On Optimizing Command and Control Structures

16th ICCRTS Gary F. Wheatley Best Paper Presentation

Kevin Schultz, David Scheidt,
{kevin.schultz, david.scheidt}@jhuapl.edu

The Johns Hopkins University
APPLIED PHYSICS LABORATORY

This work was funded in part by ONR contract N00014-0-C-0396.

Motivating Organizations

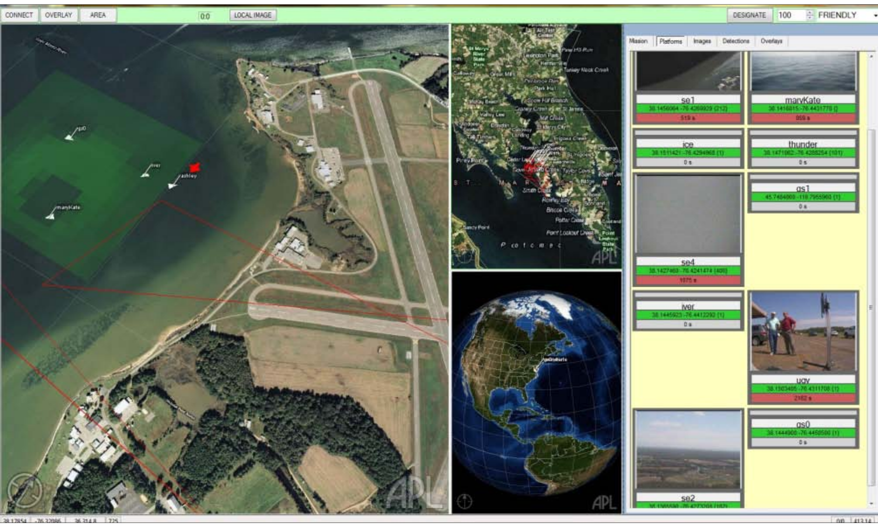
Ship Auxiliary Systems

~20,000 co-dependent components
Prone to large complex faults scenarios
Complement of 300 sailors and 23 officers

Mixed Human Robot Teams in Tactical Exercises

Organic, Persistent Intelligence, Surveillance and Reconnaissance (OPISR) 2011 OPISR Experiments
16 ISR Assets
Air (9), Ground (4), Surface (2), Undersea (1), Tactical Users (2), Commander (1)

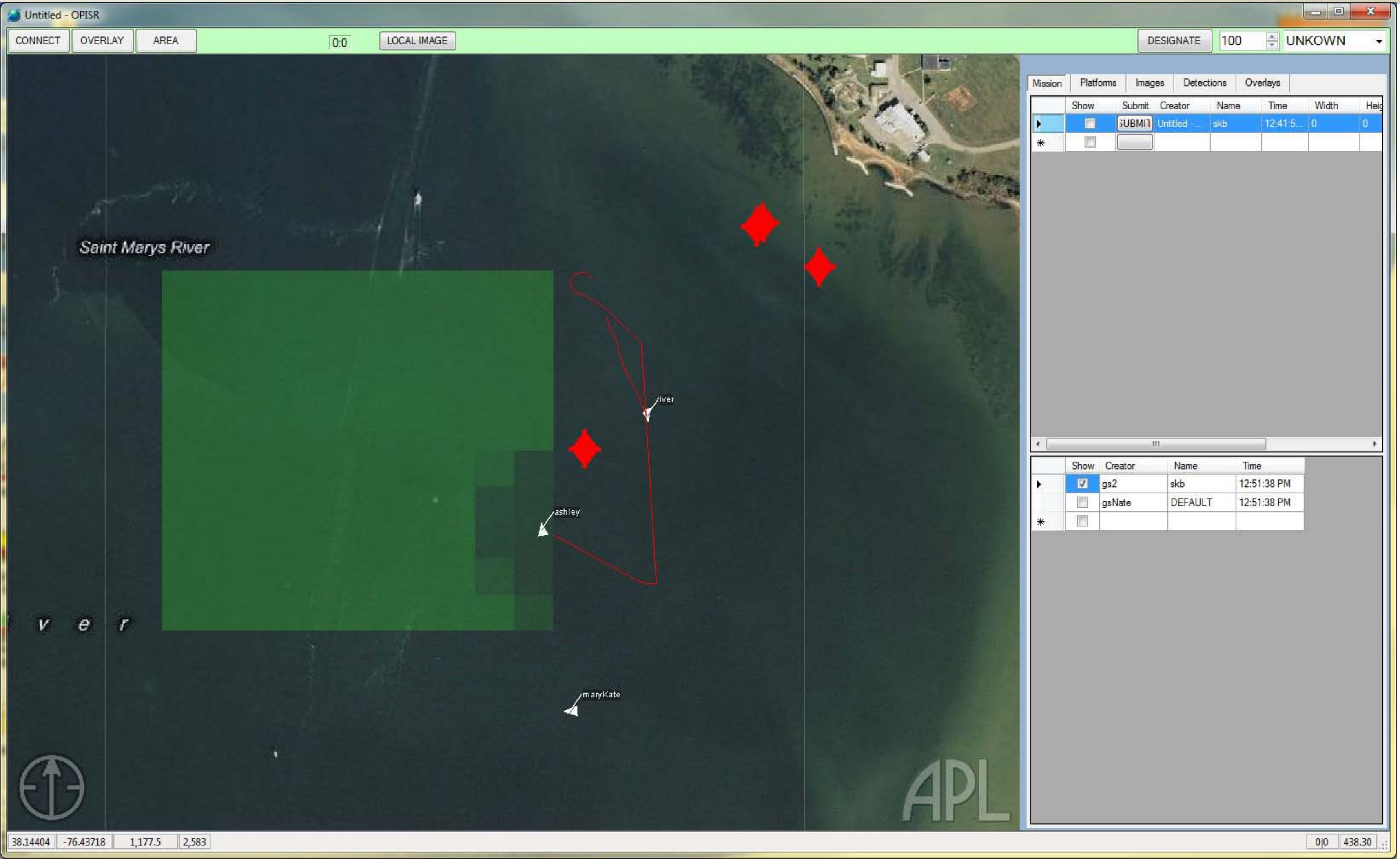
OPISR – Real-time data feeds to tactical users from heterogeneous ISR assets





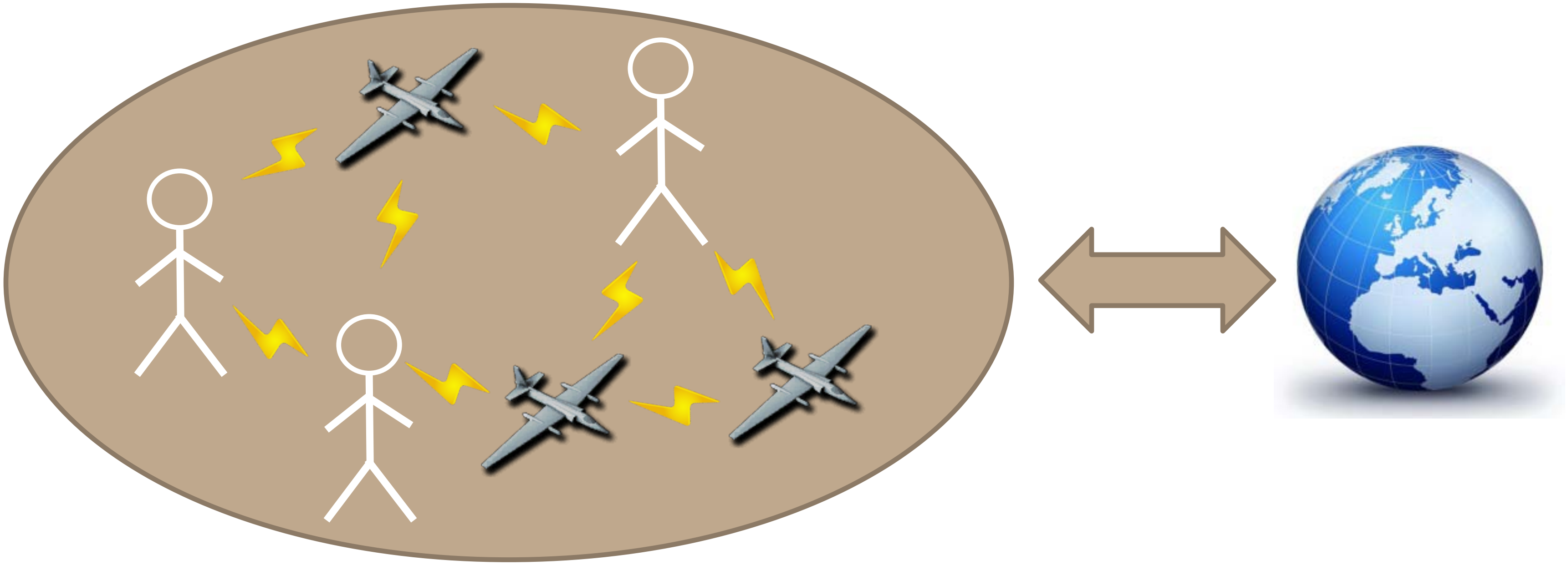


Heterogeneous Coordinating Unmanned Vehicles



When Should We Build/Use Distributed Systems?

In OPISR, all vehicles are autonomous and “agile” (power to the edge for unmanned vehicles). Is this the best approach? How can we know?

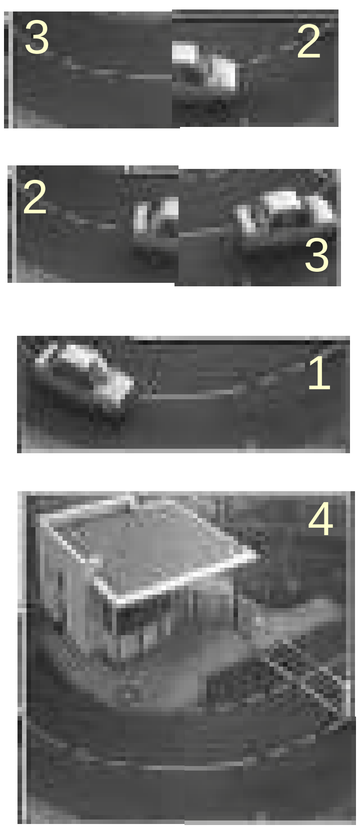


Consider a system that includes one or more humans and one or more unmanned machines. This system interacts with the world and must achieve some abstract goal or objective.

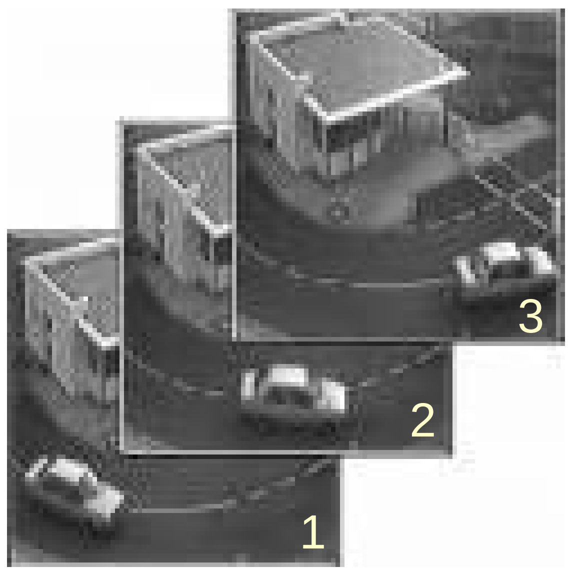
What decisions should be made by the human and what decisions should be made by the machine? Which humans should make decisions? Which machines? Answer: Whichever decisions are necessary to improve the performance of the system.

Information and Command and Control
Time and Fidelity

Which Information is Most Useful?

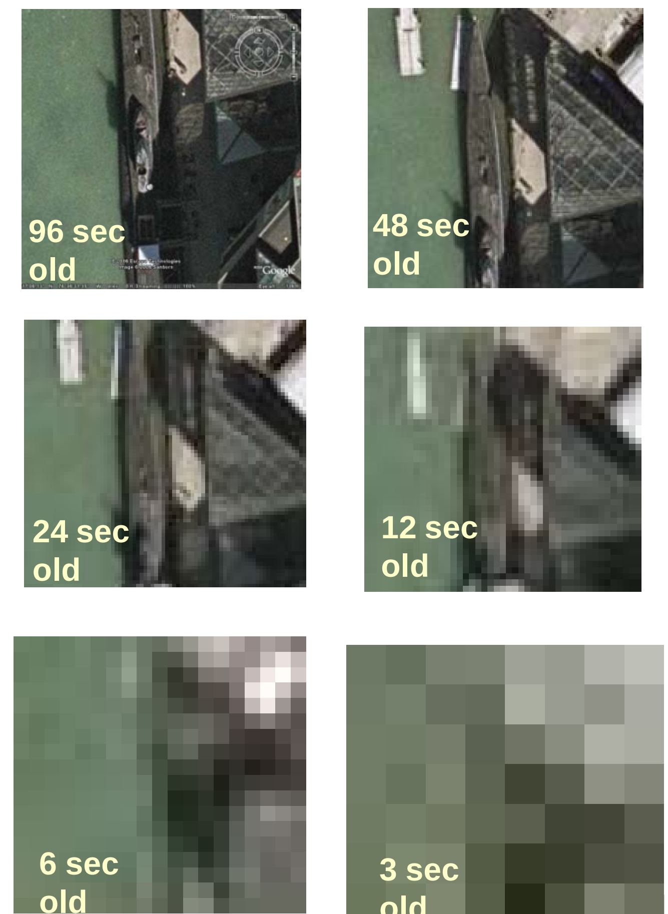


=size of data packet



Current Reality

Which Information is Most Useful?



Information Theory Basics

$$I(m) = \log\left(\frac{1}{p(m)}\right) = -\log(p(m))$$

I **is measured in bits**

m is a message

p(m) is the probability that the message was true

“Tonight it will be dark.” [24 data bytes, ~ 0.0 information bits]

“Tonight it will snow.” [21 data bytes, > 0.0 information bits]

Information Basics – Cat World

In what room is the cat?

A three bit question; I= log8 = 3 bits

Entropy (feasible locations) = 3 bits

A two bit answer! “In room ?01”

Information = 2 bits

Entropy = 1 bit

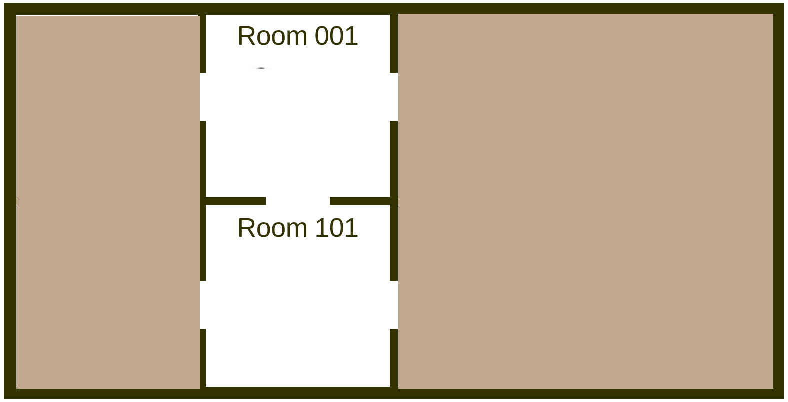
Here’s the cat! “In room 001”

Information = 3 bits

Entropy = 0 bits

But where is the cat?

- 9 bits to the nearest foot
- 11 bits to know the direction the cat is facing
-
-
- 10^{31} bits to know the location of each atom to 10^{-8}m



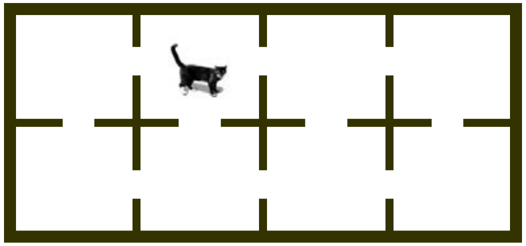
The limit of knowledge generated by the coding scheme is the *Representational Uncertainty*

APL

Minimizing Uncertainty

How many bits should we use to represent the cat?

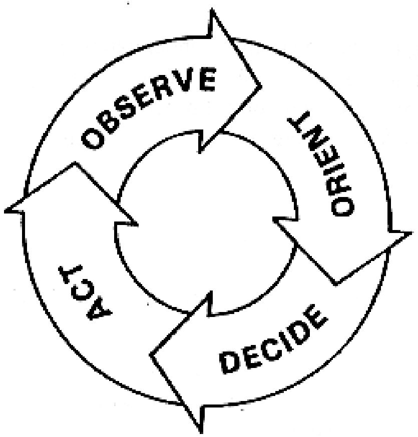
- **Room only? (3 bits)**
- **ft^2 (8 bits)**
- **ft^2 + orientation (11 bits)**

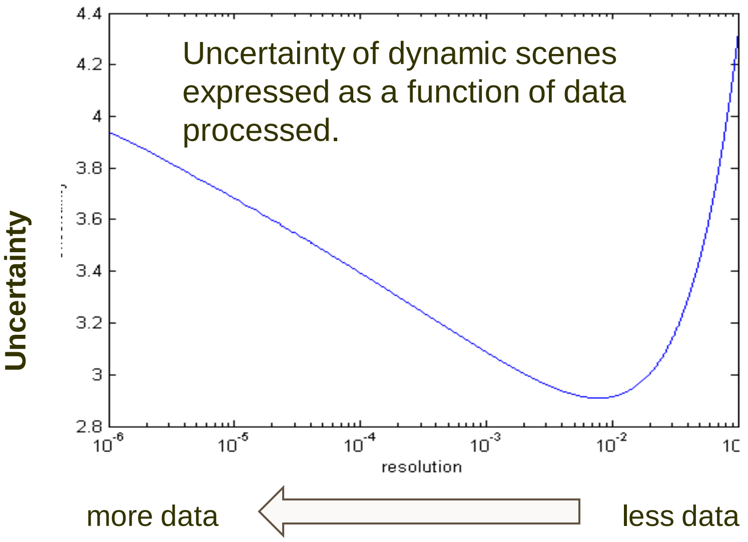


A fundamental trade-off exists between Representational Uncertainty and Uncertainty derived from Entropic Drag

An optimal level of fidelity exists. Any attempt to measure and/or communicate about the system more precisely will result in *more information being lost from entropic drag than is gained from the observation*

Command and Control in Dynamic Engagements



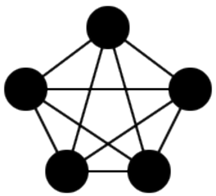


Systems with fixed cognitive bandwidth are limited in the amount of information they can effectively process

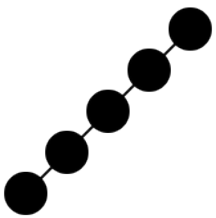
Graph Theory

- **Model the various entities and interconnections as a graph $G = (V, E)$**
- **Vertex set V represents entities**
  - Sensors a subset of V and observe $x(t)$
  - Entities share info with neighbors and process info
- **Edge set E represents comm links**
- **Sensors are exogenous comm channels**

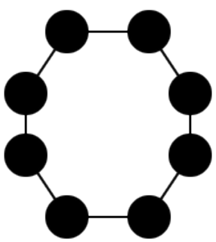
Sample Graph Topologies



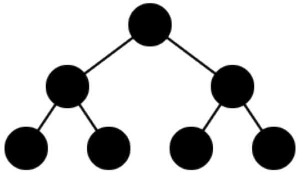
Fully Connected



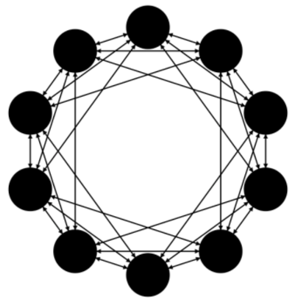
Path



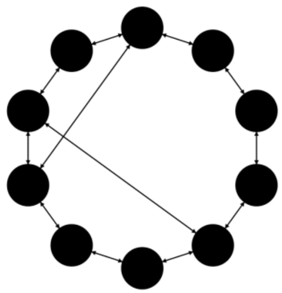
Ring



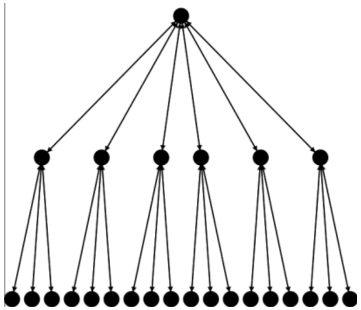
Binary Tree



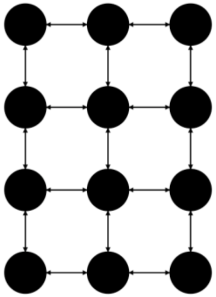
3-Ring



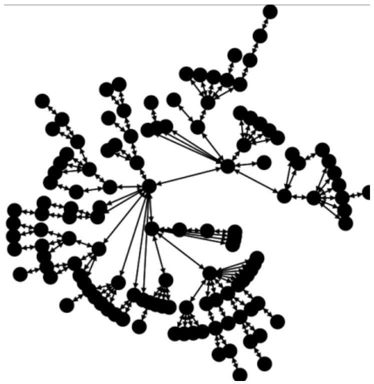
1-Ring+2 (small world)



[6,3] Regular Tree



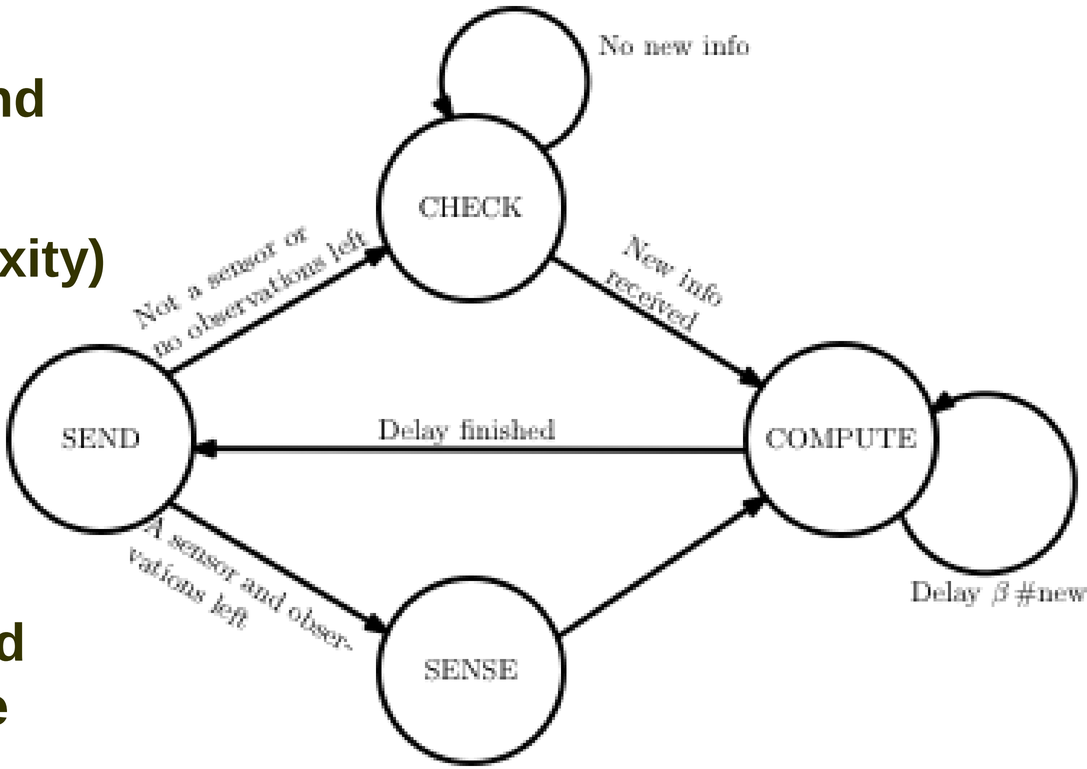
3x4 Grid



(1,1) Scale-free

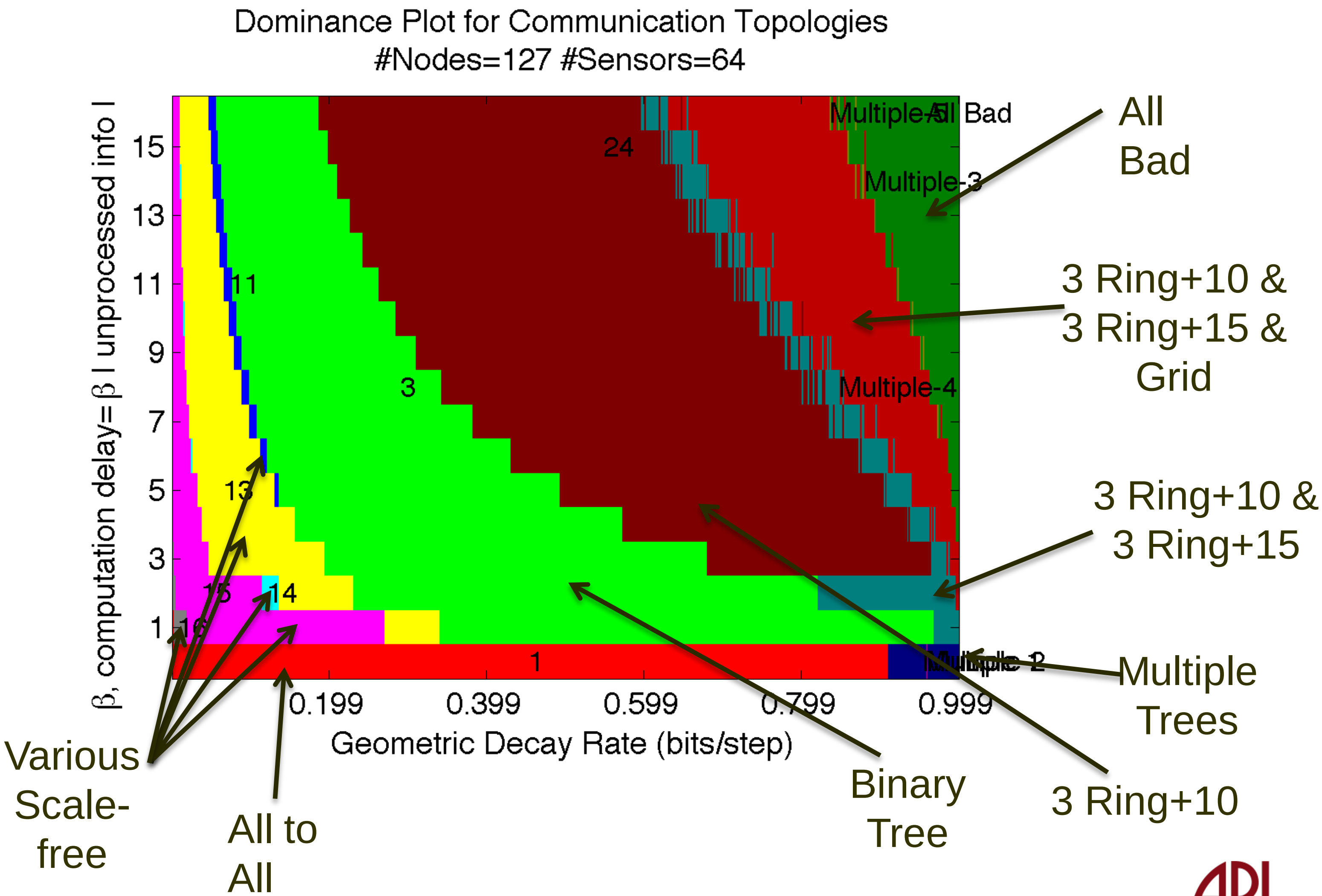
Information Flow Simulation

- **SEND, SENSE, COMPUTE and CHECK states**
- **Computational time (complexity) linearly proportional to new information received (β)**
- **Information decays via a geometric decay rate (Γ)**
- **Investigating peak processed information volume to single observation**



Topology Impact on Situational Awareness

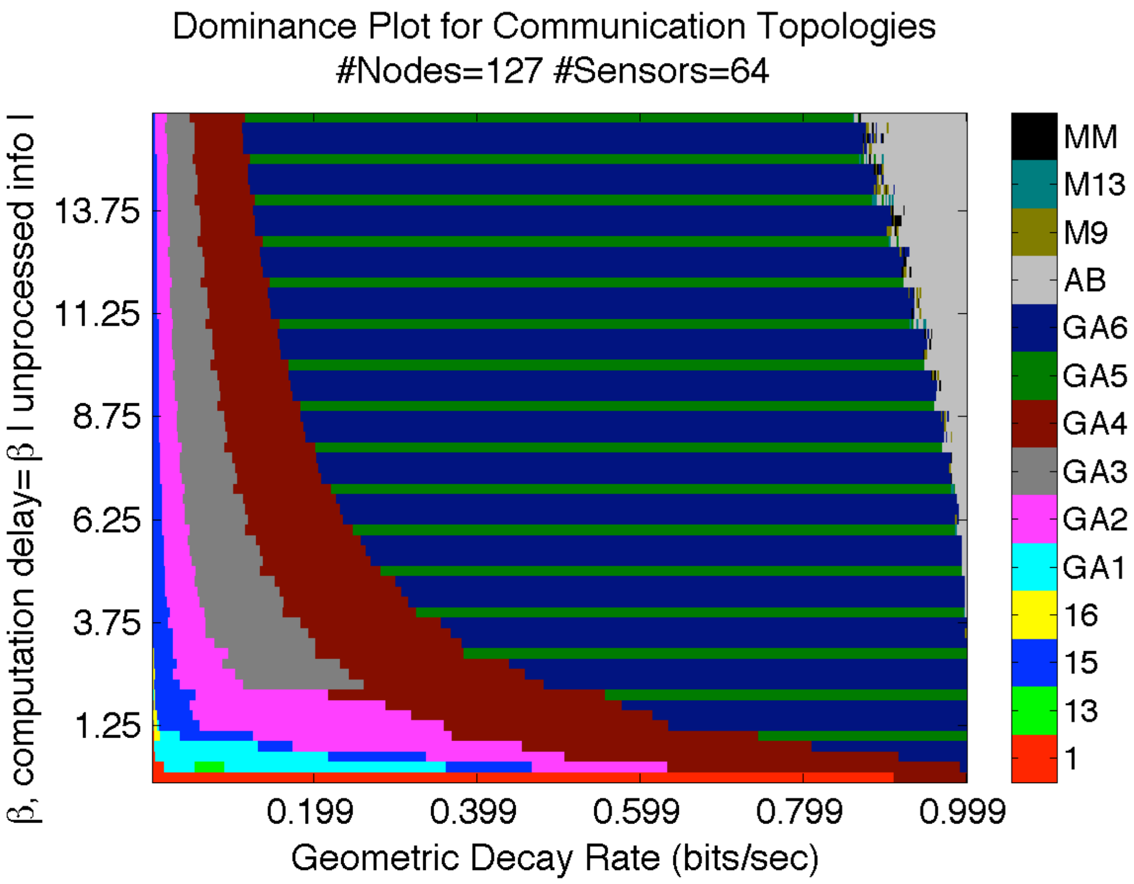
30 topologies compared



Topology Optimization using GA

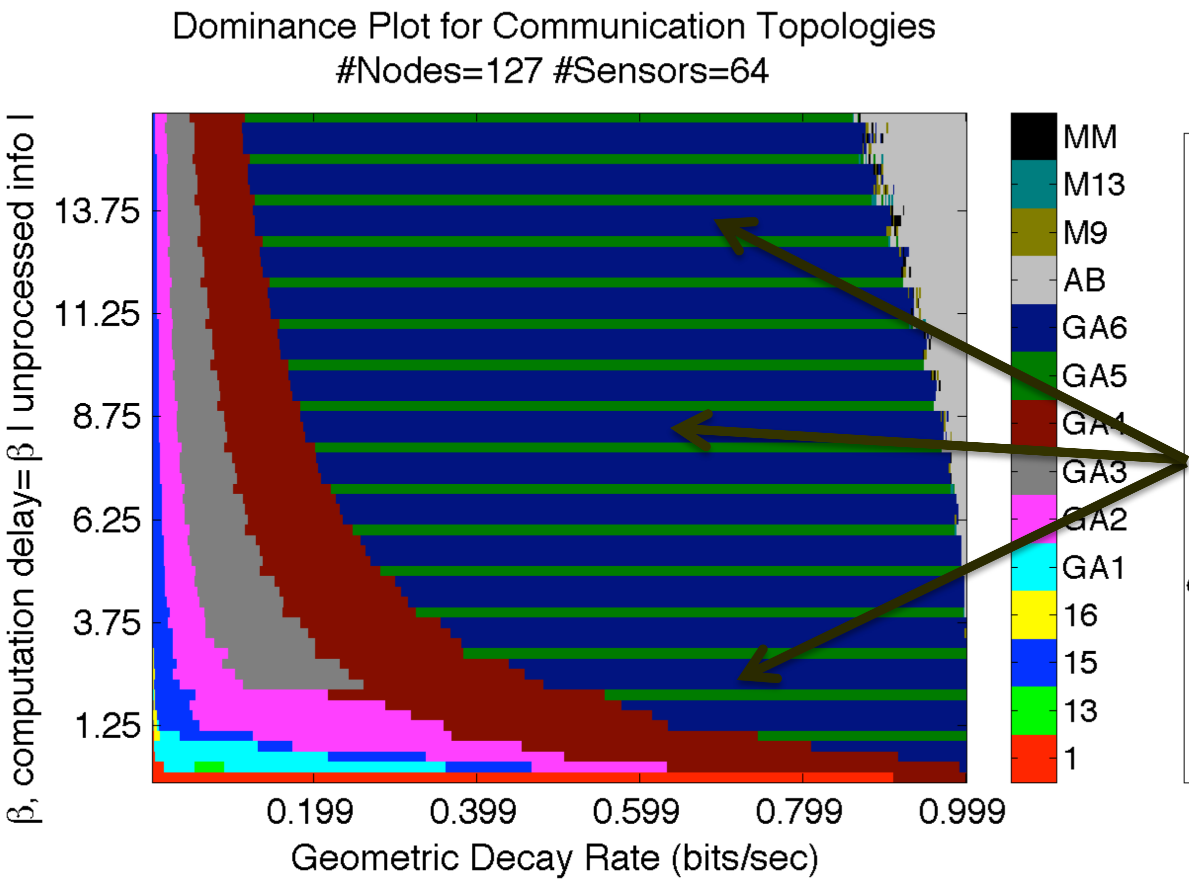
- 2012 paper builds upon this idea by directly optimizing topology in the simulation
- Using a GA, topologies were optimized at different points in the information-theoretic parameter space
- Also considered multi-point optimizations

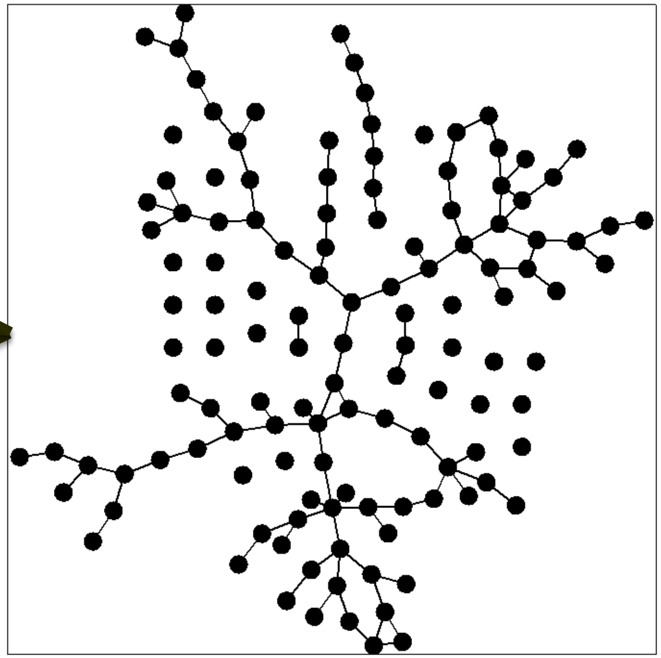
Topology Optimization using GA



Optimized topologies perform well in nearly the same regions as the topologies they improve upon

Topology Optimization using GA





Topology Optimization using GA

Results

- **It is possible to optimize for specific information theoretic parameters**
  - This optimization is robust, in that it performs well in a neighborhood
- **It is also possible to find a few optimized topologies that outperform the original set of 30**
  - So a look-up table approach may be feasible when direct optimization is not
- **Analysis of multi-point optimizations provides insight into behavior of simulation**

Information Flow with Actuation Simulation

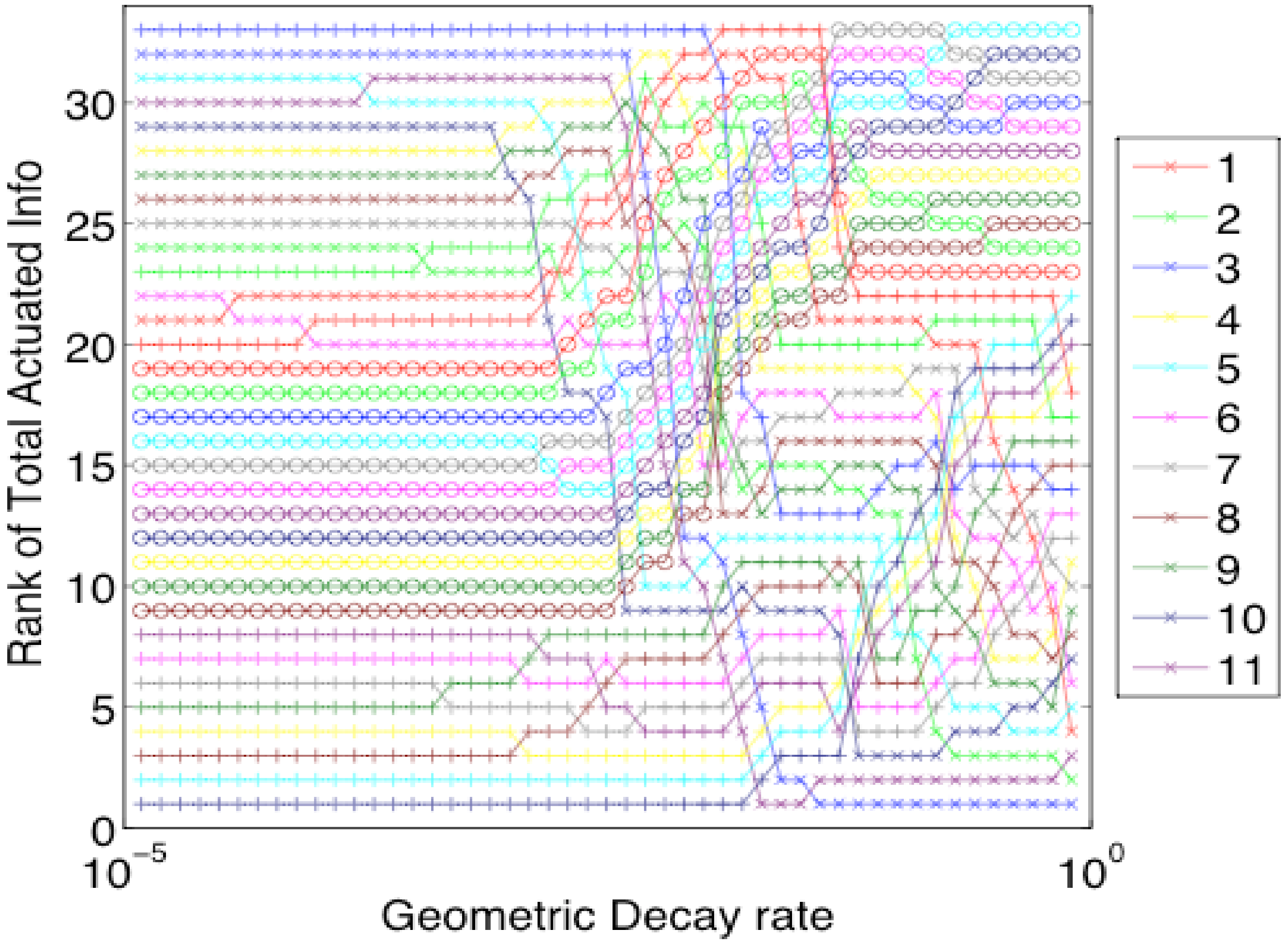
- **Extended simulation by adding control**
- **Sensors now sense and actuate**
- **Entities pass information up the hierarchy**
- **Entities pass actuations down the hierarchy**
- **Entities compute intermediate actuations for the actuators below them in the hierarchy**

Information Flow with Actuation Simulation

- **Only trees compared, but multiple sensor waiting behaviors**
  - Idle, re-sense, and re-sense+re-process
- **All graphs had 64 sensors, but varying intermediate nodes**
- **Using total information behind actuations as metric**

- **Results indicate different regions of decay rate where different topologies and sensor behaviors outperform others**

Information Flow with Actuation Simulation



Human-Autonomy Interaction

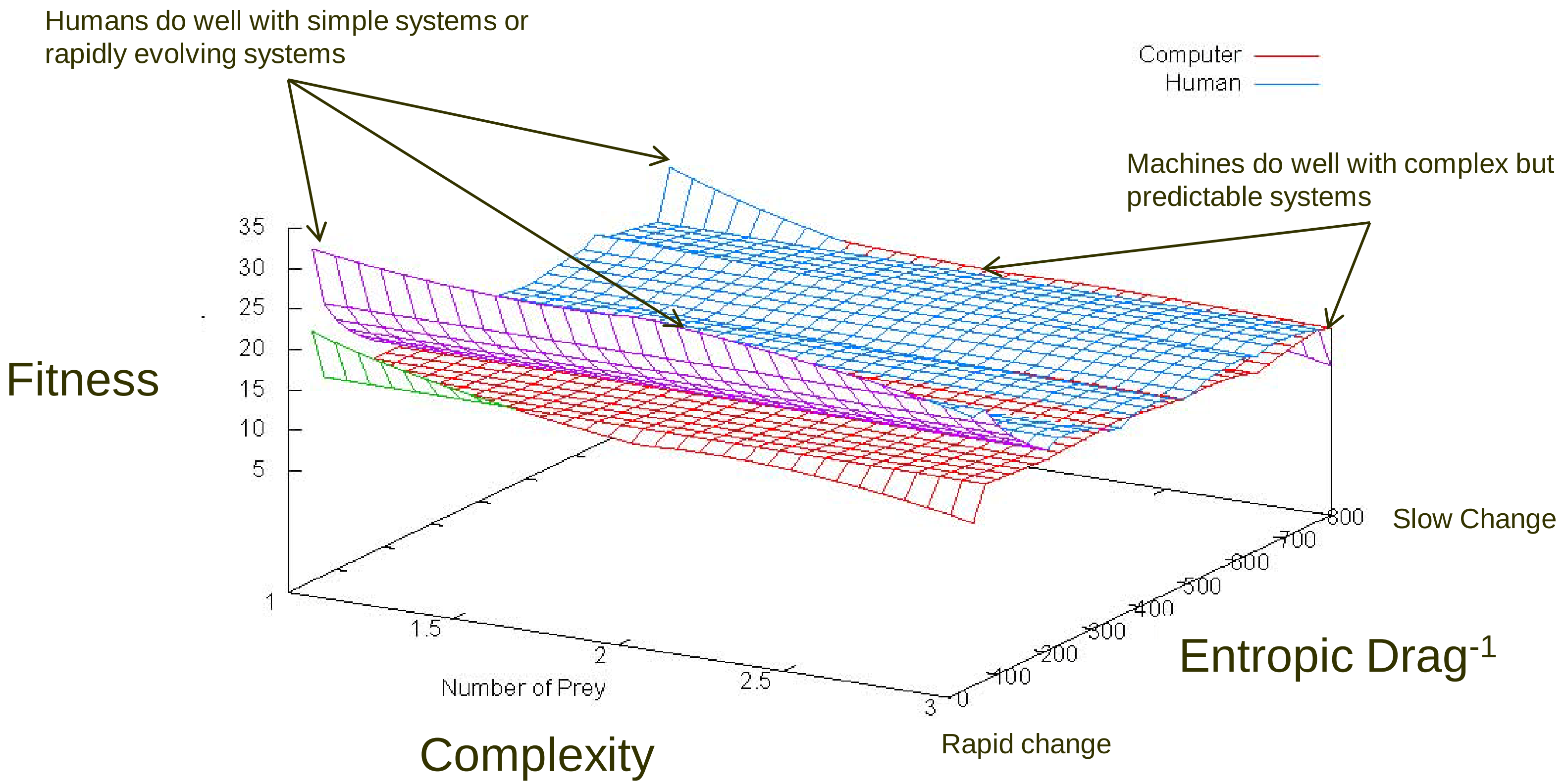
- **It is known that humans and autonomy have different strengths and weaknesses**
  - E.g., classification vs. vigilance
- **How to divide tasks between humanity and autonomy?**
- **Are heterogeneous teams more effective than homogenous teams?**
- **Can autonomy reduce the workload of humans?**

Human-Autonomy Interaction

Predator-Prey Experiment

- **Object of the game is to move sensors to detect and track “prey”**
- **Prey can observe sensors and will continually “hide”**
- **Experimental variables**
    - Number of Prey (complexity)
    - Speed of Prey and rate at which prey change direction (entropic drag)
- **Human Cognitive Model**
    - Uses Act-R Cognitive model
    - Follows Simple Algorithm
        - The human first visually finds the location of the “prey" on the screen.
        - The human then scans the screen to find the “sensor" that is closest to the “prey".
        - The human then moves the mouse to the location of the “sensor" it found in step 2.
        - Repeat.
- **Metrics**
    - Mean Positional Error

Human-Autonomy Interaction



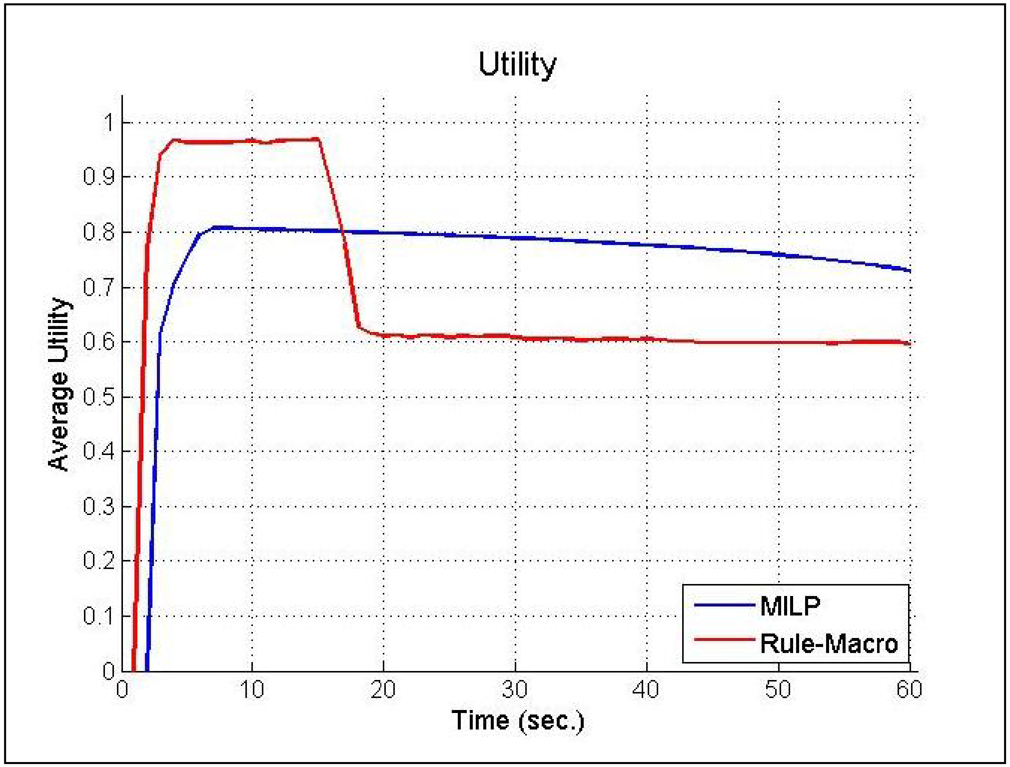
Whether a human or autonomous machine should make a decision is a function of the information theoretic characteristics of the environment

Control of Ship Auxiliary Systems

- **CONOPS: Control the complex, highly-coupled fluid and electrical auxiliary systems in next generation naval vessels**
- **How complex?**
  - Thousands of nodes: relays, valves, pumps, pipes, wires
  - Highly redundant (for fault and damage tolerance)
- **How coupled?**
  - Water chills the electrical transformers
  - Electricity powers the pumps and valves in the fluid system
- **How important?**
  - The fluid system is the ship's *potable* water supply
  - The electrical and fluid system are required for the operation of critical systems, e.g., RADAR

Efficacy of Control Schemes

- **Different reconfiguration algorithms have different complexities, but may produce better solutions**
- **State changes during computation may reduce efficacy**
- **Thus, predictability of the system is important in choice of algorithm**
- **More entropic drag requires frequent, less effective configurations**



Future Challenges

- Design of C2 Systems
- Agile C2 Systems
- Understanding learning and evolutionary entropy
- Robustness
- Resilience

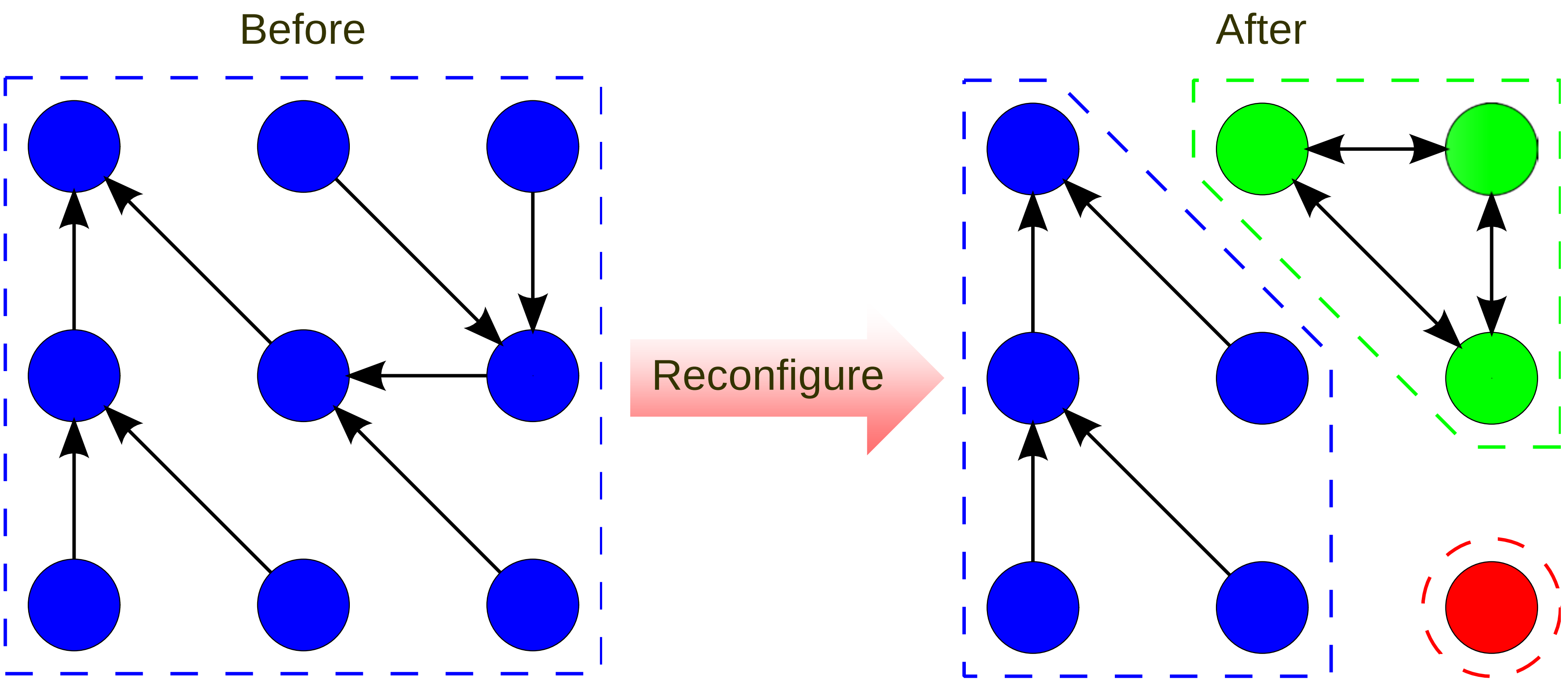
Backup

Agile Control

- **A set of distributed controllers designed for:**
  - Management of complex interconnected systems
  - Can change their structure in response to faults and damage events
- **Agent-based, Operates on the sensors, valves, pumps, pipes, etc.**
- **Agility manifested by dynamically changing:**
  - Communication Topology, control strategy, agent scoping, etc.
- **Requires research and techniques from many areas:**
  - Networked/distributed control systems, hybrid control
  - Active diagnosis, agent-based systems
  - Many more…

Agile Control

Hypothetical Response to Damage Event



Slow System Dynamics
Centralized
Planning

Variable System Speed
Multiple Topologies
Multiple Strategies

Agile Control

- **Important part of agile control is the communication topology**
  - What information to share and with whom?
- **Another part is the state of the system itself**
  - How fast do previous observations become irrelevant?
  - Is the system behaving predictably or unpredictably?
- **This leads to analysis based using**
  - Information theory
  - Graph theory

Information Theory

- **System process** $x(t)$
- **Discrete state space** $X = \{x_i\}$
- **Descriptive complexity (Hartley Information) –** $\log_2 |X|$
- **Uncertainty (Shannon entropy) –** $H(x(t)) = -\sum P(x_i, t) \log_2 P(x_i, t)$
- **Information –** $I(x_i, t) = -\log_2 P(x_i, t)$
- **Information Volume – sum of all information of all entities**
- **Observation –** $S = (\xi, t)$

Information Theory

Information Decay due to Entropic Drag

- **Typically,** $H(x(t')|S) > H(x(t)|S)$ **for** $t' > t$
  - Indicates a loss of information of the observation $S = (\xi, t)$
  - We call this decay *entropic drag*
- **Sequence of observations** $S_{1:k} = \{(\xi_j, t_j)\}$
- **Define the entropic drag**

$$\Gamma(S_{1:k}, t_k, t') = \frac{H(x(t')|S_{1:k})}{t' - t_k}$$

APL

Information Theory and Control

- **Control actuations change the state probabilities of the system**
- **(Hopefully) these changes create an increase in order**
  - Called *negentropy*
- **An actuation A has negentropy** $I_A(t) = H(x(t)|A)$
- **A sequence $A_{1:k}$ has negentropic drag**

$$\Gamma_A(A_{1:k}, t_k, t') = \frac{H(x(t')|A_{1:k})}{t' - t_k}$$

- **Negentropy measures increase in order but not the quality of decision!**
  - This requires the notion of *utility*

APL

Summary

- Information theory can be used to characterize system processes
- Graph theory is a natural model for system interconnections
- Entropic drag and computational complexity help determine optimal agile controller topologies

Related Work at JHU/APL

- Extensions – fusion/truncation, processing models, gossip, abstraction, etc.
- Genetic algorithm to find better topologies
- Agile controllers
- Information-theoretics of human/machine coalitions
- Counter-C2