Emerging Directions in Network Science

US ARMY RDECOM

ARL

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U.S. Army Research Laboratory

6th Annual Network Science Workshop

April 23, 2012 @ West Point

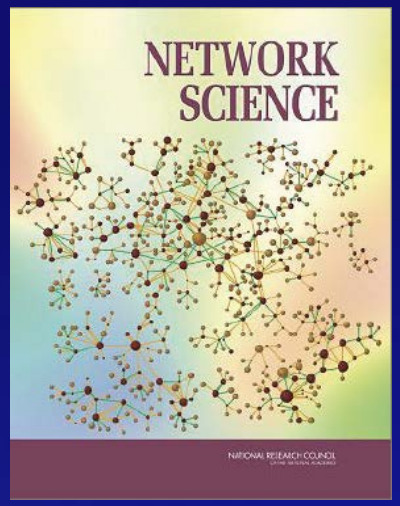
TOPICS

- 2005 NRC Report
- Trends & Emerging Challenges
- Emerging Research Directions
- Experimentation
- Army Programs Addressing Challenge

NRC Report on Network Science (2005)

DEFINITION

"The fundamental components of a network are its structure (nodes and links) and its dynamics, which together specify the network's properties (functions and behaviors). Core research principles should enable predictions of network behaviors, given the structure and dynamics of the network as inputs."



OVERARCHING CONCLUSIONS

- Networks have a pervasive influence in all aspects of life
- Fundamental knowledge to predict properties of networks is primitive
- Research is fragmented with disciplinary stovepipes

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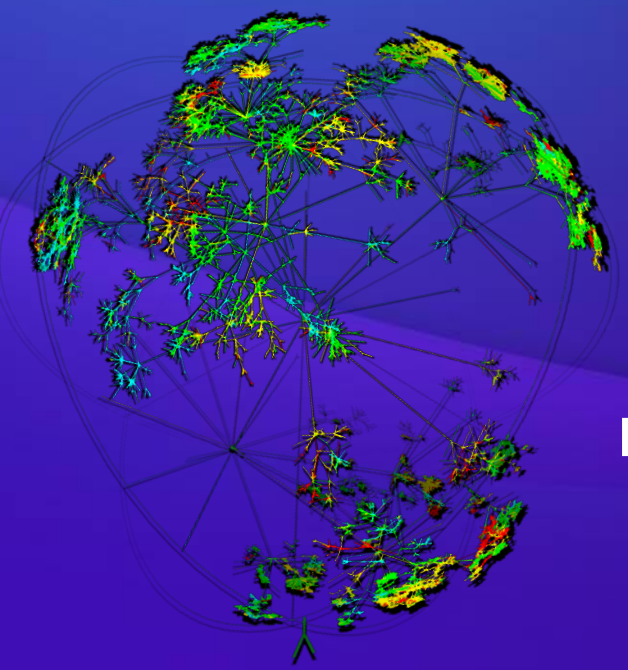
Major Research Challenges
from the 2005 NRC Report on Network Science

- Design & Synthesis of Networks to Obtain Desired Properties
- Dynamics, Spatial Location & Information Propagation in Networks



- Modeling & Analysis of Very Large Networks
- Robustness & Security of Networks

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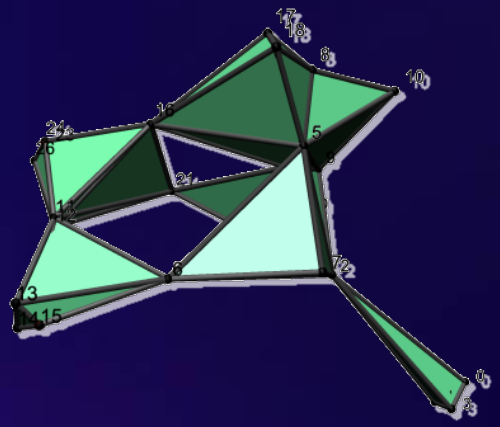
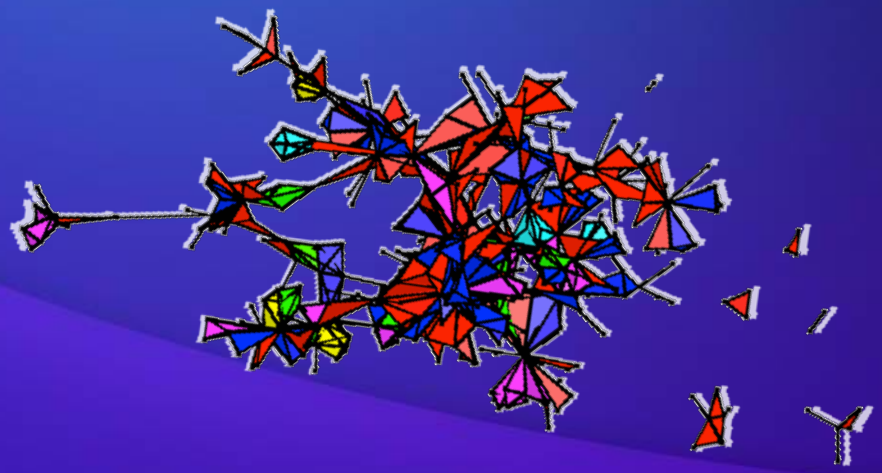
Major Research Challenges
from the 2005 NRC Report on Network Science

- **Abstracting Common Concepts Across Fields**



- **Increased Rigor & Mathematical Structure**



- **Better Experiments & Measurements of Network Science**

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TOPICS

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The Goal:
Exploit Full Potential of Composite Networks

Complex behaviors & interactions of communication, information, and social-cognitive networks must be understood, anticipated, and leveraged

HARD PROBLEMS

Assess

How to monitor, measure, & assess the performance & behavior of composite social/cognitive, information, & communication networks?

Model

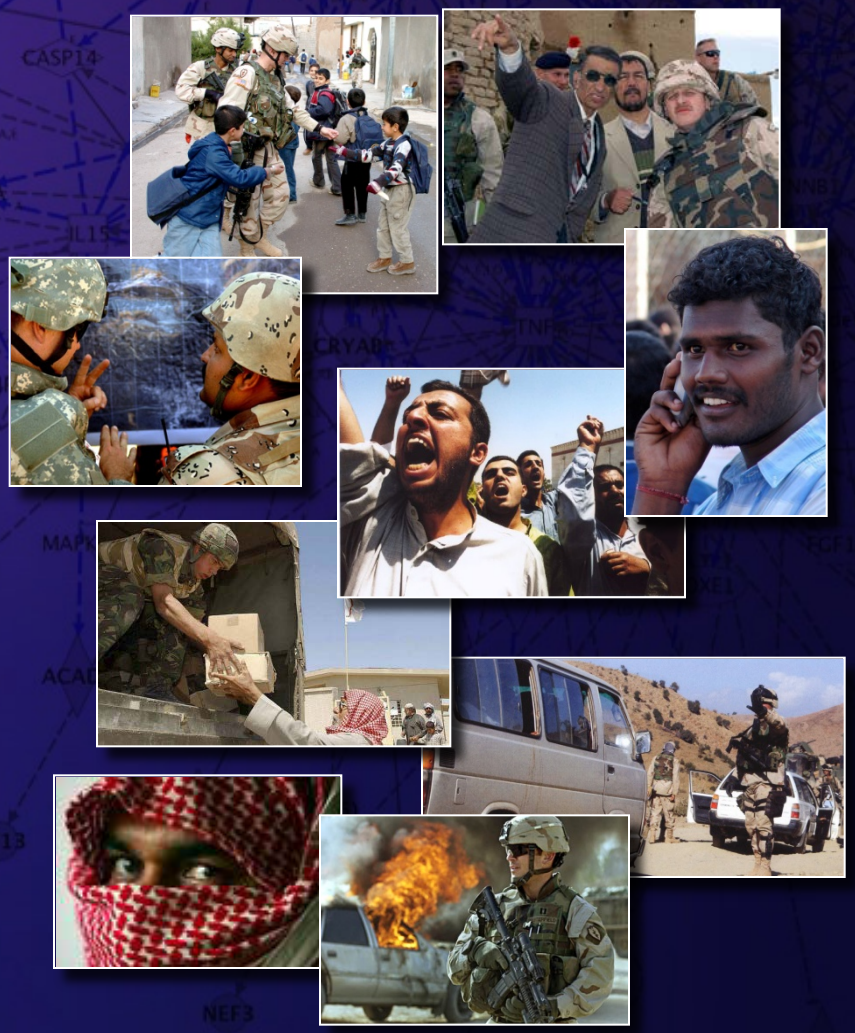
How to understand & quantify the dependencies & causalities in the complex networks?

Predict

How to predict the networks' evolution & upcoming risks (e.g., loss of information quality or trust)?

Influence

How to influence, adapt & optimize the behaviors of composite networks to support mission success?



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COLLABORATIVE VENTURES

Tools for Analysis and Design of Complex Multi-scale Networks MURI
University of California, Berkeley

Cyber Awareness Framework for Attack Analysis, Prediction & Visualization MURI
University of California Santa Barbara

Network Sciences
Collaborative Technology Alliance
BBN Technologies

Robotics
Collaborative Technology Alliance

Army High Performance Computing Research Center

Institute for Collaborative Biotechnologies

Network & Information Sciences
International Technology Alliance IBM

Mobile Network Modeling Institute
ARL

Micro Autonomous Systems & Technology
Collaborative Technology Alliance

Passive and Active Tomography of Covert Social Networks MURI
Harvard University

Cognition & Neuroergonomics
Collaborative Technology Alliance

Stochastic Control of Multi-scale Military Networks MURI
Ohio State University

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Rapid Growth in Complexity & Scope of All Network Genres

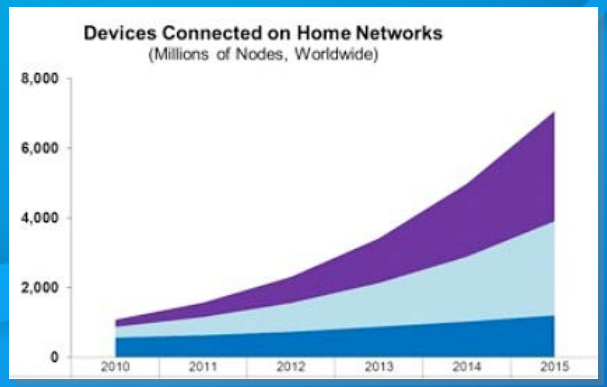
- **Increasing use of smart phones & commercial cellular networks**
- **Pervasive use of social media**
- **Continued explosive growth in volume of data →** Increasing dependence on information

- **Military operations** (e.g. counterinsurgency) **are increasingly complex**

Increasing Use of Smart Phones/ Commercial Cellular Networks

- **Smart phone/tablets becoming ubiquitous with networked multi-media apps**

6 billion mobile subscribers
(87% of population)
- 1.2 billion fixed lines, 50% broadband
- 1.2 billion active mobile broadband



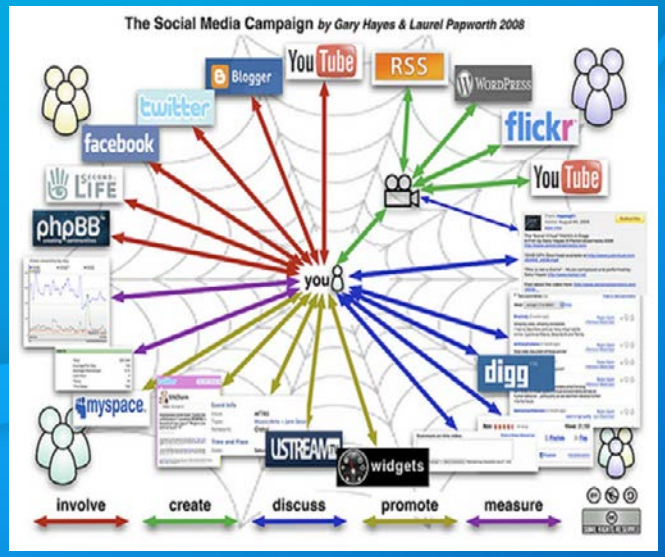
- **Increasing reliance by military on commercial infrastructure**
- **Future emergence of hybrid wireless & MANET comms**
- **Pervasive computing where sensors, cameras, video, gps are part of the network**

1.2 billion mobile web users
- 85% of 2011 handsets web-enabled
- 45% of population covered by 3G
- 1 million+ applications

Sources: mobiThinking, Park Associates Research, and ITU

Pervasive Use of Social Media

- **Social networks are becoming pervasive & increasing influential**



Pervasive Use

- 62% of those on internet use social networking
- 836 million Facebook users
- Over 15% of US internet activity is for Facebook
- 57% of adults use mobile internet

- **Explosion of group activity**
- **Online social networks & ubiquitous mobility enables spontaneous network creation**
- **Increasing connectivity & content creation (messages, videos, photos)**

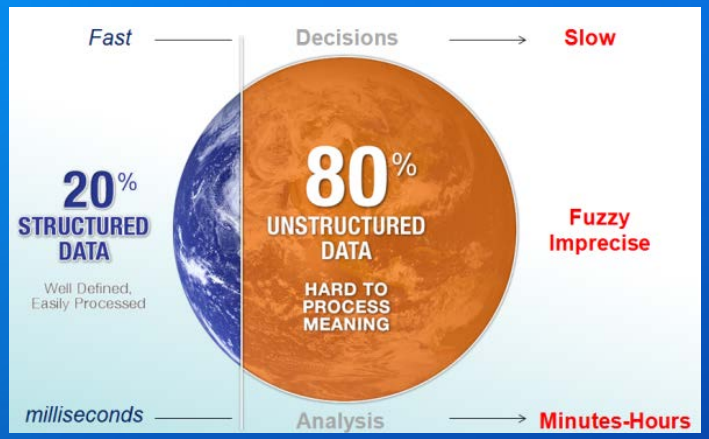
Content Explosion

- 30 billion pieces of content added/ month to Facebook
- 2 billion videos/day watched on YouTube
- 32 billion searches/month on Twitter

Sources: Gartner Group, Pew Internet, InternetWorldStats

Explosive Growth in Volume of Data

- **Increasing dependence on information**
- **Leading to data deluge, cognitive overload, & information overload**
- **Increasing production & need to process informal, unstructured data**
- **Increasing use of cloud computing & social networking to share information**

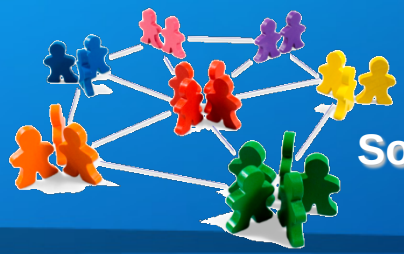


Source: TTI Vanguard Conference - Psydex

Military Operations Are Increasingly Complex

- Information & analysis being pushed to the lowest levels
- Shortened decision making time-scales
- Wider array of information sources, more inconsistencies present in data
- Analysis & information delivery increasingly coupled to decisions

Network Science Challenges
Commercial vs Military Networks

	Commercial	Military
Communications	▪ Fixed infrastructure ▪ Resource-rich ▪ Limited security constraints & interoperability by standards	▪ Mobile ad hoc & hybrid ▪ Resource-constrained ▪ High levels of security, coalition interoperability
Information	▪ Google search, information apps rapidly evolving ▪ Data mining & knowledge discovery tools	▪ Discovery of network attributes, semantic links, & structures needed ▪ Discovery/analytics of more heterogeneous, noisy, dynamic, & adversarial nets
 Social	▪ Pervasive use of social networking ▪ Social networking about connecting with friends/family	▪ Very limited use of social networking ▪ Adversarial social networking discovery

Increased complexity of design, discovery, prediction, & control

Increased interactions between comms, information, & social networks

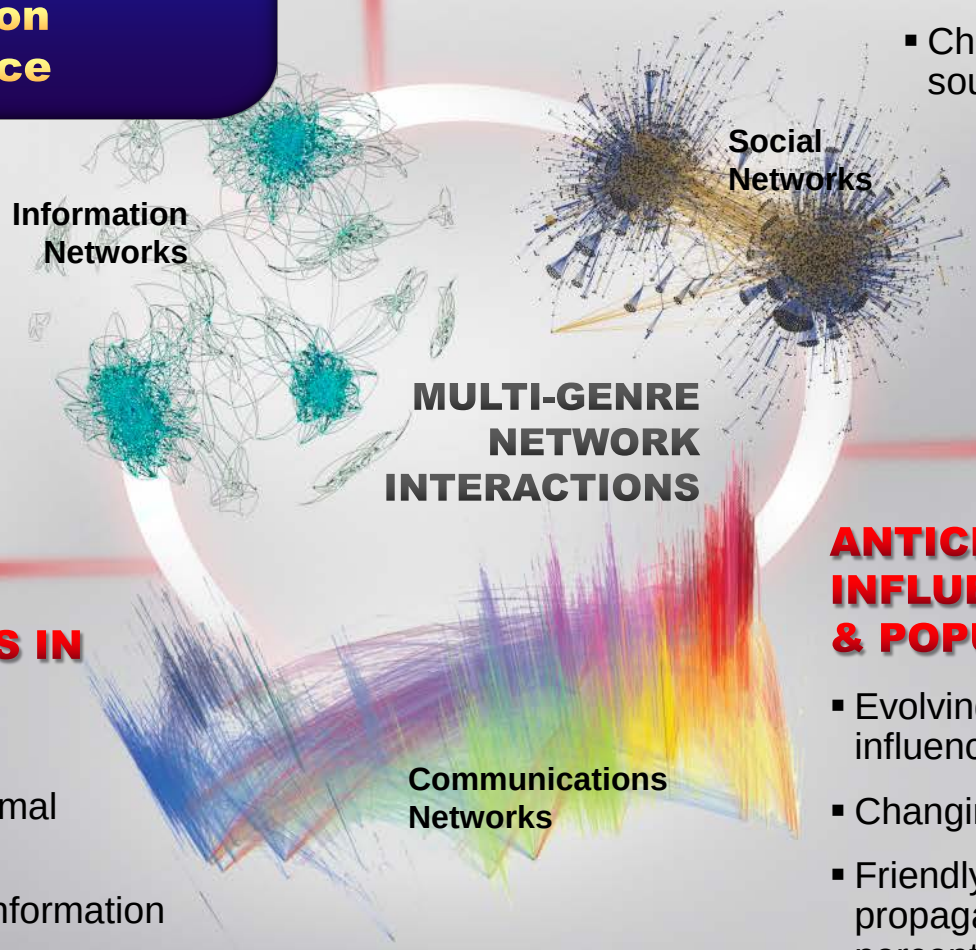
Understanding the Interplay Between Network Genres

Understand multi-genre network interdependencies & interactions

Develop a common underlying science

EXPLOITING DISTRIBUTED, DYNAMICALLY-CHANGING INFORMATION

- Evolving communication capabilities influence information collecting, processing, & distributing
- Changes in social network of sources & analysts



COMMUNICATIONS IN DYNAMIC ENVIRONMENTS

- Evolving formal & informal command structures
- Changes in available information
- Mobility & complex terrain affect connectivity

ANTICIPATING & INFLUENCING INSURGENCY & POPULATION ATTITUDES

- Evolving social structures, influence, & attitudes
- Changing communications structure
- Friendly information & insurgents' propaganda affect contacts, perceptions & connections

Understanding the Interplay Between Network Genres

Interest & Information

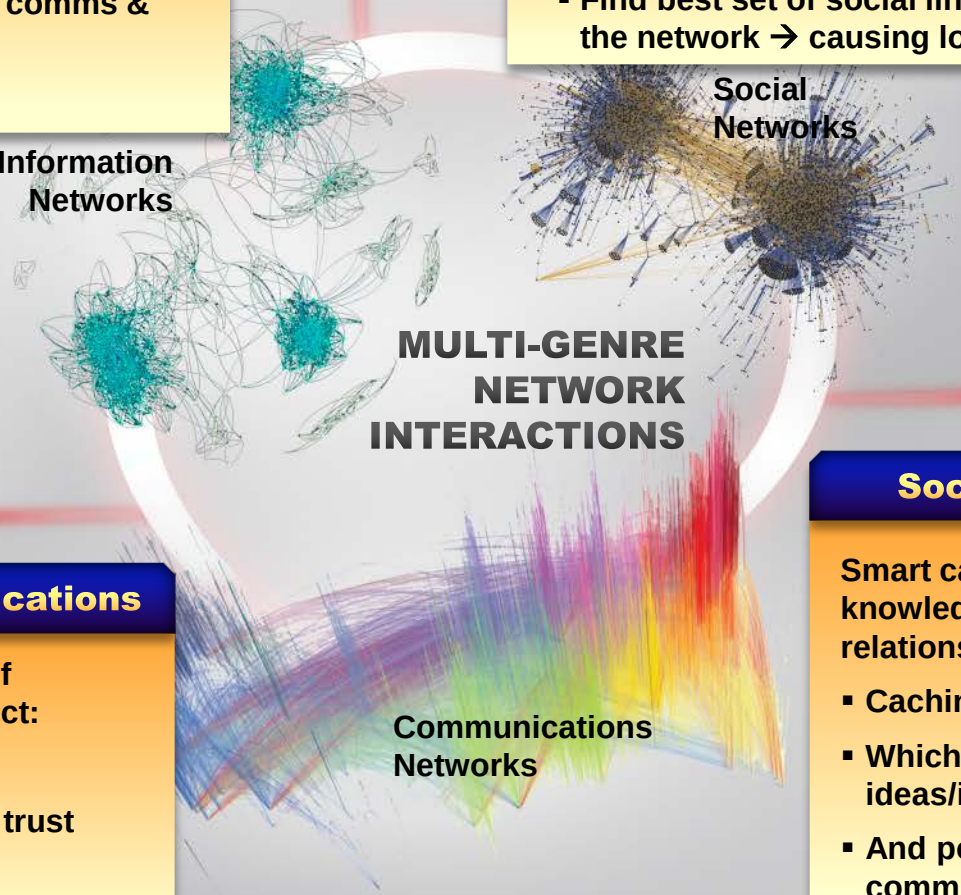
Interests dictate sources of info sought:

- Information access changes opinions, social ties, & network
- Social link formation may be predicted by analysis of comms & information behaviors
- Propaganda effects

Social Overlay on Comms/Information

Comms constrained by social requirements (e.g., chain of approval). Joint design may improve/disrupt:

- Add new strategic followers to a Twitter network so that the total time to reach everyone reduces dramatically
- Find best set of social links to thwart so as to fragment the network → causing long delays



Unreliable Communications

Reliability & availability of communication links affect:

- Social tie strengths
- Trust in information & trust of decisions
- Team effectiveness

Socially-Aware Caching

Smart caching techniques exploit knowledge of info sources & social relationships

- Caching affects availability/latency
- Which impacts spread of ideas/information
- And possible fragmentation of communities

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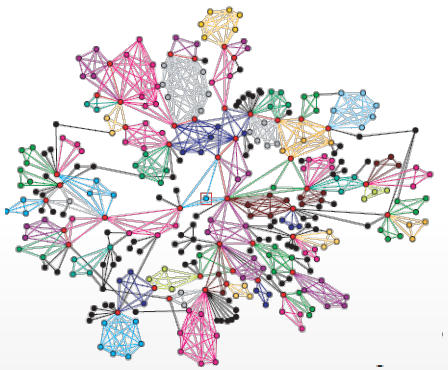
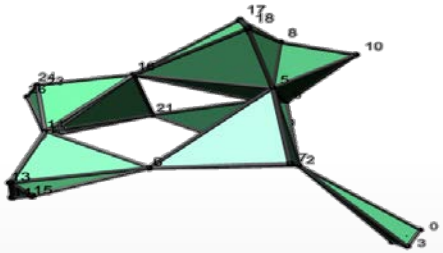
Emerging Directions in Network Science



Evolution & Dynamics of Inter-Genre Networks

Understand how multi-genre networks behave over time → dynamics, interactions, & co-evolution

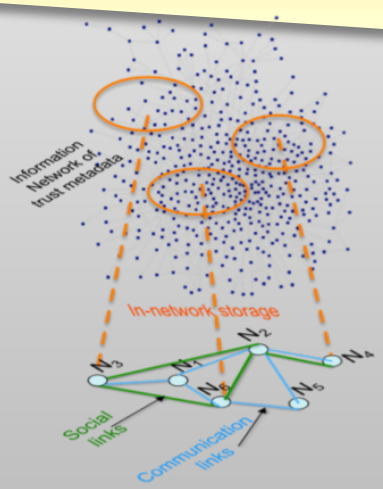


Quality of Information for Semantically-Adaptive Networks

Understand how to control network behaviors so that the capacity of the network to deliver relevant information can be maximized

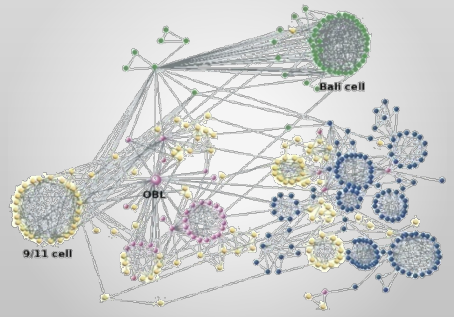
Information Processing for Distributed Understanding

Understand how information representation, discovery, & analytics contribute to distributed understanding & social influence

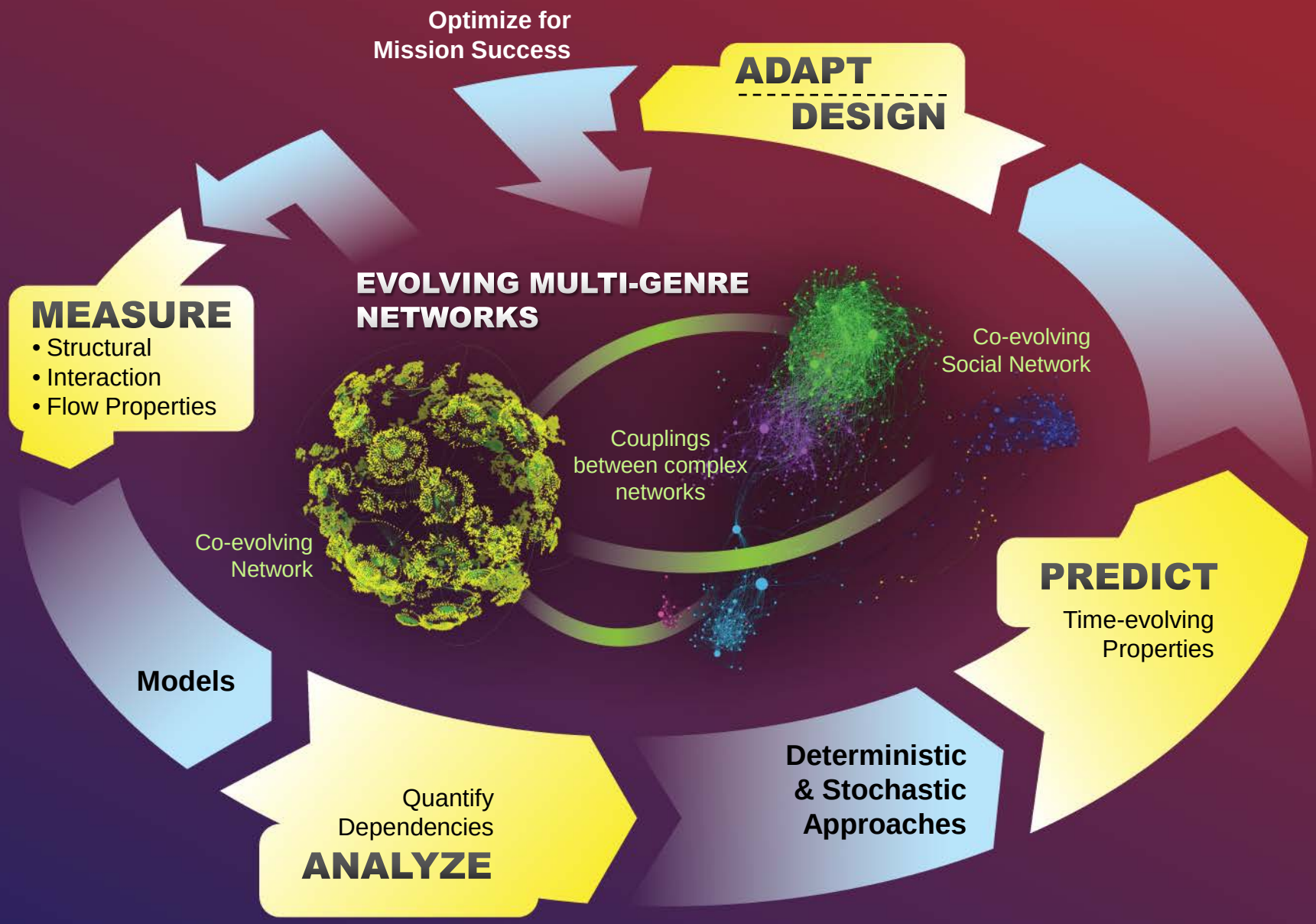


Trust in Networks

Understand trust & its impact on distributed decision-making in the presence of conflicting, incomplete or malicious information



Evolution & Dynamics in Multi-Genre Networks



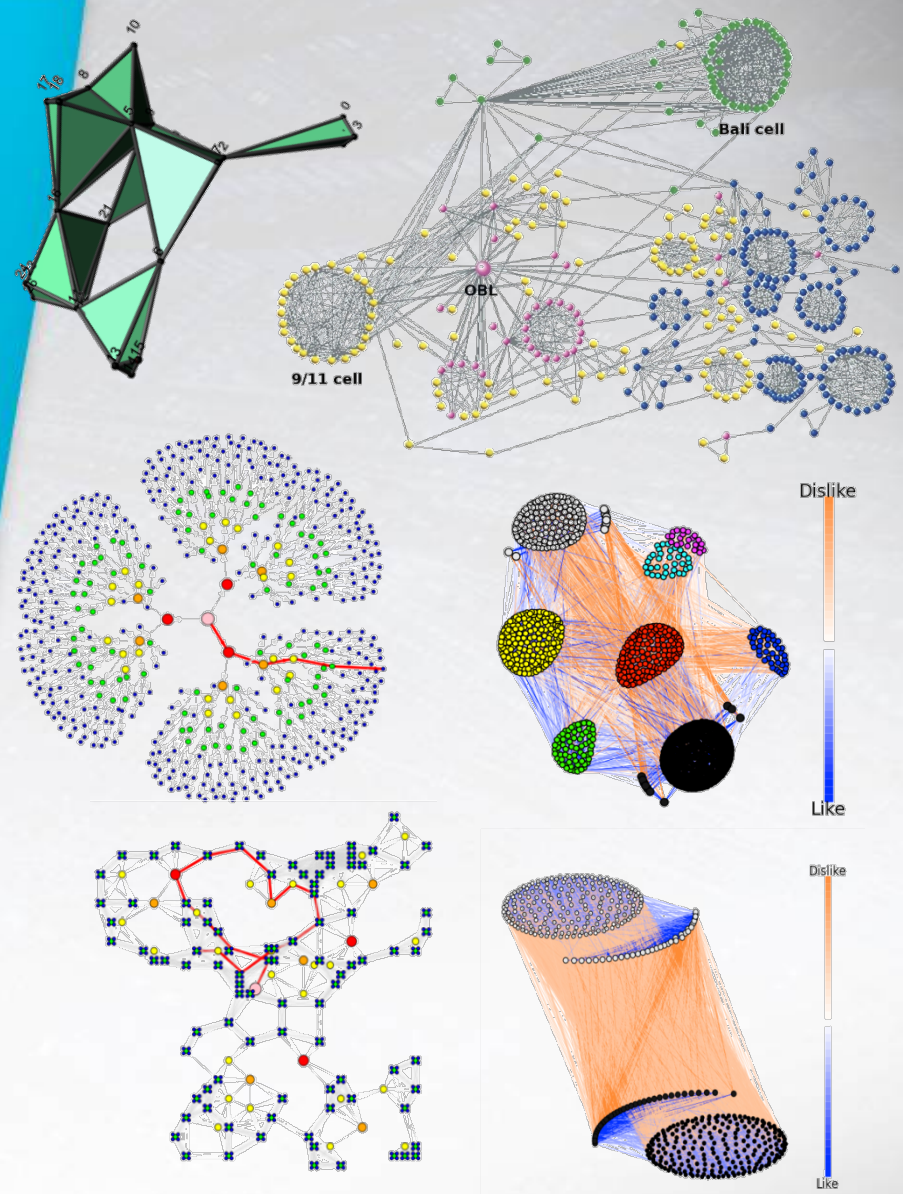
Evolution & Dynamics in Multi-Genre Networks

Understanding how multi-genre networks behave over time → dynamics, interactions, & co-evolution

Modeling approaches for capturing structural properties (graph theoretic & beyond)

Mathematical representations for analysis & prediction of properties of networks under various types of dynamics

Mathematical theory for "co-evolving" communications-information-social/cognitive networks



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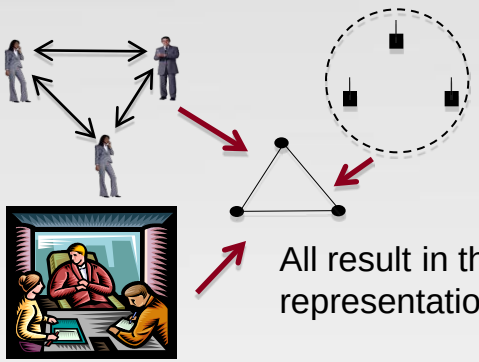
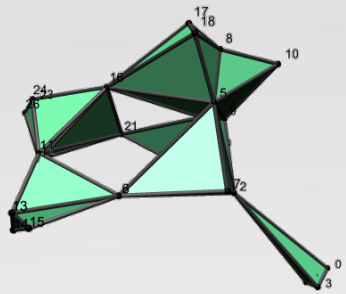
Modeling Group Phenomena Beyond Graphs

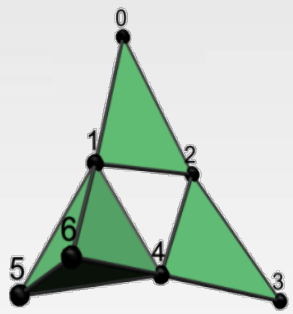
Current Network Models

- Graphs model pair wise relationships in networks
- Group relationships are modelled by a set of edges, but this is inadequate



All result in the same representation!





Army networks replete with group phenomena

- Broadcast channels
- Information clusters
- Insurgent cells, coalitions, collaborations

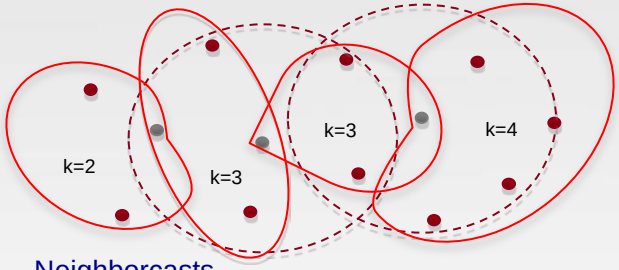
Insight: Hypergraphs (Simplicial Complexes) **are ideal for capturing group structure in a wide variety of networks**

Broadcast Using k-Neighborcast: Min cost network-wide broadcast can be formulated by considering relative costs of "simplices" resulting from multicast to subsets of neighbors

The cost function can come from comms-info-social networks

Costs per broadcast to selected k neighbors

$$cost(k) = 1 + Ak^b$$



Neighborcasts (simplices)

Objective: minimize sum cost
The structure of the cost function can model a variety of scenarios

Result: Characterized the *complexity* & *approximability* of network-wide broadcast as a function of cost parameters using this framework

PI: Ramanathan, BBN

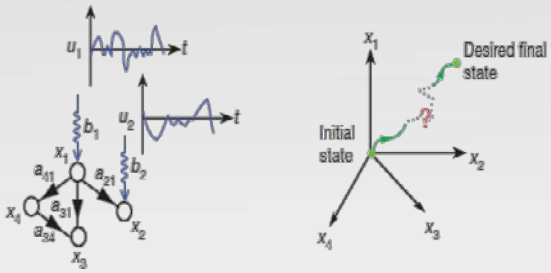
Collaborators: ARL, CUNY, PSU

Framework can be used for control of broadcast pathways for wireless networks & information flows (e.g. gossip, beliefs) through social networks

Network Controllability

Current State-of-the-Art

- Control theory does not provide insights about the minimal set of nodes that can be used to control the entire network
- Controlling large directed networks is a difficult problem

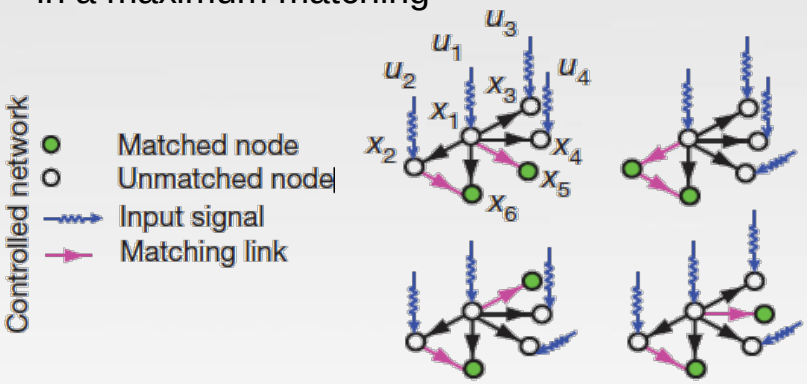


Army Networks Require

- Ways to efficiently identify a minimum set of drivers for controlling complex, multi-genre networks
- Key influencers in adversarial networks
- Potential weaknesses in our networks

Insight: The number of driver nodes in a random digraph depends on its degree distribution, (usually low degree) **& drivers are not the "hub" nodes in many real networks**

- Conventional network criteria such as centrality are not critical determinants
- Formally, a minimum set of driver nodes comprises exactly the unmatched nodes in a maximum matching



Result: Derived the size of maximum matching in random ensembles of digraphs & demonstrated that real-world networks can diverge strongly from random ensembles

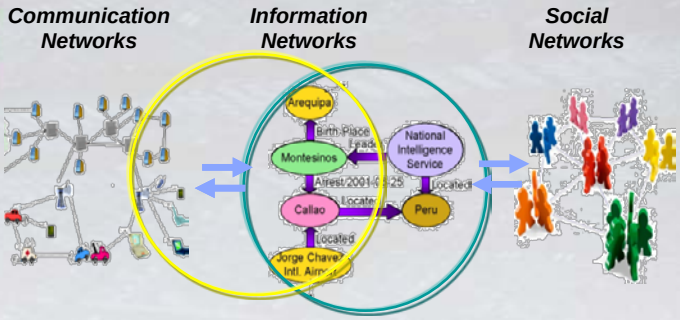
PI: Barabasi, Northeastern

Collaborators: Northeastern, MIT

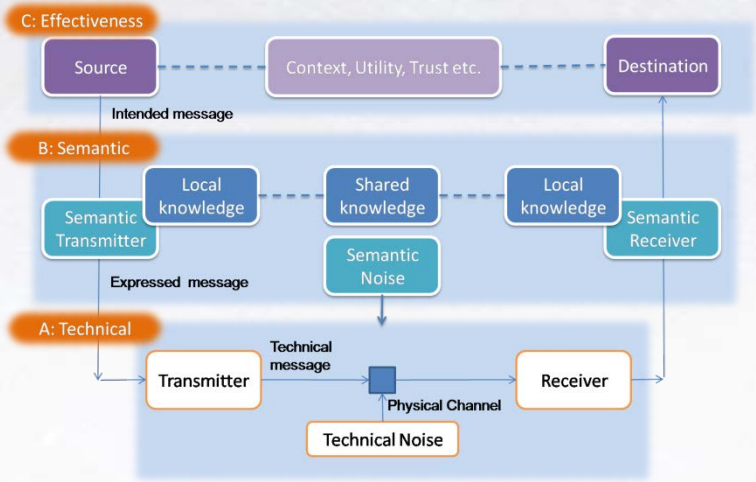
Novel theorem enables identifying the minimum set of nodes through which the control input can steer the network to the desired future state

Quality of Information (QoI) for Semantically-Adaptive Networks

Understand how to control network behaviors so that the capacity of the network to deliver relevant information can be maximized



New formal definition of network carrying capacity that considers intrinsic, contextual, and semantic attributes of information



Unified theory for QoI-aware information inference & fusion

Methods to semantically-extract context & purpose of information

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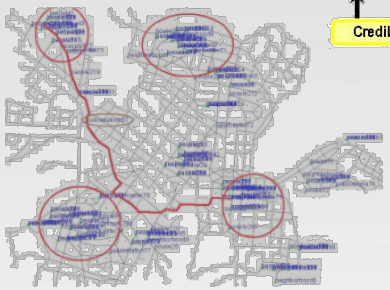
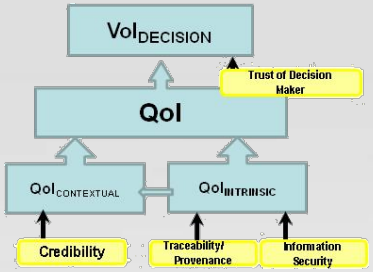
Quality of Information in Networks

Current State-of-the-Art

- Communication networks that are information agnostic
- Routing, pre-processing, fusion – unaware of quality/semantic requirements





Army Networks Require

- Means to assess operational capacity to deliver information, not merely bits
- Ways to characterize quality of information wrt operational needs
- Mechanisms to route, process, store-forward that optimize QoI in tactical networks that are semantically-aware

Insight: QoI quantification functions enable semantically-adaptive networking for best operationally-relevant quality of information

- **QoI characterization**: Formally represent tradeoffs in information metrics that depends on its use
- **Semantic information**: Characterize amount of data required to convey required semantics
- **Inferencing, corroboration & fusion**: Determine required QoI & transformations of QoI when considering multiple sources of information
- **Information capacity**: Formally define & quantify information carrying capacity (semantics) of a system of networks

Result: Developed a QoI-aware framework and demonstrated feasibility of QoI functions

PI: Ramesh Govindan, USC

Collaborators: ARL, USC, BBN, PSU, RPI, UIUC

QoI quantification functions help assess & optimize operational information capacity of tactical network

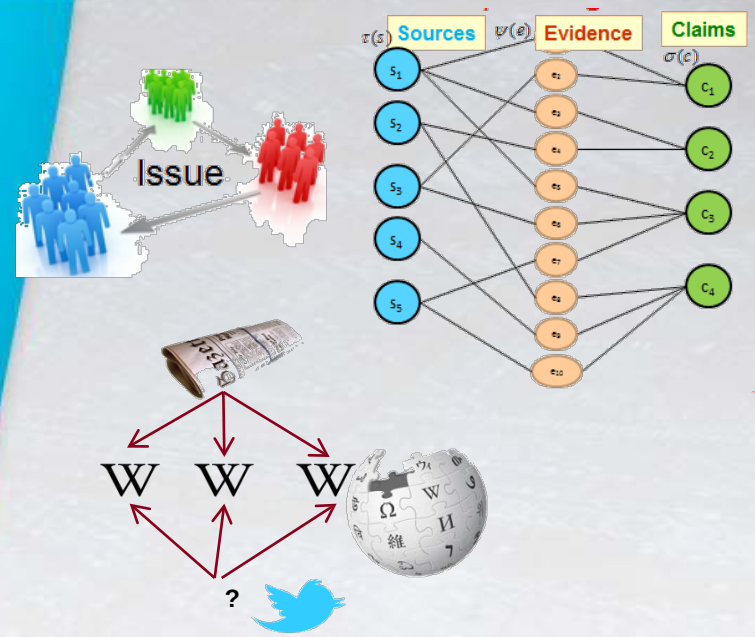
Information Processing for Distributed Understanding

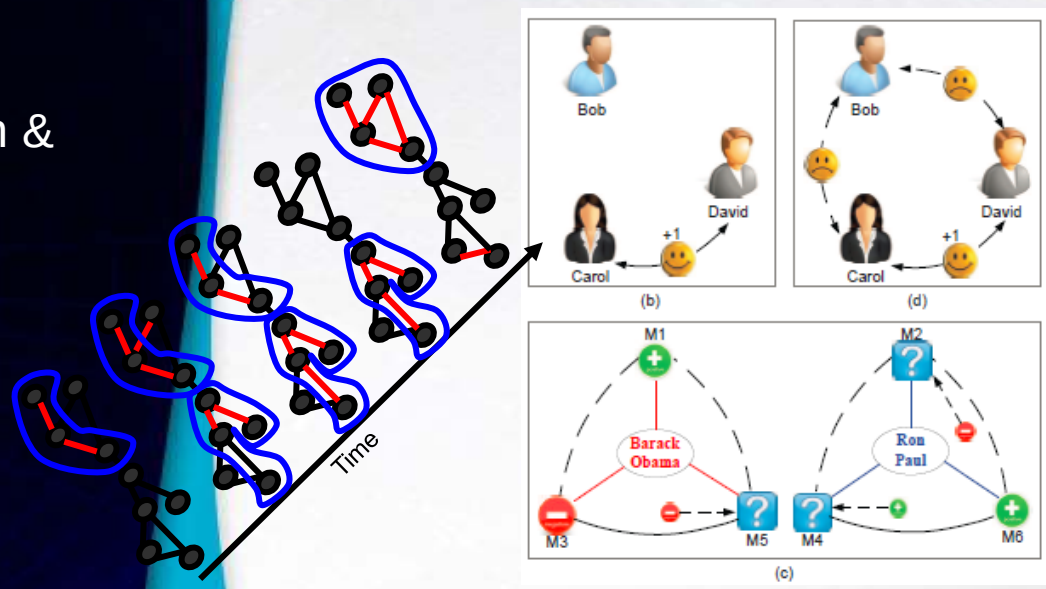
Understand how information representation, discovery, & analytics contribute to distributed understanding & social influence

Abstract representations of states of composite networks, mission & individual goals, & their impact on quality, value, & trustworthiness of information

Mathematical theories for determination of precise information needs of individual users, localization & presentation of the information

Methods of learning user needs, feedback characterization, & diffusion mechanisms in social/information networks





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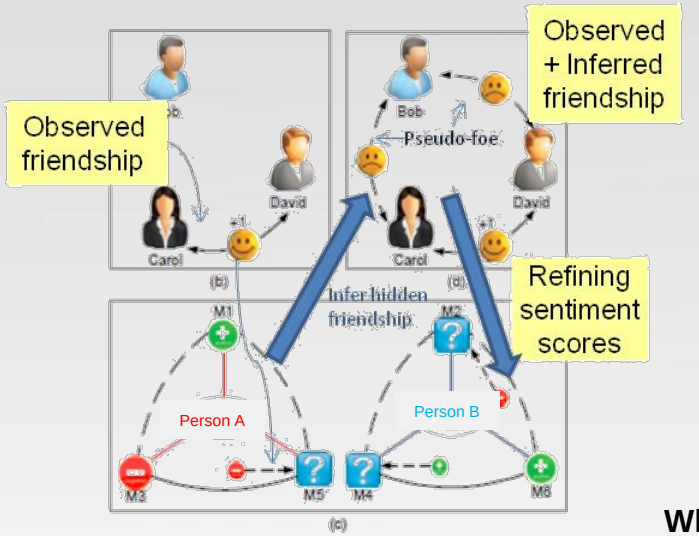
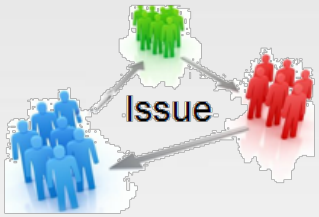
Exploring Opposing Opinions & Dissimilarities for Sentiment Analysis

State-of-the-Art

- Explore similar opinions not opposing opinions
- Typically consider text content
- Rely on observed friendship (but many are hidden)

Insight: Exploring opposing opinions may help to discover hidden friendship, which can produce better sentiment scores & user clustering. (mutually enhance each other)

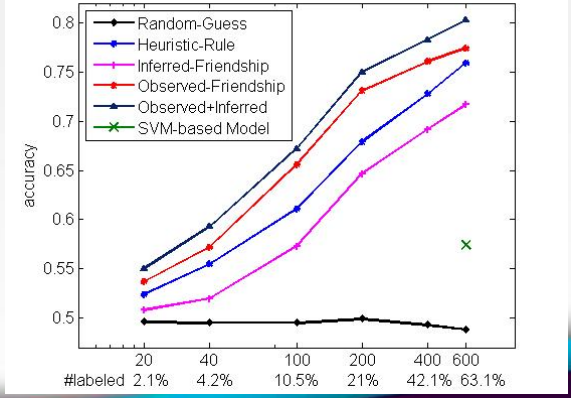




What people are thinking about certain target/issue?

- Consider information and social networks
- Explore opposite and similar opinions
- Both observed & hidden friendship are valuable
- Analysis of text-rich multi-genre networks can lead to models for mining & search in social media for military applications

What people are thinking about certain issue?



Army Need/Benefits

Army uses sentiment analysis to understand and mine public opinions on mission-related issues

- QoI-aware mining of text-rich multi-genre networks
- Intelligent methods for public threat assessment

PI: Han, UIUC
Collaborators: UIUC, CUNY

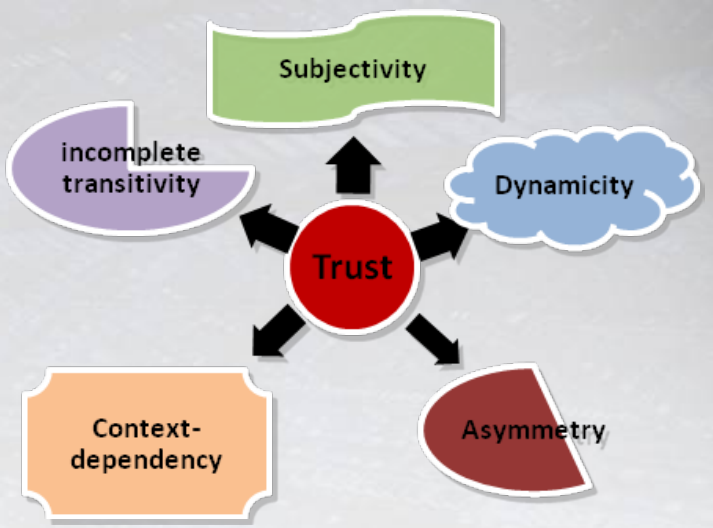
Trust in Networks

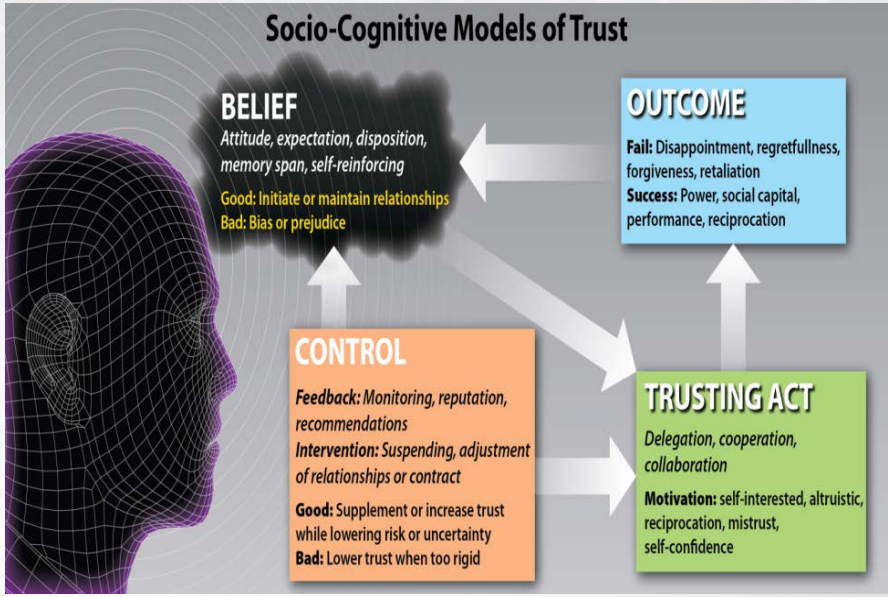
Understand trust & its impact on distributed decision-making in the presence of conflicting, incomplete or malicious information

Modeling and measuring trust from the perspective of the trustor, taking into account the interactions among network layers

Predictors of trust & distrust and techniques to enhance or exploit them

Mathematical theory for impact of trust on network evolution such as in an information-sharing network





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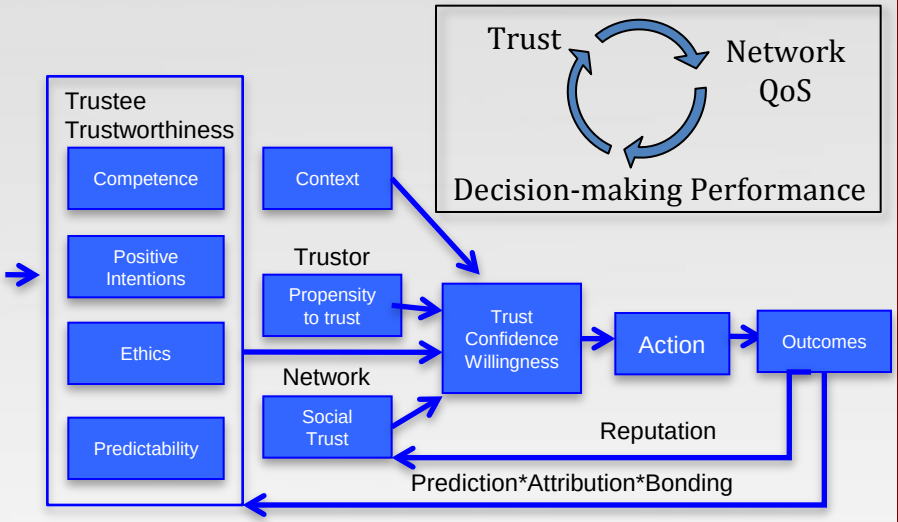
Composite Trust Metrics & Models

Current State-of-the-Art

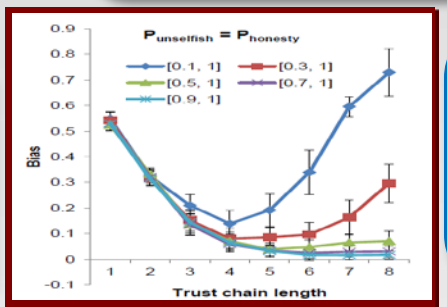
- Work on trust in decision making does not reflect reality of networks: Resource constraints & rationality assumptions
- Limited understanding of trust / relationships in multi-genre networks



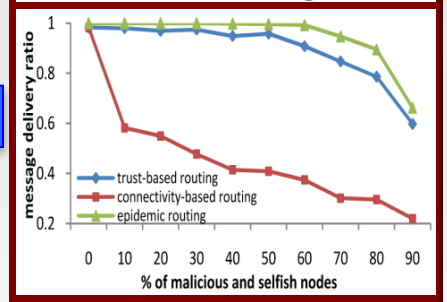
Army Networks Require

- Networks to optimize information flow, decision-making performance & situational awareness
- Trust-based tactical network, that is resilient, scalable, & sustainable

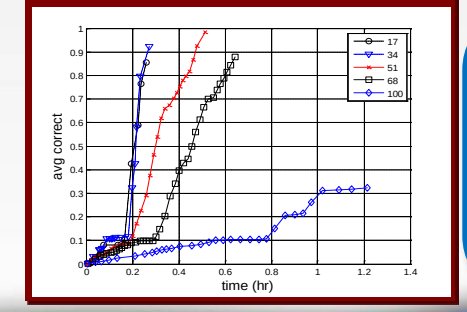
Insight: Composite trust models enhance effectiveness of tactical decision making under resource constraints, & incomplete and uncertain information in multi-genre networks



Result: Optimal trust chain balances trust accuracy with resource overhead & latency



Result: Trust-based routing in DTN performs close to epidemic routing (ideal for delivery ratio and delay), with significantly less overhead



Result: Agent-based experiments on an integrated platform using WEL and ELICIT validate simulation results on scalability

PI: Cho & Chan, ARL

Collaborators: ARL, RPI, VT, OSD/NII, NPS

Composite trust metrics can enhance decision making & mission performance

TOPICS

2005 NRC Report

Trends & Emerging Challenges

Emerging Research Directions

Experimentation

Army Programs Addressing Challenge

Without Experimentation There Cannot be a True Network Science

Distributed experimentation to improve fundamental knowledge about complex multi-genre networks

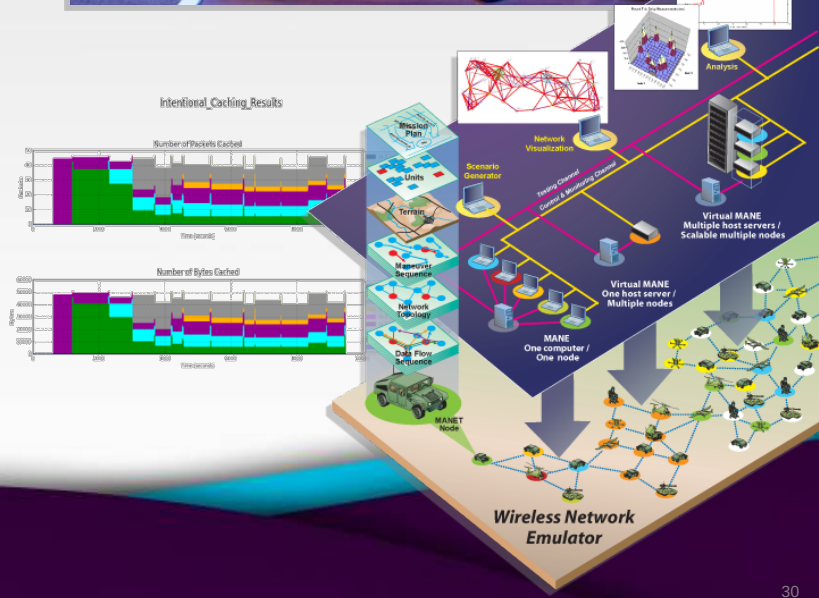
Experimentation

Validate results & datasets

Answer key research questions

Enables the Army to:

- Understand & predict the structure & behavior of interacting multi-genre networks
- Understand & exploit cross-network interactions that hinder or enhance effective use of networks
- Design & engineer multi-genre networks for their intended "domains of applications"
- Detect, measure, adapt, & shape intertwined multi-genre networks → Even without good visibility into them or authority over them



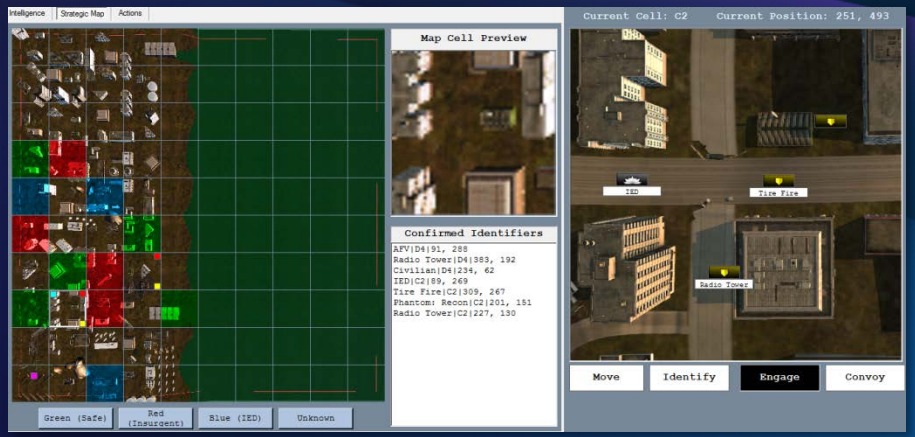
Human Behavior in Networks is Key

CURRENT

Experiments examine the interaction between trust level, communications pathways, and team success using a Multi-Team Simulation System

FUTURE

Experiments can include more complex information manipulations, integrate with simulated background networks, and explore tactical level actions



Scalable, High-Fidelity Experimentation Tools are Critical

SIMULATION

Use theory to define:

- Behavioral relationships
- Objective function
- Parameters
- Variables

FIELD EXPERIMENTATION

Dataset validation
Realistic scenarios
Actual hardware in field environment
HPC used to augment & stimulate environment

EMULATION

Laboratory environment
Applications run on nodes
PC processors represent nodes
Software models node movement & radio access
Actual MANET protocols run on nodes

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TOPICS

2005 NRC Report

Trends & Emerging Challenges

Emerging Research Directions

Experimentation

- Army Programs Addressing Challenge

Interdisciplinary Research Center

- **BBN** (LEAD)
- ArtisTech
- University of California Riverside
- University of Delaware

Social/Cognitive Networks ARC

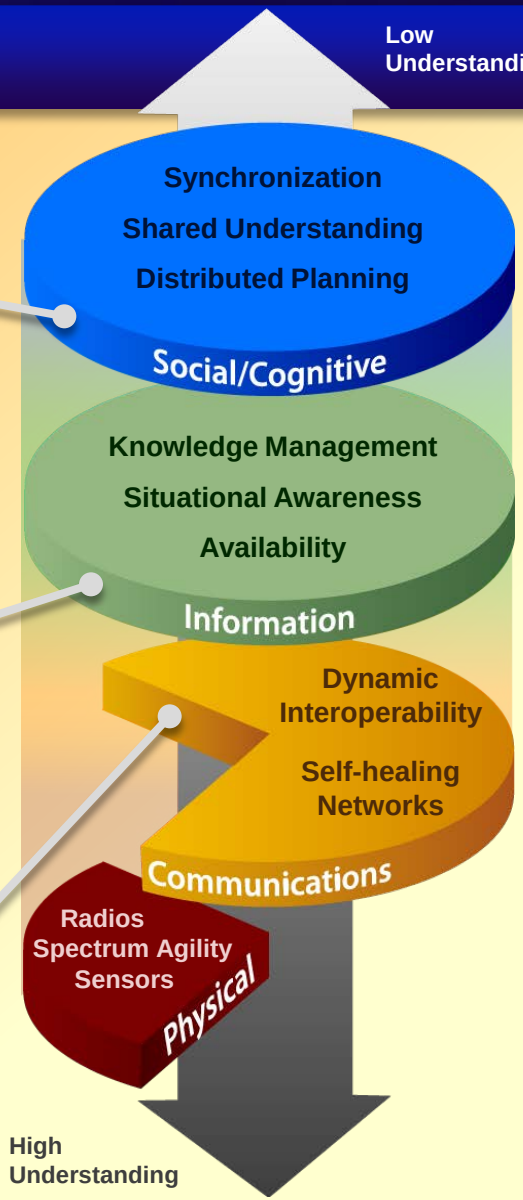
- **Rensselaer Polytechnic Institute** (LEAD)
- Northeastern University
- City University of New York
- IBM

Information Networks ARC

- **U. of Illinois at Urbana-Champaign** (LEAD)
- University of California, Santa Barbara
- City University of New York
- IBM

Communication Networks ARC

- **Penn State University** (LEAD)
- University of Southern California
- University of California, Davis
- University of California, Santa Cruz
- City University of New York



ARC = Academic Research Center

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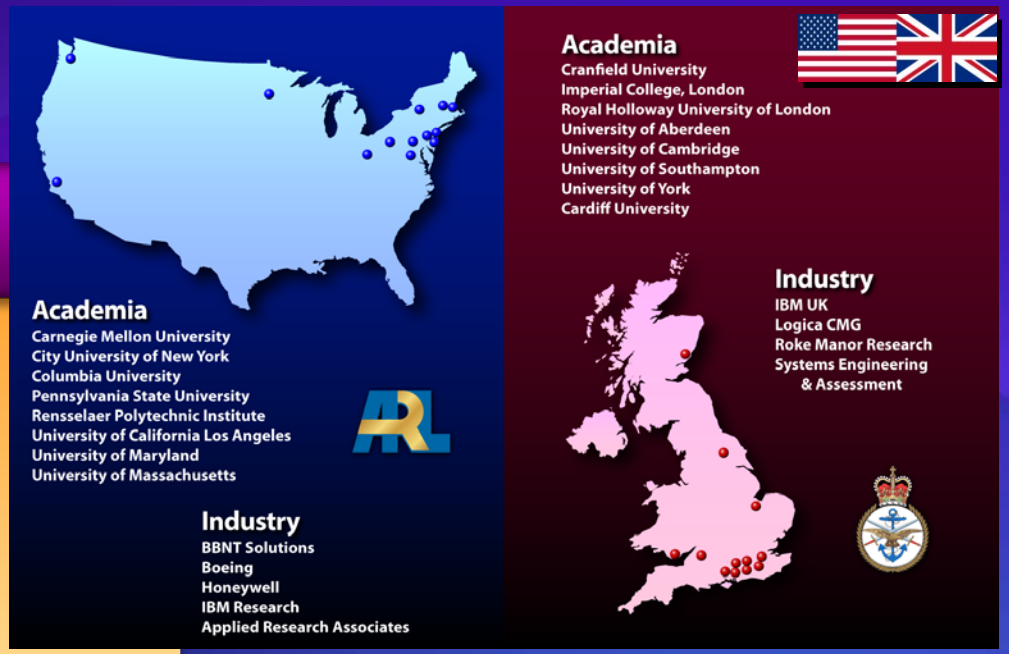
Network & Information Science International Technology Alliance

Collaborative Venture between US ARL, UK Dstl, Academia, & Industry to enhance our abilities to conduct coalition operations

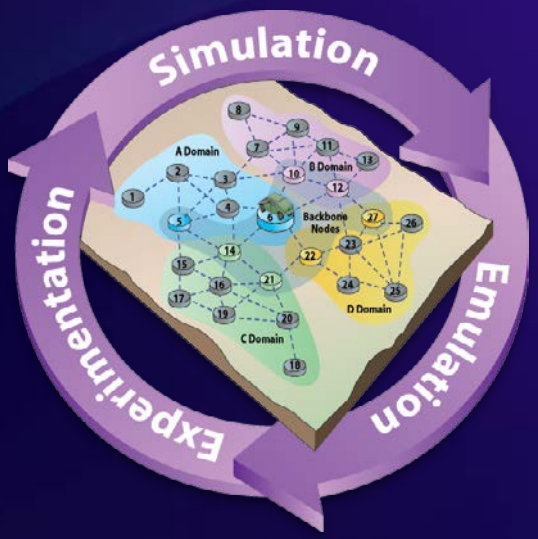
ITA Technical Areas

- **Coalition Interoperable Secure & Hybrid Networks**
  - Hybrid Networks
  - Security/Network Management & Control
  - Security for Distributed Services
- **Distributed Coalition Information Processing for Decision Making**
  - Shared Understanding & Info Exploitation
  - Service Management in Distributed Networks
  - Exploitation of Distributed & Uncertain Info



Mobile Network Modeling Institute:
An ARL-led OSD HPC Modernization Program

A Collaborative Venture between ARL, CERDEC, NRL, academia and industry to develop scalable computational network modeling tools for DoD-wide use



MNMI Objectives

- **Exploit high performance computing to:**
  - Enable DoD to design & test networks at sufficient levels of fidelity & with sufficient speed
  - Understand behaviors of network enabled capabilities
- **Develop scalable computational modeling tools**
- **Develop software that transforms the way DoD mobile networks**

ARL Cyber Research & Operations

CHALLENGES

ASSESS

PREDICT

PREVENT

RESPOND

Key Partners

CNDSP

UNITED STATES STRATEGIC COMMAND

DOD HPC MODERNIZATION PROGRAM

DISA

NATIONAL SECURITY AGENCY

NATIONAL GUARD

KEY RESEARCH AREAS

Network Metrics

Network Sensors

Intrusion Understanding

Adversarial Dynamics

MANET

Mobile Network Defense

BELIEF

OUTCOME

CONTROL

TRUSTING ACT

Trust Management

Advanced Threat

CURRENT CAPABILITIES

Policy Compliance

Training & Certification

Monitoring

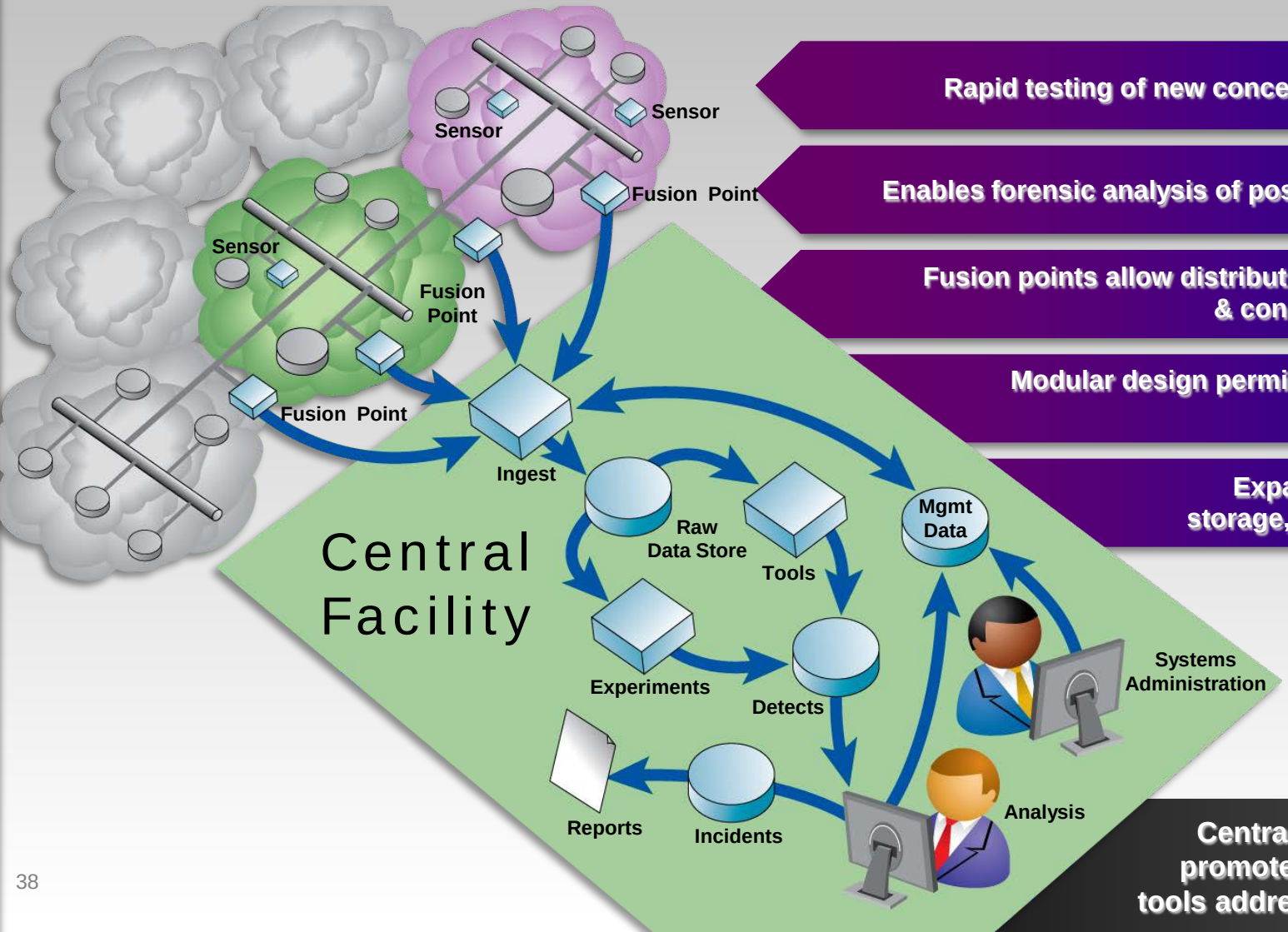
Interrogator

shell

Forensics

ARL Enabler:
Interrogator Intrusion Detection Framework

Rapid analysis of large scale networks with terabytes of live data



- Rapid testing of new concepts in live environment
- Enables forensic analysis of post-penetration activities
- Fusion points allow distribution of central workload & conservation of bandwidth
- Modular design permits flexible arrangement of fusion points
- Expandable computational, storage, & network capabilities

Centralized, modular design promotes rapid integration of tools addressing evolving threat

Creating Knowledge & Understanding of Complex Multi-genre Networks

Modern Tools for the Modern Soldier