U.S. ARMY COMBAT CAPABILITIES DEVELOPMENT COMMAND –
ARMY RESEARCH LABORATORY

Research To Enable Long Term Autonomy

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Army Research Office

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March 24 2021

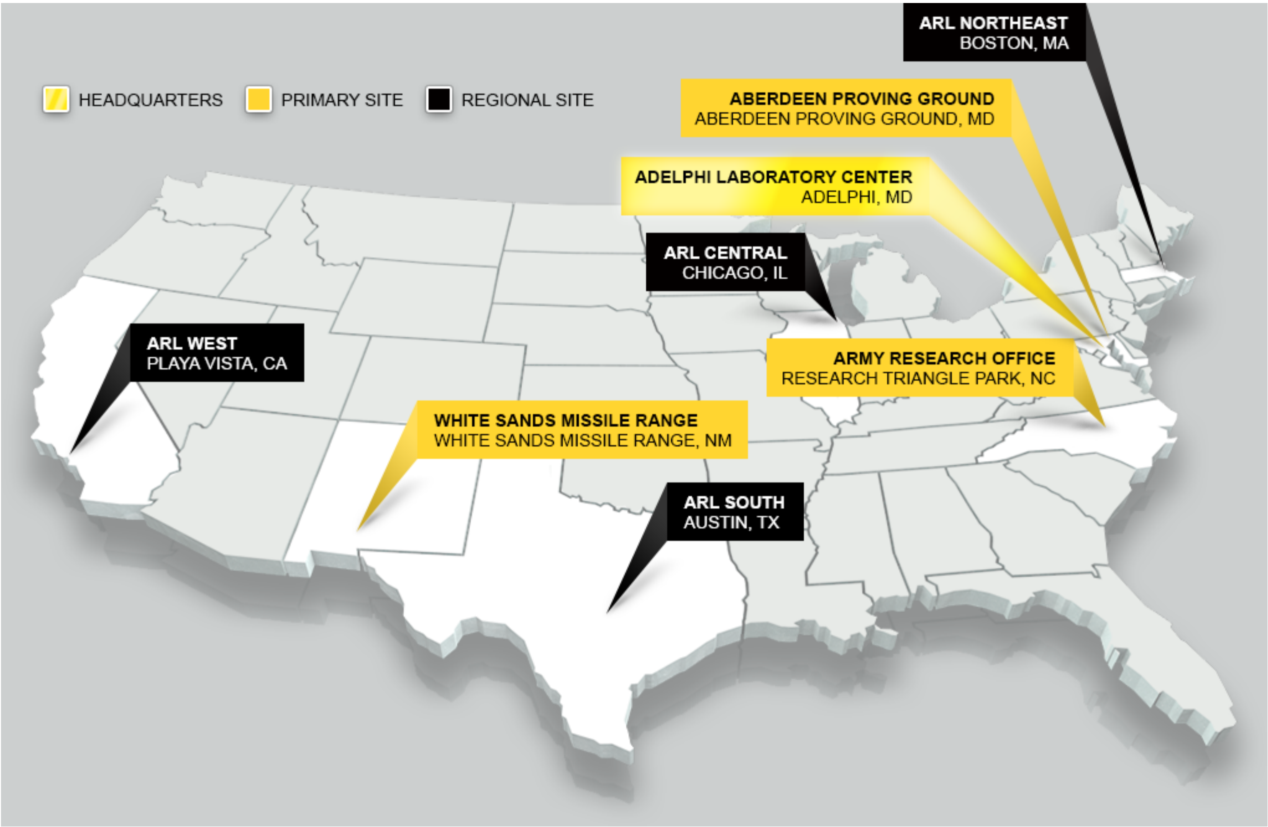
OUTLINE

- **Introduction**
- **Long Term Operations**
- **Research Areas to Support Long-Term Autonomy**
  - *Knowledge Representation, Reasoning and Decision Making*
  - *Learning Theory, Methodology, and Techniques*
  - *Assured Operations*
  - *Interaction*
- ***Opportunities***

Long-term autonomy is the ability to operate autonomously under no/or minimal supervision for days, weeks, months or even years.

ARMY RESEARCH LABORATORY

The Army's Corporate Research Laboratory provides foundational research in support of U.S. Army Modernization, and is focused on disruptive science and technology for the long term by performing research to answer the hardest S&T questions for future Army capabilities.



https://www.arl.army.mil/

ARMY RESEARCH OFFICE

Mission: Drive cutting edge and disruptive scientific discoveries that will enable crucial future Army capabilities through high-risk, high payoff research opportunities

Physical Sciences Division

Branches:

- Chemical Sciences
- Life Sciences
- Physics

Engineering Sciences Division

Branches:

- Electronics Branch
- Materials Sciences
- Mechanical Sciences

Information Sciences Division

Branches:

- Computing Sciences
- Network Sciences
- Mathematical Sciences

Websites:

https://www.arl.army.mil/who-we-are/aro/

https://www.arl.army.mil/wp-content/uploads/2019/12/arl-baa-ARO-BAA-Amendment-6.pdf

ISD Scientific Programs

- Information Science Division
  - Mathematics Branch
    - Computational Mathematics
    - Modeling of Complex Systems
    - Biomathematics
  - Computing Science Branch
    - Knowledge Systems
    - Information Processing & Fusion
    - Computational Architectures & Visualization
    - Intelligent Cyber-Physical Systems
  - Network Science Branch
    - Information Assurance
    - Social & Cognitive Networks
    - Communication Networks
    - Multi-agent Network Control

LONG TERM AUTONOMY

Future intelligent systems will need to perform a variety of tasks in complex, possibly contested, open worlds for extended periods of time

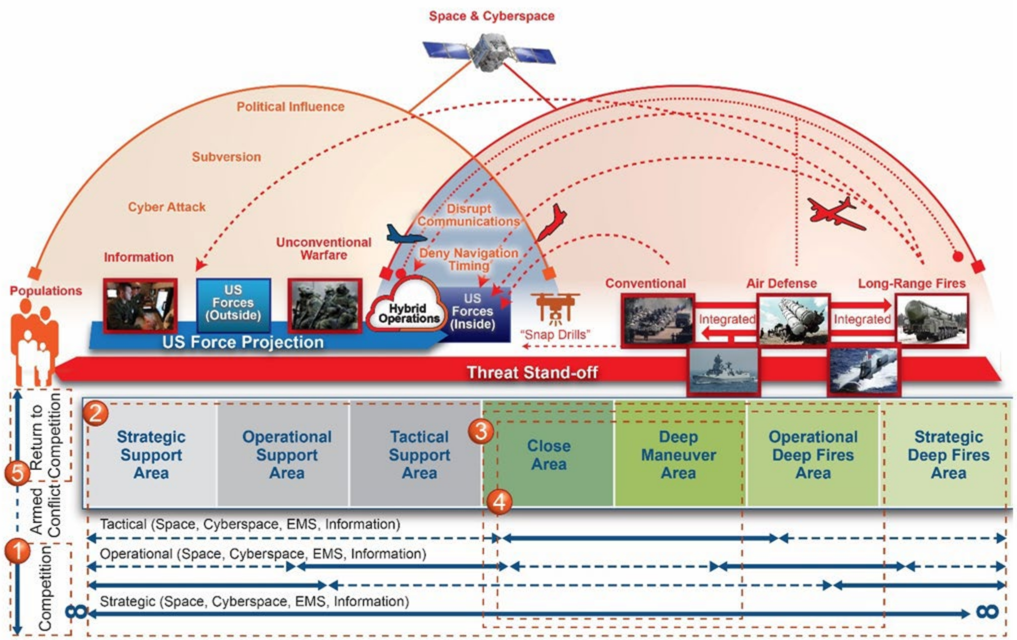
They *will* encounter previously unseen:

- **Environments**
- **Objects and Activities**
- **Contexts**

Future systems will need to adapt to

- **Changing internal and external conditions**
- **New information**
- **New and complex problems**

WHY DOES THE ARMY CARE?



Multi-Domain Operations:

……

Multi-domain formations conduct independent maneuver by continuing operations in a contested environment …. Brigades, divisions, and corps, specifically, require organic mission command, ISR, and sustainment capabilities to maintain offensive operations for several days despite highly contested lines of communications.

Fighting in Urban and Complex Terrains:

"….Across the warfighting functions --whether its intelligence, surveillance or reconnaissance, collections, maneuver, force protection, command and control, logistics and sustainment--all of those things are complicated and challenged by the compartmentalized terrain that's present in the urban environment and the 3-dimensional nature of the urban environment, which can include the subterranean environment….."

https://www.army.mil/article/215731/army_wargames_shape_the_future_of_urban_warfare

ARL'S HISTORY IN INTELLIGENT SYSTEMS

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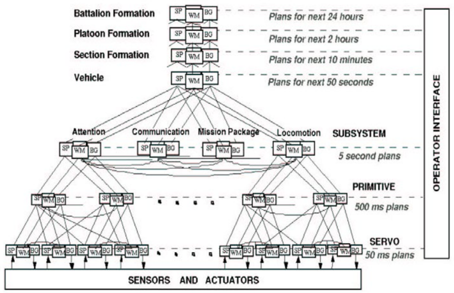
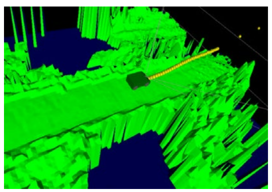
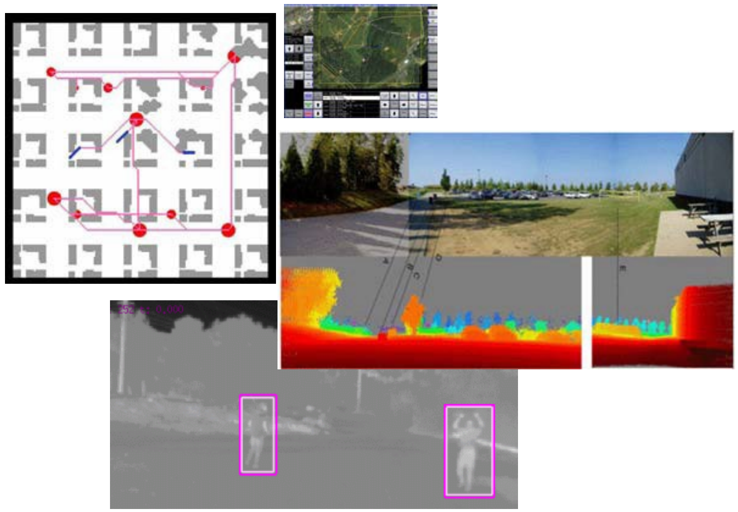






Demo III
~1998 - 2000

CTA
2002 - 2007

Robotics CTA
2009 - 2019

Distributed and Collaborative Intelligent Systems and Technology

Micro Autonomous Systems CTA
2008 - 2017

CTA- Collaborative Technology Alliance

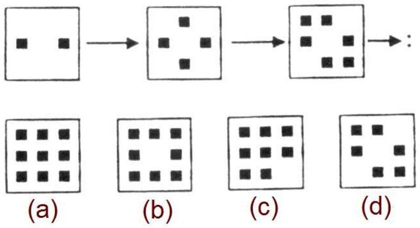
Research Areas to Support Long-Term Autonomy

- *Knowledge Representation, Reasoning and Decision Making*
- *Learning Theory, Methodology, and Techniques*
- *Assured Operations*
- *Interaction*

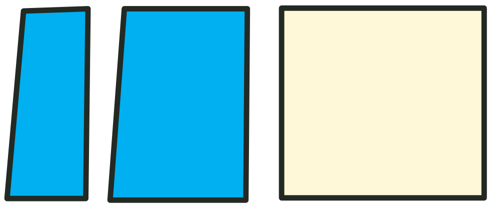
KNOWLEDGE REPRESENTATION, REASONING AND DECISION MAKING

Issues

- Representation and storage of information and the ability to for both long and short term memory that enables quick retrieval of pertinent information
- Optimizing the use of limited on-board storage capacity, and intermittent access to external knowledge stores.
- Developing new information through abstraction, analogy, reflection and learning



Sequencing



Spatial Reasoning

Can it move?

MANAGING MEMORY

Issues:

What to store to support diverse (sometimes simultaneous) tasks

Context is task dependent!

Retrieval mechanisms

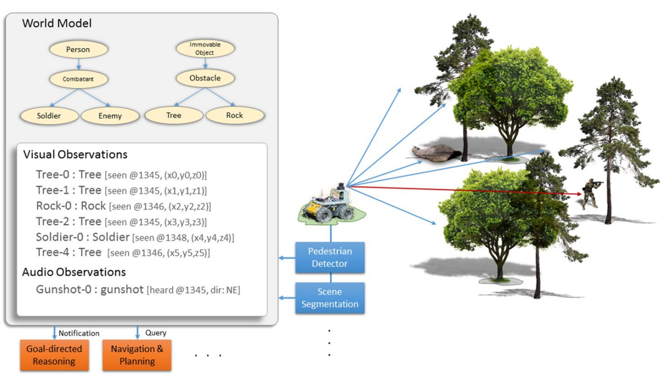
Effective use of analogy to solve problems

Updating knowledge

Effective integration of externally supplied knowledge with observations

Effective use of reflection and abstraction to add information to the world model

Lessons from human/animal memory



Semantic World Model able to support ontological queries, goal directed reasoning, navigation and planning

Adding Knowledge to the World Model

Abstraction

- Guide exploration and generalization
- Facilitate trade-offs
- Simplify computations
- Provides a principled method for scaling learning

Reflection

- Make inferences from observations gathered at different times and places
- Make connections between current observations and previously stored knowledge and beliefs

KNOWLEDGE-GUIDED SCENE GRAPH REASONING FOR VISUAL UNDERSTANDING

YOUNGCAN CAO (UTSA)

Objective

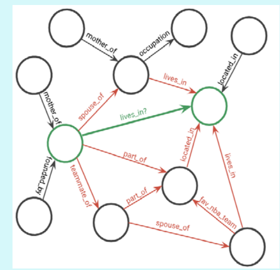
Establish new capabilities on knowledge-guided visual scene understanding, by generating and reasoning over scene graphs with the help of external commonsense knowledge.

Approach

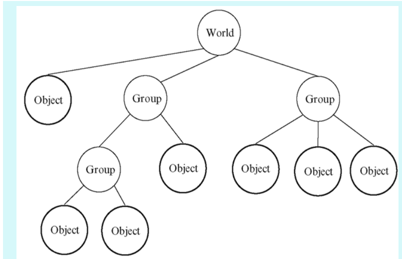
- Use graph embedding techniques to align scene graphs with related knowledge graphs derived from text sources.
- Extends methods from open set recognition and zero shot learning to discover novel categories in open environments.
- Develop techniques to improve scene understanding from sequences of video frames.

Video Understanding

Apply graph based methods to develop a meta graph that adds newly encountered objects and relationships to an initial graph based on the first frame of the video.



Knowledge Graph



Scene Graph

Use text-based commonsense knowledge graphs to enrich (add expected nodes) and reason (predict relationships) for image-based scene graphs

LEARNING THEORY, METHODOLOGY, AND TECHNIQUES

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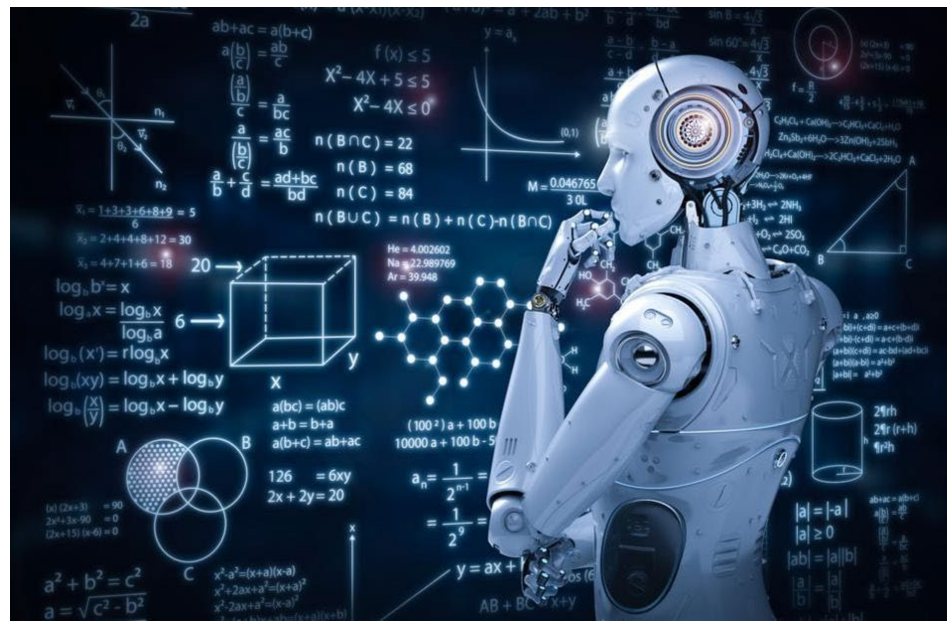
Theoretical foundation for on-line or continuous machine learning

- Approaches to address both the dimensionality challenges and temporal characteristics that may be evolving continuously
- Approaches to continuous learning will allow systems to adapt to changing contexts and environments while maintaining previously learned knowledge

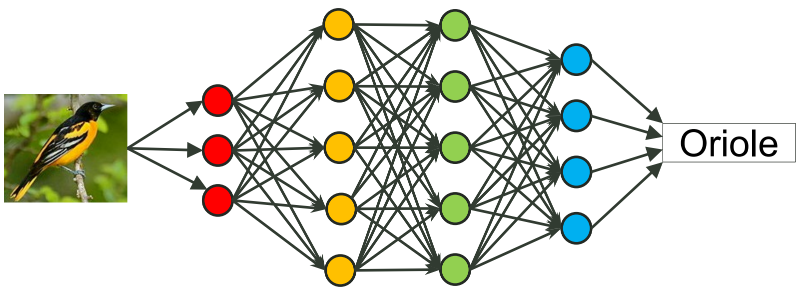
Issues:

- "Safe" online learning
- Intrinsically Motivated learning
- Time constrained learning
- A theory of few shot learning
- Dealing with dynamic, dirty, deceptive, dinky datasets
- Multi-task learning
- Generalization



Why Machine Learning Needs Semantics Not Just Statistics, Kalev Leetaru, Forbes, Jan 15, 2019

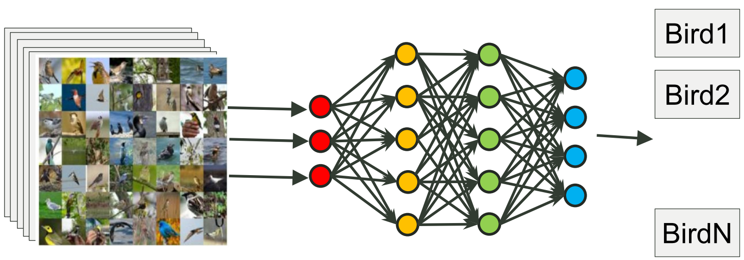
USING NEURAL NETWORKS IN ON-LINE SETTINGS



A neural network is a mathematical function that transforms an input signal (image) to a classification (label)

- Nodes act like neurons selectively transmitting information from one layer to the next
- A weight on each arrow determines the importance of information passing from one node to the next

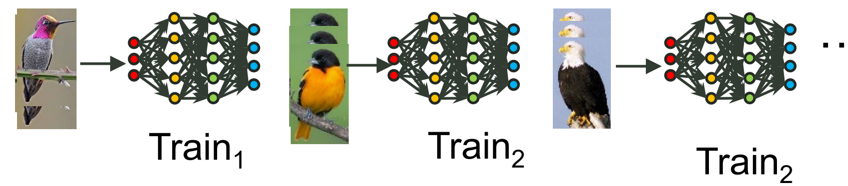
Off-line Learning



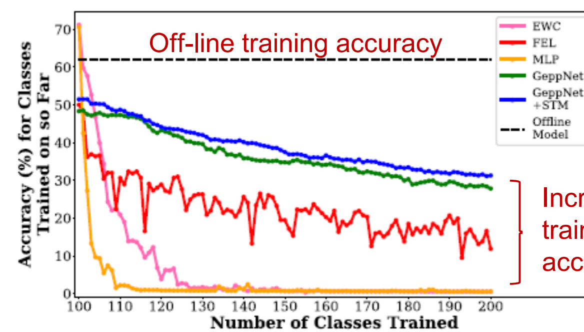
Massive datasets “train” the weights to give the best performance for all the classifications.

These are the neural nets that make the news for identifying objects, patterns, and faces.

Incremental or On-line Training



- Small datasets with a few classes introduced over time.
- Network retrained each time new data is added.



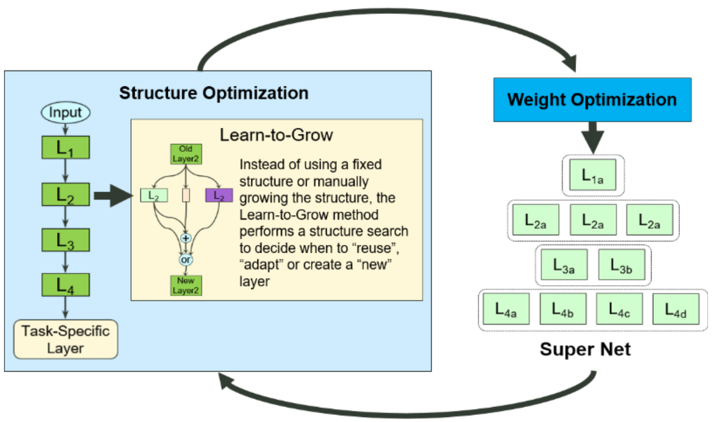
Neural Networks have a tendency to forget previously learned information – ***Catastrophic Forgetting***

IMPROVED SEQUENTIAL LEARNING WITH DEEP NEURAL NETWORKS: WU (NCSU)

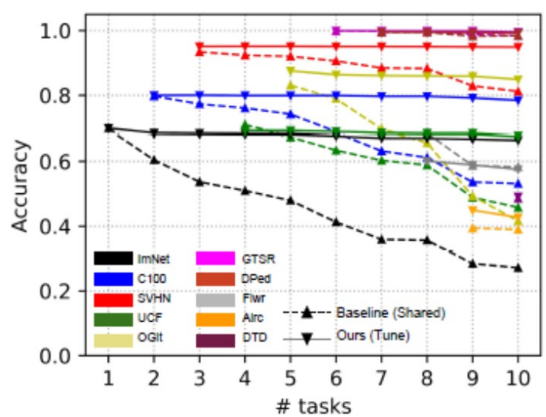
Goal: Address the catastrophic forgetting problem in continuous machine learning

Approach:

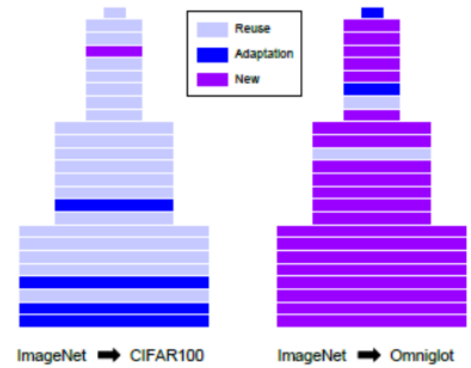
- Redesign deep neural network training process to explicitly separate the learning of the model structure from the estimation of model parameters.
- Allow network to grow or adapt as new tasks are added



Xilai Li,Yingbo Zhou, **Tianfu Wu**,Richard Socher. Caiming Xiong



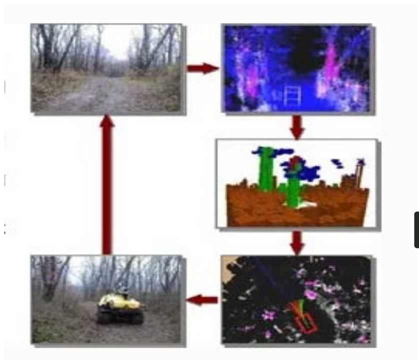
Improved performance in sequential learning tasks



Reuse of layers for related tasks

ASSURED OPERATIONS

- **Test, Evaluation, Verification and Validation**
- **Secure operations**
- **Robust long term operations in poorly understood, dynamic environments**



Component Testing

Reliable Task Performance

Issues

- **Test, Evaluation, Verification and Validation for intelligent systems is a nascent field that needs rigorous theoretical underpinnings and practical tools.**

…one study has asserted that in order to demonstrate a driverless car is as safe as humans, at least 275 million miles must be driven, which would take possibly up to a decade under current testing protocol

– Shares characteristics with model checking and formal methods but..

- Requires a systems-level evaluation of interacting components
- Looking for relatively rare event sequences
- Datasets, simulations and field tests need to include unsafe, aggressive, and adversarial behaviors for other actors in the scene
- Safety monitors that prevent vehicles from violating safety constraints – it's a start but not adequate

ROBUST LONG TERM OPERATIONS IN UNKNOWN ENVIRONMENTS

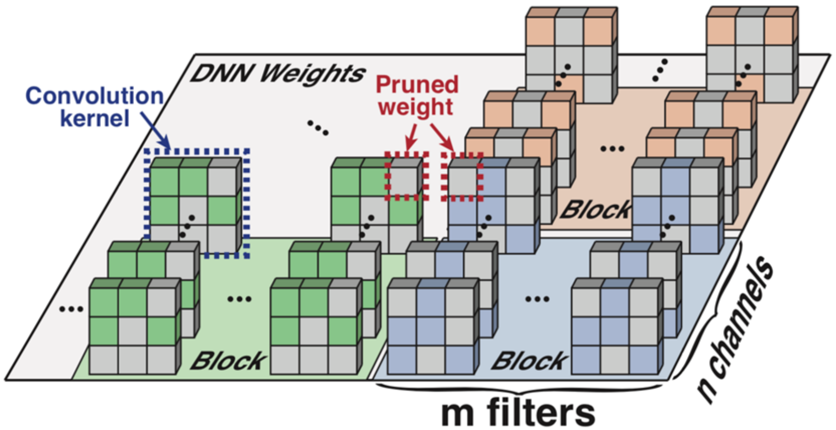
Issues

- **Recognizing and responding to failure**
  - Some work in reinforcement learning
- **Self evaluation**
- **Fault Tolerance/ Safety/ Adaptation**
  - Recent work on adaptation robot configurations to continue the mission
- **Meta Learning/Self Testing**
- **Real-time performance**
- **Working with Uncertainty**

REDESIGNING DEEP NEURAL NETWORKS FOR SMALL PROCESSORS: WANG (NEU)

Goal: Move Deep Neural Networks to constrained processors using compression techniques that are hardware-friendly while preserving accuracy.

- Achieve reasonable inference speeds on cell phone processors
- Achieve near state of the art object recognition

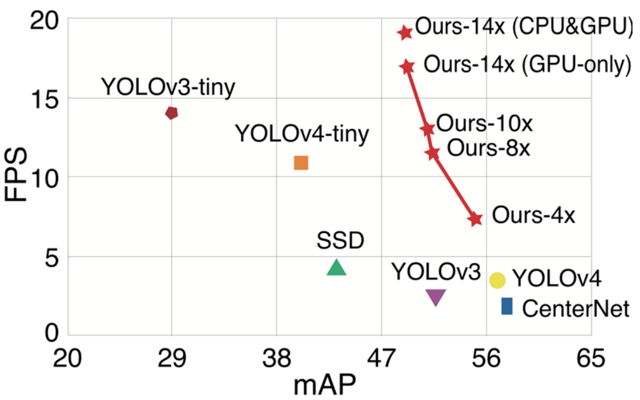


State of the Art Pruning Approaches	
Unstructured pruning	
+	High level of compression
-	Inefficient computations and long inference times
Structured pruning	
+	Efficient computation
-	Often eliminates important weights - less accurate models.

Block-pruning

- Divide the layer weights into equal-sized blocks of m filters and n channels
  - Size of the block is chosen based on the computational characteristics of the intended hardware
- Within block, prunes a group of weights at the same location in each filter and channel.
- GPU-CPU collaborative computing scheme further improves the computational efficiency.

FPS vs mAP on MS COCO dataset



INTERACTION

Future autonomous systems must interact physically with humans and other intelligent systems operating in the same space, remotely with spatially distant entities, and virtually in cyberspace with intelligent software agents.

Enable humans and robots to share the same space and work together on complex tasks.

Issues

- Effective human/system interaction during training
- Effective management of faulty or unexpected behavior
- Modeling human actions, intentions and beliefs

Sample Topics

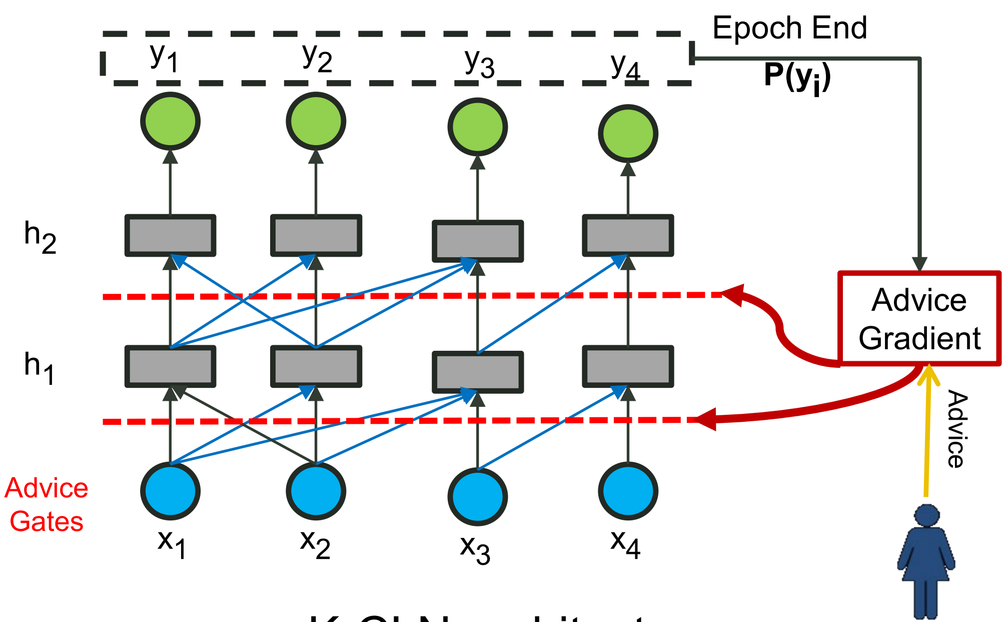
- Learning with human advice
- Teaming in different domains
- Adversarial Interactions
- Intermittent Communication
- Modeling Humans (Theory of Mind)

HUMAN GUIDED UNIFIED LEARNING OF TRACTABLE DEEP PROBABILISTIC MODELS S. NATARAJAN (UTD)

Objectives

- Develop probabilistic models that allow for rich human interaction. The key idea is to treat the experts as domain experts and solicit information from them as needed.

- develop algorithms that can reason about what they know, explain their questions in a human interpretable manner and obtain richer forms of inputs than mere labels.



K-CLN architecture

Approach

- Develop neuro-symbolic learning approaches that employ rich representations to model the domain structure and effective learning algorithms to learn from data.

-The use of symbolic representations allow for a seamless interaction with the experts, both in terms of explainability and elicitation

CONCLUSIONS

DEVCOM ARMY RESEARCH LABORATORY

Outlined a program to support long term autonomy

Identified 4 key research areas:

- Knowledge Representation, Reasoning and Decision Making
- Learning Theory, Methodology, and Techniques
- Assured Operations
- Interaction

Opportunities

STUDENT OPPORTUNITIES

- **ORAU RAP Fellowship Program**
  - The U.S. Army Research Laboratory's (ARL) Research Associateship Program (RAP) prepares science and engineering researchers for the future. Fellowship recipients are able to advance at a top research facility while contributing to the important mission of the Laboratory
- **High School Apprenticeship Program (HSAP)/Undergraduate Research Apprenticeship Program (URAP)**
  - Provide authentic science and engineering research experience to high school students interested in pursuing STEM, and undergraduate students pursuing science and engineering majors
- **College Qualified Leaders (CQL)**
  - ARL matches talented undergraduate students with scientists and engineers in a direct mentor-student relationship, that provides the student with training, firsthand research experience and exposure to DoD laboratories that is unparalleled at most colleges
- **Science, Mathematics and Research for Transformation (SMART)**
  - A Scholarship for Service Program that provides the opportunity for students pursuing an undergraduate or graduate degree in Science, Technology, Engineering and Mathematics (STEM) disciplines to receive a full scholarship and be gainfully employed upon degree completion

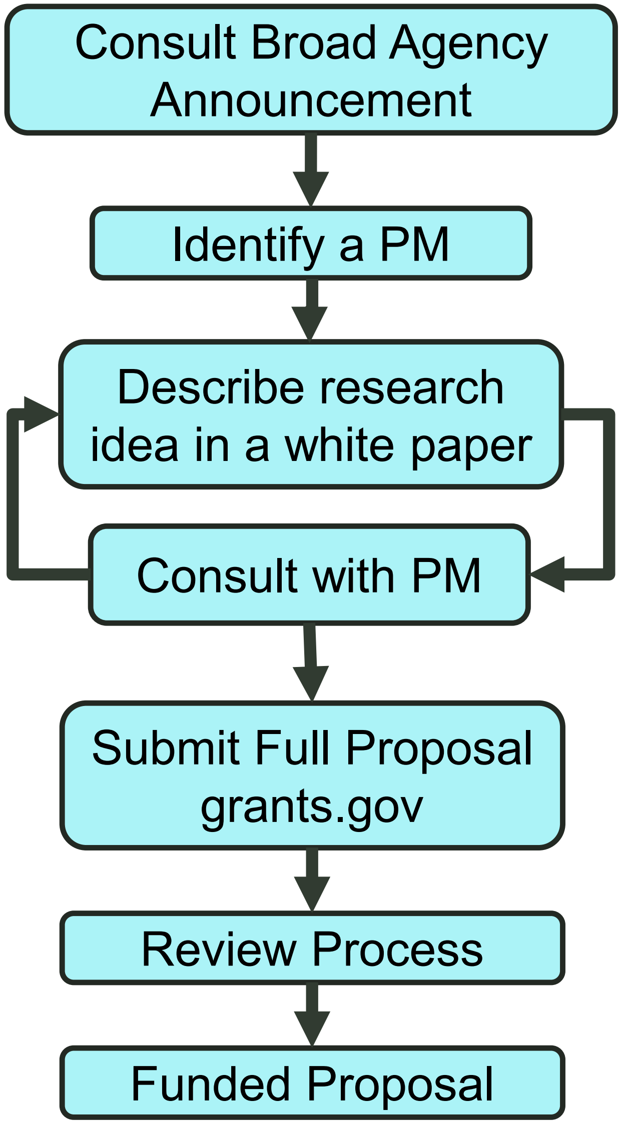
Website:
https://www.arl.army.mil/careers/students/college-and-university/
https://www.arl.army.mil/wp-content/uploads/2019/11/publication-university-programs.pdf

FUNDING OPPORTUNITIES

- Single Investigator Grant
- Short Term Innovative Research Grant
  - Support rapid, short-term investigations to assess the merit of innovative new concepts in basic research
- Multi University Research Initiative
  - A tri-service Department of Defense program that supports research teams whose research efforts intersect more than one traditional science and engineering discipline
- Early Career Program
  - Attract outstanding young university faculty members to pursue fundamental research in areas relevant to the Army (within 5 years of PhD)
- Presidential Early Career Awards for Scientists and Engineers
- Defense University Research Instrumentation Program
  - Enables universities to perform state-of-the-art research that boosts the United States' technological edge

Websites:
https://www.arl.army.mil/who-we-are/aro/
https://www.arl.army.mil/wp-content/uploads/2019/12/arl-baa-ARO-BAA-Amendment-6.pdf

WORKING WITH ARO PROGRAM MANAGERS



- ARO is interested in basic research that develops the theory and principles that underpin science and technologies
- Research needs to support Army goals
- White paper allows PM and research to refine the research ideas to align them with the goals of the program
- PMs share white papers and proposals
- Review process involves 3 academic reviewers and 1 Army scientists
- Process requires patience!

CRITICAL ENABLERS – FROM ARMY PRIORITY RESEARCH AREAS

Army Priority Research Areas	ARL – ARO Investments
1. Disruptive Energetics: Greater than 2x energetic energy over smaller footprints.	Proposed ARL Program POM 22 led by ARO. Current ARO Investments design new energetic molecules that harness reactions with significant advances in the control of sensitivity (premature explosion), increases in propulsive and explosive power, and the development of materials.
2. RF Electronic Materials: Taking advantage of optical and thermal properties of diamond materials for directed energy.	Proposed ARL Program POM 22 led by ARO. Current ARO Investments drives basic research to enable unprecedented devices that exploit optical and electronic properties of matter for sensing, information technology, optical displays, and laser components.
3. Quantum: Optimized information transfer, sensing, and communication with unparalleled security.	ARO investments drives basic research to identify and explore quantum process in beyond-classical imaging, sensing and precision measurements, materials simulation and design, exponential speed-ups in computation, and new kinds of security protocols for networking
4. Hypersonic Flight: Aerodynamics, materials, and processes.	ARO investments drives basic research underlying the flow of combusting and non-combusting fluids, and the themo-chemical physics in energetic material initiation and burning. Fundamental discoveries in support of the Propulsion Sciences for disruptive approaches to advanced mobility and maneuver.
5. Artificial Intelligence: Increasing speed and agility in which we respond to emerging threats.	ARO investments drives understanding of how human intelligence can be automated to build AI systems that are capable of being effective decision aides, efficient as components of autonomous systems and robots, allowing robots to be near-human team-mates in Human-Agent teams of the future.
6. Autonomy: Maneuverability and off-road mobility of platforms.	ARO investments develop innovative approaches for processing high performance structural materials and develop innovative new materials with unprecedented combinations and formulations of mechanical properties for breakthrough increases in agility and logistical efficiency.
7. Synthetic Biology: Reactive and responsive skins/spectrally selective materials/anti- materiel properties.	ARO investments specifically looks at microbes, biomolecules, DNA stability and mutagenesis, gene expression, and genetic regulatory pathways. Results will protect the Soldier from disease, develop sustainable bio manufacturing processes & wide range of bio-enabled, electro-optical applications.
8. Material by Design: Protection overmatch against future threats.	ARO investments specifically looks for extraordinary materials that can be rapidly manufactured, grown, synthesized, and produced cost-effectively to enable highly mobile, information reliant, lethal, and protected Army platforms.
9. Science of Additive Manufacturing: For next generation munitions for increased range and lethality.	ARO investments drives understanding of basic research to predict and control material behavior during synthesis, processing and operation, and to predict property changes over time, based on multi-scale design of materials, exquisite control and engineering of defects, and precision integration of materials

Computing Sciences Key Thrusts

Knowledge Systems

Adversarial Reasoning (Game Theory, Decision Theory, Bounded Rationality)

Natural Language Processing & Affective Computing


FOREIGN AFFAIRS

Yemen Calling

Seven Things Cell Data Reveal About Life In the Republic

Network Representation and reasoning.

Knowledge Management

<u>Army Impacts:</u> Situational Awareness, Planning, Force Protection

Intelligent Cyber-Physical Systems

Advanced Learning Theory, Methodology, and Techniques

Knowledge Representation, Reasoning and Decision Making

Assured Operations

Interaction

<u>Army Impacts:</u> Intelligent battlefield systems for soldiers

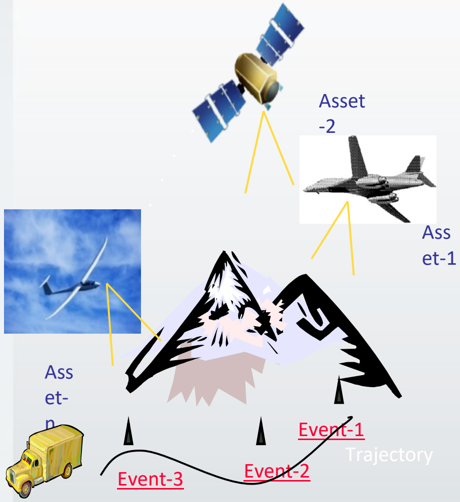
Information Processing & Fusion

Neuromorphic Learning

Distributed Fusion

Intelligent Active Sensing

Semantic Information Theory



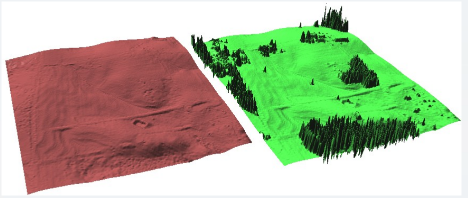
<u>Army Impacts:</u> Better C4ISR and decision making

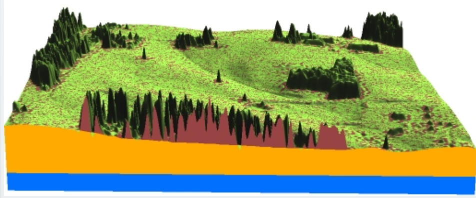
Computational Architect. & Visualization

Modeling, Simulation and Visualization

Resource optimization in Multi-core and Exa-scale computing

Optimal Algorithms for Big Data





<u>Army Impacts:</u> Battlefield real-time computing; soldier training through simulation

Network Sciences Key Thrusts

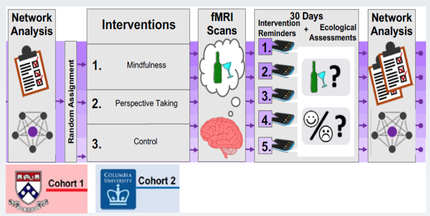
Information Assurance

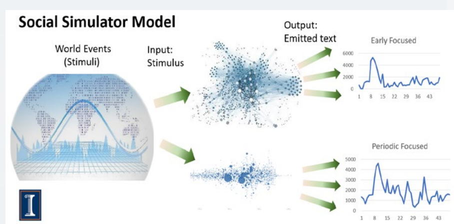
- Resilient and Robust Information Systems
- Autonomous cyber defense with human teaming
- Highly Assured Mobile Communications

Army Impact: Better preparation and more effective mitigation of cyber threats, cyber situational awareness

Social and Cognitive Networks

- Designing High Performance Teams
- Computational Social Science
- Connecting social, cognitive, and neural networks

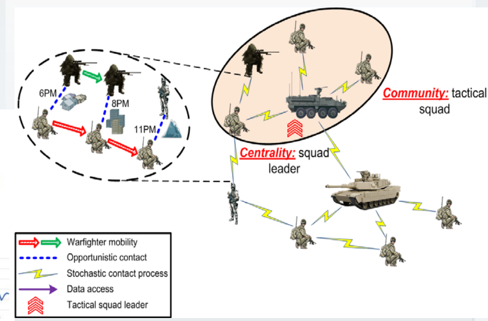




Army Impact: Accelerated Team Learning, Effective Human-Agent Teaming, Community Cognitive Resilience, Simulation of Social Systems

Communication & Hybrid Networks

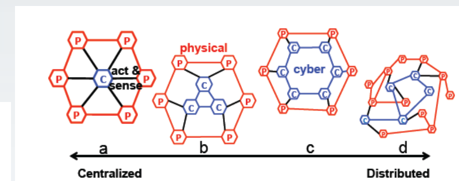
- Programmable and Mission Critical Networks
- Mobile Ad Hoc and Internet of Things Networks
- Interactions between Communications, Information and User Networks



Army Impact: Battlefield Internet of Things, Machine Learning for Wireless Networks, Exploitation of Quantum Networks

Multi-agent Network Control

- Distributed control and optimization
- Stochastic dynamical systems of networks of interacting agents
- Collective information processing



Army Impact: Battlefield Autonomy, Swarm systems, Neuro-cognition, Distributed information processing and assurance.

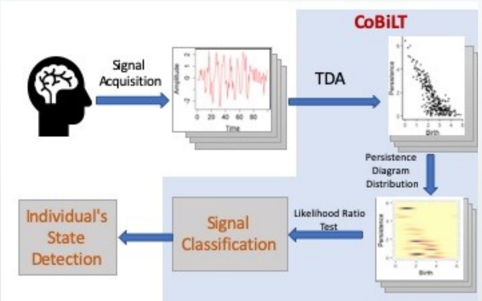
Mathematical Sciences Key Thrusts

Modeling of Complex Systems

Subspace methods/ non-smooth geometries

Mathematics for QIS

Homotopy spaces over Human/Human-Machine Interactions



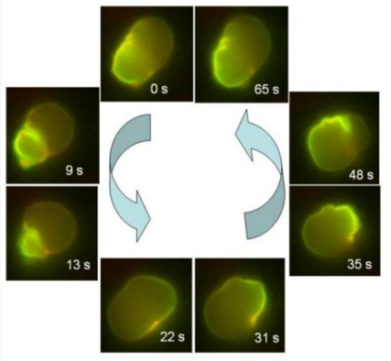
Army Impact: *Efficient data analysis/modeling, PNT, secure networking; threat detection; soldier protection*

Biomathematics

Computational Biology

Fundamental Laws of Biology

Multiscale/Inverse Methods



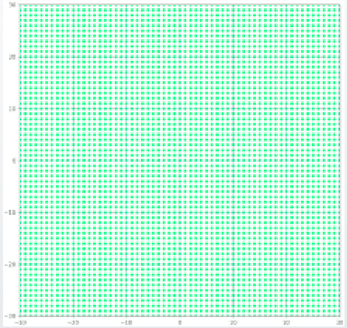
Army Impact: *Human performance, neuro-cognition, accelerated learning*

Computational Mathematics

Non-local/with-memory PDE methods

Efficient billion-dof systems

Twistronic multiscale methods



Army Impact: *Improved predictive wear and maintenance, precision fires, advanced energetics, advanced actuation and mobility, wearable low power electronics*