Pioneering Independent Research and Development Strategy in APL's Research and Exploratory Development Mission Area: Ensuring our Nation's Preeminence in the 21st Century

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The Research and Exploratory Development (RED) Mission Area is the research engine of the Johns Hopkins University Applied Physics Laboratory (APL). Its pioneering research, whether internally or externally funded, targets game-changing breakthroughs in national security technologies and capabilities. Through its independent research and development (IRAD) program, the RED Mission Area invests in the early phase of technology development, emphasizing the exploration of bold ideas and the development of advanced prototypes. This article describes the mission area's IRAD strategy and process and introduces a series of articles featuring a selection of current IRAD initiatives. This groundbreaking research being conducted today will invent the future for APL and its sponsors, ensuring our nation's preeminence when APL turns 100.

INTRODUCTION

The US Department of Defense has a long, successful history of investing in research and development (R&D) and laying the foundation for sustained technological superiority and national security. Today it faces increasingly complex challenges in a shifting global R&D investment landscape,[1,2] along with "rapid technological advancements and the changing character of war."[3] The 2018 National Defense Strategy identifies critical elements required to sustain technological superiority, including increased innovation in R&D investments. In a report to the US Congress, a distinguished committee of American leaders wrote that the only promising avenue to successfully compete, prosper, and be secure in the global landscape is through innovation.[4] Maintaining a commitment to early stage, high-risk research is critical to realizing the next generation of game-changing capabilities and technologies. Key to achieving this goal is a strategic, forward-leaning approach to investing in independent R&D (IRAD) that maximizes innovation and technological advancement.

APL was founded in 1942 to mobilize scientific research to address government challenges in national security and space. Its goal remains the same today. Throughout its tenure, APL has achieved nine defining innovations,[5] which are the realization of critical contributions to critical challenges that profoundly advance science, engineering, and military capabilities. Similar to traditional characterizations of innovation, a defining innovation may involve the invention of a new scientific principle or technology, or it might arise from the ingenious utilization of existing technologies. However, the important differentiator is the realized impact of the innovation. This impact only occurs if early research successfully matures and transitions to further development or application.

INDEPENDENT RESEARCH AND DEVELOPMENT

As APL looks toward its centennial, it is committed to ensuring our nation's preeminence. Strategic investment in early, potentially game-changing, pioneering research underpins this vision. For those technologies that successfully mature from basic, early-stage IRAD to operational deployment, the process is expected to take years, if not decades.[6] Therefore, the research that will ensure US preeminence when APL turns 100 begins today. Appropriate progression of that research requires that organizational leadership remain committed to sustained investment, and that research champions continue to persist in their pursuits of the next defining innovation.

APL has a strong record of using IRAD investments to explore and discover promising technologies that create novel capabilities and enable new missions for government sponsors. For example, more than a decade of IRAD and collaboration resulted in the thermal protection system[7] that allowed the NASA Parker Solar Probe to come closer to the Sun than any spacecraft before it.[8] At only 4.5 inches thick, the thermal protection system, or heat shield, experiences temperatures of 2,500°F on sun-facing surfaces while the instruments remain at a balmy 85°F. In a separate string of IRAD efforts, APL researchers developed machine learning techniques to rapidly find and identify deployed undersea objects, such as mines, that threaten ships, submarines, and critical infrastructures. The use of artificial intelligence could greatly increase search speed while reducing the number of systems needed to cover hundreds of square miles. More recently, APL has leveraged IRAD to invent a technology that enables the creation of flexible and safe batteries.[9] This technology, once matured, will eliminate the potential hazards associated with volatile lithium ion batteries and demonstrate how these new batteries could revolutionize battery safety, distributed power, and wearable systems. These examples, and many others, illustrate how carefully planned and effectively executed IRAD projects can lead to game-changing capabilities and impact.

Strategy-Driven Process

IRAD is intended to invest in the early phase of technology development with an emphasis on vetting initial ideas and demonstrating concepts. The IRAD investment process, aligned with and overseen by each of APL's mission areas, operates on a yearly cycle. The Research and Exploratory Development (RED) Mission Area's approach to IRAD investment targets a broad portfolio of high-risk, innovative R&D.

The RED Mission Area endeavors to imagine and realize the next defining innovation. Overseeing the research programs at APL, RED aims to invest in projects that maximize the opportunity for innovation, discovery, and disruption. RED employs a strategic planning process (Figure 1) to identify research focus areas (RFAs), target specific IRAD investments, and transition project outcomes.

RFAs are known or emerging areas of strategic national importance that will benefit from early research. They provide the basis to align and focus investments to maximize the potential for IRAD impact. The RED mission area defines RFAs in three steps: by (1) working closely with partnering mission-focused APL mission areas to understand their envisioned futures; (2) examining strategy, vision, and priorities from the national security, space, and health research domains; and (3) scanning technology trends and gauging their potential impact on APL's government sponsors. It then solicits project proposals from APL's staff for ideas that address the priorities defined within each RFA. Awards are made on a competitive basis for a single year. At the end of the performance period, the leadership team reviews and assesses each project.

Promising projects may warrant continued funding as part of the next investment cycle or may follow another transition pathway. There are four general transition

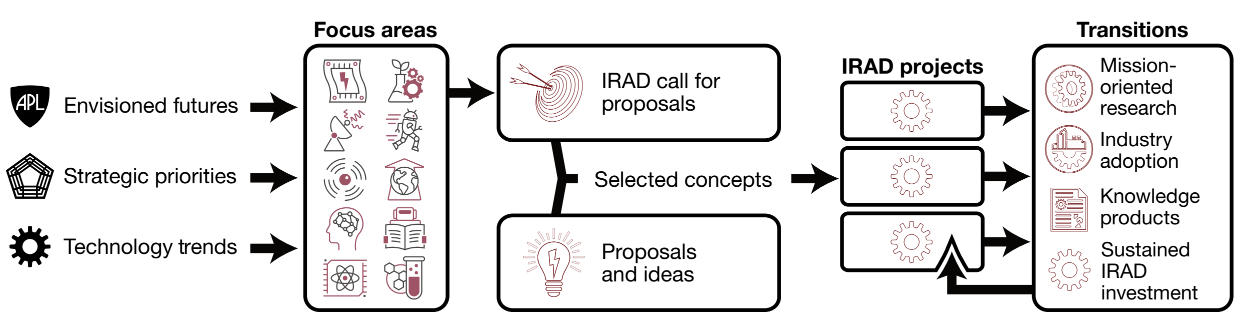


Figure 1. RED IRAD investment and transition process. To define RFAs, the RED Mission Area gains an understanding of APL mission areas' envisioned futures, examines strategic priorities in key domains, and considers technology trends. It then solicits proposals from APL staff for ideas that address the priorities defined in the RFAs. Funding is awarded competitively for a single year. Promising projects may be funded again in the next yearly cycle or may transition to government research and mission-oriented funding, industry adoption, knowledge products, or sustained IRAD investment.

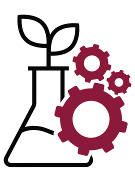
Figure 2. Staff members at work on some of the pioneering research that will enable our nation's preeminence when APL turns 100. Left, Matthew Fifer working with Robert "Buz" Chmielewski, a quadriplegic patient who demonstrated simultaneous control of two of the APL-developed prosthetic limbs through a brain–machine interface developed by APL. Middle, Jeffrey Shipp, part of APL's Biological Sciences Group, in APL's biology laboratory. Right, Staff members testing a quadcopter robot in the field.

targets for IRAD investments: (1) government research and mission-oriented funding; (2) industry adoption for either government benefit or dual-use technologies; (3) knowledge products, such as intellectual property or publication in a journal; or (4) sustained IRAD investment. Each transition enables the targeted technology to progress to the next stage of maturity or to be used in the future.

Pioneering Research

This issue of the *APL Technical Digest* features a selection of current IRAD investments that focus on conducting the pioneering research today that will enable our nation's preeminence when APL turns 100. (See Figure 2 for photos from a few of these efforts.) Those investments are grouped by RFA, as outlined below, and the research projects are described in more detail in each of the articles that follow.

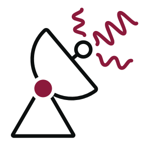
Century of Biology



Technological innovations in the biological sciences are proceeding at a rapid pace, making biology more available and understandable to a global audience. In this century, the century of biology, such advances hold promise for significant and far-reaching benefits across multiple areas, including food security, biomaterials, and environmental health. However, along with these benefits, the potential for misuse of these tools, whether accidental or intentional, is grave. Fortunately, significant opportunity exists to harness the very same technological advances to provide solutions for national security challenges. See the following two articles for examples of APL IRAD in this area:

- "Toward Autonomous Anomaly Detection within Biological Ecosystems" by Howser et al.
- "Trustworthy Synthetic Biology: Plant-Based Biosensing" by Gleason et al.

Electromagnetic Manipulation



Electromagnetic materials can exhibit extraordinary spectral control in ways that are not physically possible with bulk conventional materials. The ability to engineer and control a material's spectral, spatial, and polarization behavior in different frequency regimes—from optical to infrared to microwave—is of great interest for a number of application areas. These materials, and the structures and devices into which they are incorporated, may control electromagnetic properties passively, adaptively in response to a stimulus, or actively. Possible applications include, but are not limited to, antennas, radio frequency (RF) absorbers, sensors at all frequencies, electromagnetic windows, communications, tagging/tracking/locating, and countermeasures. See the following articles:

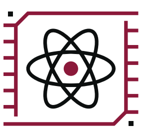
- "Epitaxial Chalcogenide Deposition for Optical Phase Change Devices" by Podpirka et al.
- "Infrared Polarization-Sensitive Imaging with Meta-Technology" by Miragliotta et al.
- "Simplifying Digital Array Architectures with Multifunctional Metasurface Apertures" by Sleasman et al.

Formulate and Fabricate

Materials innovations are needed to enable future capability for individual warfighters and their land, sea, air, and space platforms. Critical to the widespread use of advanced materials are improvements in manufacturing science and methods for producing complex, innovative, and high-value components in a scalable, rapid, and low-cost manner. Computational materials science has also become critical to the design and analysis of novel materials with unique properties. Advancements in formulations, fabrication techniques, and predictive capabilities are needed for creating future materials for defense and national security applications. See the following articles for brief discussions of APL work in this area:

- "Developing Complex Shape-Morphing Metallic Structures for Space Applications" by McCue et al.
- "Metal Matrix Composites Synthesized with Laser-Based Additive Manufacturing" by Storck et al.
- "Multifunctional Hypersonic Components and Structures" by Clemons et al.
- "Predicting Failure in Additively Manufactured Parts—'The Effects of Defects'" by Peitsch et al.

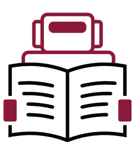
Future of Compute



From computation at the edge, to secure ecosystems, to supporting artificial intelligences (AIs), our nation demands computing at levels little imagined at the outset of the information age. We must address emerging challenges with new concepts and creative reimaginations of existing paradigms. Processors based on quantum phenomena will efficiently simulate materials exhibiting quantum phenomena; processors inspired by biological brains will be the engines of AI with unprecedented judgment, decision-making ability, and robustness. The following article details an example of APL work to change the future of compute:

- "Quantum Matched Filtering—Signal Processing in the Quantum Age" by Titum et al.

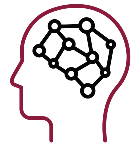
Learning Machines



Advances in machine learning and AI have dramatically altered the landscape of countless industries and technologies around the globe. While significant progress has been made, the potential for AI to revolutionize the future warfighter has yet to be fully realized. Modern AI systems are narrowly focused, brittle, easy to attack, and lack the level of reasoning required to succeed in highly dynamic and unstructured environments. These limitations must be addressed through research in breakthrough technologies that are critical to maintaining our competitive advantage, such as those described in the following articles:

- "Adversarial Machine Learning in the Physical Domain" by Drenkow et al.
- "Intent-Aware Pedestrian Prediction for Adaptive Crowd Navigation" by Katyal et al.
- "Verification of Safety in Artificial Intelligence and Reinforcement Learning Systems" by Kouskoulas et al.

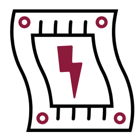
Mind and Brain



The mind and brain are among the last frontiers in science. While the cognitive and neural sciences have made enormous progress over the last decades, even the basic principles are still barely understood. Recognized as one of the grand challenges of the 21st century, understanding and harnessing the principles of the mind and brain has the potential to unlock defining innovations. What mind and brain research will create the most exciting opportunities to realize advances in AI, revolutionize education and training, motivate paradigm shifts in law or economics, and fundamentally change how we interact with technology? Some groundbreaking APL research is discussed in the following articles:

- "Motifs to Models: Leveraging Biological Circuits toward Novel Computational Substrates" by Reilly et al.
- "Neuro-Inspired Dynamic Replanning in Swarms—Theoretical Neuroscience Extends Swarming in Complex Environments" by Hwang et al.

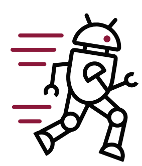
Power, Heat, and Cool



Power sources are key components for every device and system. Research in power and energy dates back centuries, and it is an ever-evolving quest going hand in hand with technological advancements in multiple scientific and engineering disciplines. While the need for better and more efficient ways to produce and store energy is directly relatable to our everyday life, this need is even more critical in the defense domain. US warfighters and defense systems often operate in extreme environments, requiring unprecedented robustness and resilience from power sources and devices, as compared to those commonly used by the commercial sector. See the following article for an example of APL research in this area:

- "Thin-Film Thermoelectric Conversion Devices for Direct Thermal-to-Electric Conversion for DC and Pulse Power" by Venkatasubramanian et al.

Robotics at the Edge



Future robotic systems must be able to operate and collaborate in complex adversarial environments with imperfect information at or beyond mission tempo. However, today's robots fall far short of the speed, agility, intuition, physical characteristics, and resilience required for meaningful operational impact. The present reality underscores the need for new, dramatically more capable robots that can operate at the very edge of physical and computational limits. APL is working toward these advances, with two efforts discussed in the following articles:

- "Aerobatic Flight for Robotic Fixed-Wing Unmanned Aerial Vehicles" by Basescu and Moore
- "Untethered Autonomous Soft Robotics" by Xia et al.

Next Adversary

Within the next few decades, our nation and the world can expect to see dramatic changes in the distribution of populations; the availability of natural and generated resources; the frequency and severity of disasters; and the prevalence and ubiquity of easily accessed information, automation, and connectivity. To ensure the successful future of our nation, we must reimagine, redesign, and reengineer human culture to provide for basic human needs: health, security, critical infrastructure, education, and opportunity toward a viable economic and societal ecosystem. An exciting example of research in this area is discussed in the following article:

- "System Integration with Multiscale Networks (SIMoN): A Geospatial Model Transformation Framework for a Sustainable Future" by Hughes et al.

Sense and Detect

Whether electronic, optical, chemical, mechanical, or biological, sensors provide information that enables missions—making the government, warfighter, or civilian safer, smarter, and better informed. The vision is to create a toolbox of powerful and versatile sensor and sensor-enabling technologies, including new transduction technologies, system components, and reconfigurable sensors. See the following article for a brief description of an APL IRAD project seeking to advance this capability:

- "DetectsVX: Organophosphate-Sensing Hydrogel Platform" by Hoffman et al.

CONCLUSION

The projects highlighted herein are examples of innovative research efforts at various stages of maturity within the RED Mission Area. Each project begins as an idea or concept informed by future mission needs. As the research ventures on a journey of scientific discovery, it endeavors to generate findings that disrupt the status quo. Through concept maturation and transition to operation, the impact of this original idea is realized. If the impact of that realization is profound, that initial idea may become the target of APL's 10th defining innovation.

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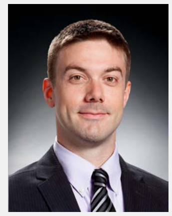

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