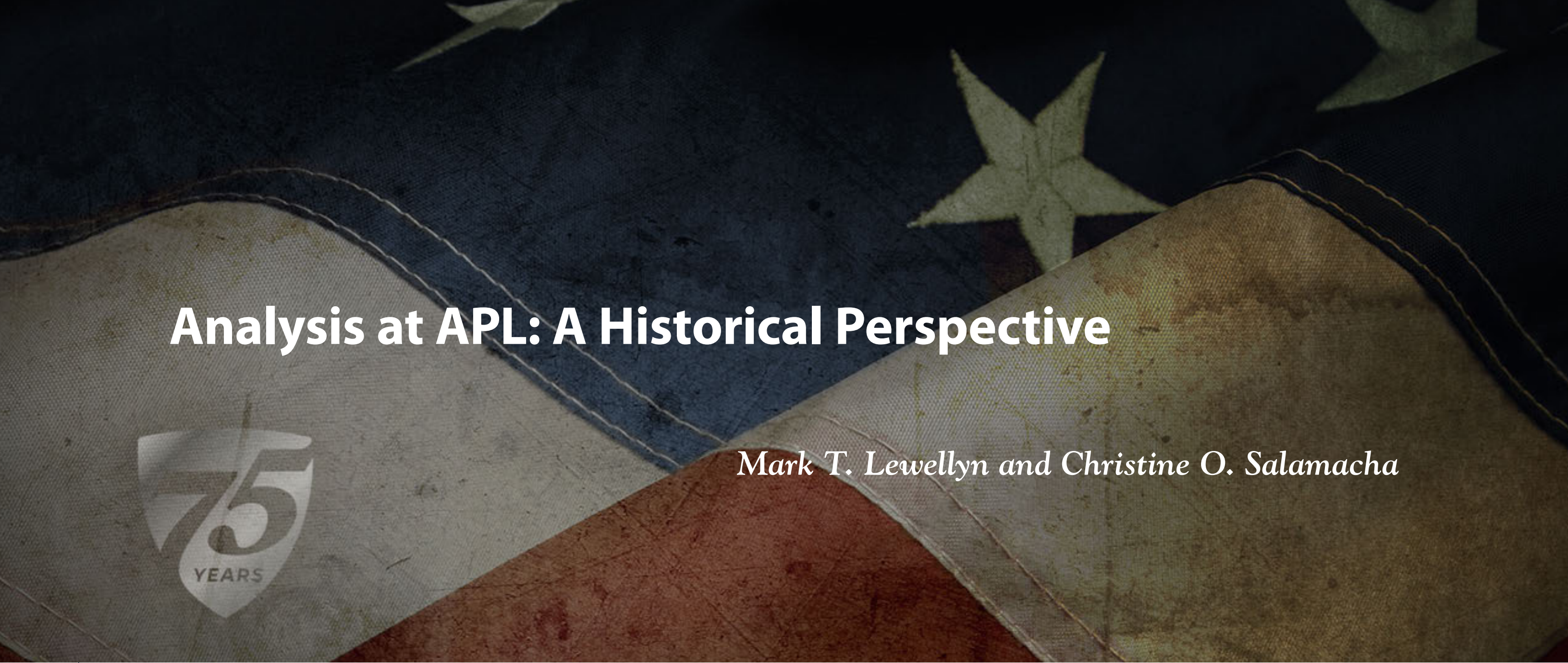

Analysis at APL: A Historical Perspective

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ABSTRACT

The foundational approaches to operations research, systems analysis, and systems engineering developed during World War II and the immediate postwar years greatly influenced the analytical work conducted by the Johns Hopkins University Applied Physics Laboratory (APL) during its first 75 years. In particular, these approaches shaped the systems perspective that has characterized APL's approach to analysis. This systems perspective, undergirded by APL's deep technical expertise and commitment to proven, data-based analytical methods, forms a solid foundation for APL's next 75 years of success.

INTRODUCTION

World War II posed an existential threat to the United States and its Allies, and all elements of national power were mobilized to ensure ultimate victory. Key among these were the scientific and engineering communities. Their combined efforts led to important technological developments, such as radar, the variable time (VT) proximity fuze, and nuclear weapons, that shaped the course of the war and the peace that followed. Efforts of scientists and engineers during the war also led to the development of important analytical tools to guide the employment of military forces in accomplishing key Allied objectives. Perhaps the best known of these tools is the discipline of operations research (OR), developed in the United Kingdom by physicists such as Patrick M. S. Blackett and his colleagues at the British Admiralty and in the United States by Philip M. Morse and his colleagues in the Anti-Submarine Warfare Operations Research Group.

The Institute for Operations Research and Management Science (INFORMS) defines OR as "the application of advanced analytical methods to help make better decisions."[1] The field is sometimes referred to as *operational research* (in the United Kingdom), *management science*, or *analytics*. INFORMS notes that analytics, defined as "the scientific process of transforming data into insight for making better decisions," is closely related to OR.[1] Practitioners of OR use many mathematical tools and methods, including modeling, statistical analysis, and mathematical optimization, to reach optimal or near-optimal solutions to complex problems.

Morse and his colleague George E. Kimball documented many of the OR methods developed for the U.S. Navy during World War II in their classic treatise, *Methods of Operations Research*.[2]

At the same time, the challenge of engineering increasingly complex and interdependent technical systems that emerged during the war helped establish the systems engineering process at the Johns Hopkins University Applied Physics Laboratory (APL) and other organizations. An early overview of systems engineering practices in industry[3] highlighted five phases of the systems engineering process—planning, analysis, optimization, integration, and evaluation—and noted the important role that OR methods played in several of these phases, particularly planning, analysis, and optimization. This overview observed further:

> Some companies consider the term systems analysis synonymous with systems engineering, but most consider it only a part of a broader concept. One exception to be noted is systems analysis as used by the Rand Corp. of Santa Monica, Calif. Here systems analysis involves weapon systems planning for years in advance.

The Rand approach to systems analysis in support of military decision-making was documented in the seminal book, *The Economics of Defense in the Nuclear Age*.[4] This same approach shaped the systems analysis tools (e.g., cost–benefit analysis) that Robert S. McNamara introduced during his influential tenure as secretary of defense in the 1960s.

These foundational approaches to OR, systems analysis, and systems engineering influenced the analytical work conducted by APL during the Laboratory's first 75 years. In particular, they shaped the systems perspective that has characterized APL's approach to analysis.

ANALYSIS AT APL—THE EARLY YEARS[5]

During World War II, APL's Analysis Unit worked to develop the optimum characteristics and use of fire-control directors for the VT fuze. Immediately following the war, ad hoc groups performed assessments of warfare systems. These assessments included defining requirements for long-range bombardment missiles, warhead designs, and future guided-missile systems; comparing the capabilities of the Talos and Terrier missiles for cruiser defense; and defining expected air attacks on naval forces. In 1948, the Central Laboratory Assessment (CLA) Group was established and charged with assessing and setting objectives for tasks assigned to or proposed for APL. Its first assignment was to assess the anti-aircraft missile problem associated with Operation Bumblebee, a U.S. Navy effort to develop surface-to-air missiles to provide a midrange layer of anti-aircraft defense for the Fleet. In these early postwar years, APL laid the groundwork for analyses of the anti-air warfare problem by defining the expected threats and developing methodologies to analyze Fleet defense with the introduction of guided missiles.

During the 1950s, CLA's studies and analyses focused on electronic jamming, cruise and ballistic missiles launched from submarines, and improved methodologies for assessing warheads and kill probabilities. In the process, CLA analysts developed formulas and doctrine for the coordination of missile fire and compared the capability of interceptors, missiles, and guns for Fleet defense as well as nuclear versions of Talos and Nike. In 1958, the CLA Group became the CLA Division.

In the 1960s, analysts in CLA developed the Air Battle Analyzer methodology for application to the Fleet air defense problem. The Battle Analyzer provided an orderly and efficient means to consider how a hypothetical battle might progress, event by event, given any preselected plan of attack and plan of defense, including the composition of forces, their deployment, and their proposed tactical moves. It encouraged the interaction of tactical, technical, and military service personnel at a working level and served as a model for subsequent development of APL's Warfare Analysis Laboratory. CLA analysts also examined the impact of the natural environment (e.g., sea states and atmospheric refractivity) on military operations. CLA supported studies on North Atlantic Treaty Organization (NATO) air defense, the Sound Surveillance System (SOSUS), point defense on large ships, missile systems for small ships, and amphibious support weapons.

With the advent of phased-array radars in the 1970s, APL focused its analytical talents on studying the effectiveness of the new Aegis Weapon System and the New Threat Upgrade Program for Terrier and Tartar ships. CLA analysts evaluated the Close-In Weapon System and other self-defense systems. Other analysis efforts focused on nuclear weapons, cruise missile survivability and attacks of enemy ships, and the requirements for highly capable surface-to-air missile systems.

The 1970s also saw the influential leadership of Admiral Elmo Zumwalt as the chief of naval operations (CNO). Admiral Zumwalt reorganized the Office of the CNO, creating platform sponsors, often called Barons—OP-02 (submarine), OP-03 (surface), and OP-05 (aviation)—and reinvigorating the Systems Analysis Division (OP-96) to serve as an integration vehicle to develop the Navy's Program Objectives Memorandum.[6] Under CNO Zumwalt, analysis became one of the important drivers of Navy decision-making.

In 1981, the CLA Division was combined with the Fleet Systems Effectiveness Group, which analyzed surface combat system effectiveness. In a move to broaden APL's efforts in naval warfare analysis, the CLA Division formed the basis for a new Naval Warfare Analysis Division (NWAD).[7] This move paralleled developments in the office of CNO Thomas Hayward to expand and elevate the mandate of the director of naval warfare (OP-095).

APL's Program Review Board recommended that NWAD emphasize five efforts as part of its mission:

1. Provide interdisciplinary, interdivisional coupling to support the Laboratory's creation of concepts for integration of diverse system areas to improve Navy capabilities.

2. Support the other departments and divisions of the Laboratory through the use of its OR, modeling, and analysis capabilities.

3. Assist the Navy in multi-warfare coordination and tactics through performing naval warfare analysis for outside sponsors.

4. Assess current Fleet operational capabilities to quantify the capabilities, identify any weaknesses, and help solve current problems.

5. Provide the Director's Office with specific analytic support, including assistance in long-range planning.

To accomplish this mission, NWAD focused on three goals: (*i*) broadening APL participation in naval warfare coordination; (*ii*) formulating new concepts for improved naval capabilities; and (*iii*) developing methods, including a Warfare Analysis Laboratory, to analyze new naval capabilities.

In the 1980s, during the latter stages of the Cold War, NWAD analysts used the Warfare Analysis Laboratory to provide physical and tactical insight into hard-kill/soft-kill interactions and outer air battle operations focused on countering the increasing Soviet threats to U.S. naval forces. Work also addressed concepts of deployment for the *Ticonderoga*-class (CG 47) Aegis cruisers, tactics guidelines for the employment of EA-6B and EF-111A electronic warfare aircraft, combat system requirements for the *Arleigh Burke* (DDG 51) destroyers, and concepts to upgrade the NATO Sea Sparrow missile system. Many of these themes came together in NWAD's contributions to the Surface Combatant for the 21st Century (SC-21) cost and operational effectiveness analysis in the mid-1990s.

The 1980s and 1990s also saw increasing emphasis on "jointness" and the need for individual military services to develop new capabilities in the context of the strengths and weaknesses of the other services. This move toward jointness became especially important during the Clinton administration as overall defense budgets were reduced as a consequence of the "peace dividend" following the end of the Cold War and the success of the United States and its allies during the first Gulf War. In 1996, NWAD became the Joint Warfare Analysis Department to emphasize the increasing importance of joint operations in shaping requirements for the Navy and other services.

After the attacks on September 11, 2001, it was clear that the national security environment was becoming more complex as threats and challenges to the United States and its interests both domestically and abroad were becoming more pervasive and sophisticated. Addressing these threats demands use of the full range of national capabilities—military, diplomatic, and economic.

To better reflect APL's intent to address the full range of these emergent national security challenges, the Joint Warfare Analysis Department became the National Security Analysis Department (NSAD) with new goals to better address critical multi-warfare analysis challenges, facilitate Laboratory engagement at the national security policy level, and focus its contributions on enterprise-wide initiatives. When APL reorganized its main lines of sponsored work into four sectors in 2011, NSAD, along with the Research and Exploratory Development Department (REDD), became an enterprise technical department tasked with supporting both external sponsors and APL sectors.

A NEW CENTURY AND NEW CHALLENGES—NSAD'S CONTRIBUTIONS TO APL

In the second decade of the 21st century, the challenges that motivated the creation of NSAD have continued to grow with the rising military and economic power of China, a resurgent Russia challenging NATO on its periphery, a dangerous and unpredictable regime in North Korea, and continuing instability in the Middle East and Africa resulting from the Arab Spring and the rise of ISIS and regional affiliates of al-Qaeda.

In this environment, APL Director Ralph Semmel challenged NSAD to serve as "headlights of the Lab," along with REDD, by illuminating new critical challenges for APL, providing objective analyses on significant issues, serving as a strategic partner to all APL sectors, and leading APL toward high-impact contributions.

Illuminating New Critical Challenges and Incubating New Lines of Work for APL

In the course of efforts to illuminate new critical challenges, NSAD analysts explored and developed, or "incubated," new lines of work for APL. Following are examples of successfully incubated work that has transitioned to long-term sponsored work in APL's sectors and departments.

Laying the foundation for work with the National Security Agency (NSA). In the early 2000s, NSAD analysts worked closely with NSA to bring a systems perspective to the way NSA marshaled its staff members and equipment to develop collection plans in response to specific threats. At the time, collection priorities were moving from a focus on military units to a focus on individuals. In addition, the way information was passed moved from point-to-point communications to Internet protocol (IP) communications. NSAD's work established a solid relationship between APL and NSA that served as a basis for the Asymmetric Operations Sector's growing portfolio of work for the agency.

Shaping APL's work in unrestricted warfare. Beginning in 2006, NSAD cosponsored a series of symposia, with the Johns Hopkins University's School for Advanced International Studies, on unrestricted warfare—a topic of particular interest following publication of an influential book by two Chinese military officers on the same subject.[8] These symposia, which continued through

2009, helped shape APL's work in support of the special operations community and the Army's Asymmetric Warfare Group, as well as research focused on developing capabilities to counter improvised explosive devices.

Improving communications for our nation's senior leaders. Following a 2010 study sponsored by the Office of the Secretary of Defense on approaches to modernizing nuclear command and control systems, NSAD analysts and engineers were asked to assist in the development and testing of secure senior leader communications technologies, including those developed by the NSA's Commercial Solutions for Classified program. The magnitude of this work grew quickly to include support for Continuity of Operations and Continuity of Government initiatives. In 2015, this work transitioned to the Asymmetric Operations Sector and has delivered capabilities now being used by the nation's senior leaders.

Growing APL's work in national health. In 2010, the Navy Bureau of Medicine and Surgery (BUMED) asked NSAD analysts to develop a planning tool to help forecast the number of medical personnel the Navy would need to recruit and train to meet its needs. The success of the Medical Manpower All-Corps Requirements Estimator (Med-MACRE) led to follow-on work for BUMED in applying systems and industrial engineering methods to improve the efficiency of processes and procedures at the Navy's hospitals and clinics. This provided an important building block for APL's new National Health Mission Area, which began operations in 2016.

Developing tactics and technologies to counter anti-access/area denial strategies. NSAD coordinated, and in several cases led, key cross-Lab efforts to develop tactics and technologies to counter anti-access/area denial strategies being developed by emerging competitors and to address the growing challenge of time-critical targets. Supporting analytical work has led to successful prototypes developed by APL sectors.

Partnering with APL Sectors

Throughout the Lab's history, its analysis organizations have partnered with its sectors/departments to bring a systems perspective to critical analyses that underpin many past, current, and future naval, joint, and national capabilities. A systems perspective includes understanding technology, operational needs, operational environments, and current and emerging threats. As our brief historical review has shown, the concept of a system has evolved over the years from naval weapons focused on air defense to complex, integrated systems of systems that address national security, operate within a global environment, and are intended for multiple warfare scenarios and multiple missions. We have also presented examples of APL's analysis organizations' involvement at the front end of addressing new problems, laying the groundwork for follow-on development of solutions and incubating new areas of work for the Laboratory. The tools of OR, systems analysis, cost analysis, and systems engineering, together with an understanding of national security policy, geopolitical trends, and emerging threats and technologies, as well as the ability to integrate expertise from diverse stakeholders across the Lab, university, and sponsor communities, have been integral to these contributions and success.

Today's Analysis Tool Set

APL's analysis organizations have developed a range of analytical tools and approaches to address the prob-

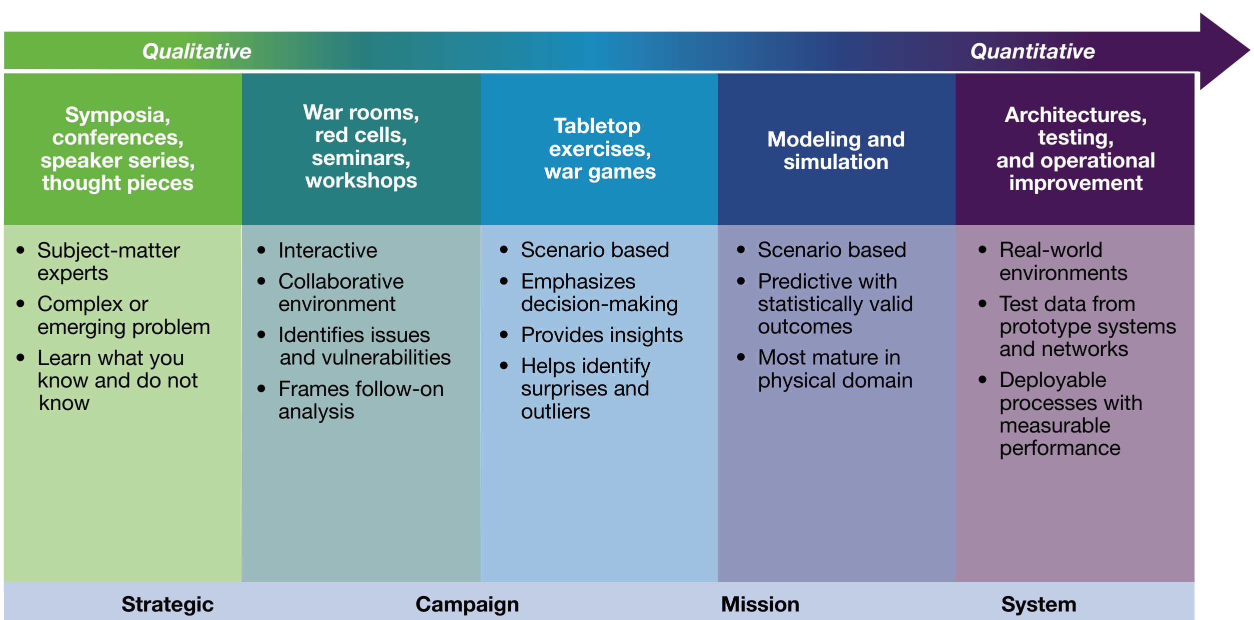

Figure 1. The national security analysis continuum.

lems they have confronted over the years. These tools and approaches are displayed in the analysis continuum in Fig. 1 and range from qualitative to quantitative applications and from the strategic to the systems level.

Defining the problem. In the problem-definition phase of analysis, one can use symposia, conferences, speaker series, or thought pieces to draw information from subject-matter experts to inform analytical work. We have already noted NSAD's use of Unrestricted Warfare Symposia to explore new types of complex and emerging conflicts that will affect the technology and systems needs of our sponsors. In addition, for the past 13 years, NSAD has sponsored an annual Rethinking Seminar series to explore emerging trends and ideas affecting national security. Speakers in this series have included serving and retired senior government officials, thought leaders from academia and the think tank communities, and APL staff members. A key outcome of the problem-definition phase is an assurance that analysts are addressing the essence of a problem and not its symptoms.

Focusing problem definition. War rooms, red cells, seminars, and workshops can bring focus to a particular problem. War rooms provide a venue where analysts charged with structuring an approach to answering a question or solving a problem can share relevant information to develop an analytical approach and a data collection and analysis plan to support it. Red cells are organized to explore weaknesses or vulnerabilities in potential approaches. Seminars and workshops offer more structured approaches to addressing a particular challenge by inviting presentations on particular aspects of a problem or question followed by discussion/debate on best approaches to address the problem or answer the question and thereby frame follow-on analysis.

Setting the dimensions of a problem. Tabletop exercises and war games explore the dimensions of problems affected by human decision-making. In applying these tools, problems and issues are set in the context of specific scenarios that describe the capabilities of threat and friendly forces, usually characterized as red and blue, respectively, and invite players to shape interactions between the forces through a set of engagements that specify limits on the outcomes affected by external factors (e.g., weather or disrupted communication), as well as physical limits on the performance of weapons systems. Players often include experienced military officers, other government officials, analysts, and engineers. These applications are similar to those developed for the Air Battle Analyzer in the 1960s and 1970s and the Warfare Analysis Laboratory and Collaborative Analysis Center from the 1980s to the present day.

Analyzing the problem. Models and simulations use physics-based mathematical models of technologies and systems to explore performance in a range of environments. They can be particularly powerful when they draw on actual data. Like traditional scientific approaches, models and simulations are most effective when they can both reproduce observed real-world performance and accurately predict performance under new types of conditions yet to be observed. Models and simulations are usually either deterministic or Monte Carlo, with the latter applied most often for simulating systems with many coupled degrees of freedom. The choice of models and simulations can be especially important for acquisition studies where the promise of future systems and technologies must be weighed carefully against current systems whose performance can be measured directly. A particular challenge for analysts at APL is how best to take advantage of detailed systems-level models developed by the Laboratory's technical staff in assessing performance at the mission level.

Testing the solutions. The most quantitative work for analysts at APL involves the testing of prototypes and systems in real-world environments to collect performance data. Analyses of these data can provide insights into opportunities to improve a system's performance. In addition, analysts can help in testing new operational concepts—different ways of using existing technologies and systems—to determine their effectiveness in addressing emerging threats. In fact, exploring alternative uses of existing systems is one of the important focus areas being pursued by the Strategic Capabilities Office in the Office of the Secretary of Defense.

Types of Analytical Work

APL's analyses often support the systems engineering spiral of continual improvement shown in Fig. 2. There are six phases of the systems engineering process: critical needs, capability assessment, concept exploration, solution validation, solution implementation, and deployment. These six phases also shape the type of work that analytical organizations at APL pursue and the types of OR tools that analysts use to support a systems approach to developing, testing, and procuring a new capability. Fundamentally, this analytical work answers two broad questions: what are the requirements for new technologies and systems, and how should these capabilities be acquired?

Identifying requirements. The initial steps of systems engineering depend on requirements analysis. When systems are defined very broadly (e.g., the government or the national security establishment), requirements can be shaped by correspondingly broad strategic-level assessments of alternative futures and courses of action that make sense in the context of an alternative future. Broad examinations of the requirements for a national security system often include assessments of the role of diplomatic, information, military, and economic actions and their political, military, economic, social, informational, and infrastructural effects on alternative courses of action. In the first decade of the 21st century, NSAD's Strategic Assessments Office conducted a number of assessments of high-level national security issues of interest to both APL and its sponsors that leveraged APL's technical expertise. For example, this work contributed to a "Terrorism 2025" assessment for the National Counterterrorism Center, informed the Navy's development of a new maritime strategy, and shaped APL's strategic planning efforts.

More commonly, military requirements are examined by mission area (e.g., air and missile defense). The process starts by assessing the capabilities that potential threats can bring to bear against U.S. forces. In the case of air and missile defense, these threats include cruise missiles, which can be launched from land bases, ships, submarines, or aircraft; ballistic missiles, which can be launched from land bases and submarines; and other types of missiles, which can be launched as surface-to-surface, surface-to-air, air-to-surface, or air-to-air systems.

Analysts work with intelligence organizations to determine the capabilities of individual threat weapons and how they will be used against U.S. systems. Using this information, analysts develop operational constructs governing the interactions between threat and U.S. systems. These constructs are often referred to as vignettes, operational situations, or tactical situations. These constructs also include environmental conditions such as the time of year, geographical location, likely sea and/or atmospheric conditions, other weather effects, and the amount of daylight. In some cases, APL analysts document this work in design reference missions or in publications such as the *Littoral Warfare Handbook*,[9] which can be used to guide a number of assessments in a given warfare area.

Once this information is established, analysts can use physics-based models and simulations to assess the effectiveness of U.S. air and missile defense systems against threat systems under conditions specified by the operational constructs. The results of these types of analyses can identify gaps or redundancies in capability for U.S. systems against existing or predicted threat systems. In 2003, these types of gap analyses were formalized in the Joint Capabilities Integration and Development System to ensure that requirements for future capabilities were developed in a joint context to avoid redundant capabilities across services.

The Joint Capabilities Integration and Development System process has evolved since its introduction to better accommodate rapidly emerging requirements from recent and ongoing operations in Iraq and Afghanistan.[10] Under its current instantiation, any service, combatant command, or other DoD component must conduct a capability-based assessment (CBA) or other studies to "assess capability requirements and associated capability gaps and risks."[9] These studies can be informed by lessons learned. CBAs are informed by high-level strategy and policy guidance in documents (e.g., the *National Security Strategy*, *National Defense Strategy*, *National Military Strategy*, *Quadrennial Defense Review*, *Guidance for the Employment of the Force*, *Defense Planning Guidance*, and *Joint Strategic Capabilities Plan*). Capability requirements must be traceable to an organization's roles and missions, service and joint concepts, and policy or legal limits on the use of certain technologies (e.g., those related to weapons of mass destruction). Associated capability gaps must be assessed relative to capabilities fielded or in development across the joint force, not just to those organic to an organization.

CBAs also inform potential solutions to identified capability gaps. These solutions include nonmateriel approaches such as using existing systems and technologies differently through new tactics or by repurposing them for other missions. Alternatively, solutions might include development of new technologies and systems designed to address the identified gaps explicitly.

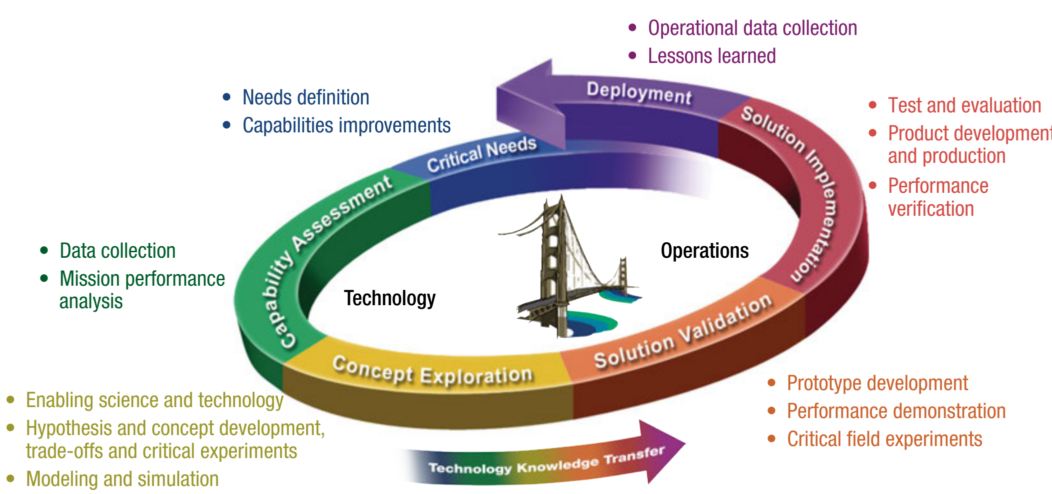

Figure 2. The systems engineering spiral.

APL analysts have supported a number of CBAs and capstone requirements analyses for the Laboratory's sponsors, including those examining top-level anti-submarine warfare requirements for the director of submarine warfare and the CNO and communications requirements for the DoD chief information officer. Most recently, APL completed a CBA for the director of surface warfare focused on understanding requirements for future surface combatants.

Deciding what to buy. Once requirements are set through needs definition and capability assessments, the concept exploration phase examines alternative solutions and their costs, effectiveness, and risks. These efforts draw on acquisition analyses specified by guidelines in the DoD Instruction 5000 series governing the Defense Acquisition System.[11] These analyses include analyses of alternatives (AoAs) and their earlier "cousins," cost and operational effectiveness analyses. AoAs feature analyses of the cost and performance/effectiveness of existing (baseline) technologies and systems and assessments of how they compare to new alternatives.

APL analysts have contributed to acquisition analyses for a range of important DoD systems, particularly for the Navy. Often APL's work is done in concert with other analytical organizations, including federally funded research and development centers and government laboratories. For example, in the 1990s and early 2000s, analysts at APL worked closely with their counterparts at the Naval Surface Warfare Center (Dahlgren), MIT Lincoln Laboratory, MITRE, and the Center for Naval Analyses on a series of cost and operational effectiveness analyses and AoAs focused on modernization plans for the surface Navy. These efforts helped shape the Navy's current plans for evolving the capability of *Arleigh Burke*-class destroyers and *Ticonderoga*-class cruisers.

Acquisition studies draw heavily on the expertise and modeling capability of analysts across the Laboratory, particularly to develop system- and mission-level models of performance and effectiveness. Because models and simulations are so important to the analytical process, NSAD analysts have devoted considerable effort over the years to ensuring that models and simulations used by both APL and our sponsors meet rigorous standards of verification, validation, and accreditation established by DoD.[12]

Acquisition studies also depend on developing accurate estimates of the costs to buy and operate candidate systems, and over the past 5 years, NSAD has been particularly focused on developing a robust cost-estimating capability in its technical staff.

AoAs also require assessments of the risks involved in pursuing new technologies and systems to address a particular requirement or set of requirements. APL analysts conduct risk assessments in multiple dimensions, including evaluations of the impact of missing expected goals for performance, schedules, and costs on the sponsor's ability to meet the specified performance requirements for a new capability within the limited time and budgets available. Risk assessments often draw on both physics-based quantitative models and subjective judgments by subject-matter experts.

Testing new capabilities. In addition to using models, simulations, and cost analyses to assess the performance of new technologies and systems, APL analysts have also supported operational utility assessments as part of technology demonstrations, including advanced concept and joint capability technology demonstrations. Prior to the disestablishment of the Joint Forces Command in 2011, NSAD analysts supported a number of joint capability technology demonstrations. Today, NSAD analysts work closely with engineers and scientists from APL's sectors and departments to coordinate realistic operational testing of prototype system solutions and new operational concepts designed to address performance gaps identified in earlier phases of the systems engineering process. This teamwork among APL's various technical communities—engineers, scientists, and analysts—shows the strength of analysis from a systems perspective.

LAYING THE GROUNDWORK FOR THE NEXT 75 YEARS

Many of the challenges facing our sponsors today and in the future cut across traditional mission areas and military service responsibilities. Indeed, emerging threats associated with terrorist movements and "gray area" operations between war and peace call for whole-of-government approaches to address them. APL's analysis department must continue evolving its tools and approaches to help our sponsors meet these challenges. This evolution is already evidenced in the way NSAD coordinates its work with APL's sectors and departments to develop solutions for emerging anti-access/area denial and time-critical targeting challenges and to support DoD efforts to envision new ways to use existing technologies to counter emerging threats to our nation's security.

At the core of these efforts are our analysts' commitments to deliver fact-based analyses that are informed by APL's deep technical expertise. As the headlights of the Lab, APL's analysts must work to identify critical challenges early, develop analytical and technical plans to address them, and communicate our results clearly to the government senior leaders we support. Our work must be informed not only by APL's deep technical bench but also by insights gained from developments in the commercial marketplace and government and private-sector policy communities.

NSAD will be an important contributor to helping APL achieve its centennial vision to create defining innovations that ensure our nation's preeminence in the 21st century.

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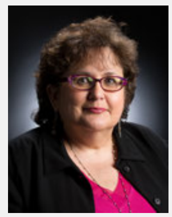

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