U.S. Army Research Laboratory Technical Implementation Plan 2016 – 2020

U.S. ARMY RESEARCH LABORATORY

MISSION: Discover, innovate, and transition science and technology to ensure dominant strategic land power.

VISION: The nation's premier laboratory for land forces.

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INTRODUCTION

The U.S. Army Research Laboratory (ARL) is the Department of the Army's corporate laboratory as well as the Army's sole fundamental research laboratory, dedicated to scientific discovery, technological innovation, and transition of knowledge products. ARL, *the nation's premier laboratory for land forces*, is strategically placed within the Army Research, Development, and Engineering Command (RDECOM) – an Army Materiel Command (AMC) Major Subordinate Command (MSC). ARL influences and impacts the Army as well as the broader DoD science and technology (S&T) communities, primarily, through transition of knowledge products to its sister organizations within RDECOM. Explicitly, ARL's mission is to *"Discover, innovate, and transition science and technology to ensure dominant strategic land power"*; to accomplish this mission, ARL executes fundamental research, defined as Basic Research (BA 1) and Applied Research (BA 2), to address enduring S&T challenges that have been identified by the Assistant Secretary of the Army for Acquisition, Logistics, and Technology [ASA(ALT)] and priorities articulated by the Chief of Staff of the Army (CSA). In addition, the laboratory conducts research and analysis in emerging fields that hold promise in realization of novel or vastly improved Army capabilities into the deep future (2030 – 2040).

Emerging trends suggest that the future Army's operational environment will likely be dominated by decreasing domestic budgets and reduced force structure; increased velocity and momentum of human interaction and events; potential for adversarial capability overmatch; proliferation of weapons of mass destruction; spread of advanced cyberspace and counter-space capabilities among our adversaries; and increased likelihood of operations among populations, in cities, and in complex terrain. Within the context of this highly non-linear and complex operational environment, the Army – America's principal land force – must shape the security environment; set the theater of operations; efficiently project national power; effectively execute combined arms maneuver in the air, land, maritime, space, and cyberspace domains; initiate and maintain wide area security; conduct cyberspace operations in the land domain; and integrate special operations across the Army's mission set. These core competencies, the Army's strengths and essential contributions to the Joint Force of the deep future, will strongly rely on S&T developments. To address the S&T-driven imperatives mandated by the deep future Army's complex operational environment and its core competencies, ARL has structured 26 Key Campaign Initiatives (KCIs) – *substantive, long-lived, primarily in-house technical programs focused on pursuing scientific discoveries, innovations, and knowledge product transitions that are expected to lead to greatly enhanced capabilities for the operational Army of 2040*. In addition, the laboratory's technical portfolio is constituted by 37 Core Campaign Enablers (CCEs) – *enduring technical thrusts dedicated to gaining fundamental understanding of new concepts and maturing foundational technologies and methodologies to enable a broad array of technical programs*. ARL's technical portfolio – defined in the ARL Technical Strategy and ARL S&T Campaign Plans – is composed of approximately 50% KCIs and approximately 50% CCEs.

This document defines ARL's KCIs and CCEs; each of the organization's KCIs is described by a long range (FY16 – FY30) plan identifying the 1) expected impact on the operational Army of 2040; 2) technical goals; 3) requisite increase in personnel above existing staffing levels; 4) infrastructure enhancements needed; and 5) alignment with the Army Warfighting Challenges (AWFCs) and Army Centers of Excellence (CoE) S&T needs. The laboratory's KCIs reflect a robust yet aggressive approach, delineated by a near-term (FY16-FY20), mid-term (FY21-FY26) and long- term (FY27-FY31) trajectory, which is anticipated to lead to capabilities that are critical to the Army in the deep future.

COMPUTATIONAL SCIENCES CAMPAIGN

MISSION: To discover, innovate, and transition S&T capabilities that (1) harness the potential of computational sciences and emerging high-performance computers (HPC) to maintain the superiority of Army materiel systems through predictive modeling and simulation technologies; (2) facilitate information dominance, distributed maneuver operations, and human sciences through computational data intensive sciences; and (3) significantly increase and tailor advanced computing architectures and computing sciences technologies on the forefront to enable land power dominance.

VISION: Computational science and the applications of advanced computing technologies will accelerate the United States Army's strategic land power dominance through critical research developments. Strategic and transformative developments in Computational Science will poise the Army of 2030 and beyond as the world's dominant land force. The desired end state is to leverage the full range of S&T enablers to position the Army to excel in distributed operations and increasingly complex operational environments.

The Computational Sciences Campaign focuses on advancing the fundamentals of predictive simulation sciences, data intensive sciences, computing sciences, and emerging computing architectures to transform the future of complex Army applications. Gains made through these underpinning multidisciplinary research efforts and exploiting emerging advanced computing systems will lead to scientific breakthroughs that are expected to have significant impact on Army materiel systems. Technologies resulting from this multidisciplinary research collaboratively with other ARL S&T campaign innovations will have a significant impact on Power Projection Superiority, Information Supremacy, Lethality and Protection Superiority, and Soldier Performance Augmentation for the Army of 2030.

The Computational Sciences Campaign has developed 3 Key Campaign Initiatives and 4 Core Campaign Enablers (CCEs) that are integrated to form a robust advanced computing foundation to understand and overcome complex fundamental challenges simultaneous to improving approaches of importance to the Army including weapon systems design; materials-by-design; information dominated and networked battle command applications; system-of-systems analyses; human performance modeling; platform maneuverability; and tactical supercomputers. The campaign heavily relies on ARL's research expertise and facilities devoted to emerging advanced computing architectures, mobile High Performance Computing (HPC), multi-scale and interdisciplinary predictive simulation sciences, multi-dimensional distributed data analytics, and computing sciences. Discoveries and innovations made in this area will exert a significant impact on the Army of the future.

TACTICAL HIGH PERFORMANCE COMPUTING (HPC) [KCI-CS-1]

EXPECTED ARMY IMPACT: This effort will provide 100 Petaflop computing power in the battlespace to enable real-time processing for Soldiers operating at the tactical edge and improve mission effectiveness and mitigate risk in hostile environments. Computing power of this magnitude is also an enabling technology for autonomous systems and real-time data analytics for Soldiers and intelligence analysts. Achieving such a system with current computing devices which are constrained devices by power and performance is untenable. By aggregating the computing processing power of deployed friendly computing devices through distributed computing, supplemented by the projection of mobile customized HPC platforms operating at the tactical edge (tactical cloudlets), a new level of capabilities is possible for mounted and dismounted Soldiers.

DESCRIPTION: Tactical High Performance Computing integrates four primary research areas including I) advanced computing research to facilitate the efficient use of emerging architectures – new algorithm design and analysis approaches must be developed to boost the computing capacity of fixed and deployed devices; II) research in provisioning these systems within a distributed computing architecture – this work includes novel concepts to schedule computing tasks over friendly networked processors to limit network hop to appropriate resources; III) dynamic binary translation to limit software re-writes and facilitate optimization in a runtime environment to achieve maximum performance; and IV) power- and architecture-aware computing for enhanced intelligence of provisioning systems – to design systems that have greater awareness of their computing capacity and mission appropriateness. The critical, mobile ad hoc networks that will form the connections in tactical cloudlets to the large-scale databases and complex applications that will be performed by these resources make this research uniquely military and Army in nature. Numerous applications are envisioned for this system in the future and include artificial intelligence aids for decision making, processing large-scale datasets (text, video), and navigation systems for autonomous vehicles (HPC-enabled autonomous vehicles providing on-demand processing).

a. TECHNICAL GOAL(S):

i. Near-term goals (FY16-FY20):

a. Develop models that can accurately couple computational performance with communication infrastructure.
b. Explore and develop scalable algorithms to optimize power for computing and networks.
c. Explore scalable and distributed algorithms for quantum networks, bio-computing, heterogeneous, quantum annealing, and neuro-synaptic computing architectures.
d. Establish a hierarchy of parameters for optimization of asset provisioning (strategic and tactical).
e. Develop scalable algorithms based on emerging models.
f. Develop and demonstrate real-time GIS and/or streaming data processing capabilities only possible through the aggregated computing capacity of tactical HPC.
g. Develop resiliency approaches to include processing and associated data in task migration and processor allocations.

ii. Mid-term goals (FY21-FY26):
   a. Scalable algorithms and software development moving from static compile-based code to real-time, dynamic binary translation for optimization and architecture re-mapping.
   b. Take advantage of the quantum network paradigm and integrate computing and communication for specific non-deterministic human-centric applications.
   c. Identify key elements of algorithm signatures to determine power-drain limiting instruction sets with required precision.
   d. Develop battle command applications utilizing scalable and distributed algorithms for quantum networks, bio-computing, heterogeneous, and quantum annealing, neuro-synaptic computing architectures.

iii. Far-term goals (FY27-FY31):
   a. Incorporation of novel processing paradigms and hardware (Quantum, neuro-synaptic, and bio-computing) as part of a broader distributed computing solution for Soldiers.
   b. Ad hoc network and quantum network planning and resiliency based on offered computing load and available resources to service these requests (coupled communication and computation).
   c. New application spaces (autonomous HPC, audio and visual processing, red and blue force analysis) and capabilities for Soldiers.

b. PERSONNEL REQUIREMENTS: This work will, ideally, be carried out by a team of researchers from the computer science, computer engineering, and mathematics disciplines as appropriate. Mathematics will be required to develop heuristics for solution spaces that span into Non-deterministic Polynomial-time Hard (NP-Hard) and NP-Complete problems. New methods of solving optimization problems dealing with temporal and spatial data will need to be developed. Computer scientists and engineers will work closely with colleagues from academia and industry as fabrication technologies continue to converge on paths of pervasive parallelism. Representative test cases will be developed on key application kernels and signatures to determine optimal binary instruction scheduling on heterogeneous architectures and identify ways to overcome key performance inhibitors including memory access patterns and spin-idle cycles from merging architectures of difference computing capacity. Identifying and discovering new capabilities from fielded HPC level performance will require inputs from across DoD and will ideally be carried out by computational scientists who understand varying domain areas and the new capacity offered by tactical HPC.

i. Near-term (FY16-FY20): Expertise in scalable algorithm development on heterogeneous parallel computing, neuro-synaptic, quantum annealing, and distributed. (4-6 FTEs)

ii. Mid-term (FY21-FY26): Personnel who understand how to bridge the capacity and capability gaps of new computing hardware and software. (4-6 FTEs)

iii. Far-term (FY27-FY31): Expertise on emerging computing paradigms and network modeling to explore and develop new scalable algorithms and software. (5-8 FTEs)

c. INFRASTRUCTURE NEEDS: Continued access to emerging processor designs and High Performance Computing platforms for development and testing of new approaches in algorithm design, code mapping (compilation), and benchmark suite analysis.

i. Near-term (FY16-FY20):
   a. Small-scale developmental computing hardware to test emerging low-power and alternate design approaches.
   b. Testbed to evaluate battle command applications including real-time complex sensor and heterogeneous data processing.
   c. Quantum annealing emulation architectures and small scale systems to explore algorithms.

ii. Mid-term (FY21-FY26):
   a. Laboratory space to develop customized architectures and enhanced ad hoc network emulation facilities.
   b. Heterogeneous computing with multi-core and neuro-synaptic architectures.
   c. Mobile systems to test functionality at tactical edge settings.

iii. Far-term (FY27-FY31):
   a. Access to emerging systems including quantum, neuro-synaptic, high-density core, and heterogeneous systems.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges and Army Capability Needs.

Army Warfighting Challenge	Description
1	Develop and sustain a high degree of situational understanding.
7	Assure uninterrupted access to critical communications and information links.
11	Conduct effective air-ground combined arms reconnaissance.
15	Conduct combined arms air-ground maneuver.
17	Coordinate and integrate Army and joint, interorganizational, and multinational fires and conduct targeting across all domains.
19	Understand, visualize, describe, direct, lead, and assess operations.

Army Capability Need Proponent	Capability Area Need
MCoE	3.c – Small Unit Lethality.
MCCoE	2.a – Fully interoperable, simple Mission Command systems.
FCoE	4.c – Next Generation Mission Command.

REAL-TIME, VERY LARGE-SCALE DATA ANALYTICS FOR THE ARMY [KCI-CS-2]

EXPECTED ARMY IMPACT: This effort will aid in the U. S. Army's information supremacy by pursuing concepts that enable analysis of big data in realistic timeframes, limit tactical surprise, improve situational awareness, and facilitate intelligence for autonomy. Data from battlefield networks, sensors, experiments, observations, human factor aspects, and large-scale numerical simulations are generating exabytes, yottabytes, and beyond quantities of data. This effort focuses on understanding and exploiting the fundamental aspects of large-scale, multi-dimension, multi-modal, dynamic, inconsistent, and incomplete data and performing analytics in almost real-time exploiting emerging and next generation hierarchical computing architectures. Real-time predictive large-scale data analytics will provide decisive advantage to commanders across a range of military operations in the homeland and abroad. Expected impacts include information supremacy and vastly improved situational awareness to aid warfighters and intelligence analysts; predictive analytics for decisions; enhancing autonomy technologies; accelerated Soldier training trough live and virtual data analytics; and catalysts for new innovations for Army materiel systems utilizing observational, experimental, and simulations data.

DESCRIPTION: The overarching goal of this effort is to develop scalable computational methods on novel, massively parallel hierarchical computing architectures to realize extraordinary potential for scientific advance inherent in large-scale complex data. Specific technical goals include creation of scalable mathematical algorithms, predictive computational methods, real-time data analytics, model order reduction, human cognition based mathematical approaches, neuro- and biologically-inspired methods, science analyzing large-scale data from wearable electronics/technologies, large-scale data sensing/compression methodologies, large-scale visual analytics, live-virtual methods for training, data mining/learning mathematical algorithms for distributed heterogeneous computing systems. Computational scalable algorithmic research in cognitive behavior, artificial intelligence, human-machine interactions and autonomous networks is also integral to this work. Novel methods to create systems capable of computing in memory and accommodating large amounts of unstructured data storage are critical to far-term success.

a. TECHNICAL GOAL(S):

i. Near-term goals (FY16-FY20):

a. Theory and algorithms for model order reduction methods, graph analytics, and scalable data mining methods.
b. Computational methods for large-scale clustered processing and agglomeration applicable to requirements associated with wearable technologies and network science experimentation and optimization.
c. Novel methods for computational neural engineering for neuronal algorithms targeting non von Neumann architectures (neurosynaptic).
d. New methods for leveraging and optimizing the use of flash storage and solid state drives in scalable data analytics.

ii. Mid-term goals (FY21-FY26):
   a. Investigate and develop new methods for uncertainty quantification to improve predictability of large-scale structured and unstructured data analytics.
   b. Develop new methods for data resiliency and fault-tolerant information discovery in temporally unstable and unpredictable distributed computational frameworks.
   c. Explore and implement new computational methods for large-scale complex experimental data analytics.
   d. Scalable model order reduction methods for assisting fast running design models, live virtual training for Soldiers, and interdisciplinary methods.

iii. Far-term goals (FY27-FY31):
   a. Improved autonomy and decision based approaches exploiting neuro-synaptic computing concepts.
   b. Development and exploitation of non von Neumann random access memory.
   c. Real-time, predictive analytics for next generation heterogeneous computing architectures.

b. PERSONNEL REQUIREMENTS: This work will be carried out by an interdisciplinary team of researchers from computational mathematics, computational informatics, computer science, computer engineering, engineering, and other subject matter experts as appropriate.

i. Near-term (FY16-FY20): Expertise in scalable algorithm for large-scale graphs, data organization on distributed computers, large-scale information visualization, computing architectures for data intensive sciences, and distributed computing environments. (4-6 FTEs)

ii. Mid-term (FY21-FY26): Expertise in scalable algorithm for evolving complex graphs, data organization on distributed heterogeneous computing systems, real-time large-scale information visualization, distributed and heterogeneous computing architecture for data intensive sciences, and applications based computing environment. (4-6 FTEs)

iii. Far-term (FY27-FY31):
   a. Expertise in scalable algorithm for dynamic complex and evolving large-scale graphs, data organization on distributed next generation computers, cognition based visualization, and computing models for next generation computing architectures (quantum, neuro-synaptic, biological, DNA). (6-9 FTEs)

c. INFRASTRUCTURE NEEDS: Continued access to emerging processor designs and High Performance Computing (HPC) platforms for development and testing of new approaches in algorithm design, code mapping (compilation), network mapping, and benchmark suite analysis.

i. Near-term (FY16-FY20):
   a. Peta-scale computing, experimental HPC architecture designed for large-scale data analytics.
   b. Experimental heterogeneous computing architecture for live-virtual training application.

ii. Mid-term (FY21-FY26):
   a. Large-scale heterogeneous architecture for distributing different data types on different systems for real-time data analytics.
   b. Exascale computer system.

iii. Far-term (FY27-FY31):
   a. Heterogeneous computer with next generation computing architecture (exascale, quantum, neuro-synaptic, DNA, biological).

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges and Army Capability Needs.

Army Warfighting Challenge	Description
1	Develop and sustain a high degree of situational understanding.
11	Conduct effective air-ground combined arms reconnaissance.
15	Conduct combined arms air-ground maneuver.
17	Coordinate and integrate Army and joint, interorganizational, and multinational fires and conduct targeting across all domains.
19	Understand, visualize, describe, direct, lead, and assess operations.

Army Capability Need Proponent	Capability Need Area
MCoE	3.e – Robotics/Autonomy.
CASCOM	3.a – Autonomous Ground Resupply.
CASCOM	3.e – Autonomous Aerial Resupply.
USAICoE	4.a – Intelligence Analysis.

COMPUTATIONAL PREDICTIVE DESIGN FOR INTERDISCIPLINARY SCIENCES [KCI-CS-3]

EXPECTED ARMY IMPACT: Predictive computational modeling significantly shortens development cycle and substantially improves performance of lethality, protection, electronics, power, and dismounted Soldier gear utilizing lightweight, multi-functional, cost effective, optimized innovative materials by design exploiting high performance computers. Rational design of such materials through predictive modeling can significantly shorten the development cycle and result in cost effective solutions for multifunctional subsystems. The materials engineered through predictive design computational methods can be fabricated according to Army specifications and with optimized performance at every spatial and temporal scale. Materials subjected to extreme conditions such as mechanical shock, pressure and electromagnetic fields are of particular importance to the Army and require advanced multi-scale and multi-physics computational strategies for successful engineering design.

DESCRIPTION: Fully validated, large-scale parallel software will simulate multi-scale complex systems in multiple technology areas. This software will integrate diverse temporal and spatial scale models, some running concurrently for highly coupled system components, and others sequentially, as dictated by the system functionality. The highly coupled model components may be separate executables, running at different time scales and potentially on different computational platforms. Some of the components may be commercial or third-party software packages where only the executable is available. The data exchange and particulars of the execution would be transparent to the user. Multi-scale analysis and material by design are supported through this scalable computational methodologies and software. The system software would be integrated with optimization algorithms and capabilities for determining design sensitivity and uncertainty quantification. Use of reduced order models will provide varying levels of computational speed and fidelity for different needs and facilitate coupling through reduced data sets and across distinct physical representations of system components.

a. TECHNICAL GOAL(S):

i. Near-term goals (FY16-FY20):

a. Develop multi-scale and Interdisciplinary computational Framework to couple field and deformation codes.
b. Enhance hydrocode frameworks for better physical representation of interfaces and fracture; fluid-thermal-structural interactions; and uncertainty quantification and verification validation methods.
c. Develop multi-scale methods for particle dispersion in realistic urban weather/battlefield environments.
d. Develop reduced order models of select computationally intensive simulations.
e. Identify and characterize the sets of component models and the data interactions needed for each system level software suite including component multi-scale models and bridging strategies to explore materials by design strategies.

ii. Mid-term goals (FY21-FY26):
  a. Develop generalized and extendable bridging methodologies for connecting models using data analytics and statistical machine learning approaches.
  b. Explore innovative analytical and scientific in-situ visualization approaches for scalable multi-scale methods. Explore and incorporate large-scale experimental data into different spatial and temporal simulations.

iii. Far-term goals (FY27-FY31):
  a. Develop robust, efficient, validated, large-scale parallel design and analysis software suites serving lethality and protection platforms, integrated sensor and material design, maneuver systems and war fighter assessment.
  b. Explore scalability and real-time simulations of predictive multi-scale urban weather modeling
  c. Integrated software relating source, effect, and consequences for cyber and electronic warfare.

b. PERSONNEL REQUIREMENTS: One segment of the personnel should be well-versed in numerical methods for scientific software--solving sets of coupled differential equations. They should also have some knowledge of the physics behind the equations they are programming, and the application space. They would work closely with colleagues from other campaigns on software verification and establishing comprehensive test suites for software quality assurance. Another aspect of the programming is software coupling in large scale parallel environments and potentially working with large quantities of data. Here information compatibility, efficiency and robustness would be concerns. Expertise on platform-specific performance is required to ensure software efficiency. A third personnel area would be needed to keep the simulation software up to date and running efficiently on evolving DoD computer platforms. Mathematical expertise is also needed for data-analytics to connect models and statistics because the model connections could be through ensemble averages and moments.

i. Near-term (FY16-FY20): Computational scientist team with expertise in computational mathematics and associated scientific fields. Personnel familiar with computing system architectures and scalable algorithmic knowledge for determining efficient software integration and interdisciplinary strategies. Computational mathematics with model order reduction expertise. (4-6 FTEs)

ii. Mid-term (FY21-FY26): Computational scientists with a good understanding of mathematical, numerical and specific discipline expertise to develop innovative coupling approaches at large scale and providing efficient parallel implementations. Scientists with experience in uncertainty quantification and software quality assurance to establish and maintain verification and validation suites. (4-6 FTEs)

iii. Far-term (FY27-FY31): Computational scientists that can take advantage of evolving hardware platforms and software models. Computational scientists with mathematical and specific discipline expertise to enhance capabilities as new models and new computing algorithms come available. Personnel with mathematical and statistical backgrounds for data analytics. (4-6 FTEs)

c. INFRASTRUCTURE NEEDS: Continued access to emerging high performance computing platforms for large scale testing and evaluation and ready access to small numbers of nodes (unfettered by lengthy queue times) for efficient software development. Access to moderate size parallel platform with reconfigurable communications that would not interfere with production computations.

i. Near-term (FY16-FY20):
   a. State of the art petascale computer system.
   b. Experimental computer platforms to create and exercise novel communication and data transfer schemes.

ii. Mid-term (FY21-FY26):
   a. Traditional exascale computer.
   b. Experimental heterogeneous computers.

iii. Far-term (FY27-FY31):
   a. Heterogeneous exascale computer.
   b. Quantum and biological-computing for diverse classes of interdisciplinary applications.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges and Army Capability Needs.

Army Warfighting Challenge	**Description**
3	Provide security force assistance.
5	Prevent, reduce, eliminate, and mitigate the use and effects of weapons of mass destruction.
7	Assure uninterrupted access to critical communications and information links.
15	Conduct combined arms air-ground maneuver.
16	Set the theater, provide strategic agility to the Joint Force, and maintain freedom of movement and action.

Army Capability Need Proponent	**Capability Need Area**
CASCOM	4.e – Advanced Materials.

PROGRAMMABLE NETWORK ALGORITHMS AND HPC MODELS FOR QUANTUM AND CLASSICAL NETWORKS [CCE-CS-1]

The Computational Sciences Core Campaign Enabler (CCE) on Programmable Network Algorithms and HPC Models for Quantum and Classical Networks incorporates Software Defined Programmable Network protocols and architectures that are revolutionizing the design of modem networks and information routing across heterogeneous network topologies. The control plane in current traditional networks is highly fragmented, non-programmable, proprietary and very difficult to modify as needed. Additionally, the emergence of quantum computing has put more demand on the development of adaptable and programmable network protocols and algorithms for building unified networks with heterogeneous node types (classical and quantum). Furthermore, despite ongoing advancements in architectures and processing power of supercomputers, they are bound by traditional static networks.

Programmable networks could offer the Army the ability operate in a secure and unified tactical network, interconnecting heterogeneous radio wave forms for faster convergence and enhanced security. Research in this area will focus on three aspects of programmable networks:

1) Extension of custom OpenFlow protocol modifications to develop a programmable control plane for optical, wireless, wired and quantum metadata networks. This work is conducted in collaboration with external partners.
2) Programmable and flexible Software Defined Networks (SDN) interfaces and algorithms to support the transport of quantum metadata between quantum nodes.
3) A SDN-based programmable network fabric enabling intelligent process scheduling and traffic routing within a High Performance Computing (HPC) cluster enabling more facile computation of large, complex problems such as very big data analysis.

The Computational Sciences CCE on Programmable Network Algorithms and HPC Models for Quantum and Classical Networks supports Key Campaign Initiatives by developing programmable network fabrics that will revolutionize the potential of supercomputing clusters through intelligent scheduling of processes and applications and traffic routing.

PERSONNEL REQUIREMENTS:

i. Near-Term (FY16-FY20): Expertise in the development of programmable network protocols and architectures for classical and quantum networks. Expertise in programmable wireless heterogeneous networks. (1-2 FTEs)
ii. Mid-Term (FY21-FY26): No new requirements above existing personnel

INFRASTRUCTURE NEEDS: NONE

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges

Army Warfighting Challenge	Description
1	Develop and sustain a high degree of situational understanding.
7	Assure uninterrupted access to critical communications and information links.
19	Understand, visualize, describe, direct, lead, and assess operations.

MULTI-SCALE MODELING FOR PREDICTIVE COMPUTATIONAL DESIGN [CCE-CS-2]

The goal of the Computational Sciences CCE on Multi-Scale Modeling for Predictive Computational Design is to accelerate development of new systems and models of complex phenomena by significantly reducing development time and evaluation costs. This goal can be achieved with 1) high-fidelity physical models at multiple scales and 2) computational methodologies (numerical methods and associated algorithms) to enable rapid creation of new high-fidelity multi-scale computer models of complex systems capable of utilizing modern extreme-scale computing.

The success of multi-scale modeling hinges on the ability to combine at-scale models into a multi-scale model. However, few numerical methodologies and associated, algorithms have been developed so far to enable such scale-bridging. Moreover, many at-scale models are extremely demanding computationally and render any multi-scale model utilizing them unsuitable for practical applications. While surrogate modeling allows reduction of this computational cost, most methodologies for surrogate modeling are global and thus characterized by a relatively high cost. New adaptive non-local surrogate modeling methodologies are needed, which can bring the computational cost to tractable levels. Finally, at-scale models are frequently endowed with uncertainty due to various sources such as natural fluctuations, model parameters or model form. This uncertainty and natural variability must be consistently incorporated into multi-scale computer models in order to enable computational design.

Four main areas will be the focus of the effort in multi-scale computational science:

1) Hierarchical Multi-scale Framework
2) Discrete Dislocation Dynamics
3) Phonon and Electron Transport
4) Density Functional Theory

The strategic approach to these focus areas include:

1) Shortened development time and evaluation costs of novel energetic materials by allowing macro-scale response to be accurately predicted directly from composition and chemical reactivity at the molecular level.
2) Development of novel materials for battery applications through expedited computational evaluation of potential compositions.
3) Advanced Soldier protective equipment and vehicle occupant protection through accurate multiscale prediction of skeletal fracture in comprehensive analysis and design simulations.
4) Accelerated material development for Army applications enabled by high-fidelity multiscale simulation methodologies (Materials by Design).

The Computational Sciences Core Campaign Enabler in Multi-scale Modeling for Predictive Computational Design will contribute to Key Campaign Initiatives by making available general, flexible, efficient, and scalable algorithms that comprise the computational framework to facilitate rapid development and deployment of multi-scale simulations on peta- and exascale computing environments, which will expedite accurate, microstructure-based design and analysis of components and full-scale systems.

PERSONNEL REQUIREMENTS:

i. Near-Term (FY16-FY20): Computer scientists with expertise in bridging computational scales spatially and temporally, scalable parallel computational development, novel methods for physical and ab initio models (2-3 FTEs).
ii. Mid-Term (FY21-FY26): No new requirements above existing personnel

INFRASTRUCTURE NEEDS: NONE

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges.

Army Warfighting Challenge	Description
5	Prevent, reduce, eliminate, and mitigate the use and effects of weapons of mass destruction.
12	Conduct entry operations.
16	Set the theater, provide strategic agility to the Joint Force, and maintain freedom of movement and action.
18	Deliver fires and preserve freedom of maneuver.

ADVANCED AND UNCONVENTIONAL COMPUTING ARCHITECTURES AND ALGORITHMS RESEARCH [CCE-CS-3]

High performance computing and computational capacity play a critical role in accelerating research and development for the Department of Defense. However, advanced computing architectures are becoming more complex with memory hierarchies and laid out as parallel processors with multiple processing cores. To harness computational capability of these advanced computing architectures new algorithms and software development paradigms are needed especially for the future Army science and technology campaigns. In addition to petascale and beyond capability, there is a need for new architectures and algorithms such as non-von Neumann systems like neuromorphic and quantum computing.

Key goals include the development of algorithms and techniques to address power, performance, portability, and efficiency through the construction of domain-specific architectures and scalable algorithms and programming models. Representative thrust areas include:

1) Threaded message passing to allow for massive on-core RISC-based architecture parallelism
2) Compiler-based software deployment on neuromorphic architectures focusing on a single control flow construct as a baseline
3) 3D rendering coupled with 3D printing of scientific visualization and modeling predictions of experimentation for verification and validation and uncertainty quantification

The Computational Sciences Campaign CCE on Advanced and Unconventional Computing Architectures and Algorithms Research contributes to Key Campaign Initiatives by enabling parallel processing for massive on-chip core architectures with complex memory hierarchies, exascale level processing, and domain specific architectures for large data analytics and advanced visualization of complex data.

PERSONNEL REQUIREMENTS:

i. Near-Term (FY16-FY20): Computer scientists with expertise in reconfigurable computing, mobile HPC, dynamic binary translation and code migration, emerging processor core architectures and algorithmic models for complex tasks (3-4 FTEs).
ii. Mid-Term (FY21-FY26): No new requirements above existing personnel

INFRASTRUCTURE NEEDS: NONE

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges.

Army Warfighting Challenge	Description
1	Develop and sustain a high degree of situational understanding.
7	Assure uninterrupted access to critical communicationsand information links.
11	Conduct effective air-ground combined arms reconnaissance.
12	Conduct entry operations.
15	Conduct combined arms air-ground maneuver.
17	Coordinate and integrate Army and joint, interorganizational, and multinational fires and conduct targeting across all domains.
19	Understand, visualize, describe, direct, lead, and assess operations.

DISTRIBUTED COMPUTING-BASED ALGORITHMS FOR QUANTUM NETWORKS AND QUANTUM CONTROL [CCE-CS-4]

The Computational Sciences Core Campaign Enabler on Distributed Computing-Based Algorithms for Quantum Networks and Quantum Control address one of the key roles of high performance computing for the Army: rapid processing of data that is obtained from sources distributed over different platforms and locations. Exploiting quantum phenomena has the potential to harness distributed information in powerful new ways, and may also allow distributed processing of such information well beyond present capabilities.

The goal of this effort is to:

1) Understand how to design and control quantum networks to harness and process information from distributed sources, and how to do so securely and efficiently.
2) Explore how quantum networks may gain an advantage over traditional parallel processing by applying distributed operations to distributed information. An important enabler for this research is the ability to model and simulate quantum networks. A significant part of this effort is therefore devoted to developing efficient methods for modelling and simulating open quantum systems and networks of these systems.

The Computational Sciences CCE on Distributed Computing-Based Algorithms for Quantum Networks and Quantum Control provides underpinning science for Key Campaign Initiatives that may employ networks of distributed sensors and networks that collect, aggregate, and distribute information with high-security.

PERSONNEL REQUIREMENTS:

i. Near-Term (FY16-FY20): Expertise in computational quantum sciences and HPC simulations including experience in quantum network concepts. (1-2 FTEs)
ii. Mid-Term (FY21-FY26): No new requirements above existing personnel

INFRASTRUCTURE NEEDS: NONE

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges.

Army Warfighting Challenge	Description
1	Develop and sustain a high degree of situational understanding.
7	Assure uninterrupted access to critical communications and information links.
9	Develop resilient Soldiers, adaptive leaders, and cohesive teams.
11	Conduct effective air-ground combined arms reconnaissance.
12	Conduct entry operations.
13	Establish and maintain security across wide areas (wide area security).
15	Conduct combined arms air-ground maneuver.
19	Understand, visualize, describe, direct, lead, and assess operations.

MATERIALS RESEARCH CAMPAIGN

MISSION: Perform fundamental interdisciplinary research in materials and manufacturing science to ensure rapid and affordable development of materials, from discovery to delivery, critical to the Army of 2030.

VISION: Discovery and unparalleled innovation of devices and Materials By-Design and On-Demand across all Army domains. Understand, exploit, and demonstrate diverse material sets with exceptional quality and capabilities relevant to the Army of 2030 via advances in manufacturing science. The desired end state is to enable the Army of 2030 to succeed in distributed operations and increasingly complex environments through realization of superior materials.

The Materials Research Campaign focuses on fundamental research to provide superior materials and devices needed to achieve lasting strategic land power dominance. Materials Research cross-cuts ARL's four focused S&T campaigns by providing materials with superior properties to address emerging requirements and capabilities for all Army platforms.

The Army of 2030 will require materials with unprecedented capabilities that can be rapidly grown or synthesized, and processed cost-effectively to enable Army platforms that are highly mobile, information reliant, lethal, and protected. The Materials Research Campaign has developed 6 Key Campaign Initiatives (KCIs) and 3 Core Campaign Enablers (CCEs) that are designed to address the future Army's need to rapidly respond to emerging threats and to eliminate tactical surprise – *caused by the proliferation of advanced technology by our adversaries* – by creating a materials by-design and on-demand enterprise; and a manufacturing science engine to ensure rapid progression from materials discovery to delivery, with the goal of producing materials in greatly reduced timeframes and at a fraction of the cost compared to today.

MATERIALS FOR SOLDIER AND PLATFORM POWER SYSTEMS [KCI-MR-1]

EXPECTED ARMY IMPACT: S&T efforts in lighter, more energy dense power sources should provide combat advantage through technologies that extend Soldier/squad endurance; provide energy situational awareness through data networked operations, and reduce the logistics demand. There is not a single solution to these challenges, but a solution can be found in a holistic, system of systems approach to Soldier and platform power systems, bringing together power generation, energy storage, and data-enabled energy management. The capabilities/impact can be summarized into three subareas: (1) The Soldier/Squad Power System; (2) Platform and Grid Power System; and (3) Sensor and Small Platform Power System. Soldier and squad level power sources with energy densities greater than 10 times that of today's lithium ion rechargeable batteries using any type of fuel (fuel flexible including fuels synthesized on site from the Manufacturing Science for Expedient Processing KCI) and harvesting energy from the surrounding environment used to re-charge energy storage will enable Soldier's and Squad's for extended mission durations, reduced burden from power, and increased mobility. On the Platform and Grid power systems the focus is on energy storage, and safe, low cost systems that will deliver increased use of energy harvesting while reducing the power footprint and the logistics demand. Multifunctional materials will simultaneously store and/or harvest energy and provide structural support and protection to dramatically reduce size and weight of platforms. Soldiers will operate within an intelligent power network with capabilities for automated allocation of the best energy resources and wireless channels for energy to be dynamically redistributed down to the dismounted Soldier on-the-move. In the Sensor and Small platform power systems a combination of wireless power transmission, energy harvesting, and high energy dense power sources will enable the Soldier to utilize numerous integrated, low power sensors for superior performance, enhanced situational awareness and heightened operation monitoring. Radioisotope power sources will enable drop-and-forget battlefield sensing (motion, radiation, photographs, and periodic communications) or built-in infrastructure health detection (vibration, corrosion) for durations ranging from 10 – 100 years or whose output power can be switched between low and high levels for persistent sensing or directed-energy applications.

DESCRIPTION: Design of Soldier and platform power as a system is required to enable indefinite power for tactical units and significantly reduces the logistics tail for power resupply. To accomplish this requires significant materials and device advancement in the areas of alternative energy, advanced energy storage, and energy conversion. This KCI focuses on increasing power supply in the three focus areas: (i) Alternative energy; (ii) Advanced energy storage; and (iii) Energy conversion technologies.

The Alternative Energy area focuses on developing ultraenergetic materials and radioisotope power sources. Radioactive isotopes represent the greatest possible energy density, about 108 Wh/kg, achievable without the use of nuclear reactors – at more than 100,000□ the intrinsic energy density of chemicals, radioisotopes are truly ultra-energetic materials. Isotopes and isomers of greatest interest are those with half-lives exceeding 10 years, while their corresponding ground states may be stable or, in many cases, unstable. A research objective in support of the application of this technology is to understand the physics underlying radiation hard materials, and to measure efficiencies for related power sources. As a separate technology, wireless power is focused to enable truly wireless distribution in which loads and sources are free to move while maintaining power levels and efficiency.

The Advanced Energy Storage area focuses on developing new materials and components for very high energy density and high power density batteries and novel energy storage technologies for Army capabilities. Battery research is focused on developing materials systems for higher voltage, higher temperature, extended cycle life, and stable chemistries for military environments and applications. Also, development of embedded, flexible, multifunctional structures that provide required structural and power/energy performance under combined load without compromising the safety or integrity of the target platform. The effort on superconducting materials is focused on second generation high temperature metal oxide superconductors with high energy storage capacity, advanced cryogenics, and advanced power electronics.

The Energy Conversion Technologies area focuses on mechanical and thermal conversion systems, used to generate electrical energy from Soldier power systems to base level power generators or to generate mechanical energy for ground and air vehicles. Efforts are focused on compact thermal sources that generate thermal energy efficiently from transportable fuels. A primary goal is to integrate the thermal source with thermal-to-electric energy converters for Soldier and Soldier system power sources capable of 1000 Wh/kg energy densities. Fuel cells as energy conversion devices offer improvements in energy density; however, miniaturization and cost reductions are necessary. Acid-alkaline hybrid fuel cell stack designs can help meet these needs and motivate the development of anion exchange membranes (AEMs). The JP-8 reformation research and development program is directed at reformation of JP-8 fuel into a hydrogen rich alternative fuel for downstream power generation. Essential will be the development of liquid phase desulfurization process and Pd-composite membrane for hydrogen separation.

a. **TECHNICAL GOAL(S):**
   i. Near-term goals (FY16-FY20):
      a. Investigate next generation energy storage chemistries for advanced batteries (such as Li/S, aqueous Li- ion, dual intercalation, and conversion electrode materials) to demonstrate either 50% improvement in specific energy or improved safety and cost compared to conventional Li-ion;
      b. Identify and synthesize combustion catalysts with 20% increased sulfur tolerance and 30% increase the efficiency of liquid fueled combustion thermal sources for use in TPV and TE energy conversion.
      c. Study sophisticated optical coupling structures integrated on TPV cells and thermal management systems to achieve ~20% radiation-to-electrical energy conversion efficiency.
      d. Research the fundamental material properties that determine pyroelectric energy conversion performance and develop thermodynamic models to determine the feasibility of pyroelectric generators to convert thermal energy from waste heat (>5% energy conversion efficiency), combustion sources (>12% energy conversion efficiency), or eye safe laser sources (>20% energy conversion efficiency.
      e. Novel power materials (high frequency magnetics and ultrasonic transduction materials such as piezoelectrics) will be developed to enable enhanced transfer efficiencies (30% improvement). Laboratory demonstration of 10W transfer using inductive wireless transfer and determine feasibility of alternatives including electromechanic and laser-photovoltaic transmission.
      f. Interface co-continuous structural electrolytes with complex structural electrodes and simultaneous electrochemical and mechanical cycling
      g. Demonstrate up to 30% weight and volume savings using multifunctional materials to integrate structure and protection function with energy storage (batteries, supercapacitors, and electrostatic capacitors).

h. Evaluate if tritium radionuclide power sources are capable of 10 years of operation and determine the fundamental physics by which energy-release rates may be controlled for isomers to enable a switchable power source.

ii. Mid-term goals (FY21-FY26):

a. Demonstrate ~80% thermal efficiency in delivering heat from combustion sources to thermal-to-electric converters; demonstrate combustion operation over a wide range of fuels including JP-8 and evaluate the durability, such as sulfur tolerance and carbon formation of catalysts.

b. Develop photovoltaic cells and selective emitters that are spectrally matched to achieve >20% radiation-to-electrical energy conversion efficiency without the need for costly optical filtering.

c. Evaluate near-field radiation heat transfer to increase TPV power densities for thermal emitters having temperatures lower than 1000 deg-C.

d. Reduce the materials cost ($/Watt) of solar photovoltaic devices using hybrid materials and develop integrated novel optical structures to allow high solar concentration, reducing the volume of PV material needed for the required power.

e. Increase both wireless power and transfer. Wireless power transfer <1 m with >60% efficiency; several meters with >30% efficiency; ~km with >15% efficiency

g. Develop new materials and components for very high energy density (>200 Wh/kg), high power density (5 kW/kg) Li-ion batteries and novel energy storage technologies for Army capabilities with focus on higher voltage (4.7V), higher temperature (70C), and extended cycle life (>1000 cycles), in safe and stable chemistries.

h. Investigate new materials manufacturing techniques, such as additive manufacturing, and improved multiphysics models and simulation to increase the energy density (20%) and mechanical properties of multifunctional, structural power materials and to allow tailoring of material microstructure for simultaneously maximizing energy storage and structural functions.

i. Extend the duration of radioisotope power sources to 12 years of operation using tritium radionuclide sources, develop the capability to use 63Ni for higher power/kg (300%) and duration (800%), develop isomeric materials to enable energy storage at minimal power levels and subsequent activation to operational levels prior to deployment for long-duration sensors or directed energy applications.

iii. Far-term goals (FY27-FY31):

a. Improve Develop combustion-based thermal sources with highly integrated balance-of-plant to enable portable thermal sources in a lightweight, small form factor package in >1000 Whr/kg power sources.

b. Evaluate new thermal conversion methods at temperatures up to 700 deg-C to enable harvesting from wasted thermal energy in the environment or on platforms.

c. Develop entirely new materials and material combinations to yield photovoltaic systems that far exceed the current efficiency limits at a cost that allows deployment throughout the Army.

d. Develop design tools and materials reliability data sets and investigate repair techniques to enable integration of multifunctional materials into a broad range of systems. Increase the performance of dielectric and structural electrolytes to enable multifunctional materials with energy densities approaching those of conventional energy storage materials.

e. Extend the duration of radioisotope power from 10 to 100 years of operation and provide a broad array of isotope sources including switchable isotope sources that can be chosen on the basis of power and duration requirements.
f. Demonstrate feasible alternative to conventional structures/armor and batteries/supercapacitors

b. PERSONNEL REQUIREMENTS:

i. Near-term (FY16-FY20): Experts in advanced energy storage and generation, radiation and nuclear physics, microcombustion, ferroelectrics, semiconductor physics, plasmonic spectroscopy, nano-material synthesis, and photonics. (10-12 FTEs)

ii. Mid-term (FY21-FY26): Experts in near-field radiation heat transfer, interdisciplinary electro mechanics and physicists, materials science, meta-materials, materials synthesis and microfabrication, and combustion modeling. (6-8 FTEs)

iii. Far-term (FY27-FY31): Experts in nuclear physics, power systems, power electronic materials, quantum physicists, and radio frequency. (6-8 FTEs)

c. INFRASTRUCTURE NEEDS:

i. Near-term (FY16-FY20):
  a. Reconfigure and expand existing battery dry room space
  b. Equipment and facilities for TEM and XPS analysis, 3D printing of materials, enhanced surface analysis tools, solar cell characterization including a pulsed solar concentrator, and materials growths including III/V – silicon molecular beam epitaxy, metal-organic chemical vapor deposition, or liquid phase epitaxy.
  c. Facilities onsite to fill tritium capsules.
  d. Update radiation generators and measurement instrumentation.
  e. Hydride vapor phase epitaxy system to grow relatively thick semiconductor layers.
  f. Laboratory space, fume hood, and equipment for catalyst synthesis and characterization.
  g. Laser, light sources, and detectors (IR, Raman, optical), gas chromatograph/mass spectrometer and Differential Electrochemical Mass Spectrometry.

ii. Mid-term (FY21-FY26):
  a. Enhance capabilities to enable testing of 63Ni power sources and matched energy-conversion technologies.
  b. Update radiation generators and measurement instrumentation.
  c. Outdoor test facility with regulatory approval for high power transmission in frequency bands of prevailing interest.

iii. Far-term (FY27-FY31):
  a. Test beds for qualification of wireless energy transfer in multi-user, high interference environments and low-power electronics and platforms.
  b. Equipment and facilities to run 24 hour durability tests on catalytic materials; develop new material systems; and test and characterize new ultra-energetic materials, energy-conversion technologies, transduction materials, power materials, and to run material durability tests 24 hours a day.
  c. Update radiation generators and measurement instrumentation.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges and Army Capability Needs.

Army Warfighting Challenge	Description
12	Conduct entry operations.
16	Set the theater, provide strategic agility to the Joint Force, and maintain freedom of movement and action.

Army Capability Need Proponent	Capability Need Area
MCoE	3.d – Unburden the Soldier.
CASCOM	3.c – Intelligent Power Management and Distribution System.
CASCOM	4.a – Hybrid Power Capabilities.

ENERGY EFFICIENT ELECTRONICS AND PHOTONICS [KCI-MR-2]

EXPECTED ARMY IMPACT: In the future, to fight and win in a complex world, Soldiers will require enhanced situational awareness, command and control, communication, and sensing with increased data processing, adaptability and reconfigurable computing, and networking -- primarily carried by the dismounted Soldier. Furthermore, there will be greater emphasis on expeditionary forces that are more maneuverable and energy independent. Achieving these greatly enhanced capabilities requires technologies that are lighter weight, flexible, and have reduced power demands to improve maneuverability by reducing the weight and volume carried by Army platforms including individual Soldiers. Power demand must be reduced through the design and incorporation of novel energy efficient materials combined with conventional electronics and photonics, to form heterogeneous, low power electronics and photonics systems. For example, energy efficient electronics aims to reduce the power demand of Solder radios by 10X, thereby increasing mission duration and situational awareness. Energy efficient photonics will enable back-packable photonic sources for use in the battlespace, such as jamming/spoofing Unmanned Aerial Systems.

DESCRIPTION: ARL aims to discover, design and develop future materials in topological phases of matter; two dimensional materials; wideband gap materials; photonics sources and detectors; and active heterogeneous interfaces to reduce the power demand of future electronic and photonic systems. Topological phases will likely facilitate access to unique electronic, magnetic, and superconducting functionalities. They are also expected to give rise to charge carriers that can be fractional and/or that do not obey normal quantum statistics. Their phase transitions go beyond the standard paradigms, and the materials fundamentally deviate from the standard semiconductor energy constraints. Similarly, two dimensional materials and their heterostructures offer unprecedented electronic/optoelectronic properties that are not possible in their 3D counterparts due to the unique quantum confinement effects of two dimensions. Advanced wideband gap materials will be critical for smart power management as well as energy efficient high-power radio frequency power amplifiers for assured communications and electronic warfare applications. Ultimately, the heterogeneous integration of novel electronic and photonic materials with conventional substrates such as silicon will open up a new paradigm for Army systems.

TECHNICAL GOAL(S):

i. Near-term goals (FY16-FY20):
   a. Synthesize lead-based topological materials such as topological crystalline insulators with conductivity approaching copper, characterize the basic electronic structure, and determine the primary defects that may obscure the unique materials function. Devise strategies for mitigating these defects.
   b. Design and demonstrate novel devices exploiting the unique properties offered by novel topological materials, 2D materials and heterostructures.
   c. Design and demonstrate novel photodetectors exploiting the unique properties of active heterogeneous interfaces between III-N/SiC heterostructures to achieve greater than 65% efficiency across the ultraviolet in a structure capable of single photon counting.
   d. Demonstrate and assess power scaling potential of a new type of single-aperture fiber laser directly scalable to 80-100 kW CW - an ultra-low quantum defect clad diode-pumped Raman fiber power oscillator.

e. Develop and demonstrate efficient wavelength–agile Mid-IR and UV, CW and pulsed bulk solid-state laser sources, with 20-50 W of power, and demonstrate first light in LWIR.
f. Study the underlying failure mechanisms in SiC MOSFETs when undergoing bias-temperature stressing.
g. Investigate GaN device structures as a function of both substrate and epitaxial growth conditions; demonstrate breakdown voltages of ~600 V using GaN test structures for continuous and pulsed power applications
h. Grow novel, low (< 5%) In containing InGaN materials for improved internal quantum efficiency (> 30%) to achieve high brightness, high power emitters in the near UV.
i. Design and fabricate MEMS piezoelectric transformers for on-chip power management; demonstrate ~60% power-conversion efficiency in a reduced form factor (~10X) over prior state-of-the-art Microelectromechanical systems (MEMS) devices
j. Design baseline architecture for heterogeneously integrated RF front-end of a 4-channel transceiver for operation at >1GHz using InP and Gallium Nitride (GaN) chiplets on silicon and determine baseline performance; refine design and simulation of realistic waveform on FPGA and accelerator cores to develop an understanding of potential performance enhancements to Army communications systems.

ii. Mid-term goals (FY21-FY26):
a. Achieve near room temperature (> 200K) functionality in one or more thin film topological materials.
b. Demonstrate "energy harvesting" sensors and circuits which are 'always on' and increase the battery life by reducing the demand power (~5X over current state-of-the art) of compact radios and distributed sensors.
c. Demonstrate and assess power scaling potential of fully crystalline (or fully-ceramic), true double-clad, Re or Tm doped core fibers from YAG-class thermal conductivity materials
d. Develop and demonstrate efficient wavelength-agile Mid-IR, CW and pulsed glass fiber laser sources, with 20-50 W of power, and bulk solid-state laser sources in the LWIR and UV
e. Develop improved growth techniques for improved quantum efficiency (> 50%) and output power for large area emitters in the UV.
f. Demonstrate reliable/reproducible SiC and GaN diodes and switches that routinely exceed the efficiency by 30% of silicon devices especially at larger breakdown voltages.
g. Grow uniformly doped AlGaN films with uniform thickness and relatively low dislocation concentrations (< 1014 cm-3) near the surface where the largest electrical fields will occur in the devices.

iii. Far-term goals (FY27-FY31):
a. Demonstrate transistors based on spin or tunneling in new topological materials and/or 2D van der Waals heterostructures that exceed the efficiency of conventional semiconductors.

b. Demonstrate that new devices based on topological or 2D materials can be heterogeneously integrated into conventional semiconductor processing methodologies.
c. Demonstrate electronic and photonic functions with efficiency 10X greater than state of the art in 2015 and enable 72 hour dismounted missions without energy resupply.
d. Demonstrate "energy harvesting" sensors and circuits which are 'always on' and increase the battery life by reducing the demand power (~10X over current state-of-the art) of compact radios and distributed sensors.
e. Devise and establish methodologies for braiding of topological quantum quasiparticles suited to enable exploitation for quantum computing and related technologies.

b. PERSONNEL REQUIREMENTS:

i. Near-term (FY16-FY20):
  a. Training in the unique physics of topological phases and the connection to materials structure and characteristics. (5 re-trained FTEs)
  b. Mat erials scientists, engineers, chemists, and physicists with multi-disciplinary skills in computational modeling or materials synthesis and processing, and mechanical and microstructural characterization. (5-10 FTEs)

ii. Mid-term (FY20-FY20):
  a. Materials scientists, engineers, chemists, and physicists with multi-disciplinary skills in computational modeling or materials synthesis and processing, and mechanical and microstructural characterization. (6 – 12 FTEs)

iii. Far-term (FY27-FY31):
  a. Materials scientists, engineers, chemists, and physicists with multi-disciplinary skills in computational modeling or materials synthesis and processing, and mechanical and microstructural characterization. (5– 10 FTEs)

c. INFRASTRUCTURE NEEDS:

i. Near-term (FY16-FY20):
  a. Dedicated growth facilities for the exploration of unique topological and 2D materials and devices.
  b. High magnetic field, ultra-low temperature (sub 1K) magneto-transport characterization facilities to verify transport characteristics.
  c. Angle-resolved photoemission for the verification of topological band structures.
  d. Low-temperature (sub 1K) scanning tunneling microscopy/spectroscopy to characterize the electronic structure of materials

ii. Mid-term (FY21-FY26):
  a. Materials processing and device fabrication facilities suitable for the wet and dry chemistries necessary to manipulate topological materials
  b. Establish crystal growth facility for nonlinear and active laser materials and ultrafast laser development facility.
  c. Expand the device testing to include testing high energy pulsed power devices.

iii. Far-term (FY27-FY31):
   a. Dedicated growth facilities for the exploration of unique topological, 2D and heterogeneous materials.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges and Army Capability Needs.

Army Warfighting Challenge	Description
12	Conduct entry operations.
16	Set the theater, provide strategic agility to the Joint Force, and maintain freedom of movement and action.

Army Capability Need Proponent	Capability Need Area
MCoE	3.d – Unburden the Soldier.
FCoE	4.a – Next Generation Sensors.

AGILE EXPEDIENT MANUFACTURING
[KCI-MR-3]

EXPECTED ARMY IMPACT: To win in the deep future operational environment, the Army will need to be more adaptive, more expeditionary, and have a near-zero logistic demand. The objective of this Key Campaign Initiative (KCI) is to develop novel adaptive and rapid manufacturing technologies to enable deployable "Materials On-Demand" capability. The ability to expedite fabrication and part certification in the field will enable operational readiness concomitant with the capability to counter new threats with point-of-use solutions. This is expected to dramatically reduce the logistic tail and mitigate uncertainties for expeditionary maneuver. The "Materials On-Demand" capability enabled through discovery, innovation, and transition of synthesis, processing, fabrication and manufacturing science methodologies will lead the way toward a new paradigm in flexible, rapid, low-rate production for the factory of the future. Science and innovation in synthesis from reclaimed, renewable, and indigenous resourcing will enable, not only cost reduction, but the capability to mobilize this manufacturing technology requiring minimal materials burden to support expeditionary operations on location and in time.

DESCRIPTION: The overriding goal of the Agile Expedient Manufacturing KCI is to enable adaptive, rapid, and low cost production of consumable parts which easily qualified for service through development of novel synthesis and processing capabilities. Manufacturing capabilities developed through this effort are expected to enable 3D additive approaches that facilitate, as for example, real-time alloying by design simultaneous to near-net-shape fabrication with shorten times from ingot-to-components. Research contributing to this goal include the thermodynamics and kinetics in meta-stable rapid heat, melting, mixing, solidification, splat bonding, and bulk solid state transformation throughout the 3D additive manufacturing process. Constitutive materials (commercial off-the-shelve, bio-derived, indigenous, and specialty materials) of varying length-scale (nano, multi-phase, 2D/3D composites, and coatings) are the bases from which property characteristics are established for component design. Designing and producing the precursor materials is a key component of this effort. Additionally, this work is focused on better understanding, preconditioning, and tailoring the reactivity and constitutive behavior of precursor materials for thermomechanical processing to achieve the designed properties and performance.

a. TECHNICAL GOALS:

i. Near-term goals (FY16-FY20)

a. Demonstrate the coupling of experimentally integrated computational cast process and advance pre- and post-solidification processing down to the interfaces for extending the cast structure predictability.

b. Demonstrate secondary thermomechanical processes coupled with physics base pre- and post-computational models at the texturing scale.

c. Establish process and demonstrate high fidelity (25% improvement in chemical and physical resolution above 2015 standards) additive manufacturing (AM) starting powder and bio-derived feedstock by design.

d. Model and demonstrate coupling of applied energy fields with the primary, secondary, or fabrication manufacturing to achieve non-linear process energy consumption effects (>20% decrease in power consumption).

e. Model and validate complex biopathways in additive or subtractive biomanufacturing processes through multi-organism and engineered systems.

f. Demonstrate expedient printing and performance of 2D flexible electronics sensor systems, to include human performance states, biological sensing elements, and natural and synthetic biology systems.
g. Quantify and develop chemical pathways for solar and ambient radiation enhanced catalytic kinetics in carbon-carbon bond cleavage, CO2 electro-reduction, O2 electro-reduction and water splitting for manufacturing efficiencies.

ii. Mid-term goals (FY21-FY26):
a. Demonstrate adaptive expeditionary manufacturing system concept for low rate production (50% of traditional turn-around transition time).
b. Demonstrate from model and simulate end-to-end primary, secondary, and finishing fabrication capability (>10X faster than the traditional transition time from prints to production).
c. Demonstrate natural and/or synthetic systems to produce critical material precursors from renewable starting materials.
d. Demonstrate 3D circuit board layouts integrated into the 3D additive tool and characterized with x-ray analysis capabilities for circuit-board layouts optimized in volume and performance.
e. Process and design rules/tools for 3D sensors, to measure human performance states, biological, and synthetic biology systems.
f. Demonstrate enhanced alternative energy harvesting and routes to fuel through functional active heterogeneous interfaces between highly mismatched alloys/ inverted polarity heterostructures and liquids such as water.
g. Demonstrate use of indigenous feedstock for on demand expeditionary manufacturing capability.

iii. Far-term goals (FY27-FY31):
a. Demonstrate component fabrication with more than 90% indigenous resources using additive manufacturing on-demand capability.
b. Demonstrate free-form thermomechanical processing of complex shape (casting complexity with forging properties).
c. Hybrid additive manufacturing coupled and expedited with catalysis innovation.
d. Demonstrate 3D sensors and printing of active components and novel process tools, to include advanced human performance states, biological sensing elements and synthetic biology systems.
e. Demonstrate synthesis of ethanol, butanol, or heavy hydrocarbons from grey water and CO2 on a tactically-relevant scale.

b. PERSONNEL REQUIREMENTS:

i. Near Term Goals (FY15-19):
a. Materials engineers with multi-disciplinary skills in computational process modeling and simulation, computational and physical metallurgy, computational deformation process modeling and simulation, and processing and manufacturing. (2-3 FTEs)
b. Bio-engineers with expertise in metabolomics, systems biology, bio-derived materials, and computational biology. (3-5 FTEs);
c. Bio-process engineers with expertise in microbial ecology for investigation of environmental, human, and industrial microbial consortia for scalable, robust and safe bio- manufacturing and bio-processing is required. (3-5 FTEs)

d. Materials engineers with computational and experimental expertise coupling materiel design optimization including bio-derived processes. (2-3 FTEs)
e. Manufacturing engineers with skills and expertise in designing and maturing novel fabrication, assembly, tooling, and machine capabilities to produce precursor materials to net-shape product specifications (4-5 FTEs)

ii. Mid-term goals (FY20-25):
a. Materials scientists and engineers with skills in researching real-time concurrent materials property-process certification. (5-10 FTEs)
b. Process engineers with expertise in scaling biological processes. (5-10 FTEs)
c. Manufacturing engineers to exploit new manufacturing capabilities. (5-10 FTEs)

iii. Far Term (FY26-20):
a. Materials scientists and engineers with skills in researching real-time concurrent materials property-process certification. (5-10 FTEs)
b. Mechanical and electrical engineers, aerospace and aeronautical engineers, and manufacturing engineers for development of AM methods. (5-10 FTEs)
c. Materials scientists and engineers with skills and expertise in characterization and predictive properties of thermomechanical processed meta-stable materials. (6-10 FTEs)

c. INFRASTRUCTURE NEEDS:

i. Near-term goals (FY15-19):
a. Research Center for Additive Manufacturing to advance additive materials to components:
   i. Feedstock synthesis research line– advanced materials processing facilities for novel feedstock development.
   ii. Bio-derived feedstock facility-increased capabilities in metabalomics; advanced chromatographic and mass spectrometric instrumentation; expansion of in-situ monitoring of bio-fermentation capabilities.
   iii. Additive manufacturing materials characterization – inspection/characterization of feedstock, process and completed part to provide data for certification/qualification to include bio-derived precursors and products.
   iv. Novel process laboratory.
b. 2D and 3D Flexible electronic printing and process tools.
c. Biological, chemical, and materials science engineering facility with single to hundreds of liters bio-processing capacities.
d. Integration of biological materials with 3D processing capabilities.

ii. Mid-term goals (FY20-25):
a. Custom research equipment with additive manufacturing functionality for fabrication of net-shape components in three-dimensional space through the use of multiple processing fields.

iii. Far-term goals (FY26-30):
a. Processing instrumented equipment to research recycling scrap and indigenous materials into refined stocks and/or components.
b. Modernization of instrumentation for real-time process control and alternations on-demand.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges and Army Capability Needs.

Army Warfighting Challenge	Description
3	Provide Security Force Assistance.
12	Conduct Entry Operations.

Army Capability Need Proponent	Capability Need Area
MCoE	3.d – Unburden the Soldier.
CASCOM	3.d - Additive Manufacturing
CASCOM	4.a – Advanced Materials.

QUANTUM SCIENCES
[KCI-MR-4]

EXPECTED ARMY IMPACT: Quantum Sciences will provide game-changing capabilities for Command, Control, Communications, Intelligence, Surveillance and Reconnaissance for stationary and mobile Army elements. Exploitation of quantum phenomena, including distributed quantum systems, will ultimately provide the enabling foundation for many capabilities and applications that are impossible or impractical to achieve through classical means, including quantum teleportation-based information transfer for quantum information distribution including various novel security protocols; enhanced information processing that, for important Army-relevant problems, may exponentially exceeds the current classical limits enabling the Army to process information collected from the battlefield in near-real time; assured positioning, navigation, and timing in GPS denied environments; and a network of high-precision globally-synchronized atomic clocks for secure timing capabilities in contested environments. Additionally, exploiting quantum phenomena will lead to new generations of quantum sensors that provide unprecedented sensitivity in field detection, including gravitation fields for locating underground structures and tunnels.

DESCRIPTION: One major initiative of the in-house Quantum Sciences program within the Materials Campaign and the Center for Distributed Quantum Information (CDQI) is a collaborative fundamental research effort connecting ARL, academic, industrial and other government researchers to develop the physical layer of a multi-site, multi-node, modular quantum network based on resilient distributed quantum entanglement preserved by quantum memory and quantum error correction. Great advances have been made to increase the fidelity of critical quantum components needed to establish a resilient network of quantum entangled resources in various atomic and solid-state systems. Although several research groups have demonstrated point-to-point quantum teleportation, entanglement distribution, quantum error correction, and quantum memory, no scalable, integrated, modular architecture exists by which one can connect three or more small quantum nodes and through which quantum information may be processed. The in-house Quantum Sciences effort working cooperatively with academia and industry will develop and demonstrate such a scalable architecture for an entanglement-based distributed quantum network; establish the physical-layer protocols and algorithms for this architecture composed of integrated, modular components; implement quantum error correction applicable to quantum repeaters and memories; explore Army-relevant applications for such a network; and identify performance limitations of a distributed heterogeneous quantum network that must be overcome or are fundamental. Specific material components include quantum memories, quantum registers, quantum processors, quantum switches, quantum frequency conversion devices, entangled photon sources, single-photon detectors, matter-photon interfaces, quantum sensors, as well as other technologies enabling the realization of integrated, chip-scale and/or modular components for robust, mobile distributed quantum information networks.

a. TECHNICAL GOAL(S):

i. Near-term goals (FY16-FY20):

a. Develop the physical architecture of a scalable, modular quantum network where the quantum nodes generate, process, and locally store quantum information and are resiliently connected by fiber-based or free-space photonic links. This includes exploration into heterogeneous system interfaces.

b. Investigate quantum entanglement creation, efficiently converted to and from photons, distributed among three or more quantum nodes, protected through error correction, and locally stored and recovered on demand with high fidelity using quantum memory.

c. Develop network algorithms and protocols, including efficient entanglement management protocols with experimental validation in the context of a multi-site (three or more quantum nodes) distributed quantum network. Quantum entanglement management takes into account entanglement routing, characterizing and manipulating multi-site entanglement, and entanglement verification. Explore software defined quantum network concepts.

d. Explore the ability of quantum networks to enhance the collective performance of distributed sensors. These may include magnetometers, accelerometers, gravimeters, and clocks.

ii. Mid-term goals (FY21-FY26):

a. Improve quantum control, fidelity, entanglement rates, frequency conversion efficiency, and storage times of a heterogeneous quantum network.

b. Refine quantum error correction and purification protocols to protect quantum information from decoherence, and develop entanglement management protocols to coincide with advances to the physical quantum network.

c. Efficiently scale the number of nodes within a quantum network to increase range and performance capability.

d. Develop novel components and technologies to enable scalability and robustness appropriate for the physical implementation to address application requirements.

iii. Far-term goals (FY27-FY31):

a. Investigate and integrate novel modular quantum components for enhanced distributed quantum system performance.

b. Implement basic quantum operations to explore capabilities beyond what is possible classically, such as secure information processing and ultraprecise positioning, navigation, timing and sensing.

c. Explore new applications for which the quantum sciences can perform Army-relevant operations in a manner impossible or impractical for commensurate classical systems.

b. PERSONNEL REQUIREMENTS:

i. Near-term (FY16-FY20): Expertise in quantum theory and modeling, quantum entanglement, entanglement distribution, entanglement purification, quantum error correction, quantum networking protocols, quantum information processing, quantum teleportation, quantum optics, quantum frequency conversion, quantum memory, quantum control, material growth/synthesis and characterization for quantum applications, fabrication of quantum components, laser-cooling and atomic physics. (12-18 FTEs)

ii. Mid-term (FY21-FY26): Expertise in quantum information management, quantum error correction, quantum purification, quantum logic, heterogeneous quantum interfaces, topological quantum systems, quantum networking, quantum communication, and integrated modular quantum technology. (8-12 FTEs)

iii. Far-term (FY27-FY31): Expertise in quantum networking, quantum operations, quantum engineering, hybrid quantum system integration, quantum repeaters, quantum communication, quantum simulation, and quantum applications. (8-12 FTEs)

c. INFRASTRUCTURE NEEDS:

i. Near-term (FY16-FY20):

a. Environmentally-stabilized laboratory space and equipment to develop quantum nodes based on ions, neutral atoms, and solid-state materials.
b. Design and fabrication facilities to develop modular, integrated components.
c. Characterization tools and software for assessing performance of quantum systems.
d. Access to ARL's Center for Distributed Quantum Information

ii. Mid-term (FY21-FY26):

a. Equipment and facilities for heterogeneous quantum network integration.
b. Expanded laboratory space for hybrid quantum network with increased range and performance capability.
c. Leverage existing facilities across the quantum science community for quantum control.

iii. Far-term (FY27-FY31):

a. Test beds for basic quantum network operations through both optical fiber and free-space.
b. Modernization of instrumentation, including replacement, upgrade, and new capability development.
c. Access to emerging quantum systems.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges and Army Capability Needs.

Army Warfighting Challenge	Description
1	Develop and sustain a high degree of situational understanding.
7	Assure uninterrupted access to critical communications and information links.
19	Understand, visualize, describe, direct, lead, and assess operations.

Army Capability Need Proponent	Capability Need Area
MCoE	2.b – Agile, robust, resilient network.
MCoE	4.b – Control the electronic environment.
USAACE	4.e – Assured communications.
Cyber CoE	3.d – Assured Position, Navigation, and Timing (PNT).
Cyber CoE	4.b – Quantum Computing.

ENERGY COUPLED TO MATTER FOR RESPONSIVE MATERIALS [KCI-MR-5]

EXPECTED ARMY IMPACT: The Army's future operational environment include contested and densely populated urban terrain will be characterized by complex and volatile conditions. Achieving decisive operations in these environments, against an elusive enemy, will require responsive and adaptive capabilities on-command to counter uncertainties. Energy Coupled to Matter (ECM) is the physics-based strategy being pursued to develop new materials, new processes, and means to activate "dial-in" materials properties for adaptive multi-functional capabilities. Disruptive materials and technologies enabled by this KCI will include "on-command" functions to enhance Soldier mobility via conformal material actuated exo-suits, flexible structural and adaptive membranes for power generation-storage-reclamation, adaptive protection via stealth and shape-shifting, and scalable lethality via tunable warhead configurations. For example, in weapons systems, rigid body projectiles fabricated using ECM technologies can "dial-in" 3-5x higher penetration capabilities than eroding projectiles. ECM for materials research will unlock significant enhancements in response to the Army's stringent demands for performance improvements through 2030 and beyond for strategic land power dominance.

DESCRIPTION: Energy coupled to matter (ECM) is an emerging technology that goes beyond the traditional process optimization factors of scale, composition, temperature, and pressure. The initial research will focus on the tenet that energy transfer or coupling is non-linear, and not simply additive. Empirical Design-of-Experiments (DoE) coupled with modeling is one approach to understand the physics and energy transfer efficiencies in processing materials under high and multi-energy fields (e.g. electric, magnetic, acoustic, microwave, radiation, and others) to manipulate and exploit material substructure orientation and phase transformation in permitting near theoretical structural and other functional properties. This research pursues innovations in altering the metals, intermetalllics, polymers, ceramics and hybrid composite transformation pathways, shifting equilibrium favoring new metastable alloys, aligning phases, manipulating and shaping nanoscale architectures, and producing materials with revolutionary on-command permanent or temporal material properties or shape changes. For example, materials developed using ECM will be designed and transitioned for application to enable adaptive "on-command" protection technologies for diverting, bending, and fracturing ballistic threat projectiles with greater efficiency, thus reducing system weight and volume. Conversely, higher strength projectiles fabricated through ECM materials research will be used as a foundation to design lethal effects for defeating future enemy protection systems. This Key Campaign Initiative (KCI) leverages the Computational Science Campaign for modeling the applied field effects.

a. **TECHNICAL GOALS:**
   i. Near-term goals (FY15-19):
      a. Determine constitutive relationship and energy transfer mechanisms for texturing ceramics and dielectrics in discrete and concurrent thermomagnetic fields to generate a 2x improvement over current isotropic material properties.
      b. Develop predictive thermodynamic and kinetic models for bulk metallic structure and property transformation pathways.
      c. Develop in-situ methods for measuring the effects of applied fields and their influence over the evolution of material structure.
      d. Demonstrate the impact of ECM fields on traditional processing and manufacturing methods with 25% less energy input.

ii. Mid-term goals (FY20-25):
   a. Develop new materials tailored specifically for processing, use, and exploitation in energetic fields (active or adaptive materials that can dynamically change and reverse properties by >50% via a stimulus energy field).
   b. Determine synthetic and production pathways for materials capable of high energy absorption or dissipation for defeat of high-energy threats.
   c. Synthesize novel active materials with on-command electromagnetic signature in energetic fields for new capabilities in low observables and stealth.
   d. Develop ECM-derived materials for energy harvesting applications.

iii. Far-term goals (FY26-30):
   a. Develop a novel class of ECM adaptive materials which provide unprecedented physical, mechanical, and shape shifting properties on-command with >60% energy transfer efficiency.
   b. Develop transformable materials and material systems that rapidly and actively transition from one state to another and >50% strain on-demand for dual offensive or defensive purposes by the user.

b. PERSONNEL REQUIREMENTS:

i. Near Term Goals (FY15-19):
   a. Materials scientists and engineers with multi-disciplinary skills in computational modeling, materials synthesis, and processing. (1 – 2 FTEs)
   b. Materials scientists and engineers with skills in electronic and magnetic materials characterization. (2 – 3 FTEs)

ii. Mid-term goals (FY20-25):
   a. Mechanical, materials, ballistic, and electrical engineers. (1 – 5 FTEs)
   b. Physicists with electromagnetic processing skills. (1 – 5 FTEs)

iii. Far Term (FY26-20):
   a. Materials scientists and engineers (2 – 5 FTEs)
   b. Mechanical and electrical engineers, aerospace and aeronautical engineers, and manufacturing engineers.(3 – 5 FTEs)

c. INFRASTRUCTURE NEEDS:

i. Near-term goals (FY15-19):
   a. In-house ECM equipment:
      1. High magnetic field thermomagnetic processing systems capable of high temperature and pressure application.
      2. Single mode microwave sintering technologies capable of high-temperature and high-pressure application.
      3. Electric-field assisted processing systems- flash sintering and hybrid, flash-based technologies.
   b. Access to existing facilities with high magnetic field sources such as the National High Magnetic Field Laboratory to leverage research on paramagnetic and diamagnetic materials.

ii. Mid-term goals (FY20-25):
   a. Specialized multi-field ECM research equipment with bulk consolidation and manipulation functionality for fabrication of net-shape components in three-dimensional space through the use of one or more fields.

b. Research instruments for in-situ and ex-situ materials characterization under precise thermo-electro-magnetic-acoustic field application.
c. Space-based microgravity facilities for ECM experimentation

iii. Far-term goals (FY26-30):
a. Portable multi-field ECM equipment to assess active and adaptive materials.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges and Army Capability Needs.

Army Warfighting Challenge	**Description**
12	Conduct entry operations.
15	Conduct Combined Arms Air-ground Maneuver.
17	Deliver Offensive Fires
18	Deliver Defensive Fires

Army Capability Need Proponent	**Capability Need Area**
MCoE	3.a – Combat Vehicle Development.
MCoE	3.d – Unburden the Soldier.
CASCOM	4.a – Advanced Materials.
USAACE	4.d – Mitigate the “chance encounter” threats.

LIGHTWEIGHT MATERIALS
[KCI-MR-6]

EXPECTED ARMY IMPACT: Weight reduction of combat platforms is a key factor for decisive operations in overmatching the enemy with agility, speed, mobility, and deployability. In response to escalating operational requirements, Army systems have increased in mass largely due to an "add-on" approach. The impact has been a reduction in mobility, increasing burden on dismounted Soldiers and a lack of strategic maneuverability for forces equipped with mobile protected firepower sufficient for early or contested entry operations. For example, the Army Future Vertical Lift will require 3x the current rotorcraft range capability. Future ground combat vehicles are requesting >50% weight reduction. Excessive Soldier's fighting load and approach march load can lead to degenerative arthritis, cervical strains and other musculoskeletal injuries. The Lightweight Materials KCI focuses on developing higher specific property materials (property/density) and apply the new approach of system materials on-demand and by-design for platform weight reduction. The capability to design and produce lightweight materials will be coupled with system design and optimization in a holistic weight reduction approach for more than 50% weight savings, increased life cycles and reduced cost. This is expected to enhance expeditionary capabilities as well as increase readiness, reduce sustainment demand, and enhance affordability.

DESCRIPTION: This effort will leverage outcomes from Materials On-Demand (flexible and affordable manufacturing innovations) and By-Design (from atoms to properties) to develop and achieve a holistic approach to concurrent materials-system design for unprecedented weight reduction. This initiative utilizes computational materials models, guided and validated by experiments with the appropriate materials physics at the appropriate length and time scales, to accurately model material properties and system design performance in the relevant functional environment. This is expected to enable the design and manufacturing of material systems in concert with system design not possible today. The materials performance in the system is not only based on materials properties (strength-to-weight ratio, high toughness, high ballistic penetration resistance, fatigue resistance, corrosion resistance, chemical-biological resistance, joining strength, reparability), but includes the component's functional design in the system. Specific research emphasis in discovering new lightweight materials and to quantify the lightweight performance space for system design include: a) property-processing-properties of lightweight metals (magnesium and aluminum alloys) in the chemistry, nano-engineering, solidification and thermomechanical processing design space; b) high rate toughening of lightweight armor ceramics that supports vehicular structural load; and c) common efficient load transfer in hybrid lightweight composites via polymer and hybrid fiber interfacial engineering.

a. **TECHNICAL GOAL(S):**
   i. Near-term goals (FY16-FY20):
      a. Develop fundamental understanding of relationships between alloy chemistry, emerging processing techniques, microstructure, properties, and performance of lightweight material systems to achieve 2x the strength of FY15 commercially available magnesium alloys.
      b. Demonstrate the physics base computational models via design-of-experiments to predict materials structure and properties with performance of a simple component design configurations (flats and semi-sphericals).

c. Develop and demonstrate an in-situ capability coupled with model to quantify microstructure, deformation, interfacial load transfer and damage evolution of lightweight metals, composites and ceramics systems in the Army-relevant performance space (e.g. during structural and ballistic loading).

ii. Mid-term goals (FY21-FY26):

a. Develop fundamental understanding of relationships between crystal structures and microstructures to design lightweight hybridized ceramics with structural armor performance of lightweight metallic systems.

b. Demonstrate concurrent design of materials and subcomponent design for >50% weight saving compared to traditional subcomponent design approach with commercially available off-the-selves materials.

c. Design of interface chemistry, processing methods, and materials requirements to enable by-design load transfer between composite reinforcing media and supporting matrix material to enable efficient (>2x baseline) long-range energy transfer for structural and ballistic applications.

iii. Far-term goals (FY27-FY31):

a. Design lightweight materials for integrated multi-functional components (sensors-mobility-armor-armament-structure) where the alloy composition and processing route is tailored for the combination of properties necessary to meet weight reduction performance requirements of components.

b. Probabilistic and physics-based methodology for lightweight materials and common component certification such that the time frame for the materials development cycle aligns with that of the part development cycle.

c. Demonstrate concurrent lightweight materials design, manufacturing planning, and system design as a holistic system weight reduction capability.

b. PERSONNEL REQUIREMENTS:

i. Near-term goals (FY16-FY20):

a. Materials scientists with multi-disciplinary skills in computational modeling, materials synthesis, and processing, mechanical and microstructural characterization. (6-10 FTEs)

ii. Mid-term goals (FY21-FY26):

a. Mechanical and materials engineers to integrate computational and experimental approaches for designing and engineering new lightweight materials. (6-10 FTEs)

iii. Far-term goals (FY27-FY31):

a. Multi-disciplinary materials scientists and mechanical engineers with research skill in integrated computational materials and system engineering. (6-10 FTEs)

c. INFRASTRUCTURE NEEDS:

i. Near-term goals (FY16-FY20):

a. Automated fiber placement technical bench with multi-axis, multi-material laser sinter thermal head system capable of depositing fibers for lightweight composite designs.

b. Refractory Metal Furnace and Mini Hot Press to process lightweight ceramics.

c. Integrated surface analysis instrumentation in plasma and ion implantation capability for bulk lightweight structural materials.

d. Radio Frequency Press to process transparent structural assembly to research reduced residual stresses.

ii. Mid-term goals (FY21-FY26)
   a. Automated surface treatment and packaging tool capable of surface processing (plasma, liquid chemical etch, chemical bond preparation) to enable rapid development of process treatments from fiber to plate.
   b. High temperature upgrades to ARL Center for Advanced Polymer Processing for novel prepreg materials and additive manufacturing feed stock, high pressure continuous consolidation equipment, and precision fiber placement composites fabrication.
   c. Synchrotron beamlines coupled with micro-, nano-, and pico-second photon and electron analysis during mechanical deformation.
   d. High-temperature (2000 degree C) TGA/DSC with gas chromatography/mass spectrometry to support lightweight ceramic research.
   e. High Temperature, High Energy X-Ray Diffraction facility for ceramic powder and bulk structure analysis.

iii. Far-term goals (FY27-FY31):
   a. Laboratory to pilot scale synthesis and scale up in well controlled environments to feed processing facilities.
   b. Molecular coatings and layer by layer molecular processing facility.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges and Army Capability Needs.

Army Warfighting Challenge	Description
12	Conduct entry operations.
15	Conduct Combined Arms Air-ground Maneuver.

Army Capability Need Proponent	Capability Need Area
MCoE	3.a – Combat Vehicle Development.
MCoE	3.d – Unburden the Soldier.
CASCOM	4.a – Advanced Materials.

DESIGNING MATERIALS
[CCE-MR-1]

The Materials Research (MR) Core Campaign Enabler (CCE) in Designing Materials is a sustained effort to systematically build a science and engineering-based capability to design materials and related devices. Whether this be for electron, photon, phonon, mechanical, chemical, or living matter behavior, it relies on predicting and advancing the physics, chemistry, biology, and related engineering between microstructure and performance to enable the design of model materials and devices for Army relevant applications.

Microstructure is the detailed description of materials from the atomistic to the relevant bulk scale for functional and performance purposes. Performance is the material system constitutive behavior in its passive or responsive state detailed by the combined intrinsic and extrinsic physical, biological, and chemical properties. Examples of materials and device performance goals are those identified in MR Key Campaign Initiatives in Quantum Science, Energy Efficient Electronics and Photonics, Materials for Soldier and Platform Power Systems, Lightweight Materials, Energy Coupled to Matter and Responsive Materials, and Agile Expedient Manufacturing. The science and engineering between materials microstructure and performance is the detailed quantifiable description on the mechanisms and processes as to how performance is manifested through the microstructure. The goal of this MR CCE is to achieve the knowledge from which model materials and devices are designed and optimized for specified performance.

The MR CCE on Designing Materials investigates and advances the mechanisms in organic, inorganic and living material microstructure relevant to three performance challenges:

1) Materials and devices to resist and perform under extreme dynamic, thermal, mechanical, chemical, biological environment; This effort considers a range of material classes such as multi-functional structural, metals, ceramics, semiconductors, insulators, polymers, composites and biological materials.

2) Materials and devices to absorb, divert, convert, emit, detect, and direct the electromagnetic space. These include photonic, spintronic, and electronic devices, as well as electrochemical energy devices and biology enabled/enhanced devices.

3) Materials and devices to store and control rate-release of energy including device design work-such as on-chip nanoporous silicon devices. These include battery materials; fuel cells; and anti-tamper components.

The strategic approach to these focuses include:

a. Application of multi-scale modeling and simulation tools for articulation and virtual exploration of scientific mechanisms, bridging the material length and time scales, for a predictive design tool. An Integrated materials by design capabilities for structural, electronic, electromagnetic, power and energetic materials for ARL Key Campaign Initiatives and Army relevant material challenges.
b. Bio-inspired from living matter and systems/synthetic biology to design material systems at high degree of fidelity and unparalleled control.

The integrated core campaign enablers in Designing Materials, Materials Synthesis and Processing, and Materials Characterization and Discovery will be the foundation to leap ahead from Integrated Computational Materials Science and Engineering, to Ab Initio Design of materials and devices, to Production for Performance.

PERSONNEL REQUIREMENTS:

i. Near Term Goals (FY15-19):

a. Physicists, materials scientists, and engineers with multi-disciplinary modeling and analytical skills in applying predictive multi-scale models and experimental validation of materials and semiconductor device models (5-10 FTEs)

b. Biologist and chemist with expertise in modeling and experimentation in systems biology, microbial ecology and systems biology (3-5 FTEs).

c. Materials RF Engineer with expertise in modeling novel materials and conformal antenna design (1-2 FTEs).

ii. Mid-term goals (FY20-25):

a. Materials, chemical, mechanical, electrical, multi-disciplinary scientists and engineers for new materials design (5-10 FTEs).

iii. Far Term (FY26-30):

a. Materials scientists and engineers, supported by the multi-disciplinary contributions of mechanical, electrical and chemical engineers, physicists, and chemists for advancing the materials by design capability (5-10 FTEs).

INFRASTRUCTURE NEEDS:

i. Near-to-Far term goals (FY15-30):

a. Data storage capacity and data stewardship to enable data mining of Materials by Design Programs.

b. Networked laboratory to enable transfer of massive amounts of processing data to databases to allow for in-depth analysis to establish ICME (Integrated Computational Materials Engineering).

c. Technology Computer Aided Design (TCAD) tools for simulation of electronic and photonic materials through devices (via drift-diffusion, self-consistent Poisson/Schrodinger solvers) are needed by multiple groups in order to simulate emerging material systems in the context of high speed performance and integration.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges.

Army Warfighting Challenge	Description
5	Prevent, reduce, eliminate, and mitigate the use and effects of weapons of mass destruction.
7	Assure uninterrupted access to critical communications and information links.
12	Conduct entry operations.
13	Establish and maintain security across wide areas (wide area security).
15	Conduct combined arms air-ground maneuver.

MATERIALS SYNTHESIS AND PROCESSING [CCE-MR-2]

The purpose of this Materials Research Core Campaign Enabler (MR CCE) in Materials Synthesis and Processing is to advance the fundamental sciences in synthesis and processing enabling fabrication of Army relevant materials and devices on-demand and by-design.

"Synthesis" is the science of manipulating atoms, molecules, and other building blocks of matter into materials in an additive way, via growth or deposition, chemical or biological synthesis, and precursor material for additive manufacturing. "Processing" involves the modification of existing materials through external stimuli for devices and or tailoring engineering materials (e.g. thermomechanical treatments, composite processing, sintering, joining, nano and microfabrication).

New approaches are necessitated by emerging requirements to fabricate model materials designed at the atomistic scale. Synthesis and processing innovations are needed to ensure transition of designed materials to tangible applications. The desired synthesis and processing science will enable fabrication from atomistic-design to engineering bulk material and devices on-demand. This knowledge based research will seed synthesis and processing innovations in manipulating organic and inorganic matter to build materials with precision placement of atoms or with biological building blocks from design.

In creating and broadening an opportunistic environment in synthesis and processing science for materials by design, three research foci will be emphasized:

1) Synthesize, refine and tailor precursor materials' chemistry and microstructure for subsequent processing to achieve the designed specification
2) Layer and construct materials at the atomistic scale, including 1 dimensional seeding, 2 dimensional surfaces, up to 3 dimensional bulk or layered element-by-element, controlling the progressive length- and time-scale uncertainties systematically.
3) Control and direct synthesis path through the use of biological systems leading to biologically inspired and/or derived synthesis of materials and devices.

This Materials Research Campaign Core Enabler in Synthesis and Processing will provide under-pinning sciences and engineering to deliver tangible materials from model material by design to support all the Key Campaign Initiatives where materials are needed on-demand.

PERSONNEL REQUIREMENTS:

i. Near Term Goals (FY15-19):
   a. Physicists, engineers, chemists, biologists, and materials scientists with multi-disciplinary skills in materials synthesis and processing, mechanical, chemical and microstructural characterization are critical for developing predictive multi-scale models and providing experimental validation of materials models in order to make new materials and creating novel capabilities. (4-5 FTEs)
   b. Processing engineers with experience in advanced processing and manufacturing, to include material and device nano/microfabrication, extrusion-based polymer processing, powder metallurgical processing, ceramic processing, process modeling and Integrated Computational Materials Engineering (2-3 FTEs).
   c. Physicists, engineers, and material scientists with expertise in characterization and process development for flexible electronics, sensors, and other devices (1-2 FTEs).
   d. Engineers with experience in Metal Organic Chemical Vapor Deposition (MOCVD) for Yttrium Barium Copper Oxide (YBCO) deposition and thin film characterization (1-2 FTEs).
   e. Physicists, Engineers, Material Scientists with experience in superconducting and electro-optic materials and devices (1-2 FTEs).

ii. Mid-term goals (FY20-25):
   a. Processing, materials, electrical, mechanical and manufacturing engineers for processing and nanofabrication research to build materials and devices by design. (5–10 FTEs).
   b. Physicist/Electronics Engineer for Advanced Materials and Devices (2-3 FTEs).
   c. Physicists, Engineers, Material Scientists with experience in superconducting and RF materials and devices (1-2 FTEs).

iii. Far Term (FY26-30):
   a. Mechanical, electrical, and manufacturing engineers, for developments in processing enabling materials transition to commercial production. (5–10 FTEs)
   b. Biologists and Bioengineers with expertise in bio-inspired, synthetic and systems biology-driven synthesis and processing of materials and devices (3-5 FTEs)

INFRASTRUCTURE NEEDS:

i. Near-term goals (FY15-19):
   a. Fully instrumented high isostatic press (HIP) to enable measurement of ceramic processing parameters spatially and temporally.
   b. Increase capabilities in metabolomics and genome editing tools to prepare desired chemicals, including acquisition of equipment to enable use of Clustered regularly-interspaced short palindromic repeats (CRISPR) / CRISPR associated protein-9 (Cas9).
   c. Integrated 3D Mechanical pick and place Si CMOS printing, and photonic sintering.
   d. 3D printer established in dry room for 3D design of materials for energy storage.
   e. Advanced spectroscopic characterization and optical source equipment

ii. Mid-term goals (FY20-25):
   b. Materials synthesis, processing, and device fabrication facilities suitable for the wet and dry chemistries necessary to manipulate topological and other advanced materials.
   c. Expanded laboratory space for biological, chemical, and materials science engineering facility with single to hundreds of liters bio-processing capacities.
   d. Expanded laboratory space and capability for processing of materials in inert environments.
   e. Differential Electrochemical Mass Spectrometry (DEMS)

iii. Far Term Goals (FY26-30):
   a. Facilities and equipment for reproducing microgravity environments on Earth.
   b. Modernization of equipment - replacement / upgrade / new developing processing and manufacturing equipment.
   c. Dedicated growth facilities for the exploration of unique materials predicted.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges.

Army Warfighting Challenge	Description
5	Prevent, reduce, eliminate, and mitigate the use and effects of weapons of mass destruction.
12	Conduct entry operations.
15	Conduct combined arms air-ground maneuver.
16	Set the theater, provide strategic agility to the Joint Force, and maintain freedom of movement and action.

MATERIALS CHARACTERIZATION AND DISCOVERY [CCE-MR-3]

The research and development of technology that can fully detail atoms-to-meters of materials will enable not just validation of what was predicted, but also discovery of the unexpected and the unknown. This Materials Research Core Campaign Enabler (MR CCE) in Material Characterization and Discovery, in conjunction with the Materials Design and the Synthesis and Processing MR CCEs, is foundational and the door to future disruptive and un-planned discoveries enabling the Materials Research Key Campaign Initiatives (MR KCIs) in Quantum Science, Efficient Electronics and Photonics, Power for Soldier and Platforms, Lightweight Materials, Energy Coupled to Matter, and Agile Expedient Manufacturing.

Contemporary methods to interrogating materials include a suite of spectroscopy, microscopy, and experimental characterization. Within each of these methods are extensive research and efforts to attain higher fidelity, better resolution, better consistencies, and in less time. The Army Research Laboratory continues to focus on advancing these techniques to explore materials enabling disruptive technologies for the Army.

The Materials Research Core Campaign Enabler (MR CCE) on Materials Characterization and Discovery is grounded on 1) designing and developing mechanistic-focused experimentation, 2) enhancing and developing novel spectroscopic, microscopic and experimental techniques in conjunction with the other MR CCEs to enable the MR KCIs, and 3) developing real-time full spectral probing, sensing, analytics and informatics to enable discovery of the unexpected.

PERSONNEL REQUIREMENTS:

i. Near Term Goals (FY15-19):
   a. Materials scientists and engineers with multi-disciplinary skills in materials microstructural characterization, non-destructive analysis, and advanced materials testing techniques. Materials scientists with expertise to enable accurate characterization of material properties. (5-10 FTEs)
   b. Spectroscopists with expertise in characterization of catalysts and adsorbates (1-2 FTEs).
   c. Physicist with expertise in characterization, design, and processing of wide-bandgap materials and devices (1-2 FTEs).
   d. Scientist with expertise in nonlinear and electro-optical materials as well as optical limiting techniques (1-2 FTEs).
   e. Power engineer with expertise in additive manufacturing for packaging (1-2 FTEs).

ii. Mid-term goals (FY20-25):
   a. Physicists, electronic engineers, computer scientists, and materials scientists with skills in instrument design and fabrication to develop instrumentation and data analysis for multi-characterization, high rate, and high resolution characterization of materials (2-3 FTEs).
   b. Physicists and materials scientists with skill in use of high resolution, high rate capabilities at national laboratories, including neutron and other particle sources and X-ray and other electromagnetic sources (2-3 FTEs).
   c. Physicists, chemical, biological, mechanical engineers and materials scientists with expertise in micro and nano-techniques. (5-10 FTEs)

iii. Far Term (FY26-20):
   a. Physicists and materials scientists with expertise in physics of solids. (5-10 FTEs)

INFRASTRUCTURE NEEDS:

i. Near-term goals (FY15-19):

a. Atomic probe microscopy provides sub-nanometer spatial resolution of individual atom positions. Provides chemical analysis of alloys at the atomic scale.

b. Triple ARL's capacity to perform FIB (Focused Ion Beam) and Laser Machining of materials for rapid and fully 3D characterization methods.

c. Data storage capacity and data stewardship to enable data mining of Materials by Design Programs

d. Low-temperature (sub 1K) scanning tunneling microscopy/spectroscopy to characterize the electronic structure of materials.

e. High magnetic field, ultra-low temperature (sub 1K) magneto-transport characterization facilities for verifying transport characteristics.

f. Angle-resolved photoemission for the verification of topological band structures

g. Advanced Characterization Capabilities: Ultrafast electron spectroscopy and diffraction capability; Advanced chromatographic instrumentation; Advanced mass spectrometric instrumentation; Peptide sequencer, fast protein liquid chromatography; Fluorescence spectrometer and Fs amplifier system; High Temperature X-Ray Diffraction (>1400C).

h. Micro-machining, micro-assembly, and micromechanical interfacial experimental capabilities.

i. High power continuous-wave fiber laser (5 KW)

j. High Speed On-chip mm-wave Frequency Extenders & Logic Analyzer

k. Wafer Bonding for Heterogeneous Device Integration

ii. Mid-term goals (FY20-25):

a. Three dimensional x-ray diffraction microscopy capability for spatial phase relationships in poly phase materials.

b. Ultrafast structural characterization (TEM, X-ray), combined with broadly tunable ultrafast optical pulses to access a wide variety of materials.

c. Flash X-ray, P-Rad and Neutron spallation sources for in-situ characterization lines devoted to Army materials by design programs.

d. Surface Science Center for characterization of materials at surfaces and interfaces using a variety of surface preparation techniques.

iii. Far-term goals (FY26-30):

a. Modernization of instrumentation is expected at ever increasing rates and replacement / upgrade / new developing characterization will need to be programmed as a continual process.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges.

Army Warfighting Challenge	Description
5	Prevent, reduce, eliminate, and mitigate the use and effects of weapons of mass destruction.
7	Assure uninterrupted access to critical communicationsand information links.
13	Establish and maintain security across wide areas (wide area security).
15	Conduct combined arms air-ground maneuver.
18	Deliver fires and preserve freedom of maneuver.
19	Understand, visualize, describe, direct, lead, and assess operations.

SCIENCES-FOR-MANEUVER CAMPAIGN

MISSION: To discover, innovate, and transition S&T enabled capabilities that significantly increase the force effectiveness and global responsiveness of the Army - America's primary ground force.

VISION: Air and ground platforms available to commanders of the Army of 2030 are designed and built that make it possible to rapidly respond to emerging conflicts at any location around the globe. Based on vastly improved materials, logistical support needs of the fighting force are greatly reduced. A globally responsive, lethal, and resilient force serves as a significant deterrent to rising conflict. The desired end state is to leverage the full range of S&T enablers to prepare forces.

The Sciences-for-Maneuver Campaign focuses on gaining a greater fundamental understanding of advanced mobility technologies that enable innovative vehicles configurations and subsystems architectures – critical to the future Army's movement, sustainment, and maneuverability. Knowledge gained through these research efforts will lead to technologies for the design, fabrication, integration, control, and platforms support that will significantly improve Power Projection Superiority for the Army of 2030.

The Sciences-for-Maneuver Campaign has developed 3 Key Campaign Initiatives and 4 Core Campaign Enablers (CCEs) that are integrated to form a robust foundation to understand and overcome complex fundamental challenges associated with Energy and Propulsion; Platform Mechanics; Vehicle Intelligence; and Logistics and Sustainability. The campaign builds on fundamental pillars of science and engineering to conduct research in manned-and-unmanned Army air-and-ground vehicles. Discoveries and innovations made in this area will exert a significant impact on the Army of the future.

FORCE PROJECTION AND AUGMENTATION THROUGH INTELLIGENT VEHICLES [KCI-SCMVR-1]

EXPECTED ARMY IMPACT: The Army Operating Concept (AOC) states that "Army development of autonomous and semi-autonomous operational capabilities will increase lethality and protection, and augment, enable and, in some cases, replace Soldiers, thus freeing them to maneuver and operate to their advantage." ARL is focused upon providing the fundamental understanding that will enable future unmanned vehicle systems (UVS) operating in the air, ground, or maritime environments – through greatly improved platform perceptual, learning, reasoning, and communication capabilities to facilitate effective interaction with Soldiers and the local populace thereby engendering trust essential to forming efficient teams. In addition, technological advances in this area are envisioned to create "the potential for affordable, interoperable autonomous and semi-autonomous systems that improve the effectiveness of Soldiers and units. Robotics will deploy as force multipliers at all echelons from the squad to the brigade combat teams. Future robotic technologies and unmanned ground systems (UGS) augment Soldiers and increase unit capabilities, situational awareness, mobility, and speed of action."

DESCRIPTION: ARL research is centered on creating the machine cognition and behaviors that can, in certain scenarios, replace the operator (driver or pilot) in future unmanned vehicles. Our focus includes the perceptual, learning, reasoning and communication skills that are required to effectively interact with both Soldiers and the local populace, and engender the mutual trust necessary for effective teaming.

a. TECHNICAL GOAL(S):

i. Near-term goals (FY16-FY20):

a. Cognitive architecture and supporting technologies to model the world in semantic terms, permit reasoning based upon abstractions, and allow interactive communication with Soldiers using structured natural language.
b. Semantic labeling of an increasingly larger vocabulary of objects and behaviors to permit a richer, more detailed description of the environment. Includes the determination of critical scene elements, actions, and relationships to be remembered for future use in machine planning, learning, and reasoning; recognition of changes in the physical and tactical environment as a cue to significant activity requiring reaction; and incorporation of contextual information and life-long learning into reasoning.
c. Expansion of research activities from a primary focus on ground vehicles to fully encompass unmanned air systems.

ii. Mid-term goals (FY21-FY26):

a. Creation of the ability to infer purpose from the relationships between objects in the environment and behaviors (activity) exhibited by people (teammates, adversaries, and non-combatants) and place objects and behaviors into context.
b. Enhanced ability of machines to generalize and rapidly learn from a limited number of exemplars; monitor execution; and identify conditions requiring reconsideration of plans and modification of behavior and autonomously initiate the replanning process.

c. Enable machines to explain knowledge, actions, and predicted outcomes enabling rapid redistribution of tasks between Soldier and robot, enhancing transparency, and engendering greater trust by human collaborators.

iii. Far-term goals (FY27-FY31):

a. Cognitive architectures and algorithms to create unmanned vehicles that possess the situational awareness, cognitive skills, learning capabilities, and reasoning prowess associated with tactical or support vehicle operators.
b. Systems capable of reasoning on an abstract level possessing basic tactical skills and knowledge.
c. Machines able to generalize, adapt, and successfully apply their knowledge base to synthesize new solution approaches to previously unknown situations.
d. Robots able to rapidly and autonomously adapt to changes in human teammate actions--operate effectively as wingmen within a manned-unmanned team without a need for direct control by a Soldier.

b. PERSONNEL REQUIREMENTS:

i. Near-term (FY16-FY20): Expertise required in computer science, applied mathematics and engineering associated with the creation and integration of software algorithms. Emphasis on cognitive architectures modeling human behavior also requires individuals with backgrounds in social sciences and psychology. Emphasis on the use of natural language for communication calls for additional leveraging of existing expertise in natural language processing. Over the course of five years, expect a net increase of between 12 and 18 Government employees, augmented through partnership arrangements with additional personnel from academia and industry.

ii. Mid-term (FY21-FY26): As the scope of dedicated facilities and testbeds increase, hire 3-4 new Government engineers and technicians, releasing S&T staff to focus on research and experimentation. Consider rotating personnel from Research, Development, and Engineering Centers to ARL for extended periods to facilitate technology transition to concept demonstration projects. Hire 1-2 S&T staff per year to explore and implement the increasing number of research topics, especially as the research focus turns towards empowering robots with more “human-like” cognitive capabilities.

iii. Far-term (FY27-FY31): As technology matures and an increased focus is on empowering systems with cognitive skills, there will be a requirement for 1-2 subject matter experts working with computer scientists and software engineers to create and explore exemplar complex tactical behaviors.

c. INFRASTRUCTURE NEEDS:

i. Near-term (FY16-FY20):

a. A set of representative testbed vehicles, both air and ground, on which to integrate, exercise, and explore integrate component technologies at appropriate scales in a relevant, reconfigurable environment. This could be accomplished in collaboration with appropriate partners (Government, academic, or industrial).
b. Upgraded component sensing and computational hardware to maintain relevance with readily available technology.

ii. Mid-term (FY21-FY26):
  a. Expanded facilities for simulated and live experimentation for increasingly complex physical and tactical outdoor environments for air, ground, and hybrid vehicles. Given the scope of this activity, potential partnering with the Test & Evaluation community, other Government agencies, or industrial partners should be explored.

iii. Far-term (FY27-FY31):
  a. Additional laboratory space to house the larger number of personnel and testbeds in the program.
  b. Additional software development facilities.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges and Army Capability Needs.

Army Warfighting Challenge	Description
1	Develop and sustain a high degree of situational understanding.
3	Provide security force assistance.
5	Prevent, reduce, eliminate, and mitigate the use and effects of weapons of mass destruction.
12	Conduct entry operations.
13	Establish and maintain security across wide areas (wide area security).
16	Set the theater, provide strategic agility to the Joint Force, and maintain freedom of movement and action.

Army Capability Need Proponent	Capability Area Need
MCoE	3.e – Robotics/Autonomy.
CASCOM	3.a – Autonomous Ground Resupply.
CASCOM	3.e – Autonomous Aerial Resupply.
USAACE	3.d – Improved Manned-Unmanned Teaming and Autonomy.
USAACE	3.h – Joint Force Commonality.
MSCoE	4.e – The Capability to Conduct Operations with Autonomous Systems.

ADVANCED, ELECTRICAL POWER TECHNOLOGIES AND COMPONENTS [KCI-SCMVR-2]

EXPECTED ARMY IMPACT: With the demand for higher efficiency and performance, the Army has, traditionally, migrated from mechanical systems to electronic systems. In the future, this evolution will be even more attractive and necessary as networked power management holds the promise of enabling additional capabilities, benefits and cost savings. The Advanced, Electrical Power Technologies and Components effort addresses the development of a broad spectrum of materiels and devices that will be required by Army systems developers in the coming years. Of special focus are high-voltage components that will accelerate the realization of compact, high-energy (sub-) systems.

This research effort is expected to have the following Army impacts:

- Improving mission effectiveness of Army platforms through the development of necessary energy and power underpinning devices and circuits that are required to enable electric-based component technologies.
- Reducing logistics burdens through the development of more efficient electrical power generation, distribution, and conversion components and systems.

DESCRIPTION: This research effort will focus on pursuing advanced, electrical power technologies and components to enable efficient Army platforms. The goals of this work are to overcome barriers to realization of intelligent, solid-state alternatives to selected electro-mechanical components; components and techniques for improved thermal management of transient heating events in electronic systems; high voltage components based on advanced wide band-gap semiconductors; intelligent power conditioning modules and interfaces for power conversion and inversion; and induction-based, electrical energy storage devices that approach 20 J/cc capacities.

a. TECHNICAL GOAL(S):

i. Near-term goals (FY16-FY20):

a. Develop intelligent, solid-state replacements for selected electro-mechanical components.

b. Develop a compact, high-voltage power source for plasma applications such as aerodynamic control of smart munitions.

c. Develop components and techniques for improved thermal management of transient heating events in electronic systems.

ii. Mid-term goals (FY21-FY26):

a. Develop high voltage components based on advanced wide band-gap semiconductors (such as aluminum nitride or gallium nitride) that allow higher voltage (>25 kV) operation for expanded power control

b. Develop intelligent power conditioning modules and interfaces to demonstrate power converters and inverters with adaptive circuit topology capability for improved efficiency and reliability

c. Develop high-slew rate electrical machines, drives, and power sources.

d. Investigate the use of three-dimensional (3-D), silicon carbide (SiC), metal-oxide-semiconductor field-effect transistors (MOSFET) for improved efficiency of power conversion circuits.

e. Demonstrate high-action, high-voltage opening switches for inductive storage devices. These components are critical for the development of energy storage based on superconducting inductors.

iii. Far-term goals (FY27-FY31):

a. Develop dielectric-based, electrical energy storage devices that approach 3 J/cc capacities to decrease the volume of energy storage capacitors by one-half.

b. Develop inductive-based, electrical energy storage devices that approach 20 J/cc capacities to provide substantial volume reductions over competing approaches.

c. Complete reliability/manufacturability validation of a vertical power transistor using, the wide band-gap semiconductor, gallium nitride (GaN).

b. PERSONNEL REQUIREMENTS:

i. Near-term (FY16-FY20): Seventeen (17) S&Es (2 ME, 3 Phys, 12 EE) with advanced education (e.g., M.S., Ph.D.) and at least 5-years of experience in applied research and development environments. External partnering with university and industrial researchers will be required.

ii. Mid-term (FY21-FY26): Eighteen (18) S&Es with advanced education (e.g., M.S., Ph.D.) and at least 5-years of experience applied research and development environments. External partnering with university and industrial researchers will be required.

iii. Far-term (FY27-FY31): Sixteen (16) scientists & engineers (S&Es) with advanced education (e.g., M.S., Ph.D.) and at least 5-years of experience in applied research and development environments. External partnering with university and industrial researchers will be required.

c. INFRASTRUCTURE NEEDS:

i. Near-term (FY16-FY20):

a. Renovation of laboratory space and implementation of advanced high-voltage packaging capability.

ii. Mid-term (FY21-FY26):

a. Renovation of laboratory space for the study of electrical machines. Energy storage using rotating mass requires a containment structure and diagnostic equipment.

b. Upgraded instrumentation for circuit characterization.

iii. Far-term (FY27-FY31):

a. Renovation of ARL Bldg. 500's 4160 VAC switch yard at the Adelphi Laboratory Center.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges and Army Capability Needs.

Army Warfighting Challenge	Description
7	Assure uninterrupted access to critical communications and information links.
16	Set the theater, provide strategic agility to the Joint Force, and maintain freedom of movement and action.

Army Capability Need Proponent	Capability Area Need
CASCOM	3.c – Intelligent Power Management and Distribution System.
CASCOM	4.a – Hybrid Power Capabilities.

DAVINCI: DISCOVER & ADVANCE VTOL INNOVATIONS, NOVEL CONCEPTS, AND IDEAS [KCI-SCMVR-3]

EXPECTED ARMY IMPACT: By 2040, the Army Aviation Center of Excellence has identified that the Army needs an expanded area of operation, improvements in aviation responsiveness, and minimization of vulnerabilities. Higher vehicle speed, range and payload are three performance attributes required in a Vertical Take Off and Landing (VTOL) vehicle to achieve these needs. Platform configurations capable of meeting such performance goals will be fundamentally different from the current fleet of Army helicopters. Research efforts by ARL will specifically impact:

- Development of technologies to enable fielding of the next generation of VTOL platforms and transfer capability to current platforms to produce significantly increased speed without degradation in hover efficiency.
- Development of technologies to enhance maneuverability in complex environments and at higher operating speeds.
- Development of next generation micro and small unmanned autonomous air vehicles.

DESCRIPTION: The technical goals are to develop algorithms, methods, and tools for flight mechanics, dynamics predictions, and performance assessment; develop new technologies to achieve revolutionary improvements in vehicle performance (including active flow control and active structural shape control to minimize performance tradeoffs across different flight conditions); and explore innovative vehicle configurations for VTOL and micro/small autonomous air vehicles. This effort will leverage analytical, computational, and experimental efforts to achieve the goals. In the far-term (FY27-FY31), high performance computing is expected to reach the exascale levels and sufficiently miniaturization to facilitate embedding into vehicle platforms to provide significant onboard computing power. Additionally, technological advances in materials science are expected to create extremely light weight, strong materials to significantly reduce system weight. The combination of these improvements will enable active shape-morphing vehicles that are optimized using developed tools, methods, and embedded computing. Exascale computational tools will manipulate the structural deformations along with active flow control to generate necessary forces in each flight regime.

a. TECHNICAL GOAL(S):

i. Near-term goals (FY16-FY20):
   a. Develop computational algorithms and methods to significantly enhance and improve accuracy and efficiency of predictions for loads, stability and performance of platform mechanics.
   b. Develop multi-fidelity approaches to understand aerodynamic interactions and exploiting them for performance benefits.
   c. Develop methods and algorithms to evaluate system utilizing emerging materials by integrating multi-physics simulations with different time and space scales.

ii. Mid-term goals (FY21-FY26):
   a. Demonstrate mature active flow control and structural shape control technologies in model scale experiments.
   b. Develop algorithms to couple sensors with the control mechanism to predict aeromechanics characteristics and configuration management for specified flight mission.

c. Develop models of biologically-inspired or smart materials and systems for application in design and comprehensive analysis tools.
d. Develop performance models of potential VTOL platforms.

iii. Far-term goals (FY27-FY31):

a. Virtual demonstration of fusion of advanced aerodynamic, structural and control technologies on VTOL platforms.
b. Develop models of enabling technologies – active flow control, active shape control, configuration morphing – across the flight spectrum.
c. Develop tools and methods for load, stability, and performance prediction of next-generation VTOL platforms.

b. PERSONNEL REQUIREMENTS:

i. Near-term (FY16-FY20): The project requires additional personnel resources with background and experience in the general area of rotorcraft aeromechanics. Personnel are also required to support teams engaged in utilizing high performance computing for fundamental fluid dynamics and structural dynamics. (5 FTEs).

ii. Mid-term (FY21-FY26): The project requires personnel with expertise in multiple disciplines to influence next generation analysis tools and methods. Such needs may be met by new hires or by leveraging personnel from material science, information science, and computational science campaigns. (6 FTEs)

iii. Far-term (FY27-FY31): Multi-disciplinary expertise to impact studies of VTOL platforms possessing significant interactions between several systems. (7 FTEs)

c. INFRASTRUCTURE NEEDS:

i. Near-term (FY16-FY20):

a. High Performance Computing resources (25 Million CPU hrs per year). b. Access to Transonic Dynamic Tunnel.

ii. Mid-term (FY21-FY26):

a. Access to Petascale High Performance Computing resources. (100 Million CPU hrs per year)
b. Access to Transonic Dynamic Tunnel.

iii. Far-term (FY27-FY31):

a. Access to ExaScale High Performance Computing resources.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges and Army Capability Needs.

Army Warfighting Challenge	**Description**
3	Provide security force assistance.
12	Conduct entry operations.

Army Capability Need Proponent	**Capability Area Need**
USAACE	3.a – Range, speed, payload, and capacity consistent with maneuver force lift demands and mission needs.
MSCoE	4.a – The Capability to Facilitate Early Entry Operations.

ADVANCED SWITCHING AND CONTROL FOR POWER ELECTRONICS [CCE-SCMVR-1]

The Sciences for Maneuver (ScMVR) Core Campaign Enabler (CCE) in Advanced Switching and Control for Power Electronics offers the opportunity to develop electrical power systems that provide the Army efficient and more capable electrical switching and distribution capabilities. This effort will be supported by analysis and characterization of devices, improved understanding of wide band gap materials and device reliability, and advancements in circuit topologies and adaptive predictive algorithms to provide intelligent power distribution and management.

The SM CCE on Advanced Switching and Control for Power Electronics Research will focus on analysis of high voltage pulse devices, circuit topologies for universal and intelligent power converters, and development of adaptive and predictive algorithms for power monitoring. Advances in switching and control will focus on three performance challenges:

1) Development and demonstration of the ARL's concept for a Universal Power Converter that will provide the flexibility to operate using available loads or sources including renewables and supports interoperability with coalition equipment. This concept will be matrix biased distribution control and will allow single and multiphased power.

2) Demonstrate basic capabilities of agent based adaption and prediction algorithms for improved operation of electrical grids to provide energy informed operations and improved logistics management.

3) Examinations of ARL's wide bad gap MOS-FET solid state circuit breaker design to provide bidirectional functionality to provide reliable fast fault protection for grid attached systems and load management.

PERSONNEL REQUIREMENTS:

i. Near Term Goals (FY15-19):
   a. Electrical engineer (multi-disciplinary skills in power conversion, controls and grid management. (2-3 FTEs)
   b. Electrical Engineering tech with expertise in power conversions. (1 FTE)

ii. Mid-term goals (FY20-25):
   a. Electrical engineer with multi-disciplinary skills in power conversion, controls and grid management (2-3 FTEs)
   b. Electrical/computer engineer with focus on machine learning (1 FTE)
   c. Electrical Engineering tech with expertise in power conversions. (1 FTE)

iii. Far Term (FY26-30):
   a. Electrical and computer engineers with expertise in adaptive and predictive grid control, understanding in power conversion, controls and grid management and expertise in machine learning (3-4 FTEs)
   b. Electrical Engineering technician with expertise in power conversions. (1 FTE)

INFRASTRUCTURE NEEDS:

ii. Near-to-Far term goals (FY15-30):
   a. Real time Digital Simulator (RTDS)- for hardware in the loop testing, with improved capability to conduct circuit level simulations.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges.

Army Warfighting Challenge	Description
1	Develop and sustain a high degree of situational understanding.
9	Develop resilient Soldiers, adaptive leaders, and cohesive teams.
12	Conduct entry operations.
13	Establish and maintain security across wide areas (wide area security).
15	Conduct combined arms air-ground maneuver.
16	Set the theater, provide strategic agility to the Joint Force, and maintain freedom of movement and action.

HIGH-POWER-DENSITY & ENERGY-EFFICIENT ENGINE & DRIVETRAIN TECHNOLOGIES [CCE-SCMVR-2]

The objective of the Sciences for Maneuver (ScMVR) Core Campaign Enabler (CCE) in High-Power-Density and Energy-Efficient Engine and Drivetrain Technologies is to advance the fundamental sciences in engine cycle and powertrain technologies for improving performance, operational capabilities, and sustainment of Army vehicles.

Power density and fuel efficiency are key engine parameters that directly influence vehicle capabilities of speed, range, and payload. Fundamental research and innovation within the scope of this CCE that impact power density, fuel efficiency and sustainment include: fuel spray, atomization, mixing, ignition, combustion; engine cycle and component efficiencies (compression, expansion, power extraction, recuperation); computational tools for modeling high-pressure turbulent multi-phase flows; and durable higher temperature engine components with foreign particle (e.g. sand ingestion) tolerance for sustained operation in Army relevant environments at altitude and temperature extremes.

Efficient and robust distribution of propulsive power enhances the mobility and survivability of military vehicles. This CCE investigates novel approaches in the efficient distribution of vehicle propulsive power routed from powerplants to propulsive devices. Efforts include fundamental scientific research in: Tribological surfaces/coatings, lubricants and manufacturing processes for improved power density and operation under starved lubrication in harsh environments; Multi-speed transmissions for high-speed vertical lift platforms; Powertrain technologies such as hybrid gears for weight reduction; Probabalistic/health-informed design methodologies for improving reliability/durability; and novel efficient and flexible electric-drive systems to transform the architecture of Army propulsion systems.

PERSONNEL REQUIREMENTS:

i. Near Term Goals (FY15-19):

a. Mechanical and/or aerospace engineers with advanced education and expertise in advanced drivetrains including clutches, mechanical interlocks, gears, and bearings.
b. Materials engineers with advanced education and expertise in tribology, advanced drivetrains materials and material processes.
c. Mechanical and aerospace engineers with multi-disciplinary skills in fuels, spray, mixing, combustion, optical diagnostics, thermoscience, and fluid mechanics (2-3 FTEs)
d. Mechanical and aerospace engineers with multi-disciplinary skills in computational fluid mechanics, thermoscience, spray, and (1-2 FTEs)
e. Mechanical and aerospace engineers with multi-disciplinary skills in fuels, injection technologies/mechanisms, and combustion (1-2 man year equivalent)
f. Mechanical and materials engineers with multi-disciplinary skills in high-temperature propulsion materials, optical diagnostics, and material characterization (2-3 FTEs)
g. Mechanical and aerospace engineers with multi-disciplinary skills in engine combustion, research engine control, combustion diagnostics, and laboratory methods (4-5 FTEs)

ii. Mid-term goals (FY20-25):
   a. Mechanical and/or electrical engineers with advanced education and expertise in electric motors and hybrid electric vehicle transmissions.
   b. Mechanical, aerospace and control engineers with experiences in combustion, optical diagnostics, fuel injection technologies, thermoscience, computational fluid mechanics, heat transfer, engine control, advanced engine (8-12 FTEs)
   c. Mechanical and materials engineers with experiences in material characterization and optical diagnostics (2-3 FTEs)

iii. Far Term (FY26-30):
   a. Mechanical/multi-disciplinary engineers with advanced education and expertise in non-contacting power transfer technology with an emphasis on energy management and distribution.
   b. Mechanical, aerospace and control engineers for development in adaptive engine control and predictive spray/combustion models (10-14 FTEs)
   c. Mechanical and materials engineers for development of high temperature coating technologies and predictive model (3-4 FTEs)

INFRASTRUCTURE NEEDS:

iii. Near-to-Far term goals (FY15-30):
   a. Complete build of Vehicle Innovative Powertrain Experimental Research (VIPER) laboratory.
   b. Storage space for transmissions and transmission mounting hardware for Vehicle Innovative Powertrain Experimental Research (VIPER) laboratory.
   c. Upgrade tribology laboratory equipment to measure in situ chemical, rheological and wear phenomena
   d. Electrical/Electro-magnetic Drive Systems Laboratory
   e. Advanced transmission research facility capable of demonstrating non-contacting, high power transfer concepts.
   f. Facilities to house high repetition rate laser system, higher light sources, high-speed particle image velocimetry (PIV) system, and laser-induced breakdown spectroscopy (LIBS) system
   g. High fidelity CFD capabilities, optically-accessible single cup gas turbine chamber, optically-accessible single-cylinder head modification
   h. Scanning laser con-focal microscope, other optical microscopes, and a profilometer characterization facility
   i. High temperature combustion chamber modification to add 2 more optical access capabilities
   j. Modify the Small Engine Altitude Research Facility combustion air supply and exhaust handling system for a full Army gas turbine engine experiment at altitude conditions
   k. High pressure burner rig facility to characterize propulsion materials at the Army-relevant operating conditions
   l. Upgrade the AC dynamometer bench of the Small Engine Altitude Research Facility to handle a gas turbine engine for Army rotorcrafts
   m. Modify the atmospheric burner rig to enhance its capabilities and add additional state-of-the-art propulsion material characterization tools

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges.

Army Warfighting Challenge	Description
11	Conduct effective air-ground combined arms reconnaissance.
12	Conduct entry operations.
13	Establish and maintain security across wide areas (wide area security).
15	Conduct combined arms air-ground maneuver.
16	Set the theater, provide strategic agility to the Joint Force, and maintain freedom of movement and action.

VIRTUAL RISK-INFORMED AGILE MANEUVER SUSTAINMENT (VRAMS) [CCE-SCMVR-3]

The purpose of the VRAMS Sciences for Maneuver (ScMVR) Core Campaign Enabler (CCE) is to discover, innovate and transition technologies that enable integrated structural health monitoring capability embedded within vehicles (air, ground, and autonomous systems) and other materiel to automatically gauge changes in their functional state, assess that functionality in the context of upcoming or ongoing missions, and respond accordingly to: 1) achieve mission objectives; 2) increase materiel availability; and 3) reduce life cycle costs. Changes in the functional status of structural components or systems include effects from: structural fatigue, wear, damage, and other aging related degradations. The changes in system functionality will be integrated with data from on/off board systems for mission and maintenance planning and battle command systems to automatically compare the materiel's readiness capability to the real-time demands imposed by mission objectives. The range of VRAMS potential responses includes: informing operators of vehicle health and capability; informing systems for recommendation of alternative courses of action; and automated adjustment of vehicle subsystem response to operator control inputs to offer maximum system performance operating envelop in balance with monitored system integrity limits.

The primary state-of-the-art structural damage indicator is crack size. Unfortunately readily detectable fatigue cracks appear relatively late in the service life spectrum, which in some cases is too late for a remedial maintenance action to prevent failure. Due to the exponential nature of fatigue crack growth and detection technology limitations, current damage detection technologies based on crack measurements provide accurate service life predictions towards the last 20% of the remaining useful life of structures and components. However, it is not only structural cracks that nucleate and grow during service under dynamic operating loads. The structural damage processes also affect other mechanical properties such as stiffness or compliance, hardness, damping, residual stresses, electrical, and magnetic properties including resistivity, permeability, dielectric constants, and other properties or characteristics.

VRAMS research seeks to investigate, identify, quantify, and correlate structural damage precursors that occur well in advance of conventional crack initiation and detection methods. Monitoring damage precursors ahead of micro-crack formation, for example, will enable informed operational options to manage and slow down the evolution of damage precursors to deter micro-crack formation. While fault detection sensing capabilities and tailored signal processing algorithms have advanced, challenges remain in the ability to identify damage precursors when platforms are not in operation, let alone, under complex loading in real-time operational environments.

The VRAMS research effort seeks to innovate and advance vehicle structure and Health and Usage Monitoring System (HUMS) technologies and capabilities the following focus areas:

1. Technologies for vehicle structure improvements for reduced size and weight, and improved reliability and affordability
2. Vehicle structures and components damage precursor fundamental detection and characterization technologies
3. Technologies and approaches for affordable and reliable "built-in" vehicle sensing of structural damage precursors
4. Understanding and modeling of damage precursor progression in complex multiaxial/multiscale environments relevant to vehicle operational characteristics
5. Concepts for damage precursor evolution mitigation through vehicle adaptive maneuvers based on real-time structural health state awareness and risk assessment

PERSONNEL REQUIREMENTS:

i. Near Term Goals (FY15-19):

a. Fatigue and Fracture scientists and engineers with multi-disciplinary skills in materials microstructural characterization, non-destructive analysis, and advanced materials testing techniques. Materials scientists with expertise to enable accurate characterization of metallic and fiber-based composite material properties. (2-4 FTEs).

b. Mechanical, electrical, multi-disciplinary scientists and engineers for prognostics and diagnostics, sensing methods, and data fusion (3-5 FTEs).

c. Scientists and engineers with educational background and expertise in structural fatigue modeling, mathematics, statistics, probabilistics, and risk assessment (4-6 FTEs).

ii. Mid-term goals (FY20-25):

a. Computer, mechanical, electrical, multi-disciplinary scientists and engineers for advancing "big data" fusion and prognostics technologies (4-6 FTEs).

iii. Far Term (FY26-30):

a. Computer, mechanical, electrical, multi-disciplinary scientists and engineers for advancing multiscale/multiaxial modeling, risk assessment, and reconfigurable flight control responses to "damage" in "real-time" (4-6 FTEs).

INFRASTRUCTURE NEEDS:

i. Near-to-Far term goals (FY15-30):

a. Fully establish the Reliability State Awareness Testbed (RSAT) Facility with additional capabilities including hover cage, real-time motion-based flight simulation, and VRAMS virtual reality environment.

b. Networked laboratory/high performing computer systems to enable transfer of massive amounts of processing data from on-board microprocessor unit/VRAMS core engine to RSAT databases and ground-based VRAMS core engine to allow for in-depth analysis and solutions in real-time.

c. Acquire next-generation prototype/experimental vertical lift with VRAMS core engine integrated on aircraft on-board processing system.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges.

Army Warfighting Challenge	Description
11	Conduct effective air-ground combined arms reconnaissance.
12	Conduct entry operations.
15	Conduct combined arms air-ground maneuver.
16	Set the theater, provide strategic agility to the Joint Force, and maintain freedom of movement and action.

MECHANICS AND DYNAMICS OF COMPLEX SYSTEMS [CCE-SCMVR-4]

This Sciences for Maneuver (SM) Core Campaign Enabler (CCE) is to holistically explore research directions focused on Mechanics and Dynamics of Complex Systems across scales from microsystems to manned platforms for both air and ground applications. Three primary areas of research include fluid structure dynamics, mechanisms and actuation, and platform concepts. The fluids technology development focus area includes research to understand aero-elastic stability characteristics of advanced rotor structures. Modeling, simulation, and experimentation are also conducted and utilized to understand the fundamental aspects necessary to further develop, advance, and evaluate passive and active technologies for stability augmentation. Theoretical and experimental investigation to understand both aero-elastic stability and aero-elastic responses are conducted to enable advanced lift-thrust systems. From a dynamics perspective, research will advance mathematical treatments and decomposition techniques of complex fluid and coupled fluid-structure phenomena that go beyond energy based methods. The research will also focus on advancing methods that isolate dynamically relevant features that may persist across multiple scales, or interact to produce multi-scale dynamics. These approaches will enable theoretical, numerical, and experimental modeling and control research in fluids and fluid-structure interaction problems that limit Army maneuver capabilities.

Future concepts may require highly complex and intricate structures for distributed forms of actuation that will need considerable resources and focus in order to make them technically and economically feasible. Research will be conducted in advanced actuation, mechanisms, and power train systems employed in locomotion and flight to include their associated methods of control. Advancements to actuator and mechanism fabrication techniques and new or novel methods for creating the materiel necessary for exploration of this area should be explored. A common thread in this area of research is the manner in which different forms of additive manufacturing and robotics may be employed to research, develop, and fabricate structures with increasing levels of complexity using unprecedented levels of control and fidelity. For example, tools and techniques for manipulating materiel at minute scales could be developed. The actuated structures that may be developed could allow exploration of highly complex systems that employ energy efficient techniques for mobility that include impedance matched actuation, variably tuned compliance, and adaptive morphologies. Complex networked, distributed actuation techniques integrated into structures could begin to rival the efficiency and utility of muscle which provides multiple functions such as mobility actuation, dexterity, structure, kinetic energy dissipation, and redirection.

Lastly, increasing system complexity paired with dynamic environmental operating contexts requires a transformation in engineering design theory, methods, and tools. Existing design engineering approaches are inadequate for detecting these interaction complexities early in design, as they assume that a system can be described as a sum of its parts. Senior leaders within the defense acquisition and research communities recognize this shortcoming and are now requiring an earlier, deeper understanding of the relationships between design decisions, requirements, costs, capability, schedule, and risk.

The research area will help to provide the underpinning science and technology which allows the Army to detect, diagnosis, visualize, and model interactions from the component level all the way up to the system-of-systems level for complex mobility systems of the future. The data-informed design and decision making environment of 2030 is expected to be fully collaborative, multidisciplinary, real-time, and immersive. Capabilities stemming from this research will allow technology developers, in an interactive and tactile environment, to see how their technology integrates with the system, the location and impact of possible detrimental interactions internal and external to the system during operation, and the probabilistic impact on measures of effectiveness – all before any components of the system are manufactured. The research will also enable the Army to determine where gaps exist in its technology development portfolio and to inform investment strategies and decisions to achieve greatest value to the Soldier.

PERSONNEL REQUIREMENTS:

i. Near Term Goals (FY15-19):
   a. Applied mathematicians and engineers with skills in developing theoretical high-dimensional numerical models, and experimental explorations of fundamental fluid and structural dynamic phenomena. (5-10 FTEs)
   b. Research aerospace engineers with skills in developing rotorcraft aero-elastic models and conducting rotorcraft loads, performance, and aeroelastic stability and response analyses as well as wind tunnel experimentation for VTOL (3-6 FTEs)
   c. Individuals with expertise in autonomous systems control and locomotion, physics, materials science, and computer science. (4 to 6 FTEs)
   d. Individuals with expertise in systems engineering, software engineering, operations research, decision science, scenario planning, story boarding, multidisciplinary analysis tools, search and sampling algorithms, and statistical data analysis. (5 to 7 FTEs)

ii. Mid-term goals (FY20-25):
   a. Mechanical, aerospace, materials, and multi-disciplinary S&Es for benchtop demonstration of flow control concepts and reconfigurable/engineered structural response (5-10 year man equivalents).
   b. Individuals with expertise in systems engineering, electrical engineering, computer science, cognitive science, physics-based multi-scale modeling of complex heterogeneous systems expertise. (4 to 6 FTEs)
   c. Individuals with expertise in human systems integration, virtual reality HW/SW, pattern recognition and classification, and econometrics. (4 to 6 FTEs)

iii. Far Term (FY26-30):
   a. Mechanical, aerospace, and multi-disciplinary S&Es for advancing fluids, structures, and dynamics enablers for novel platforms (5-10 year man equivalents).
   b. Individuals with expertise in systems engineering, software engineering, electrical engineering, robotics, computer science, cognitive science, physics-based multi-scale modeling of complex heterogeneous systems expertise. (4 to 6 FTEs)
   c. Personnel with multidisciplinary and system domain-specific expertise to conduct end-to-end assessments, maintain and upgrade equipment, and create 3D virtual environment representations of technology elements. (3 to 5 FTEs)

INFRASTRUCTURE NEEDS:

i. Near-to-Far term goals (FY15-30):
   a. Aeroelastic rotor experimental system to conduct aeroelastic stability boundary investigation on edgewise flight rotor systems, including lift-offset coaxial rotors, stiff-inplane rotors, variable speed rotors and morphing rotors.
   b. Experimental facilities, which includes robots capable of consistent deliberate dynamic motion that enables development and validation of physics-based dynamics models in which the subject interacts with the environment. Facilities to

study actuated structures and distributed actuation incorporating robots capable of advanced and/or unique forms of additive manufacturing.

c. Hardware and software to (1) apply new techniques for classifying both structural and interaction complexities within and between systems and their operational environments, (2) creating interactive 3D virtual representations of system components, (3) integrating 3D virtual components into executable embodiments of a mobility system for quantifying and visualizing the effects technologies have on meeting requirements system end states.
d. Aeroelastic tiltrotor experimental system to conduct stability boundary investigation for tiltrotor and novel design and technologies for improved tiltrotor aeroelastic stability.
e. Additive manufacturing and autonomous fabrication systems for actuated structures with embedded electrical pathways and computer network controls. Software for design and control of structures employing distributed actuation. Robotic systems to manipulate and assemble particulate materiel into intricate multi-scale systems.
f. Hardware and software for 3D virtual environment facility defining state-of-the-art by immersing researchers in the system technology tradespace environment, quantifying and visualizing the effects technologies have on system performance and capabilities.
g. Facilities for predictive modeling and design of highly complex structures capable of distributed actuation and sensing. Methods of assembly and fabrication of actuated structures are developed in conjunction with the facilities.
h. Immersive, 3D virtual environment facility that extends 2025 state-of-the-art capabilities (visualize, hear, simulate) to the desired end state of interactively effecting dynamic changes in real-time, forward-and-backward across the entire process: design, analysis, simulation, and technology tradeoffs.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges.

Army Warfighting Challenge	Description
11	Conduct effective air-ground combined arms reconnaissance.
12	Conduct entry operations.
15	Conduct combined arms air-ground maneuver.
16	Set the theater, provide strategic agility to the Joint Force, and maintain freedom of movement and action.

INFORMATION SCIENCES CAMPAIGN

MISSION: To discover, innovate, and transition S&T capabilities that (1) facilitate the availability and effective use of high assurance and high quality information and knowledge at the tactical edge in a timely manner; and (2) facilitate the development of offensive information systems to limit adversary command-and-control capabilities.

VISION: Intelligent information systems available to the Army of 2030 provide reliable, timely, valuable, and trustworthy information and knowledge at all echelons, and especially to the tactical edge – significantly mitigating tactical surprise. Army offensive information systems significantly limit the adversary's command-and-control capabilities. Intelligent information systems support and team with the force, forming an underlying socio-technical base for all things in the battlespace, from munitions targeting to maneuver to command-and-control. The desired end state is to leverage the range of S&T enablers to prepare forces to succeed in distributed operations and increasingly complex environments where information plays an ever increasing role.

The Information Sciences Campaign focuses on gaining a greater understanding of emerging technology opportunities that support intelligent information systems that perform acquisition, analysis, reasoning, decision-making, collaborative communication, and assurance of information and knowledge. Understanding gained through these research efforts will lead to technological developments that make it possible to manage and utilize information flows in the battlespace. Technologies resulting from these efforts will have a direct impact on the Information Supremacy of the Army of 2030.

The Information Sciences Campaign has developed 4 Key Campaign Initiatives and 5 Core Campaign Enablers (CCEs) that are integrated to form a robust foundation to understand and overcome complex fundamental challenges associated with Sensing and Effecting; Systems Intelligence and Intelligent Systems; Human and Information Interaction; Networks and Communications; and Cyber Security. The campaign builds on fundamental pillars of networks; advanced decision support aids; modeling and simulation of complex environments; and high performance computing to conduct research in areas including *Intelligent Agents; Enhanced Tactical Networks; Effective Decision Support Aids; Knowledge Exploitation; and Cyber Defense and Forensics*. Discoveries and innovations made in this area will exert a significant impact on the Army of the future.

CYBER FIRE AND MANEUVER IN TACTICAL BATTLE [KCI-IS-1]

EXPECTED ARMY IMPACT: The Army battlefield of 2040 will be a highly converged virtual-physical space, where cyber operations will be an integral part of the fight. As stated in the Army Operating Concept, "The cyberspace and space domains will take on added importance in the future. Global and regional competitors have invested heavily in all aspects of cyber and space operations". Cyber Fires will degrade, disrupt, deny, deceive and destroy not only informational, computational and communication resources of the adversary, but also the physical capabilities of its platforms, weapons, robots, munitions, and even of personnel. "Land-based cyber operations generate and exert combat power in and through cyberspace utilizing combined arms leaders, staffs, and formations to enable freedom of maneuver and action to deliver decisive effects." Cyber maneuver will rapidly move and/or transform as well as in conjunction with physical maneuver the friendly informational-computational resources to deny the adversary an opportunity to attack, while imposing on him a new unsolvable problem. Cyber Fires and Maneuver will rely on effective Cyber Intel capabilities. "The capability to conduct cyberspace information collection to find and identify cyberspace threats inside and outside of friendly force networks, and forensically collect, analyze and exploit an attack or intrusion, is critical to conducting friendly or enemy assessments." Operating on multiple time scales, often far faster than human cognitive processes, in a highly dynamic, non-contiguous field (as opposed to today's largely static cyber defense perimeters), these fires and maneuvers will be inseparably integrated with kinetic fires and movements. "The complexity of unified land operations further requires an expanded notion of combined arms that fully integrates physical, cyber, and electronic means." Our research will support continuous (real-time, not just deliberate) creative planning and execution control of highly agile, daring, aggressive cyber fires and maneuvers of this complex nature, in a necessarily highly automated, machine-intelligent fashion, yet responsive to human intent and in accord with slower kinetic actions.

DESCRIPTION: This research effort will focus on developing the models, methods, and understanding to overcome existing barriers to realization of effective cyber fires and maneuvers in a tactical environment. The goals of this work are to pursue near-autonomous detection and identification of malicious activity directed at friendly networks; methods to rapidly respond to adversarial activities; predictive characterization of network vulnerabilities; and a robust framework to assess networks. In addition, this research program will focus on realization of methodologies for the reliable reconfiguration of friendly cyber assets to evade or recover from attack; covert means for collection and predictive analysis of enemy actions; and methodologies to degrade or destroy adversarial cyber assets with high certainty and predictable probabilities of kill.

a. TECHNICAL GOALS:

i. Near-term goals (FY16-FY20):

a. Techniques for near-automated generation of tools for detection and identification of malicious activities, vulnerabilities, and malware using machine learning and other automated techniques with limited human supervision; including theoretically grounded methods for characterizing the detection and identification capabilities.

b. Methods of active responses to adversary presence on friendly networks, with measurable and quantitative means to select and configure a response, and to anticipate the effects of the response on adversarial behavior.

    c. Approaches to predictive characterization of risks to a network imposed by adversary, by network features and by human factors.
    d. Theoretical frameworks for quantifying effects of cyber maneuvers.
ii. Mid-term goals (FY21-FY26):
    a. Theoretically-grounded methods for robust autonomous detection of malicious activities and mitigating vulnerabilities, with adaptive collection and self-learning modifications of collection-detection agents.
    b. Techniques to move effectively and predictably through friendly and enemy cyber space using wired and wireless access means.
    c. Approaches to reliable reconfiguration of friendly cyber assets to evade or recover from an attack.
iii. Far-term goals (FY27-FY31):
    a. Autonomous techniques where collaborative teams of cyber agents under human oversight conduct focused collection and predictive analysis of enemy actions, while maintaining self-concealment.
    b. Approaches to agent-based integrated collaborative planning and wargaming; communicate and coordinate actions in execution.
    c. Methods to destroy enemy cyber assets with high and predictable probability of kill; autonomously re-synthesize and re-deploy the agents when defeated by adversary, taking into account the observed defeat mechanism.

b. PERSONNEL REQUIREMENTS:

i. Near-term (FY16-FY20): Computer scientists with skills in machine learning mathematicians with skills in advanced statistics and mathematics for applications for large-scale data analysis and mining; risk theory; system scientists with skills in human factors in application to cyber. (4 FTEs)
ii. Mid-term (FY21-FY26): Computer scientists with skills in computational complexity theory; and adaptive systems and; electrical engineers with skills in electromagnetic applications in cyber; control theory for execution of cyber maneuvers. (5 FTEs)
iii. Far-term (FY27-FY31): Computer scientists with skills in agent-based systems, artificial intelligence, autonomous negotiation, planning, game-theoretic approaches, and formal methods in software synthesis. (3 FTEs)

c. INFRASTRUCTURE NEEDS:

i. Near-term (FY16-FY20):
    a. Framework for large-scale collection, analysis, labeling, and storage of real-world cyber data suitable for further research utilization.
    b. Laboratory for efficient study of integrated, heterogeneous techniques for detection and analysis of malicious activities using large volumes of pre-collected cyber data.
    c. Facility for realistic emulation of cyber data of enterprise, tactical, and cyber-physical nature.

ii. Mid-term (FY21-FY26):
    a. Laboratory for emulation and extensively instrumented experimentations for study of realistic dynamics and effects of individual cyber fire actions and cyber maneuver of adversarial cyber environments. Minimal human input or manipulation should be required for experiments. Includes cyber-physical systems. Highly automated, continuous adoption of latest observed adversarial TTPs from real-world cyber defense operations.

iii. Far-term (FY27-FY31):
    a. Research-focused facility for emulation of cyber battlefield, and automated experimentation in realistic wargames, controllable and repeatable, with adjustable time-scale, in large-scale, high-fidelity scenarios; able to represent activities of friendly and hostile teams of cyber agents, in the context of combined arms operations.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges and Army Capability Needs.

Army Warfighting Challenge	**Description**
1	Develop and sustain a high degree of situational understanding.
3	Provide security force assistance.
7	Assure uninterrupted access to critical communications and information links..
11	Conduct effective air-ground combined arms reconnaissance.
13	Establish and maintain security across wide areas (wide area security).
16	Set the theater, provide strategic agility to the Joint Force, and maintain freedom of movement and action.
19	Understand, visualize, describe, direct, lead, and assess operations.

Army Capability Need Proponent	**Capability Area Need**
USAICoE	4.a – Intelligence Analysis.
Cyber CoE	3.e – Cyber Situational Awareness (Cyber SA).
Cyber CoE	4.a – Autonomous Active Cyber Defense

TAMING THE FLASH-FLOODS OF NETWORKED BATTLEFIELD INFORMATION [KCI-IS-2]

EXPECTED ARMY IMPACT: The Army battlefield of 2040 will be a complex dynamic heterogeneous network involving multiple interacting actors and agents (humans, robots, networked sensors, networked munitions, and intelligent agents). Their interactions within the battlespace will generate massive volumes of complex data that could, potentially, overwhelm human users. "Operating in complex environments, including dense urban areas, and against enemies that intermingle with civilian populations and avoid long-range detection, Army forces develop situational understanding through action and are prepared to fight for information while applying firepower with discipline and discrimination." In this complex environment, massive volume and complexity due to variety, velocity and veracity of distributed information - the bulk of it machine-generated - will rise, surge, morph, collapse and pulsate through this network, overwhelming and incomprehensible to humans. Our research will provide means of controlling, channeling, directing, reshaping this dynamic, cluttered information field – in accord with the underlying dynamic network of humans and machines - in a manner that meets the needs of human minds relevant to the mission context at the precise time and for their precise needs. Highly automated collective intelligence of the network will comprehend the information field; know the rapidly evolving cognitive needs and situational context of Soldiers. This will enhance the security, accessibility, and utility of information while simultaneously shifting the burden of technological complexity from the user or decision maker to the overall mission command system. The collective intelligence of the network will proactively access, shape, correlate, organize, clarify, distill and deliver to each Soldier the right, precisely meaningful content.

DESCRIPTION: This research effort will focus on developing the models and methods to overcome existing barriers to realization of analytical approaches to better understand the dynamics that characterize complex, multi-genre networks and the data generated by these networks. The goals of this work are to pursue quantitative models of information semantics trust and quality; methodologies to creating coherent information networks from distributed information sources; approaches to partially centralized and semi-autonomous control of large complex networks; and approaches to autonomously recognizing, modeling, and anticipating dynamic changes in network processes.

a. TECHNICAL GOAL(S):

i. Near-term goals (FY16-FY20):

a. Modeling and analysis of dynamics in complex multi-genre networks, including impacts of mobility in disruptive terrain, and of context-sensitive and social-sensitive information caching and routing.
b. Quantitative models of information semantics trust and quality, and approaches to applying these characteristics in networked information delivery.
c. Approaches to creating coherent information networks from distributed yet implicitly linked information sources, including analysis, summarization and linking heterogeneous information such as video and textual information, and network-distributed data mining for trends, patterns and anomalies.

ii. Mid-term goals (FY21-FY26):
   a. Approaches to partially centralized and semi-automated control of large complex networks, including stabilization after a major disruption and degradation, while accounting for information semantics, value and trustworthiness.
   b. Methods to discover, retrieve, extract, fuse relevant information from large, distributed, dynamic storages of heterogeneous, unstructured info – adaptive to situation, mission, communications resources, and cognitive state – of the individual Soldier or collaborative group.

iii. Far-term goals (FY27-FY31):
   a. Theoretically-grounded, robust techniques for autonomous and distributed control of large multi-genre networks, including large scale self-reconstruction under conditions of extensive ongoing disruptions and destruction, mobility, social and organization dynamics.
   b. Approaches to autonomously recognizing, modeling and anticipating dynamic changes in network processes, such as changes in connection and data flow patterns, including social, group and collaboration dynamics, understanding of friendly situation, adversary plans, social and political environment.

b. PERSONNEL REQUIREMENTS:

i. Near-term (FY16-FY20): Computer scientists and computational social scientists with skills in multi-genre network modeling; mathematicians and information theorists with skills in large-scale data mining and semantic information theory. (3-4 FTEs)

ii. Mid-term (FY21-FY26): Computational cognitive and behavioral scientists with skills in modeling individual and group cognitive requirements; computer scientists with skills in multi-media information extraction and fusion. (3-5 FTEs)

iii Far-term (FY27-FY31): Control theory scientists with skills in robust distributed control; artificial intelligence and computational social scientists with skills in agent-based system dynamics and predictive modeling of complex socio-technical systems. (2-4 FTEs)

c. INFRASTRUCTURE NEEDS:

i. Near-term (FY16-FY20):
   a. Laboratory for extensively instrumented study of emulated mobile communication networks with realistic automated portrayal (largely through computer-assisted scripting) of effects of mobility, EW attacks, and organizational-social and cognitive effects.
   b. Framework for analysis, linking, integration and evaluation across large collections of heterogeneous information sources.

ii. Mid-term (FY21-FY26):
   a. Facility for experimentation with human-driven control mechanisms of emulated and partially physical networks, enabling both computer-simulated human agents along with human-in-the-loop and autonomous robots; red-teaming for disruption and degradation of the network.
   b. Interoperability capabilities with the laboratory for retrieval, extraction and fusion of distributed heterogeneous unstructured information.

iii. Far-term (FY27-FY31):

a. Framework for emulation and automated experimentation of autonomous control of integrated information and communication network, in realistic wargames, controllable and repeatable, with adjustable time-scale, in large-scale, high-fidelity scenarios; able to represent extensive adversarial impacts and realistic reactions of red, blue and civilian actors.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges and Army Capability Needs.

Army Warfighting Challenge	Description
1	Develop and sustain a high degree of situational understanding.
3	Provide security force assistance.
7	Assure uninterrupted access to critical communications and information links.
11	Conduct effective air-ground combined arms reconnaissance.
13	Establish and maintain security across wide areas (wide area security).
16	Set the theater, provide strategic agility to the Joint Force, and maintain freedom of movement and action.
19	Understand, visualize, describe, direct, lead, and assess operations.

Army Capability Need Proponent	Capability Area Need
MCCoE	2.d – Units that can function in spite of degraded networks (cyber, EW, space, etc.).
USAICoE	3.b – Collection Modernization.
USAICoE	4.a – Intelligence Analysis

ACTING INTELLIGENTLY IN A DYNAMIC BATTLEFIELD OF INFORMATION, AGENTS, AND HUMANS [KCI-IS-3]

EXPECTED ARMY IMPACT: The Army Operational Environment of 2040 will be a complex dynamic environment of interacting heterogeneous agents, actors, and adversaries (humans, robots, sensors, information systems, and software agents). As we drive towards enabling concepts such as the cyber-physical squad, we expect teams to be composed of humans as well as intelligent soft and physical agents. Their interactions, and implications of these interactions, have many dimensions (military, economic, social, political, legal). Army forces must "Develop and sustain a high degree of situational understanding while operating in complex environments against determined, adaptive enemy organizations" (Army Warfighting Challenge #1). In this complex environment, understanding intent and exploiting the interactions between information systems and intelligent systems will be critical to mission success by providing automated intelligence in the form of intelligent perception, reasoning, planning, collaboration, and decision making. Our research will provide the means with which to obtain, prioritize, filter, fuse, understand, and act upon the information to support the Soldier in accomplishing the tactical mission while reducing cognitive overload. Increasingly sophisticated understanding of Soldiers' context and intent will enable intelligent systems to satisfy information requirements for effective decision-making, as well as enabling agents to act as fully effective team members, increasing resilience. Integrated social computing techniques will enable Soldiers to broaden their situational awareness to be global and incorporate economic, social, political and legal aspects to address the Army's evolving mission, including operating in anti-access and area denied environments, humanitarian assistance and disaster relief, and cyber operations.

DESCRIPTION: This research effort will focus on developing the models, methods, and understanding to overcome existing barriers to realization of robust and reliable teams of intelligent agents and Soldiers in a squad. The goals of this work are to pursue concepts for processing large-scale text and speech of low-resource languages; concepts for determining visual saliency in large scale imagery and video data sets; militarily-relevant pattern recognition and mapping methodologies; techniques to enable real-time decision making; approaches to develop new world-models of recently encountered spaces; algorithms to infer relationships between disparate elements and events; and approaches to autonomously recognize, model, and anticipate dynamic changes in information processes.

a. TECHNICAL GOAL(S):

i. Near-term goals (FY16-FY20):

a. Concepts for processing large-scale text and speech of low-resource languages drawing on machine learning techniques.
b. Data mining and analytics techniques for rapid exploitation of large-scale data sets.
c. Innovative concepts for determining visual saliency in large scale imagery and video information.
d. Robust object detection via varied modalities incorporating contextual and semantic cues.
e. Recognition and classification of simple activity in non-cluttered environments.
f. Multi-sensor information fusion of EO/IR videos, acoustic signals, and passive RF in context of semantic information.

g. Pattern recognition and mapping in relevant complex military environments to understand and incorporate newly encountered physical and abstract spaces into the knowledge representation of existing information sources.
h. Planning and execution of agent behaviors to explore the unknown and incorporate it into a known framework.
i. Intelligently control physical and software information agents by coupling sensing, communications, intelligence, and user constraints across the information science enterprise.
j. Enable real-time decision making by tasking and allocating resources across the environment with an emphasis towards long-duration missions.

ii. Mid-term goals (FY21-FY26):
a. Approaches to extract explicit meaning in social media based on contextual and semantic cues.
b. Video summarization, scene understanding, and perception of complicated dynamic scenes by incorporating multi-modal and situational contextual information.
c. Recognition and classification of activity in cluttered environments.
d. Approaches to recognize and understand the world in terms of cognitive modeling as a framework for representing and computing information across complex interacting agents.
e. Approaches to recognize patterns and develop a world model of newly encountered spaces in military environments.
f. Algorithms and representative paradigms that enable intelligent agents to infer relations between disparate elements and events, thus enabling improved situational awareness and forecasting of future events.
g. Estimates of adversarial actions based on disparate sources of data and predictive models to reason about intent.
h. Novel techniques for distributed and decentralized decision making by heterogeneous physical and software agents.

iii. Far-term goals (FY27-FY31):
a. Theoretically-grounded, robust techniques for autonomous, multi-agent information exploitation by physical and software agents, including intelligent behaviors by physical agents that can actively gather and extract information from the environment.
b. Approaches to autonomously recognize, model, and anticipate dynamic changes in information processes, including intelligent agents that can manipulate information to the detriment of adversarial agents and to the benefit of Soldier mission effectiveness, including social, group and collaboration dynamics, understanding of friendly situation, adversary plans, social and political environment.

b. PERSONNEL REQUIREMENTS:

i. Near-term (FY16-FY20): Optimization and adaptive control theorists, computational linguists with skills in machine learning, semantic information theory; and computer scientists and statisticians with skills in machine learning, large-scale information analytics, and cognitive science. (4-6 FTEs)

ii. Mid-term (FY21-FY26): Computational social scientists and social linguists with skills in modeling social, political and cultural context; computer and information scientists with skills in multi-media information extraction and fusion; and computer engineers with skills in prototyping agent behaviors. (3-5 FTEs)

iii. Far-term (FY27-FY31): Artificial intelligence and multi-agent reasoning scientists with skills in agent-based system dynamics and predictive modeling of complex intelligent systems. Control theory scientists with skills in robust distributed control. (2-4 FTEs)

c. INFRASTRUCTURE NEEDS:

i. Near-term (FY16-FY20):
   a. Laboratory for study of intelligent systems in militarily relevant environments including varied static and dynamic sensors, systems, and agents with ground truth capacity.

ii. Mid-term (FY21-FY26):
   a. Facility for large scale experimentation with multi-agent, heterogeneous teams of human, physical agents, and software agents, using real and simulated scenarios and information representations.

iii. Far-term (FY27-FY31):
   a. Framework for large scale experimentation with extended temporal social and cultural capabilities by physical agents, software agents, and high-fidelity information system simulation.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges and Army Capability Needs.

Army Warfighting Challenge	Description
1	Develop and sustain a high degree of situational understanding.
2	Shape and influence security environments.
3	Provide security force assistance.
11	Conduct effective air-ground combined arms reconnaissance.
13	Establish and maintain security across wide areas (wide area security).
16	Set the theater, provide strategic agility to the Joint Force, and maintain freedom of movement and action.
19	Understand, visualize, describe, direct, lead, and assess operations.

Army Capability Need Proponent	Capability Area Need
USAICoE	4.a – Intelligence Analysis.
Cyber CoE	3.a – Hardware Software (HW/SW) Convergence.
Cyber CoE	3.e – Cyber Situational Awareness (Cyber SA).

SENSING AND INFORMATION FUSION FOR ADVANCED INDICATIONS & WARNINGS [KCI-IS-4]

EXPECTED ARMY IMPACT: The goal of this research is to provide the foundational elements needed for future Army systems to: 1) sense and discover the presence of friendly and enemy assets and activities; 2) predict future activities for situational understanding. If successful, these improved capabilities will significantly extend the time (weeks instead of hours) that US forces, and particularly those at the tactical edge, will have to respond to threats and enable them to engage under the most favorable conditions for our warfighters. The research will focus on enabling a high fidelity common operational picture while simultaneously shifting the burden of technological complexity away from the user. The battlefield of 2040 will likely be saturated with sensor assets and information sources (both friendly and enemy) since they are readily available and interconnected. The challenge will be to fully exploit all those sensors and information sources, regardless of data provenance, reliability, or relevance and synthesize conclusions relevant to individual missions. Sensors must also keep pace with enemy camouflage, concealment and deception (CCD) techniques and be able to operate under all environmental conditions. Future information generation and exploitation will exploit not only traditional sensors but the full range of information sources including sensors (US, allies, neutrals and enemy), text sources, cyber sources, human experts, etc. The ultimate consumer of these technologies would include the Army, the Marine Corps, and USSOCOM for combat operations as well as stability and humanitarian operations. From TRADOC PAM 535-3-1: "Future Army forces require the capability to develop and sustain a high degree of situational understanding while operating in complex environments against determined, adaptive enemy organizations." This research is consistent with the following TRADOC Emerging Technology Focus areas:

- "Maximize Demand Reduction and Improve Reliability" by adding significant automation to the information generation process.
- "Maintain Overmatch" in the areas of protection and intelligence.
- "Enhance Expeditionary Capabilities" by enabling US forces to seize the information initiative and offset enemy advantages.

Key research areas include:

- New sensors and sensor processing for long range, early warnings.
- Technologies to overcome environmental impediments to sensing.
- Sensor and information fusion algorithms and architectures to reduce all available relevant data into information consumable by analysts.
- Sensor and information processing at the tactical edge in a spatially distributed networked environment.

DESCRIPTION: This research effort will focus on shifting the burden of technological complexity away from the user which will rely heavily on making information sources such as sensors more capable and more easily interconnected. Fusion of multiple information sources, not only sensors, is essential and much of the program is focused on foundational work aimedat facilitating that fusion. Fundamental research in physical phenomenology is also critical since it can lead to new sensing opportunities, enable full exploitation of sensor data, and lead to realization of new sensors which can provide more robust input to fusion algorithms.

a. TECHNICAL GOAL(S):

i. Near-term goals (FY16-FY20):

a. Demonstrate interoperability of unattended sensors based on OSUS architecture with one or more coalition partners at operational exercises. Make OSUS a formal coalition standard to be adopted by NATO.

b. Exploit vector (particle velocity) sensors; which are magnitudes smaller in size compared to current acoustic arrays, i.e. 2 cm vs ~2 meters, for acoustic detection and localization and integrate vector sensor processing algorithms with atmospheric propagation models for improved accuracy and threat classification in complex environments.

c. Algorithms for semantic classification of actions and events in full motion video; achieve classification accuracy of 65%.

d. Object classification and scene understanding using multi-platform image data; achieve 20% improvement in classification accuracy compared to single perspective image data.

e. Distributed service-oriented architecture for interoperability of disparate sensor and data assets.
- Controlled natural language techniques for metadata representations and mission programming
- Policy management tools for sensor asset control and sensor data/information
- Extension of lexicon and semantics for common representations across disparate sensing sources

f. Matching mission-driven information needs to discoverable, available sensor and data sources
- Develop common core ontologies and agile capabilities to augment ontologies
- Controlled natural language techniques for mission to information conversion
- Fusion of disparate information sources
- Development of agile and dynamic algorithms for asset discovery.

g. Anomaly Determination for Enhanced Situational Understanding
- Fusion of physics-based sensor data and human-generated data (e.g., open source, social media)
- Content-driven filtering and de-multiplexing for 50% increase in capability of event identification and localization
- Feature extraction and activity-based analysis
- Semantic reasoning for deep learning, event classification and tracking
- Ontology development for enhanced reasoning and anomaly determination

h. Physics-based RF clutter models that predict next generation radar performance in urban, rural, and forest environments; reducing the number of costly field experiment measurements needed to determine radar performance. RF interference mitigation techniques tailored for congested and contested electromagnetic environments that improve sensor performance by 20% as compared to current methods.

ii. Mid-term goals (FY21-FY26):

a. Accurate classification of impulsive acoustic events.

b. Context aware algorithms for multi-sensor fusion.

c. Robust, low level sensor meta-data standards to enable all source fusion.

d. Ontology and semantic processing algorithms for matching sensors and processing to missions.

e. Identification of video alphabet classes and action grammars for robust and accurate behavior determination.
f. 3D scene reconstruction methods from passive, near sideways-looking airborne image sensors to gain situational awareness on access denied terrain.
g. Ontology and semantic processing algorithms for matching sensor assets and processing resources to dynamic missions.
h. Distributed and integrated fusion for situational understanding; distributed composition of sensor, data and information services.
i. Unstructured data fusion and analytics with focus on video and text
j. Adaptive context-aware predictive analytics.
k. All-weather ground-based and airborne wideband penetrating radar for close-in and wide-area standoff detection of concealed targets in urban and rural environments.
l. Combined multi-function foliage penetration synthetic aperture radar (SAR) imaging and moving target indication (MTI).

iii. Far-term goals (FY27-FY31):
a. Surface and sub-surface imaging from mechanical waves.
b. Managing, processing and exploiting the growing volume and complexity (variety, velocity and veracity) data and information at the tactical edge.
c. Highly collaborative sensor to sensor and sensor to human interactions.
d. Extreme low power image & video scene analysis algorithms with the power of reliable prediction or spatiotemporal demarcation of dangerous and threatening objects and events.
e. Fully cognitive and integrated radar and EW functionality.

b. PERSONNEL REQUIREMENTS:

i. Near-term (FY16-FY20):
a. Additional experts in image understanding. (5 – 7 FTEs)
b. Social science researchers with sensor and data analytics skills. (4 – 7 FTEs)
c. Build team to develop robust meta-data for sensors and other data sources. (1 – 2 FTEs)

ii. Mid-term (FY21-FY26):
a. Ontology researchers (Government, contractors, collaborators). (5 – 8 FTEs)
b. All-source intelligence experts (Government, contractors, collaborators). (3 – 5 FTEs)

iii. Far-term (FY27-FY31):
a. Expert ARL Ontology research team. (5 – 8 FTEs)
b. Data analytics team. (8 – 12 FTEs)

c. INFRASTRUCTURE NEEDS:

i. Near-term (FY16-FY20):
a. Collaborative networked sensor test bed facility– including networking for sensors, lab facility for algorithm development and offices to big data storage and analytic capabilities.

ii. Mid-term (FY21-FY26):
a. Tightly integrated, distributed networked sensor research capability in conjunction with universities and other laboratories.

b. Robust collaborative work environment to link all ARL and collaborators.
c. Organic big data storage and analytic capabilities for Army problems.

iii. Far-term (FY27-FY31):

a. Networked sensing test bed integrated with operational Army elements for real time experimentation.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges and Army Capability Needs.

Army Warfighting Challenge	Description
1	Develop and sustain a high degree of situational understanding.
3	Provide security force assistance.
11	Conduct effective air-ground combined arms reconnaissance.
13	Establish and maintain security across wide areas(wide area security).
16	Set the theater, provide strategic agility to the Joint Force, and maintain freedom of movement and action.
19	Understand, visualize, describe, direct, lead, and assess operations.

Army Capability Need Proponent	Capability Area Need
MCoE	3.b – Advanced Sensors Technology and Integration.
USAICoE	3.b – Collection Modernization.
USAICoE	4.a – Intelligence Analysis.
Cyber CoE	3.c – Defensive Cyber Operations-Tactical.
Cyber CoE	3.e – Cyber Situational Awareness (Cyber SA).

NETWORKING AND COMMUNICATIONS IN CONTESTED AND AUSTERE ENVIRONMENTS [CCE-IS-1]

The Information Sciences (IS) Core Campaign Enabler (CCE) on Networking and Communications in Contested and Austere Environments addresses the increasingly complex battlefields, in which the Army must be able to communicate; a highly dynamic, wireless, mobile networking environment populated by hundreds to thousands of networked nodes. Often, these environments are austere in terms of availability of resources for supporting and servicing the networking equipment. They are highly congested by multiple conflicting demands on bandwidth, and severely contested by a capable adversary.

Research in networking and communications will address these multiple and complex challenges by pursuing the following overarching goals:

1) Diverse, effective channels – traditional and non-traditional – will be available for creating heterogeneous networks rapidly, predictably, and in a manner optimized for specific requirements and constraints of mission and environment, adapting intelligently to challenges of terrain, atmospheric conditions, local bandwidth congestion, and ensuring high performance along with energy efficiency and minimized probability of detection and interception by the adversary.
2) The networks will be driven, largely autonomously, but with appropriate degree of human control, by protocols and algorithms for control and processing of signal and information, as well as for self-organization of the network, that ensure persistent high performance of the network, consistent with dynamically changing missions, supportive of rapid reorganization and mobility of friendly forces, and highly robust against strong disruptions.
3) Survivability and defensive properties will be integral to the future network, making it inherently secure and survivable against disruptions by adversarial attacks such as jamming and other forms of interference, in part by minimizing probability of the communications and networks detection, interception, penetration and information exfiltration, as well as by responding to adversary actions by agile maneuver and recovery.

The Information Sciences CCE on Networking and Communications in Contested and Austere Environments will provide underpinning technology for Key Campaign Initiatives where it is critical to ensure communications remain reliable, robust and resilient in the face of disruptive effects such as task reorganization, mobility of friendly forces, and adversarial attacks on friendly networks in future tactical environments.

PERSONNEL REQUIREMENTS:

i. Near-Term (FY16-FY20): Electrical and electronic engineers, computer scientists, mathematicians, computer engineers, physicists and related scientific and engineering disciplines, 2 of which will be specifically oriented toward quantum networking. (3 FTEs)
ii. Mid-Term (FY21-FY26): Electrical and electronic engineers, computer scientists, mathematicians, computer engineers, physicists and related scientific and engineering disciplines. (1 FTE)
iii. Far-Term (FY27-FY31): Electrical and electronic engineers, computer scientists, mathematicians, computer engineers, physicists and related scientific and engineering disciplines. (3 FTEs)

INFRASTRUCTURE NEEDS:
This CCE will be supported by the completion of the Network Science Research Laboratory allowing the simulation of large scale tactical communications, information, and command-and-control (or decision-making) networks; establishing and equipping the Cognitive Networking, Communications and Protocols Laboratory, including optical and hybrid networks facilities, for experimentation in self-adaptive and multi-mode communication channels and networks; and establishing and equipping the Quantum Network Protocols and Algorithms Laboratory, including its Quantum Network Testbed, for experimentation in quantum communications and information processing.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges.

Army Warfighting Challenge	Description
1	Develop and sustain a high degree of situational understanding.
3	Provide security force assistance.
7	Assure uninterrupted access to critical communications and information links.
9	Develop resilient Soldiers, adaptive leaders, and cohesive teams.
12	Conduct entry operations.
13	Establish and maintain security across wide areas (wide area security).
19	Understand, visualize, describe, direct, lead, and assess operations.
20	Design Army formations.

NATURAL LANGUAGE PROCESSING AND MULTI-LINGUAL COMPUTING [CCE-IS-2]

The Information Sciences (IS) Core Campaign Enabler on Natural Language Processing/ Multi-Lingual Computing objective is to provide foundational understanding and applied theoretical methods to enable the rapid and precise automated translation and information extraction from documents regardless of language, dialect, or medium. Research in this area will address the issues such as: (1) Should one translate Arabic dialects to English directly or pivot through Modern Standard Arabic? (2) Is it easier to differentiate between Arabic dialects if they are written in Roman script or Arabic script? (3) Can crowdsourced workers produce accurate dependency parse annotations with minimal training? (4) When building statistical machine translation systems for polysynthetic languages what degree of decomposition of words into morphemes is most effective? (5) To what extent do Information Extraction algorithms developed for English require fundamental changes to be successfully applied to Arabic due to inherent differences in language structure? (6) How do we develop an event ontology that will aid in detecting higher-order event-event relations? (7) How can we overcome the noise and special features of social media data without over-fitting our approaches to a particular media source (e.g., Twitter)?

The strategic approach to these focuses include:

1) Machine translation (MT) of polysynthetic languages (e.g., Inuktitut) into English, Information Extraction (IE) algorithms for Arabic temporal expressions, events, and relations, protest domain ontology based on language of Twitter and adaptation of traditional IE software to language of social media.
2) Temporal and spatial linguistic cues and modified dialog management systems to support natural language communication between human and robots in a collaborative task. Event ontologies and NLP components to incorporate social media artifacts and document summarization for situational awareness.
3) A common multilingual semantic representation of a 3,000 word subset of spoken language frequently used by Soldiers in cross-lingual, cross-cultural encounters while enabling Soldiers and robots to collaborate effectively with spoken natural language communications comprising 80% of their interactions.

The IS CCE on Natural Language Processing and Multilingual Computing supports Key Campaign Initiatives by addressing underpinning science for information gathering and management, human-intelligent system interactions and intelligence and mission support tools.

PERSONNEL REQUIREMENTS:

i. Near-Term (FY16-FY20): Computer and social scientists specializing in natural language processing, social media analytics, and cultural modeling. (2-4 FTEs)
ii. Mid-Term (FY21-FY26): Computer and social scientists specializing in natural language processing, social media analytics, and cultural modeling. (2-4 FTEs)
iii. Far-Term (FY27-31): Computer and social scientists specializing in natural language processing, social media analytics, and cultural modeling. (1-3 FTEs)

INFRASTRUCTURE NEEDS:

Upgrade to Document Exploitation Laboratory to enable document image processing, optical character recognition, and handwriting recognition.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges.

Army Warfighting Challenge	Description
3	Provide security force assistance.
7	Assure uninterrupted access to critical communications and information links.

TEXT AND VIDEO ANALYTICS
[CCE-IS-3]

The Information Sciences (IS) Core Campaign Enabler on Text and Video Analytics addresses how traditional video analytic methods is improved by introducing semantic cues using textual class-based attributes. This research addresses a large gap, namely how can text-based information be combined with video analysis. We propose to develop a new approach that incorporates textual class-based attributes to impact the accuracy of methods when traditional low-level video features do not perform as well as expected, as in action recognition. The convergence of text and video from a range of sources holds promise for allowing warfighters to exploit the incredibly large and growing sources of information streaming in, an understanding of which can be critical to decision making, and therefore safety and mission success.

This exploratory research will make use of an event ontology to structure relationships between attributes, actions, events, and larger sequences of events. Three research foci will be emphasized:

1) Leverage text within video for object recognition.
2) Transition these findings into the activity recognition.
3) Expand into highly complex sequences of actions to be able to infer implicit information which may not be explicit.

The IS CCE on Text and Video Analytics will support Key Campaign Initiatives by creating a path towards developing a deeper semantic representation of unstructured data, including reasoning for improved scene understanding using real-world knowledge that can make it easy for human analysts to quickly recognize important factors and relationships.

PERSONNEL REQUIREMENTS:

i. Near-Term (FY16-FY20): Computer scientist and interdisciplinary researchers in text and video analytics. (4-5 FTEs)
ii. Mid-Term (FY21-FY26): Computer scientist and interdisciplinary researchers in text and video analytics. (2-3 FTEs)
iii. Far-Term (FY27-FY31): Computer scientist and interdisciplinary researchers in text and video analytics. (6-7 FTEs)

INFRASTRUCTURE NEEDS: None

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges.

Army Warfighting Challenge	Description
3	Provide security force assistance.
7	Assure uninterrupted access to critical communications and information links.

ATMOSPHERIC BOUNDARY LAYER EXPLOITATION [CCE-IS-4]

The purpose of the Information Sciences (IS) Core Campaign Enabler on Atmospheric Boundary Layer Exploitation is to advance the ability to accurately sense and forecast weather events that can significantly deviate from expected climatic norms, and to assess and mitigate their effects on Army personnel, systems, and operations, will be paramount. The following goals address this critical requirement:

1) Establish capability to characterize near-surface heat, moisture, and momentum fluxes in rugged, complex terrain. Essential atmospheric data will be quickly, accurately, and automatically collected from a wide variety of ground- and air-based platforms. This data will be incorporated as new parameterizations into fine-scale Numerical Weather Prediction (NWP) models to provide high resolution temporal and spatial predictions.
2) Characterize hazardous aerosols interactions with naturally-occurring atmospheric constituents. Develop research-grade, low SWaP (Size, Weight, and Power) LiDAR/RADAR systems capable of remotely-characterizing atmospheric parameters (i.e. wind, temperature, moisture, etc.) and atmospheric aerosol clouds and composition.
3) Data will be ingested "machine-to-machine" (M2M) into advanced modeling systems hosted on powerful, mobile high performance computer systems down to the smallest of mobile, Soldier-hosted handheld devices. These models will be fully validated with quantified metrics to assess their accuracy.
4) Resulting weather forecasts will then be translated into highly-intuitive decision support guidance tailored to meet a variety of mission requirements, depicting weather impacts on personnel, operations, and systems.

Friendly forces leveraging this technology will have vastly superior knowledge compared to our enemies of the current and future atmospheric state; as well as its potential effects on personnel, systems, and operations. This work will provide strategic and tactical information for the Army of the future by providing Army-scale atmospheric predictions in complex, dynamic terrain and "megacity" environments. This information will guide mission planning and execution in the field and inform intelligent systems, including smart energy systems, autonomous systems (ground and air), smart routing and others, for real-time adjustments and maneuver capability.

The IS CCE on Atmospheric Boundary Layer Exploitation provides information and intelligence tools to be used as a force multiplier in intelligence and mission command decision support tools, artillery accuracy, soldier health and performance, communications, sensing and imaging, and intelligent systems maneuvers. The underpinning science supports Key Campaign Initiatives by providing environmentally context-aware, mission relevant information.

PERSONNEL REQUIREMENTS:

i. Near-Term (FY16-FY20): Atmospheric and Computer scientists with skills in computational methods; intelligent systems; and atmospheric chemistry, physics, dynamics, fine-scale modeling, and effects. (2-3 FTEs)

ii. Mid-Term (FY21-FY26): Atmospheric, Social, and Computer scientists with skills in computer science, to include data mining and extraction; atmospheric dynamics, boundary layer effects, and fine-scale modeling; renewable energy; and application of social and atmospheric data to correlate/predict the effects of weather conditions on human behavior. (3-4 FTEs)

iii. Far-Term (FY27-FY31): Atmospheric scientists with skills in computational methods; atmospheric chemistry, physics, dynamics, intelligent systems, and geoengineering. (2-3 FTEs) Computer scientists with "big data" mining, storage, and application skills. (1-2 FTEs)

INFRASTRUCTURE NEEDS:

i. Near-Term (FY16-FY20):
   a. Complete Meteorological Sensor Array (MSA) for arid region sensing.
   b. Develop laboratory framework for optical, boundary layer aerosol characterization.

ii. Mid-Term (FY21-FY26):
   a. Develop Meteorological Sensor Array (MSA) for humid region sensing.
   b. Establish a simulated operational environment with an end-to-end (characterization and modeling to decision support applications) assessment environment for technologies up to TRL 4.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges.

Army Warfighting Challenge	Description
1	Develop and sustain a high degree of situational understanding.
3	Provide security force assistance.
11	Conduct effective air-ground combined arms reconnaissance.
12	Conduct entry operations.
13	Establish and maintain security across wide areas (wide area security).
15	Conduct combined arms air-ground maneuver.
19	Understand, visualize, describe, direct, lead, and assess operations.

SENSORS, SENSOR PHENOMENOLOGY, AND ALGORITHMS [CCE-IS-5]

This Core Campaign Enabler seeks to develop underpinning technologies that will provide the Army with a high degree of situational understanding against ground and airborne threats while operating in complex environments against adaptive enemy forces. The main objectives are to develop the necessary models, signal processing, prototype sensors and subsystems to support the next generation of route clearance, air defense, and tactical sensing RADAR technologies. Research includes: 1) Low frequency ultra-wideband (UWB) RADAR; 2) Multi-band air defense RADAR; and 3) affordable COTS based RADARs for Degraded Visual Environment (DVE) applications; 4) Sensitive RF (SeRF) for detecting electronic threats.

The low frequency UWB RADAR research will develop laboratory-grade hardware, RADAR signal processing algorithms and physics-based computational models to provide an understanding of the phenomenology of low frequency UWB RADAR applications for the detection of concealed and difficult (low signature) targets.

The multi-band air defense RADAR research will focus on designing, developing, and assessing cognitive and adaptive RADAR architectures and components for Air Defense and Counter-Rockets, Artillery, Mortar (C-RAM) missions.

Our DVE RADAR activity is to use an affordable COTS framework to perform field measurements and analysis in order to define appropriate metrics for the multifunction DVE helicopter mission. The warfighter shall benefit with situational awareness in environments obscured by weather (brownout and whiteout conditions) and other nearby obstacles.

SeRF research will identify and investigate exploitable RF characteristics and signatures that can be used for the detection of various threats including, but not limited to, unmanned air systems, radios, laptops, cellphones, etc. Research and investigate various cognitive RF approaches to develop techniques that enable continued operations (communication, RADAR, EW) in congested and contested RF environments. Research will also address RF convergence between electronic warfare, communications, and RADAR using software defined radio (SDR) technologies.

a. PERSONNEL REQUIREMENTS:

- i. Near-term (FY16-FY20): RF engineers with expertise in design and FPGA processing. (2 – 3 FTEs).
- ii. Mid-term (FY21-FY26): RF engineers with expertise in design and FPGA processing. (2 – 3 FTEs).
- iii. Far-term (FY27-FY31): RF engineers with expertise in design and FPGA processing. (1-2 FTEs).

b. INFRASTRUCTURE NEEDS:

- i. Near-term (FY16-FY20):
  - a. Collaborative networked sensor test bed facility– including networking for sensors, lab facility for algorithm development and offices for guest researchers to come to ARL to perform research experimentations.
  - b. Links to big data storage and analytic capabilities.

ii. Mid-term (FY21-FY26):
  a. Tightly integrated, distributed networked sensor research capability in conjunction with universities and other laboratories.
  b. Robust collaborative work environment to link all ARL and collaborators.
  c. Organic big data storage and analytic capabilities for Army problems.

iii. Far-term (FY27-FY31):
  a. Networked sensing test bed integrated with operational Army elements for real time experimentation.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges.

Army Warfighting Challenge	Description
1	Develop and sustain a high degree of situational understanding.
3	Provide security force assistance.
11	Conduct effective air-ground combined arms reconnaissance.
12	Conduct entry operations.
13	Establish and maintain security across wide areas (wide area security).
15	Conduct combined arms air-ground maneuver.
19	Understand, visualize, describe, direct, lead, and assess operations.

SCIENCES FOR LETHALITY-AND-PROTECTION CAMPAIGN

MISSION: To discover, innovate, and transition S&T capabilities that (1) facilitate the development of discriminant lethality across a broad range of missions; (2) facilitate the development of protection systems that are effective, fieldable, and affordable against a broad array of threats; and (3) enable robust technical tools and methodologies for evaluation and combat decision aids.

VISION: Lethality systems available to commanders of the Army of 2030 are precise, long range, and highly mobile. Protection systems are light weight, low burden, affordable, and resilient towards a broad array of threats. A fundamental understanding of injury mechanisms is exploited for a safer, more effective force. A globally responsive, lethal, and resilient force serves as a significant deterrent to rising conflict. The desired end state is to leverage the range of S&T enablers to provide forces with the right lethality at any place and time without increased warfighter risk and warfighter protection against the continuum of threats without degrading combat power.

The Sciences for Lethality-and-Protection Campaign focuses on gaining a greater understanding and discovery of mechanisms and on generating concepts and emerging technologies that support lethality and protection systems, and the mechanisms of injury affecting the warfighter. Knowledge and concepts gained through these research efforts will lead to technologies that enable a broad array of discriminate lethality systems as well as resilient protection systems and reduced incidents and severity of combat casualties. Campaign competencies and knowledge can support the Army through 2025, and the new technologies are essential for Lethality and Protection Superiority of the Army of 2030 and beyond.

The Sciences for Lethality-and-Protection Campaign has developed 5 Key Campaign Initiatives and 2 Core Campaign Enablers (CCEs) that are integrated to form a robust foundation to understand and overcome complex fundamental challenges associated with Ballistics and Blast; Electronic Warfare; and Battlefield Injury Mechanisms. Through this campaign, combinations of existing and new innovative technologies will be brought together through partnerships to realize disruptive system advances. These advances are driven by overcoming key learning and technical challenges required to further enable the Army of 2030 and beyond.

SCALABLE LETHAL ADAPTABLE WEAPONS CONCEPTS [KCI-SCL/P-1]

EXPECTED ARMY IMPACT: These efforts will provide continued lethal overmatch across the full range of weapons for both direct and indirect fires. Systems will be employed in expanding roles such as light and heavy armor with increased range and fire power as well as new lightweight manned and unmanned combat vehicles/systems and dismounts. New types of gun and missile technologies will be enabled with new launch mechanisms to deliver increased muzzle energies and new lethal mechanisms capable of defeating the toughest targets at reduced energy, reduced caliber, or reduced missile size while working with other research areas to provide necessary standoff range. Futuristic lethal mechanisms will be pursued and validated to provide a range of incapacitation effects against personnel and combat vehicles/systems. Disruptive energetic and propulsive materials will be investigated and tested to provide the Army with weapons with orders of magnitude enhancement in performance.

DESCRIPTION: This program will lead to unprecedented enhancements in lethality for the mounted and dismounted soldier against a spectrum of personnel and manned and unmanned ground and aerial combat systems.

a. TECHNICAL GOAL(S):

i. Near-term goals (FY16-FY20):
   a. Demonstrate medium caliber munition concept that can defeat personnel in the open and behind double reinforced concrete structures.
   b. Demonstrate concept capable of breeching urban structures (double reinforced concrete, triple brick) to produce a man-sized hole.
   c. Demonstrate proof of concept of new launch mechanisms that enable significant increases in muzzle energies from current launch package sizes – Advanced Kinetics.
   d. Demonstrate proof of concept of new mechanisms that take advantage of target vulnerabilities to reduce the required energy to the defeat of targets (extending range).
   e. Synthesis and characterization of novel energetic materials which have performance characteristics that exceed RDX by 30%.
   f. Develop novel methods for differentiating the effects of thermal loading, shock loading, and optical excitation in order to develop a fundamental understanding of initiation mechanisms.

ii. Mid-term goals (FY21-FY26):
   a. Maturation and transition of warhead concepts and mechanisms that provide the lethality of legacy systems using a fraction of the energy currently required.
   b. Proof of concept demonstration of single munition capable of defeating multiple threat target types.
   c. Investigate and characterize viable directed energy mechanisms and concepts to defeat combat vehicles.
   d. Development and implementation of small-scale experiments to predict full-scale performance of novel energetic and propulsive materials.
   e. Develop computer-based simulation environment for the virtual design of weapons and robust models for the prediction of effects.
   f. Maturation of revolutionary disruptive energetic and propulsive materials with performance characteristics significantly greater than current capabilities.

g. Demonstrate proof of concept for cannon-type effects with a man-portable system.
h. Develop a model to correctly predict failure of brittle materials and organic materials.

iii. Far-term goals (FY27-FY31):

a. Proof of concept demonstration of non-lethal reversible incapacitating effects.
b. Proof of concept demonstration of high energy warhead with scalable lethal effects (0-150%).
c. Maturation of adaptable directed energy weapon concepts that provide spectrum of lethal effects against personnel and vehicles.
d. Maturation and transition of disruptive and propulsive materials with performance characteristics with orders of magnitude greater than FY15 capabilities.
e. Proof of concept demonstration of sensing capabilities to detect hostile targets and assess levels of incapacitation at extended ranges, thereby identifying if the detected personnel is a continued threat.

b. PERSONNEL REQUIREMENTS:

i. Near-term (FY16-FY20):

a. Expansion of research teams investigating far-term lethality solutions that include physical and biomedical scientists and mechanical, materials, electrical, and electronics engineers.
b. Retraining of current personnel to acquire new experimental and computational skills.

ii. Mid-term (FY21-FY26):

a. Rebalancing and retraining of current personnel to meet rapidly evolving research challenges.

iii. Far-term (FY27-FY31):

a. Retraining of current personnel to acquire new experimental and computational skills.

c. INFRASTRUCTURE NEEDS:

i. Near-term (FY16-FY20):

a. Modernization of facilities and equipment to support state-of-the-art experimentation necessary to develop disruptive energetic and propulsion materials. Modernization of experimental facilities to include precision measurement tools, diagnostic instrumentation capable of capturing ballistic events in higher spatial and temporal resolution, and software upgrades (integrated and intermediate) to increase speed and accuracy of data acquisition, reduction, and analysis.
b. New facility dedicated to high-pressure synthesis and scale-up of disruptive and propulsive materials.
c. New facility to accommodate leading-edge lethal mechanism research.

ii. Mid-term (FY21-FY26):

a. Modernization of experimental and computational facilities and equipment to support development of advanced lethal weapons. Modernization of experimental facilities to include precision measurement tools, diagnostic instrumentation capable of capturing ballistic events in higher spatial and temporal resolution, and software upgrades (integrated and intermediate) to increase speed and accuracy of data acquisition, reduction, and analysis.

b. Development of facilities which permit seamless integration of multiple experimental and modeling/simulation teams.

iii. Far-term (FY27-FY31):

a. Modernization of experimental facilities to include precision measurement tools, diagnostic instrumentation capable of capturing ballistic events in higher spatial and temporal resolution, and software upgrades (integrated and intermediate) to increase speed and accuracy of data acquisition, reduction, and analysis.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges and Army Capability Needs.

Army Warfighting Challenge	Description
3	Provide security force assistance.
12	Project forces, conduct forcible and early entry, and transition rapidly to offensive operations.
15	Conduct combined arms air-ground maneuver.
17	Coordinate and integrate Army and joint, interorganizational, and multinational fires and conduct targeting across all domains.
18	Deliver fires and preserve freedom of maneuver.

Army Capability Need Proponent	Capability Area Need
MCoE	3.c – Small Unit Lethality.
USAACE	3.b – Multi-purpose weapons capable of lethal and non-lethal options.
MSCoE	3.j – The Capability to Immediately Neutralize or (Temporarily) Incapacitate Targets.
FCoE	3.c – Long Range Precision Fires.

DESIRED LETHAL EFFECTS AT STANDOFF RANGES IN CONSTRAINED ENVIRONMENTS [KCI-SCL/P-2]

EXPECTED ARMY IMPACT: The expected impact that this research will have on the operational Army's capabilities in the 2040-timeframe is significant enhancements in assured delivery of the lethal payload. Assured delivery implies that munitions will be brought to bear on the battlefield more precisely (lower collateral damage, reduced logistics burden), with more mission space (extended range, moving targets, defilade targets, smaller caliber weapons for lighter platforms), in a more complex environment (GPS denied, countermeasures) at low cost.

DESCRIPTION: Assured delivery of the lethal payload is underpinned by ballistic launch and flight sciences. Guided delivery is composed of two enabling technologies: maneuverability and navigation. Navigation provides information to understand the dynamic states relating the target and the munition and maneuverability is necessary to deliver the payload to the target. Goals are defined with these sciences and enabling technologies in mind.

a. TECHNICAL GOAL(S):

i. Near-term goals (FY16-FY20):

a. Demonstrate proof of concept of high maneuverability airframe flight required to intercept moving or defilade targets.

b. Understand flight behaviors critical to formulating control mechanism technologies and guidance and control algorithms that accommodate large uncertainties characteristic of low cost actuators and sensors.

c. Achieve image-based navigation for simple ground targets to advance the state-of-the-art in navigation in access denied environments and interception of moving targets.

d. Demonstrate proof of concept for a feasible system approach that can address the multi-shot man-portable defilade kill capability that can 1) be safely fired (recoil and noise constraints); 2) reach extended ranges (2km); 3) implement highly effective navigation and guidance approaches; and 4) implement effective lethal package.

e. Proof of concept demonstration of technologies that provide increased muzzle energies while maintaining or lowering recoil compared to current weapon systems.

ii. Mid-term goals (FY21-FY26):

a. Exploit nonlinear physics to devise flight control mechanisms and algorithms to overcome scientific barriers to maneuverability of atmospheric flight vehicles spanning Mach regimes from subsonic to low hypersonic (omnisonic speeds).

b. Enable initial swarming behaviors of modular munitions by extending physics-based algorithms, embedded computing, and low cost measurements in navigation research. The focus will be on efficient algorithms for multispectral measurements in countered environments.

c. Proofs of concept demonstration of advanced man-portable defilade kill capability.

d. Proof of concept demonstration of advanced kinetic weapons via muzzle pressure management for reduction of key ballistic launch and flight system errors.

iii. Far-term goals (FY27-FY31):

   a. Development of methodologies to elicit large forces and moments at high bandwidth (0~1000Hz) based on arbitrarily arranged sensing arrays on the skin of the flight body over omnisonic flight regimes.
   b. Devise means of navigating to complex, mixed targets based on advanced algorithms using available techniques such as flash LIDAR, redundant low cost imagers, or high-speed, low-latency communications.
   c. Maturation of compact and robust form factor technologies to facilitate the widest proliferation of technologies in the battlespace (small caliber weapons for light platforms).
   d. Proof of concept demonstration of advanced swarming behaviors for guided munitions based on understanding of omnisonic aeromechanics and control.

b. PERSONNEL REQUIREMENTS:

i. Near-term (FY16-FY20): Experienced researchers in aeromechanics, munitronics (diagnostic measurements and telemetry for munitions), propulsion, and structural dynamics (3 computer scientists, 3 electrical engineers, 3 physicists, 2 mathematicians, 2 aerospace engineers, and 2 mechanical engineers, at least half of which have PhDs). (13 FTEs)

ii. Mid-term (FY21-FY26): Multidisciplinary researchers with backgrounds in electrical engineering (5), computer science (5), and aerospace engineering (5). (15 FTEs)

iii. Far-term (FY27-FY31): Acquire, re-train, and cross-train personnel in physical sciences (5), electrical engineering (5), computer science (5), aerospace engineering (5), and mechanical engineering (5) with more than half possessing advanced degrees. (25 FTEs)

c. INFRASTRUCTURE NEEDS:

i. Near-term (FY16-FY20):

   a. Access to theoretical infrastructure, in the form of models and numerical tools, to better understand the nonlinear dynamics and stability and state estimation of controlled ballistic systems should be formulated.
   b. Control design tool infrastructure would also facilitate GNC algorithm development.
   c. Experimental facilities to more readily measure launch and flight dynamics, and implement control theories in embedded systems for validation and demonstration are necessary.
   d. Access to high fidelity computational tools.

ii. Mid-term (FY21-FY26):

   a. Modernized experimental range facilities with low cost, highly accuracy instrumentation (high speed digital photography) and data analysis techniques to enable launch and flight research.
   b. New experimental facilities to understand controlled flight behaviors, such as omnisonic wind tunnels with motion capture, flow visualization, and particle image velocimetry.
   c. Laboratory facilities for novel control mechanisms studies and feedback measurements; and applied research of guidance, navigation, and control (GNC) techniques, and launch dynamics.

iii. Far-term (FY27-FY31):
  a. Upgrades to theoretical, experimental and computational infrastructure identified in the near-term and mid-term.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges and Army Capability Needs.

Army Warfighting Challenge	Description
3	Provide security force assistance.
13	Establish and maintain security across wide areas (wide area security).
15	Conduct combined arms air-ground maneuver.
17	Coordinate and integrate Army and joint, interorganizational, and multinational fires and conduct targeting across all domains.
18	Deliver fires and preserve freedom of maneuver.

Army Capability Need Proponent	Capability Area Need
FCoE	3.c – Long Range Precision Fires.

HUMANS IN EXTREME BALLISTIC ENVIRONMENTS [KCI-SCL/P-3]

EXPECTED ARMY IMPACT: Primary injury mechanisms can be categorized into two types of insults – blast (injuries caused by shock waves including accelerative loading and TBI; and ballistic (impact of bullets, fragments and spall). Research efforts in each of these mechanistic areas will yield scientific understanding and lead to new protection concepts. Approaches will be realized to mitigate injuries from blast and ballistic insults and may include improved body armor, helmets and other forms of PPE. The long-term approach is to de-convolve the current ensemble of PPE and start from the basic human form taking into consideration the bio-diversity of the future Army. Concepts for mounted Soldiers are similar, but extend to include the coupled vehicle structure/occupant response and energy-absorbing techniques employed along the entire load path.

DESCRIPTION: The goal of this research is to provide a mechanism based understanding of the human response to blast and ballistic insults that will lead to advances in protection sciences and, ultimately, Army capabilities. This research will enable technologies that substantially enhance Soldier Personal Protective Equipment (PPE) capabilities while increasing mobility for dismounts, survivability, and overall combat effectiveness.

a. TECHNICAL GOAL(S):

i. Near-term goals (FY16-FY20):
  a. Failure models for hard and soft tissue suitable for massively parallel computations that enable rapid execution and exploration of parameter space.
  b. First generation physics-based human model for HPC simulations for mounted and dismounted threat environments.
  c. Understanding of the loading mechanisms which lead to injuries to the lower extremities and spine during accelerative loading events.
  d. Develop high fidelity models, understanding, and data correlation based on dynamic injury assessment experiments.

ii. Mid-term goals (FY21-FY26):
  a. Develop second generation physics-based human model capable of handling arbitrary threat and loading environments.
  b. Identify new proactive protection mechanisms that can be exploited for increased protection from underbody blast events.

iii. Far-term goals (FY27-FY31):
  a. Understanding of individual soldier unique response to specific blast and ballistic events and personalized model of each combat soldier.
  b. Knowledge and understanding sufficient to individualize protection for the Soldier (size, shape, biometrics) in response to given threats.
  c. Nano-bio convergence capable of enabling breakthroughs in biologic response to threats.

b. PERSONNEL REQUIREMENTS:

i. Near-term (FY16-FY20): Grow current staff with expertise in biomechanics and biomedical engineering to bridge the gap between traditional mechanical engineering design and injury mechanics. Plan to hire 3-4 new scientists and engineers / year in this area. Personnel work closely with experts in the ballistics and medical fields to study human response to ballistic loading and research appropriate protection mechanisms. (5-7 FTEs)

ii. Mid-term (FY21-FY26): Technical staff with engineers and scientists with advanced degrees in multiple disciplines. Staff will collaborate daily with medical and academic research institutions; and expand focus to include bio-materials. (5-7 FTEs)

iii. Far-term (FY27-FY31): Technical staff works seamlessly across traditional scientific, medical, and engineering disciplines to research human response and protection technologies. (5-7 FTEs)

c. INFRASTRUCTURE NEEDS:

i. Near-term (FY16-FY20):
   a. Development of multi-scale experimental facilities to characterize human and PPE damage mechanisms from blast and ballistic insults.
   b. Leverage existing facilities across medical and DoE communities.

ii. Mid-term (FY21-FY26):
   a. Enhanced diagnostic mechanisms for biological materials to detect tissue damage coupled with experimental ballistic facilities to provide enhanced visualization and insight into biological response. Facilities will include wide angle x-ray scattering, expanded micro computer-tomography, magnetic resonance imaging, and utilization of advanced photon source imaging.
   b. Access to expanded computational infrastructure to enable seamless multi-scale analysis of human response.
   c. Realize a Joint Center of Excellence for Human Response Research for Military and Civilian Traumatic Events.

iii. Far-term (FY27-FY31):
   a. Experimental facilities to detect micro-structural damage mechanisms in both organic and inorganic materials during blast and ballistic events. Experimental approaches such as advanced photon source imaging will be routinely used as part of ballistic rate experiments.
   b. Human performance experimental facilities to determine real-time response of Soldiers to virtual conditions. Computational capabilities will be closely tied to experimental data collection for real-time identification of experimental anomalies. Co-lead, with the medical community, the Joint Center of Excellence for Human Response Research for Military and Civilian Traumatic Events.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges and Army Capability Needs.

Army Warfighting Challenge	Description
12	Project forces, conduct forcible and early entry, and transition rapidly to offensive operations.

Army Capability Need Proponent	Capability Area Need
AMEDD	3.a – Brain Health and Fitness Optimization.

ADAPTIVE AND COOPERATIVE PROTECTION [KCI-SCL/P-4]

EXPECTED ARMY IMPACT: The operational threat environment that our troops face continues to grow in both capability and complexity. From near-peer adversaries to terrorist groups, the landscape is constantly evolving. The ability of our troops to exercise freedom of maneuver under these contested conditions will dictate mission success or failure. Developing a suite of technologies that provide the highest level of protection, in austere conditions, is the goal of this research. These efforts will result in transformational protection capabilities for Army platforms (ground, air, Soldier, and maritime) focused on increased levels of protection and the ability to rapidly adapt to new and unforeseen changes in threat environment at a reduced weight burden.

DESCRIPTION: This research effort combines technologies from across numerous disciplines to include technical intelligence, environmental sensing, dynamic threat characteristics, high speed signal processing, signature modification, and counter-measures in addition to conventional armor. All of these elements and combinations are linked through an intelligent agent to provide a real-time response decision that can proactively adapt. This methodology is capable of learning and applying new approaches as it evolves. An optimized combination of hard and soft protection techniques will provide a robust and redundant solution that will reduce inherent susceptibilities of current active protection systems to a variety of counter measures. It will also allow new techniques and responses to be deployed in real-time as dynamic software upgrades. This approach is seen as the only feasible means to maintain pace as the rate of threat evolution and proliferation is accelerated by globally available technologies such as digital design and additive manufacturing. The resulting advantages of this approach include; reduced weight when compared to current methodologies, increased reliability, ability to counter new threats in real-time and the ability to learn, adapt and improve.

a. TECHNICAL GOAL(S):

i. Near-term goals (FY16-FY20):

a. Shift from traditional protection methods based upon specific threats to holistic approach by fusing individual capabilities of armor, underbody blast protection, active protection systems (APS), signature control, advanced soft kill methods and conceal, camouflage and deception techniques into one solution to maximize survivability and minimize weight.

b. Develop real-time threat sensing, identification and localization with extreme reliability for all threat classes.

c. Real-time sensor fusion of multiple sensor modalities such as imaging, RADAR, LIDAR, relying upon high speed digital signal processing, adaptive signature techniques, and pulse power defeat mechanisms.

d. Develop intelligent agent algorithms that learn from each encounter, share information across the network with other platforms, and continuously improves effectiveness of response.

e. Develop understanding of the fracture and failure of current ballistic protection materials, such as lightweight Magnesium alloys and ultra-hard ceramics, using a combination of modeling and experimental techniques.

f. Incorporate new electromagnetic physics in existing modeling tools to allow proper evaluation and validation of EM armor concepts.

ii. Mid-term goals (FY21-FY26):

a. Generate a suite of protection technologies that combine aspects of active protection, camouflage, concealment, and deception with traditional armor.

b. Conceive novel threat defeat mechanisms that take advantage of postulated materials using Materials by Design approach.

c. Develop and apply advanced physics-based M&S tools to evaluate new defeat mechanisms including electromagnetic armor and other energy coupled to matter protection concepts.

d. Determine optimum set of material properties, given a specific defeat mechanism. These will include novel equilibrium and metastable materials with high combined strength, fracture toughness, and ductility to exceed existing material property limitations.

iii. Far-term goals (FY27-FY31):

a. Develop an intelligent framework containing a collection of protection technologies, connected via an intelligent agent, which determines the most effective defeat mechanism, or combination of mechanisms, to employ against a broad array of threats.

b. Develop capability to autonomously engage protection options, monitor results in real-time, adjust response on-the-fly to improve outcome and communicate results to other platforms for awareness and adaptation.

c. Develop algorithm to predict future activities to maximize situational understanding; fully exploit sensor capabilities to determine the most likely outcome; and minimize functional damage and crew injuries prior to impact and respond accordingly to minimize mission degradation.

d. Incorporate various postulated and synthesized materials into ballistic application concepts.

b. PERSONNEL REQUIREMENTS:

i. Near-term (FY16-FY20): Expertise in solid dynamics, EO/IR & EM signatures and sensors, impact physics, high speed digital signal processing, control theory, explosive effects, real-time embedded implementation, decision theory (12 FTEs)

ii. Mid-term (FY21-FY26): Personnel with knowledge across disciplines in solid dynamics, electro-magnetics, pulse power, scalable algorithms, and control theory (6-8 FTEs)

iii. Far-term (FY27-FY31): Personnel that understand electro-magnetic phenomena and approaches towards fully exploiting emerging computational assets as the lines between hardware, firmware and software blur and the ability to convert between various forms of energy reach high levels of efficiency (10 FTEs)

c. INFRASTRUCTURE NEEDS:

i. Near-term (FY16-FY20):

a. HPC-based simulation environment able to capture multi-physics problems (EO/IR interactions, flight dynamics, impact physics) at appropriate level of fidelity.

b. Embedded real-time hardware/firmware.

c. Expansion of shock physics capabilities at Dynamic Compression Sector of Advanced Photon Source.

d. Classified research facility with secure communications assets to facilitate interactions with the intelligence community.

e. High Energy Laser and Ultra-short Pulse Laser metrology laboratory to study directed energy effects on Army protection technology concepts.
f. RF metrology facility to expand capability to acquire RF signatures.

ii. Mid-term (FY21-FY26):
a. Signature control facility to include formulation, implementation, and measurement capabilities.
b. Advanced shock physics facility coupled with experimental diagnostics.
c. Experimental ballistic diagnostic facility to allow probing of ballistic events on short time scales and unprecedented length scales.
d. Directed Energy effects facility containing representative DE threats.

iii. Far-term (FY27-FY31):
a. Access to classified quantum computing assets for multi-physics simulations.
b. Pulse power facility for electro-magnetic research, experimental validation, and simulation effects.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges and Army Capability Needs.

Army Warfighting Challenge	Description
16	Set the theater, provide strategic agility to the Joint Force, and maintain freedom of movement and action.

Army Capability Need Proponent	Capability Area Need
MCoE	3.a – Combat Vehicle Development.
MCoE	3.g – The Capability to Protect from the Effects of Explosion Hazards.

DISRUPTIVE ENERGETIC MATERIALS
[KCI-SCL/P-5]

EXPECTED ARMY IMPACT: Improved models, concepts, and new energetic materials for propulsion are expected to provide enhanced range, speed of engagement, and maneuverability while maintaining weapons safety and surety. Additionally, game-changing energetic concepts with an order of magnitude more potential than conventional energetics are being pursued and are expected to enable new approaches to lethality, particularly when partnered with emerging accuracy and precision advances.

DESCRIPTION: These efforts will focus on the exploration and maturation of novel energetic and propulsive materials which are expected to provide revolutionary performance capabilities that are unachievable today. Research in this area seeks to understand very high energy density storage and release on desired timescales, methods to balance various parameters in energetic formulations, and prediction of formulation ingredient compatibility.

a. TECHNICAL GOAL(S):

i. Near-term goals (FY16-FY20):

a. Development of sustainable energetic materials with performance characteristics which exceed those of RDX by 30%.
b. Formulation of novel energetic ingredients for transition to weapons applications.
c. Optimization of multi-phase explosive and initiation concepts to maximize energy transfer to target.
d. Develop novel methods for differentiating the effects of thermal loading, shock loading, and optical excitation in order to develop a fundamental understanding of initiation mechanisms.
e. Development of techniques to control muzzle overpressure and quantification of factors controlling dispersion in small-caliber weapons.
f. Extend quantum mechanical-based modeling tool set for prediction of key performance key performance and vulnerability properties.
g. Develop performance libraries for traditional explosives characterized using conventional and small scale testing.

ii. Mid-term goals (FY21-FY26):

a. Identify, characterize, and formulate extended solid energetic materials, such as polymeric CO, which are expected to have energy densities an order of magnitude higher than RDX.
b. Explore Structural Bond Energy Release Materials for use as novel energetic components.
c. Develop propellants with 10 -15 % improvement in Specific Impulse levels.
d. Develop computational models which accurately capture salient features of reacting, heterogeneous systems and physical phenomena.
e. Develop methodologies to control muzzle overpressure and quantify factors controlling dispersion in medium and large-caliber weapons.
f. Develop predictive models for both traditional and novel explosives over a broad range of loading conditions.
g. Develop new techniques to facilitate optimization of non-ideal explosive performance concomitant with full explosive characterization from a single test.

iii. Far-term goals (FY27-FY31):

a. Identify and characterize extended solid energetic, organometallic, and metal cluster materials with projected energy densities orders of magnitude (> 10x) higher than RDX.
b. Enable a fully coupled multiscale modeling approach with accurate predictive capability of macroscale response which has been verified through direct advanced experimentation.
c. Determination of compatibility of novel energetics based on structure, functionality, and M&S results to identify promising energetic materials and formulations.
d. Develop high-speed, full dynamic range of explosive imaging for novel energetics including measurement of cessation and onset of detonation.

b. PERSONNEL REQUIREMENTS:

i. Near-term (FY16-FY20): Grow current staff with expertise in physical chemistry, physics, mechanical engineering, and modeling & simulation. Foster collaborative research with outside groups to promote cross-training of existing and next generation researchers. (5-6 FTEs)

ii. Mid-term (FY21-FY26): Grow current staff with expertise in chemistry, physics, mechanical engineering, and modeling & simulation. (5-6 FTEs)

iii. Far-term (FY27-FY31): Technical staff works seamlessly across traditional scientific and engineering disciplines to execute rapidly evolving technical goals of mission. (5-6 FTEs)

c. INFRASTRUCTURE NEEDS:

i. Near-term (FY16-FY20):

a. Modernization of facilities and equipment to support state-of-the-art experimentation necessary to develop disruptive energetic and propulsion materials.
b. New facility dedicated to high-pressure synthesis and scale-up of disruptive and propulsive materials.
c. Access to High-Performance Computing to support the development of ‘Materials by Design’ capabilities.
d. Leveraging of Department of Energy (DOE) large-scale facility investments (Oak Ridge, Advanced Photon Source, National Ignition Facility) for advanced characterization.

ii. Mid-term (FY21-FY26):

a. Modernization of existing experimental, computational facilities, and equipment to support disruptive energetic and propulsion materials development.
b. Development of facilities which permit seamless integration of multiple experimental and modeling/simulation teams.
c. Expanded infrastructure to enable small-scale characterization of novel energetics and propellants.
d. New diagnostic facilities for advanced characterization of novel materials such as in-situ imaging with 1nm resolution and time –resolved methods.
e. Creation of a Center of Excellence for Disruptive Energetics and Propulsive Technology.

iii. Far-term (FY27-FY31):

a. Continue to modernize facilities and equipment to support state-of-the-art experimentation necessary for the development of disruptive energetic materials.

b. Access to peta- and exa-scale computing environments for multi-scale simulations to enable ‘Materials by Design’ and to allow assessment of effectiveness of notional designs of lethal armaments.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges and Army Capability Needs.

Army Warfighting Challenge	Description
12	Project forces, conduct forcible and early entry, and transition rapidly to offensive operations.
15	Conduct combined arms air-ground maneuver.
18	Deliver fires and preserve freedom of maneuver.

Army Capability Need Proponent	Capability Area Need
FCoE	3.e – Next Generation Cannon.
MCoE	4.b – Next Generation Shooters.

VEHICLE PROTECTION FROM KINETIC THREATS [CCE-SCL/P-1]

The Sciences for Lethality and Protection (ScL/P) Core Campaign Enabler (CCE) in Vehicle Protection is a sustained effort to advance ballistic protection utilizing advanced materials, mechanisms, and manufacturing science to dramatically reduce overall vehicle weight while maintaining or improving protection against kinetic energy (KE) penetrators, chemical energy weapons and underbody blast threats. These CCE elements are closely coupled with the Materials Research Campaign, emphasizing the cross-cutting nature, specifically in the areas of materials and manufacturing.

For Chemical Energy Protection, this CCE will develop new ballistic mechanisms; further develop existing ballistic mechanisms; explore new materials, hybrid adaptive techniques, and manufacturing technology to significantly improve vehicle protection against anticipated future threats; or dramatically reduce overall vehicle weight while maintaining protection against existing threats for a diverse range of CE penetrator warheads.

In the area of Underbody Blast Protection, this CCE will build and develop understanding of the driving mechanisms leading to, and mitigating, injury for the warfighter and vehicle platform; establish critical diagnostic capabilities to probe underbody (UB) threat event phenomena; advance modeling capability for research, design, and analysis; and conceive innovative technologies for the mitigation of these threats.

PERSONNEL REQUIREMENTS:

i. Near-term goals (FY16-FY20):
Mechanical Engineers and physicists with combination of terminal effects modeling and experimentation for advanced armors. Specializes in ultrafast laser system alignment and design of experiments, application of advanced imaging techniques that utilize short, mid, and/or long-wave infra-red cameras, and developing data analysis routines to extract phenomena of interest. (3-5 FTEs).

ii. Mid-term goals (FY20-25):
Materials, physicists, mechanical, electrical, multi-disciplinary scientists and engineers. (6-8 FTEs).

iii. Far Term (FY26-30):
Technical staff with engineers and scientists with advanced degrees in multiple disciplines. (5-10 FTEs).

INFRASTRUCTURE NEEDS: NONE

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges.

Army Warfighting Challenge	Description
5	Prevent, reduce, eliminate, and mitigate the use and effects of weapons of mass destruction.
12	Conduct entry operations.
13	Establish and maintain security across wide areas (wide area security).
15	Conduct combined arms air-ground maneuver.
16	Set the theater, provide strategic agility to the Joint Force, and maintain freedom of movement and action.

TERMINAL BALLISTICS AND BLAST EFFECTS [CCE-SCL/P-2]

The Sciences for Lethality and Protection (ScL/P) Core Campaign Enabler (CCE) in Terminal Ballistics and Blast Effects is a sustained effort to develop the science base for new understanding of the mechanics and physics of weapon-target interactions. These technical areas include but are not limited to: solid dynamics; fracture and failure of materials; interaction of solids with blast, electrical, and magnetic stimuli; and directed energy.

To gain a greater understanding of the fundamental science which underpin weapon-target interaction, this CCE will develop coupled mesoscale poly-crystal model with inter- and intra-granular mechanisms. Develop and implement algorithms to support anisotropic materials by extending the existing scalar conductivity and permeability models to full tensor models. Complete assessment of material response of spheres and/or hemispheres subjected to dynamic tension, shear instabilities, and electro-magnetic fields. Develop algorithms and implement a baseline model to support hysteretic magnetic materials.

Further, this CCE will quantify relationships between structure, properties, and ballistic performance of a specific armor ceramic using a complete multi-scale modeling framework. Develop sub-cell resolution model to support finite thickness laminates. Complete analysis of the electrical characteristics of arcing and electrified dynamic fracture experiments.

PERSONNEL REQUIREMENTS:

i. Near-term goals (FY16-FY20):
   a. Mechanical Engineers and physicists with combination of terminal effects modeling and experimentation for advanced armors. Specializes in ultrafast mechanics and mechanisms, hydrodynamic events, microsecond and faster diagnostics such as x-rays and lasers, design of experiments, SOA advancement and utilization of short, mid, and/or long-wave infra-red imaging devices and developing data analysis methods to isolate ballistic phenomena. (2-3 FTEs).

ii. Mid-term goals (FY20-25):
   a. Physicists, materials, mechanical, electrical, multi-disciplinary scientists and engineers for high rate impact physics and armor design. (5-10 FTEs).

iii. Far Term (FY26-30):
   a. Technical staff consisting of engineers and scientists with advanced degrees in multiple disciplines, enabled by a high quality technician staff. (5-10 FTEs).

INFRASTRUCTURE NEEDS:

i. Near-to-Far term goals (FY15-30):
   a. Scientific data repository to allow large data storage capacity and data stewardship to enable data mining, coupled with electronic lab notebooks to ease data entry burden on scientific staff.
   b. Upgrade ballistic experimental facilities to include a state-of-the-art and DDESB approved firing bunker with novel videography instrumentation suites to measure precise impact conditions.
   c. Continue to expand capabilities at Dynamic Compression Sector, Advanced Photon Source, Argonne National Laboratory. Increase personnel presence at DCS to include permanent and rotating government personnel, visiting professors, and post-doctoral fellows.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges.

Army Warfighting Challenge	Description
12	Conduct entry operations.
17	Coordinate and integrate Army and joint, interorganizational, and multinational fires and conduct targeting across all domains.
18	Deliver fires and preserve freedom of maneuver.

HUMAN SCIENCES CAMPAIGN

MISSION: To discover, innovate, and transition S&T capabilities to (1) understand and improve individual and small unit performance across the full range of military operations; (2) empower leaders with enhanced cognitive capabilities to make sound decisions quickly; and (3) enable expeditionary forces to use knowledge of societal and cultural issues and social cognitive networks to shape the operational environment.

VISION: The Army of 2030 maximizes the effectiveness of Soldiers physically, perceptually, and cognitively. Small units are capable of operating effectively and efficiently in social-cultural contexts around the globe. The desired end state is to leverage the full range of S&T enablers to poise forces to succeed in distributed operations and increasingly complex environments.

The Human Sciences Campaign focuses on identifying, creating, and transitioning scientific discoveries and technological innovations underlying Human Behavior; Human Capabilities Enhancement; and Human-System Integration that are critical to the U.S. Army's future technological superiority. This campaign concentrates on high-risk and high-payoff transformational basic research; critically-focused, promising applied research; and selective advanced technology development that are expected to have revolutionary impacts on the Army's warfighting capabilities. In addition to significantly improving the Army's existing warfighting capabilities, it creates disruptive and game-changing Soldier-centric technologies for the Army, while also preventing technological surprises from potential adversaries.

The Human Sciences Campaign has developed 3 Key Campaign Initiatives and 4 Core Campaign Enablers (CCEs) that are integrated to form a robust foundation to understand and overcome complex fundamental challenges. The campaign builds on fundamental pillars of science and engineering to conduct research and development in human behavior understanding; human performance augmentation; and manned-and-unmanned teaming. Discoveries and innovations made in this area will exert a significant impact on the Army of the future.

ROBUST HUMAN AND MACHINE HYBRIDIZATION [KCI-HS-1]

EXPECTED ARMY IMPACT: The differential advantage of the Army over its potential adversaries is derived, in large part, from the integration of skilled Soldiers with advanced technologies within a team context. Training burdens and the rapid advance of technology indicates a critical need to "fit machines to Soldiers rather than the other way around" (U.S. Army Operating Concept, TRADOC, 525-3-1, 2014). Fundamental understanding of human capabilities and human-system interactions is needed to enable stronger reciprocity and coupling between Soldiers and the future Army technologies into Army units and training environments. Advances in the human sciences for cognitive, social, and physical performance and development are envisioned in new methods, models, approaches, and capabilities for strengthening the connection between Soldiers and technology in the systems design cycle. Resultant innovations in Soldier-system interfaces and interactions are expected to revolutionize communications and control between Soldiers and technology, putting the capabilities of advanced and intelligent technologies at the fingertips of individual Soldiers, and, enabling faster, more accurate, and more decisive actions needed to meet the demands of the future battlespace. Reduced technological complexity for users and decreased training demands will enhance Soldier readiness and enable Army forces to keep pace with rapid development and insertion of advanced technology capabilities, while staying ahead of our potential adversaries' technology transfer and system adaptation.

DESCRIPTION: Strengthening the Reciprocal Coupling of Man and Machines integrates empirical and theoretical efforts to understand dynamic, complex human-system interactions and apply that knowledge towards the conceptualization of unique and novel human-system integration technologies. The research has three thrusts 1) examining closed-loop human adaptation to uncertainty with specific goals to develop descriptive, mechanistic, and predictive models of human short- and long-term adaptation within system contexts; 2) investigating robust brain-computer interaction technologies with an initial goal to uncover methods and analytic capabilities that enable long-term, sustained performance while minimizing calibration and training requirements; and 3) conceiving of novel human-system interface technologies that increase the flow of information and meaning from intelligent agents system to Soldiers in complex socio-technical environments with an initial focus on novel multimodal interface technologies that enable greater understanding with less effort and training The critical challenge for human-system integration in future technologies will be the design of solutions that adapt their capabilities to maximize the human potential of the future Soldier. This effort seeks to identify general systems principles that operate across levels of analysis, providing a conceptual and modeling framework that captures human adaptation in ways that current models cannot. New methodological and analytical approaches will provide the core for technologies that revolutionize the direct interaction between Soldier and technology; increasing the bandwidth and effectiveness of information transfer, and shared understanding.

a. TECHNICAL GOAL(S):

i. Near-term Goals (FY16-FY20):

a. Characterizations of human interactions with multimodal displays and unisensory and multisensory perceptual similarity based on multi-dimensional (perceptual, semantic, physical) characterizations of stimulus features.

b. Statistical analysis techniques that account for the temporal dependencies inherent in human perceptual and physical data.

c. Closed-loop models of adaptive mechanisms in multisensory integration for functional and skilled human movement and brain-computer interactions.
d. Cybernetic models of human-system interaction in sociotechnical and sociocultural contexts.

ii. Mid-term Goals (FY20-25):
a. General theoretical framework of multisensory perceptual similarity based on multi-dimensional characterizations of stimulus features, to predict complex, and multi-modal stimulus interactions.
b. Methodologies for the assessment of multisensory function underlying adaptive performance in real-world task environments.
c. Approaches and algorithms for the adaptive use of multisensory information.
d. A brain-based closed-loop framework for augmenting the integration of different stimulus features from multiple sensory sources.
e. Proof-of-concept system demonstration of brain-based, closed-loop human-system interactions.

iii. Far-term Goals (FY26-30):
a. Design principles and guidelines for adaptive, multisensory, and augmented perceptual human-system interfaces.
b. Predictive models of human perceptual capabilities enabling multipurpose, multisensory, and adaptive decoy and deception systems.
c. General theoretical framework for adaptive integration of multisensory information to enhance Soldier perceptual capabilities.
d. Technologies for enhancing an individual's inherent capability to process multisensory information in perception, decision-making, and skilled movement.
e. Design principles and guidelines for brain-based, closed-loop, and social cybernetic approaches to human-system interaction design.

b. PERSONNEL REQUIREMENTS

i. Near-term Goals (FY16-FY20): Expertise required in applied mathematics statistics, complex and dynamical systems, computational neuroscience, computational social science, control theory, or related disciplines for computational modeling and algorithm development. Expertise needed in cognitive and social sciences. Engineering and technical support needed for hardware/software integration in experimental testbed platforms. (6 – 8 FTEs)

ii. Mid-term Goals (FY20-25): Expertise required in computer science and engineering for implementation of algorithms in proof-of-concept systems. Additional expertise in statistical modeling, signal processing, machine learning, and related domains to extend computational models and algorithms to real-world application domains. (6 – 8 FTEs)

iii. Far-term Goals (FY26-30): Expertise required in engineering and computer science to support technology transition to concept demonstration projects. (6 – 8 FTEs)

c. INFRASTRUCTURE NEEDS:

i. Near-term Goals (FY16-FY20):

   a. Re-configurable laboratory space and research-grade multisensory display testbed platforms to conduct perceptual performance research in real and augmented reality environments.

ii. Mid-term Goals (FY20-25):

   a. Ruggedized multisensory display testbed platform, including multi-aspect measurement capabilities to conduct perceptual performance research in real and augmented reality environments.

   b. Instrumented real-world research spaces for evaluating technologies, model predictions and algorithm performance in behaviorally-relevant environmental conditions.

iii. Far-term Goals (FY26-30):

   a. Mobile laboratory and multi-aspect monitoring capabilities for real-time tracking and analysis of Soldier performance in operationally-relevant environments.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges and Army Capability Needs.

Army Warfighting Challenge	Description
8	Train Soldiers and leaders.
9	Develop resilient Soldiers, adaptive leaders, and cohesive teams.
19	Understand, visualize, describe, direct, lead, and assess operations.
20	Design Army formations.

Army Capability Need Proponent	Capability Area Need
MCoE	3.f – Human Dimension and Small Unit Leader Development Technologies.
MCCoE	4.a – Optimize Human Performance.
USAACE	3.d – Improved Manned-Unmanned Teaming and Autonomy.

MULTI-FACETED ASSESSMENT OF SOLDIER VARIABILITY [KCI-HS-2]

EXPECTED ARMY IMPACT: The goal of this research is to provide the foundational elements for future Army systems to generate high-resolution, moment-to-moment, predictions of individual Soldier's internal and external behavioral and performance variability in mixed-agent team and social settings across training and operational environments through the use of multi-faceted sensing systems. This capability will provide the foundation for future Army systems to adapt to the individual Soldier's states, behaviors, and intentions in real-time, which will provide our Soldier the most favorable conditions to train, engage in operations, and team with intelligent systems and personnel from the U.S. and other nations. Adaptive approaches will provide novel capabilities to decrease time-to-train, augment physical, cognitive, and social performance, and improve human-network interactions by providing robust predictions of Soldier state and intent to integrate with the network and are critical to the emergence of individualization of equipment and maximizing and sustaining both Soldier and unit peak performance during mission critical tasks. The research will focus on enabling high fidelity prediction that can account for continuous changes in Soldier's physical, cognitive, and social states, such as stress, fatigue, task difficulty, trust, and situational awareness. The goal is to exploit the array of sensors and information streams that will be present in the operational environment of 2040 to predict Soldier variability with sufficient resolution and robustness to adapt systems in manners to directly enhance mission performance. The ultimate consumer of these technologies includes personnel across all three services both in the operational and medical domains. From TRADOC PAM 525-3-1: "Investments in maximizing human performance focus on achieving accelerated professional development; increasing cognitive and physical performance; developing Soldiers' social and interpersonal capabilities; improving the overall health and stamina of personnel; and improving talent management. These efforts will improve the adaptability and endurance of Soldiers operating in a complex environment across the range of military operations." This research is consistent with the following TRADOC Army Operating Concept for "Human performance" that improves the adaptability and endurance of Soldiers in a range of military operations. In addition, this research feeds several TRADOC Emerging Technology Focus areas:

- "Grow Adaptive Army Leaders, Optimize Human Performance" by using continuous Soldier assessment.
- "Maintain Overmatch" in the areas of protection, intelligence, and mission command.
- "Continuously Upgrade, Protect, and Simplify the Network" by incorporating human state information to enable high degree of situational understanding and greater interoperability.

Key research areas include:

- Approaches and algorithms to assess and predict non-linear human states that vary on multiple time scales across training and operational environments.
- Techniques to leverage information about other individuals, sub-groups of individuals, and groups to improve prediction of an individual.
- Techniques and fusion algorithms to interpret and predict non-stationary, human actions and behaviors in complex, dynamic, artifact-rich environments.

DESCRIPTION: The goal of this research is to provide the foundational elements for future Army systems to generate high-resolution, moment-to-moment, predictions of individual Soldier's internal and external behavioral and performance dynamics in mixed-agent team and social settings across training and operational environments through the use of multi-faceted systems.

a. TECHNICAL GOAL(S):

i. Near-term goals (FY16-FY20):

a. Algorithms for interpreting state variability in complex, dynamic, artifact-rich, environments.

b. Human performance prediction algorithms for pseudo-controlled environments.

c. Transfer learning, active learning, collaborative filtering approaches to interpreting and predicting individual behavior from other individuals.

d. Moment-to-moment interpretation of individual Soldier action and behavior and the relation to other individuals and team behavior within operationally relevant small team environments.

ii. Mid-term goals (FY21-FY26):

a. Algorithms for state and performance variability prediction in complex, dynamic, artifact- rich, environments.

b. Performance prediction algorithms that require limited training data to adapt across tasks and human states via approaches that leverage existing data from other individuals.

c. Moment-to-moment interpretation of individual Soldier action and behavior and the relation to other individuals and team behavior within operationally relevant large team environments.

d. Moment-to-moment prediction of individual Soldier action and behavior within operationally relevant small team environments.

iii. Far-term goals (FY27-FY31):

a. Algorithms for high resolution, moment-to-moment, real-time predictions of cognitive, physical and social states in complex, dynamic, artifact-rich, real-world environments through continuous, multi-faceted integration of body-derived and external information streams.

b. Self-calibrating suites for interpreting and predicting individual actions, behaviors and intentions and their consequential influences on mixed-agent team performance and social behaviors.

b. PERSONNEL REQUIREMENTS:

i. Near-term (FY16-FY20): Multidisciplinary expertise that spans fields including applied mathematics, physics, engineering, computer science, computational neuroscience, and statistics. (8 – 10 FTEs)

ii. Mid-term (FY21-FY26): Multidisciplinary expertise that spans applied mathematics, physics, kinesiology, engineering, computer science, statistics, social psychology, and cognitive neuroscience. (6 – 8 FTEs)

iii. Far-term (FY27-FY31): Multidisciplinary expertise that spans applied mathematics, physics, kinesiology, engineering, computer science, statistics, social psychology, and cognitive neuroscience. (4 – 6 FTEs)

c. INFRASTRUCTURE NEEDS:

i. Near-term (FY16-FY20):

a. 100 low-resolution multi-aspect monitoring systems to track individual's physiological and behavioral data integrated with external sensors and information streams to capture context. Infrastructure for data storage, sharing, and real-time analysis.

b. Database capabilities and tools for 250+ individuals for at least 6 months data.

c. Innovation facility for novel, adaptive human-system/environment interaction technologies. The facility will merge daily technology use with technology innovation and form the cornerstone of a wearable technologies community.

ii. Mid-term (FY21-FY26):

a. 250 mid-resolution multi-aspect monitoring systems to track individual's physiological and behavioral data integrated with external sensors and information streams to capture context. Infrastructure for data storage, sharing, and real-time analysis.

b. Database capabilities and tools for 1000+ individuals for at least 6 months of data; 250+ individuals with minimum of 2 years of data.

iii. Far-term (FY27-FY31):

a. 1000 high-resolution multi-aspect monitoring systems to track individual's physiological and behavioral data integrated with external sensors and information streams to capture context. Infrastructure for data storage, sharing, and real-time analysis.

b. Database capabilities and tools for 5000+ individuals with minimum of 6 months of data; 250+ individuals with minimum of 5 years of data.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges and Army Capability Needs.

Army Warfighting Challenge	Description
8	Train Soldiers and leaders.
9	Develop resilient Soldiers, adaptive leaders, and cohesive teams.
12	Project forces, conduct forcible and early entry, and transition rapidly to offensive.

Army Capability Need Proponent	Capability Area Need
MCoE	3.f – Human Dimension and Small Unit Leader Development Technologies.
MCCoE	4.a – Optimize Human Performance.
HD	4.d – Soldier Readiness Monitoring.
AMEDD	3.e – Health and Performance Status Monitoring.
AMEDD	4.e – The Capability for Health and Performance Status Monitoring.

TRAINING EFFECTIVENESS RESEARCH
[KCI-HS-3]

EXPECTED ARMY IMPACT: The U. S. Army Training and Doctrine Command/Army Capabilities Integration Center predicts (Strategic Trends Analysis, May 2014) predicts that by 2040 "the speed of events will unfold that will require the Army to rapidly respond (measured in hours and days vs. weeks and months) with an operationally significant force to protect vital national interests. Increased speed of information requires more rapid and discriminate responses to crises. Future crises require increased multinational and whole-of-government approaches; however, partner and interagency capacities may not be sufficient. The environment will be increasingly transparent due to widespread information technology. Mission command must be capable of handling big data. Future land forces will require the capability and capacity to gain situational understanding of complex megacity environments (physical, human, and information). As technology exponentially advances, the Army will need to replace systems more rapidly to equip the future force in an effective and timely manner."

This environment will require a real-time integration and adaptation to rapidly deployed technologies (personally worn exoskeletons, distributed unmanned systems, and cyber-warfare systems). To address these requirements, this research will demonstrate a ubiquitous, reconfigurable, fully adaptive, synthetic training environment that can quickly and accurately assess learning requirements, while reducing time required for Soldiers and their units to attain job domain competency; increasing the rate of knowledge and skill retention; increasing the rate of training transfer for mission readiness; increasing user acceptance; and reducing overall life-cycle sustainment costs.

DESCRIPTION: The main goals of this research are to: 1) discover and delineate the relationships among training environment fidelity, level of training immersiveness, and Soldier/ unit performance; 2) create models of efficient training evaluation for the Army driven by relationships between training technologies/methods and training effectiveness; 3) determine relationships between training technologies and transfer of acquired knowledge, skills, and abilities to operational contexts, and 4) optimize training for autonomous, intelligent systems.

a. TECHNICAL GOAL(S):

i. Near-term goals (FY16-FY20):
   a. Explore necessary factors conducive to training effectiveness in immersive simulation environments.
   b. Discover molecular, cellular, and computational mechanisms of multisensory information processing and cognitive adaptation during learning, simulation, and training.
   c. Explore individual and unit level performance assessment technologies to integrate and produce real-time learning with intelligent agent-based systems.
   d. Develop and demonstrate artificially-intelligent software-based agents that monitor and solicit learner reaction to determine influence and usability of training technologies.
   e. Develop and demonstrate artificially-intelligent software-based agents that monitor individual learner and unit performance and solicit job transfer data.
   f. Develop virtual humans with emotions, natural language processing, graphics and animation/ embodiment, non verbal communication and perception that can learn from others.

g. Demonstrate a framework of streamlined reusable processes, agents, models and standard interfaces to support the evaluation and validation of training transfer.
h. Demonstrate training development tools that automatically update research-based findings to recommend most effective training methods for learning and performance.

ii. Mid-term goals (FY21-FY26):
a. Explore and develop integrated individual and unit level performance assessment technologies to produce real-time learning with intelligent agent-based systems.
b. Develop molecular, cellular, and computational mechanisms of multisensory information processing and cognitive adaptation during learning, simulation, and training.
c. Develop automated unit level learning assessment technologies for augmented reality training environments.
d. Develop individual to company level human performance models to predict training effectiveness of distributed-immersive training environments with 1000's of virtual characters in the field-of-view and a real-time reconfigurable whole world terrain.
e. Develop virtual humans with emotions, natural language processing, graphics and animation/ embodiment, non-verbal communication and perception that can learn from others.
f. Develop technologies that enable simulation-based tutoring systems to automatically adapt feedback and scenario challenge level during instruction based on learner states (cognitive, affective, competence) resulting in optimized learner gains (performance, retention, accelerated learning, adaptability) during self-regulated learning sessions.

iii. Far-term goals (FY27-FY31):
a. Develop individual to company level human performance models to predict training effectiveness of distributed-immersive training environments with 1000's of virtual characters in FOV and a real-time reconfigurable whole world terrain.
b. Develop molecular, cellular, and computational mechanisms of multisensory information processing and cognitive adaptation during learning, simulation, and training.
c. Develop real-time assessment and training for optimizing control and communication between humans and intelligent agent-based systems.

b. PERSONNEL REQUIREMENTS:

i. Near-term (FY16-FY20): Multidisciplinary expertise that training/learning, human factors, computer science, and social science. (1 – 3 FTEs)
ii. Mid-term (FY21-FY26): Multidisciplinary expertise that spans training/learning, human factors, computer science, and social science. (2 – 4 FTEs)
iii. Far-term (FY27-FY31): Multidisciplinary expertise that spans training/learning, human factors, computer science, and social science. (3 – 5 FTEs)

c. INFRASTRUCTURE NEEDS:

i. Near-term (FY16-FY20): No specialized infrastructure is required to support this effort. All software concepts developed through this work can be accommodated on common computational devices. Specialized biological and behavioral sensors may be procured/developed under this program. Specialized laboratory space is required to test training effectiveness for devices such as exoskeletons.

ii. Mid-term (FY21-FY26): No specialized infrastructure is required to support this effort. All software concepts developed through this work can be accommodated on common computational devices. Specialized biological and behavioral sensors may be procured/developed under this program. Specialized laboratory space is required to test training effectiveness for devices such as exoskeletons.

iii. Far-term (FY27-FY31): No specialized infrastructure is required to support this effort. All software concepts developed through this work can be accommodated on common computational devices. Specialized biological and behavioral sensors may be procured/developed under this program. Specialized laboratory space is required to test training effectiveness for devices such as exoskeletons.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges and Army Capability Needs.

Army Warfighting Challenge	Description
8	Train Soldiers and leaders.
9	Develop resilient Soldiers, adaptive leaders, and cohesive teams.
20	Design Army formations.

Army Capability Need Proponent	Capability Area Need
MCoE	3.f – Human Dimension and Small Unit Leader Development Technologies.
MCCoE	4.a – Optimize Human Performance.
CAC-T	3.a – Future Holistic Training Environment-Live/Synthetic (FHTE-LS).
CAC-T	3.c – Training Methods for Operational Dominance.
CAC-T	4.b – An Adaptive Learning/Learner Centric Enterprise.
CAC-T	4.d – Adaptive Leader Development and Unit Training.
HD	4.j – Capability to Rapidly Learn at the Individual and Organizational Level.
HD	4.k – Adaptation of Training Models.

REAL WORLD BEHAVIOR
[CCE-HS-1]

Understanding human behavior in the real world is a core enabler to the Human Sciences Campaign. The Real World Behavior CCE is dedicated to translating laboratory-based research findings to real world contexts and environments. This is especially critical considering the extreme conditions under which Soldiers operate including extreme time pressure; physical stress; cognitive load; interacting individually or as a team with intelligent systems and agents; technical training; and mission preparation. These extremes are difficult, if not impossible, to replicate in a laboratory. Materiel and methodologies to measure and predict human behavior in real world environments will enable enhancements of human capability in real time during training or tactical operations. Understanding behavior in the real world will enable optimized human-system integration at scales from millisecond-level interactions that are dynamic and reciprocal to social-level interactions with robotic and intelligent systems or agents. Creating this understanding of behavior in the real world will accelerate transition of research findings to the field, thus speeding
the delivery of technology, and ultimately, capability to the Army.

Core research areas include:

1. Real-world complexity in human sciences research: real-world perceptual and cognitive complexity in the laboratory as a function of the characteristics of simulations that give rise to the specific real-world behaviors required for effective interaction across training, analytic, and operational domains for both individuals and teams.
2. Assessing behavior in the real world via reliable and valid biological, neurological, and behavioral sensors that provide stable, computationally tractable data that are descriptive, diagnostic, and differentiating across the full range of physical, cognitive, social, and organizational behaviors for application of augmentation and human-system integration approaches on multiple time scales.

Execution of the research in this CCE includes development of sensors that can reliably detect and capture nuanced actions, gross motor movements, and brain activity outside the laboratory. Fast and efficient computational approaches also must be in place to handle the massive amounts data that will be collected. Finally, the behavioral data must be correlated to the context and to the environment to enable a meaningful and differentiating association to higher-level and militarily-relevant effectiveness measures for training and operations.

PERSONNEL REQUIREMENTS:
Developing a multi-scale understanding of human behavior within real world contexts and environments is inherently a multi-disciplinary endeavor. In order to elucidate the properties, principles, and mechanisms governing individual and group behavioral dynamics new technologies and novel approaches are required from sciences as varied as social and behavioral science, neuroscience and physiology, biomechanics and bioengineering, computer science, and material science

INFRASTRUCTURE NEEDS:
Infrastructure requirements include an “innovation commons” environment in which data collection of naturalistic behavior and the associated analysis approaches can be generated, tested, and improved in a rapid, low-risk fashion.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges.

Army Warfighting Challenge	Description
8	Train Soldiers and leaders.
9	Develop resilient Soldiers, adaptive leaders, and cohesive teams.
20	Design Army formations.

AUGMENTATION
[CCE-HS-2]

Soldier cognition, perception, and physical performance can be augmented, aided, or protected by technology, or technology can impair Soldier performance if it is not designed, developed, and introduced in a way that is consistent with fundamental human capabilities and capacities. The goal is to augment Soldier capabilities such that they can surpass the baseline limits of performance. Through augmentation, a Soldier's sensing and perceptual abilities can be greatly enhanced, thereby enabling the warfighter to sense and perceive the environment faster, more accurately, and more comprehensively. Augmenting cognitive capabilities that are matched to individual capabilities and tuned to the operational environment will enable greater resilience to the extremes of warfighting and support the attainment and sustainment of situation awareness and ultimately, agile, knowledgeable decision making. Innovations are also expected to enhance warfighter physical capabilities by balancing load, improving protection, and enhancing performance.

Core research areas include:

1. Perceptual Augmentation: the characterization and augmentation of the perceptual requirements of visual, auditory, and tactile signals in complex, dynamic, militarily-relevant environments derived from laboratory and field studies and forming the basis of guidance principles for the system development community.
2. Physical Augmentation: focus on 'skin-out' technology that may augment physical performance, and focus on advanced technology designed to increase the physical strength of the Soldier or increase their endurance.

The objectives of this research are to understand and augment fundamental human capabilities across both short and long time scales. Under this CCE, research will be conducted to develop and assess the effects of augmentation technologies or approaches on Soldier performance through the evaluation of performance metrics and prediction of operational benefit for mission tasks ranging from marksmanship and load carriage to communications tasks, driving and navigating, and distributed decision making. Many augmentation technologies constitute a direct approach such as an exoskeleton, but other approaches may be via indirect means such as insertion or manipulation of imagery, symbology, or virtual characters by means of augmented reality techniques.

PERSONNEL REQUIREMENTS:

Scientific disciplines required for the execution of this research area include but are not limited to biomechanics, bioengineering, cognitive and perceptual psychology, electrical and mechanical engineering, and computer science.

INFRASTRUCTURE NEEDS:

Unique infrastructure requirements over the near, mid-, and far term will include advanced immersive simulations, augmented reality, and access to high performance computing.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges.

Army Warfighting Challenge	Description
1	Develop and sustain a high degree of situational understanding.
8	Train Soldiers and leaders.
9	Develop resilient Soldiers, adaptive leaders, and cohesive teams.
19	Understand, visualize, describe, direct, lead, and assess operations.
20	Design Army formations.

TRAINING
[CCE-HS-3]

The research in this Core Capability Enabler is vital to the investigation, demonstration, and advancement of a broad range of simulation technologies to enhance Army training, and the instantiation of learning methods to enable effective, efficient, and adaptive/tailored instruction at the point of need.

This CCE includes a broad-based program of fundamental research and advanced technology development to achieve significant advances in Soldier training and, ultimately, mission effectiveness. The development of future training technologies requires advances in learning sciences, human sciences, human-system interaction, computer science, engineering and modeling and simulation. Execution of the training technology program is intended to produce high-payoff achievements in learning, retention, and transfer of knowledge and skills from the training environment to the operational environment. The end goal is to discover and innovate powerful new tools, technologies, and methods that can accelerate learning, can be applied at the point of need at any time and are affordable.

Core research areas include:

1. Intelligent and adaptive tutoring systems for individuals and units that promote learning of structured and unstructured militarily-relevant domains and contexts.
2. Authoring tools that enable rapid, tailored, and effective training at-point-of-need.
3. Immersive environments fitted to the training need and engageable via such means as virtual reality helmet-mounted displays, large-scale displays, and tablets or smart phones.
4. Virtual human capabilities that are tailored and effective for supporting a full range of human-simulation interactions, to include one-on-one social interactions, and culture-specific interactions.
5. Simulation fidelity matched to the training domain, with specific challenges related to medical training such as the replacement of live-tissue and battlefield trauma care, and to environmental fidelity such as terrain.
6. Live and embedded training to enhance training realism and effectiveness.

PERSONNEL REQUIREMENTS:
This CCE in training requires personnel in a variety of scientific and engineering disciplines. Learning science and psychology backgrounds are required to execute the behavioral research; simulation and computer science are required to develop the immersive environments and displays; and specialty areas such as biomedical engineering and neuroscience are required for applications to domains such as medical simulation and adaptive tutoring.

INFRASTRUCTURE NEEDS:
A fully instrumented “innovation commons” environment, advanced immersive simulations, augmented reality, and access to high performance computing.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges.

Army Warfighting Challenge	Description
8	Train Soldiers and leaders.
9	Develop resilient Soldiers, adaptive leaders, and cohesive teams.

HUMANS IN MULTI-AGENT SYSTEMS
[CCE-HS-4]

This CCE focuses on providing the critical technological breakthroughs needed for future Army multi-, mixed-agent teams across distributed network systems. These technologies must effectively merge human and agent capabilities for collaborative decision making and enhanced team performance; ensure that diverse teams of Soldiers comprehend new and critical information to maintain unprecedented situation awareness; and interact effectively with Soldiers and non-combatants to foster trust and gain community acceptance and influence across cultures and within complex, dynamic, politically sensitive environments. These complex multi-agent networked teams will enable faster and better informed decisions; reduce Soldier workload; provide otherwise unachievable levels of situation understanding and management; and maintain strategic and tactical advantages in future operating environments requiring the integration of cyber-human-physical dimensions.

The objective of this research is to provide the critical technological breakthroughs needed to shape current and future networked operational environments consisting of Army multi-, mixed-agent (humans, robots, associate agents, and intelligent systems) in distributed network systems to: (1) effectively enable teaming among human, robotic, and mixed-agent capabilities for collaborative decision-making and enhanced team performance in dynamic, and complex socio-technical environments; (2) ensure that diverse teams of Soldiers comprehend new and critical information to achieve unprecedented situational awareness, while maintaining optimal information burden on individuals; and (3) interact effectively with Soldiers and non-combatants in civil military scenarios to foster trust and gain community acceptance across cultures, and within complex, dynamic, and politically sensitive environments; and understand the complex dense urban environment battlespace and the diverse socio-cultural dynamics in a dense urban environment to allow Soldiers to effectively execute mission plans, sustain military forces, and provide humanitarian support to civil populations.

Core research areas include:

1. Human-Agent Teams: the establishment and calibration of trust, the processes required for deep collaboration, and dynamic and individualized interactions.
2. Socio-Technical Systems: the networks required to support distributed, coordinated, and collaborative decision making across teams, with an emphasis on mission command and the cyber domain.
3. Socio-Cultural Influences: captured in virtual agents for training and operational contexts, the influences on decision making

This research results of this CCE will inform interface design for mission command, and distributed and collaborative decision making, and the cyber security domain, as well as informing organizational design. This research will examine and identify the reasonable limits of human processing of big data and multi-modal inputs. Efforts on human supervision of robotic assets will transition to fundamental research on teaming with remote and intelligent assets.

PERSONNEL REQUIREMENTS:
Research conducted under the Humans in Multi-Agent Systems CCE will require a diverse set of scientific disciplines. Research psychologists concentrating on cognitive, social, cultural, and organizational aspects of human behavior will team with human factors engineers, information scientists, robotics and artificial intelligence researchers, as well as computer scientists, and general engineers.

INFRASTRUCTURE NEEDS:
Infrastructure requirements will be developed to support selected military domains such as interaction with intelligent systems, the cyber domain, and diverse cultural contexts.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges.

Army Warfighting Challenge	Description
9	Develop resilient Soldiers, adaptive leaders, and cohesive teams.
20	Design Army formations.

ASSESSMENT AND ANALYSIS CAMPAIGN

MISSION: To discover, innovate, and transition S&T capabilities that (1) improve the technologies being developed to meet critical and Army-unique needs; (2) provide decision makers and Soldiers with accurate and detailed awareness of materiel's capabilities; and (3) link the institutional and operational forces by means of a powerful shared toolset that simplifies and improves their decision making.

VISION: Army decisions about technology investments, weapon systems acquisition, and operational employment are founded on rigorous, transparent technical bases that take account of the full Doctrine, Organization, Training, Materiel, Leadership & Education, Personnel, and Facilities (DOTMLPF) spectrum; the breadth of adversaries' potential actions and countermeasures; and the ultimate consequences in terms of our forces' effectiveness in completing their missions. The desired end state is that comparable analytical capabilities are built into materiel and fielded to operational units, allowing Soldiers to employ swiftly and decisively emerging Army systems.

The Assessment and Analysis Campaign focuses on guiding the development and integration of technologies; substantially broadening the range of challenges that can be addressed with analytical rigor; improving the throughput and responsiveness of the analytical processes; and developing ruggedized and ready-to-employ applications that make the full power of the laboratory's internal analysis capabilities available directly to the Army's operational force. This campaign builds on fundamental pillars of physics, materials science, mechanical engineering, mathematics, and chemistry to conduct analyses in areas including *Ballistic Susceptibility; Electronic Warfare; and Materiel Failure*.

The Assessment and Analysis Campaign has developed 2 Key Campaign Initiatives and 6 Core Campaign Enablers (CCEs) that are integrated to form a robust foundation to support evaluators, Program Managers (PMs), and decision makers; modernize Army's capabilities for the laboratory's historic strengths in engineering-level analyses of technologies and systems; and leveraging those strengths to create fundamentally new capabilities. Accomplishing these aims will empower the Army RDT&E community with solutions that will be demanded by technological and strategic realities, the evolution of which will only continue to accelerate

ARCHITECTURE FOR SCIENCE-BASED ANALYSIS [KCI-AA-1]

EXPECTED ARMY IMPACT: By serving as a medium for linking together high-fidelity scientific models, an architecture for science-based analysis will lead to the operational Army's possessing resilient systems capable of performing their intended functions in any contested environment. Resilience is the ability of organizational, hardware and software systems to mitigate the severity and likelihood of failures or losses, to adapt to changing conditions, and to respond appropriately after the fact. The architecture will integrate physics- and engineering-based models with tactics, techniques and procedures. It will allow modeling of technologies and systems of interest at an engineering and/or physics level of fidelity to understand the effects of specific technical parameters on mission outcome. This will inform investment decisions for S&T and acquisition by providing a more integrated, holistic perspective. Also modeled at the same level of technical fidelity will be the contested environment, which can include such considerations as threats, atmospheric phenomena, and terrain. This unprecedented analytical capability will provide detailed insight for the design and development of systems and technologies, as well as their integration with the operational force to produce the most resilient system.

DESCRIPTION: The goal of this technical program is to develop a medium for linking together high-fidelity scientific models from diverse disciplines to enable coherent analysis of the behavior of complex systems of interacting technologies. This single common M&S context will also incorporate operational considerations such as METT-TC and TTPs to allow analyses in terms of criteria with relevance to warfighting missions. By providing detailed insight for the design, development, and integration of systems and technologies, this will inform investment decisions for S&T and for acquisition.

a. TECHNICAL GOAL(S):

- i. Near-term goals (FY16-FY20):
  - a. Draft requirements.
  - b. Assess current models.
- ii. Mid-term goals (FY21-FY26):
  - a. Formulate requirements. b. Identify models.
  - c. Design architecture.
  - d. Develop simulation environment. e. Develop model interfaces.
- iii. Far-term goals (FY27-FY31):
  - a. Demonstrate prototype analytical model.
  - b. Reach IOC (of use to the Army's S&T, analysis, acquisition, T&E, and warfighter communities).

b. PERSONNEL REQUIREMENTS:

- i. Near-term (FY16-FY20):
  - a. Requirements engineers. (2 FTEs; 1 new term-hire; and 1 retrained employee)
- ii. Mid-term (FY21-FY26):
  - a. Software architects. (4 FTEs; 2 new hires and 2 retrained employee)
  - b. Software developers. (10 FTEs; 5 new hires and 5 retrained employees)
  - c. Project manager. (2 FTEs; 1 new hire and 1 retrained employee)
  - d. Project scientists. (3 cross-trained FTEs)
- iii. Far-term (FY27-FY31): No additional manpower is required.

c. INFRASTRUCTURE NEEDS:

i. Near-term (FY16-FY20):
   a. No specialized infrastructure is required to support this effort.

ii. Mid-term (FY21-FY26):
   a. No specialized infrastructure is required to support this effort.

iii. Far-term (FY27-FY31):
   a. SCIF labs at APG and ALC for simultaneous control and display of multidimensional data, including ground truth, BLUFOR and OPFOR COPs, METT-TC, RF environment, network performance, statistical roll-ups, and study-specific metrics. Assimilating these multiple perspectives is essential to assessing the subtle interactions among technologies and phenomena, which is at the heart of the framework for science-based analysis.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges and Army Capability Needs.

Army Warfighting Challenge	Description
12	Project forces, conduct forcible and early entry, and transition rapidly to offensive
15	Conduct combined arms air-ground maneuver.
17	Coordinate and integrate Army and joint, interorganizational, and multinational fires and conduct targeting across all domains.
18	Deliver fires and preserve freedom of maneuver.

Army Capability Need Proponent	Capability Area Need
USAACE	3.e – Improved Aircraft Operational Availability and Mission Reliability.
USAACE	4.g – Ultra-reliable designs, optimized maintenance, and reduced overall operating and support costs.

SMALL-UNIT MODELING
[KCI-AA-2]

EXPECTED ARMY IMPACT: Exponentially more effective combat power is available in small units today than ever before. Traditional Army squads or platoons have had significant technological constraints on their potentially available mobility, lethality, protection, intelligence, and battlefield sensing. Radically improved and in many cases miniaturized and lighter-weight technologies for mobility, lethality, Soldier protection, communication, sensing, and effectiveness evaluation are all either in hand or within 15-year reach. New possibilities made available by these new technologies are so numerous and richly variable that they scarcely yield to traditional optimization techniques. A modeling and simulation (M&S) environment for small-unit combat employing variable and user-specifiable levels of engineering resolution is currently under development to assist with this task. Such tools can help with the first part of research managers' two-fold dilemma by helping them determine the relative value of potential payoffs for investment in mobility, lethality, Soldier protection, communication, and sensor technology. Given an appropriate tactical vignette or vignettes, and SME-agreed constraints about plausible limits of system physical performance, our existing system-of-systems analysis tools are already proven capable of helping us rationally array a set of technological possibilities in terms of potential incremental gains in unit combat power.

Such system-of-systems analysis tools can also help with the second part of the researcher's dilemma. Emerging tools for assessment and analysis have already been used to characterize particular technologies at sufficient resolution to support quantitative assessment of their incremental impact on mission success in particular Army vignettes or scenarios. Maturation of these M&S tools will allow engineering trade-off analysis for envisioned small-unit technology improvements to be grounded in realistic Army tactical needs rather than in abstract and sometimes overly sterile specifications or technical requirements. In turn, the decisions we make in the Army about which technologies to pursue and which engineering trades we should make will for the first time ever be made with technical rigor.

DESCRIPTION: Through leveraging the architecture for science-based analysis developed under KCI AA-1, develop and demonstrate optimization capability to explore combinations of technologies to enhance the mobility, lethality, protection, intelligence, sensing, and communication for small-unit operations. This will facilitate engineering trade-off analyses for envisioned technology improvements for small-unit operations.

a. TECHNICAL GOAL(S):

i. Near-term goals (FY16-FY20):
   a. Draft list of potential technologies and begin to assess the highest payoff requirements, and the appropriate level of engineering fidelity with which the technology should be characterized.
   b. Draft requirements.

ii. Mid-term goals (FY21-FY26):
   a. Formulate requirements.
   b. Identify specific technologies for consideration and develop ARL-wide prioritized list.
   c. Develop technical characterization of technologies under consideration.
   d. Modify the simulation environment as needed to capture the new technologies being simulated.
   e. Develop new model interfaces as needed for the new technologies.

iii. Far-term goals (FY27-FY31):

a. Enable technology development efforts to more rapidly demonstrate prototype of most important small unit technologies.

c. Technology pushes to RDECs and development community to expedite enhancing of small units.

b. PERSONNEL REQUIREMENTS:

i. Near-term (FY16-FY20):

a. Requirements engineers. (1 new term hire; and 1 retrained employee)

ii. Mid-term (FY21-FY26):

a. Software developers. (2 FTEs)
b. Project manager. (1 new hire)
c. Project scientists. (6 cross-trained employees)

iii. Far-term (FY27-FY31):

a. Specific technology proponents for all types of small-unit technologies to be embedded with analysis team to study payoffs of alternative modes of technology implementation.

c. INFRASTRUCTURE NEEDS:

i. Near-term (FY16-FY20):

a. The science-based architecture built at PSL.

ii. Mid-term (FY21-FY26):

a. The science-based architecture built at PSL, WSMR, or APG.

iii. Far-term (FY27-FY31):

a. SCIF labs at APG and ALC for simultaneous control and display of multidimensional data, including ground truth, BLUFOR and OPFOR COPs, METT-TC, RF environment, network performance, statistical roll-ups, and study-specific metrics. Assimilating these multiple perspectives is essential to assessing the subtle interactions among technologies and phenomena, which is at the heart of the framework for science-based analysis.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges and Army Capability Needs.

Army Warfighting Challenge	Description
8	Train Soldiers and leaders.
9	Develop resilient Soldiers, adaptive leaders, and cohesive teams.
20	Design Army formations.

Army Capability Need Proponent	Capability Area Need
MCoE	3.c – Small Unit Lethality.
MCoE	3.d – Unburden the Soldier.

BALLISTICS
[CCE-AA-1]

The goal of the Ballistics CCE is to leverage the science of threat-target interactions to identify and recommend techniques to reduce ballistic vulnerabilities, enhance system and complex target survivability, and ensure optimum effectiveness of the system in the full spectrum of battlefield environments and operations. Achieving the goal for this CCE enables a focus on discovering and mitigating survivability, lethality and vulnerability (SLV) challenges in emerging technologies and in system designs throughout the acquisition life-cycle. Success in this endeavor requires the development, application, and sustainment of robust, efficient and accurate methodologies, tools and models to enable innovative analyses. Innovative scientific methodologies and tools are foundational to advancing our ability to identify, understand, quantify and model the potential effects of both emerging and future weapons against fielded and developmental systems.

Innovative methodologies, tools and analysis products that we develop will be transitioned, as appropriate, for use internally and to other DOD users who will be able to interactively conduct complex, credible analyses that meet their varied needs as new technologies mature and are applied to conceptual and developmental Army systems. Using this approach we will extend our subject matter expertise in performing early SLV analysis to "the left" for early SLV analysis and to "the right" for use in evaluation through the acquisition process as well as to operational users for mission planning purposes.

The A&A CCE in Ballistics focuses on the following objectives that support the development of:

1. Mature and sustainable scientific products that enable DoD users to interactively conduct complex SLV analysis throughout the acquisition timeline. This requires the development and application of computational techniques to deliver modernized, faster, and higher resolution V/L analysis capabilities that will enhance core V/L models such as: the MUVES Toolkit (MTK), Engineering Analysis Toolkit (EAT), Ballistic Research Laboratory Computer Aided Design (BRLCAD) and the helicopter specific DESCENT code.
2. Robust, efficient and accurate methodology–comparable to approaches using fully integrated high-fidelity multi-physics software–for estimating vehicle and occupant vulnerability to under-body blast threats.
3. Scientific tools, techniques and methods to enable lethality analyses that incorporate ballistic and nontraditional directed-energy (DE) threat effects in a combined manner.
4. Vulnerability reduction techniques that can be applied to future technologies.
5. Integrated ballistic SLV products and capabilities that provide a holistic understanding of the system or platform mission readiness.
6. Analytical and scientific methods for subterranean and megacity (SbT/MgC) environments that enable characterization of the response of building designs and construction methods to ballistic impacts.

PERSONNEL REQUIREMENTS:

i. Near Term Goals (FY16-FY20):
   a. Computer Scientists with skills for developing novel analytical techniques and software tools
   b. Mathematicians/Statisticians capable of developing methods to quantify uncertainty of SLV models at various stages of analysis process.
   c. Engineers focusing on dynamics of ballistics and threat-target interactions
   d. Engineering and Electronics technicians

ii. Mid-term goals (FY21-FY26):
    a. Computer Scientists to support tool and model development and data visualization techniques
    b. Mathematicians/Statisticians focusing on protocols and algorithms for ballistic models
    c. Physical scientists for research in ballistics
    d. Engineers and Electronics technicians for experiment and research support

iii. Far-term goals (FY27-FY31):
    a. Computer Scientists
    b. Mathematicians/Statisticians
    c. Engineers and Electronics technicians

INFRASTRUCTURE NEEDS

i. Near Term Goals (FY16-FY20):
    a. State-of-the-art instrumentation

ii. Mid-term goals (FY21-FY26):
    a. Collaborative facility enabling research of combined ballistic and DE effects.

iii. Far-term goals (FY27-FY31):
    a. Fully developed facility enabling research and assessment of combined threat damage effects, reliability failures, and development of measurement technologies that allow for full platform state awareness.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges.

Army Warfighting Challenge	Description
5	Prevent, reduce, eliminate, and mitigate the use and effects of weapons of mass destruction.
12	Conduct entry operations.
13	Establish and maintain security across wide areas (wide area security).
15	Conduct combined arms air-ground maneuver.
16	Set the theater, provide strategic agility to the Joint Force, and maintain freedom of movement and action.

CYBER SECURITY
[CCE-AA-2]

Advancements in cloud computing and commercial-off-the-shelf technology and software increase the potential to add to or expand the number of unintended vulnerabilities in DoD systems and networks that adversaries can deny, disrupt, degrade or exploit. Advancements in nanotech computing, wireless, advanced robotics, autonomous, intelligent agent, cloud computing and other technologies as well as reliance on 3rd party commercial-off-the-shelf software will also increase the cyber-attack surface in DoD systems and networks.

The A&A CCE in Cybersecurity focuses on researching, developing and sustaining methodologies and analytical tools to plan and conduct cybersecurity assessments on technologies, weapon systems, information systems and networks. This sustained effort will enable the design, development and integration of secure technologies developed for or integrated into U.S. Army warfighting systems. To keep pace with the rapid evolution of cyber threats, U.S. military defensive cyber operations rely on cybersecurity assessments and analyses on technologies, systems and network architectures throughout the acquisition process. Continuous assessment and analysis is critical to identifying and mitigating cyber vulnerabilities to ensure cyber resiliency across the acquisition enterprise.

Cybersecurity is defined as the prevention of damage to, the protection of, and the restoration of computers, electronic communications systems, electronic communications services, wire communication, and electronic communication, including information contained therein, to ensure their availability, integrity, authentication, confidentiality, and nonrepudiation.

Nearly all defense systems incorporate information technology (IT) in some form, and must be resilient from cyber adversaries. This means that cybersecurity applies to technologies used in weapons systems and platforms; Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR) systems; and information systems and networks. Cybersecurity is a critical priority for the Department of Defense, and is a vital aspect of maintaining the United States' technical superiority.

The A&A CCE in Cybersecurity will focus on researching and developing cyber-attack techniques and tools to assess the security posture of emerging technologies; cyber vulnerability assessment and instrumentation tools leveraging advanced intelligent agents, data analytics, advanced visualization; malware reverse engineering and analysis; and security code analysis.

PERSONNEL REQUIREMENTS:

i. Near Term Goals (FY16-FY20):
   a. Computer scientists and engineers to employ cyber-attack tools and techniques against acquisition systems and technologies, conduct cybersecurity assessments and analyses, and collaborate with systems engineers and developers to provide mitigation solutions and design/develop secure technologies.

ii. Mid-term goals (FY21-FY26):
   a. Computer scientists and engineers to develop cyber-attack tools and techniques to be employed against acquisition systems and technologies, conduct cybersecurity assessments and analyses, and collaborate with systems engineers and developers to provide mitigation solutions and design/develop secure technologies.

iii. Far-term goals (FY27-FY31):
  a. Computer scientists and engineers to develop cyber-attack tools and techniques to be employed against acquisition systems and technologies, conduct cybersecurity assessments and analyses, and collaborate with systems engineers and developers to provide mitigation solutions and design/develop secure technologies.

INFRASTRUCTURE NEEDS

i. Near Term Goals (FY16-FY20):
  a. No specialized infrastructure is required to support this effort

ii. Mid-term goals (FY21-FY26):
  a. SCIF labs at APG to support distributed, classified cyber-attack assessments.

iii. Far-term goals (FY27-FY31):
  a. No specialized infrastructure is required to support this effort

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges.

Army Warfighting Challenge	Description
1	Develop and sustain a high degree of situational understanding.
3	Provide security force assistance.
7	Assure uninterrupted access to critical communications and information links.
12	Conduct entry operations.

ELECTROMAGNETIC ENVIRONMENT AND WARFARE [CCE-AA-3]

The CCE in Electronic Warfare (EW) focuses on research and analysis efforts to enable the development of methodologies and tools to assess and evaluate the negative effects of adversarial attacks on Army electronic systems, utilizing readily available commercial and Government Off-the-shelf technologies, and investigate inherent susceptibilities that these and similar technologies may have when integrated into existing or future Army systems.

The A&A CCE in EW will conduct research to enable analyses relative to adverse effects and impacts on Army systems resulting from operations in a complex and dynamic Electromagnetic Environment (EME). Technological advancements in electronics, telecommunications, wireless technologies, sensors, and countermeasures that are commercially available are increasing unabated. The application of these technologies as electronic countermeasures (ECM) to Army networks, communications, sensors, manned and unmanned platforms, and weapon systems is highly likely, given their general availability and low costs, particularly relative to the Nation State sponsored technology developments in the past 30-40 years. Understanding how these technologies have the potential to adversely affect basic operation and mission effectiveness of Army systems enables the Army to research, develop and apply mitigation strategies for these technologies and the associated effects. This research will also enable the identification and mitigation of potential vulnerabilities of these technologies and subsystem components when integrated into new and existing Army weapon, network, sensor, communication, and navigation systems. The A&A CCE in EW enables the design and development of new, sophisticated, and cost effective analysis methods and tools for use throughout the acquisition cycle that can subject component level, sub-system level, and system level Army technologies to these stressing environments in a planned, predictable, and repeatable manner in order to detect and mitigate potential vulnerabilities. Utilizing advanced techniques in EME modeling, generation (including both the threat technology inherent EME and intentional EA), and measurement, in coordination with modeling and instrumentation of Army systems, in laboratory, closed loop, hardware-in-the-loop (HWIL), anechoic chambers, and open-air ranges, susceptibilities may be identified and mitigation efforts determined.

Strategic focus areas of the A&A CCE in EW includes:

a. Threat and commercial EME source generation capabilities, signatures, and predictors of presence. (Threat technique generation and identification)
b. Controlled environment (Laboratory, HWIL, anechoic chamber) analysis development
c. Counter-countermeasure development and analysis (threat EA mitigation techniques)
d. Effects of emerging threats on position, navigation, and timing
e. Effects of emerging threats on unmanned systems (both airborne and ground based)

PERSONNEL REQUIREMENTS:

i. Near Term Goals (FY16-FY20):
   a. Scientists, engineers, mathematicians and physicists with education/experience in EME/Optical modeling and/or practical experience in the field of electromagnetics, instrumentation, optics, and wireless technologies
   b. Software developers
   c. Project managers capable of organizing, prioritizing, and directing the effort

ii. Mid-term goals (FY21-FY26):
    a. Electronics engineers
    b. Optical Engineers
    c. Software developers
iii. Far-term goals (FY27-FY31):
    a. Electronics engineers

INFRASTRUCTURE NEEDS

i. Near-term (FY16-FY20):
    a. None Required
    b. Development of unattended systems analysis facility and range
ii. Mid-term (FY21-FY26):
    a. Advanced EW Devices Laboratory for conduct of studies and analysis of emerging threat technologies within a closed loop environment
    b. Development of instrumented EW Optics range and control center
iii. Far-term (FY27-FY31):
    a. None Required

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges.

Army Warfighting Challenge	Description
1	Develop and sustain a high degree of situational understanding.
7	Assure uninterrupted access to critical communications and information links.
12	Conduct entry operations.
13	Establish and maintain security across wide areas (wide area security).
15	Conduct combined arms air-ground maneuver.
19	Understand, visualize, describe, direct, lead, and assess operations.

HUMAN VULNERABILITY
[CCE-AA-4]

The Human Vulnerability CCE concentrates on the advancement of research and scientific and engineering analysis to identify, understand, quantify, and model the effects of threat-target interactions on combat personnel, including injury assessment and operational effectiveness. Advances in research and experiments in the area of human vulnerability are foundational to the identification and development of scientific techniques to 1) mitigate injury and enhance the survivability of Soldiers to the wide range of battlefield threats including ballistic, thermal, toxic substances and less-than-lethal anti-personnel weapons, 2) enhance lethality of anti-personnel ballistic munitions, and 3) understand the effects of current and future weapons against personnel and protective systems. In addition to Soldier protection, Soldier survivability is assessed in terms of Soldier lethality, the ability to effectively sense and understand critical battlefield information, and to effectively communicate and operate undetected when needed.

This A&A CCE in Human Vulnerability describes a systematic plan of multidisciplinary research that addresses critical questions about the nature of human injury mechanisms and the interactions of the Soldier with enabling technologies that provide protection, lethality, information, communication and concealment. It addresses adaptive behavior on the battlefield to increase survivability in a hostile environment and the development of methodologies and models to address critical questions surrounding these interactions and implications on Soldier Survivability.

ARL will apply these methodologies to identify the benefits and risks associated with new technologies prior to system design and integration, and transition our products for use internally and to other DOD users who will be able to interactively conduct complex, credible analyses that meet their varied needs as these new technologies mature and are applied to conceptual and developmental Army systems. Using this approach we will extend our subject matter expertise in performing early SLV analysis to “the left” for early SLV analysis and to “the right” for use in evaluation through the acquisition process as well as to operational users for mission planning purposes.

The A&A CCE on Soldier Vulnerability investigates and advances the understanding and modeling the Soldier as a system to look at human vulnerability. Human vulnerability is characterized in terms of injury, degraded Soldier performance and capability with and without injury and risks to long-term quality of life given injury. Because Soldier Vulnerability depends on enabling capabilities provided by a number of technologies, human vulnerability is studied in the context of the Soldier as a system where Soldier lethality, and the Soldiers’ ability to sense and communicate and to operate undetected are also taken into consideration. The strategic approach includes:

1. Fundamental research projects to understand human susceptibility and performance which leads to the development of human injury and performance models accounting for: a) both cognitive and physical demands, b) how performance changes over time given injury, c) the ability to accomplish the mission in the short-term, and d) the probability of long-term quality of life issues.
2. Applied research to understand and characterize next-generation Soldier augmentation systems, protective systems, novel protective materials and future non-lethal and lethal systems that target precision, scalable effects and improved range, the ability to sense and communicate on the battlefield and to operate undetected. This understanding and

characterization leads to the development of new or enhancement of existing methods and models to assess Soldier Vulnerability in the context of the Soldier as a system.

3. Development, maintenance and application of SLV analysis capability that is adaptable, interoperable, and interactive; enables timely and credible analysis across the acquisition cycle; enables analyses of complex interactions in a mission/capabilities context, exploits emerging computation capabilities and can be used within a collaborative simulation and/or immersive environment. Human vulnerability models and techniques are anatomically consistent and injury-based for the purpose of informing design tools with the assessment of technology in the hostile environment and human-systems integration.
4. Application, verification and validation and transition of tools, techniques and methodologies for evaluating Soldier performance and survivability for early SLV, system evaluation during the acquisition life-cycle and application to operational mission training and planning. Development and application of methods to rapidly analyze very large data sets and communicate results in innovative ways that are more easily understood by decision makers without in depth subject matter expertise in SLV analysis techniques.

PERSONNEL REQUIREMENTS:

ii. Near Term Goals (FY16-FY20): These near term goals may be met, in part, through hiring Post-Docs and 5-year Term appointments.
   a. Bio-medical, bio-mechanical, and electrical engineers with expertise in state-of-the-art sensing and data acquisition technology.
   b. Materials engineer with expertise required to research and investigate the use of range of material classes such as metals, ceramics, insulators, polymers and biological materials as applied for personal protective and individual Soldier equipment.
   c. Neuroscientists with expertise in modeling and simulation, and behavioral and decision-making research preferably with an emphasis on military applications.
   d. Computer scientists
   e. Military expertise to support the development and application of models addressing Soldier interaction with enabling technologies, behavior and decision making in an operational environment

iii. Mid-term goals (FY21-FY26): These mid-term goals may be met through selective hiring of personnel previously engaged in post-doc research and 5-year term appointments, and through outreach to academia and industry using direct hire authority.
   a. Forensic scientists with expertise in biology and chemistry and experimental techniques.
   b. Neuroscientists with expertise in modeling and simulation, and behavioral research.
   c. Computer scientists
   d. Military expertise to support the development and application of models addressing Soldier interaction with enabling technologies, behavior and decision making in an operational environment.

iv. Far-term goals (FY27-FY31): These far-term goals may be met through selective hiring and/or through successful collaborative research partnerships with academia and other government agencies
   a. Computer scientists, material engineers and neuroscientists with expertise in state-of-the-art sensing and data acquisition and computing technology.

b. Materials and bio-engineers with expertise in bio-inspired and synthetic materials and devices.
c. Military expertise to support the development and application of models addressing Soldier interaction with enabling technologies, behavior and decision making in an operational environment

INFRASTRUCTURE NEEDS

i. Near Term Goals (FY16-FY20):
  a. Maintain hardware; procure software to enhance visualization and analytical capabilities; and procure computers to store, manage and process the terabytes of Computed Tomography (CT) data.
  b. Establish mobile-CT capability to support work with collaborators.
  c. Upgraded and enlarge Bio-Safety level 2 facilities to enhance capabilities to test surrogates.

ii. Mid-term goals (FY21-FY26):
  a. Upgrades to enhance ballistic range capability to maintain state of the art capability to conduct rapid experimentation.
  b. Modernization of data acquisition and storage systems to include enhanced facilities to conduct visual analysis of simulation results side by side with experimentation

iii. Far-term goals (FY27-FY31):
  a. State of the art facilities supporting experimentation, simulation and analysis for collaboration with partners.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges.

Army Warfighting Challenge	Description
9	Develop resilient Soldiers, adaptive leaders, and cohesive teams.
20	Design Army formations.

HUMAN SYSTEM MODELING AND ANALYSIS [CCE-AA-5]

The Human System Modeling and Analysis CCE focuses on developing and sustaining effective models resulting from an integrated Human Factors Engineering (HFE) and System Engineering (SE) analytic suite of tools capable of predicting human, system, and mission capabilities throughout the acquisition cycle. These efforts concentrate on identifying human capabilities and limitations within physical, perceptual and cognitive areas to inform methodologies and integrate the HFE and SE domains into technical assessments.

The human functional performance in each of the perceptual, physical, and cognitive domains will be considered individually and together in order to incorporate these into the modeling and simulation methodologies developed to evaluate performance of the human and system. This will allow for inclusion of physical, perceptual, and cognitive concerns for early, cost effective insertion of HFE and SE criteria requirements with the acquisition process.

The A&A CCE on Human System Modeling and Analysis investigates and advances the sciences relevant to two performance challenges: 1) identifying Soldier performance tradeoffs on mission demands, environment, human characteristics, equipment and technology, 2) understanding human factors that include sensing, perceptual and cognitive processes, ergonomics, biomechanics and the tools and methodologies required to manage interaction within these areas and within the Soldiers' combat environment.

In developing and sustaining models resulting from an integrated HFE and SE analytic suite of tools and techniques capable of predicting human, system and mission capabilities, four research foci will be emphasized:

1. Identify, develop and apply human performance measures of effectiveness and human figure modeling tools
2. Integrate HFE and SE inputs to generate complex and critical tasks combinations that provide the necessary analytical data to support physical, perceptual and cognitive workload assessment
3. Develop simulation architecture to represent the Soldier as a system considering physical effects, cognitive load, demographic influence in the context of Soldier-materiel interactions
4. Advance computational strategies to enable the integration and interaction of existing and emerging Soldier models into a seamless Soldier as a System simulation.

Through the understanding systems' technologies integrated with complex human performance conditions, this A&A CCE in Human Systems Modeling and Analysis aims to shape technology development for the Future Force.

PERSONNEL REQUIREMENTS:

i. Near Term Goals (FY16-FY20):
   a. Engineering Psychologists to serve as evaluation team members supporting M&S to identify major design flaws, reduce system failures, and reduce life-cycle costs for procured systems.
   b. General Engineers with the capabilities to develop, identify, and implement best practices for user interface design, develop use case scenarios, utilize knowledge elicitation and representation techniques, develop rapid prototypes, and conduct cost-based analysis of alternatives as they relate to user interface and system design.

c. Interdisciplinary or General Engineers with skills to enhance models and methods and perform proactive ergonomics analysis and design to evaluate Soldier interactions with weapon system design concepts using digital human models and software such as "JACK," a three-dimensional computer-aided design tool, and IMPRINT, a human performance modeling tool.
d. Operational research analysts and mathematicians for developing novel analytical techniques and software tools.
e. Biomechanical Engineers with advanced empirical understandings and theoretical conceptualizations of human multisensory processing; capability to conduct research within an interdisciplinary research team that will test theories and hypotheses about human-systems interactions with multisensory display interfaces.
f. Military expertise to support the development and application of models addressing Soldier interaction with enabling technologies, behavior and decision making in an operational environment

ii. Mid-term goals (FY21-FY26):
a. Neuroscientists and psychologists with expertise in modeling and simulation, and behavioral research
b. General Engineers with the capabilities to develop, identify, and implement best practices for user interface design, develop use case scenarios, utilize knowledge elicitation and representation techniques, develop rapid prototypes, and conduct cost-based analysis of alternatives as they relate to user interface and system design.
c. Computer Scientists, mathematicians or Engineers with skills for developing novel analytical techniques and software tools
d. Military expertise to support the development and application of models addressing Soldier interaction with systems and emerging technology

iii. Far-term goals (FY27-FY31):
a. Neuroscientists and psychologists with expertise in modeling and simulation, and behavioral research
b. Computer Scientists, mathematicians or Engineers with skills for developing novel analytical techniques and software tools
c. Military expertise to support the development and application of models addressing Soldier interaction with systems and emerging technology

INFRASTRUCTURE NEEDS:

i. Near Term Goals (FY16-FY20):
a. Establish facilities to support collaborative exchanges.
b. Field data collection capability to a fleet of tablet/mobile hardware.
c. Server capabilities to sustain Army-sponsored web-based HSI tools (e.g., Army HSI tracker).
d. Systems Engineering software or suite of tools (e.g., Vitech CORE) to apply systems engineering functional architecture (decomposition processing and synthesis).
e. Three dimensional imaging equipment to build high resolution state-of-the-art Soldier clothing and equipment models to perform workspace analysis

ii. Mid-term goals (FY21-FY26):
   a. Upgrade field data collection capability and system hardware/software to support future experiments.
   b. Upgrade server and capabilities for web-based HSI tools
   c. Human View system modeling and simulation tools to address HIS issues pre-Milestone A

iii. Far-term goals (FY27-FY31):
   a. Upgrade open campus collaboration facilities for improved effectiveness
   b. Upgrade server and capabilities for web-based HSI tools

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges.

Army Warfighting Challenge	Description
8	Train Soldiers and leaders.
9	Develop resilient Soldiers, adaptive leaders, and cohesive teams.
20	Design Army formations.

SYSTEMS OF SYSTEMS
[CCE-AA-6]

The Systems of Systems (SoS) CCE focuses on the improvement, application and sustainment of methodologies and tools to model the performance of systems of systems at the engineering level to support the full range of force operating capabilities at the small-unit level. These methodologies and tools are crucial to assessment of technology and system tradeoffs to illuminate and evaluate survivability aspects of competing capability packages and technologies.

The A&A CCE in SoS will enable analyses of the effects and impacts of the Army's rapid transformation in capabilities as a result of rapid, multi-faceted technological progress. Current Army analysis methodologies resulted from an era that contended with a much simpler set of analysis problems. The SoS CCE will answer more complex questions by providing the Army a significant leap forward in analysis techniques, methodologies, and mindsets. Scientific advancements, for example in information sciences, have resulted in revolutionary advances in information processing, machine learning, and intelligent autonomous ground and air vehicles, just to name a few. However, clear understanding of the impact of these revolutionary developments requires clearly specified technical parameters, measures of performance, effectiveness, survivability, and utility metrics for kinds of missions we can expect on the new battlefield. The Army must identify, articulate, and develop new and advanced analysis methods that can gauge how well the Army is taking advantage of new capabilities, mitigating new threats posed by advancing adversary capabilities, and adapting to radically new environments. These will not be simplistic system to system comparisons but must consider credible mission context. Utilizing cutting edge research in simulation, simulation languages, emerging mathematical techniques, and other advancements will improve our capabilities to explore and analyze important new developments like human/machine interactions and their impact on the cognitive and physical loads of the Soldier and small-unit. The analysis methodologies will address the complexity inherent in interactions between systems including multiple, autonomous, and potentially intelligent learning machines. Analyses will also explore the rapid growth of adversary capabilities, especially in cyber and electronic warfare, due to advanced commercial technologies.

Strategic focus areas of the A&A CCE in Systems of Systems will incorporate:

1. Research from the information sciences regarding communication, processing, and storage of information.
2. Human sciences to explore the human dimension of future conflict, including human/machine interfaces.
3. Sciences for lethality and protection to analyze the effectiveness and mission impact of advanced armor and lethality mechanisms.
4. Sciences for maneuver to explore control algorithms for unmanned ground and air vehicle systems that provide physical and cognitive augmentation for the Soldier.

PERSONNEL REQUIREMENTS:

i. Near Term Goals (FY16-FY20):
   a. Scientists, engineers, mathematicians and operations research analysts with broad-based experience in translating scientific research into modeling and simulation requirements and capabilities.
   b. Software developers or computer scientists with skills for developing novel analytical techniques and software tools
   c. Project managers capable of organizing, prioritizing, and directing the effort.

ii. Mid-term goals (FY21-FY26):
   a. Software architects
   b. Software developers
   c. Project scientists and engineers
iii. Far-term goals (FY27-FY31):
   a. No additional manpower requirements are anticipated

INFRASTRUCTURE NEEDS

i. Near-term (FY16-FY20):
   a. No specialized infrastructure is required to support this effort
ii. Mid-term (FY21-FY26):
   a. No specialized infrastructure is required to support this effort
iii. Far-term (FY27-FY31):
   a. SCIF labs at APG and ALC for simultaneous control and display of multidimensional data, including ground truth, BLUFOR and OPFOR COPs, METT-TC, RF environment, network performance, statistical roll-ups, and study-specific metrics. Assimilating these multiple perspectives is essential to assessing the subtle interactions among technologies and phenomena.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges.

Army Warfighting Challenge	Description
7	Assure uninterrupted access to critical communications and information links.
15	Conduct combined arms air-ground maneuver.
20	Design Army formations.

EXTRAMURAL BASIC RESEARCH CAMPAIGN

MISSION: Serve as the Army's national research agenda-driver in the engineering, physical, information, and life sciences; with a focus on Army critical innovative science, primarily executed through the funding of research grants at the nation's premier universities, and also through research support to corporate and international partners. Discoveries and innovations generated through these programs – primarily embodied as knowledge products resulting from major scientific discoveries and advances – provide crucial underpinning support to all of the other ARL Campaigns, and are leveraged as the foundations for future Army technologies.

VISION: Direct and engage the extraordinary intellectual capability of the nation's leading research universities to create scientific discoveries that have potentially significant and enduring impacts on Army warfighting technology, and ensure that those advances are matured through the Army's S&T laboratory enterprise to benefit the nation's land forces. These high relevance discoveries and innovations are strongly leveraged by the Army's S&T laboratory enterprise to achieve capabilities far beyond the state-of-the-art. Discoveries and innovations made through collaborative efforts are essential in maintaining the land power dominance of the Army of 2040 and beyond.

ARL's Extramural Basic Research Campaign is focused on identifying, forming, driving, and transitioning innovative research discoveries in the Physical Sciences, Information Sciences, Life Sciences, and Engineering Sciences that are critical to the U.S. Army's future technological superiority. This campaign concentrates on high-risk and high-payoff transformational basic research, primarily performed by university researchers across the country, which is expected to have revolutionary impacts on the Army's warfighting capabilities. In addition to significantly improving the Army's existing warfighting capabilities, it creates disruptive and game-changing new technologies for the Army, while also preventing technological surprises from potential adversaries.

The Extramural Basic Research Campaign provides critical underpinning support to all of the other ARL Campaigns, feeding new ideas and concepts into those campaigns, and also providing key connections with world-class extramural researchers at the nation's premier universities to perform collaborative research with ARL's scientists and engineers. Additionally, when unique and important opportunities exist, research is also supported with industry partners, not-for profit organizations, other research organizations, and international researchers.

The Extramural Basic Research Campaign has developed 9 Core Campaign Enablers (CCEs) that are integrated to form a robust foundation that is strongly linked to ARL's in-house research portfolio through the myriad of transition vehicles, including collaborative research in many cases.

CHEMICAL SCIENCES
[CCE-EBR-1]

The purpose of the Extramural Basic Research Campaign's Core Campaign Enabler (CCE) in Chemical Sciences is to identify and control the fundamental properties, principles, and processes governing molecules and their interactions in materials and chemical systems that will enable critical new Army technologies. More specifically, this CCE aims to uncover the relationships between molecular architecture and material properties, to understand the fundamental processes of electrochemical reactions, to develop methods for accurately predicting the pathways, intermediates, and energy transfer of reactions, and to discover and characterize the many chemical processes that occur at surfaces and interfaces.

This CCE emphasizes four research areas to drive new capabilities for the future Army:

1) Polymer Chemistry to explore the molecular-level link between polymer microstructure, architecture, functionality, and macroscopic properties. In the long term, research in this area will provide the foundation to enable the design and synthesis of functional polymeric materials that give the Soldier new and improved protective and sensing capabilities as well as capabilities not yet imagined.
2) Molecular Structure and Dynamics to identify and measure the state-selected dynamics of highly energetic reactions of molecules in gas and condensed phases across a wide variety of conditions and to develop theories that are capable of accurately describing, predicting, and harnessing these phenomena. In the long term, these studies may serve as the basis for the design of future propellants and explosives that are more efficient to produce, more effective in the field, and safer for transport.
3) Electrochemistry to predict and control reactant activation and electron transfer and how these are coupled with electrode, catalysis, electrolyte, and interface. These studies provide the foundation for developing advanced power generation and storage technology.
4) Reactive Chemical Systems to obtain a molecular-level understanding of interfacial activity and of dynamic nanostructured and self-assembled chemical systems. In the long term, research in this area will enable the design and synthesis of new chemical systems that may provide unprecedented hazardous materials management capabilities and Soldier survivability.

The Extramural Basic Research Campaign's CCE in Chemical Sciences will reveal previously unexplored avenues for new Army capabilities while also providing fundamental results to support (i) the Materials Research Campaign's goals to create multifunctional, responsive materials, and to discover and exploit materials for more efficient power generation and energy storage, (ii) the Sciences-for-Maneuver Campaign's goal to identify and exploit innovations in energy sources, storage, and conversion, and (iii) the Sciences for Lethality-and-Protection Campaign's goal to develop new energetic materials and predictive models of their behavior.

PERSONNEL REQUIREMENTS:

i. Near-Term (FY16-FY20): Expertise in environmental sciences and chemical interactions. (1 FTE)
ii. Mid-Term (FY21-FY26): No new requirements beyond existing personnel.

INFRASTRUCTURE NEEDS:

i. Near-Term (FY16-FY20):

a. Components of ARL's Extramural Basic Research Campaign will relocate to a technologically-superior space in Research Triangle Park, NC – a burgeoning Innovation District – to better enable enhanced scientific interactions and transition opportunities. This move will provide updated space and technologies to facilitate the operational effectiveness of the laboratory to connect with its academic, small business, industrial, and international partners. This move will occur during FY16.

ii. Mid-term goals (FY21-FY26):

a. None.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges.

Army Warfighting Challenge	Description
5	Prevent, reduce, eliminate, and mitigate the use and effects of weapons of mass destruction.
12	Conduct entry operations.
16	Set the theater, provide strategic agility to the Joint Force, and maintain freedom of movement and action.

PHYSICS
[CCE-EBR-2]

The objective of the Extramural Basic Research Campaign's Core Campaign Enabler (CCE) in Physics is to discover exotic quantum, and extreme optical physics that will enable leap-ahead capabilities in critical Army capabilities such as sensors, computers, and networks. This CCE drives basic research that explores frontiers where new regimes of physics promise unique function. Examples such as ultracold molecules, complex oxide heterostructures, attosecond light pulses, and quantum entanglement all represent areas where the scientific community's knowledge must be expanded to enable an understanding of the governing phenomena.

This CCE emphasizes four research areas to drive new capabilities for the future Army:

1) Atomic and Molecular Physics to identify and control the quantum properties of atoms, molecules, and exotic quantum behavior, including matter wave interference, lasing, diffraction, and up/down-conversion. The long-term applications of this research are broad and include ultra-sensitive detectors, precision time and frequency calculation for GPS-independent navigation, and novel power sources.
2) Condensed Matter Physics to identify and exploit the novel quantum phases of matter at oxide-oxide interfaces and at surfaces and interfaces of topological insulators, with particular focus on the interface of materials that provides a mechanism for potentially controlling lattice, orbital, spin and charge structure in ways not possible in bulk, single-phase materials. In the long term, research in this area may enable ultra-low-power electronics, passive sensors, and advanced computational methods.
3) Quantum Information Science focuses on the creation and control of the wave nature of matter, including coherence properties, decoherence mechanisms, decoherence mitigation, entanglement, nondestructive measurement, complex quantum state manipulation, and quantum feedback. In the long term, research in this area may enable revolutionary capabilities in computation, sensing, and secure communications.
4) Optics and Fields focuses on the generation, emission, and manipulation of light and the formation of light in extreme conditions, such as ultra-high intensity light, light filamentation, femtosecond/attosecond laser physics, and optical angular momentum beams. The extensive potential long-term applications of this research include advanced, low-power electronics, imaging through opaque materials, dramatically improved sensing technologies, improved power sources, and cloaking at various frequencies.

The Extramural Basic Research Campaign's CCE in Physics will reveal previously unexplored avenues for new Army capabilities while also providing fundamental results to support (i) the Materials Research Campaign's goals to determine how quantum processes could be harnessed for quantum memory and secure communication, and to explore and exploit recent advances in interface physics between unique materials such as topological insulators and their quantum mechanical properties, (ii) the Information Sciences Campaign's goal to explore techniques, architectures, and properties that take advantage of the quantum and related effects for transmitting information, and (iii) the Sciences for Lethality-and-Protection Campaign's goal to identify, exploit, and protect against the effects of directed and non-directed application of energy.

PERSONNEL REQUIREMENTS:

i. Near-Term (FY16-FY20): Expertise in the area of quantum information and sensing/measurement. (1 FTE)
ii. Mid-Term (FY21-FY26): No new requirements beyond existing personnel.

INFRASTRUCTURE NEEDS:

iii. Near-Term (FY16-FY20):

a. Components of ARL's Extramural Basic Research Campaign will relocate to a technologically-superior space in Research Triangle Park, NC – a burgeoning Innovation District – to better enable enhanced scientific interactions and transition opportunities. This move will provide updated space and technologies to facilitate the operational effectiveness of the laboratory to connect with its academic, small business, industrial, and international partners. This move will occur during FY16.

iv. Mid-term goals (FY21-FY26):

a. None.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges.

Army Warfighting Challenge	Description
1	Develop and sustain a high degree of situational understanding.
7	Assure uninterrupted access to critical communications and information links.
19	Understand, visualize, describe, direct, lead, and assess operations.

LIFE SCIENCES
[CCE-EBR-3]

The objective of the Extramural Basic Research Campaign's Core Campaign Enabler (CCE) in Life Sciences is to discover and control the properties, principles, and mechanisms governing DNA, RNA, proteins, organelles, cells, organisms, cognitive systems, and human behavior at the individual, local, and state levels. More specifically, this CCE aims to elucidate the fundamental mechanisms and physiology underlying antimicrobial resistance mechanisms, microbial community interactions, organism adaptation, gene function and regulation, nuclear and mitochondrial DNA replication, DNA repair, protein and nucleic acid structure-function relationships, synthetic biology, human perception and cognition, neuro-motor output, and human behavior across different temporal, spatial and social scales.

This CCE emphasizes five research areas to drive new capabilities for the future Army:

1) Genetics to identify and map the mechanisms and factors that influence DNA stability and mutagenesis, gene expression, and genetic regulatory pathways. This includes studies to understand genetic instability at a population level, mitochondrial regulation, oxidative stress, and communication between the mitochondria and the nucleus. In the long term, research in this area may enable new methods to optimize warfighter training and Soldier performance capabilities, to reduce the incidence or severity of PTSD and stress, and for the development of new therapeutics.
2) Neurophysiology to elucidate the fundamental physiology underlying perception, cognition, learning, and neuro-motor output. This includes the study of the psycho-physiological implications of brain-machine interfaces, the measurement and modeling of individual cognitive dynamics and decision making during real-world activity, and identifying how neuronal circuits generate desirable computations. In the long term, research in this area may enable the development of interfaces enabling humans to more efficiently control machines, new training methods and devices to predict and optimize individual performance, and the potential restoration of injury at the neural level.
3) Biochemistry to elucidate the mechanisms and forces underlying the function, structure, and organization of biological molecules. Fundamental mechanistic understanding of biomolecular processes is also utilized to engineer biomolecular systems to control activity, specificity and spatial organization. In the long term, research in this area will enable the design and development of novel materials, molecular sensors, and nanoscale machines that exploit the exceptional capabilities of biomolecules.
4) Microbiology to identify and exploit the physiology, genetics, ecology, intercellular interactions, and adaptation of microbes, including viruses, prokaryotes, and single-celled eukaryotes. In the long term, research in this area will provide the basis for more effective remedies against microbes, enable more rapid eradication of bacterial contamination from water and food supplies, improved strategies for development of effective coatings on Army textiles, and enable the production of commodity chemicals/fuels/feedstocks in place of petroleum-based methods.
5) Social and Behavioral Science to identify and predict human behavior at the individual, local, and state levels, and to develop mathematical, computational, statistical, and simulation models that provide fundamental insights into factors contributing to human socio-cultural dynamics. The research involves computational and mathematical modeling, agent-based simulations, econometric and statistical modeling. In the long term, research in this area may enable the prediction, detection, and influence of decisions and activities that impact U.S. interests and national security.

The Extramural Basic Research Campaign's CCE in Life Sciences will reveal previously unexplored avenues for new Army capabilities while also supporting (i) the Human Sciences Campaign's goals to discover and predict human cognitive, physical, and social behaviors, as well as the role of training paradigms in building expertise, and to characterize the fundamental aspects of social network dynamics involving ethics, values, trust, social-cultural, eco¬nomic, and geopolitical effects, (ii) the Assessment and Analysis Campaign's goal to identify human capabilities and limitations, (iii) the Information Sciences Campaign's goal to develop predictive models that consider the availability of power or food sources and the potential for social unrest or insurgency activity, (iv) the Sciences for Lethality-and-Protection Campaign's goal to predict and exploit interactions between information and humans, including the impact of trust and value on negotiation, and (v) the Materials Research Campaign's goal to exploit the evolutionary solutions created by nature and create similar structures using synthetic biology.

PERSONNEL REQUIREMENTS:

i. Near-Term (FY16-FY20): Expertise in social and behavioral sciences. (1 FTE)
ii. Mid-Term (FY21-FY26): No new requirements beyond existing personnel.

INFRASTRUCTURE NEEDS:

i. Near-Term (FY16-FY20):
   a. Components of ARL's Extramural Basic Research Campaign will relocate to a technologically-superior space in Research Triangle Park, NC – a burgeoning Innovation District – to better enable enhanced scientific interactions and transition opportunities. This move will provide updated space and technologies to facilitate the operational effectiveness of the laboratory to connect with its academic, small business, industrial, and international partners. This move will occur during FY16.
ii. Mid-term goals (FY21-FY26):
   a. None.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges.

Army Warfighting Challenge	Description
5	Prevent, reduce, eliminate, and mitigate the use and effects of weapons of mass destruction.
9	Develop resilient Soldiers, adaptive leaders, and cohesive teams.
19	Understand, visualize, describe, direct, lead, and assess operations.
20	Design Army formations.

MATHEMATICAL SCIENCES
[CCE-EBR-4]

The Extramural Basic Research Campaign's Core Campaign Enabler (CCE) in Mathematical Sciences is focused on discovering new mathematical approaches to create a foundational framework for modeling, prediction, and computation that explain and predict broadly across the physical, biological, and informational disciplines to create revolutionary capabilities for the future warfighter. Principal interests are within the areas of Probability and Statistics, Modeling of Complex Systems, Computational Mathematics, and Biomathematics.

Advances in these areas are expected to lead to: enhanced levels of information assurance, improved awareness of and defense against terrorist threats, next generation communication networks, and improved weapon design, testing, and evaluation; full (i.e., not only physical) situational awareness through modeling of urban terrain and small-group social phenomena; faster and better analysis, design, prediction, real-time decision making, and failure autopsy; and methods to enable protection against future biological and chemical warfare agents, self-healing communication networks, and enhanced cognitive capabilities for the warfighter.

The strategic approach to the principal areas of interest include:

1) In Probability and Statistics, the research strategy is to focus on the following opportunities for crucial discoveries: innovative theories and techniques for modeling, analysis, and control of stochastic networks, stochastic infinite dimensional systems, and open quantum systems; innovative statistical theory and methods for network data analysis, spatial-temporal statistical inference, system reliability, and classification and regression analysis. Research in this area will provide the scientific foundation for revolutionary capabilities in counter-terrorism, weapon systems development, and network-centric warfare.
2) In Modeling of Complex Systems, the research strategy is to focus on the following opportunities for crucial discoveries: novel representations of complex, irregular objects and of complicated, often high-dimensional abstract phenomena and functions for modeling urban and natural terrain, and geophysical features; mathematical models that are practically useful, data-tractable, and computationally-tractable, for small-group social and sociolinguistic analysis. Research in this area will lead to development of quantitative models of complex, human-based or hybrid physics and human-based phenomena of interest to the Army by identifying unknown basic analytical principles and by using human goal-based metrics.
3) In Computational Mathematics, the research strategy is to focus on the following opportunities for crucial discoveries: innovative methodologies for solving currently intractable problems that take advantage of symmetry, conservation, and recurrence, that can adapt to both the evolving solution and to the evolving run-time resource allocation of modern computer architectures; novel algorithms that deal with different mathematical models at different scales, interacting subsystems, and coupling between models and scales; methods to create reduced order models using adaptive simplification methods based on singular value decompositions and reduced order numerics. Research in this area will ultimately lead to the development of new mathematical principles that enable faster and higher fidelity computational methods, and new methods that will enable modeling of future problems.
4) In Biomathematics, the research strategy is to focus on the following opportunities for crucial discoveries: mechanistic mathematical models of biological systems at different temporal and/or spatial scales that synchronize connections from one level of organization to another which connect top-down and bottom-up approaches to uncover relationships across different biological systems, as well as multiple spatial and temporal scales; and mathematical

formulations of the fundamental principles of biological structure, function, and development to motivate the creation of new mathematics that could contribute in as-yet-unforeseen ways to biology. Research in this area will lead to creation of new mathematical principles and innovations in spatial and/or temporal modeling of multi-level biological elements to achieve a deeper understanding of biological systems.

The Extramural Basic Research Campaign CCE in Mathematical Sciences provides crucial underpinning support to the other ARL S&T Campaigns. Research in this area supports the following ARL campaign goals: (i) the Information Sciences Campaign goal of image and video sampling and reconstruction through investigations of sparsity in combinations of distributions with unknown parameters; (ii) the Computational Sciences Campaign goals of stochastic simulation methods, interfaces and evolving topologies, and uncertainty propagation, through investigations of fast separable methods for stochastic partial differential equations (PDEs), of novel meshes for both front tracking and domain-fitting, and of weak-interaction processes; (iii) the Computational Sciences Campaign goal of computational social sciences by establishing a general theory of crisis/change through new mathematical models that go beyond network models to incorporate morphisms as model elements; (iv) the Human Sciences Campaign goals of brain networks and of cognitive and neural modeling, through investigations of neural dynamic models and their computation; and (v) the Computational Sciences Campaign goal of stochastic optimization and modeling through investigations of fast separable methods for stochastic PDEs.

PERSONNEL REQUIREMENTS:

i. Near-Term (FY16-FY20): Expertise in probability and statistics for quantum information control and in the area of mathematical complex structures that underlie complex behaviors. (2 FTEs)
ii. Mid-Term (FY21-FY26): No new requirements beyond existing personnel.

INFRASTRUCTURE NEEDS:

i. Near-Term (FY16-FY20):
   a. Components of ARL's Extramural Basic Research Campaign will relocate to a technologically-superior space in Research Triangle Park, NC – a burgeoning Innovation District – to better enable enhanced scientific interactions and transition opportunities. This move will provide updated space and technologies to facilitate the operational effectiveness of the laboratory to connect with its academic, small business, industrial, and international partners. This move will occur during FY16.
ii. Mid-term goals (FY21-FY26):
   a. None.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges.

Army Warfighting Challenge	Description
7	Assure uninterrupted access to critical communications and information links.
8	Train Soldiers and leaders.
9	Develop resilient Soldiers, adaptive leaders, and cohesive teams.
19	Understand, visualize, describe, direct, lead, and assess operations.
20	Design Army formations.

NETWORK SCIENCES
[CCE-EBR-5]

The Extramural Basic Research Campaign's Core Campaign Enabler (CCE) in Network Sciences is focused on discovering mathematical principles to describe the emergent properties of all types of networks (e.g., organic, social, electronic) to create algorithms and autonomous systems that can be used to reason across data generated from disparate sources, sensor networks, wireless networks, and adversarial human networks, with resulting information used for prediction and control. Principal interests are within the areas of Communication and Human Networks, Intelligent Networks, Multi-Agent Network Control, and Social and Cognitive Networks.

Advances in these areas are expected to lead to: discovery of fundamental network science principles as they apply to wireless multi-hop communications systems that lack fixed infrastructure, discovery of social network structures from heterogeneous data, how those structures effect decision making, and the interaction of communications and human networks; establishment of the physical, mathematical, and information processing foundations for the control of complex networks; the creation of mathematical theories, with attendant analysis of computational complexity, to capture common human activity exhibiting aspects of human intelligence; and development of measures, theories, and models that capture cognitive and behavioral processes that lead to emergent phenomena in teams, organizations, and populations.

The strategic approach to the principal areas of interest include:

1) In Communication and Human Networks, the research strategy is to focus on the following opportunities for crucial discoveries: adaptive networking techniques for dynamic allocation of resources based on operation needs, traffic characteristics, dynamic topologies, interference conditions, and security considerations through advances in adaptive source and channel coding, networking with adaptive antennas, adaptive routing to avoid failed nodes, and power control; and creation of fundamental scientific and mathematical principles of communications and human networking, and the interactions between them, by leveraging network information theory, graph theory, game theory, data mining, and Markov chains.
2) In Intelligent Networks, the research strategy is to focus on the following opportunities for crucial discoveries: methods of intelligent and autonomous systems that perceive their environment by means of sensing and through context, and use that information to generate intelligent, goal-directed desired behaviors; mathematical tools that allow integration of the sub-components of intelligent behavior (such as vision, knowledge representation, reasoning, and planning) in a synergistic fashion to reason about groups/societies in a robust manner; new approaches that tease out and harness collective intelligence inherent in crowds to solve problems of importance to societies that are deemed computationally hard. Advances in these areas will augment human decision makers with enhanced-embedded battlefield intelligence that will provide them with tools for creating necessary situational awareness, reconnaissance, and decision making to decisively defeat any future adversarial threats.
3) In Multi-Agent Network Control, the research strategy is to focus on the following opportunities for crucial discoveries: mathematically rigorous methods and physics of continuous and discrete high-dimensional dynamical systems, uncertainty propagation methods in spatiotemporally heterogeneous dynamical systems, and models for rare cascading events and failures to create new control and dynamical systems theory; new tools and mathematical techniques for causality and topological inference to discover information structure, causality, and dynamics for controlling complex and co-evolving networks; and the unification of statistical physics, nonlinear dynamics, and nonlinear control to establish a physics of large-scale far-from-equilibrium systems that will lead to unprecedented capabilities for controlling complex networks.

4) In Social and Cognitive Networks, the research strategy is to focus on the following opportunities for crucial discoveries: new discoveries in diffusion dynamics research that focus on formation and dissolution of civic-minded and violent networks, mobilization of benign to hostile political movements, propagation of and enduring changes in attitudes, and network-based interventions; creation of multi-agent models and dynamic simulations that resolve issues around scalability of networks, multilevel (nested) systems, and imputing network links; and advances in organizational network research that explore network models of collaborative communication as they relate to information spread, information fidelity, and organization performance through different structural/topological classifications of networks.

The Extramural Basic Research Campaign CCE in Network Sciences provides crucial underpinning support to the other ARL S&T Campaigns. Research in this area primarily supports ARL's Information Sciences Campaign, especially in the area of systems intelligence and intelligent systems. In particular, the following goals within the Information Sciences Campaign are explicitly addressed including: (i) assessment and control of behavior goal by creating new methods in design and controllability of composite and multi-genre networks; (ii) social effects and human-machine interaction through the exploration of social and cognitive networks; and (iii) unconventional communication networks and adaptive by making information available at the tactical edge while taking limited bandwidth and human-information interaction modalities into account.

PERSONNEL REQUIREMENTS:

i. Near-Term (FY16-FY20): Expertise in multi-agent network control and in international efforts relating to network science. (2 FTEs)
ii. Mid-Term (FY21-FY26): No new requirements beyond existing personnel.

INFRASTRUCTURE NEEDS:

i. Near-Term (FY16-FY20):
   a. Components of ARL's Extramural Basic Research Campaign will relocate to a technologically-superior space in Research Triangle Park, NC – a burgeoning Innovation District – to better enable enhanced scientific interactions and transition opportunities. This move will provide updated space and technologies to facilitate the operational effectiveness of the laboratory to connect with its academic, small business, industrial, and international partners. This move will occur during FY16.
ii. Mid-term goals (FY21-FY26):
   a. None.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges.

Army Warfighting Challenge	Description
1	Develop and sustain a high degree of situational understanding.
7	Assure uninterrupted access to critical communications and information links.
11	Conduct effective air-ground combined arms reconnaissance.
12	Conduct entry operations.
13	Establish and maintain security across wide areas (wide area security).
15	Conduct combined arms air-ground maneuver.
16	Set the theater, provide strategic agility to the Joint Force, and maintain freedom of movement and action.
19	Understand, visualize, describe, direct, lead, and assess operations.

COMPUTATIONAL SCIENCES
[CCE-EBR-6]

The Extramural Basic Research Campaign's Core Campaign Enabler (CCE) in Computational Sciences is focused on building fundamental principles and techniques governing computational methods, models, and architectures to establish the foundation for revolutionary advances in intelligent, trusted, and resilient computing that provide increased performance and computational capability to enhance warfighter situational awareness, decision making, command and control, and weapons systems performance. Principal areas of focus are in: Computational Architectures and Visualization, Information Processing and Fusion, and Information and Software Assurance.

Advances in these areas are expected to lead to: new computing architectures, computational methods, and visualization techniques that can efficiently manage and process massive data sets and perform large scale simulations of importance to the Army; creation of novel data fusion, integration, and extraction techniques for real-time situational awareness and advanced targeting; theories and frameworks that combine intrusion prevention, detection, response, and recovery to establish fundamental scientific principles for building mission-sustaining information systems.

The strategic approach to the principal areas of interest include:

1) In Computational Architectures and Visualization, the research strategy is to focus on the following opportunities for crucial discoveries: new computational theories, mathematical abstractions, and models of computation needed to address the difficulties associated with heterogeneous, parallel, and distributed processing; innovations in visualization, to include advances in computational geometry, computer graphics, large-scale computer simulations, and virtual environments. Discoveries in these areas are centered on modeling, analysis, design, and validation of computational infrastructure (hardware and software) with special emphasis on the effect emerging and future computational architectures will have on managing, processing, analyzing, and visualizing massive data sets.
2) In Information Processing and Fusion, the research strategy is to focus on the following opportunities for crucial discoveries: creation of innovative theories and algorithms for data modeling, processing, fusion, and information extraction to support real-time decision-making and advanced targeting capabilities in Army operations; discovery of fundamental principles and novel methods for image understanding, robotic perception, analysis and exploitation of high dimensional multimodal datasets, and collaborative sensing from multimodal sensors.
3) In Information and Software Assurance, the research strategy is to focus on the following opportunities for crucial discoveries: novel methods for highly assured, self-healing, and survivable software and information systems that address the processing and delivery of authentic, secure, reliable, and timely information, regardless of threat conditions; innovative cyber situation awareness theories and frameworks that combine intrusion prevention, detection, response, and recovery to establish fundamental scientific principles for building mission-sustaining information systems.

The Extramural Basic Research Campaign CCE in Computational Sciences provides crucial underpinning support to the other ARL S&T Campaigns. Research in this area supports the following ARL campaign goals: (i) the Information Sciences Campaign goal of algorithm design for object classification and scene understanding from active and passive 3D scenes and full motion video through enhanced semantic object recognition; (ii) the Computational Sciences

Campaign goal of large scale computing and modeling, and dynamic multi-dimensional heterogeneous data analytics, by devising scalable algorithms that effectively handle the size, complexity, heterogeneity, and multi-modality of data and by creating new hardware and software architectures for emerging and future computing systems that optimize the use of Army computational resources; and (iii) the Information Sciences campaign goal of estimating adversarial dynamics and infrastructure through new game models and mental estimation techniques to enable better cyber defense.

PERSONNEL REQUIREMENTS:

i. Near-Term (FY16-FY20): Expertise in the artificial intelligence associated with decision making tools and situational awareness. Expertise in another area to drive the research in advanced computing approaches. (2 FTEs)
ii. Mid-Term (FY21-FY26): No new requirements beyond existing personnel.

INFRASTRUCTURE NEEDS:

i. Near-Term (FY16-FY20):
    a. Components of ARL's Extramural Basic Research Campaign will relocate to a technologically-superior space in Research Triangle Park, NC – a burgeoning Innovation District – to better enable enhanced scientific interactions and transition opportunities. This move will provide updated space and technologies to facilitate the operational effectiveness of the laboratory to connect with its academic, small business, industrial, and international partners. This move will occur during FY16.
ii. Mid-term goals (FY21-FY26):
    a. None.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges.

Army Warfighting Challenge	Description
1	Develop and sustain a high degree of situational understanding.
11	Conduct effective air-ground combined arms reconnaissance.
12	Conduct entry operations.
13	Establish and maintain security across wide areas (wide area security).
15	Conduct combined arms air-ground maneuver.
19	Understand, visualize, describe, direct, lead, and assess operations.

MECHANICAL SCIENCES
[CCE-EBR-7]

The Extramural Basic Research Campaign's Core Campaign Enabler in Mechanical Sciences is focused on research to uncover fundamental properties, principles, and processes involved in fluid flow, solid mechanics, chemically reacting flows, explosives and propellants, and the dynamics of complex systems of relevance to the Army and the DoD. More specifically, the Division supports basic research to uncover the relationships to: (i) contribute to and exploit recent developments in kinetics and reaction modeling, spray development and burning, (ii) gain an understanding of extraction and conversion of stored chemical energy, (iii) develop a fundamental understanding that spans from a material's configuration to a systems response to create revolutionary improvements through significant expansion of the mechanical design landscape used to optimizing systems, (iv) advance knowledge and understanding governing the influence of inertial, thermal, electrical, magnetic, impact, damping, and aerodynamic forces on the dynamic response of complex systems as well as improving the inherent feature set of the components (i.e., mechanisms and sensing) that comprise them, (v) provide the basis for novel systems that are able to adapt to their environment for optimal performance or new functionality, and (vi) develop a fundamental understanding of the fluid dynamics underlying Army systems to enable accurate prediction methodologies and significant performance improvement, especially with regard to unsteady separation and stall and vortex dominated flows. Fundamental investigations in the mechanical sciences research program are focused in the areas of solid mechanics; complex dynamics and systems; propulsion and energetics; and fluid dynamics. Special research areas have been continued in the Army-relevant areas of rotorcraft technology, projectile/missile aerodynamics, gun propulsion, diesel propulsion, energetic material hazards, mechanics of solids, impact and penetration, smart structures, and structural dynamics.

The Mechanical Sciences CCE will provide the scientific foundation to create revolutionary capabilities for the future warfighter. In the long term, the discoveries uncovered through basic research in the mechanical sciences could provide understanding that leads to insensitive munitions, tailored yield munitions, enhanced soldier and system protection, novel robotic, propulsion, and energy harvesting systems, and novel flow control systems and enhanced rotorcraft lift systems. In addition, mechanical sciences research may ultimately improve Soldier mobility and effectiveness by enabling the implementation of renewable fuel sources and a new understanding of energetic materials with improved methods for ignition, detonation, and control.

The strategic focuses of this area include:

1) In Solid Mechanics, the strategy is to determine fundamental behavior of complex material systems under broad range of lading regimes in various environments, and to develop analytical and computational methods to characterize material models and to serve as physically-based tools for the quantitative prediction, control, and optimization of Army relevant material systems subjected to extreme battlefield environments.
2) In Complex Dynamics and Systems, the strategy is to develop new scientific understanding in three major research Thrusts: (i) High-dimensional Dynamical Systems, (ii) Force generation, Power and Work in Non-equilibrium Dynamical Systems, and (iii) Creating Quantitative Understanding of the Principles Underlying Biological Agility. These areas emphasize high-risk, high-reward exploratory research to create breakthroughs, push science in truly novel directions, or to support mathematical abstractions and precise physical foundations for emerging technologies deemed likely to be of significant future Army and DoD impact.

3) In Propulsion and Energetics, the strategy is to explore and exploit recent developments in kinetics and reaction modeling, spray development and burning, and current knowledge of extraction and conversion of stored chemical energy to ultimately enable higher performance propulsion systems, improved combustion models for engine design, and higher energy density materials, insensitive energetic materials, and tailored energy release rate in energetic materials.
4) In Fluid Dynamics the strategy includes the experimental and numerical determination of the flow-field over airfoils undergoing unsteady separation with subsequent dynamic stall, the development of micro-active flow control techniques for rotor download alleviation and dynamic stall control, and the development of advanced rotor free-wake methods to improve the predictive capability for helicopter performance, vibration, and noise.

Mechanical Sciences supports other campaigns through its supported fundamental research. These include the Sciences for Maneuver Campaign through research in hydrocarbon combustion, non-equilibrium dynamical systems, unsteady separation and dynamics stall, and vortex dominated flows S&T areas; the Sciences for Lethality and Protection Campaign through research in energetics, multi-scale mechanics of heterogeneous solids, and low-stiffness, non-linear materials and material systems S&T areas. These efforts also contribute to lesser extent to the Materials Research and Human Sciences Campaigns through its impacted S&T areas.

PERSONNEL REQUIREMENTS:

i. Near-Term (FY16-FY20): No new requirements beyond existing personnel.
ii. Mid-Term (FY21-FY26): No new requirements beyond existing personnel.

INFRASTRUCTURE NEEDS:

i. Near-Term (FY16-FY20):
   a. Components of ARL's Extramural Basic Research Campaign will relocate to a technologically-superior space in Research Triangle Park, NC – a burgeoning Innovation District – to better enable enhanced scientific interactions and transition opportunities. This move will provide updated space and technologies to facilitate the operational effectiveness of the laboratory to connect with its academic, small business, industrial, and international partners. This move will occur during FY16.
ii. Mid-term goals (FY21-FY26):
   a. None.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges.

Army Warfighting Challenge	Description
12	Conduct entry operations.
17	Coordinate and integrate Army and joint, interorganizational, and multinational fires and conduct targeting across all domains.
18	Deliver fires and preserve freedom of maneuver.

ELECTRONICS
[CCE-EBR-8]

The Extramural Basic Research Campaign's Core Campaign Enabler in Electronics is focused on the discovery of phenomena that involve elementary particles and wave phenomena in solid state materials and plasma. More specifically, the CCE supports basic research to discover and control the relationship between nanostructure and heterostructure designs and charge transport and carrier recombination dynamics, to understand and improve the stimulus-response properties of electronic materials/structures, to leverage nanotechnology for enhanced electronic properties, to comprehend and mitigate distortion and noise, to understand and exploit complex electromagnetic and acoustic structures and propagation, and to explore ultra-fast, solid state and plasma mechanisms and concepts. The results of this research will stimulate future studies and help keep the U.S. at the forefront of research in electronics by revealing new pathways for the design and fabrication of novel electronic structures that have properties that cannot be realized with current technology.

Electronics research is relevant to nearly all Army systems; therefore, research under this program provides the underlying science for a wide variety of developmental efforts and contributes to the solution of technology-related problems throughout the full spectrum of the Army's "System of Systems." Army-relevant research in electronics spans areas such as (i) nano- and bio-electronics to provide components that require less power, interface with biological systems, and enhance the creation and processing of information, (ii) studies in electromagnetics, acoustics, microwaves, and power to enable multimodal sensing for detection, identification, and discrimination of environmental elements critical to decision-makers in complex, dynamic areas , including defeat of electronic threat systems, (iii) optoelectronics, which involves the creation and use of electromagnetic radiation from far infrared to X-ray for sensing, communication and to interrogate, disrupt, and defeat hostile infrared sensor systems and (iv) action-reaction relationships in electronic materials and structures that may lead to new devices and methods for sensing and communication over long ranges and within complex environments.

The Electronics Core Campaign Enabler drives the creation of new research areas and provides the underlying science for a wide variety of developmental efforts and contributes to the solution of technology-related problems throughout the full spectrum of the Army's "System of Systems." It identifies, evaluates, funds, and monitors research in a range of sub-disciplines. This is focused on the following areas which provide a framework for the evaluation and monitoring of research projects: (i) Nano- and Bio-electronics, (ii) Electromagnetics and Radio Frequency Electronics, (iii) Optoelectronics, and (iv) Electronic Sensing.

1) In the Nano- and Bio-Electronics, the strategy is to create novel electronic devices including nano- and bio-based sensors and transducers based on semiconductor electronics and hybrid molecular-semiconductor devices in addition to organic-inorganic hybrid materials. It will apply biology concepts to electronics and photonics to create biomimetic structures and devices for information processing, information storage, electronic components, and actuators.
2) In Electromagnetics and Radio Frequency Electronics, the strategy is to create novel approaches to integrated antenna arrays, multifunctional antennas, EM power distribution, and new sensing modalities based on new understanding of electromagnetic (EM) and radio frequency (RF) phenomena. It also develops new concepts for circuit integration for greater functionality, smaller size/weight, lower power consumption, enhanced performance, with focus in the frequency regime from low to terahertz frequencies.

3) In Optoelectronics, the strategy is to develop novel nanostructure and heterostructure designs for the generation, guidance, and control of optical/infrared signals in both semiconductor and dielectric materials. The research in this program may enable the design and fabrication of new optoelectronic devices that give the Soldier high-data-rate optical networks including free space/integrated data links, improved IR countermeasures, and advanced 3D imaging.
4) In Electronic Sensing, the strategy is to extend the underlying science behind action-reaction relationships in electronic materials and structures as well as understand target signatures. It seeks tools to enable the Soldier to have 100% situational awareness of vehicles, personnel, weapon platforms, projectiles, explosives, landmines, and improvised explosive devices (IEDs), in day/night, all weather, and cluttered environments through natural and man-made obstructions.

Electronics supports the Materials Research Campaign in multiple areas including photonics, nanostructures, energy efficiency, active and passive RF, power generation and energy harvesting, as well as biological and bioinspired components. It also supports the Sciences for Lethality and Protection Campaign through electronic warfare and smart sensing technology and the Computational Sciences Campaign in terms of hardware performance improvements for next generation computing. Electronics will also contribute to the Human Sciences Campaign through tools for neurostimulation in addition to displays and graphics.

PERSONNEL REQUIREMENTS:

i. Near-Term (FY16-FY20): Expertise in the area of electronics, photonics with focus on unique phenomena. Expertise that focuses on semiconductors and amorphous materials for infrared and ultraviolet detectors. (2 FTEs)

ii. Mid-Term (FY21-FY26): No new requirements beyond existing personnel.

INFRASTRUCTURE NEEDS:

i. Near-Term (FY16-FY20):

   a. Components of ARL's Extramural Basic Research Campaign will relocate to a technologically-superior space in Research Triangle Park, NC – a burgeoning Innovation District – to better enable enhanced scientific interactions and transition opportunities. This move will provide updated space and technologies to facilitate the operational effectiveness of the laboratory to connect with its academic, small business, industrial, and international partners. This move will occur during FY16.

ii. Mid-term goals (FY21-FY26):

   a. None.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges.

Army Warfighting Challenge	Description
1	Develop and sustain a high degree of situational understanding.
7	Assure uninterrupted access to critical communications and information links.
11	Conduct effective air-ground combined arms reconnaissance.
12	Conduct entry operations.
13	Establish and maintain security across wide areas (wide area security).
19	Understand, visualize, describe, direct, lead, and assess operations.

MATERIALS SCIENCE
[CCE-EBR-9]

The Extramural Basic Research Campaign's Core Campaign Enabler in Materials Science seeks to realize unprecedented material properties by embracing long-term, high-risk, high-payoff opportunities for the U.S. Army with special emphasis on Materials by Design, Mechanical Behavior of Materials, Physical Properties of Materials, Synthesis and Processing, and Earth Materials and Processes. Research within this CCE seeks to discover the fundamental relationships that link chemical composition, microstructure, and processing history with the resultant material properties and behavior. The work, although basic in nature, is focused on developing new materials, material processes, and properties that promise to significantly improve the performance, increase the reliability, or reduce the cost of future Army systems. It also endeavors to advance the understanding of geological materials and processes, to establish opportunities from which to optimize the performance of future Army systems functioning within them. Fundamental research that lays the foundation for the design and manufacture of multicomponent and complex materials is of particular interest. Foundational research that integrates novel experimental work with the development of new predictive materials theory is also of significant interest. Furthermore, there is lasting interest in new ideas and cross-disciplinary concepts in Materials Science that may have future applications for the Army.

In addition to advancing and exploiting worldwide knowledge and understanding of new materials to achieve unprecedented properties, research managed through the Materials Science CCE will provide the scientific foundation to create revolutionary capabilities for the future warfighter and battle systems. In the long term, the basic research discoveries made by Extramural Research Campaign supported research is expected to provide a broad base of disruptive and paradigm-shifting capabilities to address Army needs. Advanced materials will improve mobility, armaments, communications, personnel protection, and logistics support in the future. New materials will target previously identified Army needs for stronger, lightweight, durable, reliable, and less expensive materials and will provide the basis for future Army systems and devices. Breakthroughs will come as the fundamental understanding necessary to achieve multi-scale design of materials, control and engineering of defects, and integration of materials are developed.

The Materials Science CCE drives the creation of new research areas, as well as identifies, evaluates, funds, and monitors research in a range focus areas. These areas are: (i) Materials by Design, (ii) Mechanical Behavior of Materials, (iii) Physical Properties of Materials, (iv) Synthesis and Processing, and (v) Earth Materials and Processes.

1) In the Materials by Design area, the focus is to establish the experimental techniques and theoretical foundations needed to facilitate the hierarchical design and bottom-up assembly of multifunctional materials that will enable the implementation of advanced materials concepts including transformational optics, biomimetics and smart materials.
2) In the Mechanical Behavior of Materials area, the focus is to reveal underlying design principles and exploit emerging force-activated phenomena in a wide range of advanced materials to demonstrate unprecedented mechanical properties and complementary behaviors.
3) In the Physical Properties of Materials area, the focus is to elucidate fundamental mechanisms responsible for achieving extraordinary electronic, photonic, magnetic and thermal properties in advanced materials to enable future Army relevant innovations.
4) In Synthesis and Processing of Materials, the focus is to discover and illuminate the governing processing-microstructure-property relationships for optimal creation of superior structural and bulk nanostructured materials.

Materials Science supports the Materials Research Campaign by aggressively seeking to extend the state-of-the-art in materials design, mechanical behavior of materials, physical properties of materials, and synthesis and processing research. It supports the Sciences for Lethality and Protection Campaign with extraordinary lightweight materials, force-activated materials, stabilized nanostructured materials, manufacturing process science, novel electronics, and advanced sensory materials. It supports the Sciences for Maneuver Campaign with unique materials for advanced power storage and generation and lightweight structures, in addition to low-cost manufacturing and repair processes. It also supports the Computational Sciences Campaign with research efforts that integrate computational theory and precision experimental measurement to design and optimize advanced materials.

PERSONNEL REQUIREMENTS:

i. Near-Term (FY16-FY20): No new requirements beyond existing personnel.
ii. Mid-Term (FY21-FY26): No new requirements beyond existing personnel.

INFRASTRUCTURE NEEDS:

i. Near-Term (FY16-FY20):
   a. Components of ARL's Extramural Basic Research Campaign will relocate to a technologically-superior space in Research Triangle Park, NC – a burgeoning Innovation District – to better enable enhanced scientific interactions and transition opportunities. This move will provide updated space and technologies to facilitate the operational effectiveness of the laboratory to connect with its academic, small business, industrial, and international partners. This move will occur during FY16.
ii. Mid-term goals (FY21-FY26):
   a. None.

ALIGNMENT: This effort is aligned with the following Army Warfighting Challenges.

Army Warfighting Challenge	Description
1	Develop and sustain a high degree of situational understanding.
7	Assure uninterrupted access to critical communications and information links.
11	Conduct effective air-ground combined arms reconnaissance.
12	Conduct entry operations.
13	Establish and maintain security across wide areas (wide area security).
15	Conduct combined arms air-ground maneuver.
19	Understand, visualize, describe, direct, lead, and assess operations.


EMPLOYEE ENTRANCE

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