A Report on Army Science Planning and Strategy

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U.S. Army Research Laboratory

A Report on Army Science Planning and Strategy

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Executive Summary

As a follow-up to the Army Research Laboratory (ARL) Visioneering 2050 exercises and under the direction of the Assistant Secretary of the Army for Acquisition, Logistics, and Technology, in Fall 2013 ARL hosted a series of meetings to develop a strategic vision for Army Science. Meeting topics were vetted through the ARL Fellows and approved by the ARL Director. Their selection was based on their potential to dramatically impact the Army in the long term. This report is a summary of those meetings and their outcomes.

The six areas selected were: Materials in Extreme Environments, Biological Sciences, Quantum Information and Sensing, Intelligent Systems, Information at the Tactical Edge, and the Human Dimension. Questions considered at these meetings included: “How is this area evolving? Why is it relevant for the Army in the long term? How and why should this topic area be a focus of Army expertise for the long term? What technical elements will be required to achieve excellence in this area?”

An ARL Fellow was the lead organizer for each meeting. Most, but not all, were Army STs. The organizers were aided by senior members of ARL's technical staff and representatives from the other services. For each meeting, ARL invited approximately 15 world-class experts as speakers, with a long-term, broad view of the specific area and an awareness of both commercial and defense trends. The meetings were structured to obtain a variety of viewpoints, not just near-term DoD-related expertise. Target attendance per meeting was roughly 35. Attendees spanned a large variety of Government R&D organizations, both civilian and defense.

The objective of the meeting on Materials in Extreme Environments was to review and assess the global state of the art concerning extreme static pressures in large sample chambers and magnetic fields, ultrasound and other radiation-resonant materials interactions, microstructural evolution and control in electromagnetic fields, and electromechanical response and predictive computational requirements.

The Biological Sciences meeting was unique from others in that it covered an entire discipline, rather than a sub-discipline or focused area within a specific scientific field. For this reason, the Biosciences meeting outcomes were necessarily broader than those from the other meetings. Because the ability to exploit biology is recent, biology as a technology, though not as a science, is relatively immature. The main conclusion from the Biological Sciences meeting is that it provided a solid foundation for targeted follow-up.

Quantum Information and Sensing was chosen as ripe because scientists have recently moved from merely computing quantum properties of systems to exploiting the theoretical foundations of quantum mechanics and “engineering” individual quantum states. Areas identified for particular Army in-house focus include quantum enhanced sensing and imaging, quantum communications, quantum algorithms, and quantum simulations.

The theme of Information at the Tactical Edge was the interaction among and the convergence of both large- and small-scale networks of machines with humans. Meeting foci were on the flow of information between and among complex networks of different genres; the appropriate definitions of (semantic) information in such complex systems; the impact of social, physical and other network layers on information flow; the representation of information and its effective and efficient delivery; and theories and models of performance of human-machine networks.

The meeting on Intelligent Systems focused on the capabilities of Intelligent Systems, Intelligent Systems in Dynamic Environments, and Soldiers Interacting with Intelligent Systems in Dynamic Environments. The intent of these discussions was to consider the capabilities required for a single platform, for multiple platforms in a complex, dynamic environment, and, finally, multiple platforms interacting not only with other platforms but with humans as well.

The meeting on the Human Dimension focused specifically on the study and modeling of humans and their interaction with technology. Topics included quantifying substrates of human behavior, modeling human cognition, expertise and training, human(s)-in-the-cloud, and wearable and implantable technology. These multi-disciplinary topics drew on engineering, physics, psychology, and social sciences in interesting and newly emerging ways.

Based on the output of the meetings and subsequent discussions among meeting organizers, ARL developed several strategic research recommendations and recommendations specific to each area. It was noted that high priority recommendations lie in the intersection between the physical, cybernetic, and human domains.

Strategic Research Recommendations:

ASA(ALT) should

- Support multidisciplinary investigations in the following areas
  - hybrid biological and non-biological systems
  - the integration of neuroscience and training
  - trust in information and intelligent systems
  - the mathematics and cognitive transformation of data to information
  - intelligent platforms as personal advisors and personal assistants
- Increase in-house efforts in quantum information and sensing in conjunction with the establishment of an off- base lab or a joint research institute with a university
- Hold a series of exploratory meetings on additional sub-disciplines in biological sciences deemed high priority

Research Recommendations:

ASA(ALT) should

- Materials
  - Support multi-disciplinary teams to focus on requirements and recommendations for large scale high pressure facilities
  - Support multi-disciplinary teams to focus on new roles for controlled electric, magnetic, microwave and acoustic fields in processing, and their impact on material performance

    - Support multi-disciplinary teams to establish the foundations of Predictive Engineering Design in Extreme Environments in the 21st Century
- Biological Sciences
    - Support research in systems and synthetic biology to understand metabolic processes of cells, cell communities, tissues, and organisms and use the resulting data to model, predict, control, design and construct bio-devices and systems for Army applications
    - Support research directed at biomaterials and interfaces by design, including high throughput selection, design, and on-demand production of biomaterials that have desired properties and functions, and the rapid interfacing of those materials with technology platforms for Army needs
    - Support research involving biological system data collection and analysis under complex conditions and environments, and biological sample analysis from complex matrices
- Quantum Information and Sensing
    - Build up expertise in ultra-cold atom physics and matter-wave interferometry
    - Pursue quantum sensors and robust metrology
    - Investigate methods for internal quantum state control
    - Support “Big Engineering for QIS, ” e.g., developing a 50-qubit device
- Information at the Tactical Edge
    - Investigate mathematically the information manifold and the foundations of information field theory
    - Investigate mathematically the dimensionality mismatch between data and user information, including the information manifold
- Intelligent Systems
    - Pursue animal-like intelligence in autonomous systems, such as semantic recognition and action
    - Investigate architectures that enable effective teaming of humans and intelligent systems
    - Investigate cloud technologies for tactical units
- Human Dimension
    - Investigate techniques to quantify and predict cognitive behavior
    - Support multi-disciplinary teams to investigate performance enhancement using wearable or implantable aids
    - Support multi-disciplinary teams to investigate and understand the substrates of expertise and approaches that can potentially optimize training and improve the decision making process

ARL recommends that ASA(ALT) conduct such meetings on a regular basis. A biannual cycle of meetings focused on technologies followed by meetings focused on capabilities should insure a balanced look at the science and technology portfolio. A focus on basic research should remain paramount.

1. Introduction

Two significant changes in warfare have occurred since the end of the 20th Century. There is now ubiquitous access to data (though not necessarily information, validated or otherwise), and the initial investment required to engage in armed conflict has dropped considerably.

A few things have not changed. Armed conflict remains a contest of wills and actors in conflict fundamentally seek to persuade. The means for this persuasion exist in three domains:[1]

- physical, the domain of activities defined in space and time by the laws of physics;
- informational, the domain of activities defined by thought and perception; and
- cultural (or human), the domain of activities defined by the interaction of people and societies.

Although most investments in science and technology have historically focused on combat in the physical domain, given the present global context, the Assistant Secretary of the Army for Acquisition, Logistics, and Technology (ASA(ALT)) charged the Army Research Laboratory (ARL) with the mission to develop a strategic research plan for the US Army for the next 20 to 30 years.

Based on conclusions from ARL's November 2012 Visioneering 2050 workshop, ARL chose six areas to consider initially: Materials in Extreme Environments, Biological Sciences, Quantum Information and Sensing, Intelligent Systems, Information at the Tactical Edge, and the Human Dimension. ARL chose these areas for their potential to impact dramatically the Army in the long term. Given the history of warfare and prior investments, the areas differ in their level of maturity.

The most mature area is materials. The development of human culture and society is linked to materials and mankind's ability to process them. Since this relationship has not changed for millennia, materials are of fundamental importance to all aspects of the Army enterprise, including lethality, protection, and even information gathering, processing, and dissemination.

As our tools for investigation and integration have improved and the structures we can explore and manipulate have shrunk to the molecular scale, it is now possible to model and manipulate biological building blocks and consider their integration with inorganic materials. However, the potential to exploit biology in this fashion is recent. Thus, biology as a technology, not a science, is relatively immature. Consequently, increased investment should lead to a broad set of new capabilities in Soldier protection, warfighter performance, novel adhesives, waste removal, sensors, energy production, and intelligence.

Within the physical domain, our understanding of the quantum world has advanced over the past century to a point where we can now measure, manipulate, and control quantum properties of materials. This is leading to new capabilities to sense, store, manipulate, and transmit information, with capabilities that surpass the limits imposed by classical physics.

[1] COL J. P. Buche, US Army, Special Assistant to the DARPA Director, private communication.

In the information domain, we are only beginning to understand the science of networks. Humans at the heart of many of the networks we consider and the last three areas consider humans interacting in networks comprised of both human and engineered intelligence. We consider systems in which intelligence is engineered, in which information flows between nodes that contain human and engineered intelligence, and we also consider the ultimate system nonlinearity, the human.

As represented in Fig. 1, these areas are not independent. Overlap exists between several areas, especially those related to information and to humans.

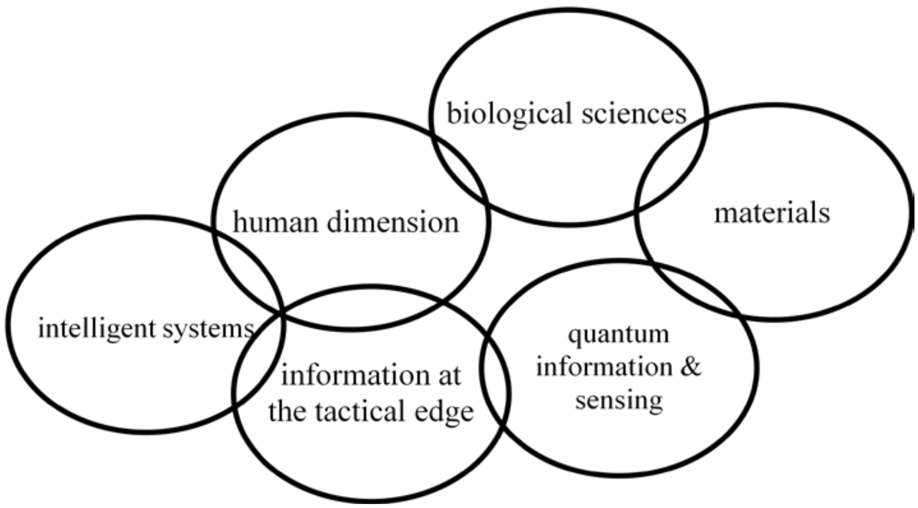

Figure 1. Topic areas for planning meetings held Fall 2013.
Overlaps are representative and not exhaustive.

During Fall 2013, ARL conducted several two-day strategic planning meetings in these topic areas. ASA(ALT) requested ARL to address the following questions: How is this area evolving? Why is it relevant for the Army in the long term? How and why should this topic area be a focus of Army expertise for the long term? What technical elements will be required to achieve excellence in this area?

For each meeting, ARL invited approximately 15 world-class experts as speakers, with a long-term, broad view of the specific area and an awareness of both commercial and defense trends. The meetings were structured to obtain a variety of viewpoints, not just near-term DoD-related expertise. ARL solicited help from the other services to organize the meetings, invite speakers, and moderate the discussion. Travel costs for all non-government invited speakers were covered. For non-speakers, attendance was by invitation-only and consisted primarily of ARL technical experts (both junior and senior), selected ARL managers, as well as a variety of other DoD experts. Target attendance per meeting was roughly 35.

The next section summarizes the discussions that occurred within each meeting. In Sec. 3 we highlight topics that overlapped two or more of the meetings. We also consider areas not covered in this initial set of six meetings and end with summary recommendations.

2. Discussion

2.1 Materials in Extreme Environments

For centuries, the fabrication of solid materials has hinged largely on manipulating a narrow range of temperatures and pressures. However, new revolutionary and targeted scientific opportunities now exist to discover, elucidate and exploit the fundamental interaction of matter with extreme static pressures and magnetic fields, controlled electromagnetic wave interactions, and acoustic waves (ultrasound) to enhance fabrication dramatically and to engineer materials with tailored microstructures that can potentially lead to revolutionary functionalities. In addition, the *in-situ* use of electromagnetic and acoustic fields on a range of matter including water, biological, and inorganic materials to control their properties systematically is in its infancy.

The objective of the meeting was to assess and review the global state of the art concerning the following themes and to identify key areas of medium- and long-term scientific opportunities: 1) extreme static pressures in large sample chambers and magnetic fields, 2) ultrasound and other radiation-resonant materials interactions, 3) microstructural evolution and control in extreme, controlled microwave, electric and magnetic fields and 4) electromechanical response and predictive computational requirements. Not included in this meeting was the interaction of intense directed energy (e.g., high energy lasers, microwaves and electromagnetic pulses). This area should be explored in a future, less public meeting.

Briefings and discussions provided initial forays into the topical areas, but the fundamental phenomena underlying the interactions with matter are largely, only roughly known and need to be investigated much more systematically. Therefore, an immense opportunity, which we refer to as "A New Era of Materials Science," exists to exploit the knowledge of the physical interactions of matter with combinations of "extreme" fields and waves to create engineered materials with tailored microstructures and revolutionary functionalities. Seizing this opportunity will free future materials designers from the tyranny of conventional constraints, and provide them more "knobs" for tailoring material properties and functionalities for the full breadth of Army applications.

With regard to large-scale super-high pressure capabilities, the US appears to have fallen behind other parts of the world. Thus, attendees considered questions such as "will new states of matter from high pressure like metallic hydrogen (~ 260 GPa) and quartz-like solid CO_2 be important? Will the emergence of large-scale polycrystalline diamond open up significant new applications?"

Attendees also considered the apparent importance of resonant acoustic effects in fabrication and in crystal growth. The interaction of microwaves with liquids has yielded dramatic effects, such as "burning water" wherein microwaves separate salt water into hydrogen, oxygen, and salt and the released hydrogen is burned. Further, microwaves have produced "hypersound effects" in biological materials using ferromagnetic resonance and the magnetoacoustic effect to transduce energy from the microwave radiation into tissue. Electric fields have also been used to process materials rapidly (e.g. Spark Plasma Sintering) and, using reverse piezoelectric effects, to control the microstructure in materials subjected to impact.

Attendees also considered the state of computational tools. To model materials subject to various fields and field strengths requires advances in predictive science and engineering and, thus, requires a strategy in computational sciences and mathematics.

2.2 Biological Sciences

Recent biotechnology, instrumentation, and computational developments have poised the biological sciences for rapid advances expected to translate to Army-relevant technologies. The resulting current excitement in the field regarding the potential of Bioscience research echoes the sentiments of leading geneticists Craig Venter and Daniel Cohen, who wrote in 1997: [2] "If the 20th century was the century of physics, the 21st century will be the century of biology."

The Biological Sciences meeting was unique from others in that it covered an entire discipline, rather than a sub-discipline or focused area within a specific scientific field. For this reason, the Biosciences meeting outcomes were necessarily broader than those from the other meetings. The main conclusion from the Biological Sciences meeting is that it provided a solid foundation for targeted follow-up. This could lead to a prioritized list of specific research opportunities for the Army to address in-house in sub-disciplines as described below.

Specific Army-relevant scientific opportunities were identified and prioritized. In general, research that includes the integration or bioscience sub-disciplines with each other and with other scientific disciplines (e.g., physics, informatics, synthetic chemistry) is paramount for success. Another characteristic critical to success is research using data collected and analyzed under real conditions and environments. The Army should avoid programs that do not push into realistic environments. Specifically, significant opportunity exists in the synergistic sub-disciplines of Biomaterials and Interfaces by Design, Systems Biology, and Synthetic Biology. In addition, a number of Biosciences sub-disciplines were identified for which opportunities also exist, though these areas were either covered only to a limited extent or not covered at all because of insufficient time. Furthermore, progress in the Biosciences area will require collaborative efforts that reach across other scientific disciplines including those listed in the Appendix.

There was clear consensus that the Army must maintain active research programs in the Biosciences to remain at the forefront of science and technology. However, prioritization of the areas and opportunities in the Biosciences and their distribution across intramural and extramural programs requires a more in-depth, targeted analysis of Bioscience sub-disciplines. This analysis should consider potential future applications, the existence of an Army-specific use, the existence of an industry driver, and the level of funding from other government institutions (e.g. NIH).

[2] G. Venter and D. Cohen, "The 21st century: The century of biology," New Perspectives Quarterly, Vol. 14 Issue 4, 26-31 (1997).

The group recommends that, after it has reviewed the areas listed in the Appendix to ensure they accurately reflect the group consensus, Army and DoD scientists should vet and prioritize the list and hold a series of similar meetings to explore the high priority sub-disciplines.

The group noted that very little can be accurately predicted. For rapidly developing areas such as the sub-disciplines discussed at this meeting, the far future outlook will continuously and significantly change; what is thought to be possible now could become out of date within a year. Identifying processes to facilitate success is as important as identifying technical scientific opportunities.

For example, regularly scheduled meetings insure dialogue between the Army, industry, and academia continues. This allows the Army to maintain awareness of the field, capture unpredicted advances, and adapt its plans accordingly. Such dialogue will, in turn, help the Army to balance its portfolio between basic and. applied research and between high-risk, high-payoff research and low-cost advancements. Further, targeted multi-disciplinary research programs can facilitate integration across the Biosciences sub-disciplines, as well as across the Biosciences and other fields.

2.3 Quantum Information and Sensing

We are in the midst of a second quantum revolution. Scientists have quite recently moved from merely computing quantum properties of systems to exploiting the theoretical foundations of quantum mechanics to drive applications in computation, communication, sensing, and imaging. Despite the Army's rapid recognition of this paradigm shift and its taking the lead to support it extramurally, paradoxically, the Army has barely taken part in it.

The Army needs to be selective in choosing from among the numerous interesting aspects within the quantum landscape. Theory is well ahead of experiments in most areas at the moment, and indeed much of what we need is theory to develop the possible landscapes, well before hardware is developed. Examples include work on topological states and quantum magnetism. Small-scale experiments testing out various ideas are also critical at this stage.

Areas identified for particular Army in-house focus include quantum enhanced sensing and imaging, quantum communications, quantum algorithms, and quantum simulations. It was clear that one area that the Army should not invest heavily in is Quantum Computing (QC). Though visionary, QC is both too limited and too specific an application and, of the areas within quantum information and sensing (QIS), it is the area in which we are least likely to have major impact.

At the other extreme, quantum key distribution (QKD) was deemed too near term, too well established, and not sufficiently visionary. Algorithms, on the other hand, are worthy of exploration. A potential Army-specific "killer app" might be an exact polynomial-time quantum-chemistry algorithm, the basics of which are already identified. This would directly impact design of propellants, explosives, medicines, and materials.

A number of criteria were established for what it would take for the Army to become an effective and even leading player, in terms of critical mass of research groups and researchers, research areas to focus on, and the need for expertise ranging from fundamental theoretical work at the foundations, to an array of experimental work across the sub-areas of QIS, and spanning through engineering. (Quantum engineering groups would be deployed in later stages, and probably at RDECs). All such capability would likely need to be bootstrapped, so that the Army can attract the caliber of people that will be required.

Such a program, if implemented, will critically impact the Army's future capabilities—far exceeding those possible with classical physics technologies—in sensing, imaging, secure communication, networking, materials design, and more. It is the stepping stone to the 21st Century's first brand-new engineering discipline, Quantum Engineering. The Army needs to lead this, or else much of this technology will need to be obtained from China, Japan, Australia, and Europe, all of whom are moving far more rapidly, and beginning to outpace the U.S. in current QIS investment.

The group recommended ASA(ALT) support an in-house build-up of effort in QIS to reach a critical mass (>5 - 10 groups with >10 scientists per group in steady-state) of mostly co-located research groups; and ensure stable, long-term support for this. Given the breadth of interacting topics, the group felt this level of support was necessary for an Army effort to become self-sustaining. Specific research topics for the internal effort are included in the Appendix.

In parallel, ASA(ALT) should support an “off Army base” lab, or a joint research institute with a university, for basic research activities to enable an open environment and work with non-US citizens. This is necessary for the Army effort to become first rate in quality, and to attract the best and brightest people.

2.4 Information at the Tactical Edge

The theme of this meeting was the interaction among and the convergence of both large- and small-scale networks of machines with humans. This interaction and convergence occurs in the Tactical Edge, an extreme environment that is asymmetric, highly disrupted, error prone, and stressed in numerous ways. The discussion focused on the flow of information between and among complex networks of different genres; the appropriate definitions of (semantic) information in such complex systems; the impact of social, physical and other network layers on information flow; the representation, and effective and efficient delivery of information; and theories and models of performance of human-machine networks. The goal of the meeting was to understand how this area is evolving and where it should or could evolve, to establish grand challenges, and identify potential areas of Army focus for the long term.

The meeting was comprised of a number of short sessions, including detailed discussions after each session and a final discussion hour that led to the identification of a number of topics in Information and Network Sciences that will be highly relevant to the Army in the next 20 to 30 years. The focus of these discussions was at the Tactical Edge which itself is likely to change significantly. The discussions did not adequately cover how the nature of the Tactical Edge might evolve over the next 10-30 years and, surprisingly, there was little discussion of cyber security.

A number of challenges for meeting the information requirements of user at the Tactical Edge were identified at the meeting. The human dimension (e.g., instrumented warrior, Watson, IBM's computer, machine-understanding of human intention, collective intelligence, and trust) came up in multiple tasks and discussions. Much of the discussion was framed by processing and delivery of information leading to improved decision making. Complexity, uncertainty, unpredictability and risk will always be characteristics of the frontier of knowledge at which the tactical Army operates; thus, the soldier at the information front will continue to be subject to stress in many forms. Major topics of interest that emerged are discussed below.

The automated analysis of the goodness of information is presently lacking. However, there was no consensus on how goodness should be defined. Attributes could include quality, relevance and trustworthiness. Especially important is a theory for the propagation of these attributes along a fusion chain. This could include semantic information processing, including dynamic creation of semantics for different situations as well as different audiences, missions and echelons. We also need to explore the role of the human in feedback loops that help engineered systems learn. This could benefit from a systematic application of 50 years of Cybernetics.

A major challenge is the high-dimensionality of the data and the resulting complexity of the information environment as manifested in the complexity of network dynamics. The emerging challenges of Big Data, such as increasing volume, velocity, variety, and uncertainty, as well as quality, retrieval, and access pose technical challenges on data storage, processing, and analysis. But, in contrast, useable information content lies in a complex, low-dimensional manifold that is highly user- and context-dependent. Although sparsity techniques may be used to address the dimensionality mismatch, to do efficiently requires a basis set that is presently unknown. In this regard, it is important to understand how observed patterns relate to the cognitive states of people (friendly forces, adversarial forces, and civilians), who interact with and influence the network. For example, understanding a "physical" relationship between measured network effects and the people driving these networks might help form this basis set.

Efficient discovery of the information manifold requires appropriate mathematical models, processing tools and representations to enable reasoning, both human and automated, about vulnerability, quality, relevance and trustworthiness of the information, and effective storage and delivery of information. Critical to enabling this are cognitive models of users and user behaviors (e.g., beliefs, goals, plans, emotional and physical states) that lift reasoning out of the restricted domain of strict logical inference. It also requires distributed computing at the edge. There is a general need for systems intelligence to provide knowledge management and decision-support for the user.

To support human decision-making at the Tactical Edge effectively, next-generation information systems are required to capture, curate, manage, and process data both globally and locally. Effective knowledge management requires a comprehensive systems-level approach that encourages goal-oriented design to handle knowledge and capabilities at both the tactical (local) and strategic (global) organization-wide levels. Approaches such as micro-clouds may be useful to bring data analytics closer to the network edge than presently exists. One challenge is how to distribute computational resources for big data processing over organic assets at the edge (potentially including humans) while exploiting large computational resources in upper echelons.

Since a mission can involve inputs from multiple tactical edge users that cannot communicate directly with each other, coordination and focused dissemination of their information to the benefit of the overall mission is a challenge.

Information Field Theory needs to be developed to account for the dynamic complexity of a battle-space that includes humans, automatons, events, and the interactions between them, both friendly and adversarial. Information dynamics, including the impact of the adversary, also needs to be developed. Such theories might include multi-brain (team) information processing and collective intelligent behaviors. Command and Control (C2) theories of information need to be developed in conjunction with conventional C2.

It may be more useful to consider multiple co-dependent information networks rather than a single information network. Such co-dependency could address the robustness of layered networking against failure and the distinction between “Black Swans” and “Dragon Kings.” Developing methods for learning and predicting temporal evolution of structure and attributes of such networks requires sustained study of multiple coevolving networks. Advances in non-linear stochastic control of multiple inter-dependent and co-evolving networks are needed. Despite some recent progress, the area of co-evolution remains in its infancy.

Radical automation is required of all processes from collection to analysis, dissemination and explanation. As a specific example, it was noted that even the seemingly classic problem of topic modeling, wherein topics in corpora of text documents relevant to a user and a mission are identified automatically, is of great importance, yet remains unresolved. IBM’s Watson came up for discussion a few times.

As an adversary improvises its tactics, traditional command and control structures may not be sufficiently agile to respond effectively. Therefore, a major challenge is to incorporate a flexible command and control policy over the network that enhances mission effectiveness while reducing confusion. This challenge includes the formation of effective teams capable of thinking on the fly instead of rigidly following static doctrine. The theory of small networks to explain team behavior is still in its infancy but ought to be aggressively pursued. The essence of teamwork within networked organizations is the ability to maintain a coherent set of tasks across people, information systems, and shared assets that mutually support and do not conflict with one another. Determining how to synchronize a force in time and space, and more generally with shared awareness along social and cognitive dimensions, is of great importance. Given the expected convergence of the artificial cyber and physical human domains, such a theory is critical to the general notion of an instrumented warrior.

Finally, experimentation should move in parallel with mathematical investigations. Constructive simulations are needed to design and conduct experiments with human participants. Experiments should focus on developing an infrastructure for data collection that is relevant to operations and mission effectiveness, yet also provides a scientific framework for hypothesis testing and theory development across the social, cognitive, and information levels.

2.5 Intelligent Systems

Over the past decade, systems capable of stable flight and locomotion, as well as navigation have been demonstrated in laboratories and in controlled field experiments. Collaborative movement between multiple platforms has also been demonstrated. Such capabilities are necessary for the development of autonomous mobile systems but are still a long way from the Hollywood-fueled expectations of robots and robot armies. Strategic planning in this area must balance the realities of research against expectations.

The meeting attempted to first set the stage for the remaining discussion by addressing the technical problems the Army faces now and the technical problems we anticipate in the next twenty years. Meeting attendees noted that focusing on platforms or on developing taxonomies for intelligence and autonomy detracts from the real discussion that is required, namely, what the Army wants their intelligent systems to do in the next 30 years. Thus, subsequent discussions focused on the capabilities of Intelligent Systems, Intelligent Systems in Dynamic Environments, and Soldiers Interacting with Intelligent Systems in Dynamic Environments. The intent of these panels was to consider the capabilities required for a single platform, for multiple platforms in a complex, dynamic environment, and, finally, interacting not only with other platforms but with humans as well.

A consensus was reached that animal-like intelligence is desired. Increased intelligence is desired for simple platforms, such as robotic followers, and for aerial and ground sensor platforms. Platforms need to set waypoints autonomously that increase mission effectiveness. Followers need to recognize the actions of their unit. For example, in addition to knowing where the unit is headed, the follower must be able to perceive when the unit is deviating from a previously prescribed plan and know enough to query why. The follower must recognize when the unit is resting. The follower must be capable of doing so without explicit instructions from a human. Similarly, when commanded to surveil a building, ISR assets should know they need to monitor windows and points of ingress and egress. ISR assets need to recognize those activities that require high-fidelity monitoring.

A key capability to enabling this functionality is recognizing action or, as stated often during the meeting, labeling nouns and verbs in a scene. Developing command and control, and system architecture are also critical to enabling the effective coordination of humans and intelligent systems.

Attendees considered the utility of intelligence beyond an animal’s and approaching that of a human. The attendees discussed potential functions for such platforms including a personal assistant for the disabled and an advisor to a field or strategic commander. Both applications require capabilities that build on lower levels of intelligence to understand human gestures, body language, speech, and tone but both also require processing algorithms to interpret situations and offer options for actions. If one considers the commander’s assistant, Advisor Watson might serve as an adjunct to the commander’s team of advisors.

Advisor Watson should also be able to tailor the information provided to his commander, in much the same way that humans do. Nurse Watson must also be capable of learning from and adapting to the person to whom it is giving care.

Issues related to the cloud were pertinent to this discussion. How does one harness and exploit the data that is available to a single unit connected to a network? Further, is it possible for a tactical unit to access the cloud?

The group raised other issues for consideration including how resource constraints alter a solution to a problem derived assuming unconstrained resources and how one performs autonomy at tempo, i.e., how one speeds up learning or even implements upgrades in a rapid fashion.

With regard to the skill set required to pursue these avenues of research, the group agreed that it needed to be multidisciplinary. It requires people capable of constructing platforms, sensors, and the algorithms that generate intelligence. However, it also requires cognitive psychologists and learning specialists.

2.6 The Human Dimension

Regardless of specific definition, the human dimension is broadly recognized as critical, and can safely be predicted to become pervasive across all Army R&D. For example, at the ARL Visioneering 2050 futures meeting, the human dimension theme emerged more strongly than any other topic. The Planning meeting on the Human Dimension focused specifically on the study and modeling of humans and their interaction with technology. Topics included (but were not limited to) quantifying substrates of human behavior, modeling human cognition, expertise and training, human(s)-in-the-cloud, and wearable and implantable technology. These multi-disciplinary topics drew on engineering, physics, psychology, and social sciences in interesting and newly emerging ways.

Three sessions broadly addressed the ability to quantify and predict cognitive behavior, examined the potential of wearable and implantable aids for performance enhancement, and considered in general terms the ethics of using technology to modulate human performance. One session focused on understanding the substrates of expertise and approaches to optimize training and decision making. Across the 13 technical talks, speakers articulated emerging trends in the field of human research, and many accepted a challenge from the meeting organizers to "conclude with a few gutsy futuristic predictions" to spark a hearty discussion among the ~50 attendees. From these lively and invigorating discussion periods, several technical trends emerged that coalesced into themes identified by the group as ideas likely to have the greatest impact (particularly on DoD and Army) over a 10 to 30 year time frame.

Quantifying and/or predicting cognitive behavior: A discussion of cognitive models highlighted the need for probabilistic approaches that capture learning and training, intuition, and that can be verified experimentally. Such models cannot be based purely on simulation, but instead require a mathematical formalism, most likely in a probabilistic framework. The development of such models is by no means complete and should be a continuing Army and DoD research focus. A computational theory of mind should account for cultural differences, might consider what is different between individuals rather than focus on what is the same, and develop theories of exceptional talent especially in the context of collaborative teams.

Predictions of social person-to-person communication based on observed gestures, eye movement, and body language are becoming possible. In addition, brain-to-brain interaction is emerging as a potential paradigm based on external sensors and brain stimulation. The Army should continue to study these and other possible techniques, to understand shared knowledge, social coordination, discourse comprehension, and detection and mitigation of conflict.

Cognitive models in combination with sensors also have the potential for dramatic breakthroughs in human-autonomy interaction, including aspects such as active learning algorithms, real-time crowd-sourcing with humans and machines in the cloud, and maximizing AI prediction accuracy. The study of human-machine interaction is entering a new phase as cognitive science, autonomy and AI, and networking all converge, and this area should receive significant and sustained research and development support. Coupled with this is a shift in natural language processing from syntax to semantics, enabling an AI to explain how an answer is achieved, and relating cognition and actions in the context of beliefs and desires. This could be the ultimate intelligent system.

Wearable/implantable aids for performance enhancement: Devices and sensors that are wearable or implantable (including biomarkers and drug therapy) have the potential to enhance human performance dramatically and to augment sensory information through new human-sensor-machine interface designs. A future goal within the human dimension is to acquire the capability to monitor continuously biomarkers of cognition in real-time, potentially coupled with implantable drug release. In addition to detecting natural cognitive states, current state-of-the-art approaches are aimed at examining various forms of human-machine interfaces that might be used to augment human performance. Significant challenges include tracking human adaptability, interaction with implantable sensors, and creating and exploiting living on-chip biological networks. We note that this technology area is already raising important ethical issues, and this trend will likely accelerate. Human capital can be boosted with enhancement, but many issues arise such as responsibility, data logging and its link with behavior, assigning blame when crowd sourcing is utilized and undesired outcomes occur, and others not yet conceived of.

Understanding substrates of expertise and/or approaches to optimize training and decision making: It is desired to work toward a future based on creating learners with adaptive expertise, beginning with early childhood education. This suggests technologies for learning that are persistently affect-aware and exhibit flexible interaction with human learners. Network models based on neuro-imaging permit the critical study of functional neural network connectivity, and will lead to deep understanding of training, learning, and performance enhancement. This can couple neural state sensing, learning, and human-autonomous machine interaction. Social data processing will augment and complement this area, for example, modeling user judgment reliability and enabling training optimization.

The human dimension will be increasingly pervasive and multi-disciplinary, including neuroscience, biology, autonomy, network science and systems engineering. Quantifiable theories and models, advances in implantable/wearable sensors, application of learning methods, crowd-sourcing, and human-autonomy interactions will lead to dramatic advances in Army capability. Like any multi-disciplinary area, there are significant science challenges, as well as organizational challenges, to bring this about. The Army should recognize the R&D opportunities and potential dramatic payoffs, and broadly organize multi-disciplinary efforts along these lines. In particular, this requires forging new links among Army scientists and engineers engaged in neuroscience, engineering, psychology, computer science, and other related areas.

3. Observations

A review of the individual meetings by the lead organizers revealed an underlying structure, represented in Fig. 2, to the recommendations presented in the next section. If one considers the domains of conflict introduced in Sec. 1 (human, information, and physical), the meetings can be delineated according to Fig. 2(a). Fig. 2(b) represents our highest priority recommendations (which we present in the next section) binned into these same domains. It is worth noting that they are located in the intersection between domains. We address two of these recommendations here.

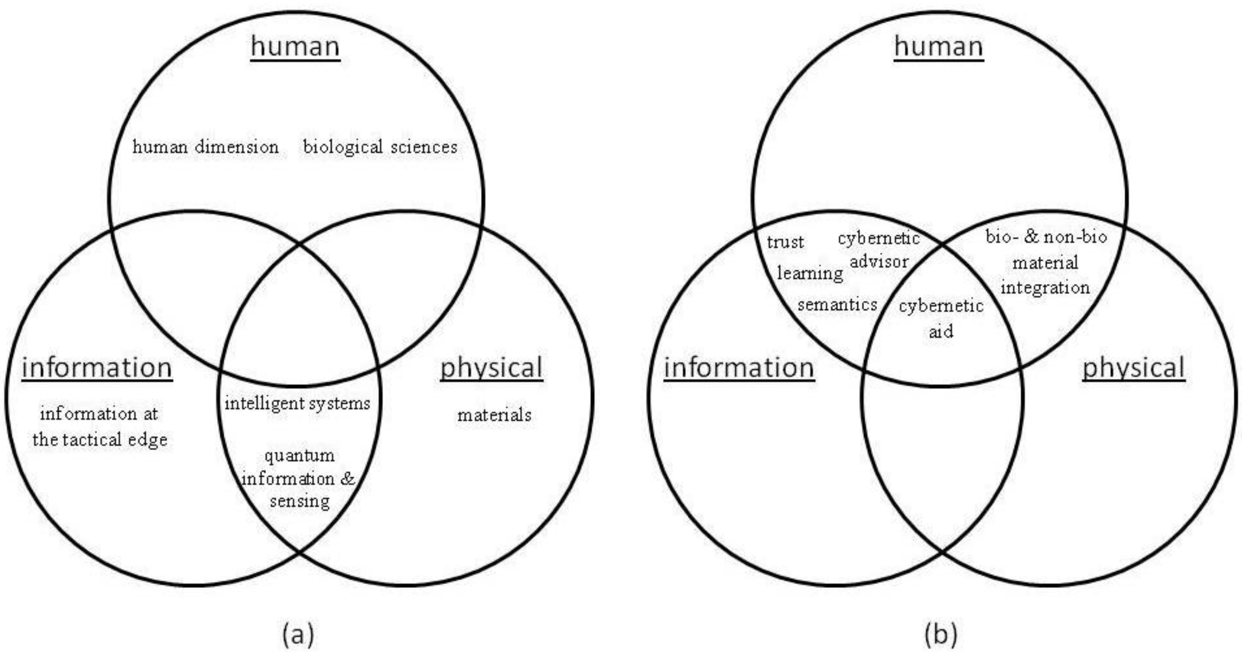

Figure 2. Science and technology in conflict domains. (a) Planning meetings held. (b) Representative high priority recommendations.

The topic of trust arose in Information at the Tactical Edge, Intelligent Systems, and the Human Dimension, and was mentioned briefly in Biological Sciences. The issue reveals the uncertainty with which humans approach the changes in their interaction with technology, especially systems with engineered intelligence. Trust arose in discussions about cybernetic advisors and in discussions about improved processes for decision making. The boundaries between humans and machines in terms of interface and usage was once obvious and well defined. Ubiquity has changed that. Intelligent systems augment not just performance but influence people's lives and activities.

Learning and the need for semantics and context to improve understanding were also discussed in several of the meetings. The need for information tailored to the recipient emerged from these discussions, as did the recognition that decision making requires a transformation of data to information and we presently lack an understanding of this process.

The utility of information is a function of raw data, its credibility, and its context. The ability to quantify, measure, and control credibility, as well as provide context, offers a technical advantage over those who continue to operate using Industrial Age perceptions of information.

4. Recommendations

Based on the output of the meetings and subsequent discussions among meeting organizers, ARL developed several strategic research recommendations, as well as recommendations specific to each area, which are presented in this section. However, attendees at all meetings stressed that, to advance knowledge and understanding of the issues discussed requires a long-term, unwavering focus and stable funding of multi-disciplinary, collaborative teams.

Strategic Research Recommendations:

ASA(ALT) should

- Support multidisciplinary investigations in the following areas
  - hybrid biological and non-biological systems
  - the integration of neuroscience and training
  - trust in information and intelligent systems
  - the mathematics and cognitive transformation of data to information
  - intelligent platforms as personal advisors and personal assistants
- Increase in-house efforts in quantum information and sensing in conjunction with the establishment of an off- base lab or a joint research institute with a university
- Hold a series of exploratory meetings on additional sub-disciplines in biological sciences deemed high priority

Research Recommendations:

ASA(ALT) should

- Materials
  - Support multi-disciplinary teams to focus on requirements and recommendations for large scale high pressure facilities
  - Support multi-disciplinary teams to focus on new roles for controlled electric, magnetic, microwave and acoustic fields in processing, and their impact on material performance
  - Support multi-disciplinary teams to establish the foundations of Predictive Engineering Design in Extreme Environments in the 21st Century
- Biological Sciences
  - Support research in systems and synthetic biology to understand metabolic processes of cells, cell communities, tissues, and organisms and use the resulting data to model, predict, control, design and construct bio-devices and systems for Army applications
  - Support research directed at biomaterials and interfaces by design, including high throughput selection, design, and on-demand production of biomaterials that have desired properties and functions, and the rapid interfacing of those materials with technology platforms for Army needs
  - Support research involving biological system data collection and analysis under complex conditions and environments, and biological sample analysis from complex matrices

- Quantum Information and Sensing
  - Build up ultra-cold atom physics and matter-wave interferometry
  - Pursue quantum sensors and robust metrology
  - Investigate methods for internal quantum state control
  - Support "Big Engineering for QIS, " e.g., developing a 50-qubit device
- Information at the Tactical Edge
  - Investigate mathematically the information manifold and the foundations of information field theory
  - Investigate mathematically the dimensionality mismatch between data and user information, including the information manifold
- Intelligent Systems
  - Pursue animal-like intelligence in autonomous systems, such as semantic recognition and action
  - Investigate architectures that enable effective teaming of humans and intelligent systems
  - Investigate cloud technologies for tactical units
- Human Dimension
  - Investigate techniques to quantify and predict cognitive behavior
  - Support multi-disciplinary teams to investigate performance enhancement using wearable or implantable aids
  - Support multi-disciplinary teams to investigate and understand the substrates of expertise and approaches that can potentially optimize training and improve the decision making process

Meeting Recommendations:

ASA(ALT) should conduct such meetings on a regular basis. Rather than organizing the meetings around technologies, the next set of meetings might be organized around capabilities. A focus on basic research should remain paramount. For example, a meeting on technologies to reduce the logistics burden might consider additive manufacturing, power and energy, waste-to-energy, and water treatment. A biannual cycle of technologies and capabilities might insure a balanced look at the science and technology portfolio.

Technology areas ASA(ALT) may wish to consider in the future include

- Integration of Biological and Biologically-inspired Technologies in Non-Biological Systems
- Countermeasures and Technology as a Threat to identify technologies that constitute significant threats to our forces
- Conventional Sensor Technology: Sensor technology resides in the thin interface between the physical and information domains. Whereas the network infrastructure behind this interface becomes more integrated, the design of many sensor technologies remains oblivious to this. Improved Data-to-Decisions requires a re-assessment of sensor technology design.
- Materials Resistant to High Power Radiation: As development of high energy lasers continues, it is important to consider the interaction of such radiation with materials. It is

also important to consider the interaction of unfocused and focused high-energy microwaves and electromagnetic pulses with materials. Given the sensitivity of this work, it is important to hold a preliminary, classified meeting prior to any open meeting to review past and current work in these areas. An open meeting can then focus on the long-term, high-risk, basic research issues that emerge from the classified meeting.

5. Summary and Concluding Remarks

The six Fall meetings reflect those areas ARL considered of critical importance to the Army. The recommendations within each area are intended to show where investment will most provide significant new understanding to advance capabilities desired by the Army.

The strategic recommendations reflect cross-cutting thrusts that encompass fundamental aspects of the individual areas and, if followed, should lead to new, broad based capabilities. It is telling that so many of these recommendations are concerned with humans and their interface to engineered systems, both physical and cybernetic. A particular emphasis in the cybernetic interface is on the flow of data and information between humans and engineered systems.

By recognizing the parallel convergences in the technical domains of physics, biology, and cybernetics and in the warfare domains of physics, information, and culture, should allow the Army to prepare for an uncertain future.

Appendix: Individual Meeting Summaries

Materials in Extreme Environments
December 10-11, 2013
Baltimore Sheraton North, Towson MD

Organizers: Dr. Suveen Mathaudhu (ARL/ARO)
Dr. Jim McCauley (ST Emeritus, ARL/WMRD) and Dr. Brad Forch (ST, ARL/WMRD)

Summary Statement: For centuries, "control" of matter has hinged largely on manipulation of a narrow range of temperatures and pressures, however a revolutionary and targeted scientific opportunity now exists to discover, elucidate and exploit the fundamental interaction of matter with "extreme" environments (high-pressure, electromagnetic waves (microwave, radiation, electrical, radio-frequency, optical and magnetic, acoustic field) or a synergistic combination of conditions to create and unleash advanced materials and to understand the in-situ degraded or enhanced behavior Army-relevant materials when exposed to "extreme" conditions.

Introduction: The objective of the two-day meeting was to review the current global state of the art concerning the effects of extreme static pressure, shear stress, electric, magnetic, microwave and ultrasound fields on the synthesis, processing and microstructure control of advanced materials, as well as their behavior in these extreme environments, and to identify key areas of medium- and long-term scientific opportunity within this theme. The topics were divided into four unique, but correlated, topical areas:

I. *Extreme static pressures and magnetic fields***:** The focus of this portion of the meeting was to investigate mechanisms of phase transformations and control that occur under extreme static pressures and ultra-high magnetic fields, and the stable/metastable materials with unique properties that can be synthesized and processed in such environments. (six speakers)

II. *Ultrasound and other radiation resonant material interactions:* This topic focused on unexplained reaction phenomena associated with the catalytic effects on liquid and solid matter under controlled microwave, radio-frequency and ultrasonic fields. (three speakers)

III. *Microstructural evolution and control in extreme, controlled microwave, electric and current fields***:** This topic served to discuss various, and somewhat contradictory theories of microstructural evolution and manipulation in electromagnetic fields, including electrical, and microwave, so as to exploit them for advanced materials synthesis and processing. (five speakers)

IV. *Electromechanical response and computational requirements***:** This diverse topical area centered on defect migration phenomena in electromagnetic fields, and in-situ characterization of quasi-static and dynamic electromechanical response, including normal and reverse piezoelectric effects under impact conditions. Discussion was also had on future requirements for validated physics-based codes for simulation and predictions of materials interactions with extreme fields. (four speakers)

The meeting was attending by 18 speakers from the USA, Germany and Belgium, other federal agencies (NASA, AFOSR, LANL, Sandia), and attendees from industry and other RDECOM Centers.

Recommendations and Opportunities
The creation and exploitation of advanced materials critically relies on the control and manipulation of matter in all its forms (e.g. atoms, molecules, condensed matter…) and for centuries, this has been largely accomplished by variations in temperature and pressure. *An immense opportunity **(A new era of materials science)** exists to exploit the knowledge of the physical interactions of matter with combinations of "extreme" fields and waves to create engineered materials with tailored microstructures and revolutionary functionalities.* Seizing this opportunity will free future materials designers from the tyranny of conventional constraints, and provide them more "knobs" for tailoring material properties and functionalities for the full breadth of Army applications. Should the Army choose NOT to support this area of opportunity, we will undoubtedly be surpassed by global efforts (mostly in Europe, China and Japan), who already have a head start of advanced facilities.

In support of this opportunity, recommendations have been extracted from presentations and discussions that took place, and focus on long-term (20-30 year) tracks for scientific investigation, with the knowledge that some thrusts will require sustained high levels of support for excellence and leadership in the science.

Scientific Recommendations and Opportunities

1. The interactions of waves within the electromagnetic spectra (electromagnetic, microwave, radiation and optical) and matter are only superficially known and poorly understood, but represent an untapped resource for the materials science and engineering community. Specific areas of interest include:
    a. Study of mass transport and defect formation and migration under applied electrical fields and currents
    b. Study of mass transport and defect formation and migration under applied magnetic fields

2. Similarly the phase transformations and undiscovered states of matter that form under extreme static pressures are only very recently being investigated due to new experimental high-pressure facilities.

    a. Study of matter under a synergistic combination of dynamic and high-pressure conditions
    b. Study on methods for stabilization of high-pressure phases in ambient conditions

3. The interactions with sound/ultrasound pressure waves with matter are mysterious. Specific areas of interest include:
    a. Study of induced hypersonic mass-transport effects under electromagnetic fields
    b. Study of resonant sound wave interactions with matter
    c. Study of the interactions of radio frequency and microwaves on matter

4. It is well known that materials demonstrate electromechanical response (e.g. piezoelectricity), and materials exposed to extreme conditions (e.g. dynamic impact, shock, high-pressure) have preliminarily been observed to emit electrical charge, and likely other unseen fields and waves. Specific areas of interest include:

a. Study of “reverse” piezoelectric and other types of wave interactions when a material is subjected to “extreme” conditions, e.g. high-rate / shock loading
b. Use of imposed electrical fields on materials subjected to impact

Programmatic Recommendations and Opportunities

1. The Army needs a large, and sustainable financial commitment to acquire and sustain the expertise and resources needed to solve the extraordinarily challenging problems that will arise given the necessity of complex theoretical, experimental and modeling linkages.
2. To stay scientifically competitive, the U.S. Army MUST invest in long-term, on-site collaborative research efforts with national institutes and facilities (e.g. Advanced Neutron Source, Advanced Photon Source, National Ignition Facility, Matter-Radiation Interactions in Extremes (MaRIE) Facility and the Carnegie Geophysical Laboratory) with unique capabilities for creating and testing materials in extreme environments.
3. Underpinning each of the scientific recommendations lays the inherent ability to characterize phenomena at relevant length scales from sub-atomic to mesoscale, and at relevant time-scale. New capabilities that can probes phenomena *in-situ* must be developed in collaboration with key external partners.
4. Similarly, multiscale computational efforts to predict *ab-initio* properties, and provide relevant and physics-accurate simulations of matter-field interactions must be developed, along with the computational infrastructures and codes that provide for computational efficiency. Foundations for Predictive Engineering Design in Extreme Environments in the 21st Century require "Strategic Science and Engineering Experimental Partnerships" including: computational mathematics, multiscale science, multi-physics applications, optimization and U.Q. and computational multi-physics.
5. Seed resources should be used to form interdisciplinary teams to tackle sub-problems in a truly collaborative way, including periodic discussions and yearly focused meetings. Two teams should be assembled to focus on (1) the requirements and recommendations for large scale high pressure facilities and their implementation and (2) new roles for controlled electric, magnetic, microwave and acoustic fields in processing, and performance of materials: ***A New Era of Materials Science***.

Biological Sciences
December 11-12, 2013
Mason Inn Conference Center, Fairfax, VA

Organizers: Dr. Piotr J. Franaszczuk (ST, ARL/HRED),
Dr. Vicky L.H. Bevilacqua (ARL/SEDD), Dr. Stephanie A. McElhinny (ARL/ARO)

1. Introduction

Recent biotechnology, instrumentation, and computational developments have poised the Biosciences for rapid advances expected to translate to Army-relevant technologies. The resulting current excitement in the field regarding the potential of Bioscience research echoes the sentiments of leading geneticists Craig Venter and Daniel Cohen, who wrote in 1997: “If the 20th century was the century of physics, the 21st century will be the century of biology” [NPQ, 1997]. Nineteen world renowned academic experts from 16 institutions, and 36 scientists representing 16 Army and other DoD/Government organizations convened for the Biosciences ASPSM. The Biosciences ASPSM was unique from other ASPSMs in that it covered an entire discipline, rather than a sub-discipline or focused area within a specific scientific field. The program therefore focused on key emerging sub-fields of broad interest to the Army S&T community. The meeting involved four sessions, each with brief presentations by 4-6 academic experts who described the current status and anticipated future achievements of their fields, followed by a moderated discussion during which participants explored requirements necessary for success (capabilities, relevant scientific breakthroughs, collaboration with other sub-disciplines or fields), as well as why/how the Army should be involved (potential payoff for the Army, areas of research, challenges, building capabilities). Each of three sessions focused on a specific sub-field: 1) Biomaterials and Interfaces by Design, 2) Systems Biology, and 3) Synthetic Biology. The fourth session, Other Emerging Biological Science Areas, explored selected areas, each represented by a single academic expert. The meeting culminated in a final discussion period including four breakout groups, with each group tasked to summarize major areas of scientific opportunity under one of the four session topics and to contemplate the implications of these opportunities for the future Army S&T Bioscience strategy.

Meeting participants concluded that significant opportunity for Army-relevant research exists in each of the sub-disciplines explored during the meeting, as well as other Bioscience areas. Recommended Bioscience research areas expected to yield Army-relevant technologies and in which the Army should consider carrying out in-house research are listed below. ***There was clear consensus that the Army must maintain active research programs in the Biosciences to remain at the forefront of science and technology.*** The most important topics for the advancement of science in the Army-relevant sub-fields addressed at the ASPSM were identified and are provided below. Decisions regarding particular areas and opportunities in the Biosciences that should be priorities for the Army, as well as how these priorities should be distributed between the intramural and extramural programs, will require a more in-depth targeted analysis of the sub-disciplines within the Biosciences. This analysis should consider the anticipated future applications that may be possible, whether an industry driver exists, whether the area is highly funded through other government institutions (e.g. NIH), and whether there is an identified Army-specific use. Lists of sub-disciplines relevant to Army requirements, but for which there was not adequate time to cover during this meeting, as well as other disciplines with significant potential for integration with the Biosciences were generated and are also provided below.

Note: "Bio-system" is generally used broadly here and includes, but is not limited to, biomolecules, organelles, viruses, cells/microbes, groups of interacting cells (e.g., biofilms), and higher level organisms.

2. General Technical Recommendation and Programmatic Suggestions

Continued investment is critical to promote advances in topic areas including systems biology, synthetic biology, and biomaterials. Moreover, the scientific community expects the real power of the biological sciences over the next century to be maximized through the integration of research across its sub-disciplines and with research in other sciences. ***A technical recommendation important for the Biosciences in general is thus to promote research that seeks to integrate and interface biological systems and biologically-inspired systems with non-biological systems and with the Soldier.*** Such integration should lead to a broad range of new capabilities in areas including Soldier protection; warfighter mental and physical performance optimization; new materials with novel adhesive, mitigation, and other characteristics; and advances in sensors, energy production, intelligence, and bioengineering.

The group also noted that very little can be accurately predicted. For rapidly developing areas such as the sub-disciplines discussed at this meeting, the far future outlook will continuously and significantly change; what is thought to be possible now could become out of date within a year. Identifying processes to facilitate success is as important as identifying technical scientific opportunities. Several recommendations towards further planning include:

- Facilitate integration and collaboration across the Biosciences sub-disciplines, as well as across the Biosciences and other fields (physics, informatics, computational sciences, synthetic chemistry, material science, environmental sciences, etc.), with targeted multi-disciplinary research programs.
- Continue to capture unpredictable advances in the field by providing tangible mechanisms for ongoing dialogue and close collaboration between Army, industry, and academia, allowing the Army to maintain awareness and adapt its plans in step with cutting-edge developments
- Continue to balance the Army research portfolio between basic vs. applied research components and high-risk, high-payoff research vs. lower-cost stepwise gains based on current technologies
- Data collection and analysis under real conditions/environments should be emphasized when planning new research efforts
- Timelines for Bioscience research programs are critical; a 2-year program is unlikely to provide sufficient time for success
- The Army would benefit from effectively balancing the focus between short-term efforts and longer-term opportunities

3. Biomaterials and Interfaces by Design Scientific Recommendations

Vision: High throughput selection/design and production on demand of a biomaterial having a desired function/property, and the rapid interfacing of that material with a technology platform of interest. This area can impact major DoD challenges in power and energy, lightweight systems, energy absorption, and the medical arena.

The topics below were identified as the most important areas for the advancement of the Army-relevant sub-discipline of Biomaterials and Interfaces by Design.

Top Repeating Themes:

- The ability of living organisms to control chemistry at interfaces is currently unmatched; we need to look to biology to provide insight into interface engineering
- The ability to evolve biological materials could provide a new capability to select biomaterials with targeted properties; the ability to design selection processes for material properties will grow as we begin to understand the underlying principles of the properties we want to select
- Immuno-silent materials and platforms for battlefield diagnostics and treatment

Additional High Impact Areas:

- Develop capabilities to design bio-, bio-inspired, and hybrid (bio/non-bio) "tools"
- High throughput materials design and production to include the identification of bottlenecks (to biomaterials design, production, testing); screening for a modulus property; bio-synthetic technologies; incorporation of non-bio materials with biomaterials for bio-hybrid materials; multi-scale processing and scale-up of biomaterials for studies in realistic environments
- Precise synthesis and assembly with atomic scale resolution
- Efficient energy transfer
- Biomimetic devices, organs on a chip/biological systems on a chip interfaced with humans, *ex-vivo* devices
- Long-term experimentation/toxicological studies

Research Directed at a Basic Understanding of Biomaterials and Interfaces by Design Should Include the Following Critical Areas:

- biochemistry and bio-systems and their interactions
- bio-communication, bio-photonics, bio-energy transduction, bio-photovoltaics, and photosynthesis
- biomolecular surface interactions, interfaces between biomaterials and technology platforms (bio-/non-bio), interface design, evolution, and control
- immune system engineering and synthetic vaccines
- distributed bio-sensing, avoidance (avoidance of false-binding; microbe avoidance of stress factors)
- enhancement of biomaterial properties by incorporating non-natural building block molecules

- understanding how material properties scale-up
- understanding how to program a biomaterial property to order

4. Systems Biology Scientific Recommendations

Vision: The ability to monitor and understand all metabolic processes of cells, cell communities, tissues, and organisms and use the resulting data to model, predict, and control bio-systems and ecology for desired applications. Potential uses apply to many areas from environmental, to sensing, to medical arenas. Due to the interdisciplinary nature of systems biology, a main Army opportunity is to champion and physically host mechanisms for scientific community data/modeling exchange in areas the Army identifies as most relevant.

The topics below were identified as the most important areas for the advancement of the Army-relevant sub-discipline of Systems Biology.

Top Consensus Areas:

- Develop capabilities to study the ecology of multi-cell and multi-organism systems in order to understand how communities of organisms function
- Standardize models to allow for free exchange among members of the scientific community
- Build, curate and champion a Systems Biology database for the scientific community
- Develop capabilities to monitor entire systems in real-time (e.g., extend from current ability to monitor limited metabolites to monitoring full metabolome of the system)

Additional High Impact Areas:

- Bio-foundries and distributed manufacturing using biotechnology
- More "omics" data (e.g., metabolomics, proteomics) plus modeling for the system dimension (from microbial systems to human systems) to include biological & environmental influences
- Determine how to efficiently identify and integrate all data available (e.g., Mass Spec – identify all peaks, employ Big Data methodology)
- Develop ability to account for dark matter in cells
- Real-time high throughput identification of organisms at the base pair level

5. Synthetic Biology Scientific Recommendations

Vision: The design and construction of biological devices and systems for desired functions/purposes. This sub-discipline of Bioscience focuses on engineering biology and biotechnology. There is not yet a significant industrial driver for this area. However, it is anticipated that specific applications could include production of polysaccharides made to order, sensing (environmental/health), therapeutics/diagnostics, and waste-related logistics (e.g., the use of bio-systems for efficient waste remediation and transformation of waste matter into useful commodities).

The topics below were identified as the most important areas for the advancement of the Army-relevant sub-discipline of Synthetic Biology.

Top Consensus Areas:

- Improving the efficiency/accelerating the bioengineering (design-build-test) process; the trend is moving away from the iterative design-build-test cycle and moving to multiplexed designs which enable massively parallel assembly and analysis of engineered pathways
- Learn and apply lessons from Green chemistry and non-aqueous biology to synthetic biology
- Merge synthetic biology with synthetic chemistry
  - e.g., use synthetic biology to produce starter compounds that feed into the synthetic chemistry process for production of the final product
- Decoupling bio-engineering objectives (to obtain functions that benefit the soldier) from the bio-system's objective (sustaining cell life)

Additional High Impact Areas:

- Massively parallel test loops/analytics/engineering as enabling technologies
- Orthogonal systems (systems that are parallel and independent of cellular control) and orthogonal chemistry
- Compartmentalization of bio-components, processes/engineering systems
- Encapsulation technologies

6. Other Bioscience Areas Identified as Army-Relevant

The group concluded that the following areas, for which there was not adequate time for discussion, should be considered as the Army develops its Bioscience strategy. These were not prioritized.

- Bio-Safety: development of safe use standards, development of safety technologies for containment of engineered bio-systems and prevention of functional exchange of genetic information (gene exchange)
- Food and Agriculture: Use of biotechnology to optimize food harvesting and production
- Biology of the Human Dimension: Understanding the biological system in, on and including the Soldier (rather than the Soldier as an isolated actor within an ecological system)
- Membrane applications, realistic artificial membranes, basic understanding of membrane structures and complex membrane protein assemblies
- Small water-like molecules: Use for means similar to suspended animation for extending survival time for medical intervention after wound; basic understanding of the affect of small molecules on microorganisms and the planet/environment
- New biodefense approaches
- Use of biotechnology to address logistical concerns such as drinking water security/safety

- Bio-sensing & sampling including sample processing, real world samples, basic understanding of target-receptor interactions, direct comparison of platforms
- Bio-aerosols
- Microbiology of the Human Dimension (e.g., microbes in the human digestive system in the context of metabolomics; research on the human genome, transcriptome, proteome and microbiome; applications such as soldier performance)
- DoD-specific causes of mortality (e.g., malaria) and pre-symptomatic pathogen detection
- Individualized nutrition: Research directed at rapid, individual response to stress; use of biotechnology to identify biomarkers to optimize capabilities for monitoring the nutritional profile of the individual soldier
- Nanobiotechnology
- Computational biology/bioinformatics

7. Other Scientific Disciplines Important for Success in the Biosciences

These were not prioritized.

- Informatics
- Theoretical ecology
- Synthetic chemistry
- Mathematical sciences
- Materials synthesis by design
- Biological and chemical analytic metrology/data analytics
- Nanotechnology
- Chemometrics
- Machine learning for uncertainty management
- Data analytics: mining, curation, meta-analysis, sharing, self-correcting data, open-format/cross-platform and database searching
- Measurement techniques to monitor molecular and nano level self-assembly in “small” spaces (spatially localized self-assembly)

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Quantum Information and Sensing
September 24-25, 2013
Bolger Center in Potomac, Maryland

Organizers: Dr. Peter Reynolds (ST, ARL/ARO), TR Govindan (ARL/ARO), and Tatjana Curcic (AFOSR)

Introduction

Twenty of the most distinguished researchers in the world (including two Nobel Laureates) met with scientists from RDECOM and from other parts of the U.S. government (including OSTP) on 24-25 September 2013. Through a number of short visionary presentations, combined with extended brainstorming sessions, numerous areas were identified within quantum information science (QIS) as highly significant to the Army with impact in 10 to 30+ years.

It was noted that we are in the midst of a second quantum revolution right now, where scientists have moved quite recently from merely computing quantum properties of systems to now being able to exploit foundations of the theory (superposition, correlation, entanglement, Bell theorem violations, etc.) to drive applications (e.g., computation, communication, sensing, imaging). This is a paradigm shift that the Army has barely taken part in (paradoxically, since extramurally Army rapidly took the lead in these areas since the inception of this paradigm shift).
The Army needs to be selective in choosing from among the numerous interesting aspects within the quantum landscape. Theory is well ahead of experiments in most areas at the moment, and indeed much of what we need is theory to develop the possible landscapes, well before hardware is developed. Work on topological states and quantum magnetism are examples. Small-scale experiments testing out various ideas are also critical at this stage.
Areas identified in the meeting for particular Army in-house focus included quantum enhanced sensing and imaging, quantum communications, quantum algorithms, and quantum simulations. It was clear that one area that the Army should not invest heavily in is Quantum Computing (QC). Though visionary, QC is both too limited and too specific an application, and of the areas within QIS it is the area we are least likely to make a major impact in. At the other extreme, QKD was deemed too near term, too well established already, and not visionary. Algorithms, on the other hand, are worthy of exploration. A potential Army-specific "killer app" might be an exact polynomial-time quantum-chemistry algorithm, the basics of which are already identified. This would directly impact design of propellants, explosives, medicines, and materials.

A number of criteria were established for what it would take for the Army to become an effective and even leading player, in terms of critical mass of research groups and researchers, research areas to focus on, and the need for expertise ranging from fundamental theoretical work at the foundations, to an array of experimental work across the sub-areas of QIS, and spanning through engineering. (Quantum engineering groups would be deployed in later stages, and probably at RDECs). All such capability would likely need to be bootstrapped, so that Army can attract the caliber of people that will be required.

Such a program, if implemented, will critically impact the Army's future capabilities—far exceeding those possible with classical physics technologies—in sensing, imaging, secure communication, networking, materials design, and more. It is the stepping stone to the 21st Century's first brand-new engineering discipline, Quantum Engineering. The Army needs to lead this, or else much of this technology will need to be obtained from China, Japan, Australia, and Europe, all of whom are moving far more rapidly, and beginning to outpace the U.S. in current QIS investment.

Scientific Recommendations

- It was recommended that Army stay away from quantum computing (QC) *per se*, as there are numerous areas more specifically Army relevant, and where Army can make much more of an impact. QC is very heavily funded by the IC, so any impact we could have would be at the margins at best. We should also stay away from quantum key distribution (QKD).
- Ultra-cold atom physics and matter-wave interferometry is considered basic, as it is the enabler of almost everything else including the development of sensors and instruments relevant to the DoD mission (inertial sensing, magnetometry, precision time, navigation via gravity gradients, etc.). Quantum sensors allow for more accurate measurements than allowed classically, and is intimately connected with quantum control. Robust metrology in turn can lead to new fundamental physics. Cold atoms also serve as simple models that can be built on in a number of important ways.
- Direct cooling is *external* quantum state control. Internal quantum states offer a whole new paradigm with far more potential power. While there are many internal atomic states, the space opens far more widely with molecules and many-body systems. Molecular detection with cold atoms/ions could play a dual role in non-QIS applications. E.g., cold atoms/ions can beat conventional mass spectrometry with almost lossless measurement.
- Hybrid quantum systems are critical, as different quantum systems have different strengths and weaknesses. A practical technology will require integration of different QIS components. This is a critical forefront area in which several MURIs are focusing, and where Army could potentially take a lead.
- Quantum networks including quantum repeaters for long distance quantum communication is viewed as a good direction for investment. This would entail long (at least seconds long) memories, entanglement of photons with memories made of potentially many other types of quantum systems, entanglement distribution and swapping, and exploration of network concepts.
- Quantum simulators are likely to provide an abundance of rich results in the nearer term, and this could be valuable to discovery of new materials of specific importance to Army (magnetic, superconducting, and unknown quantum phases).
- Atom-like solid-state systems (e.g., NV-diamond) are a potential area of investment, as it would enable development of other sensors relevant to the DoD mission while exploiting solid-state expertise.
- Opto-mechanical systems in the quantum regime are another forefront area for coupling different types of quantum states and for novel sensors. They also can be used to shift photon frequencies, and move silicon photonics into the quantum arena.
- An ion trap group would be a good investment. There are relatively few ion groups compared to neutral atom groups and yet there is lots of interesting physics to be explored. Moreover, JQI is near, and they have this expertise. So mentorship would be close by.

- Rydberg atoms may be a good source of deterministic single photons and neutral atom gates with strong coupling, making this an intriguing possibility for investment.
- “Big engineering” might be an area to consider, as that is something that would not be possible in a University setting. Examples are developing a 50 qubit device; improving diamond manufacturing (for NV centers); chip manufacturing (for atom/ion trapping, atomtronics, and electronics), integrated optics/photonics--any of which could benefit much of the ongoing research being carried out by academic groups and enable rapid progress. Things like these can be done by government and industrial labs while they are extremely difficult in a University setting.
- QIS theory is considered essential, and Army could make a big impact inexpensively. Moreover good theory teams are needed to provide the framework holding the experimental enterprise together coherently. Theory would identify new applications of QIS technology, and is underrepresented in academia. A few examples that theory could explore include:
    - Topological orbital physics of cold atoms in novel lattice geometries. There is much new physics here that could be useful for quantum emulators in search of new quantum states of matter.
    - Exploration of quantum algorithms aside from the very few known so far. Quantum chemistry is of particular relevance and importance to Army.
    - Emergent quantum systems, e.g., ones with fractional charges, new quantum effects, new capabilities, new limits. This could even involve exploration of phase transitions in Hilbert space itself.
    - Studies at the foundations of quantum mechanics (QM) can likely discover both new physics, and the limits of QM itself. For example, might there be a quantum Gödel’s theorem, implying problems that are not solvable and/or decidable?
    - Quantum robot swarms: what do they allow?

Structural Recommendations

It was pointed out that there are several models of highly successful governmental research institutes (NIST, JILA, JQI, NIH), which are first rate (e.g., NIST having four Nobel Prize winners). Probably not coincidentally, these institutes are unique in their focus and expertise. Also of note is that a few of these (JILA and JQI for example) are joint institutes with academia and others. They generally have a mission area (or projects) whose size and scope are too large for a university, but are appropriate for a government lab. NIST’s mission on time keeping (involving cutting edge atomic and optical clocks) is a good example.

Key features of successful research institutes that the Army needs to emulate

• Hire excellent scientists, comparable to the best in academia and at NIST;
• Have a critical mass (>5 -10 groups) of co-located research groups (>10 in steady-state);
• Provide excellent facilities, ideally with some unique capabilities, to attract and retain talent;
• Give groups stable, long-term support;
• Give group leaders control and freedom within the general mission;
• Hire new group leaders every ~5 years to maintain a vital, cutting-edge community;
• Encourage and enable open/meaningful interactions with academia, industry, start-ups;
• Ensure a steady flow of students and post docs.

Other recommendations

• Consider an “off Army base” lab, or a joint research institute with a university, for basic research activities to enable an open environment and work with non-US citizens.

• Nature is quantum mechanical, not classical. Therefore, the Army really needs to invest in a full spectrum of quantum/QIS research.

Information at the Tactical Edge
18-19 December 2013
Bolger Center, Potomac, MD

Organizer: Dr. Ananthram Swami (ST, ARL/CISD)
with significant inputs from Dr. Bruce West (ST, ARL/ARO), Dr. Lance Kaplan (ARL/SEDD), Dr. Alexander Kott (ARL/CISD), Dr. Norbou Buchler (ARL/HRED), and Dr. Robert Bonneau (AFOSR).

Introduction: Sixteen distinguished scientists working in the area of Network and Information Sciences met with scientists from RDECOM and other DoD agencies on 18-19 December 2013. This meeting was a follow-up to the ASA(ALT) Basic Research Concept Exploration and ARL's Visioneering 2050 meetings.

The theme of the meeting was the interaction between both large scale and small scale networks of machines and humans at the tactical edge; the flow of information between and among complex networks of different genres; appropriate definitions of (semantic) information in such complex systems; the impact of social, physical and other network layers on information flow; the representation, and effective and efficient delivery of information at the Tactical Edge.; theories and models of performance of human-machine networks in extreme environments: asymmetric, highly disrupted, error prone, stressed in numerous ways. The goal of the meeting was to understand how the area is evolving and where it should/could evolve, establish grand challenges and potential areas of Army focus for the long term.

The meeting comprised of a number of short sessions, detailed discussions after each session and a final discussion hour that led to the identification of a number of topics in Information and Network Sciences that would be highly relevant to the Army in the next 20-30+ years. The focus of these discussions was at the Tactical Edge which itself is likely to change significantly.

Scientific Recommendations:
A number of challenges for meeting the information requirements of user(s) at the tactical edge were identified at the meeting. The human dimension (instrumented warrior, Watson, collective intelligence, trust …) came up in multiple tasks and discussions. Much of the discussion was framed around processing / delivery of information to lead to improved decision making. Complexity, uncertainty, unpredictability and risk will always be characteristics of the frontier of knowledge at which the tactical Army will operate; and thus the soldier at the information front will continue to be subject to stress. Some major topics of interest that merged:

1) Automated analysis of goodness of information: There was no consensus on how goodness should be defined, but attributes could include quality (but sometimes quality is used synonymously with goodness and value), relevance and trustworthiness; especially important is a theory for the propagation of these attributes in a fusion chain. This could include semantic information processing, including dynamic creation of semantics for different situations and audiences, missions and echelons. The role of the human in helping machines/systems to learn needs exploration

2) A major challenge is the high-dimensionality of the data and the resulting complexity of the information. But information content lies in a complex low dimensional manifold that may be user and context dependent. Sparsity techniques may be used handle this complexity, but require a basis set. In that regard, it is important to understand how observed patterns relate to the cognitive states of people (friendly forces, adversarial forces and civilians), who are interacting and influencing the network. In other words, understanding a "physical" relationship between measured network effects and the people driving these networks might help form this basis set

3) Efficient discovery of the information manifold requires appropriate mathematical models and representations to enable reasoning about vulnerability, quality, relevance and trustworthiness of the information, and effective storage and delivery of information. Critical to enabling this are cognitive models of users and user behaviors (beliefs, intentions, emotions, etc.) and distributed computing at the edge.

4) Data Analytics: Approaches such as micro-clouds may be useful to bringing some data analytics closer to the network edge. A challenge is how to distribute computational resources for big data processing over the organic assets at the edge while exploiting the larger computational resources higher up the echelon. Since a mission can involve input from multiple tactical edge users that cannot communicate directly with each other, coordination of their information to the benefit of the overall mission is a challenge

5) Information Field theory that accounts for both ‘humans’ and ‘events’: information dynamics, including the impact of the adversary; such a theory might also include multi-brain (team) information processing and collective intelligent behaviors. C2 theories of information need to be developed (in conjunction with conventional C2).

6) Co-evolution: It may be more useful to consider multiple co-dependent information networks rather than a single information network. Developing methods for learning and predicting temporal evolution of structure and attributes of such networks will require sustained study of multiple coevolving networks. Advances in non-linear stochastic control of multiple inter-dependent and co-evolving networks are needed: despite some recent progress, the area is still in its infancy

7) Radical Automation: all processes from collection to delivery and explanation. As a specific example, it was noted that even a seemingly classic problem: topic modeling -- automatically identifying topics in corpora of text documents, in the context of a user and a mission - is of great importance and is not yet resolved. [‘Watson’ came up for discussion a few times]

8) Science of team-building: As the adversary improvises in its tactics, the traditional command and control structure may not be agile enough. A major challenge is to incorporate a flexible command and control policy over the network that improves mission effectiveness while not leading to more confusion. This challenge includes the formation of effective (“better thinking”) teams on the fly instead of following purely static doctrine. Given the expected convergence of artificial/cyber and physical/human, such a theory should account for a general notion of an instrumented warrior.

9) Experimentation: Move beyond mathematics and constructive simulations to design and conduct series of experiments with human participants as well as instrumenting ‘reality’ to gather the empirical data we need to test a wide variety of hypotheses

Other: The discussions did not adequately cover how the nature of the tactical edge might evolve over the next 10-30 years. Surprisingly there was very little discussion of cyber security aspects.

Intelligent Systems

November 12-13, 2013
Bolger Center, Potomac MD

Organizers: Dr. Joseph N. Mait (ST, ARL/SEDD), Dr. Brett Piekarski (ARL/SEDD), Dr. Jon Bornstein (ARL/VTD), Dr. Brian Sadler (Fellow, ARL/CISD), Mr. Stuart Young (ARL/CISD), Dr. Jim Overholt (ST, AFRL), and Dr. Marc Steinberg (ONR)

On Tuesday and Wednesday, November 12 and 13, ARL hosted an Army Science Planning and Strategy Meeting on Intelligent Systems. The meeting consisted primarily of four panels and moderated discussion. In addition, the meeting had one breakout session with a report back to the group and a special briefing by Mr. Jim Shields on the Defense Science Board's Report on Autonomous Systems.

The first panel set the stage for the remaining discussion by addressing the technical problems the Army faces now and the technical problems do we anticipate in the next twenty years? The remaining three panels were Intelligent Systems, Intelligent Systems in Dynamic Environments, and Soldiers Interacting with Intelligent Systems in Dynamic Environments. The intent of these panels was to consider the capabilities required for a single platform, for multiple platforms in a complex, dynamic environment, and, finally, interacting not only with other platforms but with humans as well.

At the end of the day on Tuesday, the attendees divided into two groups to address specifically the issue of skills required by researchers to address future technical challenges. One group represented a start-up to develop intelligent systems for the Army in 2024. The other group represented a DARPA program manager developing a new program to field intelligent systems for the Army by 2034. The company CTO was required to list the qualifications of his-her first five hires and his-her first three products, and explain why. The program manager was required to list the expertise of his-her research team and identify the scientific challenges.

As Mr. Shields stated clearly in his briefing, a focus on platforms or developing taxonomies for intelligence or autonomy detracts from the real discussion that is required, namely, what the Army wants their intelligent systems to do in the next 30 years.

From the panel discussions and break-out, a consensus exists that animal-like intelligence is desired. Increased intelligence is desired for simple platforms such as robotic followers and for aerial and ground sensor platforms. Present platforms are not only directed to move to specific locations by human controllers, humans also provide navigation. Since autonomous navigation is a present research topic, how platforms set waypoints autonomously is an obvious next research topic.

Platforms need to set waypoints that increase mission effectiveness standpoint. Followers need to recognize the actions of their unit. For example, in addition to knowing where the unit is headed, the follower must be able to perceive when the unit is deviating from a previously prescribed plan and know enough to query why. The follower must recognize when the unit is resting. The follower must be capable of doing so without explicit instructions from a human.

Similarly, when commanded to surveil a building, ISR assets should know they need to monitor windows and points of ingress and egress. ISR assets need to recognize those activities that require high fidelity monitoring.

A key capability to enabling this functionality is recognizing action or, as stated often during the meeting, labeling nouns and verbs in a scene. Developing command and control, and system architecture are also critical to enabling the effective coordination of humans and intelligent systems.

Attendees considered the utility of intelligence beyond an animal's and approaching that of a human. The attendees discussed potential functions for such platforms including the conscience of a unit and a personal assistant for the disabled, which was the first product suggested by the Breakout CTO.

Guided by a fixed set of rules as in Asimov's "I, Robot," some felt that a Unit Conscience platform could insure that warfighters followed the Rules of Engagement for an operation and reduce humanitarian crimes. The personal assistant was intended primarily as an aid for disabled veterans and follows the Japanese trend to develop platforms to serve an aging population.

Both functions require that a platform understand human gestures, body language, speech, and tone. This was regarded as being similar to a dog's ability to read his or her master's voice and body language. This requires a system for multi-sensory input and algorithms for interpretation. A speech interface is required for the assistant and is probably recommended for the Conscience platform.

Playing off IBM's Jeopardy-playing system, at a high level of intelligence, a platform called Sergeant Watson was suggested for platoon leaders. The intent was for SGT Watson to interpret for a young officer his tactical situation and provide options for action. Some felt the complexity and criticality of the situation deemed this inappropriate. The suggestion was therefore modified so that Watson served as an adjunct to a senior commander's team of advisors. Advisor Watson should be capable of interpreting strategic, global situations and offer options for actions. This function was also discussed in the Army Strategy Meeting on the Human Dimension.

Issues related to the cloud were pertinent to this discussion. How does one harness and exploit the data that is available to a single unit connected to a network? Further, is it possible for a tactical unit to access the cloud?

The group raised other issues for consideration including how resource constraints alter a solution to a problem derived assuming unconstrained resources and how one performs autonomy at tempo, i.e., how one speeds up learning or even implements upgrades in a rapid fashion.

With regard to the skill set required to pursue these avenues of research, the group agreed that it needed to be multidisciplinary. It requires people capable of constructing platforms, sensors, and the algorithms that generate intelligence. However, it also requires cognitive psychologists and learning specialists.

The Human Dimension
November 4-5, 2013
Bolger Center, Potomac MD

Organizers: Dr. Brian M. Sadler (Fellow, ARL/CISD), Dr. Jean Vettel (ARL/HRED), and Dr. Frederick Gregory (ARL/ARO)

Background: As a follow-up to the ASA(ALT) Basic Research Concept Exploration and the Army Research Laboratory (ARL) Visioneering 2050 exercises, ARL hosted a two day meeting on 4-5 November 2013 that focused on the human dimension and aimed to identify grand challenges and technical expertise needed to ensure cutting-edge research and scientific impact for Army 2050. Each day included coarsely-defined topic sessions with a series of talks followed by an extended discussion period. *It is broadly recognized that the human dimension is critical and will become pervasive across all Army R&D.*

Scope: The meeting focused on the study and modeling of humans and their interaction with technology. Topics included (but were not limited to) quantifying substrates of human behavior, modeling human cognition, expertise and training, human(s)-in-the-cloud, and wearable and implantable technology.

Three Day 1 sessions broadly addressed quantifying and/or predicting cognitive behavior, examining potential of wearable/implantable aids for performance enhancement, and ethics of using technology to modulate performance generally, while the final session on Day 2 focused on understanding substrates of expertise and/or approaches to optimize training and decision making. Across the 13 technical talks, speakers articulated emerging trends in the field of human research, and many accepted a challenge from the meeting organizers to conclude with a few gutsy futuristic predictions to spark a hearty discussion among the ~50 attendees from DoD, other government research agencies, academic, and industry research laboratories. From these lively and invigorating discussion periods, several technical trends emerged that coalesced into themes identified by the group as ideas likely to have the greatest impact (particularly on DoD and Army) over a 10 to 30+ year time frame.

Quantifying and/or predicting cognitive behavior (Tenenbaum, Dale, Nowak): (i) A discussion of cognitive models highlighted the need for probabilistic approaches that capture learning and training, intuition, and that can be verified. These lead to fundamental insights and generalization. Bayesian models of cognition are emerging and very promising, although other models should continue to be explored. These cognitive models contrast with agent-based simulation approaches. (ii) Considered predicting social communication: Using gestures, eye movements, and body language to identify person-to-person coupling or brain-to-brain interaction that characterizes capacities and/or episodes of social coordination; patterning of communication can reveal shared knowledge, discourse comprehension, escalating versus mitigating conflict. (iii) Suggested humans are a bottleneck for adaptive human-computer systems and proposed active learning algorithms on big data (or humans in the cloud) to identify the similarity space underlying human judgments and determine minimal questions needed to maximize AI prediction accuracy. (iv) Highlighted the need for a shift in natural language processing from syntax to semantics. More generally, discussed the need for an AI agent or model to be able to explain how an answer is achieved, relating to human cognition that understands actions in the context of beliefs and desires. A computational theory of mind should account for cultural differences, might consider what is different between individuals rather than focus on what is the same, and develop theories of exceptional talent especially in the context of collaborative teams.

Potential of wearable/implantable aids for performance enhancement (Plaxco, Elman, Rao, Shea): Two major themes arose from the series of talks largely focused around examining potential of wearable/implantable aids for performance enhancement: one emphasized implantable technologies to sense biomarkers in the bloodstream and/or release predetermined levels of drug therapy, while the other focused on augmenting sensory performance through novel interface designs. A future goal within the human dimension is to acquire the capability to continuously monitor biomarkers of cognition in real-time, potentially coupled with implantable drug release. In addition to detecting natural cognitive states, current state-of-the-art approaches are aimed at examining various forms of human-machine interfaces that might be used to augment human performance. Significant challenges include tracking human adaptability, interaction with implantable sensors, and creating and exploiting living on-chip biological networks.

Ethics of using technology to modulate performance generally (Sandberg): This technology is already raising important ethical issues, and this trend will likely accelerate. Human capital can be boosted with enhancement, but many issues arise including responsibility, data logging and its alteration on behavior, assigning blame when crowd sourcing is utilized, and others.

Understanding substrates of expertise and/or approaches to optimize training and decision making (Lane, Bassett, Mitroff, Frank, Shah): It is desired to work toward a future based on creating learners with adaptive expertise, beginning with early childhood education. This suggests learning technologies that are persistently affect-aware with flexible interaction with human learners. Network models based on neuro-imaging permit the critical study of functional neural network connectivity, and will lead to deep understanding of training, learning, and performance enhancement. This can couple neural state sensing, learning, and human-autonomous machine interaction. Social data processing will augment and complement this area, for example, modeling user judgment reliability and enabling training optimization.

Speakers affiliations: MIT/ISN, UC Merced, University of Wisconsin, UCSB/ICB, UMASS Lowell, University of Washington, USC/ICT, UPENN, Duke, and LMI.

Summary: *The human Dimension will be increasingly pervasive and multi-disciplinary, including neuroscience, biology, autonomy, network science and systems engineering. Quantifiable theories and models, advances in implantable/wearable sensors, application of learning methods, crowd-sourcing, and human-autonomy interactions will lead to dramatic advances in Army capability.*