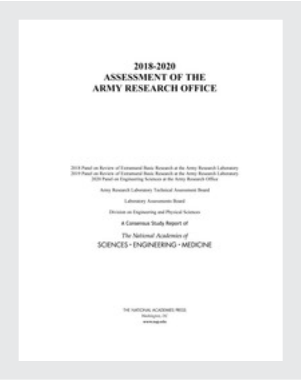

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Laboratory Assessments Board

Division on Engineering and Physical Sciences

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[4] JILA, formerly known as the Joint Institute for Laboratory Astrophysics, is a physical science research institute located on the University of Colorado, Boulder, campus. JILA is jointly operated by the University of Colorado and the National Institute of Standards and Technology.

Acknowledgment of Reviewers

This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We thank the following individuals for their review of this report:

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Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report nor did they see the final draft before its release. The review of this report was overseen by Neil G. Siegel, NAE, Northrop Grumman Corporation (retired). He was responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

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Contents

PART III: ENGINEERING SCIENCES DIRECTORATE

PART IV: ARMY RESEARCH OFFICE-WIDE CROSSCUTTING RECOMMENDATIONS

APPENDIXES

Summary

The Army Research Office (ARO) describes its mission as follows:[1]

> The mission of ARO, as part of the U.S. Army Futures Command (AFC)—U.S. Army Combat Capabilities Development Command (CCDC)—Army Research Laboratory (ARL), is to execute the Army's extramural basic research program in the following scientific disciplines: chemical sciences, computing sciences, electronics, life sciences, materials science, mathematical sciences, mechanical sciences, network sciences, and physics.
>
> The goal of this basic research is to drive scientific discoveries that will provide the Army with significant advances in operational capabilities through high-risk, high pay-off research opportunities, primarily with universities, but also with large and small businesses. ARO ensures that this research supports and drives the realization of future research relevant to all of the Army Functional Concepts, the ARL Core Technical Competencies, and the ARL Essential Research Programs (ERPs). The results of these efforts are transitioned to the Army research and development community, industry, or academia for the pursuit of long-term technological advances for the Army.[2]

This report summarizes the findings of the review of ARO's Information Sciences Directorate (ISD) in 2018,[3] the Physical Sciences Directorate (PSD) in 2019,[4] and the Engineering Sciences Directorate (ESD) in 2020 conducted by the panels of the Army Research Laboratory Technical Assessment Board (ARLTAB).

INFORMATION SCIENCES DIRECTORATE

Research programs in the ISD are focused on discovering, understanding, and exploiting the mathematical, computational, and algorithmic foundations that are expected to create revolutionary capabilities for the future Army. Discoveries in this area are expected to lead to capabilities in materials, the information domain, and soldier performance augmentation, well beyond the limits facing today's

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[1] *2019 ARO in Review*, U.S. Army, Combat Capabilities Development Command (CCDC)—Army Research Laboratory, Army Research Office (ARO), Research Triangle Park, North Carolina.

[2] Basic research is defined by the Department of Defense (DoD) as the "systematic study directed toward greater knowledge or understanding of the fundamental aspects of phenomena and of observable facts without specific applications towards processes or products in mind," while applied research "is a systematic expansion and application of knowledge to develop useful materials, devices, and systems or methods" (DoD 7000.14-R Volume 2B, Chapter 5, 2017). Basic research drives directed studies toward revolutionary discoveries that will lead (and have led) to groundbreaking new capabilities for the Army in the time frame of 30 years and beyond, whereas applied research focuses on the near-term realization of new or improved technologies to meet a specific need.

[3] National Academies of Sciences, Engineering, and Medicine, 2019, *Assessment of the Information Sciences Directorate at the Army Research Office*, Washington, DC: The National Academies Press, doi: https://doi.org/10.17226/25426.

[4] National Academies of Sciences, Engineering, and Medicine, 2020, *Assessment of the Physical Sciences Directorate at the Army Research Office*, Washington, DC: The National Academies Press, doi: https://doi.org/10.17226/25830.

Army.[5] In addition, such discoveries are intended to help prevent technological surprises. The ISD's programs are organized in three divisions: Computing Sciences, Network Sciences, and Mathematical Sciences.

Computing Sciences Division

The vision for the Computing Sciences Division is to conceive of and develop transformational research programs in the computing sciences for the U.S. Army, exploit new computing paradigms and novel information processing techniques, and provide the scientific foundation to create revolutionary capabilities for the future warfighter. The division has selected its areas of focus to complement work supported by other agencies and does coordinate extensively but informally with them. The intent is to conduct longer term research in areas of Army-specific need that is not addressed by commercial and other government entities. This is a challenge in computing, because the rate of change is so rapid, particularly since the end of Dennard scaling and the rise of data-centric computing. Needs are assessed annually; examples of currently targeted Army needs are modeling of adversaries' learning, behavior, and social/cultural factors; interaction of soldiers with autonomous systems; and modeling of soldier situational awareness and decision making.

Overall, the scientific strategy and selection of projects were of high quality. The principal investigators (PIs) engaged for the selected projects were highly qualified, and the resulting science was of high caliber. The scientific objectives were generally focused on nearer term opportunities; longer term opportunities could be considered, and higher risk, potentially higher payoff topics could be included in the portfolio.

The programs generally performed very well in terms of funding leverage, relevance to Army needs, number and quality of publications, students supported, and transitions. The mapping of project accomplishments to programs' strategic plans was not always clear, and consistent, meaningful metrics for assessing progress were generally lacking. Appendix A of this report lists a broad set of metrics that ARO could consider for assessment of its programs.

The division's programs showed impressive examples of transitions to other Army and wider Department of Defense (DoD) research and development elements and in some cases to commercial organizations.

Network Sciences Division

The vision for the Network Sciences Division is to characterize, logically and quantitatively, the emerging macro properties in multigenre networks made up of autonomous agents, human networks, online social networks, and communication networks, leading to design of robust networks with predictable properties.

The division has a unifying scientific vision defining the program area. Scientific objectives were given for fulfilling this vision. Thrust areas were defined to achieve these program objectives. Across the division, the overall scientific quality is high, although some specific programs and investment areas are stronger than others. New areas identified for investment are unique and promising, with strong possibilities for contributing to the Army science and technology (S&T) goals.

The division's program managers evinced a high level of engagement in community building and discipline building, in venues such as disciplinary meetings and academic institutions. They showed a strong sense of stewardship for these communities, particularly where the division pursued a distinct strategy, as in the social and cognitive networking area. Across the division, program managers are

[5] Army Research Laboratory, "Army Research Office: Information Sciences," http://www.arl.army.mil/www/default.cfm?page=3227, accessed October 10, 2018.

actively seeking emerging developments in relevant scientific fields that can help move their programs forward in useful ways, as well as working to capitalize on recent major scientific advances. It is important that the program managers continue to seek ripe opportunities at the gaps between major fields (e.g., self-organizing biological network structures for applications in medicine) and continue to collaborate across disciplines.

Programs across the division evidenced forethought and focus. As a result, all programs showed strong evidence of recent and ongoing transitions to applied research programs within the Army, as well as several to the broader defense science community.

In the area of quantum networking, considerable benefit could be gained from allying with other research thrusts elsewhere in ARO, the ARL, or elsewhere in DoD to obtain a combination of basic science (e.g., theoretical analyses or mathematical models) and the best experimental science.

Mathematical Sciences Division

The vision for the Mathematical Sciences Division is to develop mathematical understanding and methods that enable fundamental investigations and disciplinary progress in a variety of physical, biological, engineering, and informational areas of study, providing the scientific foundation for revolutionary capabilities for the future warfighter.

The investigators are producing high-quality research, and the subject areas seem to be appropriate and of use to the Army. Examples include projects in quantum annealing, contributions to health monitoring, and contributions to helicopter engine monitoring. The program managers are well qualified and maintain a close and continuous contact with PIs. This way of operating promotes two-way contact and can help to ensure that information is shared. By and large, the program managers followed a deliberate and reasoned process behind the choice of project areas.

The PIs and research outcomes are of generally high quality. The quality of the research outcomes has been tangibly demonstrated through the transition of a number of projects to Army applied research and development (R&D) activities. The research addresses problems of importance to the Army and DoD. Programs and projects tend to address problems or use approaches that are not considered by other funding agencies such as the National Science Foundation (NSF) or the National Institutes of Health (NIH).

The division's implementation of ISD strategic initiatives within the research portfolios of its program managers reflects a view of research approaches that is very much tied to the interests and expertise of the program managers. The division would benefit from enhanced consideration of alternative approaches to address research problems. The division would also benefit from a systematic addition of mid-performance period review of all projects for which this is not performed. The feedback from these reviews would provide a basis for the refinement of future funding allocations.

There are several examples of short-term funding (e.g., 6-9 month grants) being used to explore new lines of research. The division's program might be strengthened if such short-term funding were used as part of an entrepreneurial model with the goal of developing a diverse set of competing technical approaches to high-opportunity topics.

ISD Crosscutting Recommendations

Overall, the ISD is producing work of high scientific quality. In general, the ISD program managers are well qualified, and the PIs that were selected for the funded projects are of high caliber. In general, the funded research is relevant to the Army's S&T goals; there were many examples of transitions of the research to the Army and to the DoD community more broadly.

While the Information Sciences Directorate is producing high-quality research overall, the ISD programs did not evince a clear and consistent set of metrics by which to evaluate program impact and effectiveness. It is necessary that metrics be counted by consistent and transparent methods (e.g., what is meant by a publication, how to count graduate students who are supported by multiple programs, how to assess caliber of awards and recognition) to facilitate measurement of progress. Metrics should reflect accomplishments actually attributable to the ARO projects. Appendix A of this report lists a broad set of metrics that ARO could consider for assessment of its programs.

ISD Crosscutting Recommendation 1: The Information Sciences Directorate (ISD) should develop and apply a set of clear and consistent metrics by which to evaluate program impact and effectiveness. (Part I, Chapter 5)

The directorate follows a system of establishing personal connections between the program managers and their PIs; this almost amounts to collaboration. This system is effective, but it runs the risk that research foci might not change on appropriate time scales and that promising alternative approaches to problems might be missed if they fall outside the knowledge and experience base of the program managers. The system would benefit from deliberate efforts to inject more competition among different research approaches. This would include more rapid turnover in the PI base.

ISD Crosscutting Recommendation 2: The Information Sciences Directorate (ISD) should consider ways to expand the knowledge base beyond that possessed by the program managers when formulating approaches to selecting programs for funding. (Part I, Chapter 5)

ISD Crosscutting Recommendation 3: To the extent that program managers in the Information Sciences Directorate (ISD) demonstrate management of successful programs and expanded knowledge of their discipline and of relevant opportunities to support research with potential application to Army needs, they should be encouraged to exercise their vision for basic science to meet Army needs and be encouraged to maintain their entrepreneurial style in program management. (Part I, Chapter 5)

ISD Crosscutting Recommendation 4: The Information Sciences Directorate (ISD) should consider shorter time scales and more rapid turnover of the principal investigator base for projects that are not jointly funded or targeted for long-term funding by collaborating ISD divisions, Army Research Office (ARO) directorates, or other funding agencies. Consideration should include potential impacts on graduate students supporting funded projects, should ARO deem graduate student support a project goal. (Part I, Chapter 5)

ARO supports research by PIs and by centers of multiple researchers. In contrast with single investigator programs, the Multidisciplinary University Research Initiative (MURI) programs at ARO support centers whose efforts intersect more than one traditional research specialty, typically at $1.25 million per year for 5 years. Research topics increasingly benefit from such multidisciplinary participation, even in pairs or small sets of investigators and over shorter time periods. Including in such collaborations researchers with knowledge of transitions would be useful.

ISD Crosscutting Recommendation 5: The Information Sciences Directorate (ISD) should consider funding mechanisms to encourage pairs or small sets of researchers from divergent perspectives to work on the same problem. (Part I, Chapter 5)

The program managers in the Information Sciences Directorate evinced varying levels of engagement with other DoD research, development, and funding agencies such as the Office of Naval Research (ONR), the Air Force Office of Scientific Research (AFOSR), the Defense Advanced Research Projects Agency (DARPA), and other elements within the Army, such as the Research, Development, and

Engineering Centers. Such engagement is important for the maintenance of shared situational awareness and is a key enabler for ARO to continue to "outpunch its weight."

ISD Crosscutting Recommendation 6: Program managers within the Information Sciences Directorate (ISD) should maintain and seek to expand their engagement with other Department of Defense funding agencies such as the Office of Naval Research, the Air Force Office of Scientific Research, the Defense Advanced Research Projects Agency, and other elements within the Army. (Part I, Chapter 5)

Diversity of gender, age, and geographic location was acknowledged across the ARO as requiring attention.

ISD Crosscutting Recommendation 7: The Information Sciences Directorate (ISD) should continue encouraging the participation of females and minorities in research funded by the Army Research Office and should collect statistics to track diversity in the broad sense, including gender, age, and geographic location. (Part I, Chapter 5)

PHYSICAL SCIENCES DIRECTORATE

Research in the PSD is focused on basic research to discover, understand, and exploit physical, chemical, and biological phenomena. This research is of a fundamental nature; however, in the long term, discoveries in this area are expected to lead to revolutionary capabilities in sensing, communications, protection, wound healing, power/energy storage and generation, and materials that extend the performance of Army systems well beyond current limits.[6] The PSD's programs are organized into three divisions: Physics, Chemical Sciences, and Life Sciences.

Physics Division

The Physics Division supports research to discover and understand exotic quantum and extreme optical physics, where new regimes are expected to create revolutionary capabilities for the future warfighter.[7] Four programs were reviewed: Atomic and Molecular Physics, Condensed Matter Physics, Quantum Information Science, and Optical Physics and Fields.

The overall scientific quality of the work presented was excellent, and in many cases was significantly innovative, being at or near the forefront of the relevant fields. From a management perspective, the research funding strategy appeared to be coherent and was clearly enunciated. The objectives were designed to promote critical advances in the fields of concern. The quality of research carried out under the auspices of the ARO-funded programs was excellent. However, it was difficult to evaluate the level of risk versus payoff, because only a few examples of failures (that is, where program objectives were not met) were given. Nonetheless, all of the presentations described results that were excellent, and in some cases outstanding.

Many of the research activities supported by ARO are in "hot" fields in which many other researchers are working. In the four fields mentioned above, there were two accomplishments cited that represent significant advances. These were the work done on super-radiant laser and the materials-agnostic demonstrations of the quantum anomalous Hall effect. It is likely that four other accomplishments will

[6] Army Research Laboratory, Army Research Office, http://www.arl.army.mil/www/default.cfm?page=217, accessed August 6, 2019.

[7] Army Research Laboratory, Army Research Office, https://www.arl.army.mil/www/default.cfm?page=217, accessed October 1, 2019.

achieve breakthroughs: computing with neuromorphic dissipative quantum phase transitions, analyzing physical phenomena on topological surfaces, scaling up of trapped ion multiqubit systems, and exploitation of super symmetries in optics.

Some cross-disciplinary opportunities are listed below along with associated recommendations.

Recommendation 1: Army Research Office (ARO) program managers (PMs) should view condensed matter physics and materials science as parts of a larger whole and be proactive in stimulating connections between them. ARO management should encourage regular interactions between the ARO Physics Division condensed matter PM and the materials science PMs elsewhere to coordinate funding of multiple principal investigators (PIs). (Part II, Chapter 7)

Recommendation 2: Army Research Office (ARO) management should encourage interdivisional activity on the quantum/classical algorithmic frontier, using appropriate incentives like Multidisciplinary University Research Initiative (MURI) grants. (Part II, Chapter 7)

Recommendation 3: The Army Research Office (ARO) should consider exploring breakthrough opportunities that may exist in the boundaries between the disciplines and divisions it has traditionally supported. (Part II, Chapter 7)

Recommendation 4: The Army Research Office (ARO) should seek a better balance between funding well-established and well-funded principal investigators (PIs) in “hot” disciplines and funding early-career investigators who are entering the “hot” fields or starting entirely new fields. (Part II, Chapter 7)

Chemical Sciences Division

The Chemical Sciences Division supports research to discover and understand the fundamental properties, principles, and processes governing molecules and their interactions in materials or chemical systems to provide the scientific foundation to create revolutionary capabilities for the future warfighter, such as new protective and responsive materials, sensors, and munitions.[8] Four programs were reviewed: Reactive Chemical Systems, Electrochemistry, Molecular Structure and Dynamics, and Polymer Chemistry.

Overall, the Chemical Sciences Division supports strong science and innovative research projects that have clear potential for improving the future performance of the Army. Notable examples of the impactful science funded by this division include the following: the development of melt-castable highly energetic materials made by co-crystallization; the design of self-regulating liquid crystals triggered by motile bacteria; the combinatorial synthesis and discovery of electrochemically active Perovskite materials; and the stabilization of biological materials using novel designer polymer coatings based on mapping of hydrophobic/hydrophilic regions on a targeted protein.

The four program presentations outlined the collective efforts of researchers of significant stature who are working on an array of projects of varying degrees of risk. It is important that ARO fund the leaders in the fields it chooses to support so that the Army’s agenda will be pushed forward as fast as possible, but it must not ignore the need to identify and fund the next generation of leaders whose work in emerging fields may lead to breakthroughs that also impact the future Army. In that regard, a greater degree of funding directed toward new investigators in the field (Short-Term Innovative Research [STIR] or single

[8] Army Research Laboratory, Army Research Office, https://www.arl.army.mil/www/default.cfm?page=217, accessed October 1, 2019.

investigator [SI] grants) would be beneficial. It is important to use mechanisms like conference grants and STIR grants to identify and encourage high-risk/high-payoff research.

Overall, the research being supported by this division is innovative. However, the research conducted would benefit greatly if the interaction between theory/simulation and experiment was stronger. There is great value in the Chemical Sciences Division's programs to support fundamental research, for the discovery of new science, and the development of new technologies for defense applications.

Life Sciences Division

The Life Sciences Division supports research efforts to advance the Army and nation's knowledge and understanding of the fundamental properties, principles, and processes governing DNA, RNA, proteins, organelles, prokaryotes, and eukaryotes, as well as multispecies communities, biofilms, individual humans, and groups of humans. The interests of the Life Sciences Division are primarily in the following areas: biochemistry, neuroscience, microbiology, molecular biology, genetics, genomics, proteomics, epigenetics, systems biology, bioinformatics, and social science. The results of fundamental research supported by this division are expected to enable the creation of new technologies for optimizing warfighters' physical and cognitive performance capabilities, for protecting warfighters, and for creating new Army capabilities in the areas of biomaterials, energy, logistics, and intelligence.[9] Five programs were reviewed: Biochemistry, Genetics, Microbiology, Neurophysiology of Cognition, and Social and Behavioral Sciences.

The overall quality of the five programs was judged to be very high, with strong and innovative projects in all of the programs. The emphasis is on basic research, although there was an impressive record of transitions of successful projects to customers. Many, but by no means all, projects were deemed to be high risk and high reward and would probably be too risky for funding from more conventional federal agencies like ARO. The panel saw a clear connection to future Army needs in the projects chosen.

The Life Sciences Division has a well-balanced portfolio that includes support of new investigators, who may be at particularly creative and innovative stages of their careers, as well as new directions for established investigators, through SI, STIR, and Young Investigator Program (YIP) funding. The emphasis is thus on important ideas that do not have enough data to support proposals to conventional funding organizations such as the National Institutes of Health (NIH). Here, the division could have a very positive impact on innovation, and this emphasis, which is already evident, needs to be encouraged. In several cases, the PMs funded pairs of PIs (not necessarily at the same institution) to work together on a single SI grant. This mechanism for crossing disciplinary boundaries to accomplish innovative studies has produced outstanding results. The division needs to continue to facilitate partnerships between pairs of investigators with diverse expertise through appropriate grant mechanisms.

PSD Crosscutting Recommendations

Advances in the fields covered by the PSD increasingly rely on contributions made by scientists who have different areas of expertise. For example, in chemistry, combined efforts in modeling and experiment are often essential for significant advances. Similarly, progress in condensed matter physics often depends on collaborations between individuals skilled in materials synthesis and scientists pursuing new phenomena. In addition, all the physical sciences are increasingly relying on data analytics. The PSD currently has some selected examples where funding of pairs of researchers from different disciplines, working synergistically, has led to significant success. Priority could go to those who have a

[9] Army Research Laboratory, Army Research Office, https://www.arl.army.mil/www/default.cfm?page=217, accessed October 1, 2019.

demonstrated history of successful collaborations. PMs could set priorities in terms of desired outcome and let researchers get together to make proposals.

PSD Crosscutting Recommendation 1: The Physical Sciences Directorate (PSD) should encourage the funding of pairs of principal investigators (PIs) from different disciplines who will work together on common problems, including those that are interdivisional and interdirectorate. For the Physics Division, the Army Research Office (ARO) should consider collaborative projects that involve both materials synthesis and condensed matter physics, as well as joint quantum information algorithms and information sciences projects, which would all be interdirectorate. For the Chemical Sciences Division, ARO should consider funding of pairs of PIs who will work together on modeling and experiment, which are both within the division. For the Life Sciences Division, ARO should consider mechanisms to improve data analytics to inform their explanatory models, which is also interdirectorate. (Part II, Chapter 10)

Many advances in science now occur at the boundaries between traditional disciplines, and consequently, multidisciplinary research has become increasingly important. This stretches the limits of traditional disciplines such as those found, for example, in university departments. The projects supported by the Life Sciences Division of the PSD encompass five disciplines in the biological and social sciences. The division is already multidisciplinary, even if not as much as it could be. By contrast, the Physics and Chemical Sciences Divisions are organized along more traditional disciplinary lines, and they seem to be having more difficulty broadening the boundaries of their disciplines, where the research being done crossed over into areas that they have not supported in the past. That kind of focus can miss many important new research developments.

PSD Crosscutting Recommendation 2: The Physical Sciences Directorate (PSD) should explore mechanisms to identify and support research in areas that do not fall solely within its core disciplines, including those that rely on contributions from research areas that are not funded within these core disciplines at all. (Part II, Chapter 10)

The PMs within the PSD currently do a good job of going to conferences and staying abreast of the exciting new work within their fields. They also do well in advertising their programs and interests to their own communities at such conferences. However, this highly targeted approach to publicizing the activities of ARO means that many members of the broader scientific community are unaware that ARO is a potential source of funding. That means that ARO is not seeing all the proposals from new PIs with different perspectives that it might. This limitation is of particular importance when it comes to attracting researchers in biology and other life science disciplines because a life scientist is very unlikely to think that an organization called Physical Sciences Directorate would be interested in what he or she does.

PSD Crosscutting Recommendation 3: The Physical Sciences Directorate (PSD) should find ways to further disseminate its funding opportunities to the broader community. In particular, the PSD should find ways to reach the broader biology and life sciences community, which is unlikely to be recognized as an opportunity given its Physical Sciences name. (Part II, Chapter 10)

ENGINEERING SCIENCES DIRECTORATE

The Engineering Sciences Directorate (ESD) is focused on basic research to harness high-risk discoveries in electronics, materials science, mechanical sciences, and earth sciences. In the long term, fundamental discoveries in these areas are expected to initiate unprecedented and disruptive capabilities in protection, mobility, sensing, computing, propulsion, networks, manufacturing, and sustainment to ensure the future technological superiority of our warfighters and Army.[10] The ESD's programs are organized into three divisions: Electronics, Materials Science, and Mechanical Sciences.

Electronics Division

The vision of the Electronics Division is to strategically drive new capabilities through discovery and enhancement of electronic and photonic phenomena and functions in entities ranging from inorganic materials and devices to single living cells that result in visionary performance characteristics that enable the U.S. Army to maintain technological overmatch across the Army functional concepts. The division's aim is to discover and enhance electronic and photonic interactions and functions in new devices and a broad range of materials. Some of the outstanding achievements encompass inorganic materials such as intercalated graphite for inductors; low-energy, high-speed optoelectronics; and optical control of ion transport in single living cells. Division-level strategy emphasizes interdisciplinary interactions between physics, chemistry, materials science, and biology. The overarching aim is to achieve device and system performance characteristics that enable the U.S. Army to maintain technological superiority vis-à-vis adversaries.

Four programs were reviewed: Biotronics, Electronic Sensing, Optoelectronics, and Solid-State Electronics and Electromagnetics. Key performance parameters include, in addition to peer-reviewed publications, transitions to ARL and to industry.

The projects highlighted were uniformly of high quality but only a small percentage of the entire portfolio was presented. Overall, the quality of programs reviewed was high, but there were limited initiatives aimed at new research directions—pursuing high-risk and high-reward projects that could lead to discovery and inventions of greater scientific significance.

Recommendation 5: The Engineering Sciences Directorate (ESD) Electronics Division should expand on new research directions and high-risk, high-reward projects that could lead to discovery and inventions of greater scientific significance. (Part III, Chapter 12)

Materials Science Division

The vision of the Materials Science Division is to create novel materials with extraordinary structural and functional properties and to explore underlying deterministic composition-processing-structure-external stimuli-property relationships through initiating, promoting, and embracing high-risk, high-payoff scientific ideas with special emphasis on materials design, synthesis and processing (S&P), mechanical behavior, and physical properties of materials to transform the future Army's capabilities. Four programs were reviewed: Mechanical Behavior of Materials, Synthesis and Processing of Materials, Materials Design, and Physical Properties of Materials.

The projects presented were uniformly of high quality, but only a small percentage of the entire portfolio was presented for review by the panel. The projects overall were found to be excellent in terms of collaborations and interdisciplinarity as well as scientific quality. Thus, it is hard to assess which opportunities may have been missed, and how successful connecting scientific discovery to Army functional concepts for these funded areas will be over time.

Overall, the Materials Science Division is conducting very high-quality research. The programs are driven, in an entrepreneurial manner, by well-qualified individual program managers (PMs) who can take their programs in different directions without significant bureaucracy. However, these individual PMs

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[10] Army Research Laboratory, Army Research Office, https://www.arl.army.mil/who-we-are/aro/army-research-office-directorates/, accessed October 3, 2020.

need strategic positioning and appropriate incentives to coherently drive their programs for maximum transitions to the Army.

It was observed that many of the publications referenced in the presentations were funded by multiple funding agencies. This leveraging of funds is to be commended; however, with multiple support agencies, it is difficult to judge the impact that ARO funding had on the research. A better metric of publications, one factoring in the dominant funding organization, would be more useful both to ARO and to a review panel.

Recommendation 6: The Army Research Office (ARO) should develop a publication metric that quantifies the extent of ARO funding to the publication. ARO should present this metric in future Army Research Laboratory Technical Assessment Board (ARLTAB) reviews. In addition, ARO should highlight in these reviews the key scientific advances attained primarily by ARO funding. (Part III, Chapter 13)

The programs funded by ARO are intended to be high-risk, high-payoff research projects that drive cutting-edge research and lead to disruptive science and technologies. This science plays an important role in innovation, in follow-on investments in Small Business Technology Transfer (STTR)/ Small Business Innovation Research (SBIR) programs, and in patent generation. Numerous metrics were provided but did not include metrics for patent-related activities.

Recommendation 7: The Army Research Office (ARO) should track the number of technology disclosures, patent applications, and patent issuances that have resulted from ARO-supported funding or collaborations. (Part III, Chapter 13)

The research strategy within the ARO Engineering Sciences Directorate seems to be principally a bottom-up organization, where the PMs have primary discretion and authority regarding project selection and funding decisions. The PMs are all well qualified for their positions. The directorate strategy is to pose bold scientific questions; to seek collaborations; to engage with the Army laboratories for transitioning the research; to seek out high-risk, high-reward opportunities; to venture into new areas with long-term impact on enhancing Army capabilities; and to hire and retain an excellent workforce. All of these items are meritorious. This strategy includes "casting a wide net," even though funding levels for materials science programs are relatively small compared to peer organizations, such as the Department of Energy (DOE), National Science Foundation (NSF), Defense Advanced Research Projects Agency (DARPA), Air Force Office of Scientific Research (AFOSR), Office of Naval Research (ONR), and so on. By having the PMs follow both directorate program planning and respective division strategy, transitions to the Army could be enhanced. Because the directorate investment is relatively small and the opportunities in engineering sciences are large, focusing on fewer research topics with greater funding on those identified could possibly result in greater benefit to the Army through transitions without loss of scientific excellence.

Recommendation 8: The Army Research Office (ARO) Program Managers (PMs) should be encouraged to prioritize directorate and division strategy with respect to focusing project selection by further improving the connection of scientific discovery to Army transitions. (Part III, Chapter 13)

All of the programs have listed the transitions; however, no quantitative metric of transitions was presented and no information about how transitions are evaluated or used in program planning was presented. Transitions appear to be an important metric of the effectiveness of the scientific programs and are highlighted in the Directorate Planning Program as program assessment.

Recommendation 9: The Army Research Office (ARO) should develop a transition metric that quantifies the effectiveness and importance of transitions to the Army and use this metric as a guide in the selection of future projects. ARO should present this metric in future Army Research Laboratory Technical Assessment Board (ARLTAB) reviews. (Part III, Chapter 13)

Mechanical Sciences Division

The vision of the Mechanical Sciences Division is to conceive of and develop transformational research programs in mechanical sciences for the U.S. Army to provide the scientific foundation to create revolutionary capabilities for the future warfighter. The division supports research aligned with the following Army functional concepts: command and control, fires, maneuver, protection, and sustainment. Five programs were reviewed: Complex Dynamics and Systems, Earth Materials and Processes, Fluid Dynamics, Propulsion and Energetics, and Solid Mechanics.

In general, the scientific quality of the work funded is of sufficiently high quality and is not of concern. As expected, this fundamental research program of ARO, when considered as a whole, supports a large number of smaller projects that have a distribution from very high risk, unproven concepts (e.g., dynamic analysis frameworks) to very low risk, historically vetted methods (e.g., shock tube methods). The majority of the questions are aimed at understanding the methodology for PM-selected focus areas within their proposal. In general, the PM appears to have significant autonomy in adjusting the focus areas of the research portfolio—it is the PM who can target potential PIs, manage the proposal review process, assemble proposal review scores, and make final recommendations as to prioritization of funded projects. The individual PM-centric approach for managing division portfolios raised questions related to transparency and methodology of proposal solicitation, proposal review and final assessment, and proposal selection for risk balancing and strategic alignment. This level of PM independence could impede ARO's top-down distillation of Army needs into research thrusts for funding.

As demonstrated by the newer PM, focus questions were adjusted at review time in order to give the research portfolio a cohesive focus. This indicates that the portfolios are not being managed by a strategic plan with a long-term timeline; instead, the goals of any given year are adjusted on demand. This has implications for the autonomy of the PM to follow research that may not be best aligned with the long-term ARO strategy.

Recommendation 10: The Army Research Office (ARO) management should establish processes that help ensure that proposed research is unique, pioneering, and/or novel. ARO management should place emphasis on envisioning and conducting workshops or other events that reach beyond the current cadre of funded principal investigators to explore fields broadly and define new directions and new investigators for the programs. (Part III, Chapter 14)

In a number of divisions, areas of missed opportunity for interdivision collaboration and an apparent stovepipe of projects under each PM were identified. There were certainly examples where this is not the case, but in an agile and responsive research portfolio, more interdisciplinary projects are expected. The MURI projects provide a good example of interdisciplinary projects, yet there are not many collaborations between these and most other projects within a PM's portfolio. Efforts to promote improved collaboration across ARO divisions and scientific disciplines would be beneficial.

Recommendation 11: The Army Research Office (ARO) management should develop mechanisms that facilitate interactions within the Mechanical Sciences Division and with the Materials Science, Chemical Sciences, and Physics Divisions. ARO should focus these interactions to be on funding projects with aligned priorities within the programs, be they within the same division or across divisions. (Part III, Chapter 14)

ESD Crosscutting Recommendations

The research strategy within the ARO ESD seems to be principally a bottom-up organization, where the PMs have primary discretion and authority regarding project selection and funding decisions. The PMs are all well qualified for their positions. The directorate strategy is to pose bold scientific questions; to seek collaborations; to engage with the Army laboratories for transitioning the research; to seek out high-risk, high-reward opportunities; to venture into new areas with long-term impact on enhancing Army capabilities; and to hire and retain an excellent workforce. All of these items are meritorious. This strategy includes “casting a wide net,” even though funding levels are relatively small compared to peer organizations, such as DOE, NSF, DARPA, AFOSR, ONR, and so on. By having the PMs follow both directorate program planning and respective division strategy, transitions to the Army could be enhanced. Because the directorate investment is relatively small and the opportunities in engineering sciences are large, focusing on fewer research topics with greater funding for those identified could possibly result in greater benefit to the Army through transitions without loss of scientific excellence.

ESD Crosscutting Recommendation 1: The Army Research Office (ARO) program managers (PMs) should be encouraged to prioritize directorate and division strategy with respect to focusing project selection by further improving the connection of scientific discovery to Army transitions. (Part III, Chapter 15)

Efforts to promote improved collaboration across ARO divisions and scientific disciplines would be beneficial. In addition to technical diversification or collaboration between projects, some portfolios would also benefit from increased diversity of research PIs to include early-career PIs and less long-term continued funding provided to late-career PIs.

ESD Crosscutting Recommendation 2: The Army Research Office (ARO) management should establish processes that help to ensure that proposed research is unique, pioneering, and/or novel. ARO management should place emphasis on envisioning and conducting workshops or other events that reach beyond the current cadre of ARO PMs and funded principal investigators (PIs) to explore fields broadly and to define new directions and new, early-career, and more diverse participants for the programs. (Part III, Chapter 15)

Overall, the ESD is conducting very high quality research. The programs are driven, in an entrepreneurial manner, by well-qualified individual PMs who can take their programs in different directions without significant bureaucracy. However, these individual PMs need strategic positioning and appropriate incentives to coherently drive their programs for maximum transitions to the Army. Overall, the quality of programs reviewed was high but limited initiatives aimed at new research directions and pursuing high-risk and high-reward projects that could lead to discovery and inventions of greater scientific significance.

ESD Crosscutting Recommendation 3: The Army Research Office (ARO) should expand on new research directions and high-risk, high-reward projects that could lead to discovery and inventions of greater scientific significance. (Part III, Chapter 15)

In a number of divisions, areas of missed opportunity for interdivision collaboration and an apparent stovepipe of projects under each PM were identified. There were certainly examples where this is not the case, but in an agile and responsive research portfolio, more interdisciplinary projects are expected. The MURI projects provide a good example of interdisciplinary projects, yet these are not readily accessible to most projects within a PM’s portfolio. Efforts to promote improved collaboration across ARO divisions and scientific disciplines would be beneficial.

ESD Crosscutting Recommendation 4: The Army Research Office (ARO) management should develop mechanisms that facilitate interactions within the ARO directorates and divisions, including for example the Mechanical Sciences and Electronics Divisions and with the Materials Science, Chemical Sciences, and Physics Divisions. ARO should focus these interactions to be on funding projects with aligned priorities within the programs, be they within the same division or across divisions of different directorates. (Part III, Chapter 15)

ARO-WIDE CROSSCUTTING RECOMMENDATIONS

Based on the 2018-2020 reviews whose assessment is summarized in this report, the ARLTAB offers the following ARO-wide crosscutting recommendations.

ARO Crosscutting Recommendation 1: The Army Research Office (ARO) Program Managers (PMs) should be encouraged to prioritize directorate and division strategy with respect to focusing project selection by further improving the connection of scientific discovery to Army transitions.

ARO Crosscutting Recommendation 2: The Army Research Office (ARO) should expand on new research directions and high-risk, high-reward projects that could lead to discovery and inventions of greater scientific significance.

ARO Crosscutting Recommendation 3: The Army Research Office (ARO) should encourage the funding of pairs of principal investigators (PIs) from different disciplines who will work together on common problems, including those that are interdivisional and interdirectorate. For example, for the Physics Division, ARO should encourage the funding of collaborative projects that involve both materials synthesis and condensed matter physics, as well as joint quantum information algorithms and information sciences projects, which would all be interdirectorate; for the Chemical Sciences Division, ARO should consider modeling and experiment, which are both within the division; and for the Life Sciences Division, ARO should consider mechanisms to improve data analytics to inform its explanatory models, which is also interdirectorate.

ARO Crosscutting Recommendation 4: The Army Research Office (ARO) should find ways to further disseminate its funding opportunities to the broader community. For example, the Physical Sciences Directorate should find ways to reach the broader biology and life sciences community, which is unlikely to be recognized as an opportunity given its Physical Sciences name.

ARO Crosscutting Recommendation 5: To increase diversity within the Army Research Office (ARO) and the programs it supports, ARO should carry out a detailed assessment of the diversity of participants, both within ARO itself and in the programs that ARO supports. ARO should then establish a clear diversity policy and plan and should measure its progress against this plan.

Part I: Information Sciences Directorate

1

Introduction

At the request of the U.S. Army, on August 7-9, 2018, the National Academies of Sciences, Engineering, and Medicine's Panel on Review of Extramural Basic Research at the Army Research Laboratory (ARL) met to review the programs of the Information Sciences Directorate (ISD) of the Army Research Office (ARO), which is an organizational unit within the ARL. The meeting was held at the ARO headquarters in Durham, North Carolina.

The panel's review was guided by the following statement of task provided by the National Academies:

> An ad hoc committee to be named the Panel on Review of Extramural Basic Research at the Army Research Laboratory, to be overseen by the Laboratory Assessments Board (LAB) of the Division on Engineering and Physical Sciences, will be appointed to provide annual assessments of the Army Research Office (ARO) programs. Each year one of the ARO's three divisions (Information Sciences, Physical Sciences, and Engineering Sciences) will be assessed by a separately appointed panel. These assessments will address criteria to be defined by the ARO. Each year the panel will provide a report summarizing its findings, conclusions, and recommendations. The panel's report will be made available to the public on the National Academies Press website and will be disseminated in accordance with National Academies policies.

The current report summarizes the 2018 findings of the Panel on Review of Extramural Basic Research at the Army Research Laboratory, which reviewed the programs at the ARO's ISD. Over the 2019-2020 period, the National Academies conducted reviews of the ARO's Physical Sciences Directorate's programs in physics, chemical sciences, and life sciences and its Engineering Sciences Directorate's programs in electronics, materials science, mechanical sciences, and earth sciences.

PROGRAMS WITHIN THE INFORMATION SCIENCES DIRECTORATE

The Army Research Laboratory's ARO describes its mission as

> To serve as the Army's principal extramural basic research agency in the engineering, physical, information and life sciences; developing and exploiting innovative advances to insure the Nation's technological superiority. Basic research proposals from educational institutions, nonprofit organizations, and private industry are competitively selected and funded. ARO's research mission represents the most long-range Army view for changes in its technology. ARO priorities fully integrate Army-wide, long-range planning for research, development, and acquisition. ARO executes its mission through conduct of an aggressive basic science research program on behalf of the Army so that cutting-edge scientific discoveries and the general store of scientific knowledge will be optimally used to develop and improve weapons systems that establish land force dominance. The ARO research program consists principally of extramural academic research efforts consisting of single investigator efforts, university-affiliated research centers, and specially tailored outreach programs.[1]

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[1] Army Research Laboratory, "Army Research Office," http://www.arl.army.mil/www/default.cfm?page=29, accessed October 10, 2018.

Research programs in the ISD are focused on discovering, understanding, and exploiting the mathematical, computational, and algorithmic foundations that are expected to create revolutionary capabilities for the future Army. Discoveries in this area are expected to lead to capabilities in materials, the information domain, and soldier performance augmentation, well beyond the limits facing today's Army.[2] The ISD's programs are organized by three divisions: Computing Sciences, Network Sciences, and Mathematical Sciences. Across the three divisions, the ISD currently funds 580 projects with a budget of $108 million—$22.3 million core funding and $85.7 million leveraged funding from sources that include the Multidisciplinary University Research Initiatives (MURI) program, the Presidential Early Career Awards for Scientists and Engineers (PECASE), the Defense University Research Instrumentation Program (DURIP), the Minority Institutions Program, the Small Business Innovation Research (SBIR) program, the Small Business Technology Transfer (STTR) program, and other Army and Department of Defense (DoD) sources.

APPROACH TO THE ASSESSMENT

The panel consisted of 18 leading scientists and engineers whose expertise matched the programs at the ARO's ISD that were reviewed. All panel members were volunteers who participated without compensation. The entire panel attended overview presentations by and held discussions with the directors of the ARL, ARO, and the ISD. The panel members then divided into three teams of 6 members each; the teams separately attended presentations by and discussions with the managers of selected programs in the three ISD divisions (Computing Sciences, Network Sciences, and Mathematical Sciences). The presentations and discussions occurred over a 2-day period. On the third day of the meeting, the panel assembled to share findings from the team reviews, develop impressions common across the team reviews, and form an outline for the panel's report draft. On the afternoon of the third day, the panel met with ARO staff to seek clarification of factual and contextual understandings.

After the meeting, the panel members prepared written summaries of their findings, conclusions, and recommendations, which were iteratively reviewed by the panel and formed the basis for the draft report that was subsequently developed under the guidance of the National Academies' Army Research Laboratory Technical Assessment Board (ARLTAB), which focused particularly on the panel's approach to the review and the report's conclusions and recommendations. The ARLTAB consists of the chairs of the panels that review the scientific and technical work of all ARL directorates, including those at the ARO.

Once the panel addressed the comments offered by the ARLTAB, the report was submitted to the National Academies' Report Review Committee (RRC). The RRC appointed a team of reviewers to examine the report, considering such factors as the scope of the panel's task, the reasonableness of the panel's conclusions and recommendations, and the clarity of the panel's expression. Once the RRC reviewers' comments were adequately addressed, the report was released for delivery to the Army and for public posting on the National Academies Press website (www.nap.edu).

The panel applied a largely qualitative rather than quantitative approach to the assessment. The approach of the panel relied on the experience, technical knowledge, and expertise of its members, whose backgrounds were carefully matched to the core technical competency areas in which the ARL and ARO activities are conducted. The panel reviewed selected examples of the scientific and technological research programs at the ARO's ISD; it was not possible to review all ISD programs and projects exhaustively. ARO selected the programs and projects that were presented for review. Given the necessarily nonexhaustive nature of the review process, the omission of mention of any particular program or project should not be interpreted as a negative reflection on the omitted program or project.

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[2] Army Research Laboratory, "Army Research Office: Information Sciences," http://www.arl.army.mil/www/default.cfm?page=3227, accessed October 10, 2018.

The panel's goal was to portray an overall impression of the ARO programs in information sciences while preserving useful mention of suggestions specific to programs that the panel considered to be of special note within the set of those examined. Therefore, the panel strove to identify and report salient examples that supported discussion of accomplishments and opportunities for further improvement with respect to the ISD's programs.

ASSESSMENT CRITERIA

The panel was asked to consider the following criteria during the review:

1. *Overall scientific quality and degree of innovation:* Was there a clear and cogent strategy regarding how each of the program managers' major objectives are likely to make substantial and unique progress in advancing scientific frontiers of their discipline? Is the research novel, leading the field in an important area, and does it have the appropriate level of risk and payoff? Was related research being sponsored by other major players adequately summarized in terms of approach and goals? Were there areas of duplication?
2. *Scientific opportunity:* Is there some reasonable basis (e.g., incipient breakthrough, new understanding, novel theory, etc.) to believe that the scientific objectives might be met? Have the highest priority objectives been selected?
3. *Significant accomplishments:* Did the accomplishments represent significant scientific advances? If not, what is the potential that the accomplishments will lead to significant scientific advances? How do the accomplishments map to the stated program goals? Do the accomplishments reflect productivity and ingenuity on the part of the performers?
4. *Relevance/transitions:* Is the potential, long-term Army application of the research significant? Were there appropriate examples of significant transitions, or anticipated transitions of research, to follow on applied research or exploratory development either within industry or within an Army or DoD laboratory?
5. Additional considerations:
    a. What were the particular strengths in the program, and what were the weaknesses, if any?
    b. If there were notable weaknesses, what are suggestions for improvements in these areas?
    c. Are there any high-priority missed opportunities/areas?
    d. If so, what lower priority area(s) should be reduced or eliminated to accommodate the new area?

The panel was instructed that the following items are outside the scope of the panel's charge and that these items should not be considered in the assessment:

- Other divisions or offices within the ARO and ARL: The panel is charged only to assess the Information Sciences Directorate of the ARO.
- Organizational changes: The ARO organizational structure is not subject to the assessment.
- Employee morale or motivation: The assessment panel does not conduct scientific surveys nor analyze the data required to assess morale, and is not asked to do so.
- Funding: The panel is not asked to assess or recommend the amount or sources of ARO funding.

PART I CONTENT

This chapter discusses the process used to conduct the assessment and report the resulting findings, conclusions, and recommendations. Part I Chapters 2 through 4 provide assessments of the programs within each of the ISD divisions (Computing Sciences, Network Sciences, and Mathematical Sciences). Chapter 5 presents crosscutting recommendations common across two or more of the divisions.

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Computing Sciences Division

The Information Sciences Directorate (ISD) describes its programs in computing science as follows: Programs in the Computing Sciences Division are "focused on understanding the fundamental principles and techniques governing computational models and architectures for intelligent, trusted, and resilient computing." These programs provide "the foundation for revolutionary capabilities for future warfighters in signal and data processing, data fusion, and social informatics." The programs are Information Processing and Fusion, Computational Architecture and Visualization, Information and Software Assurance, Intelligent Systems, and Advanced Computing (an international program).[1] The Computing Sciences Division seeks to conceive of and develop transformational research programs in the computing sciences for the U.S. Army to exploit new computing paradigms and novel information processing techniques.

To accomplish this vision, the division has organized around four programs: Information Assurance, Information Processing and Fusion, Computational Architecture and Visualization, and Intelligent Systems. Currently only three, Information Assurance, Information Processing and Fusion, and Computational Architecture and Visualization, have program managers and active programs, and only those three were reviewed. The fourth, Intelligent Systems, is awaiting the appointment of a program manager. The division's budget of $29 million, including $6.6 million in core funds and $22.4 million in leveraged funds, supports 188 projects.

INFORMATION ASSURANCE PROGRAM

Overall Scientific Quality and Degree of Innovation

The scientific strategy and selection of projects were of very high quality. The principal investigators (PIs) engaged for the selected projects were highly qualified, and the resulting science was of the highest caliber. The Information Assurance Program had a clearly defined, cogent, and compelling strategy. The focus on the investigation of integrity, trustworthiness, and availability of cybersystems for future military installations and warfighters is substantive yet broad enough to address future environments. The strategic investments in cyberawareness and cyberdefenses are well placed at making progress in key scientific areas.

The Information Assurance Program was well executed, and the resulting science and innovation was exceptional. The investments in strategic projects with high-quality investigators has led to major results and consistent progress in key scientific problems of essential importance to the Army. Army Research Office (ARO)-sponsored investigators at the University of California, Santa Barbara, have created an automated evasive malware detection method based on real hardware systems that can enhance warfighter capability in cyberdefense. A common shortcoming of current virtual machine-based malware analysis

[1] Army Research Laboratory, "Army Research Office: Information Sciences," http://www.arl.army.mil/www/default.cfm?page=3227, accessed October 10, 2018.

and detection systems is that adversaries can detect the presence of virtual machines and avoid exhibiting malicious behavior to evade detection. The new approach, which executes and analyzes malware samples on native hardware instead of on a virtual machine, enables the capturing of true behavior profiles of evasive malwares for detection. The malware analysis system was recently transitioned to the Cyber Systems Division of the Air Force Life Cycle Management Center at Joint Base San Antonio-Lackland in San Antonio, Texas, for field test and usage. Algorithms of feature extraction for explosive hazard detection for countering improvised explosive devices have been developed at the University of Missouri with ARO funding. The technology has been transitioned to the U.S. Army Communications-Electronics Research, Development, and Engineering Center (CERDEC) Night Vision and Electronic Sensors Directorate for evaluation and field test.

The program has had substantially more impact on the science of security than might be expected given the research expenditures. This appeared to be largely owing to the continuity of the program and the effectiveness of the program manager.

There does not appear to be any need to make major adjustments to the program. The overall direction and the process used to create and execute the program portfolio are appropriate. An increase in the size and scope of the research program might allow better alignment with future Army needs.

Scientific Opportunity

The program could have more impact on the Army, without impacting existing program substance or strategic investments, by adding investments in higher risk and higher potential research projects. These investments would benefit from more direct integration with other ARO programs.

Significant Accomplishments

The impact and accomplishments of the program were outstanding. The number and quality of the publications resulting from this program were exceptional for a program of this size. For a program of this size, the number of students and postdoctoral researchers supported was outstanding.

The connection between the program accomplishments and the strategic plan was not always clear. It is important that the program manager identify the most important accomplishments as they relate to the key strategic goals for the Army and clearly define and use a set of metrics to measure the progress of the program. Appendix A of this report lists a broad set of metrics that ARO could consider for assessment of its programs.

Relevance/Transitions

There were many examples of significant transitions to start-ups and other companies, and to other Army organizations, including the Army Research Laboratory (ARL). The number and quality of transitions were exceptional for a program of this size (52 current projects). The portfolio was highly relevant and responsive to future Army needs.

ARO-funded research on anti-phishing techniques at Carnegie Mellon University (CMU) was transitioned to Wombat Security, a CMU start-up company. ARO also provided critical support during the early stage of the company to mature the technology for commercialization. Wombat has grown to become the major player in the anti-phishing market and was acquired in 2018 for $225 million, showing a huge impact that ARO-funded research and commercialization has brought about. Under ARO support, Intelligent Automation, Inc., developed the DeepRadio technology to provide reconfigurable embedded implementation of deep neural networks as a stand-alone radio platform for characterizing the radio frequency (RF) spectrum environment in real time and adapting to spectrum dynamics. This technology has been transitioned to the CERDEC. At the Fort Dix field test, DeepRadio demonstrated effectiveness in detecting RF-interfering sources and mitigating their effects on wireless communications. In the field test, DeepRadio successfully learned the behavior of a dynamic jammer that does not transmit continuously and is hard to detect, using a deep neural network model and providing a more than 85 percent success rate of detecting potential jammers.

Additional Considerations

The projects, PIs, focus, relevance, and results of the Information Assurance Program were exceptional. This strength of the program was largely owing to the effectiveness and continuity of the program manager, who is widely viewed in the cybersecurity science and technology community as a thought leader. Documentation and formalizing of the mechanics and strategy of the Information Assurance Program could be used to educate other program managers and replicate the success of the program.

INFORMATION PROCESSING AND FUSION PROGRAM

Overall Scientific Quality and Degree of Innovation

The Information Processing and Fusion Program exhibited high-quality, innovative research with an excellent and diverse group of PIs. There is a very good mixture of projects. The program also extensively leverages funding sources such as Multidisciplinary University Research Initiatives (MURIs) and Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs, and it makes close connections with related Army efforts such as the Collaborative Technology Alliances (CTAs) at the Army Research Laboratory. The program performed very well in terms of funding leverage, collaboration, relevance to Army needs, publications, students supported, and transitions.

ARO-sponsored research in compressive sensing at Rice University has led to magnetic resonance imaging (MRI) technologies that are likely to revolutionize soldier healthcare by significantly reducing MRI acquisition time, enabling dramatically shortened scans. The compressive sensing framework provides methods and algorithms to computationally reconstruct images from minimum, compressed measurements, which reduces image acquisition time from 4 minutes for traditional MRI technologies to just 16 seconds. The major MRI vendor, Siemens, Inc., has licensed the technology from Rice University to create new systems based on compressive sensing MRI, which recently received approval from the Food and Drug Administration. This compressive sensing framework can also be applied to other imaging applications that use infrared or radar modalities for efficient image acquisition.

The presentation of the program vision did not make clear its connection with the research topics chosen for funding. The presentation of highlighted research projects did not articulate the significance of the research very well, making it challenging to assess the quality of the research. The value of some of the research topics, such as the MURI on Information Noncommutativity, was not made clear. There are challenges of communicating research content and new advances in this program area, but it should be possible to craft compelling material that shows the value of the research and the advances that are being made. For example, the presentations had a number of equations and graphics that did not effectively communicate any new information.

Scientific Opportunity

The objectives of the program cover a broad range of topics with growing scientific opportunities, such as multimodal data, information frameworks, sparse representations, causality inference, and value-driven information processing. The scientific objectives were focused on nearer term opportunities; longer term opportunities could be considered, and higher risk, potentially higher payoff topics could be included in the portfolio. There could be good future opportunities for this research area related to manned/unmanned teaming, robotic and autonomous systems, and robotic swarms.

Significant Accomplishments

New techniques using compressive sensing algorithms for data reconstruction have been transitioned from Rice University to Conoco-Phillips, a major energy company in the application of seismic sensing for oil exploration. Implementation of the new technique on the company's system has saved several hundred million dollars in data acquisition and analysis costs.

The large amount of MURI funding, alignment with CTAs at the ARL, and SBIR/STTR funding indicates a high degree of success in building a diverse, dynamic research portfolio. The program could endeavor to feature major programmatic accomplishments (such as compressive sensing) more prominently. The publication count and quality are strong. Considering the size of the budget ($9 million supporting 75 projects, of which $2.5 million is ARO core funds and $6.5 million is leveraged funds), a commendable number of students and postdoctoral researchers are supported. However, it was sometimes hard to determine how the accomplishments mapped to the goals of the program.

Relevance/Transitions

The research areas covered by the Information Processing and Fusion Program overall have an extremely high relevance to the future Army and align with several of the army modernization priorities. The quantity and quality of the transitions, which include transitions within the Army and to the commercial sector, are commendable. The following are examples of transitions that have been accomplished in Army-relevant areas: video surveillance for human activity detection, multimodal biometrics, human-robot communication, and battlefield decision-making systems. The program manager makes a concerted effort to reach out to investigators with other organizations in the Army to create leveraging and transitions. However, the relevance of the programs to future Army needs was not articulated well during the review.

Additional Considerations

The Information Processing and Fusion Program includes projects that could transition to the new Intelligent Systems Program to accelerate the start of that program.

COMPUTATIONAL ARCHITECTURE AND VISUALIZATION PROGRAM

Overall Scientific Quality and Degree of Innovation

The Computer Architecture and Visualization Program articulated three scientific objectives: create interactive yet accurate visualizations coupled with simulations; create new energy-efficient architectures for multicore, hybrid, and exascale systems to operate in a resource-constrained environment; and devise scalable and communication-efficient algorithms to effectively handle the complex data arising from Army applications. Within this, the work on visualization is largely independent of that in computer architecture. The strategy relating scientific objectives to the fundamental, long-term science was not as explicit and well-articulated as in the other programs within the division.

Particular strengths of the program are that the PIs have impressive research credentials, or promise thereof for the younger PIs, and that for the most part the areas under investigation are relevant to Army needs.

The visualization work is aimed at capabilities beyond classical visualization while remaining in line with the generation of simulation results in a way that avoids the display of visual artifacts that distort the interpretation of the results. This is an area that may have value both to classical computational science and in newer multi-agent applications. The work described addressed both areas.

The bulk of the recent computer architecture work seemed to be focused on a shorter time frame than that of many of the division's other programs and was not focused on architecture as classically defined. The work described on message-passing libraries for big data and on scheduling for graphics processing units was reasonable but very short term; it is likely that similar work is being performed at a much larger scale by major commercial concerns. However, considering the titles of some of the other projects funded under the program but not reviewed, such as the work on approximate computing, and the backgrounds of their PIs, it is likely that some of the architecture work funded in the recent past did have a longer time horizon with a deeper microarchitecture focus, and that work may have held out the potential for developing more fundamental results.

The current portfolio of work in computer architecture within the Computer Architecture and Visualization Program may be more appropriately aligned with the yet-to-be initiated Intelligent Systems Program. The portfolio of work in computer architecture needs to include some higher risk, potentially higher payoff topics. In particular, the portfolio of work in computer architecture needs to include more projects that are focused on computer architecture, that have a longer time horizon, and that have the potential to suggest fundamental changes to computing systems. The above-mentioned approximate computing work is a good example of this. Working with some of the ARL projects, such as at Aberdeen on neuromorphic (e.g., IBM's TrueNorth processor) and tiled architectures, may help identify issues with today's emerging architectures that may be fodder for alternative approaches. Alignment with the proposed Intelligent Systems Program may also provide identification of application-level issues that may engender the need for new architecture features (e.g., special-purpose coprocessors to accelerate machine learning, such as Google's tensor processing unit).

Scientific Opportunity

The computer architecture portion of the program is not forward-looking enough. There is significant scientific opportunity in computer architecture—in particular, in the design of special-purpose processors that can accelerate the solution of applications important to the Army. This also offers the opportunity to significantly reduce power consumption, which does not seem to be a focus of the current computer architecture projects, although it was one of the three stated scientific objectives of the Computer Architecture and Visualization Program. There appear to be only two projects in the portfolio of 34 projects that had energy efficiency as one of the design goals.

It is important that new projects in the Computer Architecture and Visualization Program have higher potential and higher risk. This is particularly the case for projects in the computer architecture space, which currently are too short-term focused and not focused enough on energy-efficient design.

Significant Accomplishments

Considering the size of the program ($1.6 million, including $1.2 million in core funding, supporting 34 current projects), the publication count and quality are strong, and a commendable number of students and postdoctoral researchers are supported. It was sometimes hard to determine how the accomplishments of the projects mapped to the scientific objectives of the program. It is necessary that the project PIs know about and understand the scientific objectives of the program and align their work with at least one of those objectives.

Relevance/Transitions

There were many examples of significant transitions to start-ups, companies, and other Army organizations. Examples are a personalized gait simulation, transitioned to the Institute for Creative Technology; new data structures and uncertainty qualification techniques, transitioned to Scalable Algorithmics, Inc.; mixed-criticality scheduling software, transitioned to General Motors Corporation; and load balancing algorithms, transitioned to the U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC). However, none of these involved architecture-related artifacts. On the whole, the portfolio was relevant to future Army needs.

Additional Considerations

A very large percentage of the recent grants seemed to be for institutions in the state of North Carolina. The pool of project proposers was not presented; ARO may want to examine that pool to determine whether greater diversity in institutions supported by the program's funding is warranted.

INTELLIGENT SYSTEMS PROGRAM

The Intelligent Systems Program has not yet been initiated, but an overview of the plan for the program was presented. The topics to be covered by the Intelligent Systems Program represent a major and relevant opportunity for addressing future Army needs.

The program needs to be started as soon as possible, employing, if necessary, an interim program manager to get it started. Because this is a very "hot" topic and competition is fierce for experts, it may be worthwhile to consider a program manager who can grow into the position or an adjustment to the program's focus to make the position more attractive. Appropriately performed, program adjustment, if any, would remain within the bounds of the stated program thrusts: advanced learning theory, methodology, and techniques; and adaptive, robust, and pervasive intelligent systems.

OVERALL ASSESSMENT

Overall Scientific Quality and Degree of Innovation

Overall, the scientific strategy and selection of projects were of high quality. The PIs engaged for the selected projects were highly qualified, and the resulting science was of high caliber.

Scientific Opportunity

The scientific objectives were generally focused on nearer term opportunities; longer term opportunities could be considered, and higher risk, potentially higher payoff topics could be included in the portfolio.

Significant Accomplishments

The programs generally performed very well in terms of funding leverage, relevance to Army needs, number and quality of publications, students supported, and transitions. The mapping of project accomplishments to programs' strategic plans was not always clear, and consistent, meaningful metrics for assessing progress were generally lacking. Appendix A of this report lists a broad set of metrics that ARO could consider for assessment of its programs.

Relevance/Transitions

The division has selected its areas of focus to complement work supported by other agencies and does coordinate extensively but informally with them. The intent is to conduct longer term research in areas of Army-specific need that are not addressed by commercial and other government entities. This is a challenge in computing because the rate of change is so rapid, particularly since the end of Dennard scaling and the rise of data-centric computing.

The division's programs showed impressive examples of transitions to other Army and wider DoD research and development elements and in some cases to commercial organizations.

3

Network Sciences Division

The Information Sciences Directorate (ISD) describes its programs in network science as follows: Programs in the Network Sciences Division pursue “discovery and understanding of robust mathematical principles and laws that govern a broad variety of networks including organic, social, and electronic. These principles and laws serve as the foundation for the creation of algorithms which may be leveraged for autonomous system reasoning.” The programs are Multi-Agent Network Control, Wireless and Hybrid Communication Networks, Social and Cognitive Networks, Communications and Hybrid Networks, Intelligent Information Networks, and Network Science and Intelligent Systems (an international program).[1]

Four of the Network Sciences programs were presented for review: Multi-Agent Network Control, Social and Cognitive Networks, Communications and Hybrid Networks, and Intelligent Information Networks. The division’s $58.7 million budget, including $8.3 million in core funding and $50.4 million in leveraged funding, supports 236 current projects.

MULTI-AGENT NETWORK CONTROL PROGRAM

Overall Scientific Quality and Degree of Innovation

The projects presented were strong, and although consistent with the scientific objectives, covered a very narrow selection of them. The scientific objectives were stated differently in various presentations but are interpreted to be as follows: distributed control (i.e., to design new frameworks for distributed control of multi-agent systems with nonlinear behavior); co-evolving networks (stochastic dynamical systems of interacting agents—i.e., to design new frameworks for describing and analyzing dynamics of asymmetric network interactions between heterogeneous agents); and collective information processing (i.e., to create distributed information collection and processing systems for inference, prediction, and control of system-level dynamics, with special attention paid to emerging properties in interactive learning in distributed state estimation).

Scientific Opportunity

This program has been in existence for a number of years and is currently in transition, as a new program manager is expected to arrive within a few months of the August review. A new program manager can be expected to bring a welcome injection of new energy and ideas to this program to drive a new wave of innovation and contributions, and to increase the coherence of the portfolio of research, as the vision and agenda are manifest in the addition and elision of program elements.

[1] Army Research Laboratory, “Army Research Office: Information Sciences,” http://www.arl.army.mil/www/default.cfm?page=3227, accessed October 10, 2018.

This is one of the longest running programs in the Network Sciences Division. It targets a set of areas that is relatively mature. Careful management will be needed to continue to find new opportunities for significant progress here. A potentially productive activity for the incoming program manager would be to hold one or more brainstorming workshops to identify a set of opportunities that could impact the Army in the coming decades, reflecting the long look ahead inherent in the Army Research Office's (ARO) basic research mission.

While examples of coevolving networks were presented, there could have been more substance to the specific research issues associated with them. For example, given the emergence of cyberwarfare and its importance to the Army, using the mathematical principles developed might provide insight into the mathematics of coevolution of cyberdefense and cyberoffense. A mathematical treatment of software coevolution in a world of rapid releases, software vulnerability marketplaces, and advances in cybervulnerability discovery—for example, as demonstrated in the Defense Advanced Research Projects Agency (DARPA) Cyber Grand Challenge—could form a basis for next-generation software development practices for the Army. The topic of emerging properties in interactive learning in distributed state estimation is timely and interesting.

In the area of multi-agent network control, as applied to fields such as biology, an application (particularly a potentially reachable visionary application that is Army-centric) might include self-forming physical objects, or physical objects that are transformable. For example, a parachute, rather than buried to conceal a Ranger's presence, might be reshaped on command into clothing if decentralized control were used. Another possibility is self-fitting adhesive wound-dressing for battle space wound treatment. For both, polymers would be well-suited; it is the distributed control that the body exhibits with clotting and scabbing that would allow the basic research developed here to save soldier lives when applied.

Significant Accomplishments

Several impressive accomplishments were identified: new frameworks for distributed control, based on reduction to optimization and proof that it works for linear time-invariant systems; a new framework to account for global temporal constraints by mixing discrete and continuous control under uncertainty; experimentation with swarm behavior of insects, deriving global principles; and evolutionary game theory-based formalization of interacting networks in nature.

Relevance/Transitions

Many Army problems map into a multi-agent network framework, so the potential for transition of significant results should, in principle, be high. The reported transitions demonstrate interest both inside and outside the Army. For example, one project developed methods incorporated into a Small Business Technology Transfer project sponsored by the U.S. Army's Aviation and Missile Research, Development, and Engineering Center (AMRDEC). This project could both address an Army requirement at AMRDEC and lead to commercialization through the small business partner. The list of transitions for this program was shorter and less impressive than for other programs in the Network Sciences Division, perhaps as a result of the lack of a consistent program manager in recent years.

SOCIAL AND COGNITIVE NETWORKS PROGRAM

Overall Scientific Quality and Degree of Innovation

The Social and Cognitive Networks Program has a strong coherence in pursuit of its strategic aims in team science and computational social science. Within the team science space, there is a clearly defined pursuit of research investigating the fundamental principles of team effectiveness and most specifically on quantification of cognitive dimensions of teamwork and team design and assembly. Within the computational social science domain, there is a clear articulation of focus on understanding online/in-person behaviors and how to meaningfully make sense of and use high-flow rate social media data. These programs align well with the ARO science and technology (S&T) goals and have potential to meaningfully contribute to proximal and far-term Army needs. Across the program there are multiple investigators on separate awards pursuing different, sometimes complementary, approaches to the same scientific topic or problem. This approach increases the likelihood of overall program success and helps the program manager avoid inadvertent immersion and adhering to a single approach.

The Social and Cognitive Networks Program capitalizes on recent scientific developments in unobtrusive measurement techniques to extend and deepen the models of cognitive dimensions of teamwork, with a particular emphasis on transactive memory systems. The program is moving this area of research in new directions to explore a wider array of knowledge-sharing behaviors as well as mechanisms to track these and other behaviors within teams in near-real time. Additionally, the program appears to be capitalizing wisely on developments in machine learning applications from computational social science and other advanced analytic techniques to improve the science and productivity in the team effectiveness.

The research on deviant and socially destructive behavior in social media was interesting and appears to have strong potential to make both significant accomplishments as well as transitions to national security organizations. It is already garnering interest from several agencies and producing early transitions.

The idea of studying the impact of social networks on the brain and vice versa, involving functional magnetic resonance imaging (fMRI) data, is an ambitious, high-risk endeavor, because it is a priori unclear what insights could be gained from such end-to-end study. Additionally, it would be beneficial to identify and understand the boundary conditions of the scientific topics and findings within the program, for appropriately managing the transitions and to help drive the innovations by pushing against those boundaries when possible. The two basic research objectives—namely, the science of team formation and computation social science—were articulated very clearly. The specific research challenges (scientific barriers), approaches for solutions, and payoffs were clearly defined.

Scientific Opportunity

Two research objectives were given the highest priority: the discovery of fundamental principles of human team formation and the modeling of networked human behavior. In both areas, the specific project goals, scientific barriers, and proposed approaches provide a reasonable basis to believe that the objectives will be met.

Significant Accomplishments

The preliminary accomplishments have provided new and interesting insights with respect to factors affecting performance of human teams, and the formation of deviant cyber flash mobs. The key performance metrics currently applied by ARO were described, and preliminary results indicate high principal investigator (PI) productivity and outside recognition. Appendix A of this report lists a broad set of metrics that ARO could consider for assessment of its programs.

Relevance/Transitions

Research results have been transitioned to a variety of stakeholders, including a system to improve team formation processes, transitioned to the Army Research Laboratory (ARL); research methodologies used to identify and study deviant groups, transitioned to the Federal Bureau of Investigation and the U.S. Cyber Command; and cyberforensic methodologies transitioned to the North Atlantic Treaty Organization (NATO), the Office of Naval Research (ONR), and DARPA.

COMMUNICATIONS AND HYBRID NETWORKS PROGRAM

Overall Scientific Quality and Degree of Innovation

The three basic research objectives—finding fundamental (e.g., capacity) bounds of the physical layer in networks and how to achieve them; mathematical models of network performance; and network coevolution—were articulated very clearly. The specific research challenges (scientific barriers), approaches for solutions, and payoffs were clearly defined. Overall, there is a healthy mixture of work in traditional areas of wireless mobile networks and innovative use of new techniques in distributed learning and optimization.

Scientific Opportunity

In all three areas the specific project goals, scientific barriers, and proposed approaches provide a reasonable basis to believe that the objectives will be met.

Significant Accomplishments

Preliminary results indicate high PI productivity and outside recognition. Examples included prize medals, best paper awards, and elevations to fellow grade in professional societies. The preliminary accomplishments included interesting new insights in multiple-input and multiple-output systems (e.g., the study of robustness of the interference alignment technique), optimal real-time network traffic scheduling with tight deadlines, and autonomous sharing of a limited quality channel. Potential applications include those related to social networking and the ability to network in ground warfare across service lines.

The accomplishments represent significant scientific progress. For example, a major challenge in wireless networks is management of interference. This program has funded multiple efforts aimed at identifying methods for aligning interfering signals, as well as finding bounds on the performance of these methods. These projects have delivered results such as generalizing the degree of freedom metric to contend with channel uncertainty and identifying the total transmission capacity in millimeter wave networks. The latter result is an example of work that is of greater interest to the Army than to private industry, because millimeter wave technology is potentially better suited for military applications. These results directly address the scientific objectives for this program.

Relevance/Transitions

The transitions of the research results have been to a variety of stakeholders within the U.S. Army (e.g., ARL and Communications and Electronics Research, Development, and Engineering Center [CERDEC]). Transitions to industry (NXP Corp.) and other government agencies (ONR and Naval Research Laboratory [NRL]) indicate the high degree of interest in this area. There are additional opportunities to transition novel approaches for controlling end-to-end delay bounds—for example, in DARPA programs where backpressure-based scheduling policies have been used owing to throughput optimality in the wide area—while for tactical wireless networks used by deployed Army warfighters, the channel state information is often uncertain or unknown, and the new work supported by the ARO may lead to better performance of DARPA approaches in this specific Army network scenario.

INTELLIGENT INFORMATION NETWORKS PROGRAM

Overall Scientific Quality and Degree of Innovation

Three of the four basic research objectives—algorithmic game theory, reasoning about crowds, and algorithms for network inference—were articulated very clearly. The fourth objective, natural language processing, seemed less naturally connected to network science than these three, although a deep mathematical connection exists between graph construction and the often inconsistent observables in textual and visual data. The specific research challenges (scientific barriers), approaches for solutions, and payoffs were clearly defined. The novelty of the specific problems was addressed both independently and in the context of their relevance of specific U.S. Army concerns.

Scientific Opportunity

In each of the first three research objectives—game theory, crowds, and inference—the specific project goals, scientific barriers, and proposed approaches provide a reasonable basis to believe that the objectives will be met.

Significant Accomplishments

The preliminary accomplishments have provided new and interesting insights. Examples are game theory applications in learning in the context of partial observations and bounded rationality. In particular, the applications to attacker-defender games, repeated games and strategy updates, and application to real-life scenarios were interesting. For example, an analysis of risk-taking biases of attackers rooted in the behavioral economics work was validated in a series of experiments and led to an optimal strategy for security games. A notable characteristic of the game theory work was the diversity and relevance of the applications, including human immunodeficiency virus prevention strategies for the large homeless population in Los Angeles, U.S. government agency impacts (Transportation Security Administration and the U.S. Coast Guard), and international impacts such as poacher behavior prediction to optimize placement of patrols in a Ugandan national park.

Key performance metrics (peer-reviewed publications, manuscripts, graduate students, postdoctoral researchers) were described, and preliminary results indicate high PI productivity and outside recognition, such as endowed chairs, elevations to fellow in professional societies, honorary degrees, and best paper awards. Appendix A of this report lists a broad set of metrics that ARO could consider for assessment of its programs.

Relevance/Transitions

The transitions of the research results have been to a variety of stakeholders within the Army (e.g., application of Bayesian reasoning about societies, transitioned to the ARL) and to industry (e.g., GraphLab, a framework for developing AI algorithms, transitioned to Apple; and game theoretic algorithms for security, transitioned to Avata Intelligence), indicating the high degree of interest in this area. An opportunity for a different dimension of research is designing distributed systems (team missions) for resilience in spite of misbehaving participants (whether owing to conscious malice or incompetence). It is not always possible to identify that there is a bad actor or to identify which actor is behaving counterproductively. Particularly in large anonymous teams, it is likely that the team will include badly behaving participants, and designing a collaborative algorithm that will make positive progress despite bad actors can be challenging. Given the applications of this research direction in the cyberdomain, the strength of the Network Sciences Division in identifying and funding principled and mathematically based foundational approaches to such problems may have significant promise for transition and impact on the Army. For example, the Iterated Feature Boosted Decision Tree scheme used to improve patrol placement to deter poachers in Uganda is applicable to similar Army roles such as peacekeeping in urban areas.

OVERALL ASSESSMENT

Overall Scientific Quality and Innovation

The Network Sciences Division has, despite its small size, supported a broad swath of strong basic science that in spite of a long time horizon is directed toward areas of anticipated future needs of the U.S. Army. The division interprets the term “network” broadly as spanning the science to include social science (where a social network might arise) as well as traditional telecommunications networking. Telecommunications science research crosses technologies ranging from mobile networks to emerging quantum communications capabilities.

Across the division, the overall scientific quality is high, although some specific programs and investment areas are stronger than others. New areas identified for investment are unique and promising, with strong possibilities for contributing to the Army S&T goals.

Each program manager presented a unifying scientific vision defining the program area. The Social and Cognitive Networks Program is a particularly good example of this. Scientific objectives were given for fulfilling this vision. Thrust areas were defined to achieve these program objectives.

Scientific Opportunity

The Network Sciences Division’s program managers evinced a high level of engagement in community building and discipline building, in venues such as disciplinary meetings and academic institutions. They showed a strong sense of stewardship for these communities, particularly where the division pursued a distinct strategy, as in the social and cognitive networking area.

Across the division, program managers are actively seeking emerging developments in relevant scientific fields that can help move their programs forward in useful ways, as well as working to capitalize on recent major scientific advances. The challenge is for the program managers to identify those opportunities that will allow them to make a unique and meaningful contribution to the advancement of science in alignment with the Army S&T goals. It is important that the program managers continue to seek ripe opportunities at the gaps between major fields (e.g., self-organizing biological network structures for applications in medicine) and continue to collaborate across disciplines.

Significant Accomplishments

The programs in the Network Sciences Division are relatively new in comparison to those of the other divisions in the Information Sciences Directorate. While some of these programs (e.g., multi-agent network control and intelligent information networks) have been in existence in approximately their current form for 8-10 years, others (e.g., social and cognitive networks) are less than 5 years old. As a point of reference, the Mathematical Sciences Division has existed for decades, and many of its programs have 10-20 years of history. Because the Network Sciences Division is newer, it has fewer accomplishments compared to the older divisions; however, each program in the Network Sciences Division has a number of substantive accomplishments.

Specific scientific accomplishments were named for only the example projects detailed under each program. No global list of scientific accomplishments analogous to the lists of transitions was provided. The only means for assessment then were the key metrics presented (e.g., number of publications, students, and postdoctoral researchers). Appendix A of this report lists a broad set of metrics that ARO could consider for assessment of its programs.

Relevance/Transitions

Programs across the division evidenced forethought and focus. As a result, all programs showed strong evidence of recent and ongoing transitions to applied research programs within the Army, as well as several to the broader defense science community. The program managers were very conscious of the need for basic science to remain relevant to the Army S&T goals, and they show the potential to bring new developments to the Army. An indicator of the broader perceived value of the research commercially is the software package GraphLab, which was subsequently purchased by Apple for over $400 million.

Additional Considerations

The overall scientific quality was strong and, taking into account the magnitude of the budget available in ARO, quite impressive. It would be impossible for the division to support every relevant research area. The programs in this division address the wide variety of network topics beyond communication networks, although that is a central topic that they address. The high-quality research on social, cognitive, and information networks is to be commended.

The programs reviewed all funded strong basic science, but differences existed among the programs in the degrees of coherence and uniqueness within the government research funding ecosystem. To first order, this seemed related to the time that a program manager had shaped the priorities within their portfolio within the larger Network Sciences Division and ARO more generally.

In the area of quantum networking, considerable benefit could be gained from allying with other research thrusts elsewhere in ARO and the ARL or elsewhere in the Department of Defense (DoD) to obtain a combination of basic science (e.g., theoretical analyses or mathematical models) and the best experimental science. For quantum science generally, it makes sense to maintain a strong and constant scientific interchange between models and experiments.

There are key methodological differences between ARO and research funding entities such as the National Science Foundation (NSF) and DARPA. ARO program managers energetically try to create communities with workshops, visits to universities, and talks. ARO program managers engage in an interactive process with proposers to mature ideas into projects through discussion, white papers, and the Short-Term Innovative Research (STIR) program. ARO program managers are hands-on managers of their projects; this may be a function of the process whereby program managers work with potential proposers (which NSF does not generally do)—the ARO process seems to resemble DARPA's management style. ARO program managers view as a transition a follow-on effort at another government research funding agency that stems from one of their projects. This has two important benefits: (1) ARO program managers seek opportunities, in particular with other DoD components such as DARPA, to keep the basic research results alive in the research and development ecosystem; and (2) ARO program managers are encouraged to trace the progress of an idea from its origins in basic research through development, deployment, and use.

4

Mathematical Sciences Division

The Information Sciences Directorate (ISD) describes its programs in mathematical sciences as follows: Programs in the Mathematical Sciences Division underlie and enable

> understanding of complex nonlinear systems, stochastic networks and systems, mechanistic models of adaptive biological systems and networks, and the vast variety of partial differential equation-based phenomena. Nonlinear structures and metrics for modeling and studying complex systems are sought, as is creating theory for the control of stochastic systems, spatial-temporal statistical inference, data classification and regression analysis, predicting and controlling biology through hierarchical and adaptive models, enabling new capabilities through bio-inspired techniques, creating high-fidelity computational principles for sharp-interface flows, solving inverse problems, deriving reduced-order methods, and developing computational linguistics.

The programs are Computational Mathematics, Biomathematics, Modeling of Complex Systems, and Probability and Statistics.[1] The division's budget of $20.2 million, including $7.5 million in core funding and $12.7 million in leveraged funding, supports 156 current projects.

COMPUTATIONAL MATHEMATICS PROGRAM

Overall Scientific Quality and Degree of Innovation

The objectives of this program are to develop mathematical characterizations and computational models for (1) common themes in anomalous physics; (2) material-related issues in layered and two-dimensional geometries, energetic crystals, and porous media; and (3) high-fidelity computational electrodynamic modeling and associated inverse problems. The program manager's strategy for achieving these objectives seemed less clear and cogent than for other programs in the Mathematical Sciences Division. The program of research is substantial, but it does not evince a consistent theme across the funded projects. However, the research funded is novel and is leading the field in several important ways. The program's thrusts in fractional order operators and models for quantum stochastic differential equations, for example, offer a potentially transformative alternative to competing approaches in anomalous physics and material. The program manager's willingness to trade off risk versus innovation has enabled the program to have a portfolio that is distinguishable from the bulk of the research supported by the National Science Foundation (NSF) and other research sponsors.

[1] Army Research Laboratory, "Army Research Office: Information Sciences," http://www.arl.army.mil/www/default.cfm?page=3227, accessed October 10, 2018.

Scientific Opportunity

It appears that the program's scientific objectives will be met. The program has found some unique areas to fund that are not duplicative of those funded by other sponsors and that represent a meaningful niche for the Army Research Office (ARO) mission. For example, the program is proposing to fund research that investigates the use of conservation laws to assist with large data sets. This is an interesting, speculative, and high-risk idea that will have enormous benefit if successful. No other sponsor in the mathematical sciences is actively supporting this type of work.

Significant Accomplishments

The Computational Mathematics Program had some significant scientific advances. For example, the work on fast solvers for fractional partial differential equations represents a significant advance in the field. Also, the funded work in support of ground vehicles is important and significant.

Relevance/Transitions

One of the most important transitions is the work supporting the Army's Ground Vehicle Program. This effort is transitioning into the replacement/upgrade for the North Atlantic Treaty Organization (NATO) Reference Mobility Model, called Next Generation NRMM. Funded work is also supporting the Engineered Resilient Systems Program at the Army's Engineer Research and Development Center and was used on the Joint Light Tactical Vehicle Program. Other significant transitions have been the funded work on effective Hamiltonians for monolayers and the work on mesh adaptation.

BIOMATHEMATICS PROGRAM

The Biomathematics Program is relatively small. The program's budget of $4.8 million includes $1.3 million in core funding and supports 35 current projects. Consequently, its research scope is not broad, although the quality of the projects is generally high. The vision of the program is to identify and mathematize the fundamental principles of biological structure, function, and development applying across systems and scales, to enable revolutionary advances in soldier health, performance, and materiel. Consistent with this vision, the Biomathematics Program focuses on areas such as understanding circadian rhythm to improve sleep/alertness of soldiers in the field, and molecular interventions to improve healing of wounds.

Overall Scientific Quality and Degree of Innovation

In general, the research funded under this program is of good scientific quality and is responsive to the scientific objectives of the program. The program funds research that is of interest to the Army and to the Department of Defense (DoD) in general, yet it is unlikely to receive funding from other agencies. In this light, the funding allocated by the Biomathematics Program to research projects does not overlap what other agencies would be funding. While projects are generally of good scientific quality, the tools that researchers use to address the scientific questions appear to be limited. As an example, considering stochastic techniques in addition to deterministic techniques would seem to be appropriate when one of the scientific objectives is to understand principles behind biological heterogeneity.

The program would stand to benefit if the range of research approaches used to address problems were broadened, where appropriate. Given a specific objective, such as enhancing molecular responses to improve healing, this could be accomplished by seeking out researchers who would bring differing perspectives and competing approaches.

Scientific Opportunity

Supported researchers appear to be chosen under the Biomathematics Program in a principled way. The portfolio of projects in this program makes up a coherent whole focused on the program's scientific objectives. The program manager seems to be in close communication with the researchers in the field and has an opportunity to discuss potentially productive changes to the research scope. The changes in focus from decision theory to learning and from determinism to stochasticity are timely.

Learning methods have been successfully deployed in many sciences. The program would be significantly enhanced if its scope were broadened to include researchers working on learning methods and paradigms.

Potential benefits would come from making use of short-term funding mechanisms to encourage multiple researchers to work on the same problem, ideally from divergent perspectives. There may be opportunities to increase the feedback and cooperation of managers of other programs for projects with intellectual themes that cross over into other areas of the mathematical sciences.

Significant Accomplishments

Most researchers appear to be accomplishing stated research goals. For example, a project with the goal of understanding group behavior found that when leaders in a network are chosen to maximize information centrality, it is possible to predict group behavior with the smallest tracking errors.

Program researchers have received an impressive array of awards and recognition. That said, the program would benefit from the development and deployment of a set of metrics designed to reflect the impact that the Biomathematics Program research is having on Army programs and on science in general. Appendix A of this report lists a broad set of metrics that ARO could consider for assessment of its programs.

Relevance/Transitions

The program is responsive to Army and DoD needs. The program manager provides ample opportunity for input to the Army at multiple phases of the research process. Multiple projects have resulted in outputs of interest to various government agencies, including the Defense Advanced Research Projects Agency (DARPA) Defense Sciences Office, the Office of Naval Research (ONR), the Army Research Laboratory (ARL) Human Research and Engineering Directorate, as well as to several organizations in the private sector (e.g., Marriott Hotels, Sustainable Bioproducts). A project focused on the transfer of protein analysis techniques to the analysis of social networks has generated considerable interest in the Army for translational follow-on work.

It would be beneficial to pair researchers with different areas of expertise—that is, a basic researcher and researchers with the ability to translate research results into practice. The program has strong relevance to Army needs and would benefit from continued encouragement of active participation by Army professionals in the design of research objectives.

While much of the funding can be used to address problems that are current, the program would benefit from giving some thought to the needs of the future. This might be accomplished by engaging with a futurist who may be able to predict which problems will become relevant in 10 or 20 years.

Additional Considerations

The Biomathematics Program funds several female principal investigators (PIs) as well as researchers from minority-serving institutions. The program manager also emphasizes the value of funding earlier-career researchers over more established researchers. This can bring to the fore new talent with new ideas, if the quality and value of the research portfolio is maintained.

MODELING OF COMPLEX SYSTEMS PROGRAM

Overall Scientific Quality and Degree of Innovation

Starting from a hypothesis that direct simulation approaches (e.g., computational partial differential equations) are insufficient for effective characterization of the systems of Army/DoD interest, this program has chosen to focus its activities on the nascent fields of geometric and topological analysis of complex systems. The program oversees a relatively small component of approximately 10 percent of the overall Mathematical Sciences Division budget. Within the budgetary constraint and chosen geometric/topological focus, the program has judiciously selected topics related to data analysis and modeling, learning theory, social group dynamics, and convergence of theoretical foundations with computational aspects.

Grants have led to research of good quality that includes extension of facial recognition techniques, feature recognition from incomplete data, and combining machine learning with topological concepts (e.g., persistence diagrams). There is a mix of support of experienced researchers perfecting established methods with novel investigations. An example of the former is the research on multimodal facial recognition to extend work from the 1990s on linear algebra (Eigenfaces) or statistical approaches (Fisherfaces). Within the latter category are the works on terrain recognition from sparse observation or transformation of data into persistence diagrams.

Whereas some of the supported research (e.g., facial recognition) also receives funding from NSF, several projects seem to fit exclusively within ARO's niche (e.g., environment recognition and reconstruction from incomplete data), and combine innovation in mathematical approaches with relevance to Army/DoD interests.

Scientific Opportunity

The challenge facing the program is to balance a multitude of recently proposed techniques for geometric and topological analysis of realistic systems, of untested efficacy, with the constraints of a limited budget and need for practical results. Within these parameters, the current portfolio of funded projects does capture a good sample of the currently known or promising science in this area. The funding mechanism itself could be refined. There are a number of long-term projects (4-5 years), which allow for depth but come at the price of leaving promising areas uninvestigated. Given the nature of this program, short, exploratory investigations might be preferable unless there is cross-support from other divisions interested in a well-defined application. This approach is already present to some extent but could be further refined by analogy to the National Institutes of Health (NIH) approach of exploratory R21 projects leading to R01 projects upon buy-in from other Army entities. Morse theory, topological visualization, and statistical manifolds are examples of other promising approaches that might find space within the program if the funding model favors short-term exploratory investigations.

Significant Accomplishments

Funded researchers have received notable external recognitions (fellowships, including an Intel Early Career fellowship). All projects have been productive in terms of scholarly publications and the training of graduate students.

Relevance/Transitions

Funded projects have led to tangible benefit to the Army such as the work on environment reconstruction delivered to the ARL Survivability and Analysis Directorate or the work on improved facial recognition delivered to the ARL Sensors and Electron Devices Directorate. In addition to these direct transitions, funding has led to efficient identification of adversarial groups from topological considerations (work by a Small Business Innovation Research program researcher for the Psychological Operations Group at Fort Bragg). All these efforts are highly relevant to the DoD S&T goals.

Additional Considerations

The program manager has cogently and judiciously started a transition from previous strategic goals of this program (e.g., computational linguistics) to topological and geometric methods suitable for non-smooth analysis.

PROBABILITY AND STATISTICS PROGRAM

Overall Scientific Quality and Degree of Innovation

This program has been managed by a temporary program manager for more than 2 years. A new program manager is expected to arrive within a few weeks and to conduct a review of program strategy in the upcoming year. Such a reassessment is necessary to avoid overlap with missions of other funding agencies (e.g., NSF) and to better tailor program funding to Army needs. The program objective of development of theory and techniques in quantum, stochastic, and statistical systems is broad and tends to lead to funding of fundamental research with a large lag-time to direct application to Army/DoD systems.

The quality of the supported work is excellent. One researcher found a near-optimal random matrix concentration bound, a major improvement over bounds from many physicists and mathematicians. This is a very significant accomplishment and would be a coup for any funding agency. The work on quantum annealing seems to have played a significant role in the establishment of the new Quantum Enhanced Optimization research program at the Intelligence Advanced Research Projects Activity (IARPA). Research on novel characterizations of stochastic differential equations and on insight into properties of random matrices are additional examples of an impressive portfolio of results from the funded research. Furthermore, all funded topics exhibit significant innovation (e.g., research on application of Skorokhod-Malliavin calculus, far-from-equilibrium transitions, and nonlinear filtering).

The webpage for the program lists an interesting collection of research areas in probability and statistics that are within the program's purview.[2] The projects that have been funded, however, are virtually all in the area of probability. This is presumably because the last permanent program manager was a probabilist, more comfortable in that domain, and his temporary successor apparently maintained

[2] Army Research Laboratory, "Army Research Office: Mathematical Sciences," https://www.arl.army.mil/www/default.cfm?page=185, accessed October 18, 2018.

the nature of the program. The proposed new program manager is a statistician and is likely to correct this imbalance.

Scientific Opportunity

The need for probabilistic approaches to problems of Army/DoD relevance is as great as ever, and the ARO needs to play a role not only in applications but also in nurturing development of fundamental theory. That being said, the scope of the problem is so vast that some fields may best be funded through joint mechanisms with other interested agencies. As an example, quantum communication and information processing would seem a prime candidate for a joint funding mechanism. The collaboration of NSF/NIH in the joint Division of Mathematical Sciences/National Institute of General Medical Sciences program could serve as a useful role model and allow the ARO to leverage limited funds with more impact. In particular, once areas of common interest are identified, the ARO could concentrate its own funds on subtopics that other agencies would not fund but that are of Army interest.

The research areas funded in the program were quite different from what would be routinely funded by, say, NSF. Indeed, the previous program strategy was to find good people to do very unusual things. Enormous opportunities open up with the new program manager's being a statistician. This is not only because this allows engagement with data science, but also because there are other programs at ARO that could naturally develop synergies with the program. One clear example is the interest in statistical methods and reinforcement learning in biology.

Significant Accomplishments

The accomplishments were primarily theoretical, such as the interesting development of distribution-free solutions to stochastic differential equations (the solution method did not depend on the distribution, but the answer surely does). This could be of eventual interest practically, but it is not clear that one does better by first developing a very complicated general solution method, and then specializing, as opposed to just tackling the solution for a particular distribution directly. But this is the nature of high-risk research: you never know until you try. The improved random matrix concentration bound is another primarily theoretical development, but it will lead directly to improved bounds on the convergence rates of various practical algorithms involving random matrices, and it thus gives better insights into the practical utility of those algorithms.

Funded projects have shown excellent productivity in terms of scholarly output and professional recognition. Program management has been highly effective and original in fostering collaboration between development of theory and computational applications.

Relevance/Transitions

This program has seemed to have reasonable transitions between different research problems, although they have been almost entirely in probability. Evidence of the quality of the funded research is furnished by the transition of results into practical tools. Notable transitions include contributions to quantum annealing (which motivated the new Quantum Enhanced Optimization research program at IARPA), contributions to health monitoring (used at Los Alamos National Laboratory [LANL]), and contributions to helicopter engine monitoring (used at United Technologies Corporation).

Additional Considerations

The paucity of female statisticians and probabilists among the funded individuals needs to be corrected. This will again be helped by seeking a better balance between probability and statistics, because the percentage of women in statistics is much higher than the percentage in probability. Still, direct action is needed, such as specifically requesting submission of white papers from women, as a start toward eventual funding.

OVERALL ASSESSMENT

The investigators are producing high-quality research, and the subject areas seem to be appropriate and of use to the Army. The program managers are well qualified, and the ARO system allows them to maintain a close and continuous contact with PIs. This way of operating promotes two-way contact and can help to ensure that information is shared.

Overall Scientific Quality and Innovation

The PIs and research outcomes are of generally high quality. There are many examples of the PIs receiving prestigious academic recognition, including Presidential Early Career Awards for Scientists and Engineers (PECASE) and other young investigators awards. The quality of the research outcomes has been tangibly demonstrated through the translation of a number of projects to Army applied research and development (R&D) activities.

The research addresses problems of importance to the Army and DoD. Programs and projects tend to address problems or use approaches that are not considered by other funding agencies such as the NSF or NIH.

Broadly speaking, the Mathematical Sciences Division's research portfolio reflects a view of research approaches that is very much tied to the interests and expertise of the program managers. The division would benefit from enhanced consideration of alternative approaches to address research problems. Ideally, the broadening of research approaches would be accompanied by an expanded definition of performance metrics to include impact factors of products from funded research, especially research solely funded by ARO. Appendix A of this report lists a broad set of metrics that ARO could consider for assessment of its programs. The division would benefit from a systematic addition of midperformance period review of projects. The feedback from these reviews would provide a basis for the refinement of future funding allocations.

Scientific Opportunity

Within budget constraints, funded projects concentrated on topics with high scientific payoff combined with applicability to Army needs. By and large, the program managers followed a deliberate and reasoned process behind the choice of project areas. The programs were also distinguished by their principled and thematic approach to project choices.

Program managers have much more direct and continuing contact with PIs than would be the case in some other funding agencies, such as the NSF or the Air Force Office of Scientific Research (AFOSR). The practice of maintaining close connections between program managers and PIs has given the managers a mastery of the research details that is deeper than that seen at larger funding agencies. There is also some evidence that such close intellectual engagement increases the career appeal of managing a program. Career appeal might be further enhanced if ARO expanded work models—such as reduced duties or incentives for publication—that encourage program managers' personal research efforts.

There are several examples of short-term funding (e.g., 6-9 month grants) being used to explore new lines of research. The division's program might be strengthened if such short-term funding were used as part of an entrepreneurial model with the goal of developing a diverse set of competing technical approaches to high-opportunity topics. Promising areas for the expansion of the scientific program include statistical methods and reinforcement learning in biology and learning combined with computational partial differential equations.

Significant Accomplishments

Over the years, the programs have resulted in many significant research outcomes and PIs' awards for excellence. Examples of significant research outcomes include the development of world-leading algorithms for face recognition under adverse conditions and for estimation of circadian phases. Examples of awards and recognition for the division's PIs include appointment to the National Academy of Engineering, award of the Gold Medal of the Sobolev Institute of Mathematics, and receipt of an Intel Early Career Faculty Fellowship.

Relevance/Transitions

Through the efforts of the program managers, there have been a number of successful transitions of research to DoD and elsewhere. On a regular basis, program managers work with Army agencies to develop ideas for new research. In some cases, program managers have structured projects creatively to enhance potential for transition to practice. For example, researchers who are strong in fundamental work have been paired with researchers with a demonstrated record in translation. Based on the success of the ad hoc pairings to date, the division might benefit from making this a regular practice.

The division follows a formal process for setting research priorities. Army feedback is solicited during multiple phases in the process, and so it appears that there is ample opportunity for the needs of the Army to influence research direction. The division would benefit from encouraging continued input from the Army on the focus of the research programs. Strategic research plans would benefit from discussions about the problems of the future and hypotheses about where the Army's and DoD's needs will be in 15 or 20 years.

Additional Considerations

The division's entrepreneurial model for research is effective. The program managers exercised their autonomy in many creative and effective ways that would not be possible under the systems in place at larger funding agencies. Successful practices in this regard include matchmaking between researchers to form partnerships, such as teaming a quantum physicist with a mathematician. There is also a focus on younger researchers that facilitates consideration of new ideas.

Evidence of a close connection between the ARO and higher Army echelons was not apparent. Such connections might exist, but they were not elucidated. This matter of connection could be especially important at present, when the Army appears to be under some pressure for review and adjustment in its structure and activities, with the aim of increased readiness in a relatively short period of time. If such a reorganization program also has longer range components, it is possible that some of those could benefit from mathematical research.

With the exception of the Biomathematics Program, there appeared to be limited demographic diversity across the programs. Program managers have the ability to encourage female and minority researchers to submit white papers and follow up with complete proposals, and there is need for an analysis and tracking of demographic diversity across the ISD.

ARO supports research by PIs and by centers of multiple researchers. In contrast with single investigator programs, the Multidisciplinary University Research Initiative (MURI) programs at ARO support centers whose efforts intersect more than one traditional research specialty, typically at $1.25 million per year for 5 years. Research topics increasingly benefit from such multidisciplinary participation, even in pairs or small sets of investigators and over shorter time periods. Including in such collaborations researchers with knowledge of transitions would be useful.

5

Crosscutting Recommendations

The Information Sciences Directorate (ISD) is producing high-quality research. In general, however, the ISD programs did not evince clear and consistent sets of metrics by which to evaluate program impact and effectiveness. It is necessary that metrics be counted by consistent and transparent methods (e.g., what is meant by a publication, how to count graduate students who are supported by multiple programs) to facilitate measurement of progress. Metrics should reflect accomplishments actually attributable to the Army Research Office (ARO) projects. Appendix A of this report lists a broad set of metrics that ARO could consider for assessment of its programs.

ISD Crosscutting Recommendation 1: The Information Sciences Directorate (ISD) should develop and apply a set of clear and consistent metrics by which to evaluate program impact and effectiveness.

The division follows a system of establishing personal connections between the program managers and their principal investigators (PIs); this almost amounts to collaboration. This system is effective, but it runs the risk that research foci might not change on appropriate time scales and that promising alternative approaches to problems might be missed if they fall outside the knowledge and experience base of the program managers. The system would benefit from deliberate efforts to inject more competition among different research approaches. This would include more rapid turnover in the PI base.

ISD Crosscutting Recommendation 2: The Information Sciences Directorate (ISD) should consider ways to expand the knowledge base beyond that possessed by the program managers when formulating approaches to selecting programs for funding.

ISD Crosscutting Recommendation 3: To the extent that program managers in the Information Sciences Directorate (ISD) demonstrate management of successful programs and expanded knowledge of their discipline and of relevant opportunities to support research with potential application to Army needs, they should be encouraged to exercise their visions for basic science to meet Army needs and be encouraged to maintain their entrepreneurial style in program management.

ISD Crosscutting Recommendation 4: The Information Sciences Directorate (ISD) should consider shorter time scales and more rapid turnover of the principal investigator base for projects that are not jointly funded or targeted for long-term funding by collaborating ISD divisions, Army Research Office (ARO) directorates, or other funding agencies. Consideration should include potential impacts on graduate students supporting funded projects, should ARO deem graduate student support a project goal.

The ARO supports research by PIs and by centers of multiple researchers. In contrast with single investigator programs, the Multidisciplinary University Research Initiative (MURI) programs at ARO support centers whose efforts intersect more than one traditional research specialty, typically at $1.25 million per year for 5 years. Research topics increasingly benefit from such multidisciplinary participation, even in pairs or small sets of investigators and over shorter time periods. Including in such collaborations researchers with knowledge of transitions would be useful.

ISD Crosscutting Recommendation 5: The Information Sciences Directorate (ISD) should consider funding mechanisms to encourage pairs or small sets of researchers from divergent perspectives to work on the same problem.

ARO is organizationally a subset of the Army Research Laboratory (ARL), which in turn resides within the U.S. Army's Combat Capabilities Development Command (CCDC) along with CCDC's other research and development (R&D) centers. ARO program managers interact formally with their colleagues at ARL and CCDC by collaborative reviews of research project proposals, status reports, and Army operational concept documents, which are also provided by the U.S. Army's Training and Doctrine Command (TRADOC). The ARO Core Program also organizes and facilitates scientific and technical conferences, workshops, and symposia attended by Army, commercial, and other Department of Defense (DoD) agencies. This program provides a method for conducting scientific and technical meetings that facilitate the exchange of scientific information relevant to the long-term basic research interests of the Army and help define research needs, thrusts, opportunities, and innovation. In particular, workshops are a key mechanism that ARO uses to identify new research areas with the greatest opportunities for scientific breakthroughs that will revolutionize future Army capabilities. ARO program managers also establish and maintain less formal interactions with other DoD agencies.

The program managers in the ISD evinced varying levels of engagement with other DoD research, development, and funding agencies such as the Office of Naval Research (ONR), the Air Force Office of Scientific Research (AFOSR), the Defense Advanced Research Projects Agency (DARPA), and other elements within the Army, such as the Research, Development, and Engineering Centers. Such engagement is important for the maintenance of shared situation awareness and is a key enabler for ARO to continue to "outpunch its weight."

ISD Crosscutting Recommendation 6: Program managers within the Information Sciences Directorate (ISD) should maintain and seek to expand their engagement with other Department of Defense funding agencies such as the Office of Naval Research, the Air Force Office of Scientific Research, the Defense Advanced Research Projects Agency, and other elements within the Army.

Diversity of gender, age, and geographic location was acknowledged across the ARO as requiring attention.

ISD Crosscutting Recommendation 7: The Information Sciences Directorate (ISD) should continue encouraging the participation of females and minorities in research funded by the Army Research Office and should collect statistics to track diversity in the broad sense, including gender, age, and geographic location.

The material provided for this review described a limited set of projects funded by the programs. The review could have been augmented by providing copies of the broad agency announcements for all of the currently funded projects, a more complete and organized description of all of the projects, and abstracts of the projects.

There was a wide variety in the content and relevance of the presentations about individual projects. A consistent template for the description of projects could address in sufficient detail such questions as the following:

- How does the project map to the long-term vision for the program?
- What are major consequences for the science if the project succeeds?
- Why is the problem difficult and what are the major technical risks?
- What is the network of contacts involved in the project?
- How, specifically, does the project address one or more critical challenges that the Army of the future will face?

Part II: Physical Sciences Directorate

6

Introduction

At the request of the U.S. Army, on August 5-7, 2019, the National Academies of Sciences, Engineering, and Medicine's Panel on Review of Extramural Basic Research at the Army Research Laboratory met to review the programs of the Physical Sciences Directorate (PSD) of the Army Research Office (ARO), which is an organizational unit within the Army Research Laboratory (ARL). The meeting was held at the ARO headquarters in Durham, North Carolina.

The panel's review was guided by the following statement of task provided by the National Academies:

> An ad hoc committee to be named the Panel on Review of Extramural Basic Research at the Army Research Laboratory, to be overseen by the Laboratory Assessments Board (LAB) of the Division on Engineering and Physical Sciences, will be appointed to provide annual assessments of the Army Research Office (ARO) programs. Each year one of the ARO's three divisions (Information Sciences, Physical Sciences, and Engineering Sciences) will be assessed by a separately appointed panel. These assessments will address criteria to be defined by the ARO. Each year the panel will provide a report summarizing its findings, conclusions, and recommendations. The panel's report will be made available to the public on the National Academies Press website and will be disseminated in accordance with National Academies policies.

The current report summarizes the 2019 findings of the Panel on Review of Extramural Basic Research at the Army Research Laboratory, which reviewed the programs at the ARO PSD. This is the first time that the National Academies is reviewing ARO's PSD. In 2020, the National Academies conducted a review of the ARO Engineering Sciences Directorate programs in electronics, materials science, mechanical sciences, and earth sciences. In 2018, the National Academies conducted a review of the ARO Information Sciences Directorate programs in computing sciences, network sciences, and mathematical sciences.

PROGRAMS WITHIN THE PHYSICAL SCIENCES DIRECTORATE

The Army Research Laboratory's ARO describes its mission as:[1]

> To serve as the Army's principal extramural basic research agency in the engineering, physical, information and life sciences; developing and exploiting innovative advances to ensure the Nation's technological superiority. Basic research proposals from educational institutions, nonprofit organizations, and private industry are competitively selected and funded. ARO's research mission represents the most long-range Army view for changes in its technology. ARO's research represents the most long-range Army view, with system applications often 20-30 years away. ARO priorities fully integrate Army-wide, long-range planning for research, development, and acquisition. ARO executes its mission through conduct of an aggressive basic science research program on behalf of the Army so that cutting-edge scientific discoveries and the general store of

[1] Extracted and adapted from the Army Research Laboratory, Army Research Office, http://www.arl.army.mil/www/default.cfm?page=29, accessed August 6, 2019.

scientific knowledge will be optimally used to develop and improve weapons systems that establish land force dominance. The ARO research program consists principally of extramural academic research efforts consisting of single investigator efforts, university-affiliated research centers, and specially tailored outreach programs. Each approach has its own objectives and set of advantages. Programs are formulated in consultation with the Army Research Laboratory Directorates; the U.S. Army Combat Capabilities Development Command (CCDC) Research Centers; the Army Medical Research and Materiel Command; the Army Corps of Engineers; and the Army Research Institute for the Behavioral and Social Sciences. The programs are also jointly coordinated and planned through the Defense Science and Technology Reliance process under the Basic Research Panel.

Research in the physical sciences is focused on basic research to discover, understand, and exploit physical, chemical, and biological phenomena. This research is of a fundamental nature; however, in the long term, discoveries in this area are expected to lead to revolutionary capabilities in sensing, communications, protection, wound healing, power/energy storage and generation, and materials that extend the performance of Army systems well beyond current limits.[2] The PSD's programs are organized in three divisions: Physics (fiscal year [FY] funding of $26.7 million), Chemical Sciences (FY funding of $54.6 million), and Life Sciences (FY funding of about $82.3 million). Across the three divisions, in FY 2018, PSD funded 472 projects with a budget of $156.7 million—$26.2 million core funding and $130.5 million leveraged funding from sources that include the Multidisciplinary University Research Initiative (MURI) programs, the Presidential Early Career Awards for Scientists and Engineers (PECASE), the Defense University Research Instrumentation Program (DURIP), the Minority Institutions Program, the Small Business Innovation Research (SBIR) program, the Small Business Technology Transfer (STTR) program, and other Army and Department of Defense (DoD) sources.

In general, the PSD's metrics are strong, with 2,120 peer-reviewed publications in the FY 2016 to FY 2018 period, and funding for 1,034 graduate students and 511 postdoctoral researchers during the FY 2017 to FY 2018 period. However, most impressive for PSD focused on outcomes for the Army was the number of successful transitions from bench to application. There were 104 transitions reported for the 3-year period from FY 2016 to FY 2018, including the development of several commercial products and start-ups based on the science and technology supported by PSD. The transition of fundamental physical science research funded by ARO to applications developed in the ARL intramural laboratories is another good indicator of the success of PSD.

APPROACH TO THE ASSESSMENT

The panel consisted of 25 leading scientists and engineers whose expertise matched the programs at the ARO's PSD that were reviewed. All panel members were volunteers who participated without compensation. The panel members' independence is ensured by the National Academies using its rigorous vetting and approval process for appointment to its panels. The entire panel attended overview presentations by, and held discussions with, the directors of ARL, ARO, and PSD. The panel members then divided into three teams that separately attended presentations by and discussions with program managers (PMs) in the three PSD divisions (Physics, Chemical Sciences, and Life Sciences). The presentations and discussions occurred over a 2-day period. On the third day of the meeting, the panel assembled to share findings from the team reviews, develop impressions common across the team reviews, and prepare the panel's report draft. On the afternoon of the third day, the panel met with ARO staff for wrap-up discussions to seek clarification of factual and contextual understandings.

The panel members prepared written summaries of their findings, conclusions, and recommendations, which were iteratively reviewed by the panel and formed the basis for the draft report that was subsequently developed under the guidance of the National Academies Army Research Laboratory Technical Assessment Board (ARLTAB), which focused particularly on the panel's approach to the

[2] Army Research Laboratory, Army Research Office, http://www.arl.army.mil/www/default.cfm?page=217, accessed August 6, 2019.

review and the report's recommendations. ARLTAB consists of the chairs of the panels that review the scientific and technical work of all ARL directorates, including those at ARO.

After the panel addressed the comments offered by ARLTAB, the report was edited by professional editors at the National Academies and submitted to the National Academies Report Review Committee (RRC). The RRC appointed a team of reviewers to examine the report, considering such factors as the scope of the panel's task, the reasonableness of the panel's recommendations, and the clarity of the panel's expression. Once the RRC reviewers' comments were adequately addressed, the report was submitted to the Army for security review. After the report cleared the security review, it was publicly posted on the National Academies Press website (www.nap.edu).

The panel applied a largely qualitative rather than quantitative approach to the assessment. The approach of the panel relied on the experience, technical knowledge, and expertise of its members, whose backgrounds were carefully matched to the core technical competency areas in which ARL and ARO activities are conducted. The panel reviewed selected examples of the scientific and technological research programs at the ARO's PSD because it was not possible to review all PSD programs and projects exhaustively in the time allotted. ARO selected the programs and projects as representative examples in its portfolio that were presented for review. Given the necessarily nonexhaustive nature of the review process, the omission of mention of any particular program or project should not be interpreted as a negative reflection on that program or project. Similarly, recommendations for some programs but none for others should not be read to imply that those programs are of lower quality or have more operational challenges than the other programs. Thus, some of the report chapters of the PSD divisions may have recommendations but not others.

The panel's goal was to provide an overall impression of the ARO programs in physical sciences while preserving useful mention of suggestions specific to programs that the panel considered to be of special note within the set of those examined. Therefore, the panel strove to identify and report salient examples that supported discussion of accomplishments and opportunities for further improvement with respect to the PSD's programs.

ASSESSMENT CRITERIA

The panel was charged to apply the following criteria during the review:

1. *Overall scientific quality and degree of innovation:* Was there a clear and cogent strategy regarding how each of the program managers' major objectives are likely to make substantial and unique progress in advancing scientific frontiers of their discipline? Is the research novel, leading the field in an important area, and does it have the appropriate level of risk and payoff? Was related research being sponsored by other major players adequately summarized in terms of approach and goals? Were there areas of duplication?
2. *Scientific opportunity:* Is there some reasonable basis (e.g., incipient breakthrough, new understanding, novel theory, etc.) to believe that the scientific objectives might be met? Have the highest priority objectives been selected?
3. *Accomplishments:* Did the accomplishments represent significant scientific advances? If not, what is the potential that the accomplishments will lead to significant scientific advances? How do the accomplishments map to the stated program goals? Do the accomplishments reflect productivity and ingenuity on the part of the performers?
4. *Relevance/transitions:* Is the potential, long-term Army application of the research significant? Were there appropriate examples of significant transitions, or anticipated transitions of research, to follow on applied research or exploratory development either within industry or within an Army or DoD laboratory?
5. Additional considerations:
    a. What were the particular strengths in the program, and what were the weaknesses, if any?

b. If there were notable weaknesses, what are suggestions for improvements in these areas?
c. Are there any high-priority missed opportunities/areas?
d. If so, what lower priority area(s) should be reduced or eliminated to accommodate the new area?

The panel was instructed that the following items are outside the scope of the panel's charge and that these items should not be considered in the assessment:

- Other divisions or offices within ARO and ARL: The panel is charged in 2019 only to assess the Physical Sciences Division of ARO.
- Organizational changes: The ARO organizational structure is not subject to the assessment.
- Employee morale or motivation: The assessment panel does not conduct scientific surveys nor analyze the data required to assess morale, and is not asked to do so.
- Funding: The panel is not asked to assess or recommend the amount or sources of ARO funding.

PART II CONTENT

This chapter discusses the process used to conduct the assessment and report the resulting findings, conclusions, and recommendations. Part II Chapters 7 through 9 provide assessments of the programs within each of the PSD divisions (Physics, Chemical Sciences, and Life Sciences). Chapter 10 presents findings common across two or more of the divisions.

7

Physics Division

The Physics Division supports research to discover and understand exotic quantum and extreme optical physics where new regimes are expected to create revolutionary capabilities for the future warfighter.[1] The division's core budget of $9.3 million was leveraged against a $16.2 million investment by the Defense Advanced Research Projects Agency (DARPA) and other Department of Defense (DoD) programs and agencies in the physics domain. During fiscal year (FY) 2018, a total of 66 single investigator (SI) awards were funded along with nine Short-Term Innovative Research (STIR) awards focused on jump-starting high-risk projects. Four programs were reviewed: Atomic and Molecular Physics, Condensed Matter Physics, Quantum Information Science, and Optical Physics and Fields.

In general, the division's metrics are strong, with 745 peer-reviewed publications in the FY 2016 to FY 2018 period, and funding for 279 graduate students and 113 postdoctoral researchers during the FY 2017 to FY 2018 period. There were 23 transitions reported for the 3-year period from FY 2016 to FY 2018, including the transition of fundamental physics research funded by ARO to applications developed in the ARL intramural laboratories, which is another good indicator of the success of this program.

ATOMIC AND MOLECULAR PHYSICS PROGRAM

The Atomic and Molecular Physics (AMP) Program seeks to discover and exploit quantum properties of atoms and molecules to support Army functional concepts of fires, intelligence, maneuver support, and mission command. Its research focuses on discoveries that will enable the development of new quantum sensors and computational platforms, with three main objectives, which will aid the development of light, low-power devices suitable for warfighter use on the battlefield: (1) metrology—to ensure that quantum systems measure the desired quantity; (2) connectivity—to determine the role played by connectivity in interacting many-body systems; and (3) optimization—to create efficient classical and quantum optimization platforms.

Specifically, the Atomic and Molecular Physics Program efforts are focused on the exploitation of the quantum properties of atoms and molecules with the long-term goal of achieving significant scientific breakthroughs. Major long-term technological opportunities likely to be enabled by those scientific breakthroughs include (1) the development and use of many-body quantum states for robust precision metrology; (2) the development of precision position, navigation, and timing in global positioning system (GPS)-denied environments; (3) the development of distributed sensor platforms and networks beyond the classical limit; and (4) the development of quantum neural networks—although whether they have the theoretical potential to present advantages over classical systems remains an open question at this time.

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[1] Army Research Laboratory, Army Research Office, https://www.arl.army.mil/www/default.cfm?page=217, accessed October 1, 2019.

Overall Scientific Quality and Degree of Innovation

Considering the limited budget of ARO, the decision to stay away from the actively funded effort that is being made to develop quantum computers and to focus instead on quantum sensors seems well-advised, especially in view of the importance of position, navigation, and timing (PNT) for the Army. Nevertheless, it needs to be kept in mind that experimental work of this sort will still require very substantial support. It cannot be expected, therefore, that principal investigators (PIs) will be able to work at the forefront of this field if they are supported only by ARO funds. The funding that ARO provides will not necessarily be duplicative. It needs to function synergistically instead.

From the information provided, it appears that many, if not most, of the key players in this field are supported at some level by ARO and that the program manager (PM) has developed an excellent working relation with these groups. The PMs involvement in other programs, such as Defense Advanced Research Projects Agency (DARPA) programs, is also proving helpful. The leverage that this provides seems crucial for persuading the leading groups to consider the ARO-sponsored component of their work a key part of their activities, rather than a side program.

The risk/payoff balance is difficult to assess, because progress in the field is exceedingly rapid. Results that seemed impossible just a few years ago are now almost routine in the very best laboratories. These include, for instance, the realization and use of atomic microscopes, the achievement of molecular cooling, progress in atomic clocks, the realization of the first noisy intermediate-scale quantum (NISQ) computers, and almost routine measurements below the standard quantum limit. Nevertheless, the PM also indicated that in many cases, the results achieved by the PIs include discoveries that were not initially expected at the writing of the proposal. This is what happens when PIs pursue the best science, but also reflects the ability of creative and motivated PIs to turn problems into opportunities.

Scientific Opportunity

Major issues in many-body quantum sensing include the following:

1. *Decoherence and sensitivity to noise.* For this reason, significant work needs to be done to ensure that sensors measure the desired quantities. Among the kinds of projects that need to be pursued are the theoretical study and experimental realization of stable quantum states—for instance, entangled states—in the presence of noise, including topological protection.
2. *Lack of theoretical understanding of many-body systems.* Hence, the challenge of realizing controllable evolution of many-body-based sensors—here, the future use of NISQ computers may prove particularly useful.
3. *Experimental challenges having to do with the likely need to work at low temperatures*.

Some of the foundational research directions fundamental to AMP's objective are not currently well represented in the program. These include identifying simple systems with the longest possible coherence times and the best quantum control. One recent example of such development is the optical tweezer for single atoms, which was first demonstrated over a decade ago in France, but only recently started to be explored in depth. It is now used in the Harvard multitweezer array quantum simulator. Because the quantum information science program is focused on development of systems based on already-demonstrated qubits, it would make sense for the AMP program to put more focus on the basic physics of clean quantum systems. Identifying such systems would allow improvements in both PNT and quantum information applications. At the same time, studying many-body interactions and some of the first demonstrations of quantum algorithms might fit better in the quantum information area.

Significant Accomplishments

This program is supporting an impressive array of some of the very best groups in the field. Their general productivity is remarkable. The progress witnessed in recent years in AMP and related quantum information science is extraordinary. It can be traced to three major developments: (1) the development of the super-radiant laser; (2) improvement in the understanding of the mechanical effects of light on atoms; and (3) the realization of the profound implications of Bell inequalities. These were disruptive advances. An amazingly rich harvest of new developments has resulted—starting from the isolating, cooling, and control of atoms, ions, and photons, and their manipulation at the quantum level, to the realization of quantum degenerate gases, extraordinary advances in clocks, molecular physics, and the development of new experimental tools aimed at the understanding and control of many-body quantum effects.

Relevance and Transitions

The ARO program builds on these developments, and its success reflects the ingenuity and creativity of the PIs it has supported and of the PM as well. Some of the best ARO success stories have resulted from its funding of fairly risky and relatively long-term projects, such as development of the super-radiant laser and the identification of the nuclear transition in thorium. ARO is better positioned to support programs like these than many other science agencies.

Several projects funded by ARO have clear potential for transition—in particular, the super-radiant laser, where many-body correlations allow one to achieve a remarkably narrow linewidth laser. This will have a dramatic impact on precision time keeping, similar to that produced by the development of the hydrogen maser. The search for and recent likely identification of the laser-accessible nuclear transition in a thorium isomer will also likely result in an ultra-stable and portable nuclear clock with remarkable stability. For other projects, such as demonstrations of collective quantum effects in various quantum systems, the potential for PNT applications is more speculative at this point.

This program competes effectively for ARO corporate resources such as Multidisciplinary University Research Initiative (MURI) and Defense University Research Instrumentation Program (DURIP). It strongly cooperates with DARPA and the other service agencies and is notable for its support of early- and mid-career researchers. It also gives appropriate support to conferences and international collaboration.

The usual path for transitions for successful ARO projects is through DARPA, which has the capability to bring research results closer to applications. At the same time, ARO has more flexibility and granularity in funding smaller scale projects that have high potential for eventual transition to practical applications, but that are not yet ready for Small Business Innovation Research/Small Business Technology Transfer (SBIR/STTR)-type funding.

CONDENSED MATTER PHYSICS PROGRAM

Overall Scientific Quality and Degree of Innovation

The Condensed Matter Physics (CMP) Program presented a clear and cogent strategy for ensuring that the major objectives of the program managers will result in CMP supporting projects that are likely to advance the scientific frontiers of their discipline. The vision of the CMP program is to discover and explain new electronic phenomena in the solid state that, for example, will make it possible to develop electronic devices that are unusually energy efficient. More specifically, advances in condensed matter physics can lead to the development of sensors with higher magnetic field noise rejection and advanced small platform computation capabilities. To this end, the CMP program is focused on four areas: (1) understanding the interactions between topological and magnetic states; (2) realizing and controlling anyons; (3) discovering new nonequilibrium states of solids; and (4) exploring strong correlations in oxide heterostructures. These areas are at the forefront of modern CMP, and the CMP program has done a commendable job of including in its portfolio a good mix of projects being pursued by both well-established and new investigators. For each of these areas, both the scientific objectives and the challenges were described, and the results that have been obtained were presented. Although there was good synergy between the ARO-funded projects, information was not provided about the other sponsors of related research of the ARO-funded PIs or their competitors.

Scientific Opportunity

The scientific goals of the CMP program are well defined, and it is clear that much thought has gone into the project selection process. For the first topic, understanding topological-magnetic state interactions, the focus is on exploring the limits of (local) disorder on global (topological) properties. Because the CMP program is "materials agnostic," this concept is being investigated in multiple systems. The accomplishments to date include demonstrations of the anomalous quantum Hall effect at topological-magnetic interfaces (at Pennsylvania State University) and in hBN-graphene-hBN (at the University of California, Santa Barbara). The second topic is concerned with realizing and controlling anyons. Here, the accomplishments include (1) observations consistent with Majorana quasi-particles at graphene-superconductor interfaces (at Duke University); (2) density functional theory predictions of the influence of superconducting contacts on graphene band structure (at the University of Texas, Dallas); and (3) electrostatic gating of hBN-WTe_2-hBN to achieve the quantum spin Hall effect (at the Massachusetts Institute of Technology and Harvard University). For the third topic, discovering nonequilibrium states of solids, there are significant efforts in coherent electromagnetic excitation (at the California Institute of Technology), and nano-infrared spectroscopy has been developed and used to demonstrate thermally and optically induced phase transitions (at Columbia University). For the fourth topic, exploring strong correlations in oxide heterostructures, detailed plans and accomplishments were not discussed, but it was mentioned that the few remaining projects will be deemphasized.

A good case was made for each subgroup of topics on how the research being pursued would advance the interests of the Army—for example, sensors work in the field, real-time computation, and PNT. There is a good balance between well-established and new researchers in this program. There was good synergy between the ARO-funded projects.

Significant Accomplishments

Most of the research proposed and accomplished fits nicely with the advances that have been achieved by the major groups that make this an exciting field. The PIs have especially focused on some fundamental aspects that have not been studied before—for example, work at Pennsylvania State University has revealed the magnetic interactions at a topological/magnetic interface. These accomplishments map directly onto the stated program goals. It is clear that much thought has gone into the decision-making process.

The search for the elusive Majorana quasi-particle continues worldwide with significantly more funding than ARO's entire budget. Nonetheless, the project being undertaken by the Duke University and Appalachian State University groups presents an interesting approach to using graphene edge contacted by superconductor and gated at the open ends. Preliminary experiments on graphene in a magnetic field show topologically quantized conductance.

Magic angle twisted bilayer graphene (tBLG) has been under intensive study over the past year since the discovery of Moiré-induced flat bands, superconductivity, and Mott insulators as a function of doping. With ARO support, the University of California, Santa Barbara, team has now added the possibility of high-temperature quantized resistance. They sandwich the tBLG between flakes of boron nitride and voltage gate the system into an orbital-polarized state. The sample then exhibits a quantum anomalous Hall effect with plateaus at $\pm h/e^2$ switchable by applying a magnetic field, H, and then returning to H = 0. The Hall resistance remains quantized at h/e^2 up to 4 K.

Theoretical support for understanding the graphene-superconductor interface is provided by density functional theory calculations by the University of Texas, Dallas, group, which provides the depth-of-band structure modulation from the contact superconductors.

Beyond graphene, the community has been investigating other two-dimensional (2D) van der Waals solids such as WTe_2. With ARO support, a Harvard University/Massachusetts Institute of Technology team has obtained evidence for more topological phases and new physics in this material, including quantum spin Hall effect in a sample with superconducting edge contacts. Such a configuration is a step toward anyon physics with implications for quantum computing.

Relevance and Transitions

The research supported by the CMP program has high relevance for long-term Army applications. Examples include enhanced navigation capabilities, energy-efficient electronics and sensors, and ultra-lightweight optical elements for increased warfighter awareness. Several examples of the transfer of basic research to applied research were presented, including follow-on work on topological Josephson junctions, energy-efficient electronic devices, frequency-selective limiters, and circulators in the GHz range, supported by ARL and DARPA.

The CMP program has had at least 16 years of leadership, which has enabled its manager to strategically build the program through leveraging various Department of Defense (DoD) cooperative opportunities. At the same time, the CMP program needs to beneficially continue its cooperative activities with the program managers in materials science and electronics.

QUANTUM INFORMATION SCIENCE PROGRAM

Overall Scientific Quality and Degree of Innovation

Within ARO, the locus of quantum information science is in the Physics Division, which has a dedicated Quantum Information Science program manager. An additional program manager specializing in the subject, who is an employee of another federal agency, is embedded in the division. The division's Atomic and Molecular Physics and Condensed Matter Physics Programs engage in topics that cross-fertilize with quantum information, such as implementation of quantum logic in ultracold atoms and ions, and identification of quasi-particles in condensed matter potentially useful for future qubits.

Scientific Opportunity

The Quantum Information Science program manager articulated a clear focus on Army-specific objectives—information dominance on the battlefield, bolstered by sensing and secure communication, with low power and footprint requirements suitable for warfighters in the field.

These goals are pursued with research on multiqubit systems and protocols, the limits of quantum versus classical sensors, and noncryptographic quantum algorithms. The research performers include theorists and experimentalists, ranging from early-career scientists to the most eminent senior figures in the field. There is appropriate support for conferences and international collaboration.

The Quantum Information Science Program's research is complementary to that of the Atomic and Molecular Physics Program, which addresses similar long-term objectives using different techniques. The interactivity and collegiality between the division's PMs is noteworthy.

An interesting anecdote was told by the Quantum Information Science program manager. A quantum algorithm had been found to be superior to the public Netflix recommendation algorithm. A new classical algorithm was found later that performed comparably to the quantum algorithm—both exponentially more powerful than the original classical performance. Of particular note, the new classical algorithm was inspired by discoveries within quantum information. This is an important example of how classical and quantum approaches can strengthen each other and of the value of communication between physics and information sciences.

Significant Accomplishments

The overall scientific quality and degree of innovation of this program is high. It supports some of the best performers in the field, in both experiment and theory, while avoiding duplication of much larger programs that are focused on building scalable quantum computers or quantum key distribution systems. This shows good judgment and effective use of ARO resources.

The program aggressively pursues scientific opportunities, as demonstrated by recent successes in demonstration of spin textures in nitrogen-vacancy (NV) diamond systems, circuit quantum electrodynamics in synthetic hyperbolic spaces, and the theory of generative adversarial networks. These rank among the top recent achievements in this highly competitive field of science.

Relevance and Transitions

The transitions associated with this program are associated with commercialization of software, venture capital investment in an ion-trap start-up company, initiation of a DARPA program, and the placement of trained personnel in DoD science and technology positions. These are good outcomes for a basic research program in this field.

OPTICAL PHYSICS AND FIELDS PROGRAM

The PM of this program recently retired, and the report of the program's progress was presented by two PMs who are involved in other programs in the Physics Division. This seems a good opportunity for the Physics Division to combine the search for a new PM with a discussion about possible new directions. The Optical Physics and Fields area has long been highly relevant to the Army, and there is compelling argument to continue this program, with potentially new directions and focus areas.

Overall Scientific Quality and Degree of Innovation

The quality of the program is high, and the projects it has supported have substantially advanced the science. Particularly noteworthy is the successful transition of a number of its key projects to larger programs.

The major research programs in this program are field-leading. They involve both well-established and early-career investigators, and the balance between perceived high success rate and high-risk/high-return projects is excellent.

Parts of the research portfolio seem to be uniquely ARO-funded or ARO-heavy, such as the light filament program and the thorium nuclear optical transition program. Others include niche areas that ARO has identified as being of particular interest, including novel symmetries in optics and epsilon near zero (ENZ) materials for optics.

No duplications of funded research were observed, and there is synergy between this program and other programs within the Physics Division, as well as with other divisions in Engineering and Materials Science. As an example, the thorium optical transition project may be scientifically related to the AMP program.

Scientific Opportunity

The Optical Physics and Fields Program's scientific opportunities are in transition. Recent accomplishments in demonstrating light filaments and attosecond physics have resulted in successful transitions for follow-on funding. Continuing present opportunities include exploiting novel symmetries in optics and exciting opportunities for discoveries with the supersymmetric (SUSY) optics and ENZ materials. The program intends to initiate a new initiative to explore alternative solutions to Maxwell's equations based on recent reported advances.

Significant Accomplishments

The project to accurately localize the ^{229}Th isomer nuclear transition for doped thorium crystal was successful, culminating a long-standing, international effort to search for this transition energy. This accomplishment offers promise as the enabling technology for a compact, portable, precision optical clock with greater stability and accuracy than present-day clocks as a key element of PNT. Further work is planned to confirm the exact transition, to verify the transition quality, and to develop a clock.

The objective to extend the physics of extreme forms of light beyond established knowledge includes exploring optical materials with ENZ and supersymmetry. Adiabatic wavelength conversion was demonstrated with time varying change of the index of refraction to modify the frequency with approximately 100 times greater frequency shift over 100 times less distance than with indium tin oxide. This was a significant departure from known perturbative nonlinear optics. The result offers the opportunity to provide very compact optical isolator or optical protection components. The program intent is to continue to address the theoretical and experimental challenges of the ENZ regime.

The project applying and exploiting novel supersymmetry in optics has been successfully validated, which opens the door to many opportunities in the near future. This approach, based on passive elements to manipulate optical modes, is attractive not only for high-efficiency lasers but also for many other forms of optoelectronics. There is a parallel between optical and electronic properties when it comes to novel symmetries. One may expect synergy between condensed matter physics projects on symmetry and topological states and optics on novel symmetry.

In line with the objective to extend the physics of extreme forms of light beyond established knowledge, the project to understand and control the mechanisms of light filamentation and light filament-matter interactions was successful. The project involved use of a short-pulse laser to induce a plasma filament over significant distances to deliver potential effects such as microwave through submillimeter wavelength radiation to enable electromagnetic interference, sensing, or communications reception at a targeted object. Based on successful testing, the project was reported to have been transitioned to other parts of the DoD for potential applications.

Relevance and Transitions

The four highlighted projects have all been successfully transitioned to larger programs—light filaments to ARL and other DoD units, optical generation of MeV X-rays to ARL, demonstration of SUSY to DARPA-Microsystems Technology Office (MTO), and thorium isomer transition to DARPA-

MTO and U.S. Air Force. This is an excellent indicator of the magnitude of the impact the optics program is having.

Despite the limited resources, no notable program weaknesses were identified. The PMs are doing an excellent job in focusing efforts in selected areas. The PMs are clearly aware of the dynamic nature of the research frontier. The search for a new PM needs to be seen as an opportunity to identify research priorities at the boundaries of traditional areas. The new PM may further foster the interactions among the different programs within the Physics Division.

OVERALL ASSESSMENT

Four programs were reviewed: Atomic and Molecular Physics, Condensed Matter Physics, Quantum Information Science, and Optical Physics and Fields. The overall scientific quality of the work presented was excellent and in many cases was significantly innovative, being at or near the forefront of the relevant fields. From a management perspective, the research funding strategy appeared to be coherent and was clearly enunciated. The objectives were designed to promote critical advances in the fields of concern. The quality of research carried out under the auspices of the ARO-funded programs was excellent. However, it was difficult to evaluate the level of risk versus payoff, because only a few examples of failures were given. Nonetheless, all of the presentations described results that were excellent, and in some cases outstanding. ARO is by no means the largest supporter of the work being done in the scientific areas described, but it has managed to benefit significantly from piggybacking on larger programs.

Many of the research activities supported by ARO are in “hot” fields in which many other researchers are working. In the four fields mentioned above, there were two accomplishments cited that represent significant advances. These are the work done on super-radiant laser and materials-agnostic demonstrations of the quantum anomalous Hall effect. It is likely that four other accomplishments will achieve breakthroughs: computing with neuromorphic dissipative quantum phase transitions, physical phenomena on topological surfaces, scaling up of trapped ion multiqubit systems, and exploitation of super-symmetries in optics.

The basic research that ARO supports is expected to provide knowledge that will ultimately form the basis of applications for the Army. The time scale for that transition is expected to be anywhere from 5 to 25 years (or longer). It is very commendable, therefore, that some of the research now being supported by the Physics Division of ARO is already being transitioned to other agencies and to potential end users.

Some cross-disciplinary opportunities were noticed, and these are listed below along with associated recommendations.

Condensed matter physics depends on the discovery of new phenomena in existing materials, and on the observation and exploitation of known phenomena in new materials. The interaction between the condensed matter activities and the materials science activities that ARO sponsors is not close enough, although assurance was provided that the two relevant ARO PMs are in contact.

Recommendation 1: Army Research Office (ARO) program managers (PMs) should view condensed matter physics and materials science as parts of a larger whole and be proactive in stimulating connections between them. ARO management should encourage regular interactions between the ARO Physics Division condensed matter PM and the materials science PMs elsewhere to coordinate funding of multiple principal investigators (PIs).

Large advances in quantum information science are unlikely to occur unless there are correspondingly large advances in the development and analysis of algorithms. Little evidence was presented of any active engagement on algorithms between the Physics Division Quantum Information Science Program and its classical counterpart in the Information Sciences Division. This is a generic issue in modern information science. The expertise and collegial environment evident at ARO suggest that ARO could become a nexus for breakthroughs in understanding the quantum/classical algorithmic frontier.

Recommendation 2: Army Research Office (ARO) management should encourage interdivisional activity on the quantum/classical algorithmic frontier, using appropriate incentives like Multidisciplinary University Research Initiative (MURI) grants.

Collaborations between researchers in condensed matter and materials science and between investigators working on quantum information and information science have led to significant accomplishments, but such collaborations appear to be the exception rather than the rule. There is a growing recognition in the scientific community that the breakthroughs of the future are likely to occur in the boundaries between disciplines.

Recommendation 3: The Army Research Office (ARO) should consider exploring breakthrough opportunities that may exist in the boundaries between the disciplines and divisions it has traditionally supported.

A substantial number of the single investigator (SI) grants that ARO makes are to individuals in "hot" fields who are at the peaks of their careers, and consequently are also supported by other organizations. This approach to research support makes the exploration of the frontier move faster, as well as making the programmatic activities of these PMs more successful. However, this strategy shortchanges early-career investigators.

Recommendation 4: The Army Research Office (ARO) should seek a better balance between funding well-established and well-funded principal investigators (PIs) in "hot" disciplines and early-career investigators who are entering the "hot" fields or starting entirely new fields.

8

Chemical Sciences Division

The Chemical Sciences Division supports research to discover and understand the fundamental properties, principles, and processes governing molecules and their interactions in materials or chemical systems to provide the scientific foundation to create revolutionary capabilities for the future warfighter, such as new protective and responsive materials, sensors, and munitions.[1] The division's core budget of $9.4 million was leveraged against a $41.7 million investment by the Defense Advanced Research Projects Agency (DARPA) and other Department of Defense (DoD) programs and agencies in the chemical sciences domain. During fiscal year (FY) 2018, a total of 87 single investigator (SI) awards were funded along with 24 Short-Term Innovative Research (STIR) awards focused on jump-starting high-risk projects. Four programs were reviewed: Reactive Chemical Systems, Electrochemistry, Molecular Structure and Dynamics, and Polymer Chemistry.

In general, the division's metrics are strong, with 751 peer-reviewed publications in the FY 2016 to FY 2018 period, and funding for 354 graduate students and 171 postdoctoral researchers during the FY 2017 to FY 2018 period. However, most impressive for a program focused on outcomes for the Army was the number of successful transitions from bench to application. There were 56 transitions reported for the 3-year period from FY 2016 to FY 2018, including the development of several commercial products and start-ups based on the science and technology supported by the Chemical Sciences Division. The transition of fundamental chemical science research funded by the Army Research Office (ARO) to applications developed in the Army Research Laboratory (ARL) intramural laboratories is another good indicator of the success of this program.

REACTIVE CHEMICAL SYSTEMS PROGRAM

Overall Scientific Quality and Degree of Innovation

The Reactive Chemical Systems Program supports three Army functional concepts: to understand chemical mechanisms for sustainment and maneuver support, to explore new materials for maneuver support and mission command, and to discover new materials and properties for sustainment. The research objectives of the program are (1) to attain a mechanistic understanding of mass transport, adsorption, and reactivity on surfaces and at interfaces; (2) to create chemically and biologically functionalized surfaces with precise control of structure and function; and (3) to rationally design and assemble synthetic molecular systems that sense and respond to external stimuli.

There is no doubt that opportunities for innovation in the program are significant and that the research supported is interesting and novel, but it is of some concern that the sponsored work may be duplicated in other funding agencies, such as Department of Energy's (DOE) catalysis science program. Nevertheless, when properly guided, this research can have a major impact on the development of new technologies that

[1] Army Research Laboratory, Army Research Office, https://www.arl.army.mil/www/default.cfm?page=217, accessed October 1, 2019.

are critical to the Army. The research highlighted included the application of single-molecule fluorescence microscopy to analyze catalytic activity in individual metal nanorods, the development and understanding of abiotic-biotic interfaces for water-free biologics, the design and fabrication of a liquid-cell transmission electron microscope that led to the in situ observation of radical polymerization, and a self-regulating system based on a liquid crystal-water interface where antibiotics trapped in the liquid crystal phase are released into the water by mechanical disruption caused by mobile bacteria, which, in turn, are killed by the cargo released. In addition to the scientific outcomes from this work, tangible evidence for immediate impact also comes from the training of scientists who now are engaged in research at the ARL, Naval Research Laboratory (NRL), and elsewhere. The support available for high-risk projects (for example, the STIR program projects) and conferences are critical, respectively, to identify high-risk, high-return projects and to maintain the vitality of science of interest to ARO.

Scientific Opportunity

Considering that surfaces and interfaces are ubiquitous and differ widely in chemical and physical complexity, they afford many opportunities for scientific development and technological advances. Noteworthy examples were presented with a focus on strategies for developing stimuli-responsive systems that may be capable of triggering sensing or protective functions. The specific systems and tools illustrate a range of applications that represent the tip of an iceberg, suggesting that one of the challenges of this program will be to focus its efforts on high-impact areas. The examples covered suggest that the objectives of the program are being met. They include the ability to observe single-catalytic events by taking advantage of single-molecule fluorescence microscopy, which revealed long-range cooperativity on scales of time and distance that could not have been anticipated from current paradigms, and that open the door for further testing on these and other nanomaterials. Other examples address strategies to mimic the solvent environment in immobilized enzymes and stimuli-bioresponsive systems that lead to signal amplification on liquid-liquid crystal interfaces. Strategies to strengthen and invest in promising thrust areas while decreasing support or even removing areas of limited interest to the scientific community would help focus the program's efforts.

Significant Accomplishments

The accomplishments described in the report *ARO in Review 2018* represent significant scientific advances.[2] It is noteworthy that a diverse set of investigators at varying career stages were involved in that work. The projects cover a broad cross section of catalysis using metal-organic frameworks, metal carbide MXenes, metal-supported catalysts, assembly and disassembly of polymer materials, and advanced characterization techniques. Although it is difficult to determine the ingenuity and impact of the work done by the investigators involved based on limited project details provided by ARO, members of the panel are familiar with the work done by many of these principal investigators (PIs), and it is of very high quality. The metrics presented in terms of number of papers published, student and postdoctoral researchers trained, and transitions of the projects are indicative of a well-managed program.

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[2] Army Research Laboratory, Army Research Office, https://www.arl.army.mil/www/pages/172/docs/AROinReview2018-online.pdf, accessed October 3, 2019.

Relevance and Transitions

This program has had a substantial level of success, as indicated by a significant number of transitions in the form of personnel development as well as accomplishments adopted by Army and industrial customers for a number of diverse applications. These transitions highlight the importance of the successes that have resulted from the basic chemical science research funded by this program. Examples of such transitions include development by TDA Research of an advanced detergent formulation—SSDX-12—that is used by FDNY HazMat Battalion as an all-hazards, nonreactive decontaminant; and the development at Northwestern University of an automated piezo-based instrument for depositing liquid droplets that Scienion is making commercially available.

Additional Considerations

The presentations made were of excellent quality. The objectives of the program are appropriate, and good science has been done. However, the title of the Reactive Chemical Systems Program does not encompass the breadth and complexity of the science it sponsors, which involves multifunctional surfaces and assemblies for advanced materials applications. This may limit the degree to which a large part of the relevant component of the academic community is aware of the program's activities.

The work highlighted is of high quality and fits well within the main objectives of the program, but the selection of projects for funding, which is heavily influenced by the program manager, needs to be reassessed by ARO.

ELECTROCHEMISTRY PROGRAM

Overall Scientific Quality and Degree of Innovation

The Electrochemistry Program has three major scientific objectives: (1) to synthesize and characterize new electrolyte species so as to better understand transport in heterogeneous charged environments; (2) to understand how material and morphology affect electron transfer and electrocatalysis; and (3) to explore new methods for controlling electrochemistry. These objectives are clearly relevant to the Army. They relate to the development of improved sensors, batteries, and fuel cells.

The program's decision to decrease its emphasis on catalysis under acidic conditions is well justified, based on the availability of nonnoble metal catalyst materials. Also well justified is the plan to decrease the emphasis on lithium-based energy storage, which is an area that is being massively supported by other agencies. The decision to increase the resources devoted to electrodeless electrochemistry is a high-risk investment aimed at clarifying the phenomena associated with plasma-generated solvated electrons, and their coupling with double-layer phenomena and electrochemical reactions. The continued development of additional experimental and simulation methods to characterize this novel, complex system will contribute to a better understanding of the underlying phenomena, and will strengthen the scientific impact of the work done in pursuit of this objective.

The program incorporates a healthy blend of fundamental science supporting new applications and high-risk projects that, if successful, will lead to new ways of controlling redox chemistry. It is going to be facing stiff competition, especially from the DOE, but it has carved out several unique opportunities that are relevant to the ARO mission. Of the awards it made during FY 2016 to FY 2018, 31 were relevant to objective 1 and 42 were relevant to objective 2 (see above), and in that same interval, 7 awards were made that relate to objective 3, which is an emerging area for the program.

Scientific Opportunity

There are already examples of research accomplishments indicating that the program's scientific objective will be met. One example is the high-throughput discovery and characterization of a complex oxide catalyst for the oxygen evolution reaction; this oxygen reduction reaction project began as a Young Investigator Program (YIP) and is now a Multidisciplinary University Research Initiative (MURI). The next step will be to employ these methods to generate solid-oxide fuel cells capable of using complex hydrocarbon fuels that are relevant to the Army. A second example is the work in cascade catalysis starting from enzymes to synthetic molecular catalysts, which is a true breakthrough. This particular MURI team comprises experts in synthesis, electrochemistry, and modeling, and is a fine example of how multidisciplinary approaches can greatly accelerate the advance of science. With regard to highest priority work, efforts in multivalent "beyond Li-ion" are high risk but would have high impact if successful.

Significant Accomplishments

The examples mentioned in the previous subsection represent significant scientific advances. Moreover, although not highlighted in the presentation, the work being supported on interfacial electron-transfer dynamics in chromophore assemblies is also game changing with regard to solar-cell design and photoredox catalysis. Electrochemical C–C bond activation in alkaline environments also is a significant advance. There are a couple of accomplishments that, while significant, may diverge from the program's stated objectives: probing catalytic sites for the oxygen evolution reaction by scanning electrochemical microscopy, and solid-state protonic conductors. In all cases presented, however, the accomplishments of the PIs reflect productivity and ingenuity on the part of the teams they are leading. It is encouraging that the program manager (PM) contributes intellectually to the planning of these teams so as to refine their specific aims in such a way as to align them with the program objectives. The STIR program is used to explore new directions and higher risk projects.

Relevance and Transitions

A rethinking of energy conversion and storage needs that focuses on how warfighters operate is of significant interest to the Army. Accordingly, the five or so significant transitions to other areas of Army research serve as concrete examples of this interest. These transitions include carbon dioxide model, salt-induced protective cathodes, TiO_2 transient absorption, synthesis of transition metal dichalcogenide photoelectrodes, and synthesized new block copolymer anion conductive membranes. In addition, the transitions to the private sector (companies and venture capital) and complementary laboratories (DOE, National Renewable Energy Laboratory) show impact.

Additional Considerations

A sharp focus on fuels and energy storage is a particular strength. Basic research in the oxygen-evolution or oxygen-reduction reactions could be coupled with their fuel-forming redox partners to generate the most impactful science and differentiate this program from other funded National Science Foundation (NSF) and DOE efforts.

MOLECULAR STRUCTURE AND DYNAMICS PROGRAM

Overall Scientific Quality and Degree of Innovation

The objectives of the research supported by the Molecular Structure and Dynamics Program are (1) to achieve quantum-state control in the preparation of molecules for state-to-state studies of reaction dynamics and intermolecular forces; (2) to develop novel theoretical paradigms for elaborating chemical properties and reaction propensities with unprecedented accuracy and efficiency; and (3) to discover new energetic materials that surpass the capabilities offered by the best substances currently available.

The program manager outlined several examples of innovative endeavors that collectively span the following Army functional concepts: movement and maneuver, fires, maneuver support, intelligence, and sustainment. The highlighted studies of inelastic scattering have the potential to impact multiple scientific domains of programmatic interest (including quantum computing and energetic materials) while simultaneously offering singular information for assessing and refining theoretical scattering models. Overarching concepts emerging from fundamental studies of intermolecular interactions have been exploited to discover new families of energetic materials based on melt-castable co-crystallization motifs and hydrogen-peroxide hydrates—all of which have superior performance metrics. New computational tools based on remarkably efficient implementations of the two-electron reduced-density matrix ansatz have been demonstrated that have made it possible to carry out quantitative investigations of strongly correlated molecular systems (e.g., transition-metal catalysts) that cannot be studied effectively using canonical quantum-chemical methods. An effort that utilized pulsed electrical discharges in cryogenic liquid nitrogen to generate new nitrogen polymers/allotropes and other novel nitrogen-based materials afforded a good example of discovery-oriented research that offers the tantalizing possibility of creating hitherto inaccessible energetic materials capable of breaching the energy-density limitations of conventional organic compounds.

The overall program of research is innovative, involving a unique combination of cutting-edge experimental and theoretical work that has enormous potential for making discoveries that will have far-reaching implications. While similar endeavors may be supported by other funding agencies, the distinctive nature of the collective efforts supported by this program, as evidenced by the specific combinations of molecules and processes curated by the program manager, ensures that the projects supported by this program will be steered actively toward ARO programmatic goals.

Scientific Opportunity

The wide range of studies pursued in this program offer unique opportunities for technical innovation and conceptual advancement on many fronts. The support being provided to both experimental and theoretical groups is unique and could be further fostered, as could efforts to identify early-career PIs whose fledgling programs can often embody the most inventive ideas. The studies of plasma-based syntheses in liquid nitrogen have provided intriguing evidence for the creation of novel polynitrogen compounds that are stable under ambient pressures, yet capable of storing enormous amounts of chemical energy. This work would benefit from more detailed experimental and theoretical analyses designed to fully characterize the species being created, and to assay their ultimate utility for programmatic goals.

Significant Accomplishments

The accomplishments highlighted by the program manager (and described briefly above) are noteworthy and represent significant advances in the conceptual understanding of molecules and their interactions, as well as in the development of experimental tools and theoretical methods that offer unprecedented capabilities for unraveling complex molecular phenomena. The fundamental information emerging from studies like these can establish new paradigms for controlling and manipulating chemistry in ways that were not previously considered—as demonstrated by the relatively new thrust in the area of energetic materials.

The list of PIs supported by the Molecular Structure and Dynamics Program includes many well-known experimental and theoretical chemists, and the titles of their projects mesh well with the stated programmatic goals of the Army. Efforts to identify early-career investigators with newly established research programs are evident and presumably will be continued.

In addition to the tangible metrics of scientific impact (as gauged by peer-reviewed journal publications) and training of technical personnel (in the form of graduate students and postdoctoral fellows), significant transitions of materials and concepts to facilities operated by the Army, other DoD and DOE agencies, and private industry were highlighted. Some examples include the following: a patent for CL-20:H_2O_2 co-crystal; distribution of SAPT code to 834 registered users; Manzara Therapeutics' engagement in peptide discovery for therapeutics; and customers using automated kinetics code EStokTP and NO_x mechanism in proprietary research.

Relevance and Transitions

The Molecular Structure and Dynamics Program has enjoyed a substantial number of successes, as gauged by the transitions of projects it has initiated. These transitions include the transfer of fundamental concepts, novel materials, and trained personnel to Army facilities and other DoD and DOE sites, as well as the establishment of several ventures with private industry. These successes provide clear evidence of the innovative nature of results emerging from this program, and demonstrate the crucial importance of continued funding for basic chemical sciences.

Additional Considerations

A particular strength of the Molecular Structure and Dynamics Program at ARO is the strong overlap between experiment and theory in the projects it supports. This synergy needs to be fostered and promoted—perhaps even by granting awards to multiple investigators who can bring unique skills—for example, new experimental tools and emerging theoretical methods—to bear on problems of programmatic interest.

The new thrust in energetic materials is especially promising, and particularly relevant to Army objectives. No areas of decreasing emphasis were identified during the overview presentation by the program manager, and the PM needs to more fully identify funding sources that will help keep the exciting work this program is sponsoring in novel energetic materials growing. It could be that untapped relationships exist between these experimental projects and the consistently strong work that is being done in control of quantum molecular processes that is supported by theory. There may be opportunities to blend scholarly efforts in the synthesis of energetic materials with the advances in spectroscopic methods to probe and elaborate key structure-property correlations.

POLYMER CHEMISTRY PROGRAM

Overall Scientific Quality and Degree of Innovation

The Polymer Chemistry Program supports high-quality, innovative research that is being carried out by excellent PIs. There is a very good mixture of projects that span a wide range of modern polymer science. The program extensively leverages funding sources such as MURIs and increasingly the Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs. The program is doing very well as measured by its funding leverage, collaborations, relevance to Army programmatic needs, peer-reviewed publications, students and postdoctoral researchers supported, and transitions of technology and concepts to both DoD and private organizations.

The Polymer Chemistry Program has four interrelated scientific objectives: (1) to create polymers with precise control over molecular structure and composition (sometimes called the holy grail of polymer synthesis), with a goal of creating synthetic polymers that have the kind of structural and functional complexity characteristic of proteins; (2) to determine how molecular structure impacts morphology and properties; (3) to devise strategies for controlling polymer assembly to render complex functional materials; and (4) to create polymeric materials that exhibit precise programmed responses to external stimuli. Thus, this program addresses some of the most fundamental needs in polymer chemistry, ranging from the development of synthetic methods capable of controlling polymer chain sequence and catalysts to synthesize stereo-regular polymers from polar monomers, the interfacing of synthetic polymers with biological materials to bring beneficial enzymatic functions into nonnatural contexts, and the development of controlled polymerization and depolymerization methods.

The program strategy will be to place greater emphasis on stereochemical control in polymers, and to deemphasize research in polymer-based membranes, while maintaining efforts related to sequence-defined polymers, 2D organic polymers, and responsive polymer systems. The rationale for deemphasis on polymer membranes stems from decreasing return on investment in this maturing field. Overall, the strategy reflects an emphasis on polymer synthesis, including synthetic methods and catalysis, which is in harmony with the program objectives—with perhaps less effort in characterization and evaluation of materials for specific applications. The program is thus playing a leading role in several emerging basic-science initiatives with a level of risk and payoff toward the high-risk side of the spectrum. Other major players are also supporting work in these areas, but the program has identified a number of differentiating opportunities within the ARO mission, and careful guidance by the program manager can help to ensure that projects develop toward such programmatic goals.

Scientific Opportunity

The objectives of the program tend to be very fundamental in nature, and, if successful, will have broad and deep impacts not only for the ARO mission but also throughout polymer science and, even more broadly, throughout materials science and engineering. For the objective of precise control over molecular structure and composition, for example, quoting from Lutz et al., “monomer sequence regulation plays a key role in biology and is a prerequisite for crucial features of life, such as heredity, self-replication, complex self-assembly, and molecular recognition. In this context, developing synthetic polymers containing controlled monomer sequences is an important area for research.”[3] This is a prototypical example of a high-priority objective for which the risk and motivation are clear—yet a successful outcome requires long-term investment. In the related area of control over polymer stereochemistry, breakthroughs have been made in catalyst design and will open several entirely new research topics. Likewise, breakthroughs have been made in control of polymer assembly to render functional hybrid synthetic/enzymes complexes and depolymerization of polymers in response to chemical stimuli. Collectively, such notable accomplishments suggest that many if not all of the scientific objectives will be met to some degree and positively impact the Army.

[3] J.F. Lutz, M. Ouchi, D.R. Liu, and M. Sawamoto, 2013, Sequence-controlled polymers, *Science* 341(6146):1238149.

Significant Accomplishments

Several case studies were presented that represent significant scientific advances and map directly onto the stated objectives of the program. Two projects of very high significance stand out. The first is an STIR-funded project that developed a library of imidodiphosphate catalysts toward the stereo-regular cationic polymerization of poly(vinyl ethers) (PVEs). One consequence of high degrees of stereoregularity is that the materials can crystallize and be deployed as thermoplastics, akin to isotactic polypropylene. A catalyst was identified that yields 88 percent to 93 percent isotactic PVE. The impact of this breakthrough in polymer synthesis is tremendous not only in yielding polymers with previously inaccessible properties and functions (chemistry), but also in processability (structures, films, and composites) for a plethora of new applications. The second is a single investigator project that synthesized random heteropolymers composed of four types of monomer subunits, each with chemical properties designed to interact with chemical patches on the surface of proteins of interest. The heteropolymers interact favorably with protein surfaces, and co-assemble with the protein to maintain correct protein folding and stability outside of the cell and in nonnatural environments. The synthetic and biological assemblies retained enzymatic function, could be integrated into fiber mats, and were effective for bioremediation of toxic chemicals such as those found in insecticides and chemical warfare agents. This strategy to retain biological activity in nonbiological environments potentially opens the door to a wide range of hybrid materials that harness the power of biological materials for Army-related applications. There are also other accomplishments that reflect positively on the productivity and the creativity of the researchers in the Polymer Chemistry Program, as well as on the part of the PIs and the many graduate students and postdoctoral researchers now trained in scientific activity of interest to the Army.

Relevance and Transitions

The ability to control the structure of polymers is key for the development of properties and functions of interest to Army applications. In the process of helping to address interesting and emerging scientific questions, the program has been successful in the promotion of new technologies and the development of talent. Several technology transitions to Army agencies and industries covering a wide range of polymer applications are listed in the report,[4] suggesting that the program is meeting its goals in this area. Some of these applications include new classes of responsive polymers for self-healing structural materials, adaptive fabrics, and self-repairing electronics and additively manufactured thermally cured thermoset polymers with a myriad of industrial and military-relevant applications.

Additional Considerations

The program has a strong record of significant experimental accomplishments in several critical aspects of polymer science. Nevertheless, there exist significant opportunities to introduce modern theoretical and simulation techniques for the systematic design and characterization of targeted polymeric materials.

[4] Army Research Laboratory, Army Research Office, https://www.arl.army.mil/www/pages/172/docs/AROinReview2018-online.pdf, accessed October 3, 2019.

OVERALL ASSESSMENT

Four programs were reviewed: Reactive Chemical Systems, Electrochemistry, Molecular Structure and Dynamics, and Polymer Chemistry. In general, division metrics were strong, with 751 peer-reviewed publications during FY 2016 to FY 2018, and funding for 354 graduate students and 171 postdoctoral researchers average per year during FY 2017 and FY 2018. However, most impressive in a program focused on outcomes for the Army was the number of successful transitions from bench to application. The translational metrics provided showed 56 transitions in the 3-year period from FY 2016 to FY 2018, including the development of several commercial products and start-ups based on the science and technology supported in these grants. The transition of fundamental chemical science research funded by ARO to applications developed in the ARL intramural laboratories also provides a good indicator of the success of the programs.

Overall, the Chemical Sciences Division supports strong science and innovative research projects that have clear potential for impacting the future performance of the Army. Some notable examples of impactful science funded by this division include the following: the development of melt-castable highly energetic materials made by co-crystallization; the design of self-regulating liquid crystals triggered by motile bacteria; the combinatorial synthesis and discovery of electrochemically active Perovskite materials; and the stabilization of biological materials using novel designer-polymer coatings based on mapping of hydrophobic/hydrophilic regions on a targeted protein.

The Chemical Sciences Division programs fund topics of national relevance that also are important to other funding agencies (e.g., for the development of catalysts, batteries, fuel cells, smart materials, and sensors). The potential overlap with other funding agencies is an advantage, because this enables ARO PMs to leverage large funding streams and to fund within those topic areas projects that have a unique niche for the Army. For example, the division provided funding for the following: to develop catalytic materials that could function in extreme environments unique to Army applications (large temperature swings or extremely dirty environments); and to evaluate unique methods for creating batteries and fuel cells with the potential to outperform other approaches but that would not be of interest to the consumer market owing to cost. The PMs were careful to evaluate potential projects based on the quality of the science and relevance to the interests of the Army. However, the Chemical Sciences Division might benefit from a more global perspective that could be provided by the formation of an external academic advisory group. There also was evidence of coordination with other DoD funding agencies to identify gaps in the combined research portfolios, to seek opportunities to work together to leverage funding streams, and to identify areas that specifically impact the Army versus other services for targeted investment.

The four program presentations outlined the collective efforts of researchers of significant stature working on an array of projects of varying degrees of risk. Acknowledging the importance of funding the leaders in their respective fields to push forward the Army's agenda, there is also need for identifying and funding the next generation of leaders in emerging fields where breakthroughs might also impact the future Army. In that regard, it would be beneficial to consider devoting a greater degree of funding to new investigators in the field (STIR or single investigator grants). It is also important to use mechanisms like conference grants and STIR grants to identify and encourage high-risk/high-payoff research.

Overall, innovative research is being supported by this division; however, the research conducted in several of the program areas would benefit greatly from a closer interaction between theory/simulation and experiment.

In general, the valuable fundamental research supported by the Chemical Sciences Division's programs has commendably enabled the discovery of science and development of new technologies for defense applications.

9

Life Sciences Division

The Life Sciences Division supports research efforts to advance the Army and nation's knowledge and understanding of the fundamental properties, principles, and processes governing deoxyribonucleic acid (DNA), ribonucleic acid (RNA), proteins, organelles, prokaryotes, and eukaryotes, as well as multispecies communities, biofilms, individual humans, and groups of humans. The interests of the Life Sciences Division are primarily in the following areas: biochemistry, neuroscience, microbiology, molecular biology, genetics, genomics, proteomics, epigenetics, systems biology, bioinformatics, and social science. The results of fundamental research supported by this division are expected to enable the creation of new technologies for optimizing warfighters' physical and cognitive performance capabilities, for protecting warfighters, and for creating new Army capabilities in the areas of biomaterials, energy, logistics, and intelligence.[1] The division's core budget of $9.2 million was leveraged against a $67.9 million investment by the Defense Advanced Research Projects Agency (DARPA) and other Department of Defense (DoD) programs and agencies in the life sciences domain. During fiscal year (FY) 2018, a total of 81 single investigator (SI) awards were funded along with nine Short-Term Innovative Research (STIR) awards focused on jump-starting high-risk projects. Five programs were reviewed: Biochemistry, Genetics, Microbiology, Neurophysiology and Cognition, and Social and Behavioral Sciences. The Army Research Office (ARO) Biomathematics and Biotronics programs are not part of the Physical Sciences Directorate (PSD) and were not reviewed.

In general, the division's metrics are strong, with 624 peer-reviewed publications in the FY 2016 to FY 2018 period, and funding for 401 graduate students and 227 postdoctoral researchers during the FY 2017 to FY 2018 period. There were 30 transitions reported for the 3-year period from FY 2016 to FY 2018, including the development of commercial products. The transition of fundamental life science research funded by ARO to applications developed in the Army Research Laboratory (ARL) intramural laboratories is another good indicator of the success of this program. However, the most impressive achievement was the 2018 Nobel Prize in Chemistry awarded to Dr. Frances H. Arnold of the California Institute of Technology for the directed evolution of enzymes. The ARO Microbiology Program funded the work that led to the 2018 Nobel Prize in Chemistry for Dr. Arnold and has contributed to highly significant scientific advances.

BIOCHEMISTRY PROGRAM

Overall Scientific Quality and Degree of Innovation

Moving biology outside the cellular environment is a promising direction for high-impact discoveries in biochemistry and biomaterials. Determining the structure and function of macromolecules so that we can modify them in useful ways will require an increased understanding of biological pathways,

[1] Army Research Laboratory, Army Research Office, https://www.arl.army.mil/www/default.cfm?page=217, accessed October 1, 2019.

molecular function, self-assembly, and biomimetic materials. This research area has long been recognized as a potentially useful area to explore for new discoveries. However, the field is still emerging, with much left to discover as new information and technologies become available. The program manager (PM) is focusing on interesting problems and to work with outstanding investigators. The portfolio of the Biochemistry Program encompasses a diverse and healthy range of early career and established investigators.

Use of advanced characterization methods such as cryo-electron microscopy enables the determination of structure at near-atomic resolution and provides new opportunities for rational design of materials and functional assembly of macromolecules. These methods have not been extensively explored thus far in synthetic biomaterials and will be an important method to achieve future growth.

The risk/reward level varies among the research presented. No Short-Term Innovative Research (STIR; proof-of-principle) projects are funded by this program. Such initiatives could help encourage investigation of riskier ideas at an early stage. While some excellent investigators are involved, the information presented is focused on basic research, and the degree to which the successful approaches could be transitioned into impactful devices could be more clearly delineated by the program manager. The Multidisciplinary University Research Initiatives (MURIs) in the Biochemistry Program address current high-visibility topics, but the intended value of these specific projects to the Army is not apparent. That said, none of the projects seem to duplicate other projects funded by the Department of Defense (DoD) and all include potentially valuable research initiatives.

Scientific Opportunity

The Biochemistry Program has three areas of focus and significant findings have been obtained in all three. Of the examples highlighted by the PMs, the integration of biomolecules and plastics into a high-strength composite is particularly innovative, with potential to lead to new high-strength, lightweight materials. The protein assembly project is elegant with a definitive proof-of-principle, but the small lumen size of the protein assemblies is a critical hurdle that will need to be addressed if this project is to result in the development of useful new materials. The program manager is thinking in this direction—research on functional bacterial nano- and micro-compartments is included among the proposals in the research portfolio. The project on structural analysis of multiprotein assemblies is impressive as well, especially if the proposed follow-up studies on computational design are accomplished. For each research thrust, a short description of what else is going on in that research space would have helped to assess the level of innovation of the projects being considered.

Significant Accomplishments

In terms of scientific accomplishments, all of the projects described have been successful. The most impressive results came from small complementary teams of two investigators, in which the individual areas of each are very effectively leveraged to yield the most innovative data. This was especially true of the Ellington/Glotzer and Ellis/Lee collaborations, which have already yielded impressive results. Ellington/Glotzer are applying understanding of shape, packing, and assembly of patchy nanoparticles to develop generalizable design principles for protein assembly via charge complementarity. Ellis/Lee are investigating interface synthetic biology and materials science to manipulate the microstructure of bacterial cellulose for reinforcement of lightweight transparent polymeric armor materials. In general, all of the projects presented are productive and demonstrate tangible results suitable for publication.

In order to document the assumption of appropriate risk, it would have been useful to know if there were some failures. Computational modeling relating function and structure is mentioned in several proposals, but it is not clear whether this is an emphasis of the program. Stronger interactions between groups doing biological research and those doing computation and modeling need to be encouraged.

Relevance and Transitions

Some of the results are very interesting from a basic science point of view. It would have been useful to have received further clarifications about the degree to which the work is unique in its field, and its potential for leading to new opportunities for the Army. The following important questions were not answered: Is the program manager thinking about how resultant materials or technologies perform under operational conditions? What are target metrics that are relevant to the program manager? What metrics for the system being studied are actually being measured now? If not already doing so, the program manager could help investigators think in terms of goals that will create new materials or biologically derived functions that will ultimately have high impact.

The program manager is transitioning the projects to the next phase in research and development (R&D) through collaborative research with the Army Research Laboratory (ARL) and through the Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs.

Additional Considerations

The planned expansion of initiatives in hybrid materials could be very rewarding. With regard to force-activated biochemical mechanisms, a stated goal is the translation of solution-based to non-solution-based materials, but none of the projects described seem to exhibit this focus. The implementation of the stated goal of transition to noncellular systems is also not exemplified in the data presented; all of the investigations focused on biological systems. The decision to decrease funding for mechanisms of biomolecular specificity is appropriate, because this area is funded by many other agencies in a wide variety of embodiments. The area that could use more emphasis is integration of the current programs with computational design methods and data science approaches.

Productivity of individual programs nearing completion could be measured in terms of patent applications and publications, but these data were not provided on a project-by-project basis. A list of possible next steps would be helpful to assess the potential impact of projects that PMs view as producing exciting results.

GENETICS PROGRAM

Overall Scientific Quality and Degree of Innovation

The projects presented appeared to be relevant to the Army, despite their very basic and highly diverse nature. Indeed, the projects were so diverse that it is questionable as to whether it is appropriate to consider some of the projects “genetics.” All of the projects presented were marked by their highly innovative nature, including a visionary (but ultimately unsuccessful) project that failed to reach its original objective but may yet produce new avenues to protect warfighter health in the field through simple dietary manipulation. Four projects were presented in detail. The research teams represented a good mix of seasoned star researchers and new investigators.

One project is focused on developing robust DNA barcoding capabilities to identify pollen in mixed samples in order to identify the origin of items of interest including, for example, surface residues on improvised explosive devices. Plant species grow in different niches and bloom at different times, surface samples typically contain pollen from multiple species, and species identification can reveal where the item came from, sometime narrowing the source down to tens of square miles but at other times pointing to a single building. Current state of the art is microscopic analysis, done by an expert forensic palynologist, which requires 2 weeks (and expert forensic palynologists are in short supply). DNA barcoding would enable real-time analysis and eliminate the need for the expert forensic palynologist. A new MURI will continue the development of robust DNA barcoding and will develop models to incorporate the effects of humans on plant distribution, in order to create a robust framework for interpreting pollen identification results. A potential missed opportunity here is to develop an alternative approach that would take advantage of automated imaging, machine learning, and image recognition algorithms to identify pollen grain types and numbers. This parallel approach could be encouraged through an SBIR or a single investigator (SI) grant mechanism to supplement the MURI.

A second innovative project described a program to develop a high-throughput system in *S. cerevisiae* to screen human polymorphisms in genes that encode enzymes whose activity is affected by the availability of vitamin or mineral cofactors. Polymorphisms in the 600 vitamin- or cofactor-dependent genes are widespread enough that a warfighter has an average of two functional polymorphisms in these 600 genes. Identifying the effects of these polymorphisms and the extent to which these defects in enzymatic activity can be ameliorated with supplementation of specific vitamins or minerals has the potential to significantly improve warfighter health and performance at an extremely low cost.

There is a substantial program of projects on mitochondrial genomic integrity and regulation with the eventual goal of extending warfighters' health, performance, and longevity in active service. The mitochondrial health project presented is a high-risk/high-payoff project that grew out of an initial observation that zebra fish and rodents can be put into a state of suspended animation, with no heartbeat or brain activity, by exposure to hydrogen sulfide, and that these organisms can be brought back to life after several hours of exposure and suffer no detectable adverse effects. The effect on animals that have been injured resembles that which can be brought about by cooling the body—namely, a marked extension of the time window available for treating wounds. Research was done subsequently to explore the possibility of using hydrogen sulfide to induce suspended animation in warfighters who are critically wounded and expected to die before they can be transported to medical care; however, human trials indicated that the therapeutic index is too narrow for safe use, and this Defense Advanced Research Projects Agency (DARPA)- and ARO-funded initiative was abandoned. There are now indications that iodide ion can reduce the impact of traumatic injuries including stroke, heart attack, and hemorrhagic shock. This particular project is novel, but a priori there is no obvious reason to think that iodide will turn out to be useful in this context. The most compelling evidence that it might be resulted from studies of the dependence of the sizes of infarcts caused by ischemia on iodide levels. While something good may come of the current version of this initiative, it is still early.

The giant African pouched rats ("pouchies"), which are actually giant hamsters, have been used to detect buried land mines in Africa. The objective of this ARO-funded research is to establish a colony in the United States, to investigate reproduction and learning, and to determine whether pouchie psychology can be exploited to automate training. These animals are now established at Cornell University and breeding, and results to date have demonstrated that their reproduction is regulated at the colony level, unlike almost all other mammals. There is good reason to think that the pouchies may prove to be at least as good as dogs for this purpose, with additional benefits coming from their smaller size and from the likelihood of reduced emotional repercussions for their handlers when they are killed, compared to dogs. The level of innovation is high, and the program is unique. How well these animals perform, how to breed them, and ways of training them that are fast and cheap are being addressed. Prior African experience indicates that automation will be feasible.

Scientific Opportunity

The Genetics Division is large and has a broad portfolio within the Life Sciences Directorate. The scientific objectives were clearly articulated and mapped onto the research portfolio in a clear-cut manner.

Significant Accomplishments

The “pouchie” project was seen as particularly significant for the Army. It was also noteworthy for its potential to win over civilian populations affected by land mines in their homeland. ARO has a substantial portfolio of publications and trainees supported, as well as PI awards and honors in this program.

Relevance and Transitions

Successful transitions of multiple diverse projects to DARPA, the State Department, the Army Medical Command, the Army Soldier Center, Defence Science and Technology Laboratory (U.K.), the Defense Forensic Science Center, intramural research at the Army Research Laboratory, and other agencies have been accomplished. Some examples of these include ARO-funded research leading to characterization of metabolic mechanisms and new therapeutics to potentially extend the time for treatment after severe blood loss and other trauma. With external funding, the safety of this therapeutic has now been established in human clinical trials, and human clinical trials to validate the efficacy are under way. Also, ARO-funded research led to the first successful breeding pairs of pouchies in captivity at Cornell University.

MICROBIOLOGY PROGRAM

Overall Scientific Quality and Degree of Innovation

The goal of the Microbiology Program is to identify and understand the fundamental principles governing microbial communities and their eukaryotic interactions, with the eventual goal of exploiting microbiome capabilities for biomanufacturing and for enhanced warfighter performance and protection. The program focuses on three general topics—two associated with analysis and understanding of bacterial communities and one focused on metabolic programming under environmental stress. Not discussed in the presentation but highlighted in the *ARO in Review 2018* report[2] are studies on the human microbiome and its effects on health and cognition, as part of the Tri-Service Microbiome consortium—this focus is clearly relevant to warfighter health and performance. ARO’s complementary initiatives that develop insights into how the microbiome can enhance warfighter performance is well justified. Understanding and dissecting bacterial communities is directly relevant to the microbiome effort, and the approach to accomplishing this is still a challenge. A subset of the currently supported projects was discussed in substantial detail.

Four projects were presented in some depth: two SI projects to study the role of phenazines in pseudomonas biofilms and to study RNAs within *B. subtilis* spores; one STIR project to investigate how two different *Clostridia* share metabolic capabilities; and one Young Investigator Program (YIP) project to develop the use of microfluidics to look at interactions within complex communities. The scientific quality of all of these projects was high. Innovation was particularly high for the STIR project, following up on a provocative set of initial observations with supportive experiments. This project has the potential to result in the discovery of unexpected new biology that has significant implications for understanding how bacteria function within complex communities, and how microbes may deliver useful products. In addition, this work on anaerobes emphasized the continuing need for appropriate reporters for anaerobic cell biology. The microfluidics project to develop and study bacterial communities using state-of-the-art approaches may yield significant results in the future, but it is currently focused on developing a new type of platform for which funding is very hard to find from other sources. Progress thus far is promising, and

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[2] Army Research Laboratory, Army Research Office, https://www.arl.army.mil/www/pages/172/docs/AROinReview2018-online.pdf, accessed October 3, 2019.

the opportunity to support a very promising early-career investigator is particularly attractive. The project to study RNAs within *B. subtilis* spores has resulted in the discovery of a subset of mRNAs within spores that may not be serving as messages, but instead as a source of nucleotides for supporting the metabolic activity of the spores when they germinate. However, this remains to be proven, and it was not made clear how this finding underpins the proposed development of spores as environmental sensors. Similarly, while the observation that phenazines appear to stimulate cell death in a subset of pseudomonas cells when energy is limiting is of interest, the implications, other than that biofilm dynamics are complicated, were less clear.

Scientific Opportunity

The current set of projects seem likely to provide some new insight to the objectives, but given the breadth of lifestyles of different microorganisms, the range of relevant environments, and the general nature of the stated objectives, it is unlikely that these objectives will be fully achieved in the near future. The projects focused on development of robust means of biomanufacturing are primarily among the SBIR and STTR projects, and the level of innovation is not clear. Nonetheless, some projects are addressing basic needs for analyzing complex communities.

Significant Accomplishments

The more mature of the projects presented have led to advances that are generally significant. The work that has been supported has been productive and reflects ingenuity and development of useful new approaches in some cases. The project to investigate how two different *Clostridia* share metabolic capabilities and the microfluidics project were at an earlier stage, and at this point, its accomplishments are provocative and promising. It is difficult to evaluate the overall quality of the entire set of projects being supported because all projects were not presented to the panel. Suffice it to say that this program funded the work that led to the 2018 Nobel Prize in Chemistry for Dr. Frances Arnold and has contributed to highly significant scientific advances.

Relevance and Transitions

Reasonable and useful transitions have occurred for a significant number of projects, including projects on microbiome characterization or manipulation and rapid detection of microbial pathogens, especially in water supplies.

Additional Considerations

The study of bacterial communities is an important but challenging general aim—with one approach requiring ways to remove specific members of a community to understand their role. Bacteriophages and clustered regularly interspaced short palindromic repeats (CRISPR) might be tools to consider in this context, and in any case, in the long run, phages are undoubtedly important components of natural communities and therefore could eventually be included in thinking about how these communities operate and respond to changing conditions.

NEUROPHYSIOLOGY AND COGNITION PROGRAM

Overall Scientific Quality and Degree of Innovation

This program aims to measure and model the neurophysiological underpinnings of perception, sensorimotor integration, and behavior in order to support the development of interfaces that promote cognitive control and rapid decision making. The scientific objectives are (1) to measure and model the structural and functional neural underpinnings of multisensory synthesis and information processing; (2) to determine how brains structure, process, and refine biological neural networks to generate efficient decisions and behaviors; and (3) to determine the neurobiological mechanisms mediating vulnerability of the brain to injury. Pursuit of these goals could result in findings of high significance. Human-machine teaming, augmenting human sensory and cognitive processes, optimizing learning, and adaptive decoding of sensor information were each identified as endpoints—each with unique questions to be answered. The program has been quite successful in coordinating funding through collaborative mechanisms and has focused funding so as to avoid redundancy with other agencies and programs, including intramural programs in the ARL. The program has also been active in coordinating with overseas research endeavors.

Scientific Opportunity

The Neurophysiology and Cognition Program has funded innovative approaches, including important collaborative multidisciplinary MURI grants. The specific MURI projects highlighted were (1) developing closed-loop adaptive algorithms and models of multisensory neural activity to maximize brain-computer interface information transfer rate and enhance decision accuracy; and (2) imaging all the synapses of a cortical interneuron. Two other projects highlighted were (1) developing and validating a method to accurately predict transcranial stimulation-induced current flow in the brain and measure interactions with neural activity and plasticity; and (2) elucidating neural mechanisms that underlie camouflage-breaking. Featured research projects included work using multimodal sensing data (spikes, implanted electrical measurements, heart rate, skin conductance, or possibly functional magnetic resonance imaging [fMRI]) to model the mental state of the animal or human to develop systems that predict, and possibly control or modify, behavior. The current portfolio collects data from animals and humans, with the former seeming to be a point of particular emphasis. Animal studies indeed provide a key scientific opportunity for informing the development of human models. That said, to adaptively integrate human function in the context of more complex multiscale modeled systems suggests the importance of incorporating more research focused on human neurocognitive systems in the portfolio.

Significant Accomplishments

The scientific quality both in larger scale MURI projects and in single investigator projects presented is very strong. The quality of the scientists who are being funded, and of the science being produced are both excellent. Several projects are usefully integrating neurophysiological research with mathematical or machine learning techniques to generate cutting-edge approaches to fundamental problems. The productivity of the grant portfolio was strong and of high quality.

Relevance and Transitions

The relevance of the work for the Army was clear with respect to the development of novel methods to support optimized performance in human-machine teams and to understand integrated brain-body dynamics that drive neural processes for performance enhancement and resilience—for example, sleep deprivation, resilience to post-traumatic stress, and the promotion of superior learning rates. The connections between several featured projects focused on cellular or subcellular data and their potential applications were somewhat less clear. However, they may reflect high-risk, longer term investments. There have been a significant number of transitions of research products or successor projects to ARL and other defense agencies or programs, including a transition of brain-computer interface algorithms, development environments, and neural network models. Co-publications or collaborations with ARL scientists and spin-offs of technology to several companies have also occurred. Several previously supported projects had received substantial funding from the Brain Research Through Advancing Innovative Neurotechnologies (BRAIN) Initiative of the National Institutes of Health (NIH), DARPA, and other large funding sources.

Additional Considerations

Several important lines of research involving human-agent teams, human-systems integration issues, human-based sensor interpretation, and other research related to the overarching goals of the program seem to be located elsewhere within the ARL structure, as described briefly in the broader documentation. The connections between these programs could be made more apparent. These areas collectively are relevant, and potentially may have a large payoff. The extent to which these other elements incorporate aspects of human-systems integration was not addressed, but symbiotic relationships between the cognitive neuroscience program and more targeted programs might yield benefits.

SOCIAL AND BEHAVIORAL SCIENCES PROGRAM

Overall Scientific Quality and Degree of Innovation

The vision of the Social and Behavioral Sciences Program is to identify and characterize micro-to-macro links tying human characteristics to population dynamics embedded within natural and physical systems to improve detection of emerging social dynamics and security risks in multidomain operations. The program has three strategic objectives: (1) to identify measurement methods that will detect shifts in collective human behavior; (2) to generate predictive models of population behavior; and (3) to model interactions among social, natural, and physical systems with the goal of identifying the complex interdependencies that causally underlie sociopolitical risks. These goals blend well, enabling the program to identify, explain, and predict important sociological, political, and economic outcomes in global contexts. In a relatively short period of time, the program manager has assembled an impressive array of projects that appear to lie on the cutting edge of social science. Examples of these projects highlighted included (1) developing objective measures of individual propensities for aggression and establishing pathways from individual to collective violence; (2) determining the relationships between vocal accommodation in the nonverbal band (below 300 Hz) and influencing dynamics through shifts in the nonverbal band; (3) predicting relationships among group structure, risk, and payoffs in non-kin groups; and (4) investigating interdependencies among environment, infrastructure, and conflict.

Scientific Opportunity

The potential for current projects to succeed is very high. If the projects presented are representative of the full portfolio, there is scope to increase the program's reach into more risky projects. At present, the focus seems to be on methodological development using existing data sets. There is certainly much to learn here, but there is also room to engage with less certain projects (e.g., projects that rely on the compilation of new data sets or that foster access with new or understudied populations) without exposure to unacceptable levels of risk. Therefore, the program manager's plans to increase funding for projects that seek to acquire new data regarding the factors affecting the dissemination of knowledge and to decrease funding for projects related to data archives are appropriate.

Relative to peer programs in the division, the program manager seems to rely more heavily on single investigator grants. The relationship between this program and the Minerva Research Initiative is likely very important, although the degree to which these mechanisms of funding are symbiotic is unclear. The Minerva Research Initiative is a DoD social science grant program that funds unclassified basic research relevant to national security. Opportunities for a MURI could be a point of focus; this is an underutilized source of funding within the program, particularly given its rather distinct goals when compared to the other four programs in the division.

Significant Accomplishments

Within the review period FY 2016 to FY 2018, the program has generated a respectable number of peer-reviewed publications (59) and supported a commendable number of graduate students (115 per year) and postdoctoral researchers (11 per year). The reviewed projects mesh well with the program's stated goals and display a high degree of scientific rigor.

Relevance and Transitions

The potential long-term applications of the Social and Behavioral Sciences Program's projects are readily apparent, with the ability to predict social unrest and to understand influence networks being particularly important. Current transitions consists of briefings of results and predictive models of human errors, human behavior, and sociopolitical dynamics delivered to and used by the U.S. Navy Third Fleet Command, the National Security Administration, the 98th Civil Affairs Battalion, NASA, U.S. Army Special Operations Command, U.S. Joint Staff/J9, Headquarters of the Department of the Army/Institute for Business and Defense, U.S. Central Command, and intramural ARL scientists as well as several workshops and seminars within the DoD and other government agencies. It is encouraging to see that data archiving and the reporting of conclusions to Army commands are occurring.

OVERALL ASSESSMENT

The results of fundamental research supported by this division are expected to enable the creation of new technologies for optimizing warfighters' physical and cognitive performance capabilities, for protecting warfighters, and for creating new Army capabilities in the areas of biomaterials, energy, logistics, and intelligence.[3] Five programs were reviewed: Biochemistry, Genetics, Microbiology, Neurophysiology and Cognition, and Social and Behavioral Sciences.

It is somewhat surprising that the Life Sciences Division is a component of the physical sciences focus area of the ARO. It has an extraordinarily broad range of subjects, which in academia would be housed in quite separate departments. The cross talk that occurs between the disparate projects supported by this division is proving to be extremely useful. However, because the number of people in the division is small, and the amount of money they command is miniscule compared to that available to agencies like NIH, the programs it supports cannot encompass by any means the full range of subjects that might be

[3] Army Research Laboratory, Army Research Office, https://www.arl.army.mil/www/default.cfm?page=217, accessed October 1, 2019.

relevant to the Army, and it needs to take advantage of all the leverage it can from other DoD agencies, in particular DARPA, to get the projects done that it has elected to support.

The overall quality of the five programs was judged to be very high, with strong and innovative projects in all of the programs. The emphasis is on basic research, although there was an impressive record of transitions of successful projects to customers. Many, but by no means all, projects were deemed to be high risk and high reward and would probably be too risky for funding from more conventional federal agencies. The panel could usually see a clear connection to future Army needs in the projects chosen.

The Life Sciences Division has a well-balanced portfolio that includes support of new investigators, who may be at particularly creative and innovative stages of their careers, as well as new directions for established investigators, through single investigator (SI), Short-Term Innovative Research (STIR), and Young Investigator Program (YIP) funding. The emphasis is thus on important ideas that do not have enough data to support proposals to conventional funding organizations. Here, the division could have a very positive impact on innovation, and this emphasis, which is already evident, needs to be encouraged. In several cases, the PMs funded pairs of principal investigators (not necessarily at the same institution) to work together on a single SI grant. This mechanism for crossing disciplinary boundaries to accomplish innovative studies has produced outstanding results. The division needs to continue to facilitate partnerships between pairs of investigators with orthogonal expertise through appropriate grant mechanisms.

10

Crosscutting Recommendations

This chapter discusses crosscutting recommendations that apply across two or more Physical Sciences Directorate (PSD) divisions.

Advances in the fields covered by PSD increasingly rely on contributions made by scientists who have different areas of expertise. For example, in chemistry, combined efforts in modeling and experiment are often essential for significant advances. Similarly, progress in condensed matter physics often depends on collaborations between individuals skilled in materials synthesis and scientists pursuing new phenomena. In addition, all the physical sciences are increasingly relying on data analytics. PSD currently has some selected examples where funding of pairs of researchers from different disciplines, working synergistically, has led to significant success. Priority could go to those who have a demonstrated history of successful collaborations. PMs could set priorities in terms of desired outcome and let researchers get together to make proposals.

PSD Crosscutting Recommendation 1: The Physical Sciences Directorate (PSD) should encourage the funding of pairs of principal investigators (PIs) from different disciplines who will work together on common problems, including those that are interdivisional and interdirectorate. For the Physics Division, the Army Research Office (ARO) should consider collaborative projects that involve both materials synthesis and condensed matter physics, as well as joint quantum information algorithms and information sciences projects, which would all be interdirectorate. For the Chemical Sciences Division, ARO should consider funding of pairs of PIs who will work together on modeling and experiment, which are both within the division. For the Life Sciences Division, ARO should consider mechanisms to allow data analytics to inform their explanatory models, which is also interdirectorate.

Many advances in science now occur at the boundaries between traditional disciplines, and consequently, multidisciplinary research has become increasingly important. This stretches the limits of traditional disciplines such as those found, for example, in university departments. The projects supported by the Life Sciences Division of PSD encompass five disciplines in the biological and social sciences. The division is already multidisciplinary, even if not as much as it could be. By contrast, the Physics and Chemical Sciences Divisions are organized along more traditional disciplinary lines, and they seem to be having more difficulty broadening the boundaries of their disciplines, where the research being done crossed over into areas that they have not supported in the past. That kind of focus can miss many important new research developments.

PSD Crosscutting Recommendation 2: The Physical Sciences Directorate (PSD) should explore mechanisms to identify and support research in areas that do not fall solely within its core disciplines, including those that rely on contributions from research areas that are not funded within these core disciplines at all.

The program managers (PMs) within PSD currently do a good job of going to conferences and staying abreast of the exciting new work within their fields. They also do well in advertising their programs and interests to their own communities at such conferences. However, this highly targeted approach to publicizing the activities of ARO means that many members of the broader scientific community are unaware that ARO is a potential source of funding. That means that ARO is not seeing all the proposals from new principal investigators (PIs) with different perspectives that it might. This limitation is of particular importance when it comes to attracting researchers in biology and other life science disciplines because a life scientist is very unlikely to think that an organization called Physical Sciences Directorate would be interested in what he or she does.

PSD Crosscutting Recommendation 3: The Physical Sciences Directorate (PSD) should find ways to further disseminate its funding opportunities to the broader community. In particular, the PSD should find ways to reach the broader biology and life sciences community, which is unlikely to be recognized as an opportunity given its Physical Sciences name.

A major success of several PSD programs has been their funding of very early career investigators, for whom ARO funding has been their first, and for a period of time, their only source of funding. This kind of support can help launch careers. Also, graduate student and postdoctoral researcher training and integration into the research efforts at universities through ARO grants and contracts are essential both for ongoing research as well as for the workforce pipeline. Similarly, PSD funding can be particularly valuable for more established researchers who want to pursue new directions. In addition, funding often goes to well-established groups, where the ARO funding can be leveraged by large amounts of funding from other sources. This leverages the relatively small support from the ARO, enabling the PMs to focus on that research specifically related to Army needs. ARO benefits because even modest ARO funds can leverage the results of much larger programs. However, there is also merit in funding new PIs doing different work, because this is also a good source of potential new research topics. Funding from PSD is particularly suitable for each of these groups of investigators because of the willingness of ARO to fund research that is not funded by other agencies, and because of the use of white papers as the initial stage of a proposal that makes the proposal selection process more efficient.

Also, the PSD research budget is small, and thus it cannot compete with other larger funding agencies. However, the strength of the PSD programs is the active interaction among the PMs to identify new areas for funding early, before they are generally recognized, and to act in concert with other Department of Defense (DoD) programs. Thus, there is an internal tension between the structure of the program into defined areas and efforts to find new areas. A PM who feels an obligation to continue funding in a defined area may be less willing to “give up” some of this funding to establish a new area. The Army Research Office (ARO) needs to examine what can be done to make the formal organization of its programs less rigid and to prioritize new areas of opportunities with the highest potential leverage.

Because the PSD research budget is small and thus it cannot compete with other larger funding agencies, PSD could take advantage of facilities built, managed, and operated by other agencies such as x-ray, laser, and neutron sources, as well as genomic facilities (i.e., Department of Commerce, DOE, and NIH). These facilities complement what can be provided by DoD laboratories and are necessary for advancing many of the science goals that are articulated for PSD.

Part III: Engineering Sciences Directorate

11

Introduction

At the request of the U.S. Army, the National Academies of Sciences, Engineering, and Medicine formed the Panel on Engineering Sciences at the Army Research Office, which met virtually on August 3-5, 2020, to review the programs of the Engineering Sciences Directorate (ESD) of the Army Research Office (ARO), which is an organizational unit within the Combat Capabilities Development Command (CCDC) Army Research Laboratory (ARL) of the U.S. Army Futures Command (AFC).

The panel's review was guided by the following statement of task provided by the National Academies:

> An ad hoc committee to be named the Panel on Engineering Sciences at the Army Research Office, to be overseen by the Army Research Laboratory Technical Assessment Board (ARLTAB) and its parent Laboratory Assessments Board (LAB) of the Division on Engineering and Physical Sciences, will be appointed to provide triennial assessments of the Army Research Office (ARO) programs. Each year one of the ARO's three divisions (Information Sciences, Physical Sciences, and Engineering Sciences) will be assessed by a separately appointed panel. These assessments will address criteria to be defined by the ARO. Each year the panel will provide a report summarizing its findings, conclusions, and recommendations. At the end of each third year, the three annual ARO assessment reports will be combined into a triennial report. The panel's report will be made available to the public on the National Academies Press website and will be disseminated in accordance with National Academies policies.

This part of the report summarizes the 2020 findings of the Panel on Engineering Sciences at the Army Research Office, which reviewed the programs at the ARO's ESD. This is the first time that the National Academies is reviewing ARO's ESD programs in electronics, materials science, and mechanical sciences. In 2019, the National Academies conducted a review of the ARO's Physical Sciences Directorate's programs in physics, chemical sciences, and life sciences. In 2018, the National Academies conducted a review of the ARO's Information Sciences Directorate's programs in computing sciences, network sciences, and mathematical sciences.

PROGRAMS WITHIN THE ENGINEERING SCIENCES DIRECTORATE

The Army Research Laboratory's ARO describes its mission as follows:[1]

> The mission of ARO, as part of the U.S. Army Futures Command (AFC)—U.S. Army Combat Capabilities Development Command (CCDC)—Army Research Laboratory (ARL), is to execute the Army's extramural basic research program in the following scientific disciplines: chemical sciences, computing sciences, electronics, life sciences, materials science, mathematical sciences, mechanical sciences, network sciences, and physics.

[1] *2019 ARO in Review*, U.S. Army, Combat Capabilities Development Command (CCDC)—Army Research Laboratory, Army Research Office (ARO), Research Triangle Park, North Carolina.

> The goal of this basic research is to drive scientific discoveries that will provide the Army with significant advances in operational capabilities through high-risk, high pay-off research opportunities, primarily with universities, but also with large and small businesses. ARO ensures that this research supports and drives the realization of future research relevant to all of the Army Functional Concepts, the ARL Core Technical Competencies, and the ARL Essential Research Programs (ERPs). The results of these efforts are transitioned to the Army research and development community, industry, or academia for the pursuit of long-term technological advances for the Army.[2]

The Engineering Sciences Directorate (ESD) is focused on basic research to harness high-risk discoveries in electronics, materials science, mechanical sciences, and earth sciences. In the long term, fundamental discoveries in these areas are expected to initiate unprecedented and disruptive capabilities in protection, mobility, sensing, computing, propulsion, networks, manufacturing and sustainment to ensure the future technological superiority of our warfighters and Army.[3] ESD's programs are organized into three divisions: Electronics (fiscal year [FY] 2019 funding of $32.3 million), Materials Science (FY 2019 funding of $32.2 million), and Mechanical Sciences (FY 2019 funding of about $21.9 million).

In general, ESD's metrics are strong, with 2,038 peer-reviewed publications in the FY 2017 to FY 2019 period, and funding for 781 graduate students per year and 326 postdoctoral researchers per year during the FY 2017 to FY 2019 period. There were 133 transitions reported for the 3-year period from FY 2017 to FY 2019. The transition of fundamental physical science research funded by ARO to applications developed in the ARL intramural laboratories is another good indicator of the success of ESD.

APPROACH TO THE ASSESSMENT

The panel consisted of 21 leading scientists and engineers whose expertise matched the programs at the ARO's ESD that were reviewed. All panel members were volunteers who participated without compensation. The panel members' independence is ensured by the National Academies, using its rigorous vetting and approval process for appointment to its panels. The entire panel attended overview presentations by, and held discussions with, the directors of ARL, ARO, and ESD. The panel members then divided into three teams that separately attended presentations by and discussions with program managers (PMs) in the three ESD divisions (Electronics, Materials Science, and Mechanical Sciences). The presentations and discussions occurred over a 2-day period. On the third day of the meeting, the panel assembled to share findings from the team reviews, develop impressions common across the team reviews, and prepare the panel's report draft. On the afternoon of the third day, the panel met with ARO staff for wrap-up discussions to seek clarification of factual and contextual understandings.

The panel members prepared written summaries of their findings, conclusions, and recommendations, which were iteratively reviewed by the panel and formed the basis for the draft report that was subsequently developed under the guidance of the National Academies Army Research Laboratory Technical Assessment Board (ARLTAB), which focused particularly on the panel's approach to the review and the report's recommendations. ARLTAB consists of the chairs of the panels that review the scientific and technical work of all ARL directorates, including those at ARO.

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[2] Basic research is defined by the Department of Defense (DoD) as "systematic study directed toward greater knowledge or understanding of the fundamental aspects of phenomena and of observable facts without specific applications toward processes or products in mind," while applied research "is a systematic expansion and application of knowledge to develop useful materials, devices, and systems or methods" (DoD 7000.14-R Volume 2B, Chapter 5, 2017). Basic research drives directed studies toward revolutionary discoveries that will lead (and have led) to groundbreaking new capabilities for the Army in the time frame of 30 years and beyond, whereas applied research focuses on the near-term realization of new or improved technologies to meet a specific need.

[3] Army Research Laboratory, Army Research Office, https://www.arl.army.mil/who-we-are/aro/army-research-office-directorates/, accessed October 3, 2020.

After the panel addressed the comments offered by ARLTAB, the report was edited by professional editors at the National Academies and submitted to the National Academies Report Review Committee (RRC). The RRC appointed a team of reviewers to examine the report, considering such factors as the scope of the panel's task, the reasonableness of the panel's recommendations, and the clarity of the panel's expression. Once the RRC reviewers' comments were adequately addressed, the report was submitted to the Army for security review. After the report cleared the security review, it was publicly posted on the National Academies Press website (www.nap.edu).

The panel applied a largely qualitative rather than quantitative approach to the assessment. The approach of the panel relied on the experience, technical knowledge, and expertise of its members, whose backgrounds were carefully matched to the core technical competency areas in which ARL and ARO activities are conducted. The panel reviewed selected examples of the scientific and technological research programs at the ARO's ESD because it was not possible to review all ESD programs and projects exhaustively in the time allotted. ARO selected the programs and projects as representative examples in its portfolio that were presented for review. Given the necessarily nonexhaustive nature of the review process, the omission of mention of any particular program or project should not be interpreted as a negative reflection on that program or project. Similarly, recommendations for some programs but none for others should not be read to imply that those programs are of lower quality or have more operational challenges than the other programs. Thus, some of the report chapters of the ESD divisions may have recommendations but not others.

The panel's goal was to provide an overall impression of the ARO programs in engineering sciences while preserving useful mention of suggestions specific to programs that the panel considered to be of special note within the set of those examined. Therefore, the panel strove to identify and report salient examples that supported discussion of accomplishments and opportunities for further improvement with respect to the ESD's programs.

ASSESSMENT CRITERIA

The panel was charged to apply the following criteria during the review:

1. *Overall scientific quality and degree of innovation*: What are the most effective aspects of each program manager's planned strategy to make substantial and unique progress in advancing scientific frontiers? How could each program manager's strategy be further enhanced? How effectively is each program manager executing his or her strategy? What are the most significant high-payoff scientific discoveries described?
2. *Scientific opportunity*: What are the most compelling opportunities (e.g., incipient breakthrough, new understanding, novel theory, etc.) for future novel high-payoff scientific discoveries? How are unique interdisciplinary opportunities being identified and supported? How agile is the program? What other areas or breakthroughs should the program manager should be monitoring? Are there other partnerships that could help expand the program manager's network?

Additional possible assessment criteria include the following:

1. *Significant accomplishments*: How do the program accomplishments represent significant scientific advances? How did the program manager play a significant role? How has the program manager led or guided the scientific community? What is the level of productivity and ingenuity of the performers?
2. *Partnerships and transitions*: How well is the program manager leveraging coordination, collaborations, and partnerships with ARL in-house research, the Army, and the Federal Research Enterprise? What were the most significant examples of transitions, or anticipated transitions, of funded research?

3. *Level of effort*: How effectively is the program manager utilizing the available programs and funding sources to make significant progress toward his or her strategy?
4. *Other*: What were the particular strengths in the program and what were the weaknesses, if any? If there were notable weaknesses, what would be some suggestions for improvements in these areas? Specifically, are there any high-priority missed opportunities/areas that require new or additional funding? If so, what lower priority area(s) should be reduced or eliminated to accommodate the new area? Also, are there any efforts that are insufficient for any reason (e.g., marginal scientific quality, marginal degree of innovation, redundancy, insufficient partnerships, subcritical funding, etc.) and should be phased out?

Specifically excluded from the assessment criteria are the relevance to, and impact of, the scientific and technical work with respect to Army missions.

Also, the panel was instructed that the following items are outside the scope of the panel's charge and that these items should not be considered in the assessment:

1. Other divisions or offices within ARO and ARL: The panel is charged in 2020 only to assess the Engineering Sciences Directorate of ARO.
2. Organizational changes: The ARO organizational structure is not subject to the assessment.
3. Employee morale or motivation: The assessment panel does not conduct scientific surveys nor analyze the data required to assess morale, and is not asked to do so.
4. Funding: The panel is not asked to assess or recommend the amount or sources of ARO funding.

PART III CONTENT

This chapter discusses the process used to conduct the assessment and report the resulting findings, conclusions, and recommendations. Part III Chapters 12 through 14 provide assessments of the programs within each of the ESD divisions (Electronics, Materials Science, and Mechanical Sciences). Chapter 15 presents findings common across two or more of the divisions.

12

Electronics Division

The goal of the Electronics Division is to strategically drive new capabilities through discovery and enhancement of electronic and photonic phenomena and functions in entities ranging from inorganic materials and devices to single living cells that result in visionary performance characteristics that enable the U.S. Army to maintain technological overmatch across the Army functional concepts. The division's aim is to discover and enhance electronic and photonic interactions and functions in new devices and a broad range of materials. Some of the outstanding achievements encompass inorganic materials such as intercalated graphite for inductors; low-energy, high-speed optoelectronics; and optical control of ion transport in single living cells. Division-level strategy emphasizes interdisciplinary interactions between physics, chemistry, materials science, and biology. The overarching aim is to achieve device and system performance characteristics that enable the U.S. Army to maintain technological superiority vis-à-vis adversaries.

The division is organized into four programs: Biotronics, Electronic Sensing, Optoelectronics, and Solid-State Electronics and Electromagnetics. The division's total budget was $32.3 million for fiscal year (FY) 2019. The division funds a mix of single investigator (SI) projects—about $143,000 per project per year—and larger Multidisciplinary University Research Initiative (MURI) projects. The division also funds and manages Small Business Innovation Research (SBIR)/Small Business Technology Transfer (STTR); Presidential Early Career Awards for Scientists and Engineers (PECASE); Defense University Research Instrumentation Program (DURIP); and so on. During FY 2019, 75 SI awards were funded and 94 were active, along with several Short-Term Innovative Research (STIR) awards focused on jump-starting high-risk projects.

BIOTRONICS PROGRAM

The vision of the Biotronics Program is to exploit the unique capabilities of electronic systems to unravel the intracellular electronic and bioelectric processes among or between organelles within the living cell and its immediate surroundings, not amenable to traditional cellular sensing approaches. The program includes nontraditional acoustic, vibrational, mechanical, and phonon approaches as well. This program's research strategy is to address the following two key scientific questions: (1) How can the unique new capabilities of electronics, optoelectronics, and mechanics be used to stimulate a signature from a single cell providing information about its internal biological processes and to modulate and control the intracellular processes? (2) How can the unique capability of electronic instrumentation be used to observe and interpret the electrical, mechanical, electronic, and optoelectronic signatures of intracellular biological processes?

Overall Scientific Quality and Degree of Innovation

Over the FY 2017 to FY 2019 review period, the Biotronics Program has focused on two key scientific questions, stated above. In an effort to address the first question, results were presented from a project funded at the University of Chicago on "Coaxial Silicon Nanowires for Photoelectrochemical Modulation of Cardiomyocytes." Currently in its third year, the PI has successfully developed a method to optically modulate cardiac beating frequency, at the subcellular level, of both cultured cardiomyocytes and adult rat hearts. This project developed a polymer elastomer-silicon nanowire composite where the Si nanowires have *p*-*i*-*n* dopant modulation that produces a photoelectrochemical effect. Upon laser scanning, a massive number of optical inputs are produced at biointerfaces that can be used to modulate cardiac beating frequency. The project creates exciting opportunities to develop less bulky and invasive alternatives to devices such as today's pacemakers. The results were disseminated in a 2019 peer-reviewed publication in the *Proceedings of the National Academy of Sciences*.

Related to the second question, three projects at Northwestern were presented. All three are in their first year of funding and broadly relate to neuroscience. One aims to develop three-dimensional (3D) microscale electronic frameworks to monitor neural activity and neurological biomarkers for studies of human 3D brain tissue cultures. The availability of microfabricated soft and compliant 3D frameworks will provide a versatile platform that will expand the scope of electrophysiological and biochemical studies of the brain. Another effort aims to study processes of neuromodulation using human brain organoids. These studies could provide for the scientific foundation leading to effective cures for impaired warfighters. A third study will develop customized 3D frameworks for human brain assembloids. These will serve as a foundation to study neurodevelopmental diseases and processes of neuroregeneration, leading to new therapies and rehabilitation protocols.

Scientific Opportunity

Scientific opportunities for the Biotronics Program are significant. The program is small (FY 2019 total budget of $2.32 million); however, the targeted approach to use electronics—materials, processes, and measurements—to probe, record, and change the internal functionality of biological entities appears distinct from much larger programs funded by the National Institutes of Health (NIH) and other agencies. The differentiator offered by the Biotronics Program provides opportunities for interactions with other agency-funded initiatives. For instance, materials, devices, and imaging techniques developed in this ARO program could lead into beneficial collaborations with the biophysics groups that play a dominant role in the brain initiative program of NIH.

The envisioned evolution of today's Biotronics Program into Bionic Electronics by 2030 appears transformative. In the long term, the articulated strategy will lead to integrated bionic electronics modules capable of performing complex tasks.

Significant Accomplishments

Over the current review period, Biotronics Program funding has led to 47 peer-reviewed publications in high-impact journals. On average, the program has provided funding for 18 graduate students and 6 postdoctoral researchers per year during the FY 2017 to FY 2019 period. Several Biotronics Program PIs are the recipients of significant awards. For instance, Daniel Sievenpiper is the 2019 recipient of the IEEE AP-S John D. Kraus Antenna Award; Bozhi Tian was named as Chemical Society Review's 2020 Emerging Investigator; and John Rogers was elected to the National Academy of Medicine and was the recipient of the Benjamin Franklin Medal for Materials Engineering, among others.

Partnerships and Transitions

While the Biotronics Program is new—established in 2017 out of the 2014-2017 Bioelectronics Program—projects funded by the program are already being transitioned to the commercial sector or leading to partnerships with other organizations. Notably, research on developing new assembloids from three cortical spheroids has led to a collaborative research project to study reduced brain preparations with ARL Weapons and Materials Research Directorate. Research that led to the development of a device able to capture 512 × 512 pixel images—QC Labscope—is an accomplishment of interest to Lumedica. This project was selected for the third-place prize of $250,000 at the Luminate incubator competition in Rochester, New York. More recently, research funded at the University of California, Irvine, on developing a method to identify anit-SARS-COV-2 antibodies could form the basis for an aptamer sensing method. The customer, U.S. Army Medical Research and Development Command, is interested in the approach for evaluation as a point-of-care test.

Level of Effort

The program is small—with a FY 2019 total budget of $2.32 million. However, the Biotronics Program has made significant advances that influence global society as mentioned above—for example, development of a method to identify anti-SARS-COV-2 antibodies that forms the basis for the aptamer sensing method. The strategic vision for the program is exciting and challenging. To ensure that the program is able to achieve its future vision, greater effort will be required.

Other

The Biotronics Program aims to use electronics—materials, processes, and measurements—to probe, record, change, and understand the underlying mechanisms of the internal functionality of biological entities. In comparison to other programs, it is relatively new and thus it has a very small budget. The PM defined the Army's needs clearly and provided good examples. The program supports very high quality scientific work in several leading bioengineering and biomaterials groups at universities. Commensurate with the level of funding, output is small but very significant.

Planned work for the future is well formulated. An important observation is that in the formulation of the future plans, the PM is playing a critical role in leading the program to achieve the program vision.

ELECTRONIC SENSING PROGRAM

The vision of the Electronic Sensing Program is to discover and devise new electronic sensing concepts through advances in the fields of electronics, photonics, and piezotronics to enhance detection capabilities that can enable intelligence, surveillance, and reconnaissance dominance at remote, warfighter, and mobile platform levels. This program's research strategy is to address the following three key scientific questions: (1) Can one make (thermal, photovoltaic, or photoconductive) detectors perform at background-limited levels at room temperature? (2) Can Type-II Superlattice (T2SL) detectors compete with and even outperform HgCdTe in detectivity? (3) What epitaxial heterostructure advances can be garnered to enhance photodetection—ultraviolet (UV) or infrared (IR)?

Overall Scientific Quality and Degree of Innovation

The work presented comprises a strong portfolio demonstrating cutting-edge device concepts that are driving advanced materials development in a very tightly coupled partnership. Almost all the examples were on advancing capabilities in infrared detection, an area with obvious high relevance to Army functional concepts. The PM strategy is based on an integration of theory, advanced materials synthesis, and heterostructure engineering supporting novel design. This strategy was also captured in very well-defined priority questions about impact and outcomes, which focused on the potential for innovations for background-limited sensitivity at room temperature, T2LS material to outperform HgCdTe, and heterostructure engineering from UV to IR.

The sensors area has benefited from a history of PMs who have selected programs that have a demonstrable progression from a well-founded scientific thesis regarding advanced materials synthesis to the successful demonstration of novel device designs with improved performance. Notable examples of foundational scientific advances include results from the MURI on the Fundamental Study of Defects and Their Reduction in Type II Superlattice Materials. This program demonstrated record long carrier lifetime for both medium-wavelength infrared (MWIR) and long-wavelength infrared (LWIR) as well as evidence and modeling to explain the reason for the long carrier lifetime in Ga-free T2SL.

Scientific Opportunity

Proposed future priority scientific questions are natural extensions of the prior activity and remain focused largely on optical detection, including the impact of new designs harnessing metamaterials and microcavities to manipulate or direct incident energy toward sensing regions and enhance the potential for background-limited, room-temperature operation; and the use of novel heterostructure-enabled carrier multiplication for high-speed, room-temperature single-photon detectors.

There is potential to expand the program for impact in sensing modalities other than optical, and in new emerging opportunities for collaboration in quantum information science and sensing with the Physics Division.

Significant Accomplishments

The PM provided an overview of nearly a dozen funded projects from the FY 2017 to FY 2019 review period. While this was only a small fraction of the funded programs—there were 48 programs active in FY 2019 alone—the chosen examples clearly documented the support of outstanding investigators across the nation who are strong leaders in their field with high research productivity.

The results detailed in the presentation ranged from highly promising in the newest areas to powerfully enabling in areas that are maturing with extensive agency partnerships or industry transitions. Some particularly notable examples of ARO-supported areas include resonant-cavity-enhanced pyrometer arrays, the first clear demonstration of staircase avalanche photodiodes, and extensive development of T2SL materials in nBn detectors.

The Electronic Sensing Program has provided an outstanding example of how "device-inspired materials development" can have strong impact. While the majority of major advances in device performance are indeed traceable to advances in underlying materials synthesis, the interplay with device design for critical performance in real applications provides a powerful driver and focus for materials research.

Partnerships and Transitions

Within the ARO Electronics Division, the Electronic Sensing Program led in Army transitions. This stems in part from the relatively strong research-portfolio focus on optical sensing, but is also reflected in the overall maturity of the projects and direct linkage to applications relative to the other program areas.

In addition to linkages and impactful transitions to commercial partners (for example, Lockheed Martin Corporation and Raytheon), these programs illustrated strong collaborations and partnerships between ARL in-house research and other programs supported by the overall federally funded research enterprise. Examples include extensive partnerships with DARPA, Army's CCDC Soldier Systems Center, Night Vision and Electronic Sensors Directorate, ARL Sensors and Electron Devices Directorate (SEDD), and Small Business Innovation Research (SBIR) programs.

Level of Effort

The Electronic Sensing Program leveraged ARO's core average funding of about $2.0 million per year by attracting external partner support and raising the overall average total to about $4.5 million per year; this funding supported an average of 41 students and 20 postdoctoral researchers, and produced about 53 publications annually during the FY 2017 to FY 2019 period.

Other

Noting the critical impact of sensors for the Army, there may be opportunities to supplement the Electronic Sensing Program portfolio by expanding into some new directions. Such an expansion could attempt to repeat the device/materials research ecosystem successes in different sensing modalities beyond IR and UV optical sensors, such as photoacoustic gas detection, vibration sensing, and new field sensing applications.

This could also be explored by looking more closely at synergies with other program areas at ARO, as many of the concepts currently pursued within the Electronics Sensing Program are also well positioned to impact ultra-low-energy nanophotonics in the Optoelectronics Program and quantum sources and detectors that would complement activities centered in the ARO Physics Division.

OPTOELECTRONICS PROGRAM

The vision of the Optoelectronics Program is to develop transformative optoelectronics to process faster and direct energy farther, as well as revolutionary speed-up and miniaturization for electronic systems along with capabilities to provide for a larger area of battlefield dominance. This program's research strategy is to address the following three key scientific questions: (1) What device architectures can be developed to create low-energy, high-speed optoelectronics? (2) What types of semiconductor active regions need to be advanced to achieve high-intensity radiation? (3) How can directed energy be harnessed to more effectively mitigate against atmospheric conditions?

The Optoelectronics Program aims to utilize advances in optoelectronics for faster processing of information and direct energy farther, by capitalizing on the speed improvement and miniaturization of electronic components and systems. Such improvements will provide increasing capabilities to the Army for battlefield dominance through microlaser structures for intelligence, fires, protection, maneuver, and sustainment. Oxide-free vertical cavity surface-emitting lasers with dramatically improved thermal properties for cryogenic optical connectors will provide increasing capabilities such as high-speed focal plane read-out, chip-scale directed energy weapons, and combat readiness. Nanopatterned UV lasers will provide improved water purification and surface sterilization.

Overall Scientific Quality and Degree of Innovation

The work in the Optoelectronics Program was presented in a very clear and compelling fashion, with the bulk of the presentation being divided into three main areas that each addressed one of the three key scientific questions stated above. Each of these main areas has high potential for making significant impact within the scope of the portfolio and the resources available. Significant technical accomplishment was achieved in each of these three main areas. Innovation was evident in many of the supported technologies, demonstrating advances in devices and underlying materials at a variety of important wavelength ranges that have potential application in key Army needs. Results were published in some of the most selective and prestigious journals.

In general, the funded program goals were of high value and pushed the state of the art. Compelling evidence was presented of advances toward achieving these goals. Some examples for optoelectronic devices (e.g., different types of lasers) using advanced fabrication approaches include increasing modulation speed, output power, and temperature range; decreasing size (micro- and nano-cavities) and phase noise; finding limits of quantum noise; exploiting 2D and 3D quantum structures in different wavelength ranges, from ultraviolet to far infrared; increasing switching speed and power efficiency, especially for different temperature ranges; and improving the integrity of light propagation in free-space.

The Optoelectronics Program, including its proposed future focus, appears well positioned to continue its successful vision with significant impact and high scientific quality. It is important to continue the impactful transitioning of projects and the leveraging of other resources. There are a small number of projects that could be terminated to make room for new and higher risk, higher reward directions that may have greater impact in the long run.

Scientific Opportunity

There may be opportunities for strengthening synergy within the portfolio to achieve even more programmatic impact. The future strategic questions within the presentation already illustrate a strong synergy. These include leveraging advances in integrated photonics and advanced optical materials toward high-power photonics, extending wavelength ranges of operation through novel 2D and quantum nanostructured materials, and enhancing performance through microcavity and subwavelength structures.

For emerging device and materials programs that are strongly driven by proposed systems performance gains, such programs need to continue and increase interactions with systems groups to help optimally prioritize investments.

Significant Accomplishments

The PM has had strong and influential personal contributions in the broader scientific community and has made significant impact by his activity in prestigious professional societies. Specifically, the PM’s contributions in organizing conferences and workshops—for example, optical interconnects—bring significant attention to the ARO Optoelectronics Program and help the community thrive.

During the current review period, Optoelectronics Program funding—directly through the core program or indirectly through other programs such as MURI, and so on—has resulted in the PIs receiving awards and honors from prestigious science and engineering societies, including SPIE, OSA IEEE Photonics Society, and APS.

Partnerships and Transitions

The current strategy and portfolio reflect a priority on strong performers in areas of Army needs, and this has resulted in a portfolio containing impactful contributions. The overall current portfolio of projects can be described by the following three observations:

1. *Stage of projects:* There was a healthy mix of projects that were at different stages in terms of time (projects ranged from just starting to being transitioned out) and readiness (even within the category basic research, there was a spectrum of projects ranging from ones that were more speculative to ones that were ready to transition to applied).
2. *Leveraging of resources:* Resources from outside core ARO funds are leveraged to enhance the impact of the Optoelectronics Program. This includes DARPA, DURIP, and MURI programs, as well as the directed-energy programs and integrated photonics efforts. The Optoelectronics Program needs to continue to seize on such opportunities for the betterment of the whole program.
3. *Transition:* Significant transition examples were provided, notably that of advanced laser technologies by start-up Telaris that led to their acquisition by Intel. Other strong transitions included semiconductor lasers that supported directed-energy programs by the Joint Directed Energy Transition Office and several impactful Phase II SBIR programs.

Level of Effort

The Optoelectronics Program leveraged ARO's core average funding of about $2.4 million per year by attracting external partner support and raising the overall average total to about $11.0 million per year; this funding supported an average of 55 students and 21 postdoctoral researchers, and produced about 50 publications annually during the FY 2017 to FY 2019 period.

Other

There may be opportunities to refresh parts of the portfolio that are nearing their end with projects in new directions. There is laudable interaction between the Optoelectronics Program and members of the other areas within the Electronics Division, and the Optoelectronics Program needs to take advantage of innovative opportunities with materials programs that could enable new device capabilities.

SOLID-STATE ELECTRONICS AND ELECTROMAGNETICS PROGRAM

The vision of the Solid-State Electronics and Electromagnetics Program is to exploit unique physical phenomena in emerging quantum materials and their heterostructures to create novel electronic capabilities in information processing, communications, radar, and electronic warfare to maintain information superiority and spectral dominance for the Army. This program's research strategy is to address the following four key scientific questions: (1) What unique carrier transport properties in low-dimensional materials can be exploited for novel electronic functionalities? (2) How do photons with different energies across the electromagnetic spectrum (microwave, THz, optical) interact with topological materials and reveal different materials properties? and (3) How can topologically protected spin-momentum locked carrier transport be utilized for novel electronic functionalities?

Overall Scientific Quality and Degree of Innovation

This Solid-State Electronics and Electromagnetics Program aims to exploit unique physical phenomena in emerging quantum materials and their heterostructures to create new electronic capabilities in information processing, communications, radar, and electronic warfare to maintain information superiority and spectral dominance for the Army. The program has been effective in leveraging collaborative opportunities with the Physics and Materials Science Divisions, to make substantial progress in a number of topics of current interest that are additionally Army relevant. For instance, research related to electrochemical doping of 2D Van der Waals heterostructures through interface engineering is expected to lead to reduced size and weight form factors, while intercalation of graphene with $AlCl_4$ may afford high-density energy storage solutions. Planned work for the future is well formulated.

The PM presented a summary that pointed to a highly productive program aimed at materials and device development with low-dimensional and topological materials. Overviews of research conducted by groups at Purdue University, University of California, Santa Barbara, Harvard University, Rice University, and University of Southern California point to productive efforts that are leading to significant peer-reviewed publications in premier journals. Similarly, productivity on materials and device development using low-dimensional and topological materials is high. While this program is somewhat narrowly focused, resources have been leveraged to support several DURIP grants to University of Texas, Austin, University of Pennsylvania, and Johns Hopkins University, in addition to a Young Investigator Program (YIP) at the University of Pennsylvania on THz studies of multifold fermions and magnetic Weyl semimetals, and an STTR. The spin-momentum locking initiative is supporting a DURIP and three MURIs, and the efficient THz generation and detection program is supporting several internationally recognized efforts.

Scientific Opportunity

Scientific opportunities for the Solid-State Electronics and Electromagnetics Program are significant. However, the process of making the selection of the specific research topics (e.g., topological materials) against other topics was not clearly articulated. Certainly, topological materials have been the subject of intense research interest for a number of years, with most recent focus being on the topological dependence of their mechanical properties and the use of this for the development of localized memory. Historically, foundational developments with topological materials were driven by other agencies. It is uncertain at this junction whether devices developed using these materials are expected to be the key component in improving communications.

Significant Accomplishments

During FY 2017 to FY 2019, Solid-State Electronics and Electromagnetics Program funding, directly through its core program or through related programs from MURI, and so on, has led to 178 peer-reviewed publications in high-impact journals. On average, the program has provided funding for 62 graduate students and 23 postdoctoral researchers per year. Investigators funded under this program have also been the recipients of several internationally recognized awards. For instance, Allan MacDonald is the recipient of the 2020 Wolf Prize in Physics; Kang Wang is the recipient of the 2018 IUPAP Magnetism Award and Neel Medal; and Eugene Mele was awarded the 2019 Breakthrough Prize in Physics and was elected to the National Academy of Sciences in that same year. It is notable that several additional funded PIs are the recipients of internationally recognized awards during the review cycle.

Partnerships and Transitions

Several funded research efforts conducted under the umbrella of the Solid-State Electronics and Electromagnetics Program have transitioned to the commercial sector or led to partnerships with other organizations during FY 2017 to FY 2019. To name just a few, funded efforts at Johns Hopkins University related to THz characterization of a topological insulator led to collaboration with ARL SEDD. The materials are of particular interest for low-power electronics, and the collaboration led to a peer-reviewed publication. Similarly, research on p-diamond Tera-field-effect transistors designs are of interest for ultrawide-bandgap radio frequency and power electronics, which are being explored collaboratively with ARL SEDD. Research at UCLA on high spin-orbit torques in magnetic topological insulator structures is of interest to Intel for spintronic devices.

Level of Effort

The Solid-State Electronics and Electromagnetics Program leveraged ARO's core average funding of about $2.8 million per year by attracting external partner support and raising the overall average total to about $9.9 million per year; this funding supported an average of 62 students and 23 postdoctoral researchers, and produced about 59 publications annually during the FY 2017 to FY 2019 period.

Other

The Solid-State Electronics and Electromagnetics Program has made significant advances that are expected to have impact to the Army. A strategic vision for the program was not clearly articulated. A strategic vision will lead to even better outcomes.

OVERALL ASSESSMENT

The division's aim is to discover and enhance electronic and photonic interactions and functions in new devices and a broad range of materials. Some of the outstanding achievements encompass inorganic materials such as intercalated graphite for inductors; low-energy, high-speed optoelectronics; and optical control of ion transport in single living cells. Division-level strategy emphasizes interdisciplinary interactions between physics, chemistry, materials science, and biology. This interdisciplinary strategy has worked well for this division. The overarching aim is to achieve device and system performance characteristics that enable the U.S. Army to maintain technological superiority vis-à-vis adversaries.

The division is organized into four programs: Biotronics, Electronic Sensing, Optoelectronics, and Solid-State Electronics and Electromagnetics. The division's total budget was $32.3 million for FY 2019. The division funds a mix of SI projects—about $143,000 per project per year—and larger MURI projects. The division also funds and manages SBIR/STTR, PECASE, DURIP, and so on. During FY 2019, 94 SI awards were funded, along with several STIR awards focused on jump-starting high-risk projects.

Key performance parameters include, in addition to peer-reviewed publications, transitions to ARL and to industry. There were 55 transitions reported for the 3-year period from FY 2017 to FY 2019, including the transition of fundamental biotronics research funded by ARO at Northwestern University on new assembloids from three cortical spheroids to ARL-SEDD for study of cellular dynamics in reduced brain preparations. An example of the transition of fundamental optoelectronics research funded by ARO includes ultra-narrow linewidth "slow-light laser" transitioned to Telaris, Inc., which garnered two phase II STTR/SBIR programs. Following success with manufacturability and isolator-free performance, Intel Corp. bought out Telaris, Inc., aiming at autonomous navigation and ultra-high-bandwidth data links.

The projects highlighted were uniformly of high quality, but only a small percentage of the entire portfolio was presented. Overall, the quality of programs reviewed was high, but there were limited initiatives aimed at new research directions and pursuing high-risk and high-reward projects that could lead to discovery and inventions of greater scientific significance.

Recommendation 5: The Engineering Sciences Directorate (ESD) Electronics Division should expand on new research directions and high-risk, high-reward projects that could lead to discovery and inventions of greater scientific significance.

13

Materials Science Division

The goal of the Materials Science Division is to create novel materials with extraordinary structural and functional properties and explore underlying deterministic composition-processing-structure-external stimuli-property relationships through initiating, promoting, and embracing high-risk, high-payoff scientific ideas with special emphasis on materials design, synthesis and processing (S&P), mechanical behavior, and physical properties of materials to transform the future Army's capabilities.

The division is organized into four programs: Mechanical Behavior of Materials, Synthesis and Processing of Materials, Materials Design, and Physical Properties of Materials. The first two programs emphasize structural materials, while the latter two emphasize functional materials. The research programs collectively have high potential to enable future transitions to the Army. The division's total budget was $32.2 million for fiscal year (FY) 2019. The division funds a mix of single investigator (SI) projects—about $140,000 per project per year—and larger Multidisciplinary University Research Initiative (MURI) projects. The division also funds and manages Small Business Innovation Research (SBIR)/Small Business Technology Transfer (STTR), Presidential Early Career Awards for Scientists and Engineers (PECASE), Defense University Research Instrumentation (DURIP), and so on. During FY 2019, 81 SI awards were funded along with nine Short-Term Innovative Research (STIR) awards focused on jump-starting high-risk projects.

In general, the division's metrics are strong, with 943 peer-reviewed publications in the FY 2017 to FY 2019 review period, and funding for 312 graduate students per year and 139 postdoctoral researchers per year during the same period. There were 41 transitions reported for this same 3-year period, about 40 percent to both the Army and industry. The projects highlighted were uniformly of high quality, but only a small percentage of the entire portfolio was presented.

MECHANICAL BEHAVIOR OF MATERIALS PROGRAM

The vision of the Mechanical Behavior of Materials Program is to promote the discovery, understanding, and control of mechanical behaviors across a broad spectrum of advanced structural materials through investigations of extreme environments and phenomena that enable active mechanical response; the research in this program is expected to shape unprecedented capabilities in protection, sustainability, and maneuver. This program's research strategy is to address the following three key scientific questions: (1) Can extreme environments be exploited to enable materials with extraordinary mechanical properties? (2) How may heterogeneous materials include desirable mechanical properties from subsystems while excluding nondesirable behaviors? (3) How can mechanical forces be manipulated within materials to lessen or concentrate stress at particular spatial locations? The focus is on extreme environments, heterogeneous materials, and mechanical cloaks.

Overall Scientific Quality and Degree of Innovation

Many, but not all, of the selected directions and investments of this program are appropriate. The highlighted projects were excellent, and several transitions of research results to Army laboratories were noted. A positive example is the effort to discover phase transformation behavior of ceramics under high pressure and shear loadings. Ceramic materials are an increasing focus in many countries in the context of traditional applications such as armor to nanoelectronics. Adding to the processing knowledge and atomic layer modeling of such materials is a good example of transformational research.

Scientific Opportunity

The projects highlighted were uniformly of high quality, but only a small percentage of the entire portfolio was presented. It is hard to assess which opportunities may have been missed, and how impactful these funded areas will be over time. Joint publications with investigators at Lawrence Berkeley National Laboratory (LBNL), National Aeronautics and Space Administration (NASA) Ames, Los Alamos National Laboratory (LANL), and the Combat Capabilities Development Command (CCDC) ARL-Vehicle Technology Directorate are examples of high-payoff scientific discoveries and a strong strategy for investment. Another opportunity for investment is the general direction of liquid crystal elastomers, which also attracted several sponsors and partners.

Significant Accomplishments

Accomplishments are excellent in terms of traditional scientific metrics, such as peer-reviewed articles in top journals, support of researchers, and so on. However, these metrics need to be supplemented with others—for example, citations and quantitative assessment of technology transitions.

Partnerships and Transitions

Collaborations and transitions within ARL as well as with other organizations are extensive and part of the research culture. Excellent leveraging of funds—for example, with the Defense Advanced Research Projects Agency (DARPA)—is noted. Program managers could better focus funding sources, with less-fragmented portfolios. High-quality science is being supported in the programs, but the programs could be more effective if they have a sharper focus on potential transitions. The transitions listed for FY 2017 to 2019 do not provide convincing evidence for the selection of high-payoff investments by this program.

Level of Effort

The Mechanical Behavior of Materials budget of $38.42 million for FY 2017 to FY 2019 is the largest of the four programs in the Materials Science Division, but the higher program cost per peer-reviewed publication—about $258,000—is the highest. Analysis of publications by funding source may elucidate this result.

Other

High-quality science is being supported in the programs, but the programs could be more effective with a sharper focus on transitions to the Army. ARL overview concepts emphasize the changing and especially broadening scope of the ARO in the context of multi-domain operations. In this context, ARO strategy on supporting research that enables active mechanical response is appropriate. ARO expects that the research in this program will shape unprecedented capabilities in protection, sustainability, and maneuver. It is a delicate and uncertain balance, and needs to be closely examined and adjusted as results and events justify. Like every reorganization and adjustment of an organization, this corporate growth needs to be closely monitored and adjusted as necessary in the short and long term. Encouragement by ARO management for balancing scientific opportunity with Army transitions would, most likely, improve the effectiveness of transitions without sacrificing scientific quality.

SYNTHESIS AND PROCESSING OF MATERIALS PROGRAM

The Synthesis and Processing (S&P) of Materials Program vision is to create the superior structural materials that will be used in future Army equipment by studying and understanding the underlying mechanisms and phenomena (e.g., solidification, phase transformation, and grain growth, etc.) that govern materials processing. There is a targeted focus on structural materials, and the program aligns well with Army functional concepts of protection, maneuver, and fires with strong evidence of transitions to the Army. This program's research strategy is to address the following three key scientific questions: (1) How can one move from empirical to quantitative approaches for defining the relationships between material processing parameters and the final materials structure and properties? (2) What fundamental phenomena are influencing the final microstructures of materials under the relevant processing conditions, and how can we capture these phenomena and define them? (3) What new approaches can be explored to provide a new level of control for structural materials processing? Specifically, the goals are to bring consistency to additive manufacturing and understand fundamental phenomena of grain growth and correlate them to mechanical properties leading to higher performing structural materials.

Overall Scientific Quality and Degree of Innovation

The program portfolio is robust and well-coordinated to establish crosscutting relationships between (1) quantitative correlation of materials processing parameters with structural properties; (2) understanding fundamental phenomena that affect microstructure and structural properties; and (3) demonstrations of high levels of process controllability and consistency. The PM has a strong commitment in emphasizing the role of understanding fundamental phenomena in processing. This focus is exemplary, particularly in the synthesis and processing area, where most research has been empirical. There is clear evidence of the use of this strategy in every project. The programs integrate modeling, computation, simulation, and experimental verification. The research highlights included program examples of (1) computational methods to predict processing parameters in additive manufacturing combined with experimental verification; (2) kinetic studies of nanostructures and grain growth using novel characterization methods and computational simulations; and (3) development and understanding of new forces—for example, electric fields, acoustic interactions, or plasmas—in synthesizing structural materials. The projects related to the third category are high risk but show potential to have high impact in synthesizing new metamaterials and functional materials. Of particular note is the innovative MURI program—Consolidation of Novel Materials and Macrostructures from a Dusty Plasma—to develop a process using dusty plasmas to control particle placement on the nanoscale.

Scientific Opportunity

Program examples were presented that successfully support the strategy and development of consistency in additive manufacturing and exploration of new processing methods. These efforts have high potential to lead to improved controllability of materials produced in additive manufacturing and the synthesis of new materials with tailored properties. Further gains in control of additive manufacturing processes could be made by fostering new collaborations with researchers in the electronics, physics, and mechanical sciences divisions in exploring new imaging systems for in-situ process monitoring of the crystallization process. One can envision in situ process monitoring integrated with a feedback control system to adjust feed rate, solidification rate, cooling rate, and so on, in order to controllably and reproducibly generate materials with desired properties. The creation of Si_3N_4/SiO_2 coatings with near blackbody heat radiation in the dusty plasma MURI is an excellent example of a disruptive technology that could provide significant opportunity.

Significant Accomplishments

The technical accomplishments presented by the PM represent significant advances in reaching the overall program goals of creating superior structural materials. The number of peer-reviewed publications—179 during FY 2017 to FY 2019—is high compared to the level of funding—about $10 million during FY 2017 to FY 2019. The PM has made significant efforts to engage new researchers and maintain tight focus on the S&P vision. MURI, DURIP, and SBIR/STTR programs were established and are a strong complement to enhance program vision.

Partnerships and Transitions

All the transitions cited in the presentation have been to CCDC ARL Weapons and Materials Research Directorate (WMRD) or Air Force Research Laboratory (AFRL), and this speaks to the effectiveness of the program research topic and high quality of execution. Noteworthy is that the Army is currently using the Thompson method for analysis of nanocrystalline grain boundaries, even before completion of this project.

Level of Effort

There is a fine balance of funding to early-career and well-established PIs. In FY 2019, the Synthesis and Processing of Materials Program portfolio was heavily leveraged by MURI, DURIP, and SBIR/STTR funding, which effectively complemented research efforts. There were 34 awards in FY 2019, and the median 12-month SI grant was $135,000. The $10.04 million budget for FY 2017 to FY 2019 is the smallest of the four programs in the Materials Science Division, but the "cost per peer-reviewed publication" is about $56,000—which is the lowest.

Other

The Synthesis and Processing of Materials Program is well managed, and the projects described show a clear strategy toward the overall program goal. The highly relevant research projects focused on bringing consistency to additive manufacturing of structural materials and exploring novel processing methods for improving structural properties of materials. Expanding research efforts for in situ monitoring and characterization during synthesis and processing of materials is an area that would provide further insights and improved control of materials.

MATERIALS DESIGN PROGRAM

The Materials Design Program vision is to establish new smart materials concepts by pursuing fundamental science that exploits multiple physical and chemical forces at play during directed self-assembly to create stimuli-responsive, multifunctional materials with designer geometries, hierarchical complexity, and the ability to dynamically switch among configurations, thereby enabling the future warfighter to adapt to any environment or situation. This program's research strategy is to address the following three key scientific questions: (1) What internal and external forces are at play during (non-) equilibrium self-assembly, and how can they be controlled to achieve specific targets? (2) What are the design rules for creating novel functional materials that display hierarchical structure, emergent behavior, and/or reconfiguration? (3) How can machine learning be combined with cutting-edge soft matter theory and experiment to revolutionize the design of self-assembled and reconfigurable materials? The Materials Design Program is thus focused on self-assembly and directed assembly to create stimuli-responsive, multifunctional materials to potentially enable the future warfighter to adapt to a range of environments or conditions. The PM gave an excellent presentation and has done a good job in transitioning to managing the program from the previous PM.

The FY 2017 to FY 2019 Materials Design Program was further focused on bottom-up assembly for soft materials. Within this realm, the further focus was on understanding the science of self-assembly, designing novel reconfigurable and hierarchical materials, and computer-aided materials design. By far, this was the most focused of the materials science area presentations, and hence with the disparate projects funded, could be more easily defined as a connected portfolio. The specific, individual projects that were presented in more detail reported impressive results and scientific advances. However, it was not clear what this portfolio of projects would lead to and how the chosen portfolio could lead to transformative technology. Several FY 2017 to FY 2019 transitions were presented, but these were not clearly compelling with respect to being transitioned to the Army functional concepts. Leveraging of funds from DARPA by the previous PM was very impressive, and attempts to regain interest from DARPA in this area needs to be pursued. Funding has dropped about 40 percent or more in FY 2018 and FY 2019 owing to the decrease in DARPA funds, and this clearly needs to be pursued further, because the topic of materials design is of interest to DARPA. Significant success was reported in obtaining funding for MURI projects related to this multidisciplinary area, and these need to continue. Future directions indicated included soft materials that learn, computer-empowered materials design, and self-propagating additive materials. While these are certainly of interest, a methodology needs to be developed to ensure that these are indeed the highest priority areas to pursue.

Overall Scientific Quality and Degree of Innovation

The overall scientific objectives were compelling from a fundamental science perspective. However, it was not apparent whether these objectives would maximize future transitions. The funded projects could advance the frontiers of their specific project areas and in some cases make transformational advances. However, it was not clear whether the portfolio of projects funded were driven by strategic planning related to transitions to the Army. Projects were fundamental and mainly high risk, high payoff. It was not fully clear what the defining impact of ARO funding was, because in many cases, the single investigators funded also had funding from other agencies for many of the reported outputs presented—such as publications and awards. No attempt was made by the presenters to unequivocally establish how funding from ARO was crucial for the research reported compared to that from other sponsors.

Scientific Opportunity

If the overall scientific objectives are more clearly defined in a focused way, the likelihood of reaching the objectives or goals will be higher. At present, the objectives are very broad, and most outcomes could be argued to meet the objectives. The projects highlighted were uniformly of high quality, but only a small percentage of the entire portfolio was presented. The highest priority thrusts would be those that balance scientific excellence and transitions to the Army.

Significant Accomplishments

Some of the papers appeared to be significant advances in the specific areas probed. Projects did report a large number of publications in high-impact journals. However, in many cases, the investigators had funding from multiple funding agencies. This makes it difficult to gauge the defining impact of ARO investments. The science of assembly projects—colloidal diamond lattices for photonic bandgap materials and polymer-stabilized, tubular liquid-liquid interfaces—are to be commended for scientific excellence.

Partnerships and Transitions

Nine transitions were presented, of which eight were to the Army. The MURI projects were collaborative, complementary, and coordinated. DARPA-funded and ARO-managed projects were collaborative and coordinated. All of this could be more transformative if there was a more deliberate and overall strategic positioning and planning, as discussed above. With respect to the base portfolio of single investigator projects, it was not apparent that the projects were complementary, collaborative, coordinated, and integrated, where appropriate, with other ARO, ARL, Army, or DoD programs.

Level of Effort

The Materials Design budget of $30.82 million for FY 2017 to FY 2019 is the second lowest of the four programs in the Materials Science Division, but the "cost per peer-reviewed publication"—about $117,000—is the second highest. With limited funds available to each PM, annual investments need to be more focused to make an impact.

Other

A great strength is that this program is driven in an entrepreneurial manner by individual PMs, so they have advantage to take their programs in different directions without significant bureaucracy. A corresponding weakness is that it is not easy for an individual PM to coherently drive a program for maximum impact without a clear and overarching, strategic positioning to maximize transitions to the Army. As suggested by ARO program planning, PMs need to balance scientific excellence with deeper strategic thinking about the Army's key modernization priorities. The next-level detail of the science and technologies that are needed for these priorities could then be developed. These can be "blue sky" in nature and can then drive the fundamental science supported by ARO. One possibility is to have an "Ideas Lab" within the Army and involve some key external researchers for each of the six modernization priorities. The end output after significant deep dives will be the scientific breakthroughs needed to arrive at the end goals. These then could drive the fundamental research investments by the ARO in an even more focused manner.

PHYSICAL PROPERTIES OF MATERIALS PROGRAM

The vision of the Physical Properties of Materials Program is to discover novel functional materials with extraordinary electronic, photonic, magnetic and thermal properties and establish underlying processing-structure-defect-property relationships to empower the future Army with transformational overmatch capabilities in the areas of sensing, communication, power and energy, and so on. This program's research strategy is to address the following three key scientific questions: (1) How can we create materials of novel compositions and structures through fundamental understanding of nucleation/growth mechanisms, reaction kinetics, interface control, composition/structure control during top-down approaches, and so on? (2) What unique characterization techniques are needed and how can they be developed to explore functional properties of novel materials through exploiting the latest technological developments? (3) How does processing influence defects in materials that influence the functional properties, and how can defect-property correlations be established in novel materials to impact properties? The research focus of this program is to discover novel functional materials, develop extraordinary characterization techniques, and understand and exploit influence of defects.

Overall Scientific Quality and Degree of Innovation

The projects presented within the Physical Properties of Materials Program were uniformly of high quality but represented only a small percentage of the entire portfolio. Many reported publications had multiple funding agencies listed, and so key scientific advances enabled by ARO funds was not clear. The Physical Properties of Materials portfolio as briefed presents a truly impressive breadth of fundamental research in the broad area of functional materials spanning materials discovery to create new properties and capabilities, new characterization technique development, and research aimed at linking processing to defect generation and their effects on properties. Many of these are strongly supporting scientific advances of importance to the Army. The linkages to potential advances in sensor technology, heat management and control, and advances in optical materials were clearly briefed, and the level of science presented was excellent. The truly impressive list of publications listed within this program reflects the high productivity and high level of fundamental science funded within this program element. In addition, owing to the breadth of the program and the limited funds available, its collective impact can only be limited. With limited funds, it is necessary to focus efforts in strategically chosen areas to achieve maximum impact. Last, funding of graduate students and postdoctorates in this program element is supporting the needed stream of the next-generation talent of scientists and engineers that is needed for the entire U.S. S&T research and industrial base, and this is highly commendable.

It was apparent that the selection of projects is mostly a bottom-up one, where the PMs exercise a lot of discretion and authority regarding project selection and funding decisions with minimal direction from above aimed at transitions to the Army. While the PMs are all well qualified for their positions to seek and pose bold scientific thrust areas, engagement with the Army laboratories in pursuing discovery and fundamental science supporting Army functional concepts seems unbalanced.

Scientific Opportunity

The projects highlighted were uniformly of high quality, albeit only a small percentage of the entire portfolio was presented. Accordingly, this presentation format makes it more difficult to assess which future opportunities may have been missed, and how impactful these funded areas will be over time is unclear.

The lack of advanced new disruptive materials focused projects is apparent. Predictive modeling linking processing to structure to properties to performance in materials remains a clear area for fundamental research topics and present fruitful areas for new research.

Significant Accomplishments

Accomplishments are excellent in terms of traditional scientific metrics—such as peer-reviewed articles in top journals, support of researchers, and education of the next generation of scientists and engineers to provide potential new staff entering Army S&T employment. These metrics could effectively be supplemented with others—for example, long-term impact on Army transitions and citations to assess research impact more broadly. The near-field radiative transfer project is an example of an excellent project. The significant accomplishments here are the first experimental demonstration of near-field photonic cooling (without laser light) using a custom-fabricated nanocalorimetric device and a photodiode as well as the demonstration of a 100-fold enhancement in far-field heat transfer rates via nano-structuring of radiating surfaces.

Partnerships and Transitions

Collaborations, within ARL as well as with other organizations, are extensive and part of the culture. Given the portfolio presented and the focus of the thrust areas briefed, it remains unclear how the changes in the Army S&T investments enacted, with the future Army functional concepts, is currently being supported by the current Materials Science Division research portfolio. In particular, the lack of emphasis on investment in fundamental materials R&D in areas owned by the Army asks this question: Where are the long-range research investments in innovative discovery research supporting the fundamental science underpinning Army functional concepts such as long-range precision fire, next-generation combat vehicles, and soldier lethality? It is true that detailed structural materials fundamental R&D for armor, warheads, and platforms is certainly too close to restricted areas of S&T owing to classification and therefore inappropriate to fundamental research and especially funding graduate students. However, there still remain many basic experimental and modeling fundamental science challenges linking processing to structure to properties and defects and their reproducibility of relevant Army structural materials absent at present in the world and clearly reflective of top-notch science problems. Breakthroughs in these areas of science can also pose the possibility of re-engaging American industry in running with scientific breakthroughs to the benefit of the Army large contractors building Army hardware and not simply importing it from overseas, such as the current high-hard armor example, among many.

Level of Effort

The Physical Properties of Materials budget of $34.52 million for FY 2017 to FY 2019 is the second largest of the four programs in the Materials Science Division, but the "cost per peer-reviewed publication" is about $77,000—which is the second lowest. PMs could assess whether the current focus of funding sources, with less fragmented portfolios, might provide a path to achieve more significant progress toward future Army transitions through funding of a reduced number of projects but funded at a higher individual level.

Other

ARO in the materials area is clearly funding high-quality science in its programs, but it appears that the programs could be more effective with a sharper focus on the transitions to the Army, especially in the science areas that the Army owns relative to the other branches of the DoD such as soldier lethality, future land-based vehicles, and long-range precision fire.

OVERALL ASSESSMENT

The projects presented were uniformly of high quality, but only a small percentage of the entire portfolio was presented for review by the panel. The projects overall were found to be excellent in terms of collaborations and interdisciplinarity as well as scientific quality. Thus, it is hard to assess which opportunities may have been missed, and how successful connecting scientific discovery to Army functional concepts for these funded areas will be over time. Metrics for collaboration are high, with 15 active collaborative MURIs during FY 2017 to FY 2019. Secondary funding—for example, from DARPA—is the key to expanding programs leading to high scientific quality and transitions.

Overall, the Materials Science Division is conducting very high-quality research. The programs are driven, in an entrepreneurial manner, by well-qualified individual PMs who can take their programs in different directions without significant bureaucracy. However, these individual PMs need strategic positioning and appropriate incentives to coherently drive their programs for maximum transitions to the Army.

It was observed that many of the publications referenced in the presentations were funded by multiple funding agencies. This leveraging of funds is to be commended; however, with multiple support agencies, it is difficult to assess the impact ARO funding had on the research. A better metric of publications, one factoring in the dominant funding organization, would be more useful both to ARO and to a review panel.

Recommendation 6: The Army Research Office (ARO) should develop a publication metric that quantifies the extent of ARO funding to the publication. ARO should present this metric in future Army Research Laboratory Technical Assessement Board (ARLTAB) reviews. In addition, ARO should highlight in these reviews the key scientific advances attained primarily by ARO funding.

The programs funded by ARO are intended to be high-risk, high-payoff research projects that drive cutting-edge research and lead to disruptive science and technologies. This science plays an important role in innovation, in follow-on investments in STTR/SBIR programs, and in patent generation. Numerous metrics were provided but did not include metrics for patent-related activities.

Recommendation 7: The Army Research Office (ARO) should track the number of technology disclosures, patent applications, and patent issuances that have resulted from ARO-supported funding or collaborations.

The research strategy within the ARO Engineering Sciences Directorate seems to be principally a bottom-up organization, where the PMs have primary discretion and authority regarding project selection and funding decisions. The PMs are all well qualified for their positions. The directorate strategy is to pose bold scientific questions; to seek collaborations; to engage with the Army laboratories for transitioning the research; to seek out high-risk, high-reward opportunities; to venture into new areas with long-term impact on enhancing Army capabilities; and to hire and retain an excellent workforce. All of these items are meritorious. This strategy includes "casting a wide net," even though funding levels are relatively small compared to peer organizations, such as DOE, NSF, DARPA, AFOSR, ONR, and so on. By having the PMs follow both directorate program planning and respective division strategy, transitions to the Army could be enhanced. Because the directorate investment is relatively small and the opportunities in engineering sciences are large, focusing on fewer research topics with greater funding on those identified could possibly result in greater benefit to the Army through transitions without loss of scientific excellence.

Recommendation 8: The Army Research Office (ARO) program managers (PMs) should be encouraged to prioritize directorate and division strategy with respect to focusing project selection by further improving the connection of scientific discovery to Army transitions.

All of the programs have listed the transitions; however, no quantitative metric of transitions was presented and no information about how transitions are evaluated or used in program planning was presented. Transitions appear to be an important metric of the effectiveness of the scientific programs and are highlighted in the Directorate Planning Program as program assessment.

Recommendation 9: The Army Research Office (ARO) should develop a transition metric that quantifies the effectiveness and importance of transitions to the Army and use this metric as a guide in the selection of future projects. ARO should present this metric in future Army Research Laboratory Technical Assessment Board (ARLTAB) reviews.

14

Mechanical Sciences Division

The goal of the Mechanical Sciences Division is to conceive of and develop transformational research programs in mechanical sciences for the U.S. Army to provide the scientific foundation to create revolutionary capabilities for the future warfighter. The division supports research aligned with the following Army functional concepts: command and control, fires, maneuver, protection, and sustainment.

The division is organized into five programs: Complex Dynamics and Systems, Earth Materials and Processes, Fluid Dynamics, Propulsion and Energetics, and Solid Mechanics. The division's total budget was $21.9 million for fiscal year (FY) 2019, which includes $1.4 million from Office of Secretary of Defense and Small Business Innovation Research (SBIR)/Small Business Technology Transfer (STTR) programs. It supported a total of 122 single investigator (SI) awards; 19 conference, research instrumentation (RI), and Short-Term Innovative Research (STIR) efforts; and 9 awards to Historically Black Colleges and Universities and Minority Serving Institutions. In addition, the division supported 10 Multidisciplinary University Research Initiative (MURI), 2 Presidential Early Career Award for Scientists and Engineers (PECASE), and 18 Defense University Research Instrumentation Program (DURIP) awards.

Metrics provided for the 3-year period of FY 2017 to FY 2019 indicate that this is a healthy and successful division. There were 568 peer-reviewed publications and 37 significant transitions during this period, and the division supported an average of 297 graduate students and 118 postdoctoral researchers.

COMPLEX DYNAMICS AND SYSTEMS PROGRAM

The vision of the Complex Dynamics and Systems Program is to develop novel analytic and algorithmic methodologies for exploiting the interactions by which high-dimensional dynamical systems store, dissipate, predict, and shape information and energy in dynamically changing environments. This program's research strategy is to address the following three key scientific questions: (1) What analytical structures capture the most important dynamic features of high-dimensional nonlinear systems and how do one predict, infer, and control them? (2) How do intrinsic information processing, stochasticity, and feedback control modulate the energetics (and vice versa) of nonequilibrium systems? (3) What are the principles by which agile and adaptive cognition, computation, and control are physically encoded within organisms and machines?

Complex dynamics and systems have risen in recent decades to become a study area of both natural science and applied science. The Complex Dynamics and Systems program was divided into three portions by the PM—high-dimensional dynamical systems, nonequilibrium information physics and control, and embodied learning and control.

Overall Scientific Quality and Degree of Innovation

The program has high-quality researchers, some of whom are regarded as deep thinkers in the field. The topics are bold and novel. There is a balance of traditional and new topics. The individual projects generally have potential for impact on the particular area of theory. The program is an interesting basic research enterprise based on extension of traditional models of mechanics of complex systems, indirect influences, elastic stress descriptions and modeling owing to gradients of displacement, noncommutative grouping of elements, statistics of linear and nonlinear stochastic control and learning within non-equilibrium systems, and defining the relationship between embodied dynamics and control in animals and robotics/machines. This body of work appears to be highly valued by the basic research communities represented. The program's supported teams of researchers are taking on risky areas by exploring the limits of Koopman operators and non-Abelian group operators. Similarly, funded research involving causation entropy and odd elasticity show progress at the basic research level. Funded research on defining dynamical relationships between animals and robots is developing a much-needed community accepted framework, including metrics.

The potential overlap of dynamical systems with solid mechanics and fluid dynamics is very large because problems in continuous media are high-dimensional—in fact, they are infinite dimensional in their primitive form as partial differential equations. The overlap seems to have been largely avoided but not totally, as mentioned above.

Because of the breadth of topics, the program's impact will likely be smaller than possible. The absence of a precise definition of limitations and pathways of extension of funded research in complex dynamics and systems is a weakness of this program. The program needs to be continued and some important issues needs to be addressed: Where is this research headed? How is success measured in this program? What role does dissipation play in some of the modeling efforts? What is the relationship between the funded research projects and the three pillars of the program?

Scientific Opportunity

The program separates into three components, which individually are unusually broad, as noted above. The connections of the individual projects into smaller groupings and the relation to transitions to the Army were not clarified. The opportunity for greater impact might result from greater focus in the program.

Three questions are listed to describe the strategy to lead future scientific discovery. They appear to relate more to the area of embodied learning and control. It is not clear whether this implies an intended emphasis of that third area with de-emphasis of the other two areas. No argument was given for greater opportunity in any area.

Significant Accomplishments

The Complex Dynamics and Systems Program is the biggest of those in the Mechanical Sciences Division, having an FY 2019 budget of about 31 percent of the total and per-project funding of about 127 percent of the division average. Peer-reviewed publications at about 1.3 per project-year and graduate student-postdoctoral support of about 1.1 per project-year are each modest.

Partnerships and Transitions

Transition was broadly defined, including, for example, co-authored papers and takeover of funding by another industrial organization. Nevertheless, the purchase of a company started under ARO sponsorship by Delphi for $450 million is impressive. In addition, ARL's Vehicle Technology Directorate showed interest in two of the ARO research projects. There were no other indications of transition from 6.1 level research to the 6.2 or higher level. Potential transitions were also not clarified—that is, the relation of the research to enabling technology was usually not obvious.

Level of Effort

The program leaned toward the theoretical side, although some experimental research was included. The program has healthy-size components in both the single investigator and MURI areas.

While the breadth of the program is a positive feature, care is urged to examine the program for excessive fragmentation that leads to a loss of focus.

Other

The program vision described analysis and methodology for high-dimensional dynamical systems in dynamically changing environments. The appearance of dynamically changing environments was not obvious in highlighted projects. More importantly, it is not generally required for classification as a complex system.

The highlighted topics in high-dimensional systems often dealt with continuum problems that might profit from interactions with other programs such as solid and fluid mechanics and materials—for example, elasticity, metamaterials, and phase transition.

EARTH MATERIALS AND PROCESSES PROGRAM

The vision of the Earth Materials and Processes Program is to enable maneuvering, communication, and situational awareness in all terrain through understanding and prediction of the physical and mechanical properties and behaviors of rocks, soil, and man-made earth surfaces and their interactions with their surrounding environment. This program's research strategy is to address the following two key scientific questions: (1) How do grain-scale features influence bulk properties in unconsolidated earth materials? (2) How can earth surface interaction with air and water be predicted at warfighter-relevant spatiotemporal scales—microns to hundreds of kilometers?

The program supports three Army functional concepts: to understand the mechanical behavior of granular and fine particle systems for maneuver; to understand physical interactions in the dense urban environment for command and control; and for intelligence with a plan to explore mountain communications for command and control.

Overall Scientific Quality and Degree of Innovation

The research completed within the program is novel and broad, similar to activities potentially supported at DOE and NSF, but with relevance to the Army. Research specifically highlighted related to granular mechanics investigations of granular assemblages with the effects of grain roughness, mineralogy, and comminution accommodated to define evolving rheology, to develop realistic and efficient digital elevation models (DEMs) to accommodate the complex response of angular granular assemblages, and to understand the geophysical signatures of such assemblages. Related activities included understanding the entrainment, transport, and deposition of dilute granular suspensions, relevant to alluvial and aeolian systems—in particular, with models capable of accommodating realistic grain geometries and domains of sufficient dimension or grain-numbers to test scientific hypotheses of aggregate response. A current MURI on coarse-grained systems and a forthcoming MURI on fine-grained granular systems offer potential for important advances in these areas. Specifically, such projects that link single investigators with complementary skills in analysis, imaging, and observation is an effective method in boosting scientific value from a small team and its broadened scientific perspective.

This overall theme of the response of heterogeneous systems extends to other projects. One such project is the behavior of ice and ice-laden materials involving phase change owing to melting and the evolution of rheology. Another such project is the integration of transport and disaggregation of earth materials across a broad range of scales in contributing to the understanding of stratified flows together with the impact of moisture and state of materials on their geophysical signatures. These projects, broadly representative of earth-water-atmosphere interactions, have complementary linkages to the mechanics of such systems. These projects that define the program portfolio provide coherence between the dual themes of granular mechanics and earth-water-atmosphere interactions.

Scientific Opportunity

The program has been successful in establishing a broad theme linking the mechanics of complex earth materials with processes and textures that evolve from earth-water-atmosphere interactions at a wide range of length scales. These areas are rich for discovery—in particular, the proposed extension to explore the more complex mechanics of fine-grained materials is an exciting one that will probe the important impacts of chemical, biological, and complex fluid-solid interactions. The currently proposed directions of the program are largely in continuation of the successful and productive direction of the current program—understanding the complex response of multi-phase materials, across the scales and with specific application to earth-water-atmosphere interactions—a very broad suite of potential disciplines. Proposed extensions to this are to tailor the large-scale interactions of earth-water-atmosphere to include implications for the built environment and to explore controls on information transmission in challenging environments via seismic acoustic and electromagnetic signals. The former of these is linked to urban environments and presents important scientific challenges. The second proposed focus, on information transmission, is also rich in potential discovery, with application to both wireless communication and in process-based understanding of remote sensing signals that is logically linked to the mechanics-based elements of the existing and evolving program.

Significant Accomplishments

Accomplishments described in the review represent significant scientific advances. In particular, the program appears to host a large number of early- through mid-career researchers with a diverse and creative portfolio of investigations. In particular, the program accommodates this diverse array of projects under the dual themes of the complex mechanics of multiphase earth materials and earth-water-land interactions—essentially defining behavior across the scales. Scaling micromechanical analyses to engineering-relevant representative-volumes is noteworthy. Such calculations intrinsically limited by the grain number, the grain-grain interactions, and limits on computational resources are noteworthy. Although it is difficult to determine the ingenuity and impact of the work done by the investigators involved based on limited project details provided by ARO, members of the panel are familiar with the work done by many of these principal investigators (PIs), and it is of very high quality. Integrated metrics of papers published, numbers of students and postdoctoral researchers supported, and a broad array of transitions is indicative of a well-directed program.

Partnerships and Transitions

This program has been particularly successful in developing follow-on linkages with other DoD offices—notably, with the Cold Regions Research and Engineering Laboratory (CRREL) but also with broader government agencies, such as National Oceanic and Atmospheric Administration (NOAA). These linkages include internally funded basic research projects, joint field campaigns, and intellectual linkages through summer internships. Together, these transitions identify the broad relevance of the program in transitioning its scientific vision to engineering applications.

Level of Effort

In addition to the intrinsic scientific outcomes, the program covers an unusually broad spectrum of spatial and temporal length-scales and complex solid-liquid-gas/land-water-atmosphere interactions and integrates laboratory and analytical investigations that span micrometer to kilometer scales. The large number of successful transitions with awards to other DoD programs identify the broad applicability and relevance of the supported research.

Other

The program has been successful in developing a coherent and interleaved research program between multiple investigators that leverages the existing resources and maximizes scientific impact—the program is producing important results and discoveries. This thoughtful and well-executed development of an interdisciplinary research program is commendable. The development of the program included grantees meetings and workshops as two potential mechanisms to retain momentum, broaden the catchment of research topics, and to expand the success.

There are clear and close linkages of the Earth Materials and Processes Program with the Solid Mechanics and Fluid Dynamics Programs and potentially with the Complex Dynamics and Systems Program.

FLUID DYNAMICS PROGRAM

The vision of the Fluid Dynamics Program is to develop frameworks for understanding and exploitation of nonlinear flow interactions. This program's research strategy is to address the following three key scientific questions: (1) Does turbulence possess a "structure"? If so, can it provide a useful description of turbulent flow behaviors and permit control? (2) Can the complexity of the Navier-Stokes equations be reduced while maintaining essential physics of a given flow? (3) What novel strategies allow computation of flow physics, balancing accuracy and efficiency, without simply relying on massive parallelization?

The general aim of the Fluid Dynamics Program is to improve the current understanding of flow phenomena via theory, computation, and experiment. Specific objectives are the efficient prediction of flow physics, the discovery of novel flow phenomena, and the generation of new strategies for flow control. Interest in this general area is related to the Army's Functional Concepts for maneuver (e.g., projectiles direction in flight, vertical lift vehicles, and attack reconnaissance aircraft), sustainment (e.g., the endurance required to operate in sufficient scale over ample duration), and fires (e.g., precision strike missiles and extended range cannon artillery).

Overall Scientific Quality and Degree of Innovation

The overall scientific quality of the program is very good, with a proper mix of very capable established and young investigators, and theoretical, computational, and experimental projects. Several researchers supported by the program—nearly 30 percent—have received significant awards. The general focus of much of the research, with its emphasis on turbulence, the development of reduced-order models for fluid flow and computing, is rather predictable, but, in an established field such as fluid dynamics, it could not be otherwise. While these are the dominant topics of the program, appropriate breadth is achieved by supporting research in other areas as well, such as particulate and biological flows, harnessing flow for material assembly, and the prediction of unsteady boundary layer separation. Compressible flows—structure of supersonic flow, shock-boundary layer interaction—are also an important and appropriate component of the program, although the character of the program in this area is somewhat less innovative than in some of the others. Side-by-side with established methods of investigation, new methods are being developed, an example being the application of machine learning to pursue a reduction in the complexity of fluid flows.

The program currently supports three MURIs—two devoted to the development of novel computational methods and one exploring flow in the glymphatic system of the brain. These are all high-quality projects in the hands of very capable investigators and one can expect significant fruits from these investments.

Scientific Opportunity

Several investigators are trying to open new research pathways in unconventional directions and there is a certain amount of risk associated with these efforts. While machine learning and, more generally, big data ideas and methods are finding their way in the broad field of fluid dynamics and can be considered, therefore, a rather safe bet, the jury is still out for others, such as the application of network theory to fluid flow problems or the development of hyperbolic Navier-Stokes equation methods. Close attention needs to be paid to these projects, and a critical evaluation of their results is appropriate. The need to pursue niche opportunities and support work not supported by the larger, in a sense competing, programs mentioned before, is understandable, but an excessive reliance on this strategy is also a risky proposition.

The support of novel and sophisticated experimental methods—for example, luminescent micro-beads for particle-image velocimetry, molecular tagging velocimetry in liquid helium, micro skin-friction sensors, and highly resolved tomographic particle image velocimetry—is an interesting facet of this program. Computation is also an essential component of modern fluid dynamics. ARO's research program in this area is properly based on the recognition that standard approaches will never be sufficient owing to the basic limitations of the existing and future computing equipment. For this reason, in addition to the further improvement of standard approaches, the program includes less-traditional components—such as operator-based methods, hyperbolic Navier-Stokes equations, and fractional order methods for conservation laws—to which the previous comments are applicable.

A suitable research opportunity may exist in the area of compressible flow turbulence, which would seem highly appropriate for ARO's Fluid Dynamics Program. Additional research opportunities in the biofluids area might also be considered.

Significant Accomplishments

It is understandable that the major accomplishments to date have been achieved in what may be considered the more established and, perhaps, traditional areas of the program. New ideas and methods will take a longer time to bear comparable fruits. Examples of significant accomplishments to date are the refinement of large-eddy simulation methods by means of a clever use of information on the local flow physics, high-order overset methods for accurate computational fluid dynamics (CFD) solutions in complex geometries, and the stabilization and control of projectile trajectory by an improved understanding of aerodynamic force generation.

Partnerships and Transitions

The program has generated some interesting transitions and partnerships. NASA is in the process of adopting the hyperbolic Navier-Stokes equations for its FUN3D code. An overset method developed under support of the program has been adopted for the Army's rotorcraft code HELIOS. A cooperative agreement has been entered which supports the long-range distributed and collaborative engagement ERP.

Level of Effort

Several other research programs in the fluid dynamics area are in existence supported by other government organizations (e.g., NSF, NASA, AFOSR) as well as private entities (e.g., the Boeing Corporation). The ARO's effort cannot compete with many of these in terms of scale. Rather, it tries to find niche opportunities of particular relevance to ARO approaching new investigators and trying to promote research collaborations.

Other

Historically, fluid dynamics has played an important role in the development of methods for, and understanding of, complex systems. A well-known example is the Lorenz model and its role in the early days of chaos theory. Thus, natural crosscutting opportunities for the Fluid Dynamics Program exist with the Complex Dynamics and Systems Program. For example, applications of the Koopman operator are being pursued by the fluid dynamics research community, and this is one of the areas supported by the Complex Dynamics and Systems Program. Fluid problems are naturally high-dimensional systems, and this is another research area of interest to the Complex Dynamics and Systems Program.

Another natural crosscutting opportunity exists with information sciences, given the strong current interest on the part of the fluid dynamics community in the general area of big data. In spite of extensive research conducted over the past 30 years, predictive models of the dynamics of turbulent flows over a wide range of scales and frequencies remains an unmet demand. Machine learning and neural networks techniques are currently being used with some degree of success to analyze the dynamics of nonlinear complex turbulent flows.

PROPULSION AND ENERGETICS PROGRAM

The vision of the Propulsion and Energetics Program is to develop the ability to control chemical energy release rates in energetic materials and fuels via the understanding of phenomena governing initiation, burning, reaction, and extinction. This program's research strategy is to address the following three key scientific questions: (1) What are the chemical mechanisms that control ignition and initiation in high energy density systems? (2) How can researchers manipulate processes in materials and material interfaces to achieve control over reactions and reaction rates? and (3) What modeling frameworks enable predictive, computationally efficient models of large-scale processes? The Propulsion and Energetics Program aims to perform basic research (6.1) to create revolutionary capabilities for the future warfighter. This vision, while unspecific, is well suited to drive novel scientific advancements. A capability of the

U.S. Army to tailor energetic material performance in terms of delivery time scale, location, and total energy has unique opportunities to facilitate adversary overmatch for the warfighter. A modern demonstration of this vision would be expected to include crosscutting projects that bridge areas such as solid mechanics, interface transport phenomena, turbulent combustion, or advanced manufacturing.

Overall Scientific Quality and Degree of Innovation

The program includes high-quality research projects, yet some concerns do exist, as discussed here. In some cases, strong claims have been made without supporting evidence.

One research project seeks to develop a liquid-phase chemical reaction mechanism for the explosive compound RDX, intended for application as a burn modifier. The confined rapid thermolysis (CRT) experimental method is limited to detection of rapid thermolysis type reactions from the liquid phase. RDX is solid at ambient conditions, meaning that the reaction mechanism does not include any kinetics of condensed-phase reactions, surface and interfacial reactions, gas/solid reactions, and even gas/gas reactions and focuses exclusively on unimolecular decomposition reactions. In real processes, decomposition species evolution occurs in time, yet these time dependencies are not possible to segregate by the CRT method. These limitations suggest caution when applying the mechanism to combustion models where complex physiochemical processes exist or to models at detonation pressures. What the program failed to make clear is the transformative opportunities and innovative nature of this RDX reaction mechanism that has limitations in capturing processes from materials initially at ambient, solid-state conditions. Additional detail about the transition of the HMX reaction model to in-house codes and Army customers may help to address this concern.

The research project to advance kinetic mechanisms of Army fuels using shock tube methods seeks to address the auto ignition behavior that causes knock in engines. While the shock tube method has been used quite extensively to study the gas-phase kinetics of various fuel/oxidizer mixtures, the method is not able to represent the fuel spray dynamics and the in-cylinder temperature and pressure most relevant to engines. This work has not yet been applied to Army-relevant fuels (e.g., JP-8) and fuel blends, nor does the work indicate that kinetic mechanisms to support the flame speed measurements will be an outcome of this project. The researchers need to clarify the relationship of the objectives of this project to compliment other Army TARDEC-funded research occurring in more engine-relevant conditions and with Army-relevant fuels and fuel blends.

There are some concerns about the projects addressing the key scientific question on frameworks for predictive models. Emphasis was placed on the higher dimension of the manifold rather than the higher dimension of the physics or the addition of new physics. One-dimensional manifolds are not limited to 1D physics; they might have higher dimensionality in terms of physics than 2D manifolds; and they might have more embedded physics than 2D manifolds. The emphasis on the manifold leads the observer to infer that the work is not extending the physics or the physical dimensionality of the flamelet configuration. Extending the manifold without extending the physics only increases computational cost without any clear gain. This comment has relevance to the project on adaptive modeling of cool flame-assisted ignition and combustion where mention is also made of 2D manifolds.

The claim of greater efficiency than given by tabular storage can be achieved by calculating manifold solutions only as needed and then storing for repeated use is unsubstantiated and is questionable. When a set of quantities from one calculation is stored to five or more significant digits, they will likely never be repeated exactly over space and time in the large-eddy simulation. So, when are they reused and why are they saved? They would only be useful for storage if one were willing to interpolate between stored values. The question then arises whether the stored data allows optimal interpolation. A table can be arranged to give optimal interpolation. It can also be limited to cover the range of needed inputs and outputs. Furthermore, the concern about memory cost for tabular storage was addressed years ago by

Ihme et al. at Stanford University.[1] Deep learning neural networks require low memories and provide better means for interpolation than traditional tabular storage.

The work on adaptive modeling of cool flames is interesting and is widely believed to be relevant to knock problems in diesel engines. A concern is that computations for cool flames have been strongly dependent on boundary conditions, and therefore it must be inferred that they cannot be viewed as independent flames. Rather, their stability is dependent on a global environment. Perhaps a solution has been found but clarification is needed.

The research on adaptive modeling and diagnostics of cool flame-assisted ignition and comb claims that an order of magnitude reduction in computational time is achieved compared to traditional chemical solver solutions. It is not explained what that method is other than with the undefined "PFA" label. If the method is the use of flamelet theory, then that is old news, established by many other researchers. The use of neural networks for flamelet theory also is not new, as noted above.

In summary, several claims have been made in justifying the launching of some work. More justification is needed for such work.

Scientific Opportunity

The scientific opportunities of the current program are difficult to discern. This results from a program heavily weighted on gas-phase combustion that involves long-established researchers in the field or projects making strong, unsubstantiated claims. In many projects, the reliance on existing experimental facilities that are evolving incrementally to reach extreme test conditions may be limiting entrance of innovative ideas and a diversity of researchers.

The focus to unravel complex kinetic mechanisms is noteworthy and commendable. The ability to reduce those detailed kinetics into strategic transitions to the Army was not fully explained.

Significant Accomplishments

The current program contains projects with low technical risk exposure. That is, the projects generally encompass incremental advancements to established experimental or computational methods or application of methods to materials already in existence. As a result, the accomplishments of the program are not anticipated to drive significant transformation in their respective field. This program could benefit from shifting focus to new projects with higher technical risk.

Partnerships and Transitions

Transitions are broadly defined to include research deliverables and personnel for internal and external Army customers. Of the eight transitions listed for the review period, only half of listed transitions show immediate delivery to the Army.

For the project on the RDX reaction mechanism, the project accomplishments include the validation of an HMX reaction mechanism. It is not clear if the reported transition of an HMX reaction model to Army in-house codes is a direct result of ARO funding. For the project on the dynamic response of reactive materials, the deliverables were not clear.

The relationship of future potential transitions to the Army modernization priorities were not clear.

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[1] M. Ihme, C. Schmitt, and H. Pitsch, 2009, Optimal artificial neural networks and tabulation methods for chemistry representation in LES of a bluff-body swirl-stabilized flame, *Proceedings of the Combustion Institute* 32(1):1527-1535, https://doi.org/10.1016/j.proci.2008.06.100.

Level of Effort

The current program is heavily focused on gas phase kinetics for the purpose of developing or improving existing kinetic mechanisms for liquid fuels and possible propellant burn modifiers. As a result, the current program does not differ significantly in its goals and focus from a program that would have been reviewed more than 10 years ago.

Other

The program seeks to address three key scientific questions. These questions are broadly posed such that they do not provide a useful discriminator for proposal evaluation and prioritization. The first question—What are the chemical mechanisms that control ignition and initiation in high energy density systems?—suggests that mechanisms of condensed explosives is of interest, yet much of the research supporting this question is in liquid fuels and engine applications. The second question—How can researchers manipulate processes in materials and material interfaces to achieve control over reactions and reaction rates?—is supported by a project that could be considered more appropriate for applied research (6.2). The third question—What modeling frameworks enable predictive, computationally efficient models of large-scale processes?—was missing a discussion of technical gaps in existing DOE/DoD codes that already perform simulations across scales.

The program did not plan for adjustments in FY 2021 to the key scientific questions. The program's vision and key scientific questions need to be reviewed in order to refocus the program to modern opportunities and technical knowledge gaps, to remove barriers for accessing new research opportunities, and to improve transparency in proposal selection. The program could strongly benefit from increased breadth in researchers via crosscutting initiatives bridging chemistry, materials science, fluid dynamics, and solid mechanics.

SOLID MECHANICS PROGRAM

The Solid Mechanics Program aims to uncover the physical processes responsible for deformation, damage initiation and propagation, and failure of material systems—particularly under extreme pressure, strain rate, and repetitive loading—ultimately leading to the creation of lightweight, resilient, and adaptable soldier and system protections. This program's research strategy is to address the following four key scientific questions: (1) How can a material system's response to dynamic or complex loads be analytically described and predicted? (2) How can dynamic crack growth be visualized and predicted? (3) How do material defects, system morphology, and temperature affect damage propagation? and (4) What can researchers learn from biological and geological systems to strengthen and toughen material systems?

Overall Scientific Quality and Degree of Innovation

The goal of the program is light, resilient, and adaptable materials for protection of both the warfighter and vehicles or other systems. Of principal concern are high-pressure loadings, high strain rates, and repetitive loadings. Lightweight but strong materials can reduce the weight of personnel protection in body armor, thus enhancing maneuver and protection for the soldier. Better understanding of material defects and fracture can both increase the strength and durability of protective systems. Improved performance under repetitive loads can extend the service life of protective systems and vehicles, thus enhancing maneuver and resilience.

The new PM has done an excellent job in rationalizing the existing portfolio of projects. The portfolio has been reorganized around three themes: constitutive response; visualization and prediction of fracture patterns; and defect, morphology, and temperature effects. The quality of the individual projects and PIs is strong on average but variable. The program hosts several well-known and accomplished researchers, and has a good mix of young and capable researchers at lesser-known universities. Some projects may not be at the cutting edge of important problems in solid mechanics, but the PM needs the leeway in reformulating the portfolio.

Scientific Opportunity

The current transition to new leadership offers a moment of opportunity to direct and focus the research of the program. This will not happen in a sharp turn but in a progression of terminating projects and judiciously funding new ones. The questions to be decided are how best to focus research opportunities to achieve Army objectives of protection, maneuver, resilience, and sustainment; and what areas of work to de-emphasize in the transition. The current ARO thinking that response to dynamic loads and crack growth and visualization may be de-emphasized in future awards seems consistent with current opportunities in the field.

The areas of focus for the program in the near future have tentatively been identified as (1) damage across scales—hierarchical materials and structures; (2) the isolation of defects and inhomogeneities to control damage; and (3) nature-inspired design. Each of these builds in part on existing strengths of the program. The first two were briefed in the presentation, but the third was only mentioned and it is not clear to what extent it constitutes a separate thrust for the future. Nonetheless, this third focus may represent the boldest shift and biggest opportunity, but one caution is that this field is not entirely new and the mechanics of biological systems has been an active field for some time. A concern is the program moving away from solid mechanics to design. Of course, these fields are related, but the question is where is the emphasis going to be placed? The concept that there are important new lessons to be learned from geomaterials might be questioned, and did not seem well supported. Many of the current projects in the portfolio relate to one or more of these new directions, but not all. A decision will have to be made on what current directions to de-emphasize. This transition in program direction is a critical moment of opportunity and needs to be both carefully planned and critically reviewed. The projects that have already been awarded in the new thrust areas of hierarchical structures and inhomogeneities appear modest steps in the new directions. To be successful, bolder projects may need to be funded.

Significant Accomplishments

The Solid Mechanics Program is the smallest of those in the Mechanical Sciences Division, having an FY 2019 budget of about 8 percent of the total and per-project funding of about 80 percent of the division average. Peer-reviewed publications at about 1.4 per project-year and graduate student-postdoctoral support of about 1.5 per project-year are each modest. The raw number of peer-reviewed published papers is, of course, an inadequate metric for research quality. The venues of publication would be useful additional information.

Partnerships and Transitions

The number of transitions in the Solid Mechanics Program is modest compared to the other programs. This, in part, can likely be ascribed to the lack of permanent leadership in recent years, to the broad funding of seed projects, and to limited overall funding. Four transitions to customers are described, of which two are co-authored publications. No MURI or PECASE opportunities have followed from the current portfolio.

Collaborations with other ARO programs are possible and could leverage resources and expertise. There is one present project involving the geomechanics of Berea sandstone with an obvious connection to the Earth Materials and Processes Program. However, it is not in one of the thrust areas of that other program. Effort could be invested in reviewing for opportunities in the Materials Science Division areas. A particularly attractive area of collaboration could exist in the area of biomechanics, from the perspectives of nature-inspired materials, warfighter interactions with protective systems, and injury prevention.

Level of Effort

Solid mechanics is by definition a broad discipline, and the scope of the current portfolio of projects reflects that breadth. The program is in transition from a multiyear period of acting leadership to one with a recently recruited but permanent PM. Thus, the current portfolio of projects represents, by its history and intention, a collection with an unusual number of seed opportunities awaiting a centralizing vision. The recent recruitment of a new PM could facilitate defining that vision.

Other

The current transition in the program has led to a rationalizing of the structure of the portfolio and a tentative identification of new areas of focus, both building on existing projects and developing new ones. This is a promising time to assemble workshops to bring the principal investigator community together to help inform planning for the new portfolio. This needs to be a high-priority initiative.

OVERALL ASSESSMENT

In general, the scientific quality of the work funded is of sufficiently high quality and is not of concern. As expected, this fundamental research program of the ARO, when considered as a whole, supports a large number of smaller projects that have a distribution from very high risk, unproven concepts (e.g., dynamic analysis frameworks) to very low risk, historically vetted methods (e.g., shock tube methods). The majority of the questions are aimed at understanding the methodology for PM-selected focus areas within their proposal. In general, the PM appears to have significant autonomy in adjusting the focus areas of the research portfolio—it is the PM who can target potential PIs, manage the proposal review process, assemble proposal review scores, and make final recommendations as to prioritization of funded projects. The individual PM-centric approach for managing division portfolios raised questions related to transparency and methodology of proposal solicitation, proposal review and final assessment, and proposal selection for risk balancing and strategic alignment. This level of PM independence could impede ARO's top-down distillation of Army needs into research thrusts for funding.

In addition to technical diversification or collaboration between projects, some portfolios would also benefit from increased diversity of research PIs to include early-career PIs and less long-term continued funding provided to late-career PIs.

As demonstrated by the newer PM, focus questions were adjusted at review time in order to give the research portfolio a cohesive focus. This indicates that the portfolios are not being managed by a strategic plan with a long-term timeline; instead, the goals of any given year are adjusted on demand. This has implications for the autonomy of the PM to follow research that may not be best aligned with the long-term ARO strategy.

Recommendation 10: The Army Research Office (ARO) management should establish processes that help to ensure that proposed research is unique, pioneering, and/or novel. ARO management should place emphasis on envisioning and conducting workshops or other events that reach beyond the current cadre of funded principal investigators to explore fields broadly and define new directions and new investigators for the programs.

In a number of divisions, areas of missed opportunity for interdivision collaboration and an apparent stovepipe of projects under each PM were identified. There were certainly examples where this is not the case, but in an agile and responsive research portfolio, more interdisciplinary projects are expected. The MURI projects provide a good example of interdisciplinary projects, yet these are not readily accessible to most projects within a PM's portfolio. Efforts to promote improved collaboration across ARO divisions and scientific disciplines would be beneficial.

Recommendation 11: The Army Research Office (ARO) management should develop mechanisms that facilitate interactions within the Mechanical Sciences Division and with the Materials Science, Chemical Sciences, and Physics Divisions. ARO should focus these interactions to be on funding projects with aligned priorities within the programs, be they within the same division or across divisions.

15

Crosscutting Recommendations

The research strategy within the Army Research Office (ARO) Engineering Sciences Directorate (ESD) seems to be principally a bottom-up one, where the program managers (PMs) have primary discretion and authority regarding project selection and funding decisions. The PMs are all well qualified for their positions. The directorate strategy is to pose bold scientific questions; to seek collaborations; to engage with the Army laboratories for transitioning the research; to seek out high-risk, high-reward opportunities; to venture into new areas with long-term impact on enhancing Army capabilities; and to hire and retain excellent workforce. All of these items are meritorious. This strategy includes "casting a wide net," even though funding levels are relatively small compared to peer organizations such as the Department of Energy (DOE), National Science Foundation (NSF), Air Force Office of Scientific Research (AFOSR), Office of Naval Research (ONR), and so on. By having the PMs follow both directorate program planning and respective division strategy transitions to the Army could be enhanced. Because the directorate investment is relatively small and the opportunities in engineering sciences are large, focusing the research topics could possibly result in more benefit to the Army through transitions without loss of scientific excellence.

ESD Crosscutting Recommendation 1: The Army Research Office (ARO) program managers (PMs) should be encouraged to prioritize directorate and division strategy with respect to focusing project selection by further improving the connection of scientific discovery to Army transitions.

In general, the scientific quality of the work funded is of sufficiently high quality and is not of concern. In general, the PM appears to have significant autonomy in adjusting the focus areas of the research portfolio—it is the PM who can target potential PIs, manage the proposal review process, assemble proposal review scores, and make final recommendations as to prioritization of funded projects. The individual PM-centric approach for managing division portfolios raised questions related to transparency and methodology of proposal solicitation, proposal review and final assessment, and proposal selection for risk balancing and strategic alignment. This level of PM independence could impede ARO's top-down distillation of Army needs into research thrusts for funding.

In addition to technical diversification or collaboration between projects, some portfolios would also benefit from increased diversity of research PIs to include early-career PIs and less long-term continued funding provided to late-career PIs.

ESD Crosscutting Recommendation 2: The Army Research Office (ARO) management should establish processes that help to ensure that proposed research is unique, pioneering, and/or novel. ARO management should place emphasis on envisioning and conducting workshops or other events that reach beyond the current cadre of ARO PMs and funded principal investigators (PIs) to explore fields broadly and to define new directions and new, early-career, and more diverse participants for the programs.

Overall, the ESD is conducting very high-quality research. The programs are driven, in an entrepreneurial manner, by well-qualified individual PMs who can take their programs in different directions without significant bureaucracy. However, these individual PMs need strategic positioning and appropriate incentives to coherently drive their programs for maximum transitions to the Army. Overall, the quality of programs reviewed was high, but there were limited initiatives aimed at new research directions and pursuing high-risk, high-reward projects that could lead to discovery and inventions of greater scientific significance.

ESD Crosscutting Recommendation 3: The Army Research Office (ARO) should expand on new research directions and high-risk, high-reward projects that could lead to discovery and inventions of greater scientific significance.

In a number of divisions, areas of missed opportunity for interdivision collaboration and an apparent stovepipe of projects under each PM were identified. There were certainly examples where this is not the case, but in an agile and responsive research portfolio, more interdisciplinary projects are expected. The MURI projects provide a good example of interdisciplinary projects, yet these are not readily accessible to most projects within a PM's portfolio. Efforts to promote improved collaboration across ARO divisions and scientific disciplines would be beneficial.

ESD Crosscutting Recommendation 4: The Army Research Office (ARO) management should develop mechanisms that facilitate interactions within the ARO directorates and divisions, including for example the Mechanical Sciences and Electronics Divisions and the Materials Science, Chemical Sciences, and Physics Divisions. ARO should focus these interactions to be on funding projects with aligned priorities within the programs, be they within the same division or across divisions of different directorates.

Part IV: Army Research Office-Wide Crosscutting Recommendations

16

Army Research Office-Wide Crosscutting Recommendations

Based on the 2018-2020 reviews whose assessment is summarized in this report, the Army Research Technical Assessment Board (ARLTAB) offers the following Army Research Office (ARO)-wide crosscutting recommendations.

In general, the research strategy within ARO directorates seems to be principally a bottom-up one, where the program managers (PMs) have primary discretion and authority regarding project selection and funding decisions. The PMs are all well qualified for their positions. The directorates' strategy seems to be to pose bold scientific questions, to seek collaborations, to engage with the Army laboratories for transitioning the research, to seek out high-risk, high-reward opportunities, to venture into new areas with long-term impact on enhancing Army capabilities, and to hire and retain excellent workforce. All of these items are meritorious. This strategy includes "casting a wide net," even though funding levels are relatively small compared to peer organizations such as DOE, NSF, AFOSR, ONR, and so on. By having the PMs follow both the respective directorate program planning (Topic Formation: Scientific Opportunity/Army Impact) and respective division strategy, transitions to the Army could be enhanced. Because the ARO investment is relatively small and the opportunities are large, focusing the research topics could possibly result in more benefit to the Army through transitions without loss of scientific excellence.

ARO Crosscutting Recommendation 1: The Army Research Office (ARO) program managers (PMs) should be encouraged to prioritize directorate and division strategy with respect to focusing project selection by further improving the connection of scientific discovery to Army transitions.

Overall, ARO is conducting very high-quality research. The programs are driven, in an entrepreneurial manner, by well-qualified individual PMs who can take their programs in different directions without significant bureaucracy. However, these individual PMs need strategic positioning and appropriate incentives to coherently drive their programs for maximum transitions to the Army. The quality of programs reviewed was high, but had limited initiatives aimed at new research directions and pursuing high-risk and high-reward projects that could lead to discovery and inventions of greater scientific significance.

ARO Crosscutting Recommendation 2: The Army Research Office (ARO) should expand on new research directions and high-risk, high-reward projects that could lead to discovery and inventions of greater scientific significance.

Advances in the fields increasingly rely on contributions made by scientists who have different areas of expertise. For example, in chemistry, combined efforts in modeling and experiment are often essential for significant advances. Similarly, progress in condensed matter physics often depends on collaborations between individuals skilled in materials synthesis and scientists pursuing new phenomena. In addition, all the physical sciences are increasingly relying on data analytics. The PSD currently has some selected examples where funding of pairs of researchers from different disciplines, working synergistically, has led to significant success. Priority could go to those who have a demonstrated history of successful collaborations. PMs could set priorities in terms of desired outcome and let researchers get together to make proposals.

ARO Crosscutting Recommendation 3: The Army Research Office (ARO) should encourage the funding of pairs of principal investigators (PIs) from different disciplines who will work together on common problems, including those that are interdivisional and interdirectorate. For example, for the Physics Division, ARO should encourage the funding of collaborative projects that involve both materials synthesis and condensed matter physics, as well as joint quantum information algorithms and information sciences projects, which would all be interdirectorate; for the Chemical Sciences Division, ARO should consider modeling and experiment, which are both within the division; and for the Life Sciences Division, ARO should consider mechanisms to improve data analytics to inform its explanatory models, which is also interdirectorate.

The PMs within ARO currently do a good job of going to conferences and staying abreast of the exciting new work within their fields. They also do well in advertising their programs and interests to their own communities at such conferences. However, this highly targeted approach to publicizing the activities of ARO means that many members of the broader scientific community are unaware that ARO is a potential source of funding. That means that ARO is not seeing all the proposals from new PIs with different perspectives that it might. This limitation is of particular importance when it comes to attracting researchers in biology and other life science disciplines because a life scientist is very unlikely to think that an organization called Physical Sciences Directorate would be interested in what he or she does.

ARO Crosscutting Recommendation 4: The Army Research Office (ARO) should find ways to further disseminate its funding opportunities to the broader community. For example, the Physical Sciences Directorate should find ways to reach the broader biology and life sciences community, which is unlikely to be recognized as an opportunity given its Physical Sciences name.

Diversity of gender, age, and geographic location was acknowledged across the ARO as requiring attention. Efforts to promote improved collaboration across ARO divisions and scientific disciplines would be beneficial. Program managers have the ability to encourage female and minority researchers to submit white papers and follow up with complete proposals, and there is need for an analysis and tracking of demographic diversity across ARO. In addition to technical diversification or collaboration between projects, some portfolios would also benefit from increased diversity of research PIs to include early-career PIs and less long-term continued funding provided to late-career PIs.

ARO Crosscutting Recommendation 5: To increase diversity within the Army Research Office (ARO) and the programs it supports, ARO should carry out a detailed assessment of the diversity of participants, both within ARO itself and in the programs that ARO supports. ARO should then establish a clear diversity policy and plan and should measure its progress against this plan.

Appendixes

A

Possible Metrics for Assessment of Program and Project Accomplishments and Plans

PROGRAM AND PROJECT ACCOMPLISHMENTS

- Did the accomplishments represent significant scientific advances?
- What are major consequences for the science if the project succeeds?
- Is the potential, long-term Army application of the research significant?
- Is the research novel, leading the field in an important area, and does it have the appropriate level of risk and payoff?
- Was related research being sponsored by other major players adequately summarized in terms of approach and/or goals? Were there areas of duplication?
- When comparisons are made, are the comparison groups well defined?
- How do the accomplishments map to the stated program goals and Army Research Office (ARO) strategic plans?
- Do the accomplishments reflect productivity and ingenuity on the part of the performers?
- What portion of the accomplishments is attributable to the ARO funding?
- What is the network of contacts involved in the project?
- Were there appropriate examples of significant transitions, or anticipated transitions of research, to follow on applied research or exploratory development either within industry or within an Army or Department of Defense (DoD) laboratory?
- Are there any high-priority missed opportunities/areas relating to the program or project?
- Was the speed of knowledge acceleration or transfer appropriate?
- What are the number, type, and caliber of awards and recognition related to the program or project?
- Has follow-up funding been awarded for the project or program?

PROGRAM PLANNING

- How, specifically, does the project address one or more critical challenges that the Army of the Future will face?
- Should research funding topically align with the current or the anticipated future focus of a division/program?
- Is there a clear and cogent strategy regarding how each of the program managers' major objectives are likely to make substantial and unique progress in advancing scientific frontiers of their discipline?
- Is there some reasonable basis (e.g., incipient breakthrough, new understanding, or novel theory) to believe that the scientific objectives might be met?
- Have the highest priority objectives been selected?

- If not, what is the potential that the accomplishments will lead to significant scientific advances?
- What mixture of collaboration (within ARO and with outside teams/agencies) and competition is best? What percentage of projects should be unique to ARO?
- If higher priority areas are identified, what projects or programs should be reduced or eliminated to accommodate the new areas?
- Are anticipated transitions within the Army likely to be greater than transitions to the commercial sector or other government agencies—for example, the Naval Research Laboratory (NRL) or Office of Naval Research (ONR)?
- Should funding portfolios be homogeneous or heterogeneous? Should funding of divergent or convergent works be preferred?
- What diversified portfolio of short-/medium-/long-term projects; low-/high-risk projects; and collaborative versus ARO-only projects is best, and why?
- What project type (e.g., preliminary exploration, longer term research, workshop, or Multidisciplinary University Research Initiative [MURI]) is best, and why?
- What ratio of faculty, staff, and students is best for a given topic and type of project, and why?
- What principal investigator (PI) turnover rate is best?
- How closely should program managers work with principal investigators? Are research collaborations between both required for a given project?
- What diversity ratios (e.g., gender, age, ethnicity) are best for a given project or program, and why?
- What percentage of a given project or program should be undertaken by postdoctoral researchers and graduate students?
- Are the most qualified applicants selected, independent of geospatial distribution?
- What composition of researchers, practitioners, and entrepreneurs is best to ensure high-quality research results that can be translated into products?
- What are the difficult aspects of a proposed project, and what are the major technical risks involved?

B

Army Research Laboratory Technical Assessment Board Members and Staff Biographical Information

JENNIE S. HWANG, *Chair*, is CEO of H-Technologies Group and a Board Trustee at Case Western Reserve University. Dr. Hwang's career encompasses corporate and entrepreneurial businesses, innovative research, advanced manufacturing, technology transfer and global leadership positions, as well as corporate and university governance, and she is author of 650+ publications/editorials and several internationally used textbooks. Among her many honors/awards are Congressional Certificates of Achievement & Recognition; induction into International Hall of Fame—Women in Technology; named the R&D-Stars-to-Watch; Ohio Women Hall of Fame; Distinguished Alumni Awards; Honorary Doctoral degree; and YWCA Achievement Award. Dr. Hwang was the CEO of International Electronic Materials Corp. and has held senior executive positions with Lockheed Martin Corp., Hanson, PLC, and Sherwin-Williams Co. and co-founded entrepreneurial businesses. Internationally recognized as a pioneer and long-standing leader in the interconnecting electronic materials, electronics miniaturization and advanced manufacturing, she has served as global president of the Surface Mount Technology Association and in other global leadership positions. An international speaker, Dr. Hwang has lectured to tens of thousands of managers/engineers/researchers on emerging technologies and advanced manufacturing via professional development courses. Her speeches range from university commencement addresses to the keynote at DoD Federal Women's Program to tutorials at the U.S. Patent and Trademark Office. She is also a prolific author and speaker on education, workforce, and social and business issues. Additionally, Dr. Hwang has served as a board director for Fortune 500 NYSE-traded and private companies and various university and civic boards (e.g., International Advisory Board of the Singapore Advanced Technology and Manufacturing Institute and a number of international industry boards). At the National Academies, she has served as the NAE Membership Search Executive and Chair of Peer Committee (Materials Section) and on the National Materials and Manufacturing Board, Army Science & Technology Board, NIST Technical Assessment Board and Panels, DoD R&D Globalization Board, Committee on Forecasting Future Disruptive Technologies, Diversity Forum, and NAE Award Committee, among others. She also chaired the Board on Army RDT&E, Systems Acquisition, and Logistics and chairs the Technical Assessment Board of Army Research Laboratory. Dr. Hwang's formal education includes the Harvard University Executive Program, Columbia University Business School Governance Program, and four academic degrees (Ph.D., M.A., M.S., B.S.) in materials science and engineering, chemistry, and liquid crystal science. The Dr. Jennie S. Hwang Award for Faculty Excellence was established at her alma maters. The Dr. Jennie S. Hwang YWCA Award is established in her honor, now for 20 years running, to encourage and recognize outstanding women students in STEM. The Dr. Jennie S. Hwang Endeavor Fund, an endowment at NAE, funds programs that support high school and college students—with a preference for women and underrepresented minorities—to enhance exposure to diverse and/or international perspectives in engineering education, networking, and the profession. For further information, see www.JennieHwang.com.

FREDERICK R. CHANG is the chair of the Computer Science Department in the Lyle School of Engineering at Southern Methodist University (SMU). Dr. Chang is also the executive director of the

Darwin Deason Institute for Cyber Security, the Bobby B. Lyle Endowed Centennial Distinguished Chair in Cyber Security, and a professor in the Department of Computer Science. He is a senior fellow in the John Goodwin Tower Center for Political Studies in SMU's Dedman College. Additionally, Dr. Chang's career spans service in the private sector and in government including as the former director of research at the National Security Agency. Dr. Chang was elected as a member of the National Academy of Engineering in 2016. He is currently the co-chair of the Intelligence Community Studies Board of the National Academies of Sciences, Engineering, and Medicine, and he is also a member of the Army Research Laboratory Technical Assessment Board. Dr. Chang has served as a member of the Computer Science and Telecommunications Board of the National Academies and as a member of the Commission on Cybersecurity for the 44th Presidency. He is the lead inventor on two U.S. patents and has appeared before Congress as a cybersecurity expert witness on multiple occasions. Dr. Chang received his B.A. degree from the University of California, San Diego, and his M.A. and Ph.D. degrees from the University of Oregon. He has also completed the Program for Senior Executives at the Sloan School of Management at the Massachusetts Institute of Technology. He has been awarded the National Security Agency Director's Distinguished Service Medal.

MARK E. EBERHART is a professor in the Department of Chemistry and Geochemistry at the Colorado School of Mines, where he directs the Molecular Theory Group (MTG). At the MTG, knowledge of bonding is obtained through detailed topological analyses of the spatial distribution of electrons in molecules and solids. Many subtle aspects of the distribution become obvious when viewed from a topological perspective. The accompanying topological formalism gives well-defined, unambiguous, meaningful and consistent definitions to previously indeterminate quantities such as atomic bonds and basins. Dr. Eberhart's work is based primarily on first principles computations, which provide the electron charge densities, and topological analysis software developed at the MTG. He is also exploring the topological and geometric origins responsible for the stability of amorphous metallic alloys. In addition to his work on condensed phase systems, his group has active research programs exploring the relationships between charge density and the chemical properties of molecular systems, both organic and inorganic. Dr. Eberhart holds a B.S. degree in chemistry and applied mathematics from the University of Colorado, an M.S. degree in physical biochemistry from the University of Colorado, and a Ph.D. in materials science and engineering from the Massachusetts Institute of Technology.

PRABHAT HAJELA is provost and professor of mechanical and aerospace engineering at the Rensselaer Polytechnic Institute. Dr. Hajela's research interests include analysis and design optimization of multidisciplinary systems, system reliability, emergent computing paradigms for design, artificial intelligence, and machine learning in multidisciplinary analysis and design. Before joining Rensselaer, he worked as a research fellow at the University of California, Los Angeles, for a year, and was on the faculty at the University of Florida for 7 years. Dr. Hajela has conducted research at NASA's Langley and Glenn Research Centers, and at the Eglin Air Force Armament Laboratory. In 2003, Dr. Hajela served as a Congressional Fellow responsible for Science and Technology Policy in the Office of U.S. Senator Conrad Burns (R-MT). He worked on several legislative issues related to aerospace and telecommunications policy, including the anti-SPAM legislation that was signed into law in December 2003. Dr. Hajela is a fellow of the American Institute of Aeronautics and Astronautics (AIAA), a fellow of the Aeronautical Society of India (AeSI), and a fellow of the American Society of Mechanical Engineers (ASME). He has held many editorial assignments, including editor of *Evolutionary Optimization* and associate editor of the *AIAA Journal*, and is on the editorial board of six other international journals. He has published more than 270 papers and articles in the areas of structural and multidisciplinary optimization, and is an author or co-author of four books in these areas. In 2004, Dr. Hajela was the recipient of AIAA's Biennial Multidisciplinary Design Optimization Award.

JAMES S. HARRIS is the James and Ellenor Chesebrough Professor Emeritus in the School of Engineering at Stanford University. Prior to joining the Stanford Department of Electrical Engineering in

1982, Dr. Harris was with Rockwell International Science Center, where he held various positions, from technical staff member to director of optoelectronics research. His major interest is to use molecular beam epitaxy (MBE) to produce unique materials. The growth of such unique combinations of materials enables quantum-size effects to create entirely new device structures based on tunneling electron spin and transitions between quantum states. Most recently, Dr. Harris has applied this technology to incorporate photonic crystal and plasmonic structures to produce an integrated biofluorescence sensor that has been implanted into mice to study cancer development and therapies. He is a fellow of IEEE, the American Physical Society, and the Optical Society of America. In 2000, Dr. Harris received the IEEE Third Millennium Medal. In 2011, he was elected to the NAE "for contributions to epitaxial growth of compound semiconductor materials and their applications." In 2013, he received the Aristotle Award from the Semiconductor Research Corporation. In 2014, he received the Alfred Y. Cho MBE Award at the International MBE Conference. Dr. Harris received his B.S. (1964), M.S. (1965), and Ph.D. (1969) in electrical engineering from Stanford University.

WESLEY L. HARRIS is the Charles Stark Draper Professor of Aeronautics and Astronautics and director of the Lean Sustainment Initiative at the Massachusetts Institute of Technology. Dr. Harris was elected to the National Academy of Engineering "for contributions to understanding of helicopter rotor noise, for encouragement of minorities in engineering, and for service to the aeronautical industry." He has performed research and published in refereed journals in the following areas: fluid mechanics; aerodynamics; unsteady, nonlinear aerodynamics; acoustics; lean manufacturing processes; and military logistics and sustainment. Dr. Harris has substantial experience as a leader in higher education administration and management. He also has demonstrated outstanding leadership in managing major national and international aeronautical and aviation programs and personnel in the executive branch of the federal government. He is an elected fellow of the AIAA, AHS, and NTA for personal engineering achievements, engineering education, management, and advancing cultural diversity.

WILLIAM S. MARRAS is the Honda Chair Professor in the Department of Integrated Systems Engineering at Ohio State University, and holds joint appointments in the Departments of Orthopedic Surgery, Physical Medicine, and Neurosurgery. Dr. Marras is also the executive director and scientific director of the Spine Research Institute and the executive director of the Institute for Ergonomics. His research is centered on understanding the role of biomechanics in spine disorder causation and its role in the prevention, evaluation, and treatment of spine disorders. Dr. Marras's research includes epidemiologic studies, laboratory biomechanics studies, mathematical modeling, and clinical studies. His findings have been published in more than 200 peer-reviewed journal articles and have been cited more than 15,000 times. Dr. Marras also has written numerous books and book chapters, including his most recent book titled *The Working Back: A Systems View*. He holds fellow status in six professional societies including the American Society for the Advancement of Science (AAAS) and has been widely recognized for his contributions through numerous national and international awards, including two Volvo Awards for Low Back Pain Research. Dr. Marras has been active in the National Academies, having served on over a dozen boards and committees, and has served as chair of the Board on Human Systems Integration for multiple terms. He has also served as editor-in-chief of *Human Factors* and is currently deputy editor of *Spine* and is the immediate past president of the Human Factors and Ergonomics Society. Dr. Marras recorded a TEDx talk titled "Back Pain and Your Brain" and was recently featured on NPR's *All Things Considered*. He received a B.S. in engineering from Wright State University, an M.S. in industrial engineering from Wayne State University, a Ph.D. in bioengineering and ergonomics from Wayne State University, and a D.Sc. Honoris Causa from the University of Waterloo.

DANIEL A. REED was named the senior vice president for academic affairs at the University of Utah in April 2019. Dr. Reed is the past vice president for research and economic development at the University of Iowa. He was also the University Computational Science and Bioinformatics chair, and professor of computer science and electrical and computer engineering. Dr. Reed was corporate vice president at

Microsoft from 2009-2012, responsible for global technology policy and extreme computing, and director of scalable and multicore computing at Microsoft from 2007 until 2009. He founded the Renaissance Computing Institute in 2004 and served as its director until December 2007. Dr. Reed was also Chancellor's Eminent Professor and served as senior advisor for strategy and innovation to Chancellor James Moeser, University of North Carolina (UNC), Chapel Hill. He served as CIO and vice chancellor for information technology services at UNC, Chapel Hill, from June 2004 through April 2007. Prior to that, Dr. Reed was director of the National Center for Supercomputing Applications (NCSA), and Gutgsell Professor and head of the Department of Computer Science at the University of Illinois, Urbana-Champaign. He was appointed to the President's Council of Advisors on Science and Technology (PCAST), by President George W. Bush, in 2006 and served on the President's Information Technology Advisory Committee (PITAC) from 2003-2005. As chair of PITAC's computational science subcommittee, Dr. Reed was lead author of the report *Computational Science: Ensuring America's Competitiveness*. On PCAST, he co-chaired the Networking and Information Technology subcommittee (with George Scalise of the Semiconductor Industry Association) and co-authored a report on the Networking and Information Technology Research and Development (NITRD) program called *Leadership Under Challenge: Information Technology R&D in a Competitive World*. He is also a member of PCAST's Personalized Medicine subcommittee. Dr. Reed is the past chair of the board of directors of the Computing Research Association (CRA) and currently serves on its Government Affairs Committee. CRA represents the research interests of the university, national laboratory, and industrial research laboratory communities in computing across North America. Dr. Reed received his B.S. (summa cum laude) in computer science from the University of Missouri, Rolla, in 1978, and his M.S. and Ph.D. in computer science from Purdue University in 1980 and 1983.

LESLIE E. SMITH is scientist emeritus at the National Institute of Standards and Technology (NIST) after retiring as director of the Materials Science and Engineering Laboratory. Dr. Smith was previously chief of the Polymers Division at NIST, where he built a world-class scientific program in polymer science that has made both fundamental advances to science and significant contributions to industrial technology. His personal research interests have been in the absorption of polymers and biological polymers relevant to artificial vascular materials and degradation reactions of polyesters, primarily as related to the lifetime of magnetic storage media. Dr. Smith has also edited a number of professional reference books. His external positions have included U.S. editor, *Polymer Communications*; member, Advisory Committee on Preservation, National Archives; Advisory Board for Polymer Programs, University of Connecticut; Council for Polymer Science and Engineering, University of Akron; chair, Materials Technology Subcommittee, NSTC, OSTP; and member, Board of Directors ASTM International.

DAVID A. WEITZ is the Mallinckrodt Professor of Physics and Applied Physics at Harvard University in the John A. Paulson School of Engineering and Applied Science (SEAS). Dr. Weitz is also the director of the Materials Research Science and Engineering Center (MRSEC), the co-director of the BASF Advanced Research Initiative, a core faculty member of the Wyss Institute for Biologically Inspired Engineering, and a member of the Kavli Institute for Bionano Science and Technology. At Harvard University, Dr. Weitz's research interests are the physics of soft condensed matter, specifically their structural and mechanical properties, the properties of colloidal suspensions, the mechanical properties of biomaterials, and microfluidics for making emulsions using multiphase flow. He also works closely with industry, having served on the board of directors for several start-ups including microfluidics-driven start-ups GnuBIO and Raindance. Dr. Weitz has served as associate editor and member on the *Proceedings of the National Academy of Sciences* editorial board, was a member of the National Academies Panel on Review of the Physical Measurement Laboratory at the National Institute of Standards and Technology, and was a chair on the Condensed Matter and Materials Research Committee. Dr. Weitz has served as a member of the National Academies standing Committee on Biological and Physical Sciences in Space.

Dr. Weitz earned his B.Sc. with honors in physics in 1973 from the University of Waterloo, his A.M. in physics in 1975 from Harvard University, and his Ph.D. in physics, also from Harvard University.

Staff

AZEB GETACHEW is a senior program assistant at the Laboratory Assessments Board (LAB). Ms. Getachew joined the LAB in March 2017 and is responsible for administrative and logistical planning for project meetings and other activities. She previously worked as an interim administrative assistant in several administrative capacities at the National Academies including the LAB, the Naval Studies Board, and the Institute of Medicine. Ms. Getachew has an associate of applied science degree in information systems from Columbia Union College, which is now Washington Adventist University.

EVA LABRE is the administrative coordinator for the LAB. Since 2009, Ms. Labre has been responsible for assisting in the management of the administrative aspects of panel formation, panel meetings, report publication and dissemination, and program development. In addition, she has been responsible for travel expense accounting. In 2014, she was promoted and has recently taken on more responsibilities related to financial aspects of the work of the LAB. Ms. Labre previously held administrative positions at the National Academies on the staff of the Committee on International Organizations and Programs in the Office of International Affairs and on the staff of the Research Associateship Program in the Office of Scientific and Engineering Personnel. Ms. Labre has a B.A. in art history from George Washington University.

JAMES P. MCGEE is the director of the LAB, the Army Research Laboratory Technical Assessment Board (ARLTAB), and the Committee on the National Institute of Standards and Technology (NIST) Technical Programs, all within the Division on Engineering and Physical Sciences (DEPS) at the National Academies. Since 1994, Dr. McGee has been a senior staff officer at the National Academies, directing projects in the areas of systems engineering and applied psychology, including activities of the ARLTAB and projects of the Committee on National Statistics' Panel on Operational Testing and Evaluation of the Stryker Vehicle and the Committee on Assessing the National Science Foundation's Scientists and Engineers Statistical Data System, the Committee on the Health and Safety Needs of Older Workers, and the Steering Committee on Differential Susceptibility of Older Persons to Environmental Hazards. He has also served as staff officer for the National Academies projects on air traffic control automation, musculoskeletal disorders and the workplace, and the changing nature of work. Prior to joining the National Academies, Dr. McGee held technical and management positions in systems engineering and applied psychology at IBM, General Electric, RCA, General Dynamics, and United Technologies. He received his B.A. from Princeton University and his Ph.D. from Fordham University, both in psychology, and for several years instructed postsecondary courses in applied psychology and in organizational management.

ARUL MOZHI is senior program officer at the LAB. Since 1999, Dr. Mozhi has been directing projects in the areas of defense science and technology, including those carried out by numerous study committees of the LAB, the ARLTAB, the Naval Studies Board, the Air Force Studies Board, the Aeronautics and Space Engineering Board, and the National Materials and Manufacturing Board. Prior to joining the National Academies, Dr. Mozhi held technical and management positions in systems engineering and applied materials research and development at UTRON, Roy F. Weston, and Marko Materials. He received his M.S. and Ph.D. degrees (the latter in 1986) in materials engineering from Ohio State University and then served as a postdoctoral research associate there. He received his B.Tech. in metallurgical engineering from the Indian Institute of Technology, Kanpur, in 1982.

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Acronyms

2D	two-dimensional
3D	three-dimensional
AFC	Army Futures Command
AFOSR	Air Force Office of Scientific Research
AFRL	Air Force Research Laboratory
AMP	atomic and molecular physics
AMRDEC	U.S. Army Aviation and Missile Research, Development, and Engineering Center
ARL	Army Research Laboratory
ARLTAB	Army Research Laboratory Technical Assessment Board
ARO	Army Research Office
BRAIN	Brain Research Through Advancing Innovative Neurotechnologies
CCDC	Combat Capabilities Development Command
CERDEC	U.S. Army Communications-Electronics Research, Development, and Engineering Center
CFD	computational fluid dynamics
CMP	condensed matter physics
CMU	Carnegie Mellon University
CRISPR	clustered regularly interspaced short palindromic repeats
CRT	confined rapid thermolysis
CTA	Collaborative Technology Alliance
DARPA	Defense Advanced Research Projects Agency
DEM	digital elevation model
DoD	Department of Defense
DOE	Department of Energy
DURIP	Defense University Research Instrumentation Program
ENZ	epsilon near zero
ERP	Essential Research Program
ESD	Engineering Sciences Directorate
fMRI	functional magnetic resonance imaging
FY	fiscal year
GPS	global positioning system
IARPA	Intelligence Advanced Research Projects Activity

IR	infrared
ISD	Information Sciences Directorate
JILA	Joint Institute for Laboratory Astrophysics
LAB	Laboratory Assessments Board
LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkeley National Laboratory
LWIR	long-wavelength infrared
MRI	magnetic resonance imaging
MTO	Microsystems Technology Office
MURI	Multidisciplinary University Research Initiative
MWIR	medium-wavelength infrared
NIH	National Institutes of Health
NISQ	noisy intermediate-scale quantum
NRL	Naval Research Laboratory
NSF	National Science Foundation
ONR	Office of Naval Research
PECASE	Presidential Early Career Award for Scientists and Engineers
PI	principal investigator
PM	program manager
PNT	position, navigation, and timing
PSD	Physical Sciences Directorate
PVE	poly(vinyl ether)
R&D	research and development
RF	radio frequency
RI	research instrumentation
RRC	Report Review Committee
S&P	synthesis and processing
S&T	science and technology
SBIR	Small Business Innovation Research
SEDD	Sensors and Electron Devices Directorate
SI	single investigator
STIR	Short-Term Innovative Research
STTR	Small Business Technology Transfer
SUSY	supersymmetric
T2SL	Type-II Superlattice
TARDEC	U.S. Army Tank Automotive Research, Development, and Engineering Center
tBLG	twisted bilayer graphene
TRADOC	U.S. Army Training and Doctrine Command
UV	ultraviolet
YIP	Young Investigator Program