U.S. Army
Research Laboratory
Essential Research Areas
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Introduction

As outlined in the Executive Summary to the ARL Technical Strategy, ARL uses eight Science & Technology (S&T) campaigns to organize its intellectual framework for planning technical strategy, and aligning and synchronizing resources, people, and infrastructure. The S&T Campaigns consist of Human Sciences, Information Sciences, Sciences for Maneuver, Sciences for Lethality and Protection, Materials Research, Computational Sciences, Assessment and Analysis, and Extramural Basic Research. To further focus the S&T essential to ARL’s highest priority work, nine Essential Research Areas (ERAs) were identified. The ERAs have been developed with the understanding that future warfare will be fought across all five domains (Land, Air, Space, Cyberspace, and Maritime) and among three realms: the physical, the domain of activities defined in space and time by the laws of physics; the informational or virtual, 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. In each ERA, technical gaps with Army outcomes have been identified that are critical in the path of progress in these ERAs. This document provides a brief summary of each ERA, along with Army relevance, key expected outcomes, and technical gaps. These descriptions were developed by campaign leads, senior campaign scientists, ERA leads, and ARL scientists and engineers to enable strategic planning for research programs within ARL in coordination with its partners and stakeholders. While each ERA has been assigned a coordinating or lead campaign, ERAs encompass many campaigns that come together to provide a connected, cumulative, and converged vision to embody the S&T the Army deems essential to delivering advanced capabilities to the Warfighter.

For additional details regarding each ERA and its corresponding gaps, please contact the ERA coordinators specified in the summaries.

Each ERA is summarized in the following.

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**Human Agent Teaming**

**Description:** Human Agent Teaming (HAT) is focused on leveraging the strengths of both the human and intelligent agents to improve overall operational performance. Thus, teams of humans and intelligent agents are performing military-relevant tasks more efficiently and effectively than either group does alone.

**Army relevance:** Current Soldier teams provide the capability to complete the mission—any mission, regardless of the challenges that dynamically arise and the adjustments that need to be made. The HAT ERA provides Human-Agent teams that have the capability to perform as well as Soldier teams but with additional capabilities including greater team resilience with robust, adaptive performance; fast, dynamic team reconfiguration to match capabilities to mission requirements; faster, more informed decision making; and reduced risk to Soldiers.

**Outcomes:**
1. Human-Agent Collaborative Processing and Behaviors
2. Tailoring Information to Individual Soldiers and Agents
3. Effective Team Responses to Adverse Events
4. Dynamic Team Composition
5. Comprehensive Analysis of Human-Agent Teaming

**Technical Gaps:**
1. Development of human-agent integration principles and approaches that accentuate the strengths of individual humans and agents while mitigating weaknesses for improved decision making.
2. Novel technologies and approaches mix augmentation of human information processing, adaptability, and decision making with intelligent agents to maximize performance.
3. Greater capability to estimate and predict human variability, behavior, and intent across dynamic contexts (tasks, people, and environment) given multiple, disparate sources.
4. Foundations and methods need to be devised to provide distributed control and decision making that are responsive to human intent, interactive to changes in that intent, and are able to function in complex environments with high degrees of a priori uncertainty and adversity.
5. There is a lack of high-resolution, real-time, human-in-the-loop methods and approaches to analyzing HAT performance.
6. Theories/models linking individual dynamics and emergent, dynamic properties of HATs.
7. Systems-based approaches to develop and dynamically adapt technologies to optimize HAT performance.
8. Methods to effectively share concepts, intentions, and situations across heterogeneous human-agent teams are inhibited by platform differences and technological divides.
9. Approaches for controlling human-autonomy interactions that account for and exploit adaptation in human and intelligent agents, and enable control of emergent states and behaviors of HA teams.
10. Techniques to effectively integrate intelligent analysis technologies with human subject matter expertise for collaborative analysis.
11. Advancements in system engineering practice and models are needed to account for dynamics of work, team, individuals, and environment, and for intelligent systems working collaboratively with humans.

**Coordinating Campaign:** Human Sciences  
**Campaign Lead:** Mr. Corde Lane  
**ERA Coordinator:** Dr. Kaleb McDowell, kaleb.g.mcdowell.civ@mail.mil
Artificial Intelligence and Machine Learning

Description: Develop and employ a suite of artificial intelligence (AI)-inspired and machine learning (ML) techniques and systems to assist Soldiers in dynamic, uncertain, complex operational conditions. Systems will be robust, scalable, and capable of learning and acting with varying levels of autonomy, to become integral components of networked sensors, knowledge bases, autonomous agents, and human teams. Advances will be informed and inspired by cognitive neural science, leading to new computational algorithms and hardware architectures, with far-reaching applications such as discerning adversaries’ intent, supporting course of action analysis, providing real-time perception for rapid op-tempo autonomy, automated building of predictive models, and developing intelligent adaptive Soldier training.

Army relevance: Future operational environments will be increasingly complex in both the physical and virtual realms. The AI & ML ERA will provide capabilities and systems to assist Warfighters in Army-relevant environments including: diverse and dynamic missions, tasks, goals at varying tempos; highly dynamic, mobile, and resource-constrained environments; extreme heterogeneity with mixtures of sensor, data, and information assets with varying security, provenance, and capabilities; varying scales from very dense (mega-cities) to sparse (remote FOBs); and adversaries already on the network, advanced persistent threats.

Outcomes: Develop artificially intelligent agents on the battlefield—heterogeneous and distributed—that rapidly learn, adapt, reason, and act in contested, austere, and congested environments of the future. Specifically:

1. AI agents that learn, adapt, reason and act with *Dinky, Dirty, Dynamic, Deceptive Data* (D5)
2. AI agents that learn, adapt, and reason in a dynamic, distributed manner over highly heterogeneous data with impaired communications
3. AI agents that perform computations under extreme constraints of *Size, Weight, Power and Time available* (SWAPT)
Technical Gaps:
1. Learning in Complex Data Environments
   • AI & ML with small samples, dirty data, high clutter
   • AI & ML with highly heterogeneous data
   • Adversarial AI & ML in contested, deceptive environment
2. Resource-constrained AI at the Point-of-Need
   • Distributed AI & ML with limited communications
   • AI & ML computing with extremely low SWAPT
3. Generalizable and Predictable AI
   • Explain-ability and programmability for AI & ML
   • AI & ML with integrated quantitative models

Coordinating Campaigns: Information Sciences (IS) and Computational Sciences (CS)
Campaign Leads: Ms. Cynthia Bedell (IS) and Dr. Raju Numburu (CS)
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Accelerated Learning for a Ready and Responsive Force

Description: Accelerated Learning for a Ready and Responsive Force focuses on more effective Soldier training solutions that take optimal advantage of the pervasive learning opportunities that occur within and outside of the training environment. Achieving this goal will reduce times to achieving Soldier proficiency and complex skills expertise through systems that can intelligently provide appropriate, timely feedback whenever training-relevant learning opportunities are presented.

Army relevance: The increased complexity of the multi-domain battlefield will impose even greater demands on Soldier training. Various skills applied in varied contexts will strain Soldiers who already lack sufficient training time. Reducing time to proficiency and developing expertise will be crucial to future Soldier readiness. This may be particularly so for the complex skills needed to meet the complex demands of the multi-domain battlefield, such as situational awareness, decision making under uncertainty, resilience or grit, or emotional intelligence and sociocultural awareness.

Outcomes:
1. Fully-integrated technology solutions that enable pervasive training delivery at the point of need
2. Instructional methods that account for the interdependencies across the full spectrum of Soldier tasks
3. Adaptive systems and augmentation tools to enable individualization of training delivery
Technical Gaps:

1. Soldier interfaces must be improved to enable effective delivery of training at the point of need.
2. Advances in the architectures and frameworks are required for hardware-software integration of live-virtual-constructive and gaming technologies.
3. Better intelligent agents for live-virtual-constructive training applications need to be developed.
4. Intelligent, agent-based pervasive interfaces—a virtual “coach”—are necessary to optimize interactions between Soldiers and full-spectrum training systems.
5. A unified, multiscale synthetic environment to support full-spectrum training is needed, with tools for rapid scenario authoring.
6. Diverse teaching (pedagogical) methods are needed to tailor domain-specific instructional content to individual learner state and learning style.
7. New capabilities to account for and exploit the interdependencies across Soldier tasks and skills are needed to enable cross-task and cross-domain instruction.
8. Validated methods and metrics to assess the effectiveness of training are needed.
9. Advances are needed in current software architectures, frameworks, and tools for rapid development of adaptive instructional systems.
10. Robust models of Soldier states that impact learning processes and training effectiveness do not exist.
11. Augmentation methods to enhance learner states are needed to maximize the impact of training.

Coordinating Campaign: Human Sciences
Campaign Lead: Mr. Corde Lane
ERA Coordinator: Dr. Kelvin S. Oie, kelvin.s.oie.civ@mail.mil
Tactical Unit Energy Independence

**Description:** Tactical Unit Energy Independence (TUEI) is ARL’s research program to enable energy independence of future widely dispersed tactical units operating in contested multi-domain battlespace environments to increase operational effectiveness and eliminate vulnerabilities and logistics burden due to energy resupply.

**Army Relevance:** The TUEI ERA brings together research across ARL that seeks to improve Army tactical unit operational effectiveness and endurance, while reducing vulnerability and logistics burden due to energy-related resupply. In this context, tactical units refer to company size (150 individuals) or fewer, deployed in a widely dispersed expeditionary manner. It is expected that Army tactical units of the future will include manned-unmanned teaming (MUM-T) with heterogeneous teams of intelligent systems that need to conduct sustained operations in resource constrained, austere, and hostile environments without access to safe refueling/recharging, and possibly without Forward Operating Bases. To enable such operations for future multi-domain battlespace concepts, ARL’s TUEI ERA focuses on power and energy research to develop increased energy and power density Soldier-worn and manned/unmanned platform power sources, enable energy harvesting and scavenging from renewable and locally available resources, and improved conversion/transmission efficiencies and energy demand for Soldier and platform applications relevant to Army tactical operations.

**Outcomes:**
1. Increased Soldier, Squad, and Company level operational mission duration
2. Self-sustaining and energy efficient intelligent systems that can match Soldier endurance
Technical Gaps:

1. Soldier-portable electronic device energy efficiency
2. Energy density for wearable power sources and development of novel wearable hydrocarbon-based source technologies such as thermophotovoltaics
3. Integrated or embedded energy storage
4. Multifunctional and multimode energy harvesting and storage
5. Efficient multi-fuel tolerant engines
6. Lightweighting and additive manufacturing methods for increasing energy and power density
7. Intelligent integration of hybrid powertrains
8. Flexible asynchronous energy transfer across sensor-Soldier-platform domains
9. Self- and system-aware energy and power devices, and components capable of organizing/informing intelligent energy networks
10. Novel renewable power sources, such as upgrading biomass fuel sources
11. More direct and efficient energy conversion mechanisms to enable actuation and mobility
12. Intelligent and energy aware maneuver for autonomous systems

Coordinating Campaign: Sciences for Maneuver
Campaign Lead: Mr. Jaret Riddick
ERA Coordinator: Dr. Brett H Piekarski, brett.h.piekarski.civ@mail.mil
Manipulating Physics of Failure for Robust Performance of Materials

**Description:** Overall, ARL will develop materials and systems that can sense and adapt at the “speed of the fight.” To realize this overarching goal, ARL must discover materials and systems that detect, characterize, and manipulate the physics of failure, including dynamic damage, to create disruptively capable structures that are affordable, available, and adaptable. These materials are stimuli responsive and are capable of adapting locally and globally to failure or damage. As the area of dynamic fracture and failure is vast, this ERA will focus in the near term on improving the ballistic performance of body armor. Emerging threats will require increased protection resulting in heavier armor which is unacceptable for the dismounted soldier. Utilizing a Materials by Design approach, the ERA will discover novel modalities of protective capabilities to include new materials, multi-material solutions, multi-geometric designs and defeat mechanisms to provide unprecedented performance for our Warfighters of the future. Exploiting these novel fundamental discoveries, the ERA will quickly expand the scope to include other protective and offensive capabilities. The ability to control and manipulate dynamic fracture and/or failure will give the US Army unprecedented protective and offensive capabilities.
**Army Relevance:** Since the inception of the US Army in 1775, the ability to protect its assets (Warfighters and materiel) and to deliver overwhelming firepower to its adversaries, has been paramount for its success and survival. Currently fielded dismounted and mounted armor systems are extremely heavy, which significantly limits their ability to have assured mobility; moreover, adversarial weapons systems are increasingly more advanced, thus challenging our armor systems. Therefore, an advanced and adaptive armor systems will provide an ever-increasing ability to protect US Army systems. Conversely, as ARL develops a highly sophisticated and fundamental understanding of dynamic fracture and failure of materials and systems, this will allow insights into lethal mechanisms to overcome the most protected adversarial assets.

**Outcomes:**
1. Lightweight and flexible armor that can sense impending danger (kinetic energy/chemical energy/electromagnetic energy/et cetera), react at the “speed of the fight” to mitigate said danger, and return to its “normal” state.
2. Projectile(s) that can be fired, sense their intended target protective scheme, adjust their effects in real-time at the “speed of the fight” to defeat a myriad of targets.

**Technical Gaps:**

Understanding the physics of failure:
1. In situ characterization at extreme conditions at appropriate spatial and temporal scales
   Predictive modeling – understanding of length/time scale effects, probabilistic aspects
2. Validated modeling at scale
3. Scale bridging

Exploit/Manipulate Failure at relevant time/length scales:
4. Mechanisms to mitigate failure

Stimuli responsive materials that sense their state:
5. Synthesis and Processing of Gap 4 mechanisms

**Coordinating Campaign:** Materials Research

**Campaign Lead:** Mr. Andrew Ladas

**ERA Coordinator:** Dr. Adam Rawlett, adam.m.rawlett.civ@mail.mil, 410-306-0695
**Cyber and Electromagnetic Technologies for Complex Environments**

**Description:** Historically, Electronic Warfare (EW) and Cyber have been separated in operations, research, and system development. Future challenges require integrating EW and Cyber technologies and activities, and a shift for EW to a more surgical offensive posture against more advanced adversarial systems. This ERA will provide both basic and applied research to enable tactical Cyber Electromagnetic Activities (CEMA) dominance through non-kinetic fires to eliminate or degrade threat capabilities, protection against all CEMA threats in tactical environment, sensing the electromagnetic and cyberspace environment, and providing mobility within the battlefield and cyberspace.

**Army Relevance:** Army operations are inherently cross-domain, with the Army conducting combined arms maneuver in the land, air, maritime, space, and cyberspace domains to accomplish assigned missions in a complex operational environment. The future physical and cyber operating environment will be connected, congested, contested, and constrained. This research will help enable Army tactical CEMA dominance, thereby empowering the Army to fight and win against a near-peer threat in a congested and contested environment, shape an area of operations or area of influence, and control CEMA damage, effects, and interferences.

**Outcomes:**

1. Enable tactical CEMA capability for the Army through a collection of distributed, heterogamous platforms designed for frontline CEMA combat, with offensive capability, strong protection, and manned, unmanned, and Soldier platforms providing battlefield maneuverability.
2. Ensure domination of the tactical CEMA battlespace by enabling the following capabilities:
   - **Shoot:** Provide non-kinetic fires to eliminate or degrade threat capabilities.
   - **Defend:** Protect against all CEMA threats in tactical environment.
   - **Sense:** Understand the Electromagnetic and Cyberspace environment.
   - **Move:** Maneuver within the battlefield and cyberspace.
3. Establish the CEMA Proving Ground, which will provide an environment to analyze and assess CEMA technologies and their potential effects across all functional layers (operational, human, cyber, electromagnetic, and physical).
Technical Gaps
1. EM-Enabled Cyberspace Operations
2. Understanding CEMA Effects
3. Understanding Human Behaviors Related to CEMA
4. Cognitive Sensing and Processing of Cyber and EM Information
5. Camouflage and Decoy of CEMA
6. Complementary PNT approaches
7. Alternate Dynamic Communication Approaches

Coordinating Campaign: Analysis & Assessment
Campaign Lead: Dr. Pat Baker
ERA Coordinator: Dr. Tom Stadterman, thomas.j.stadterman.civ@mail.mil
Distributed and Cooperative Engagement in Contested Environments

**Description:** Distributed and Cooperative Engagements in Contested Environments (DCECE) is ARL’s scientific program to enable focused effects from dispersed battlefield entities (mounted and dismounted Soldiers deploying focused and area effects) while simultaneously frustrating the lethal intent of our enemies. The program will address the most challenging aspects of lethality and protection in the context of both kinetic and electronic warfare.

**Army Relevance:** Adversary combat formations are reaching both “peer” capability and numerical superiority. Our goal is to recapture Overmatch and to avoid technological surprise by empowering 1) Soldiers with the capability of a main battle tank, 2) squads with the full flexibility of combined arms and, 3) armored brigades with full freedom of maneuver in the most challenging environments. Our intention is to develop the science base that will enable all our battlefield assets (fires, vehicles, and Soldiers) to provide focused effects before, during, and after a maneuver from even the most disbursed positions. This will require science for lethality that allows a small number of dispersed entities to deliver overwhelming kinetic and non-kinetic effects combining omni-speed (from low to high speed), radical maneuverability, and efficient payload kill mechanisms. Simultaneously we seek science that allows one to protect a body/platform against complex single and multiple entities by combining electronic warfare technologies, physical materials, and kinetic mechanisms that adapt in real-time to an emerging battlefield environment. It is envisioned that echelons of low-cost, multi-mission agents could create cost-effective quality-of-mass effects and be deployed in a tiered fashion with the most capable entities being the mounted or dismounted Soldiers, themselves. These swarms combine effects and mechanisms, maneuver, and high-speed robust decisions to deliver/protect from many-on-many through few-on-few bodies. Such a vision has emerged within the ARL’s Essential Research in Distributed and Collaborative Engagements in Contested Environment.
Outcomes:
1. Overwhelming kinetic and non-kinetic battlefield effects
2. Agents acting in concert to guide, navigate, and control themselves toward collective effects
3. Radical maneuverability of vehicles, Soldiers, and munitions
4. Formation protection from multiple near-simultaneous lethal payloads

Technical Gaps:
1. Modular and scalable lethality; swarm-specific models, efficiencies, and mechanisms for concepts that execute cumulative lethality.
2. Multi-agent estimation and navigation that is small; robust against denial, deception, and misinformation; and embedded within the platform for accurate terminal guidance. Decision techniques that are robust against uncertainty and misinformation. The ability to propagate appropriate information for group action.
3. Coupled flight physics optimized for aero and ballistic interaction of fast, close, maneuverable, and exploding agents.
4. Kinetic, directed-electromagnetic, and electronic mitigation of a like-enabled peer advisory.

Coordinating Campaign: Sciences for Lethality and Protection
Campaign Lead: Dr. Jeff Zabinski
ERA Coordinator: Dr. Scott Schoenfeld, scott.e.schoenfeld.civ@mail.mil
Science for Manufacturing at the Point of Need

**Description:** Enable the rapid development and certification of lightweight multi-functional materials technologies for protection, maneuver, and situational awareness by enabling new, adaptable manufacturing processes and robust predictive models that link materials chemistry and physics, manufacturing processes, and design and optimization tools, as well as respond to local resource constraints (such as time, available materials, and power).

**Army relevance:** This ERA is fundamentally about achieving unparalleled flexibility at the tactical edge, providing timely alternatives not possible via a conventional supply chain. The opportunity arises from recent advances in additive manufacturing, which enables the production of parts with complex geometries directly from CAD (including many geometries not possible using conventional machining), with rapidly advancing materials properties. The ability to produce parts at will enables the near-instantaneous fielding of custom materiel to respond to changing circumstances, such as mission specific autonomous platforms, custom antennas, and weapons. The capability to produce parts on demand can significantly reduce Army inventory requirements, as well as reduce the cost of maintaining warm domestic supply chains. Further logistics relief is possible by recycling materials already present on the battlefield, such as scrap and indigenous mass.

**Outcomes:**

1. Enable on-demand production of certain parts categories, thereby reducing Army inventory burden.
2. Realize a significantly more responsive logistics chain, and ultimately reduce cost, weight, and maintenance.
3. Produce high confidence as-printed parts in a multi-product system, which minimizes the effort necessary to certify products and enables production to become more expeditionary.
4. Enable the fabrication of a new class of parts—for example, an armature with increased hardness on the wearing surface, with graded ductility elsewhere in the part.
5. Advanced material system understanding will lead to complex multi-material and component integration to achieve extremely dense function, such as fully printed tailored munitions.
6. Comprehensive materials and process understanding facilitates the adoption of expeditionary/deployable recycling processes to recover materials from waste and indigenous sources to produce high quality feedstock materials with minimal logistic burden.
Technical Gaps:
1. Multi-role high-performance agile materials for Army applications
2. Process models to achieve high confidence printing/rapid certification and intra-part property optimization
3. Multi-field design optimization tools
4. Part performance modeling and simulation tools that consider design, material, and process selection
5. High-resolution, precise-alignment hybrid multi-material additive processing for advanced technology integration and fabrication of multi-material multi-field metamaterials
6. Weapons of mass construction—develop technologies to exploit waste and indigenous material processing/recycling to address diverse materiel needs with minimal logistics burden

Coordinating Campaign: Materials Research
Campaign Lead: Mr. Andrew Ladas
ERA Coordinator: Dr. William Benard, william.l.benard.civ@mail.mil
Discovery

Discovery is essential to ARL’s mission and is defined as the process of identifying, creating, developing, and exploiting innovative, yet Army-relevant, science and engineering advances. It insures the Army’s continuing and future technological superiority, and creates technological surprise for our adversaries while avoiding technological surprise for ourselves. This ERA calls out the five “Exemplars” of Discovery.

**Quantum Information Sciences (QIS)** is based on exploiting the “second quantum revolution” to achieve beyond classical functionalities in all elements of C4ISR. Work ranges from the foundations of QIS, where one seeks to understand complexity in quantum systems and fundamental quantum limits; to quantum sensing (including the discovery of new sensing modalities); to quantum computing (exploring the challenges of constructing small qubit systems and the algorithmic power of such systems to solve hard computational problems); to quantum networking (seeking to understand entanglement distributed in a network and explore new methods of computing, communications, and sensing using such networks); to quantum simulation for new materials discovery; and lastly to new regimes reachable because of quantum control, connectivity, and the strong nonlinearity in qubit systems.

**Technical Gaps:**

1. New approaches to design, fabricate, test, and evaluate small high-fidelity quantum systems.
2. New approaches to quantum-limited sensing using entanglement, such as strong atom-photon coupling in ultralow loss photonic environments.
3. New methods to generate and explore exotic quantum states of light and/or matter based on capabilities of engineered quantum systems.

**Living Materials** takes advantage of advances in synthetic biology, enabling engineering of complex function into biological systems that can function as isolated machinery outside of a cell or within living microorganisms, or exploiting microbial diversity to guide advances toward precise spatial patterning of microbial communities. Among other things, it encompasses materials with integrated biological components; non-biological materials assembled by biology; non-biological materials replicating biological functions; principles of natural microbial community organization, structure, and function; and cellular survival in austere environments. It enables engineering the extraordinary capabilities ubiquitous to biological systems with particular emphasis on being adaptive and responsive.

**Technical Gaps:**

1. Design, implementation, and maintenance of engineered functions in non-traditional chassis organisms.
2. Methods to harness natural and artificial evolution, and for selection and propagation of successful candidates, to achieve complex and high performance materials or functions without loss of living composite or function(s).
3. Control over consolidated instructions for synthesis, assembly and/or function of biomanned materials, including controlled inheritance of parent biology.
4. Reconciling the critical role of water in biological systems with engineered synthetic material systems, including general environmental robustness and the impact of temperature, humidity, etc. on operation and stability.
**Topological Matter** deals with a recently discovered new realm of electronic and photonic matter where certain properties are “protected” (e.g., against decoherence). There are recently observed phenomena never before seen, and existing theory is insufficient to completely describe the physics observed. It includes predicting new topological materials; understanding of defects and disorder in topological matter, which can in some cases destroy and in other cases stabilize a topological state; the development of novel probes; exploration of interfaces and proximity effects; materials optimization; exploring and exploiting . anyonic and other novel quantum statistics; light-induced topological states; and topological photonics.

**Technical Gaps:**

1. The role of defects and disorder in topological matter needs better understanding and control, particularly at the surface of topological materials and at their interfaces with other functional materials. This includes defect mitigation schemes on the one hand, and exploitation of defect-stabilized topological states on the other.

2. Topological device concepts are needed, going beyond, e.g., spin injection using a topological insulator, to exploitation of states with novel quantum statistics (neither Fermionic nor Bosonic), and creation of quantum spin liquids. These device concepts should provide functions or capabilities that are not attainable with standard semiconductors.

3. Understanding and exploiting next generation topological phenomena. This includes understanding the role of symmetries; going beyond condensed-matter embodiments (photonic, cold atom...); exploring topological superconductivity; and creating and exploiting anyonic matter.

**Biophysics-Based Measuring & Modeling of Social Dynamics** deals with emergent social behavior from a collection of individuals, and is enabled by advances in biometric and geospatial detection/tracking of signals indicating collective action, including response to threat, emergence of social influence, large-group mobilization, shifts in affective states, and identification of epigenetic triggers for aggression/cooperation. It builds on breakthroughs in data availability and analytic methods, new Bayesian phase transition methods, and the application of computational models from physics. It encompasses social biometrics, population modeling and prediction, measuring and modeling cross-cultural dynamics, understanding sociocultural influences at human and small-group levels, biometric sensing of large-scale social behavior to generate new theory and models, population models of complex triggers of social unrest, and theory and models to predict cross-cultural conflict (eliminating need for deep culture-specific training).

**Technical Gaps:**

1. Need understanding/models of how individual biometric signals combine to indicate the state of a collective, and how individual actions relate to development of collective action.

2. Relationship between population-level sensing data and population-level dynamics is not known.

3. Predictive models of cross-cultural dynamics are lacking of transitions between cross-cultural interaction and collective action.
Complexity and Emergence is a broad and crosscutting realm that, among other things, builds upon the availability of big data; new ways of modeling/thinking about complex systems/networks in multiple disciplines; breakthroughs in the fractional calculus and its applications; and many other advances in understanding complexity broadly as a science with connections to numerous disciplines. It encompasses network science; complexity science; new mathematical strategies; non-equilibrium behavior of systems close to and far from equilibrium; search for underlying physical principles; understanding of information exchange and its control; big data; and uncertainty quantification and optimal verification and validation.

Technical Gaps:

1. No principled understanding of energetic and information processing characteristics of active matter and incipient emergent dynamic properties.
2. Critical need for mathematical models of finite size, far-from-equilibrium, complex systems, beyond statistical physics and nonlinear dynamics.
3. Algorithmic theory of learning and control: How do exteroceptive and proprioceptive sensing amalgamate for model inference and fast action in unstructured environments, and how do we emulate this?
4. Interplay between energy, entropy and information generation, storage, and transfer in complex interacting systems?
5. Need experimental and theoretical approaches to quantify sources, control of uncertainty and failures.

Coordinating Campaign: Extramural Basic Research
Campaign Lead: Dr. David Skatrud
ERA Coordinator: Dr. Peter Reynolds, peter.reynolds@us.army.mil