand. This system allows the train to be easily modified to respond to capacity or availability needs without interfering with the overall functionality of the train. In addition, should one car need repair, it can easily be removed from the system and sent to the repair shop. Trains are therefore good examples of modularity of use because the end user is able to configure the train cars in a way that helps the railway operator respond to changing demand.

The train example is also useful for highlighting a secondary point: Many modular systems are often modules of modules. The train car's wheel module, for example, consists of the wheels, axes, trucks, and brakes. The wheel module is therefore a subcomponent of the overall train car, which, itself, is a module.

And how do space-based remote sensing systems fit in with the types of modularity that we outlined above? Space systems typically have modularity of design and production but not usually modularity of use. As we mentioned above, the subsystems within space payloads are often designed and fabricated separately by independent engineering teams. The advantage to this approach is that each engineering specialty (optical, thermal, mechanical, propulsion, etc.) is able to focus its expertise to design and fabricate modules in parallel with one another. Throughout the project, a system engineering team works to define and then enforce the interfaces between the modules. After the build process is complete, all of the components are integrated into the final package and tested to ensure that they operate as a single unit.

Now that we have highlighted some of the findings from our literature review on modular systems, we will consider how the NRO's space systems fit into this context. We will draw deeper comparisons in the coming sections, but we assumed that the NRO is most interested in leveraging *modularity of use* to provide the change agents needed to respond to future events. We make this assumption with the understanding that the NRO's current space systems have much in common with the Swiss Army knife: They rely heavily on modularity of design and fabrication, but they often do not provide modularity of use to any great extent. Therefore, we focused our subsequent research (which is explained on the next slide) to look at methods that designers can use to implement or improve the modularity of use.



When considering modular effects that can be manipulated by the end user, Ulrich and Tung (1991) observed that there are varying degrees to which modularity can be leveraged to meet specific user needs. For example, some products only allow the user to proliferate a set function, while other products give the user complete control over the functions that the product is able to perform. Using Ulrich and Tung's observation as a starting point, we developed our own observations on how modularity allows for different types of changes. Three main categories are described below.

The first example of flexibility is simply scaling the existing functionality, in which modularity only allows for changing the scope or size without allowing the user to create brand new functions. Carpet and batteries are good examples of this: Both are designed to be readily scaled based on user needs, but the primary functions of each never change. Batteries just provide a voltage, but that voltage is a variable that the user can vary by adding (or subtracting) more battery modules together. Similarly, carpet is a floor covering, and the user can change the square footage and two-dimensional geometry of that coverage. In both cases, though, batteries and carpet cannot be modified to do anything beyond their primary functions.

The next example is using modularity to customize existing functions without dramatically changing the primary purpose of the product. For example, a digital single-lens reflex (SLR) camera system is sold alongside an array of lenses representing different focal lengths. This allows the user to exercise greater options when capturing images, but the interchangeable lenses do not change the primary function of the camera, which is to take photographs. Another example is bedding, which comes in standard sizes (e.g., twin, queen, king). This standardization allows the end user to easily change the look and feel of the bed (perhaps to match a change in the room's paint color) using fabrics and colors from different manufacturers.

The most robust examples in the slide are modular systems that allow the user to add or change the basic functionality of the device. The best example of this is an electronics breadboard with the requisite resistors, capacitors, chips, and wires. This system offers the user an infinite number of options to change and adapt to future needs, allowing the user to design and create entirely new functionality using these components.

One key observation that we made is that moving from left to right on the chart in the slide provides more flexibility to the user, but it also places a greater onus on the user to have more knowledge and vision for her or his ultimate needs. Carpet and batteries are easy to use and install, but they only have one function. By contrast, an electronics breadboard system allows for nearly infinite functionality, but it also requires superior knowledge and expertise from the user. In addition, the most-flexible systems require greater time and planning to design and implement. This observation is an important one to consider when determining the level of flexibility desired in a modular architecture: Greater flexibility places more demands on the knowledge base of the user who looks to exploit the resulting architecture.

Modularity Requires Careful Design of Three Key Components

Component	Purpose	Design considerations
Modules	Provide future options, allows separation and reassembly	• What current and future functions are needed? • What are the performance priorities? • What aspects should be frozen/freed? • How to protect proprietary information?
Interfaces	Allow interaction between modules	• How can all of the modules be accommodated? • What is the design space for future requirements?
Test infrastructures	Verifies that modules will work when inserted into the system	• What is needed to ensure a module will work as expected when inserted into the system? • Is it cost-effective to build a test system?

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Now that we have provided background information on what it means to design and use modular systems, it is worth taking a more detailed look at the three key components of any modular architecture: the modules, interfaces, and test infrastructure. All of these components are recognized in the literature as being essential to modular systems, but they are described nicely in Baldwin and Clark (2000).

Modules. The modules are the elements of a system that provide the freedom, allowing users to swap old missions or obsolete technologies for newer ones. Using physical and/or conceptual separation of system elements, modules can be altered without disrupting the rest of the system components—a key feature in enabling users to adapt to new changes using a modular architecture.

When designing a modular architecture, the system engineer needs to consider some key questions when determining how to partition an overall system into individual modules. The system engineer must consider what functions are needed, along with how those functions may evolve over time. The answers to these questions will identify what aspects of the system should be partitioned into modules, as the modules are the components that will come and go to provide those change agents to the user. The system engineer also needs to consider the balance between reliability and performance: Dividing a system into modules will add interfaces and increase the number of parts, which will likely increase the complexity of the system. In some cases, complicated systems have more parts and interdependencies, which may make them less reliable.

Interfaces. The interfaces need to be the most accommodating part of the system: As modules come and go, the interface remains embedded within the system. Therefore, the most successful interfaces will be compatible with changing technology, even when future trajectories of the technology are not yet known. This is a significant challenge when modularizing a system, but it is not an impossible feat: There are many examples of successful interfaces that have demonstrated long service lifetimes.

One example is the physical interface of the Universal Serial Bus (USB) plug, which has remained consistent for over 20 years. Despite the rapid change of technology, USB ports still use the same physical plugs, are backwards compatible, and demonstrate the possibility of anticipating future needs. In an industry known for changing every 18 months, the fact that USB remains the primary input/output (I/O) interface for consumer PCs is a testament to the original architects' ability to engineer a very flexible interface.

A second example of a successful interface is the physical plugs associated with electrical alternating current (AC) appliances. While each country does have a different standard, each of these plugs has been very robust: Appliance designers have relied on the same physical interface with the U.S. (consumer) electrical grid since the early part of the 20th century. This interface is now just as adept at handling a modern computer as it was with a 1950s-era toaster.

Test infrastructure. A test infrastructure is the third component of a successful modular system. The test infrastructure is a way to ensure that new modules will work as expected when they are inserted into the production or operational system. Developing a test infrastructure usually means building some level of a stand-alone redundant system, recognizing that this will incur additional cost. The alternative to this is to plug modules into a final production system, but this defeats the purpose of having a modular architecture because the production system will serve as a piece of test equipment. If the new module does not work, the fielded system will then have to function as a testbed, taking the system away from its regular duties. As one modularity expert with whom we spoke noted, if the method for testing new modules is just plugging them into the final system, there is no advantage to building a modular system (Baldwin, 2012).

These three components highlight an important philosophical approach that is inherent with modular system design: Every modular architecture must "freeze" some components in order to "free" others (Baldwin, 2012). This idea is evident in all aspects of modular design: Something has to be held constant in order to let other components come and go. This is a powerful idea because it suggests that the options that come with modular systems do not come without cost. In freezing components (usually the interfaces), the architect is putting constraints in place, but these constraints are (ironically) a requirement to obtain the freedom that he or she is seeking.

All of the background presented so far has suggested that modular architectures have both strengths and weaknesses. This implies that there are some missions or needs that may be more suited to modularity than others, and we set out to develop some factors that could be used to evaluate whether an arbitrary system is a good candidate for *modularity of use*. The factors that we propose in this list are a product of our research and thinking on modular theory, but the idea of developing a list of factors was motivated by Schilling (2000) and Gershenson et al. (2003).

The first factor is associated with how easy it is to physically separate the functions that will later be assigned to different modules. We use the word *component* to describe these functions, and in using this word we refer to the parts that make up the final device as seen from the end user's perspective.[2] If the system can be easily decomposed and reassembled via some components that roughly map to different functions, the system (or the mission set) is a good candidate for modularity. Conversely, the need for highly integrated parts makes modularization extremely challenging. This is because highly integrated parts will impose a high cost during the early (and subsequent) systems engineering processes, as engineers deconflict all of the integrated components to determine how all of them interact with one another. If this initial cost of added systems engineering is too high, it may overshadow any gains in flexibility that the modular system will be able to provide further down the road.

The second factor speaks to the needs of the user: Does the user prefer flexibility or highly optimized functionality? As we mentioned earlier, modular systems have the potential to provide great flexibility, with the trade-off being that modular systems will never perform as well as singular tools designed for the specific tasks.

The third factor has to do with how mature the technology is. Widely used, mature, or universal technologies are likely to have existing standards in place, and this makes modularizing these technologies less challenging. (This practice of leveraging universal technologies is sometimes referred to as *standards-based innovation*.) By contrast, emerging technologies will have less-mature standards, and it will be more challenging to design a set of enduring interfaces. For this reason, emerging and specialized technology is more difficult to modularize.

The fourth factor is related to the third: If the technology is changing in a predictable, incremental way, modularizing will allow new technology to be easily adapted (assuming that the interfaces have been designed to accommodate these changes.) However, if the trajectory is unknown or revolutionary changes are expected, modularizing could actually inhibit innovation by tying the user to a set interface that will potentially not be able to adapt to dramatic changes in technology. This factor motivates an important observation: Disruptive products are unlikely to arise out of modu-

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2 Of course, the end user is likely to have very little knowledge about these components, but that is unlikely to affect the item's modularity of use. For example, the people who work in train yards coupling and uncoupling cars only need to understand how the cars' interfaces work; they do not need to understand the details of the components, such as the wheel assemblies, passenger compartments, or electrical systems.

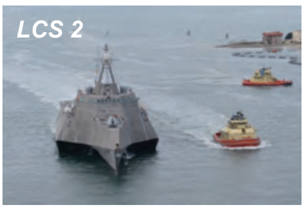
lar systems because the interfaces (of modular systems) will likely have a hard time accommodating such dramatic change.

The fifth factor assesses the level of uncertainty in future user needs. If the future needs are well defined, this factor suggests that it makes more sense to build a singular system specifically suited for the particular task. By contrast, if future needs are unknown, modularity is a suitable way to provide flexible options.

Taken together, applying these factors to a system or mission will give a first-order indication of whether a modular architecture is a good match.

The LCS is a Relevant Example Because the U.S. Navy Shares Similar Goals with the NRO

Both the U.S. Navy and NRO are looking for platforms that are flexible and capable of responding to a variety of future threat environments.



Mission	Primary Function
Antisubmarine warfare (ASW)	Detect, track, and target enemy submarines
Mine countermeasures (MCM)	Hunt, sweep, and neutralize mines
Surface warfare (SUW)	Counter threats from small boats via human capital-driven means

RAND

LCS images courtesy of U.S. Navy

Before we show how NRO space systems rate using our factors, we will show the results of applying our factors to the missions serviced by the U.S. Navy's LCS. This exercise will serve as a "sanity check" to demonstrate that our factors can correctly identify missions that would be well served by a modular architecture.

We chose the LCS for three reasons. First, the LCS is recognized as having been designed to be modular from the start of the program; indeed, as noted in a 2007 RAND report on the ship, "[m]odularity is at the heart of the LCS concept" (Alkire et al., 2007, p. 6). Second, the LCS is a system that is being procured by the U.S. Department of Defense (DoD) and will thus serve as a more appropriate comparison to the NRO's systems than evaluating a consumer product, such as a messenger bag or a computer peripheral. (DoD is motivated by different incentives than private companies that build consumer goods, and we wanted to ensure that our example roughly aligned with the IC's incentives associated with protecting national security.) Finally, the creation of the LCS was motivated by many of the same goals that the NRO currently has. Specifically, the U.S. Navy built the LCS because it was looking for a platform that was flexible and capable of responding to a variety of future threat environments, and we heard similar language when asking NRO/AS&T personnel about their future architecture desires (U.S. Navy personnel, 2012).

Testing These Factors on LCS Is a "Sanity Check" That the Factors Can Identify a Modular System

	What factors encourage modularization?	Which factors discourage modularization?
✓	Components are easily separable	Components are highly integrated
✓	Flexibility valued over performance	Highly-optimized performance desired
	Mature technology	Emerging technology
✓	Incremental changes in technology	Dramatic changes in technology
✓	Uncertainty of future user needs	Well-defined future user needs

RAND

By testing the LCS against the list of factors, we determined that the missions serviced by the LCS are good candidates for a modular architecture. Our reasons for making these assessments are described in more detail below, and we base our judgments on data that we collected about the LCS from discussions with both ship operators in San Diego and personnel in the LCS program element office in Washington, D.C. (U.S. Navy personnel, 2012).

- **The components are easily separable.** At the start, the LCS was envisioned to accommodate technologies that had been previously developed for other DoD platforms. The designers made this decision because they knew it would be easier to build modules based on existing technology rather than to develop state-of-the-art modules based on new technologies. This is one of the key trade-offs that LCS designers made when building the system: The LCS mission packages are indeed modular, but the components used in the mission packages are based on existing, widely available technologies. Because the designers used existing technology, they were able to easily separate the mission packages and enclose each mission package in standard volumetric units made out of intermodal containers (Conex boxes).

- **Flexibility in functionality is desired.** As we mentioned on the previous slide, the LCS was designed to flexibly respond to a variety of needs. The LCS was designed to replace legacy (singular) ships—specifically, the *Avenger* class—that performed the mine countermeasures (MCM) mission.
- **The LCS designers expect incremental changes in the technologies associated with the LCS mission packages.** As an example, the modular hardware associated with the surface warfare (SUW) mission includes 16 personnel, two inflatable boats, and a few heavy machine guns. None of these resources will experience such significant change that the mission package will no longer be accepted by the LCS seaframe.
- **The Navy is uncertain to what extent it will need antisubmarine warfare (ASW), MCM, and SUW capabilities over the long term.** Of course, this factor depends heavily on the user's field of view (FOV) and overall context. However, the Navy is uncertain what percentage of antisubmarine, antimine, and surface warfare needs it will be called upon to deliver in the future. The Navy personnel with whom we spoke noted that before LCS, the Navy used different ships for the MCM and SUW/ASW missions. In addition, they noted that the Navy has not been called upon to do substantial MCM operations very frequently over the past 30 years. This uncertainty means that the LCS offers a flexible option because it allows the Navy to support all three missions using one piece of hardware (assuming that the Navy has time to swap the mission packages to meet the mission need).

We were unable to make a definitive assessment on the third factor: Is the technology on LCS mature or state of the art? In our conversations with LCS personnel in both San Diego and Washington, D.C, we were given evidence to suggest that some of the components within the LCS's mission packages were based on existing technology used elsewhere in DoD. For example, the SUW package has two 30mm guns that were originally designed for use on a Marine Corps personnel transport vehicle. (The guns that have been repurposed for the LCS still have the Marine Corps vehicle's seats attached, despite the fact that these seats are not used by the LCS crew.) In another example, LCS personnel noted that portions of the computing infrastructure that serve the seaframe's software are commercially available. However, despite these examples, we recognize that the LCS does have extensive custom-built equipment, especially on the technically complex ASW module. In the end, we did not have enough data with which to make a decisive determination on modularization factor.

Overall, though, four of the five factors suggest that the LCS missions are well suited for a modular architecture, and we conclude that our factors pass our "sanity check" for being able to identify missions that are well suited for modular systems.

NRO Systems Have Significant Constraints to Consider When Designing a New Architecture

NRO system constraints/ requirements
Unique, one-off models
State-of-the-art technology
Lack of physical access
Reliability is a high priority
Secret/proprietary design

RAND

Before we test the NRO system against our factors, it is worth noting that there are some additional constraints that are unique to NRO space systems.

First, each NRO mission represents a unique, "one-off" design. As a result, few key components have been standardized. If the system is going to be modularized, this lack of standardization will place additional burdens on the system engineer, who will have to develop effective interfaces and identify all of the interdependencies between the various subsystems.

NRO systems rely on state-of-the-art sensing technologies, making it difficult to determine how these technologies will advance in the future. This makes grouping together like-paced elements (for the purpose of containing them all within a single module) very challenging.

There is no readily available physical access to these systems once they are deployed. This not only inhibits the ability to test on the actual system, but this lack of access also makes adequate testing prior to deploying a system into space that much more vital.

NRO space systems perform a critical mission to the nation and, therefore, must remain highly reliable. If these systems are going to be modularized, engineers will have to devote additional resources to ensure that this reliability is not compromised.

Finally, NRO systems have secret or proprietary design specifications, and modularizing the system may help maintain this protection of information. Protected information can be encapsulated in a module, with only the interface communicating with other components of the system.

Our First-Order Factors Yield Inconclusive Results for NRO Space Systems

	What factors encourage modularization?	Which factors discourage modularization?	
	Components are easily separable	Components are highly integrated	✓
✓	Flexibility valued over performance	Highly optimized performance desired	
	Mature technology	Emerging technology	✓
	Incremental changes in technology	Dramatic changes in technology	
✓	Uncertainty of future user needs	Well-defined future user needs	

To first-order, NRO systems do not lean one way or another toward modularization. So how do we move forward from here?

RAND

This slide evaluates the first-order suitability of NRO space systems to modularization.

There are two factors that seem to encourage modularization: The NRO desires highly flexible systems that are able to adapt to meet a set of future user needs that are equally uncertain. Adopting a modular architecture would allow the NRO greater flexibility to change user functions and grant the NRO the agility to respond more quickly to newer technologies.

There are also two factors that seem to discourage modularization: Current NRO systems are highly integrated (because of the space constraints imposed by the launch vehicle), and these systems are built around emerging sensing technologies. The prevalence of emerging technology will make modularizing these systems challenging because of a lack of standardization between components.

We have left the fourth factor as neutral; the trajectory of the technology is difficult to predict, and the NRO systems may be faced with either technology trajectory. In addition, we had a hard time assessing this factor ourselves because we did not have enough resources (or the proper access) to research this factor in detail. Indeed, even when we presented this factor to NRO/AS&T personnel, half of them leaned one way and the other half leaned the other. Even if we had been able to make an assessment on the fourth factor, this would have effectively broken the tie and shifted the bias one way or another, and this would have suggested an artificial preference toward modularity or singularity that does not really exist.

The result of applying these factors is inconclusive: To first-order, the factors suggest that the NRO space systems are not perfectly suited for modularization or singularity. How could we break the tie or move forward to determine a more conclusive answer?

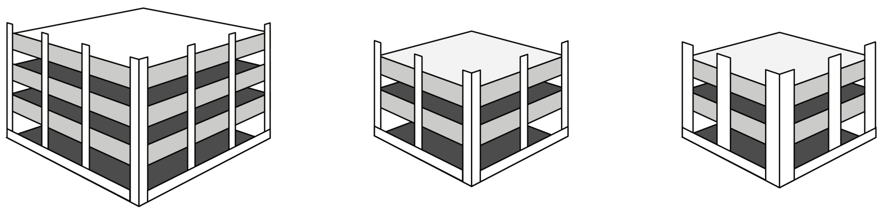
The first way to move past the impasse would be identify the relative weights assigned to each of these factors. We recognize that some of the factors are likely to be more important than others, and the first step for AS&T is to prioritize which factors are most important. After this is done, the result might provide guidance on how to break the tie, especially if the factors that encourage modularization are determined to be weighted more heavily than the others (or vice versa). If flexibility and being able to respond to future user needs are most important to the NRO, then this would suggest that a modular architecture is best suited for meeting these needs. However, it is worth recognizing that the equivalent modular systems are likely to be more expensive and complicated than the existing ones. Likewise, if the space constraints imposed by the launch vehicle and the desire to always use state-of-the-art sensing technologies are most important, this suggests that singular systems would be most appropriate.

One consideration that we have not mentioned so far is monetary cost, and this suggests another way to break the tie. So far, we have assumed that cost is what determines the initial boundary conditions of this problem. For example, launch costs are high, and this is what encourages the current practices of using highly integrated components.

One way that we could include cost in these factors would be to develop a mathematical device that relates different levels of flexibility to the likelihood of losing or gaining money across the lifetime of the project. To investigate this idea, we turn to an example industry that has already developed such a device: the parking garage industry.

There Are Three Choices When Deciding How to Size a Parking Garage to Meet Demand

A **B** **C**



A
- ✓ *High capacity to meet future demand*
- ✓ *Risk of unused spaces*

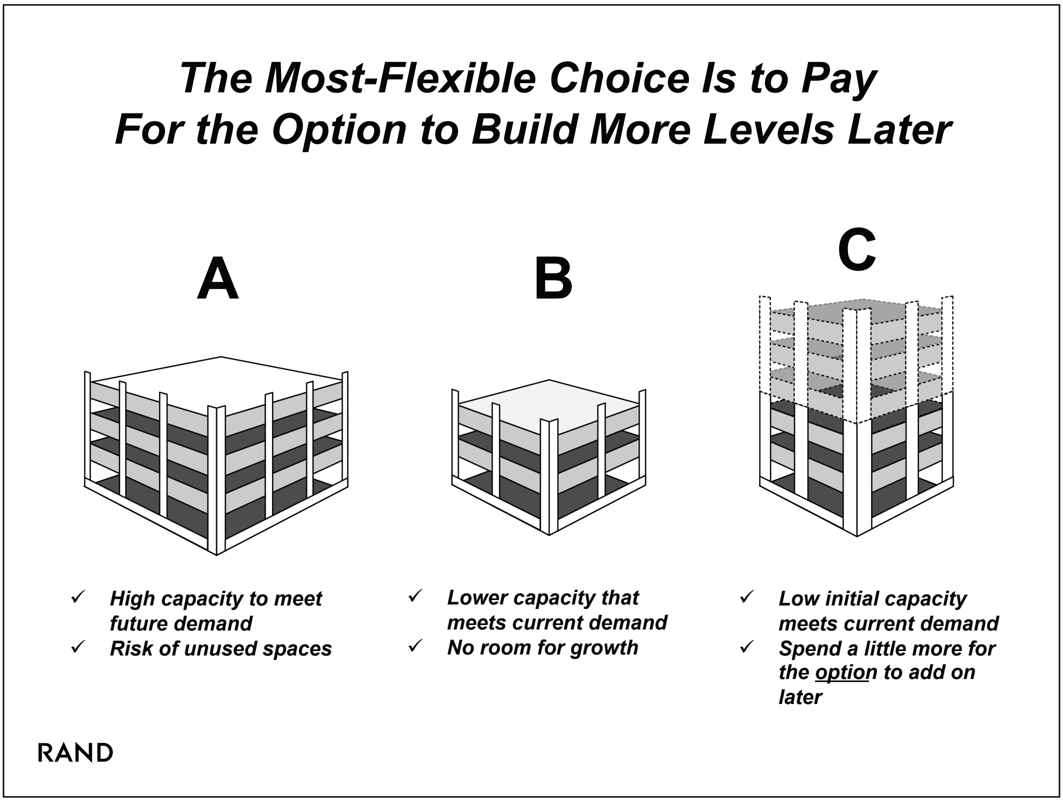
B
- ✓ *Lower capacity that meets current demand*
- ✓ *No room for growth*

C
- ✓ *Low initial capacity meets current demand*
- ✓ *Spend a little more for the option to add on later*

RAND

We chose the parking garage example because it offers a simple analog to the same problem that the IC is trying to solve. Specifically: Is there a way to determine how much more should be spent up front (if anything) buying options for increased flexibility in the future? As we will show, parking garage designers rely on a simple net present value (NPV) calculation to quantify the balance between investment risk and potential benefits (de Neufville and Scholtes, 2011). After we describe how parking garage designers quantify this balance, we will draw parallels to the NRO's space-based collection systems and identify what quantities are needed to repeat this approach for these systems. However, we will begin by describing the different choices that a parking garage developer has when trying to size a new garage to meet expected demand.

Assuming a simple scenario, the parking garage developer has three choices when determining what kind of garage to build. The developer could build a garage that is larger than what she or he needs today to meet current demand (option A in the slide). This choice represents the largest up-front investment, but it also provides the most excess capacity (and therefore additional revenue) should the demand ever increase. The opposite of option A is to build a small garage that exactly meets the current demand (option B). This option is the least expensive, but it provides no room for growth. If the demand for parking spaces increases, the developer will have to build a new garage. The final option is to build a garage is that sized for today's demand but also has a stronger foundation that would allow the developer to add additional floors should the demand increase in the future (option C).



The most-flexible choice is to pay for the option to build more levels later. Option C will be less expensive than A and more expensive than B, but it allows the garage developer to spend more today for the option to add extra floors later to meet future demand. So how does the garage developer decide exactly what dimensions he or she needs, based on his or her appetite associated with the risk of investment loss (along with the desire for potential gain)? Or, to pose a question that is often asked when designing modular systems: Where is the "knee" in the modularity curve? How many options should the developer purchase to achieve a suitable level of future flexibility?

The Parking Garage Designer Can Quantify the Balance Between Flexibility and Investment Risk

- **What can we learn from the method used to design parking garages?**

expected demand
construction, mx costs
revenue
interest rate

f(x) → *Net Present Value (NPV)*

- **Result: relates likelihood of gaining or losing $N for a desired level of flexibility.**
- **When compared to a rigid design, a flexible garage offers the ability to better match future demand with less likelihood of taking a loss.**

RAND

So how does the parking garage developer decide how to proceed? The answer is that the developer performs an NPV calculation that allows him or her to quantify the balance between future flexibility and likelihood of investment gain or loss (de Neufville and Scholtes, 2011).

There are four key quantities that the developer uses to perform this calculation:

- The first quantity is the expected future demand; this is represented by a probability distribution.
- The developer also considers the construction and maintenance costs across the life of the garage.
- The developer determines how much to charge each car that enters the garage, and this is used to calculate revenue, given a particular demand curve.
- Finally, the developer uses an interest rate to normalize price across the lifetime of the project and determine the NPV.

If the developer chooses a single-input demand probability, he or she can calculate an NPV across the lifetime of the project for options A, B, and C. To make this calculation more useful, the developer could perform a Monte Carlo calculation, varying the demand curve each time. The result of this calculation will provide the developer with a set of curves that relate a given level of flexibility with the likelihood of gaining or losing $N across the lifetime of the project.

This is exactly the type of relationship that we are seeking to develop for NRO space systems, so what would it take to repeat this calculation for the NRO?

The Parking Garage Highlights the Difficulty in Quantifying Flexibility of Intelligence Systems

Metric	Parking Garage	Satellite	Comments on Satellite Case
Demand	Probability distribution (# spots/yr)	Probability distribution	
Costs	O&M, upgrades (dollars)	Knowable (dollars)	
Value	Revenue (Price per spot)	?	**How does the IC assess "value"? By number of collects? What metric can assess the value of intelligence?**
Effect that time has on value	Interest rate	?	**How much more is a collect worth today than a week from now? Or a year from now?**
Total lifetime value	Likelihood of profit (Dollars)	Likelihood of gain/loss	

Observation: An early step in becoming more flexible is determining how to measure the value of the intelligence collection systems.

RAND

This table relates the quantities used for the parking garage calculation to what would be needed to repeat this calculation for intelligence-gathering satellites. The first two metrics, demand and costs, might be challenging to obtain for a satellite, but an experienced practitioner should be able to make a reasonable estimate on what the demand and costs would be for building such a system.

A larger problem arises when asked to consider the *value* of an intelligence-gathering system. The value of the parking garage is assessed using revenue (number of dollars collected per parked car); what is the equivalent of this for the IC? How does the IC assess value? In addition, what metric is used to determine the effect that time has on value? What was the value of an overhead image of the bin Laden compound a day before the raid? What would the value have been for the same image a week later? The parking garage example therefore highlights the difficulty in quantifying the flexibility of intelligence systems.

We recognize that we are not making a new observation when we note that developing metrics to assess the value of intelligence systems is very difficult. However, we propose that this is exactly what is required to solve the problem of balancing cost with flexibility to assess the suitability of modular systems. Without being able to assess the value of an intelligence system, it is not possible to develop a calculation that tells the user when it makes sense to modularize or not, or to what degree a system should be modularized.

We Recommend Two Approaches to Make Further Progress on This Topic

- **Our criteria suggest inconclusive results on whether to pursue modularization.**
- **Moving forward, there are two options:**
  - **To properly determine how much flexibility (modularity) is needed, a system architect needs to be able to quantify the value of intelligence.**
  - **In the meantime, a more qualitative (although less satisfying) approach would be to identify 2 to 4 performance needs that *really* matter:**
    - **Is it possible to build modules that support the performance objectives?**
    - **What interfaces will be needed?**

RAND

We conclude this section by noting our key finding: NRO space systems are not obvious candidates for modularization. So what can be done to proceed?

The parking garage analogy yielded one suggestion for making progress: Develop methods to assess the value of space-based intelligence-gathering systems. This is the best way to progress toward developing a quantitative approach to answering the question that most system architects ask when considering a modular design: Where is the knee in the modularity curve? Or, how much modularity provides the most flexibility for a modest up-front investment? As our analogy to the parking garage demonstrated, getting a quantitative answer to these questions means solving the problem of quantifying the value of the intelligence provided by the system.

We recognize that quantifying the value of intelligence sensors is one of the IC's biggest challenges. NRO/AS&T is currently working on this problem for its own sensors, but it recognizes that more work is needed before an effective solution is developed.

In the meantime, we recommend a secondary approach for moving forward. As a starting point, the modularity experts with whom we spoke recommended thinking about what could be done if starting from scratch, without any restrictions (Baldwin, 2012; Schilling, 2012). What would the NRO design to do today's mission, if it were allowed to ignore legacy missions or capabilities that are being carried forward as forced requirements? What key performance metrics are captured by this "from scratch" system?

After identifying the appropriate mission needs, the NRO could then consider the benefits of modularity by determining if these needs would be easily modularized using the factors that we presented earlier. Does it make sense to build modules to support these needs? Is it even possible, given the existing technology trajectories? What interfaces will be needed?

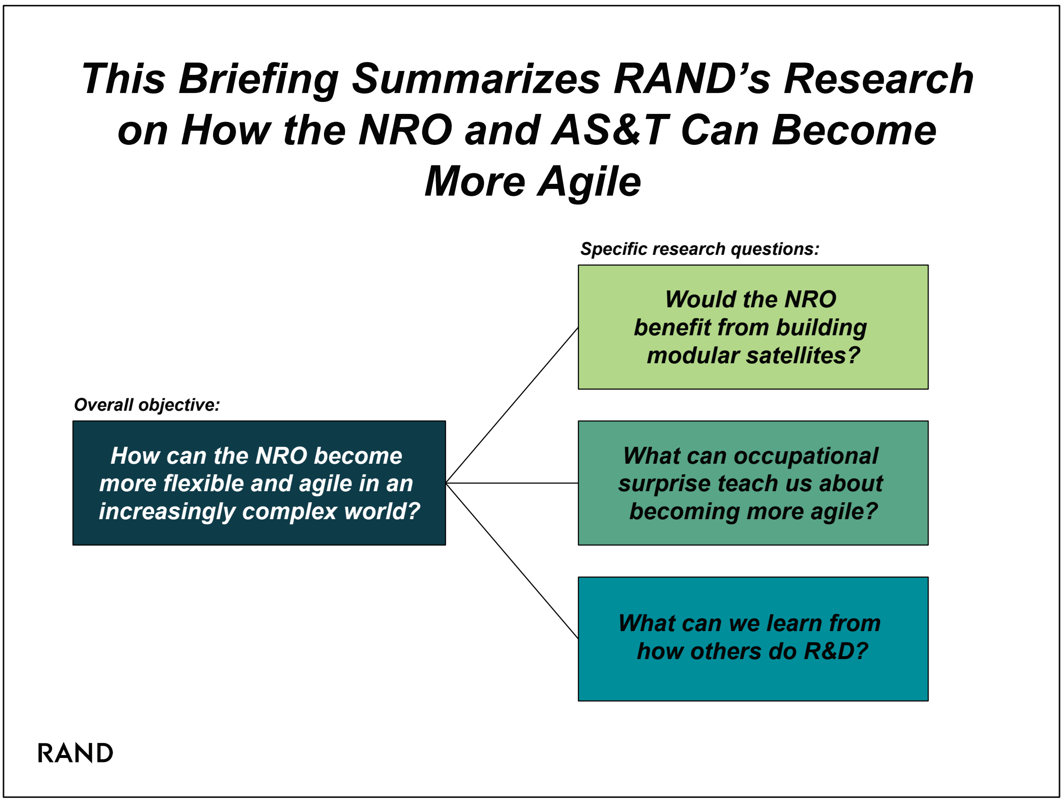
We recognize that the results from this approach will never be as satisfying as the results from solving the IC's analog to the parking garage problem because it will not yield a quantitative result. Instead, it offers an interim solution for making progress before the larger challenge of addressing intelligence value is addressed. However, even though this approach offers an easier path (in return for less-satisfying answers), there are still several challenges that must be addressed. Specifically, identifying the right components to modularize to accommodate change will be a significant challenge, and modularizing when there are many unknowns can be precarious. There is a significant amount of risk in committing to any specific trajectory or performance metric when the direction of the technology is uncertain, and for this reason modularizing too early in the development of a technology is often not recommended. If the technology trajectory is misidentified, the user could be left with an obsolete system, having wasted effort on modularizing and subsequently finding it to be incompatible with newly evolved technology.

An example from the music industry, which was brought to our attention by one of the modularity experts with whom we spoke, is helpful for illustrating this point (Schilling, 2012). Up until the mid-1990s, the technologies used for music playback all progressed with increases in playback fidelity, starting with vinyl records before moving to cassette tapes and then compact discs (CDs). In the '90s, the music industry started looking for a playback medium that was of even higher fidelity than the compact disc, and they started working on a standard called Super CD. Yet, Super CDs do not exist today. What happened?

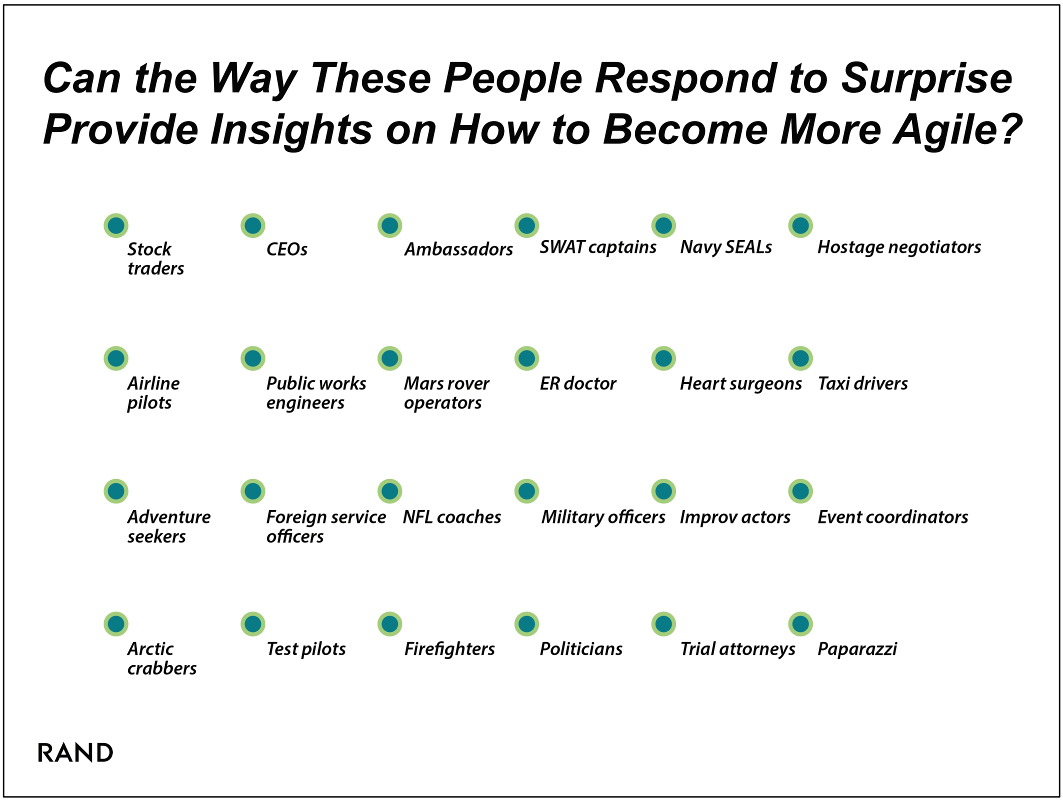
The reason that Super CDs have not been commercialized is because the music industry got it wrong: They thought that consumers wanted higher-fidelity sound, but consumers really wanted portability. While the industry was trying to settle on the standards for the Super CD, the rise of inexpensive personal computing gave rise to MP3, an electronic file format. What is interesting about this example is that the progression from records to cassettes to CDs aligns with increasing improvements in both fidelity *and* portability, but the music industry either failed to identify this parallelism or simply followed the wrong metric. The lesson is that predicting future needs is not straightforward and is highly uncertain. Choosing the wrong parameters and technology trajectories can end up inhibiting innovation and enhancement of a system and, in the worst case, can leave the user with a system with functions she or he does not need and lacking the functions that are needed.

CHAPTER THREE

Occupational Surprise



We now move on to the second research topic: What can we learn about agility by looking at how different occupations respond to surprise?



Surprise is universal. Virtually all professionals must plan for and deal with unexpected events as part of their daily practice. This makes "occupational" surprise an attractive study topic because the lessons promise to apply broadly across a variety of professions, including the U.S. IC.

Our work began with two basic questions about how people react to surprise:

1. How can we become more adept at planning for an uncertain future?
2. Are there lessons in how different occupations respond to surprise?

Our research objective for this task was therefore to investigate how different occupations respond to unexpected events.

We started our research by considering a list of occupations, some examples of which are shown in this slide. We started our list with professions like National Football League (NFL) coaches, Navy SEALs, and test pilots, but we also realized that longer-term thinkers like CEOs and ambassadors also have to deal with the unexpected.

After identifying a starting list of professions, we consulted the academic literature to identify a basic decisionmaking model. We then built on that model, developing a framework that would allow us to more easily characterize and classify the professions. We used the framework to help us develop our hypotheses as we started our research.

Before we describe our method and findings in detail, it is worth noting that this research topic proved to be so rich that we have also published a stand-alone document that more completely describes this research (Baiocchi and Fox, forthcoming). For the purpose of this report, we will outline our initial hypotheses, research method, and findings. We will conclude by making observations on how our findings can be used by NRO/AS&T. Our longer document greatly expands on these topics, including additional context on our hypotheses and data collection methods, along with additional anecdotes that we gathered from all of our practitioners. In addition, we expanded the context of our findings and recommendations so they could be accessible to an audience outside the U.S. IC.

Finally, at the request of our sponsor, we purposely did not include occupations from the IC in our assessment. We did this for two reasons. First, we did not want to bias our result by including our immediate audience in our research. If we had, we may have favored conclusions toward one group or another, possibly favoring one conclusion over another. Second, the sponsor was interested in presenting the results from this research to the IC at large, and we suspect that different parts of the IC will fall into different portions of our framework. Leaving the IC out of our initial dataset means that each group can make its own assessment on where it stands within our framework and conclusions.

At the most basic level, preparing for and responding to surprises is about effective decisionmaking. Therefore, our initial approach was to begin by reviewing the pertinent decision-science literature that relates to unexpected events.

There are a number of books that address aspects of the surprise problem. Weick and Sutcliffe's *Managing the Unexpected: Resilient Performance in an Age of Uncertainty* (2007) presents a set of rules that high-reliability organizations (HROs) should follow in order to effectively mitigate the negative effects associated with unexpected events.[1] Bazerman and Watkins's *Predictable Surprises: The Disasters You Should Have Seen Coming, and How to Prevent Them* (2008), focuses on the nature of the surprise itself, and they outline a set of characteristics that are useful for identifying "predictable surprises" before they cascade into more-damaging effects. In *Thinking in Time: The Uses of History for Decision-Makers* (1986), Neustadt and May focus on the utility of using historical analogies to inform present-day decisionmaking. McCall, Lombardo, and Morrison's *Lessons of Experience: How Successful Executives Develop on the Job* (1998) discusses how important experience is for effectively responding to unexpected events.

As we would later confirm, all of the components highlighted in these works—strategies for developing effective response techniques, methods for identifying surprise indicators, development of personal and institutional experience, and the ability to

[1] The term *high-reliability organizations* (HROs) is used by Weick and Sutcliffe to describe organizations that have "no choice but to function reliably. If reliability is compromised, severe harm results" (Weick and Sutcliffe, 2007). Specific examples of HROs include nuclear power plants, air traffic control systems, and hostage negotiation teams.

leverage historical analogies—are important elements of an effective preparation and response plan. However, as the starting point of our own research, we needed to understand the specifics of the decisionmaking process that professionals use when confronting surprise. This required identifying a relevant model as a starting point from which to develop testable hypotheses to probe through our discussions with expert practitioners.

In the end, we settled on Gary Klein's *Sources of Power: How People Make Decisions* (1998). Through years of field observations watching firefighters, aircraft carrier operations, and intensive care units, Klein has refined what he calls the recognition-primed decision model (RPD). The RPD provides a notional framework for how high-stakes decisions are made (Klein, 1998, p. 7).[2] As Klein notes in his exposition of the model, it fuses two processes: how decisionmakers use prior experience to recognize a situation and how decisionmakers decide on an appropriate course of action (Klein, 1998, p. 24).

Klein's model outlines three potential paths that decisionmakers follow when confronting a decision:

- The first is for executing prescribed responses to easily identified problems: The decisionmaker recognizes the change as something that has been seen before and proceeds using a previously prescribed course of action.
- The second variant is for when the problem cannot be immediately identified. In this case, the practitioner will attempt to diagnose the situation by matching observed features with past experience. If this is not immediately successful, the practitioner continues to observe the scenario to collect more data until he or she is able to determine causality.
- The third RPD variant applies when the practitioner can identify the problem but does not have a prescribed solution at hand. In this case, the decisionmaker often uses mental simulation to evaluate each potential response to identify the best option. Once the optimal solution is identified, the decisionmaker can implement that as the proper course of action.

Klein provides a helpful analogy for understanding these paths, likening decisionmaking to an "if-then" process. The first variant is when the decisionmaker knows both the "if" and the "then." The second is when the decisionmaker only knows the "then," and the third is when he or she only knows the "if" (Klein, 1998).

Klein's model therefore provides an initial framework that describes how professionals make decisions in uncertain environments. The model suggests three key aspects regarding how people respond to surprise:

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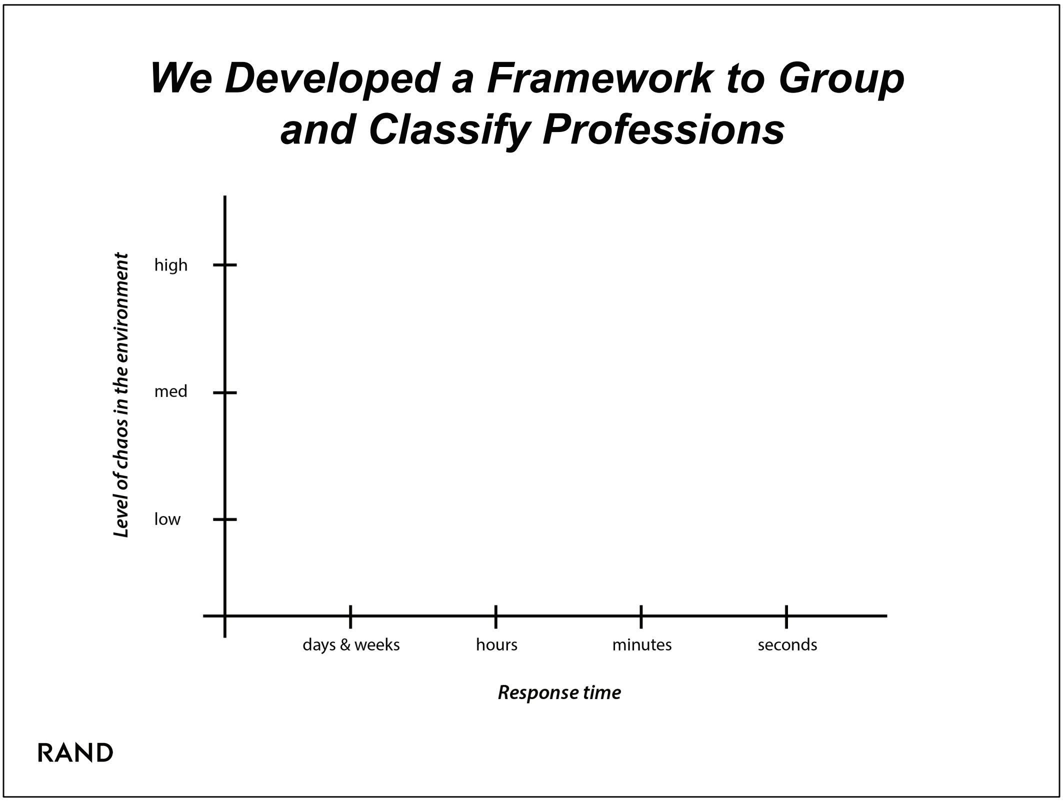
2 Klein implicitly defines high-stakes decisions as decisions in which lives or significant resources are at stake (Klein 1998, p. 4).

- Whether conscious or subconscious, decisionmakers rely on a notional decision loop to evaluate and make decisions.
- Decisionmakers will use different mental mechanisms to respond, depending on whether the surprise is immediately recognized.
- When confronted with a situation for which they lack a prescribed solution, decisionmakers use mental simulation to test out potential responses before deciding on a course of action.

We were also interested in probing deeper into the nature of the surprise, so we drew inspiration from nine factors that Klein uses to define a naturalistic decisionmaking setting (2008). These factors are experienced decisionmakers, high-stakes scenarios, dynamic conditions, inadequate information, time pressure, ill-defined goals, poorly defined procedures, team coordination, and cue learning. Because our research objective required distinguishing between various surprise operating environments, we focused on three key factors of naturalistic decisionmaking settings: time pressure, inadequate information, and dynamic conditions. Those three factors appeared (to us) most likely to influence the approach that experienced professionals use when responding to unexpected events.



We refined Klein's factors of time pressure, inadequate information, and dynamic conditions into a two-dimensional classifying framework, or "surprise space." The framework that we developed is shown above. The two axes are categorized by *typical response time* and *level of environmental chaos* (which combines the concept of a dynamic environment with one of inadequate information).

We used *typical response time* to characterize the horizontal axis, and we have four discrete points (seconds, minutes, hours, and days and weeks) that characterize an occupation's most common operating mode.[3] An example of someone who operates with a typical response time of a few seconds is a combat airplane test pilot; an example of someone who operates with a response time of days and weeks is a CEO.

We used *level of chaos in the environment* to characterize the vertical axis, and we chose three levels: low, medium, and high. We define *chaos* as a subjective measure of the frequency, diversity, and predictable orderliness of events, and this meaning seemed to best fit the quality that we were trying to assess. This definition followed from the recognition that some professions work in more controlled environments than others, and we hypothesized that this would be an important factor when considering how

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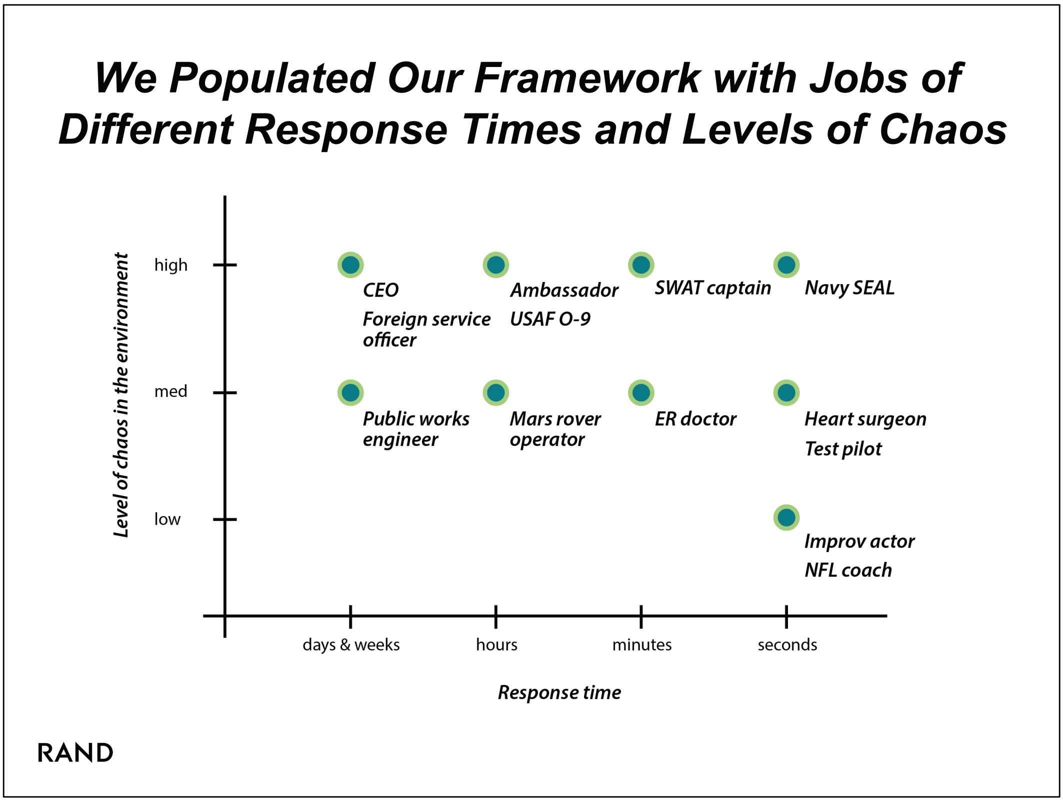
[3] We characterize *response time* as the span between the surprise being detected and the point at which a decision must be made to mitigate or prevent the event from becoming a more-challenging scenario.

professions approach and respond to surprise. Our definition incorporates that inability to predict or control events but also includes a measure of how frequently those events occur and how disorderly the resulting environment is.

Those occupations working in low-chaos environments are jobs that take place in very contrived environments. An NFL coach is a good example of someone who works in a low-chaos environment because he or she works in an athletic arena, where the grounds are carefully manicured, the climate is often controlled, and the fans are separated from the players by physical barriers. A heart surgeon is a good example of someone who works in a moderately chaotic environment. The surgeon works in a semi-contrived environment: Operating rooms are sterilized, full of instrumentation, well lit, and climate controlled. However, the surgeon faces more complexity than the NFL player because a greater number of factors can influence the situation. An example of someone who works in a highly chaotic environment is any profession that works mainly "in the field," where the environment cannot easily be controlled. For example, Special Weapons and Tactics (SWAT) teams must deal with civilians, criminal perpetrators, pets, equipment, weather, and other law enforcement colleagues. All of these factors contribute to what we are calling "highly chaotic" environments.

Our goal in developing this framework was to ensure that we considered a broad spectrum of interviewees (professions) based on the two characteristics that we describe above. We recognized from the outset that we did not have the resources to conduct a comprehensive study on this subject. Instead, we developed the framework because we were looking for a simple method that we could use to quickly draw lessons about how different classes of practitioners use different methods.



After developing the framework, we populated the axes with a list of example professions. Our goal in populating the axes was to identify at least one occupation for each intersection.[4] (We will defer discussing our selection method for a moment and will first describe the research hypotheses that we wanted to test.)

The framework shown in this slide was particularly helpful because we used it to motivate the hypotheses for our research. For example, our first research question came from looking at all of the professions shown in this slide: Are there preparatory and surprise techniques that are common to all (or most) occupations?

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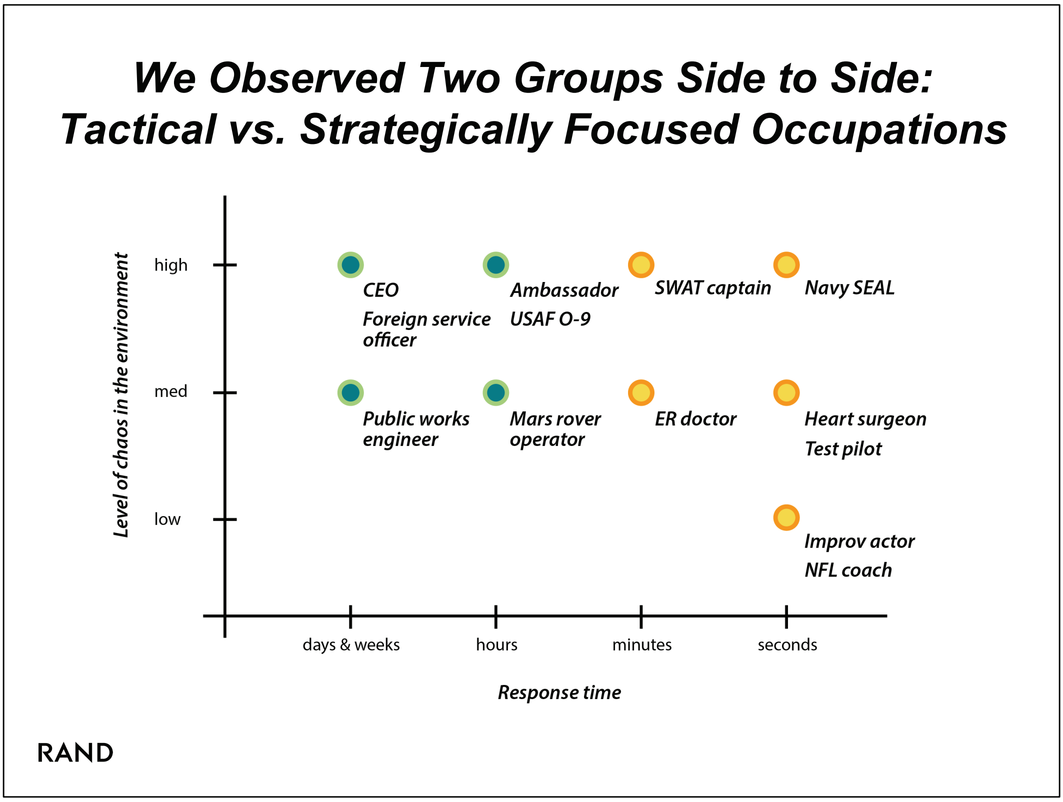
[4] We chose not to populate the lower left corner of the framework. The goal of this research was to identify ways to become more agile and flexible, and we assumed that occupations operating in a low level of environmental chaos with hours, days, and weeks of response time would not yield satisfying conclusions toward our research objective.



In developing our second hypothesis, we observed that splitting the visual framework down the middle of the chart creates two groups. Those occupations on the right side of the framework (in yellow and orange) are all very tactical in nature, so we started referring to this group as the *tactical professions,* using the military's connotation of the word *tactical*.[5] One observation about most of the tactical professions is that they are skilled in touch labor: They work with their hands. This is likely due to the fact that all of these professionals need to get things done *quickly*, and personally interacting with their environment is the best way to be most responsive.

By contrast, those occupations on the left side of the framework (in blue and green) are all more strategic in nature, with practitioners often having hours, days, or weeks to respond to unexpected events. We started referring to this group as the *strategic professions*. Workers in these occupations are also referred to as "knowledge workers," and they are valued for the knowledge capital that they contribute to their respective organizations.[6]

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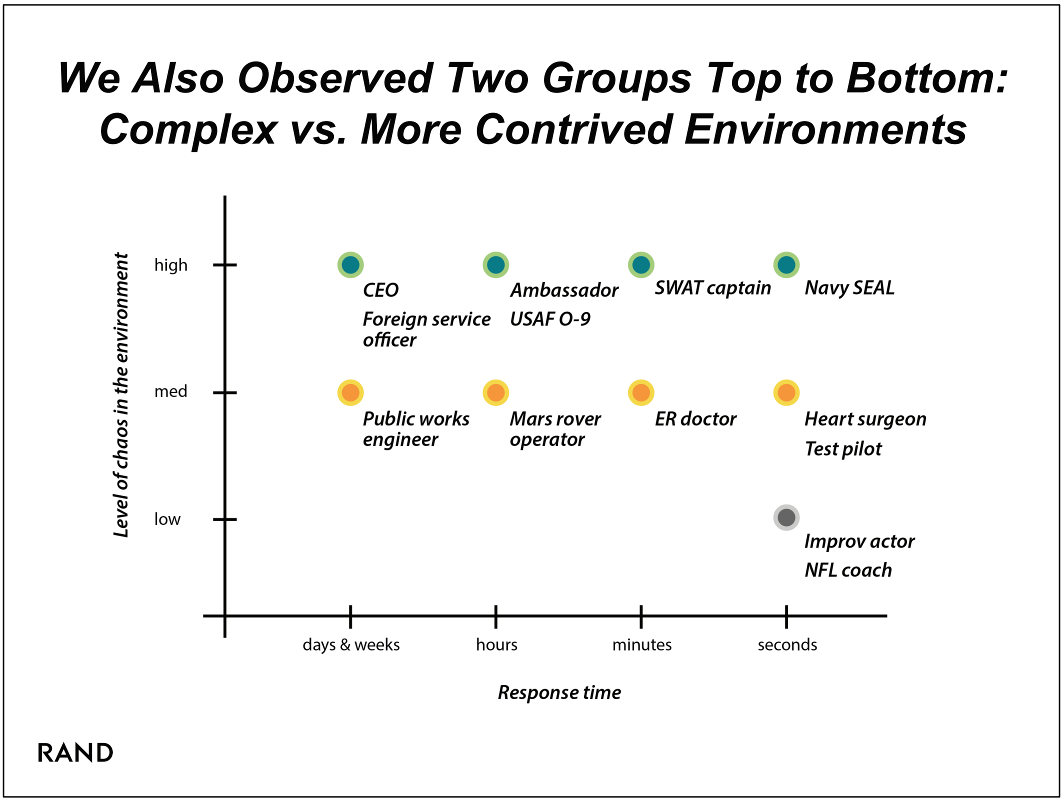
5 In military usage, a tactical operation is one that requires or involves near-term (short time frame) support actions.

6 By associating the term *knowledge workers* with the more strategically oriented professions, we inadvertently suggest that the tactical professions are not valued for their own knowledge capital. This is certainly not our

Finally, in using the terms *strategic* and *tactical* for occupations, we recognize that those individuals working in more-tactical occupations certainly do engage in long-term (strategic) planning as well, and vice versa for the strategic professions. We use the terms *strategic* and *tactical* to indicate each profession's most common operating mode when responding to unexpected events.

This observation of tactical and strategic professions motivated our second hypothesis: Do the tactical professions respond to unexpected events using different methods than those of the strategic professions?

intent. We chose to use the term *knowledge worker* because it is a phrase that is already part of the vernacular, and the colloquial meaning is in convenient alignment with our strategic professions.



Our third hypothesis is based on an observation that the occupations in the most chaotic environments differ from those in the other two rows. We observed that all of the occupations operating in the most chaotic environments all face surprise that is generated by other humans most of the time. By contrast, all of the professions working in moderately chaotic workspaces face surprises that are (generally) not caused by human actions, and this results in a less chaotic environment.[7]

These observations motivated our third hypothesis: Does the level of environmental chaos affect the way practitioners prepare for unexpected events?

[7] The NFL coach and improv actor do face surprises that are generated by other humans, so why do we list them as working in a low-chaos environment? The reason is that there are two contradictory processes at work: These professions face surprise that is usually generated by other humans, but they also work in very structured environments, which constrains everyone's decisions and actions. In addition, there are no third parties in NFL football or improvisational theater (save for the spectators). Thus, while unconstrained humans seem able to generate the most-chaotic surprise environment of any we studied, the constraints of a structured environment and paucity of third-party actors cancel this factor out.

We Developed Hypotheses and Sought Out Practitioners to Test Our Initial Assumptions

- **Our key hypotheses were based on observations made using our framework:**
  1. **Are there response techniques common to all practitioners?**
  2. **Does the response depend on timescale?**
  3. **Does the response depend on the level of chaos in the environment?**
- **We conducted discussions with experts to test our hypotheses:**
  - **Did we get the correct response time/chaos?**
  - **What are some examples of surprise?**

RAND

Once we developed our key research questions, we took a methodical approach to answering them. Our aim was to span the spectrum of surprise environments by selecting an occupation for each X-Y intersection. We made these selections based on several criteria. The first factor was entirely due to practicality: We had limited time and resources for this project, so we wanted to select professions for which we were confident that we could readily recruit and speak with an experienced practitioner. We also viewed the variety of professions as an asset toward meeting our research objective. By interviewing a wide variety of practitioners (instead of just health care providers, for example), we hoped to gain a wider variety of backgrounds and perspectives. Indeed, as we will describe, this ended up being an asset when we heard similar themes emerge from seemingly different perspectives: It helped reinforce the notion that the response strategies we were hearing were robust and could be used across multiple professions.

In addition to these primary criteria, our participating practitioners had to have at least ten years of post-training professional experience, have achieved a high supervisory or equivalent level of responsibility, and have otherwise distinguished themselves (through commendations, awards, or peer recognition) as superior performers in their fields. We imposed these additional criteria because we assumed that speaking with experienced and successful individuals would be the most efficient way to learn effective and best practices.

We were fortunate in that everyone with whom we attempted to speak agreed to participate in the project. The final list included 13 representative occupations: CEO, retired U.S. ambassador, test pilot, foreign service officer, cardiothoracic surgeon, recently retired Navy SEAL, recently retired NFL coach, professional improv actor, public works/civil engineer, space mission planner/operator, recently retired Air Force lieutenant general, SWAT team commander, and emergency room (ER) physician.

We have refrained from disclosing the names of those with whom we spoke because part of our research approach was to promise our participants anonymity. Conversations lasted from 45 to 90 minutes, with approximately half conducted by phone and the other half in person. Two researchers participated in each discussion, with one taking the lead role, and the other primarily taking notes.

We had three goals for these discussions. First, we wanted to confirm that we had correctly located each profession within our axes. To do this, we asked each representative how quickly he or she had to react when responding to surprise. We also asked them questions about their operating environments to make sure that our estimate about their level of chaos was accurate. The positions shown on the previous slides reflect the final, representative locations of all the exemplar occupations.

The second goal of the discussions was to learn more about the techniques and tools each person used when responding to surprise. To do this, we asked the participants questions about how they typically responded to surprise and what (if any) professional or organizational protocols they relied on when responding. Our questions were based on our hypotheses and research objectives, but the conversations were allowed to progress organically, and they did not follow a highly structured protocol.

The final goal of these discussions was to obtain anecdotes that could be used to support and illustrate our findings. Participants offered a surprisingly rich and varied set of such stories, some of which we share in the following pages.

We conducted semistructured interviews with practitioners working in each of these professions to achieve the three goals mentioned above. Before beginning the interviews, we developed a basic protocol that outlined the key topics that we hoped to discuss in every conversation. Specifically, we focused on the following (exemplar) questions:

- What is the level of chaos and usual available response time in the typical operating environment?
- What are some other parameters and constraints of the typical operating environment?
- What are the criteria for operational success or failure?
- What role does surprise play in the operating environment?
- What does the response process look like when surprises occur?
- What resources, tools, and strategies are available for dealing with surprise, and how are they typically applied?

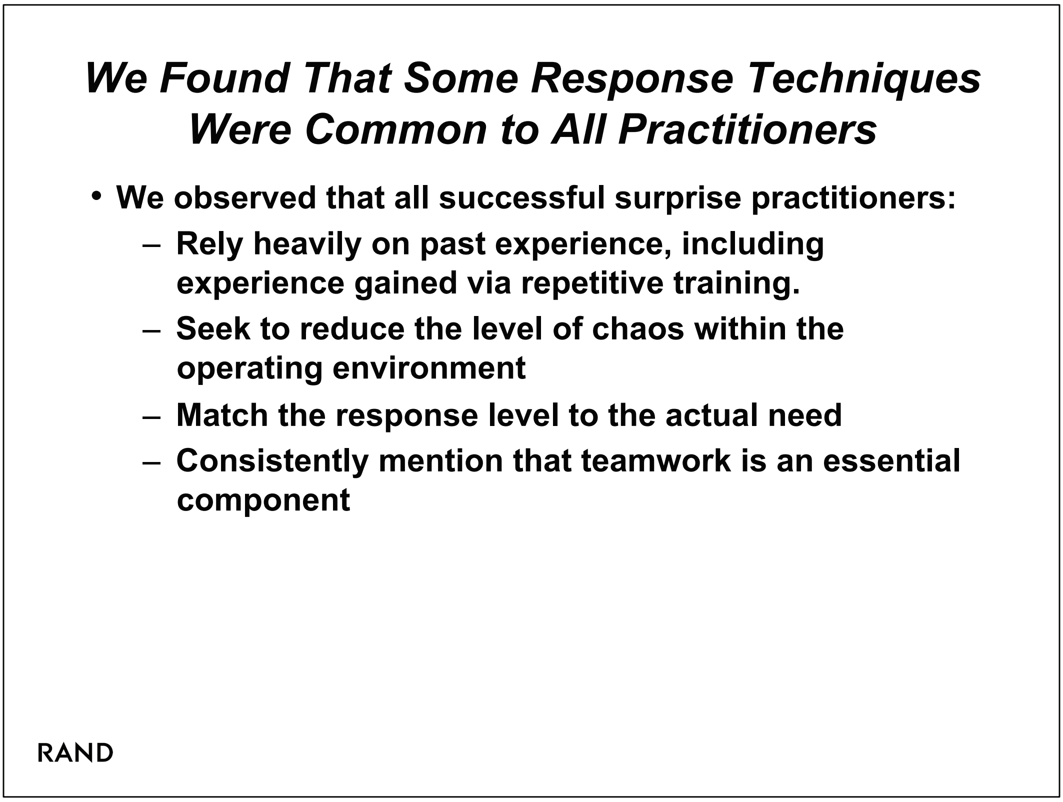
- How much do flexibility and finesse apply when dealing with surprise?
- To what extent are surprises viewed as opportunities rather than obstacles?
- What are the key elements needed to successfully deal with surprise? What are some examples of when those approaches failed?
- What are some characteristics of a professional in the field that allow the person to best handle surprise?
- Finally, we always gave participants the opportunity to express additional thoughts on topics that had not been covered earlier.

Data from each practitioner conversation was analyzed using qualitative methods. Both investigators discussed the content and debriefed each other within 24 hours following each conversation. We compared information provided by the professional against the relevant components of our initial conceptual model, looking for confirmation, disconfirmation, and novel insights or features. We used the descriptions that participants described about their methods and processes to test our hypotheses.

We also compared their information against that provided by other professionals, looking for subjective similarities and differences in their approaches to surprise. The goal of this particular exercise was to identify key themes across the different practitioners. Where differences in approach could be identified, we also attempted to characterize any associated differences in the surprise environment between those professions. These iterative updates to our initial hypotheses, including any tentative conclusions regarding the reasons for differences and similarities in approaches between professions, were then subsequently tested when discussing related topics with other professionals. Following the completion of our discussions with all recruited professionals, the results of this analysis were then organized and grouped by initial hypothesis.

It was not our intent to evaluate our interview data using quantitative or statistical means. For example, we did not set out to make statements like, "75 percent of all CEOs rely on the same method to respond to an unexpected event." This is because such an approach was not in alignment with our project's goal of simply identifying general trends across the professions. A second reason is that we interviewed 15 professionals in total, which is not a statistically large sample.

How did we know that interviewing 15 professionals was sufficient in meeting our goal for identifying general trends? For guidance on this, we followed a suggestion by Robert S. Weiss in *Learning from Strangers: The Art and Method of Qualitative Interview Studies* (1994): "[Y]ou stop when you encounter diminishing returns, when the information you obtain is redundant or peripheral." About two-thirds of the way through the interview process, we began to recognize familiar narratives, a good indication that our small data set was nevertheless providing empirically reliable data. This suggested that we had reached what survey managers call the "saturation point" and was a good indication that the number of interviews was sufficient for meeting our research objective.



We found a number of coping strategies that were common across all of the professions.

First, we observed that all practitioners rely on experience. Experience is one of the best insurance policies against the negative effects of surprise because it provides the context necessary to recognize and respond to unexpected events. Experienced practitioners are able to quickly identify surprises and generate potential reactions and solutions based on what they have done in the past.

We also observed that all professions try to reduce the level of chaos in the operating environment, since reducing chaos also reduces the complexity and size of the solution space. Reducing chaos can be done in different ways, either by controlling the environment or spending a few extra moments (or days, depending on the profession) gathering more data on the situation.

For example, test pilots only execute one maneuver at a time. In addition, the test plane is outfitted with a suite of environmental sensors that are constantly being monitored by a room of test engineers. When the engineers detect a problem, they are able to provide the pilot with data and context that help him to focus his response procedures toward the root cause of the problem.

Similarly, the cardiothoracic surgeon with whom we spoke prefers to work with the same team of nurses and doctors for all of his procedures. In addition, he organizes his surgical tools using the same layout for every surgery, and he tends to repeatedly use pieces of monitoring equipment with which he is most familiar. Both of these examples demonstrate ways that practitioners reduce the size of the surprise space to minimize the number of things that can go wrong.

We also learned that it is best to react to surprises with a measured response to preserve further options as the surprise unfolds. As examples of this, both the CEO and the Navy SEAL used essentially the same language to tell us that it is important not to overreact when confronted by a surprise. Along with nearly all of our participants, they emphasized the importance of matching the remedy to the actual need.

Finally, we observed that teamwork plays an essential role when responding to unexpected events, even for those professions that are usually perceived as relying on individual actors, like heart surgeons or test pilots. All of the professions emphasized that they all relied heavily on teamwork to successfully deal with surprise events.

We Observed That the Level of Environmental Chaos Determines How Practitioners Prepare

- **In the most contrived environments, practitioners develop and rely on specific "what if" plans**
- **In moderately complex environments, practitioners**
  - **Prepare "what if" plans for likely and existential threats**
  - **Rely on protocols and training for all else**
- **In complex environments, practitioners**
  - **Develop robust and generalized response frameworks (and exercise them)**

RAND

We found that the level of environmental chaos strongly affects how practitioners prepare for and respond to surprise. Specifically, we found that practitioners who work in the most structured (low-chaos) environments, like athletic fields or theatrical stages in which most environmental factors are controlled, face only a finite range of possible outcomes. Because of this, these practitioners are able to plan reactions for nearly any event, and practitioners in the NFL, for example, regularly do so. For many working in low-chaos environments, it makes sense to develop comprehensive "what if" plans because the size of the surprise space is small (compared to other professions) and finite.

Practitioners who work in moderately chaotic environments like operating rooms or test plane cockpits rely on preplanned protocols for the most likely events, along with anything that represents an existential threat. As an example, the ER physician with whom we spoke indicated that he had protocols to deal with some of the most common injuries that arrive in the emergency department. However, he also recognized that there are too many unforeseen events in moderately chaotic environments to plan against every possibility, so he relied on basic response frameworks when the surprise event was not covered by a specific protocol.

In addition to preparing for the most common threats, we found that practitioners in moderately complex environments also make "what if" plans for existential threats. For example, the Mars rovers take most of their commands directly from mission managers on Earth each day. However, a small number of commands are embedded (preprogrammed) on the spacecraft to guard against existential threats. An example of a mission-ending threat would be if the rover's communications dish were ever positioned below the horizon line. If this occurred, the rover would not be able to receive commands from earth, and this would effectively represent the end of the rover's life. To address this possibility, the rovers are preprogrammed with instructions to automatically reposition the antenna back toward Earth.

The most challenging circumstances are faced by those practitioners working in highly chaotic environments, such as in a foreign embassy or behind enemy lines. Their environments are so complex and unpredictable that it does not make sense to do much planning against specific surprise events. (This is because workers in the field must deal with third parties, unpredictable weather, and unfamiliar terrain.) Instead, practitioners working in highly chaotic environments develop and exercise a general-purpose framework that can be deployed whenever a major surprise is encountered.

As an example, the former ambassador with whom we spoke referred to his framework as a "task force" and noted that the task force is the standard tool that he used whenever he encountered a surprise. Therefore, he and his staff had worked out the details of assembling a task force ahead of time. While they did not know what the specific surprise was going to be, they knew it would require office space, lines of communication, and the support of some key people inside and outside the embassy. They then prepared and practiced a process for quickly deploying this infrastructure when needed.

We Observed That Strategists Use Different Response Mechanisms Than Tacticians

- When a surprise happens to a tactician, they are often trying to control fear and anxiety. Their response tends to involve the following steps:
  - Control panic
  - Buy time
  - Revert to fundamentals learned in training, allowing effective response using minimal analysis.
- By contrast, strategists often have to control ego, anger, and overreaction. To do this, effective strategists will
  - Control emotions to maintain objectivity
  - Take initial enabling actions
  - Assemble the staff
  - Socialize the longer-term plan

RAND

We found that practitioners within our *tactical professions* rely on different tools than those within our *strategic professions*.[8]

Based on the data that we collected during our interviews, we found that when tacticians are surprised, they often have to deal with emotions of fear and anxiety. As a result, we found that their response loop is designed to combat those emotions. We also note that tacticians typically rely on protocols to overcome these emotions in order to respond effectively using minimal analysis. As an example, the test pilot noted that he was trained to "wind the watch" in the moments after a surprise, which refers to the menial task of winding the stem on his mechanical wristwatch. The goal of this task is to focus on a basic manual chore, with the hope that it would provide calmness and clarity in the immediate moments after a surprise occurs. Likewise, the former Navy SEAL noted that when SEAL teams are fired upon, they quickly take steps designed to control panic and buy time: They fall into rehearsed positions on the ground that help them establish a strong defensive position. In taking these positions, the team is

[8] Again, we use the words *tactical* and *strategic* with specialized meanings in this document: The tactical professions are those that have to typically respond within minutes or seconds. Members of the strategic professions typically have days, weeks, or months to respond. As we stated earlier, we recognize that those individuals working in more tactical occupations certainly also engage in long-term (strategic) planning, and vice versa for the strategic professions.

able to gain confidence by quickly executing a familiar task that they have performed hundreds of times before.

In contrast to the tacticians, we found that surprising a strategist can cause anger and impulse desires to overreact. To combat this, we found that many successful strategists employ the same four-step process to counter these issues: take steps to control emotion and ego, initiate first-order enabling actions, assemble a trusted inner circle of advisors and direct reports, and disseminate a coherent longer-term response throughout the organization.

The CEO gave us the most intuitive example of a way to control emotion and ego; he noted that instead of responding immediately when surprised by an email, he places the message in his drafts folder and revisits it 24 hours later to confirm that the message is objective and constructive.

The retired three-star general officer gave us the best example of taking initial enabling actions after a surprise occurs. The general with whom we spoke was in command of some key logistics resources on September 11, 2001. As the day unfolded, no one was sure what was going on, but the general was confident that he would be called upon to provide his resources to the national command authority. Because of this, he started mobilizing a measured number of resources early on to ensure that a basic level of service would be available. This proved to be an effective decision because his leadership did call on him later that afternoon, and he was already in a position to start responding to their needs.

As we have already noted, most strategists are valued for their knowledge capital, and this means that most work in larger, hierarchical organizations. Most of the strategists with whom we spoke were senior people at the tops of their respective hierarchies, and this means that they relied heavily on direct reports and trusted staff members whenever a surprise occurred. Therefore, we observed that the next step strategists took after taking steps to control their emotions was to assemble the staff and develop a plan for moving forward. In doing this, all of the strategists noted that it is very important to decide on a plan, socialize that plan throughout the organization, and present a unified front when executing that plan.

We Also Observed Two Key Findings That Were Not Part of Our Initial Hypotheses

We were surprised to observe that

1. **The most chaotic environments all feature surprises that are motivated by other humans rather than the environment.**
2. **The largest surprises come from third parties rather than a direct stakeholder or adversary.**

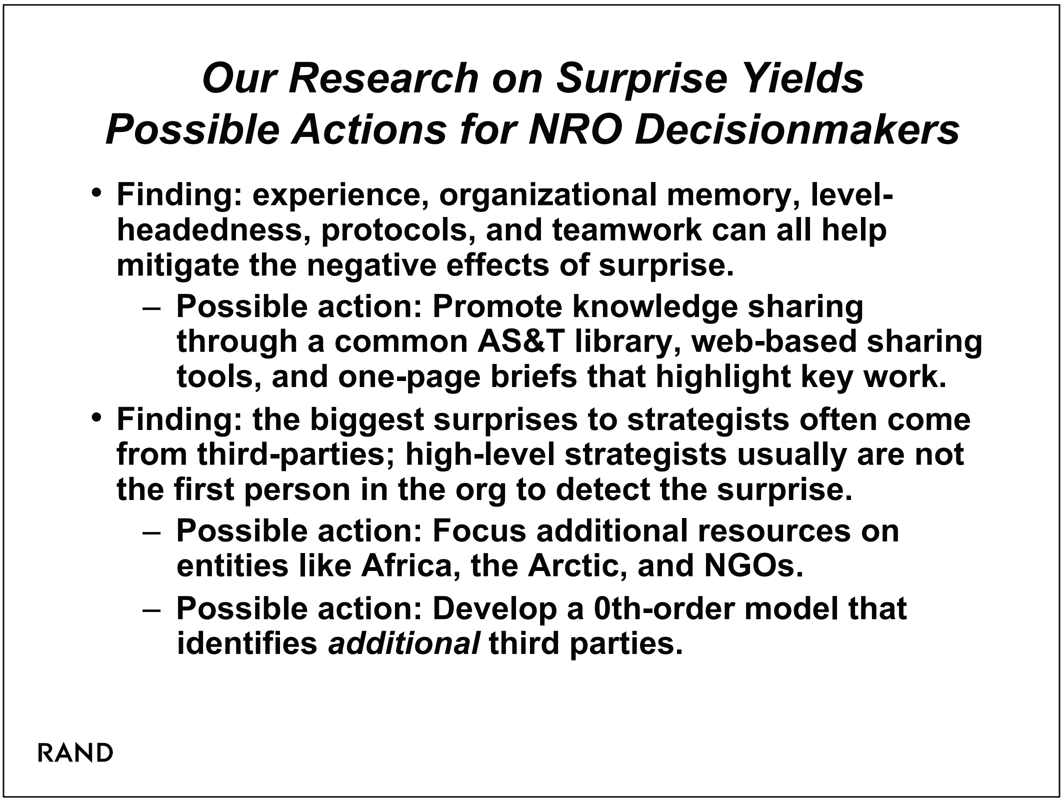
RAND

As researchers, we were surprised by two findings that were not part of our initial hypotheses. First, as we have already mentioned, the most chaotic environments all feature surprises that are driven by other humans rather than the operating environment. Furthermore, we observed that the biggest surprises tend to come from third parties rather than a direct stakeholder or adversary.

Our initial insight into this idea that surprises tend to come from third parties came from the Navy SEAL, who noted that he did not generally encounter major surprises from his adversaries. After all, he had spent a lot of time thinking about what motivated them, along with determining what calculus the adversaries were likely using to achieve their goals. Going into a mission, he would have spent time thinking about their objectives and would have a reasonably good chance of being able to predict how his adversary would behave.

So what surprises the Navy SEAL more than his adversary? Our practitioner told us that domesticated animals and civilians present the largest surprises to his team while on a foot patrol. These two groups represent big surprises because their motivations and actions cannot be easily predicted by the SEALs. Specifically, civilians are particularly risky for his team to encounter because the SEALs do not know how civilians will respond to them.

These two observations lead to our recommendations.



To conclude this section, we will recap our findings and present possible actions that NRO/AS&T could take to move forward.

First, we noted that experience, controlling emotions, having effective protocols, and relying on teamwork can all help mitigate the negative effects of surprise. There are several possible actions that AS&T could take based on these findings:

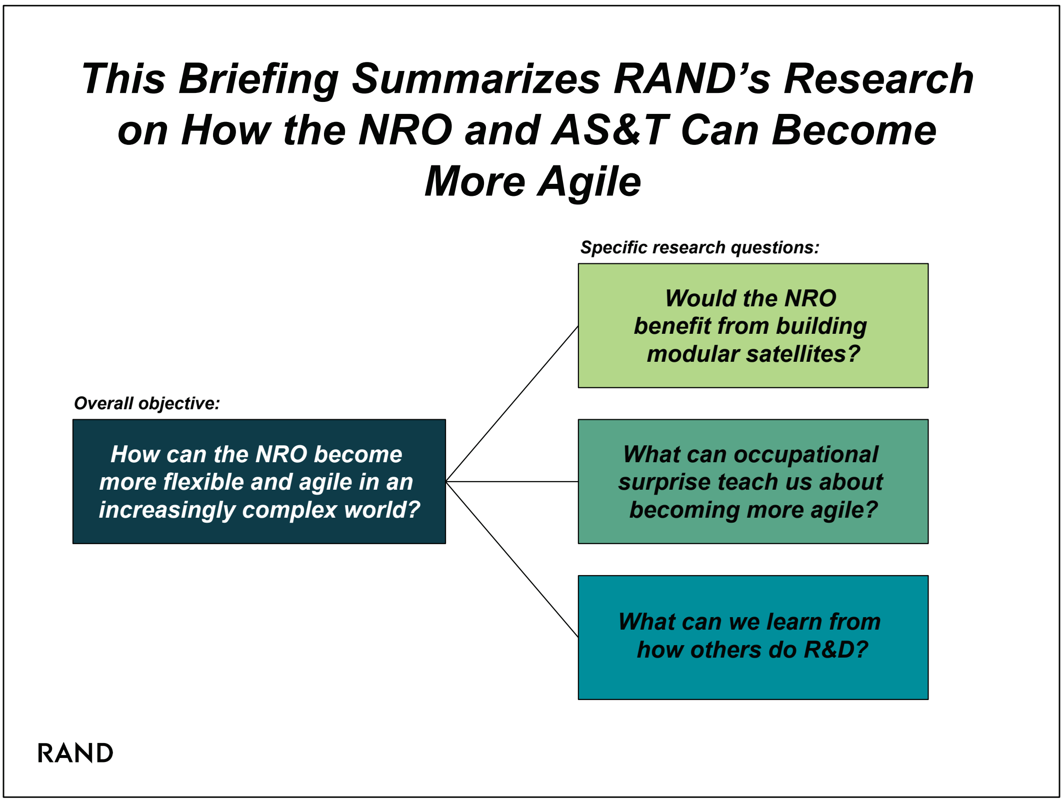
- First, AS&T can promote knowledge-sharing and experience-sharing through electronic means by developing a central repository that is designed to facilitate information-sharing throughout the organization. This could be achieved either through an online library or web-based tools that help employees share their experiences with one another. Recognizing that AS&T analysts are often very busy, it may be most efficient to manage knowledge-sharing by relying more on one-page briefs that concisely summarize findings rather than longer, more-involved reports.
- The second way to facilitate experience-sharing is through improved human-to-human interactions. For example, multidisciplinary core teams designed to tackle specific problems could be developed, with everyone on the team having common security credentials.

Our second key finding was that surprises tend to come from third parties, and that a high-level strategist usually is not the first person in the organization to detect the surprise. (This is often due to the fact that senior strategists are usually located near the top of an organizational hierarchy.) In practice, this finding suggests two possible actions for AS&T:

- First, the fact that the biggest surprises are most likely to come from third parties suggests that AS&T should focus some resources toward researching third-party intelligence problems. Three examples of these third parties for the IC might be Africa, the Arctic, and nongovernmental organizations (NGOs), which are playing increasing roles in world politics and third-world development. In addition, AS&T might also benefit by considering a more nuanced version of this lesson: What third parties exist in threat environments that are already established?
- Second, AS&T would likely benefit from investing in a model that identifies additional third parties that may pose a threat in the future. We make this suggestion with the knowledge that AS&T invests in developing "what if" plans against existing (known) threats. This recommendation suggests investing in models that can identify possible threats (or threat factors) in the future. After all, simply *identifying* potential threats is the first step toward mitigating any negative effects that may be caused by them.

CHAPTER FOUR

Organizational Mechanisms That Increase Responsiveness



For the last section of this report, we will describe some pilot research that looked at how other organizations run their research and development (R&D) processes.

Our Objective Was to Identify Similar Approaches Organizations Use to Become More Responsive

Company	End state	Actions
Pfizer	**Became more centralized**	• Sold off unrelated businesses • Closed research centers, increased collaboration with universities
IBM	**Shifted from products to services**	• Sold hardware business lines • Shifted to software/IT consulting
Caterpillar	**Became more decentralized**	• Created self-contained business units • Focused on increasing flexibility in the workforce

We hypothesized that these companies' restructurings would provide lessons on becoming more competitive, but the results were inconsistent. Why?

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In the previous two sections, we examined ways that the NRO could allow its people and hardware to become more flexible. In this final section, we performed preliminary research on how an organization's processes can be used to improve responsiveness. Our research on this topic was motivated by questions that were given to us by AS&T personnel: What methods have other organizations used to become more responsive? Are there observable similarities that could benefit the NRO?

To do this, we examined three companies that were suggested by AS&T: Pfizer, IBM, and Caterpillar. These companies were chosen because they have all been recently recognized in the media as having gone through transformations in order to better respond to pressures in the marketplace.

We examined these companies and found very different end states between the three: Pfizer become more centralized, IBM started selling a completely different product, and Caterpillar become more decentralized (Deviney et al., 2012; and Zarroli, 2011). Why did these companies take such different approaches?

We Hypothesize That Different Objectives Will Require Different Approaches

- **There are different ways to become more responsive:**
  - **Become more efficient (do more with less)**
  - **Increase agility (quickly adopt new technology)**
  - **Pursue the state-of-the-art (develop a brand new capability)**
- **We hypothesize that companies take different approaches depending on their objectives:**
  - **Pfizer reallocated resources to pursue high-risk, high-reward goals.**
  - **IBM changed their business line to avoid an existential threat.**
  - **Caterpillar reorganized to become more responsive to customer needs.**

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The reason for this, we hypothesize, is that there are different ways to become more responsive. We list three ways on this slide, but there are certainly more: Some companies become more responsive by improving efficiency—they do more with less. We also note two other methods: increasing agility (by always staying current with new technologies, for example) or inventing something that is state of the art. The reason or reasons driving change will determine the methods for getting there.

For example, Pfizer decided to concentrate on anticancer and Alzheimer's drugs (Thomas, 2012; and Wilson, 2011). In order to do this, it sold off and divested all of its unrelated properties so it could concentrate on this high-risk, high-reward goal. In the process, it centralized its organization and processes to pursue a single mission.

By contrast, Caterpillar was interested in becoming more responsive to its customers' needs. To do this, it decentralized and set up fully contained Caterpillar offices around the country, each containing everything needed to run the business: product experts, sales and maintenance teams, and finance and accounting personnel. In doing this, it was able to customize its service to the local market, but this required the company to take a different approach than Pfizer.

Finally, IBM took yet a third approach: It fundamentally changed its product lines by choosing to focus more on consulting services rather than primarily delivering computing hardware.

One Future Research Objective Would Be to Match An Organization's Goals to Specific Processes

- **Why do it?**
  - **Cost effective**
  - **Reliability**
  - **Agility**
  - **State-of-the-art**
  - **Disruptive products**
- **How to do it?**
  - **In house v. outsourced**
  - **Inline R&D v. skunkworks**
  - **Singular v. multidisciplinary workforce**
  - **Specific v. diverse research portfolio**

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We observed that Pfizer, Caterpillar, and IBM each took a different approach for becoming more responsive in their responsive marketplaces. The next step for this research would be to develop a formal framework that connects the methods with the specific goals. In other words: Is it possible to develop guidance that instructs the organization on the best way to achieve those goals? We present these ideas here for future researchers who may be interested in pursuing these topics.

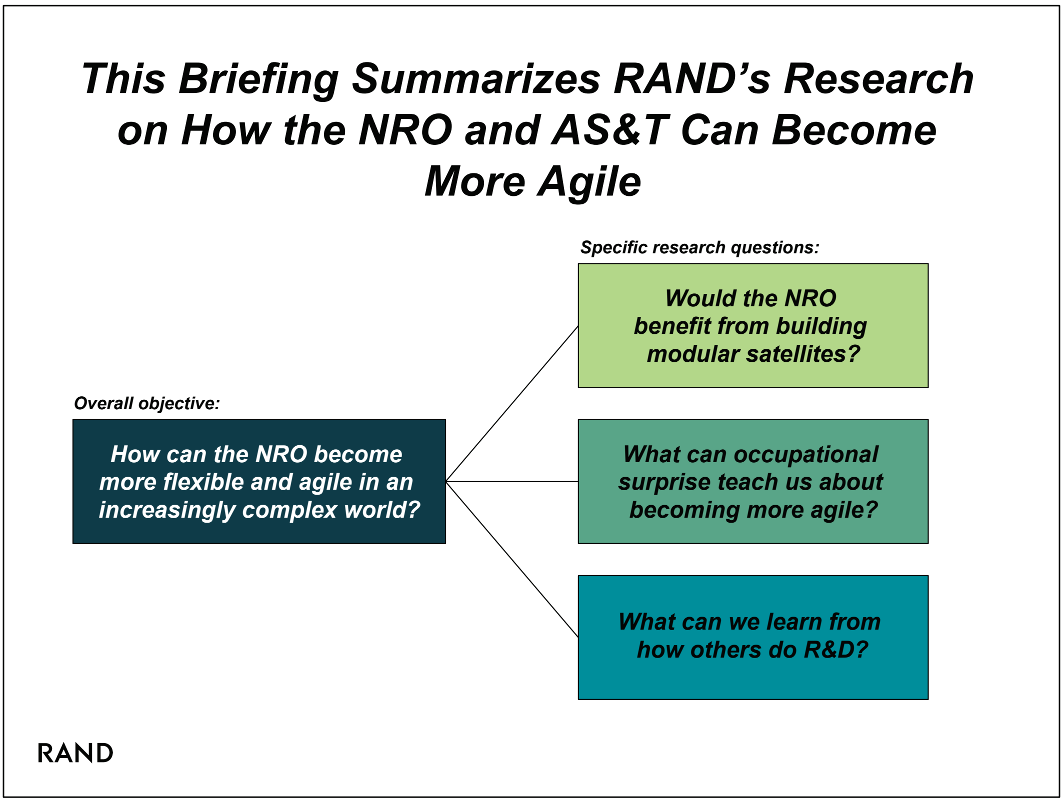
For example, we recognize that there are several decisions that organizations have to make when determining how to become more responsive. What aspects of the organization should be changed? Should R&D be performed in house, or should it be outsourced? Should the company rely on strategic investments for new intellectual property, or should it develop its own set of highly skilled innovators?

In addition, how should the research department be organized? Should it be designed as a skunkworks, in which a few of the most capable individuals do all of the work? Or should the company democratize the process by giving every engineer a small percentage of free time to work on pet projects?

Finally, what skills should the overall workforce possess? A multidisciplinary workforce is more likely to generate a wider spread of ideas (more golden nuggets along with more rotten eggs). Alternatively, a singular workforce will, on average, have more productive ideas than the multidisciplinary force, but their golden nuggets will be less likely to be as golden as those from the multidisciplinary team.

We did not have the resources to start matching the reasons for innovating with the best mechanisms for getting there, but we describe this issue as one to be addressed in future work.

CHAPTER FIVE
Conclusions



We conclude this report by making some observations that tie all three topics together, and we present some ideas for future work.

Despite the Diversity of Research Topics, There Were Common Lessons Throughout

- **Observation: Modularity and innovation methods are not goals by themselves—they are tools.**
  - **Takeaway: Need to set specific priorities and objectives before proceeding.**
- **Observation: Success in modularity, innovation, and averting surprise requires some future insight.**
  - **Takeaway: Invest in strategic vision, planning, and exercises that probe the future.**
- **Observation: Modularity, surprise, and innovative processes yield ways to evolve hardware, people, and corporate structures, respectively.**
  - **Takeaway: Becoming more agile requires an effort in all three areas (hardware, people, and corporate processes).**

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At first glance, all three of these research topics appear to be very different, but we did observe several common lessons throughout this project.

The first observation is that modularity and innovative methods are not goals by themselves—they are tools for meeting a particular goal. No one sets out to make a modular architecture for the sake of making a modular system. A modular architecture is motivated by a set of user needs, which usually include a desire to develop systems that are more flexible and adaptable. Similar reasoning holds true for implementing innovative methods: They are always used to achieve a larger goal. The takeaway from this observation is that, before considering modularity or new innovative practices, the practitioner needs to set priorities that will drive how to proceed using modularity and innovative processes, not the other way around.

A second common theme is that being successful in modularity, innovation, and averting surprise all benefit from at least a partial ability to generate future insight. Therefore, we conclude that any investments in developing strategic plans or visions, along with exercises designed to probe the future, can benefit all three topics.

Finally, we noted that modularity, surprise, and innovative processes yield ways to evolve hardware, people, and corporate structures, respectively. Our research shows that there is more to becoming more agile and responsive than just developing new hardware. Instead, improved responsiveness comes from an investment in all three areas. New hardware requires an equally flexible staff to design and operate it.

Based on These Common Lessons, We Propose Three Topics for Future Research

- **Finding: A wide FOV can avert surprise.**
  - **Task: Develop a wide FOV model to help AS&T expand their "surprise space."**
- **Finding: Modularity can limit how disruptive a technology could be.**
  - **Task: How do engineered systems evolve in disruptive ways?**
- **Finding: Organizations innovate for different reasons.**
  - **Task: What organizational structures are best for achieving a particular goal?**

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We conclude this report by proposing three topics for future research.

As we noted earlier, the research on surprise taught us that adopting a wide FOV can help mitigate the negative effects caused by surprise. Therefore, we propose developing a first-order wide FOV model to help AS&T expand its view over the surprise space. There are several methods that could be used to address this task: RAND's Delphi Method and RAND's existing work on robust decisionmaking could both be used to generate a list of the most likely third-party actors that may surprise the IC in the coming years, along with a set of scenarios that represent likely outcomes from these surprises.

Our research on modularity highlighted the fact that modular systems do pose limits on how disruptive a particular technology can be. Disruptive technologies create products or services in unexpected ways, and modularity's frozen interfaces put some restriction on how much a product is able to change in the future.

Swiffer® is a good example of a disruptive technology. Developed by Proctor and Gamble, Swiffer uses a woven dry cloth to clean floors without using any liquids. Before Swiffer, people usually cleaned their floors with a mop, a bucket, and some hot soapy water. When Swiffer was being tested in house, Proctor and Gamble's experts in cleaning floors noted that Swiffer was unlikely to succeed because it did not perform as well as conventional wet cleaning methods. This is certainly true, but what these experts failed to realize was that many consumers had never wet-mopped their floors because it was too much work to get out the mop and the bucket of water. When Swiffer was introduced to the market, it was well received by a large section of the population that had never mopped before, and Swiffer effectively opened a new market for mopping floors using dry cleaning methods.

One of the implied goals of the IC is to create and field more disruptive products. We propose performing research that looks to the biological sciences to develop a set of factors that highlight the conditions needed to generate disruptive products. For example, what environmental factors have led to some of nature's most disruptive patterns, like wings or legs? Or, on a more micro level: what conditions resulted in one species gaining more colorful plumage than a neighboring species? After examining some case studies, we propose looking to see what the engineering community can learn from these patterns. By looking at some analogs in nature, we hope to at least identify the conditions that might tend to generate disruptive products.

Finally, in our research on R&D processes, we noted that different organizations innovate for different reasons. We propose to continue this research by investigating one of the questions that we posed earlier in this briefing. Given a particular reason for innovating, what organizational measures are most likely to achieve that goal? For example, what types of problems is a skunkworks best at solving? When would it be more appropriate to conduct "inline" R&D by giving every engineer 10 percent free time to pursue pet projects, as is done at Google and 3M?

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To help the National Reconnaissance Office (NRO) become more flexible and agile in an increasingly uncertain world, RAND sought answers to two key questions. First, would the NRO benefit from building modular satellites? RAND researchers developed a method for evaluating whether a system is a good candidate for modularity and applied it to systems both inside and outside the NRO. The authors found that NRO space systems do not appear to be strong candidates for modularization. Second, what lessons might be drawn from how chief executive officers, military personnel, and health care professionals (among others) respond to surprise? RAND developed a framework to categorize professionals' responses to surprise and then conducted discussions with representatives from 13 different professions, including former ambassadors, chief executive officers, military personnel, and physicians. The authors observed that all interviewees used common coping strategies. The authors also found some differences in response to surprise that depend on two factors: time available to respond and the level of chaos in the environment. The report concludes with recommendations on actions that the NRO can take to improve the flexibility of its hardware and the workforce.

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