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Introduction to Complex Adaptive Systems-of-Systems (CASoS) Engineering

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Sandia National Laboratories

Seminar in Interdisciplinary Biological and Biomedical Sciences (SiBBs)
University of New Mexico
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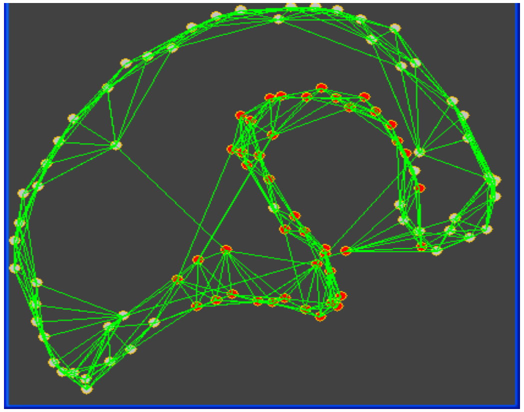

http://www.sandia.gov/CasosEngineering

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Outline

- Halloween Story: Potential Pandemic Influenza Outbreak
- Complex Adaptive Systems-of-Systems (CASoS)
  - Examples
  - Definitions
- Engineering within (or of) Complex Adaptive Systems-of-Systems
  - Aspirations & Modeling
  - Uncertainty
  - Framework & Tools
- Other CASoS Engineering Applications
- Research Challenges
- Q&A

A Halloween Story

In 2005, NISAC got a call from DHS on Halloween. Public health officials worldwide were afraid that the H5N1 "avian flu" virus would jump species and become a pandemic like the one in 1918 that killed 50M people worldwide.

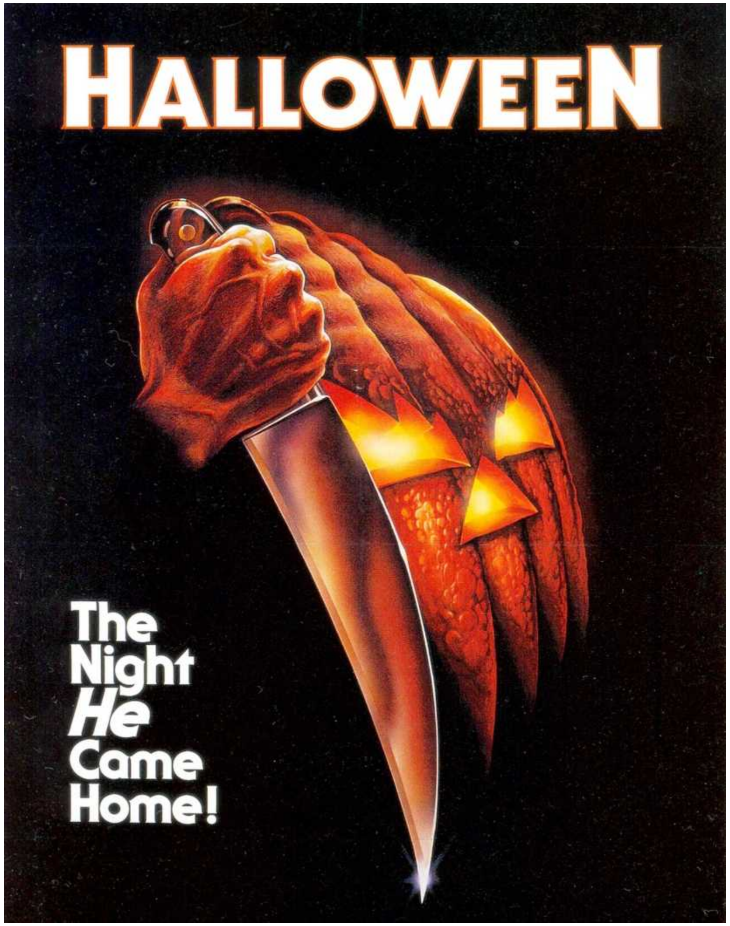
Pandemic now.

No vaccine, No antiviral.

What could we do?

Chickens being burned in Hanoi

Why Was This A Scary Story?



Source: PosterWire.com

- A pandemic outbreak is a complex adaptive system-of-systems (CASoS)
- Mitigation of an outbreak is controlling a CASoS (or engineering a solution to a CASoS)
- So … what exactly *is* a CASoS?

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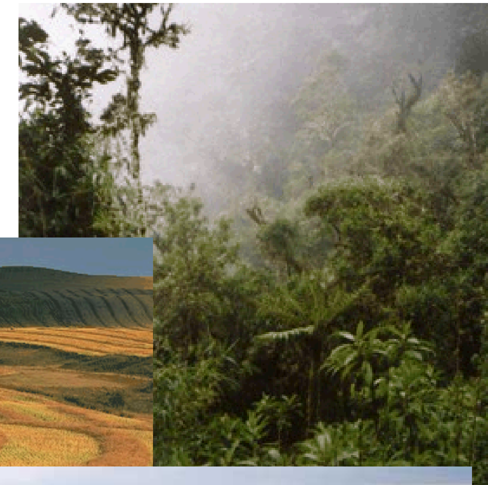
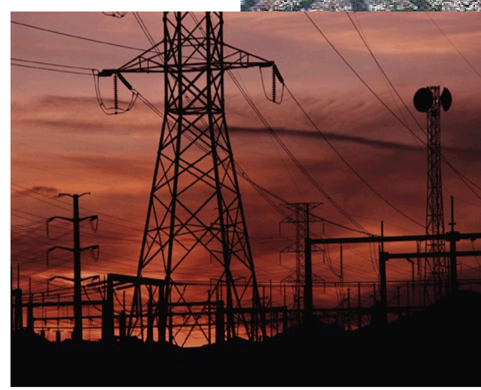
Many Examples of CASoS



- Tropical Rain forest
- Agro-Eco system
- Cities and Megacities (and their network on the planet)
- Interdependent infrastructure (local to regional to national to global)
- Government and political systems, educational systems, health care systems, financial systems, economic systems and their supply networks (local to regional to national to global)
- Global energy system and greenhouse gasses

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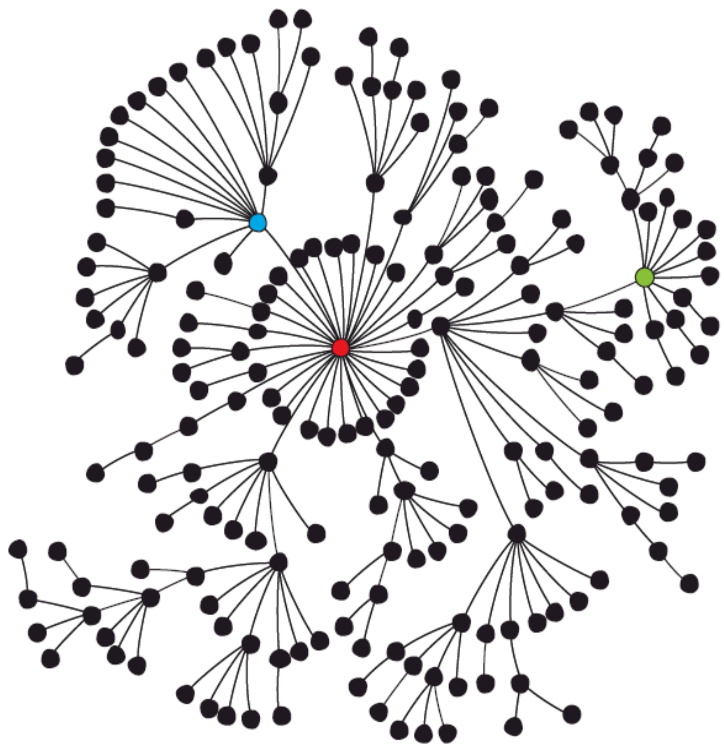
COMPLEX: Emergent scale-free structure with power laws & "heavy tails"



Simple preferential attachment model:
"*rich get richer*"
yields
hierarchical structure
with
"kingpin" nodes

Properties:
tolerant to random failure
but
vulnerable to
informed attack

1999 Barabasi and Albert's "scale-free" network

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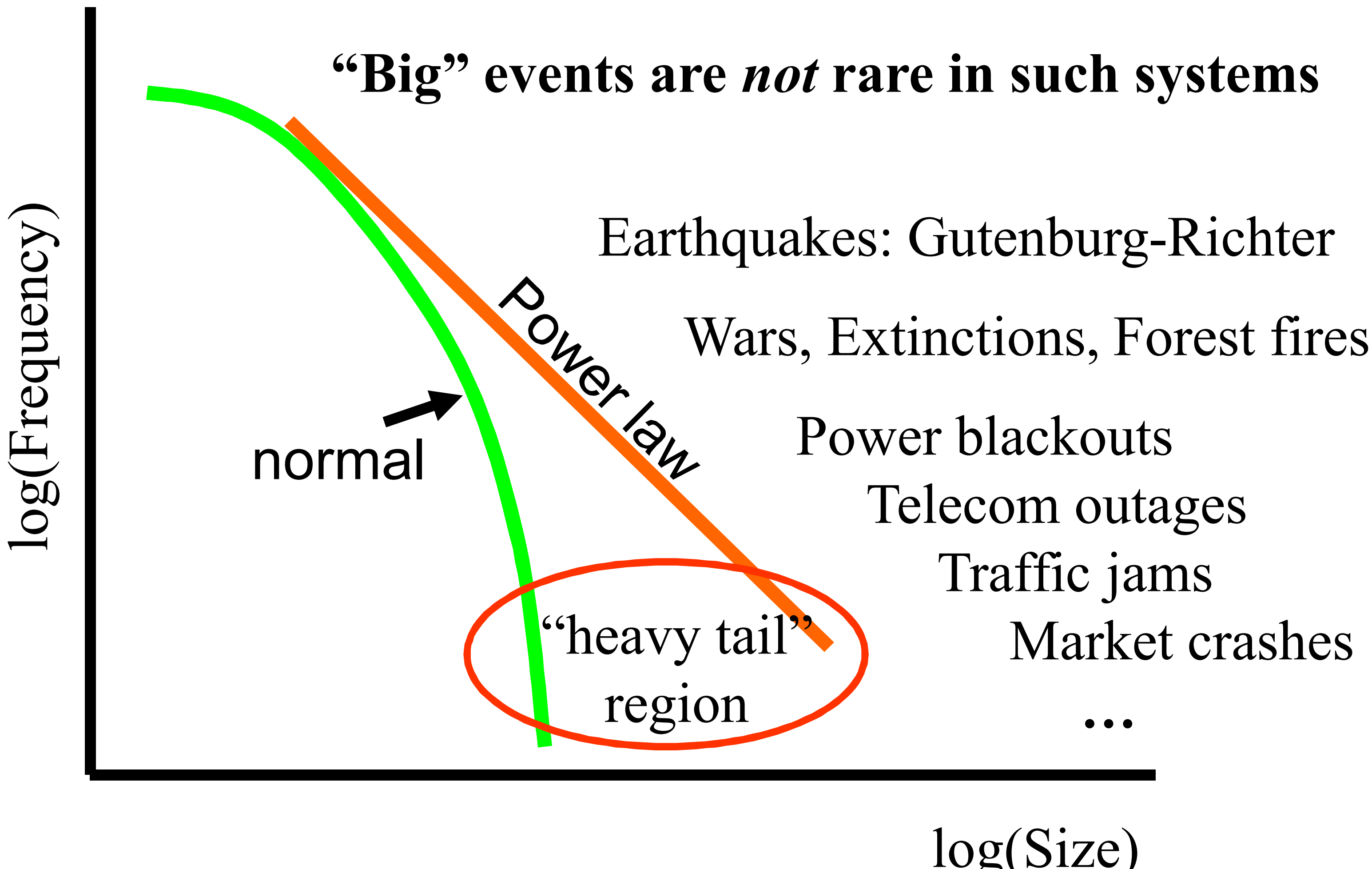
COMPLEX: Emergent behavior with power laws & "heavy tails"



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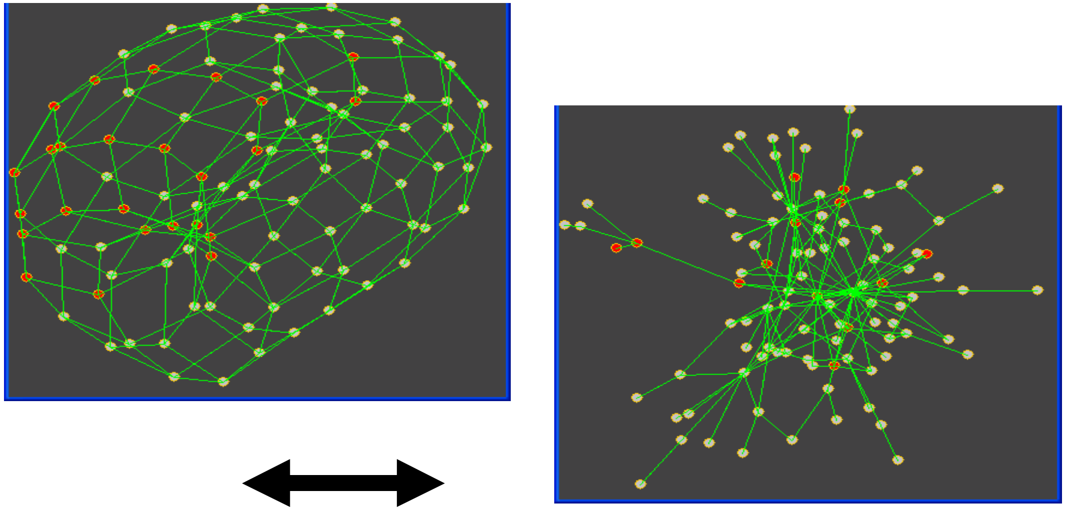
ADAPTIVE: Adaptation occurs at multiple scales

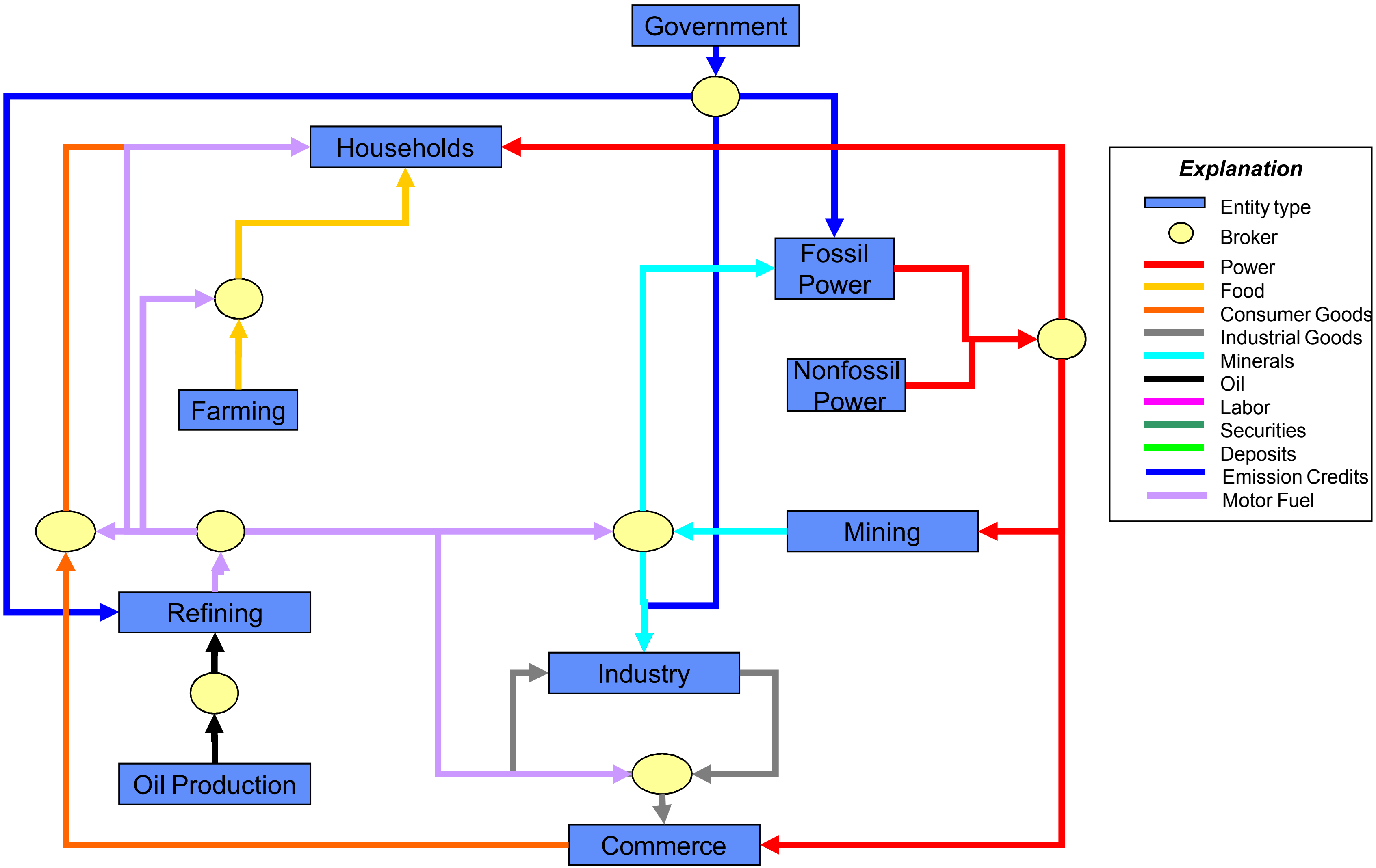
Adaptive: The system's behavior changes in time. These changes may be within entities or their interaction, within sub-systems or their interaction, and may result in a change in the overall system's behavior relative to its environment.

Temporal
Spatial
Relational



Grow and adapt
in response to local-to-global ***policy***

SYSTEM: Core Economy



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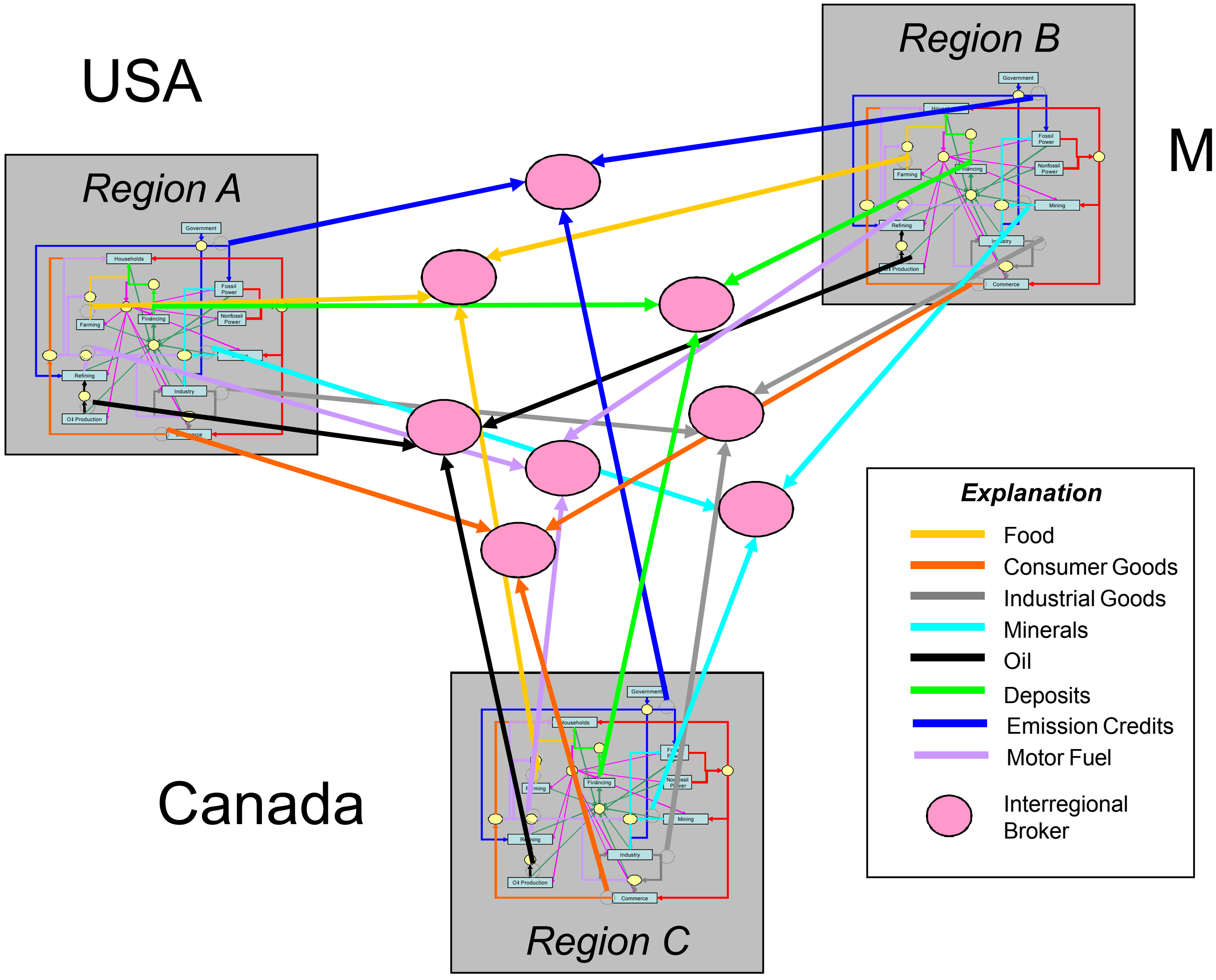
SYSTEM OF SYSTEMS: Trading Blocks composed of Core Economies



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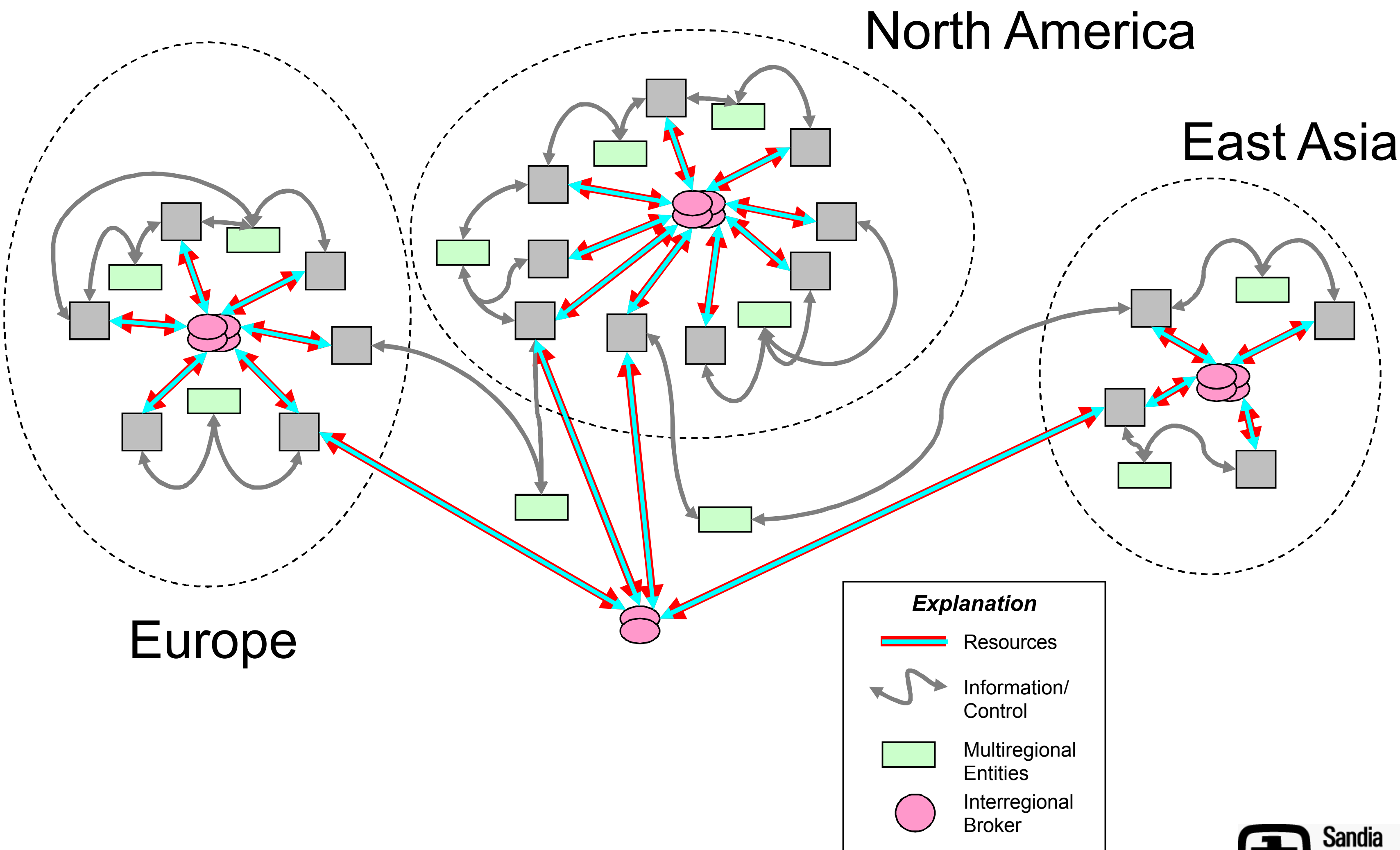
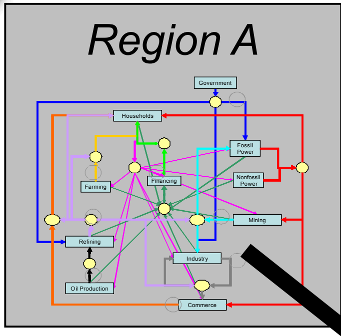
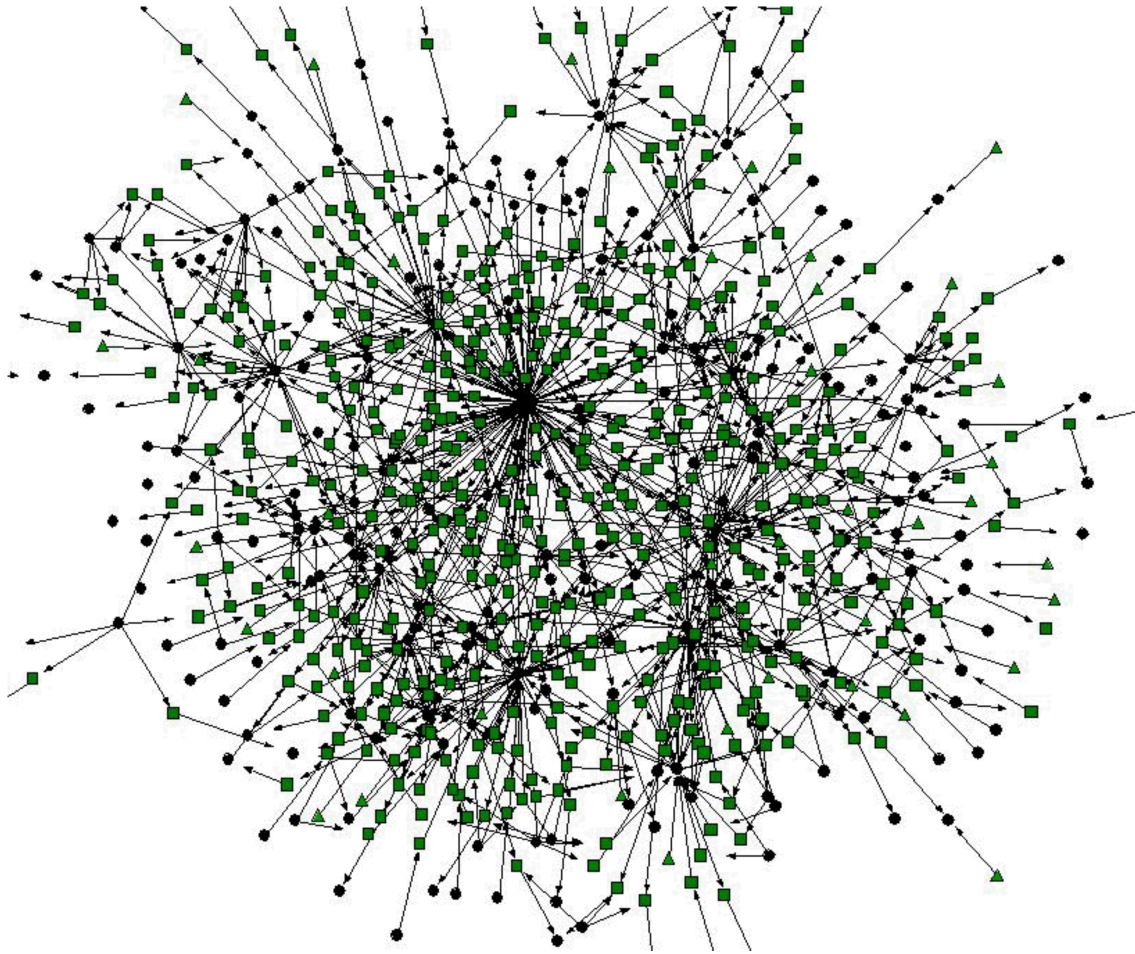
SYSTEM OF SYSTEM OF SYSTEMS: Global Energy System



NETWORKS within NETWORKS





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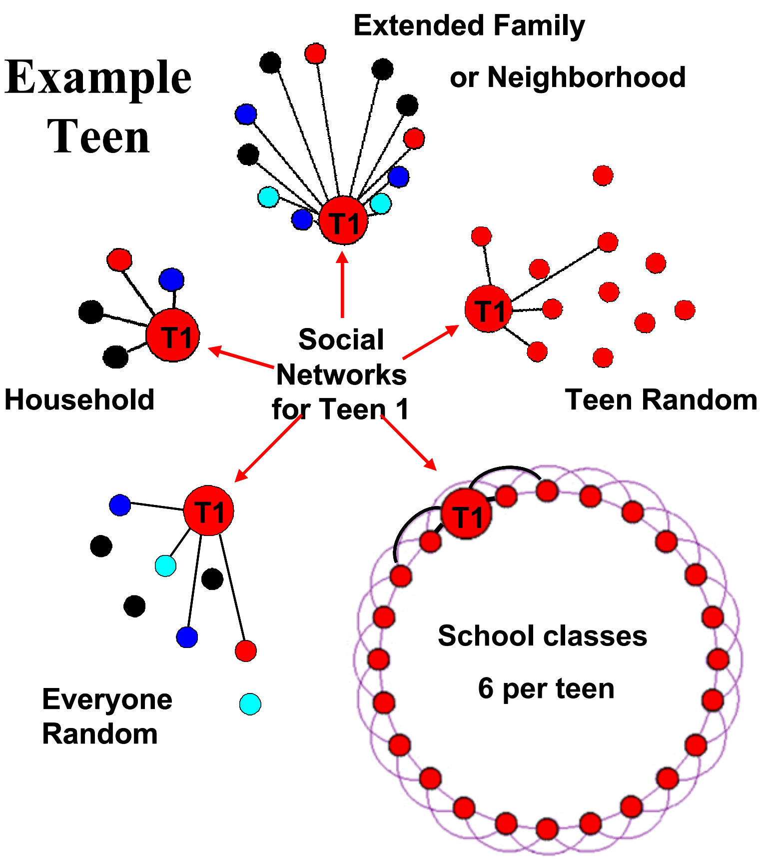
The Halloween Story as a CASoS

- **System:** Global transmission network composed of person to person interactions beginning from the point of origin (within coughing distance, touching each other or surfaces…)
- **System of Systems:** People belong to and interact within many groups: Households, Schools, Workplaces, Transport (local to regional to global), etc., and health care systems, corporations and governments place controls on interactions at larger scales…
- **Complex:** huge number of interactions between many, many similar components (billions of people on planet) and groups
- **Adaptive:** each culture has evolved different social interaction processes, each will react differently and adapt to the progress of the disease, this in turn causes the change in the pathway and even the genetic make-up of the virus

HUGE UNCERTAINTY

How Do We Control This CASoS?

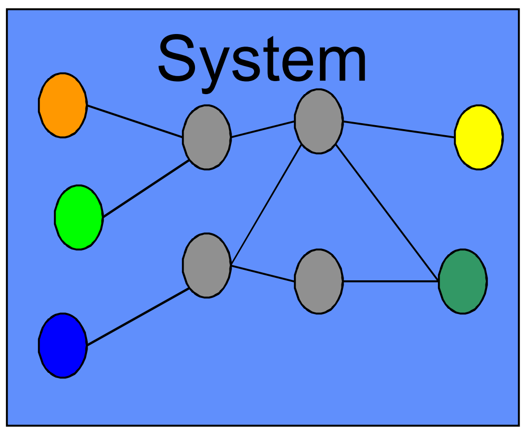
- We map aspirations to solutions via modeling and uncertainty quantification



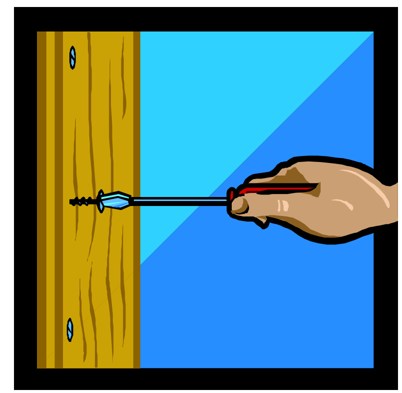
How to Model a CASoS

- There is no general-purpose model of any system
- A model describes a system for a purpose
- “All models are wrong, but some are useful” (George Box)

What do we care about?



What can we do?



Model

Additional structure and details added *as needed*

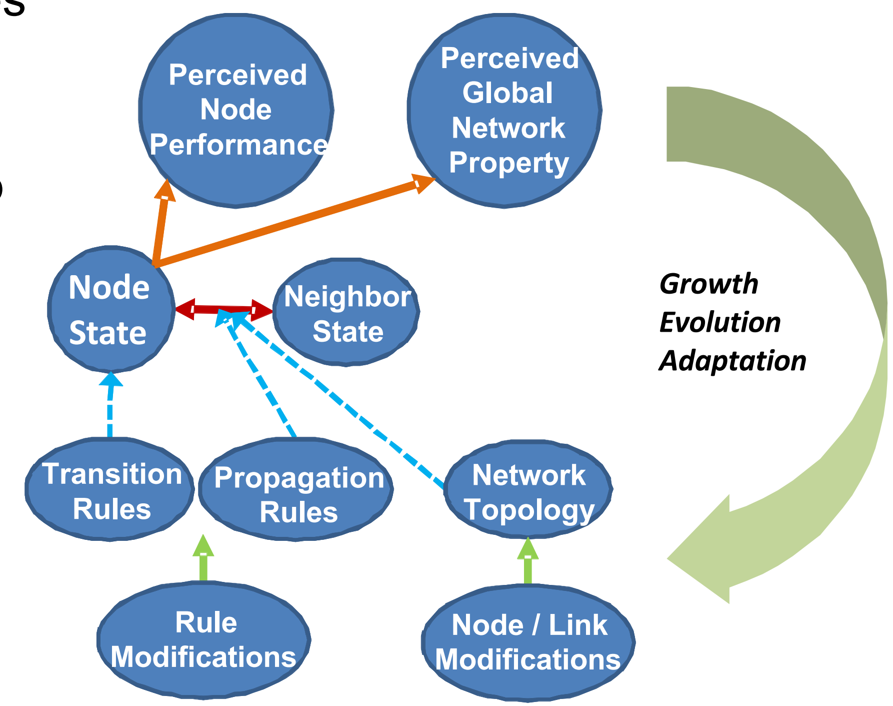
Conceptual Lens for Modeling/Thinking

Take any system and abstract as:

- Nodes (with a variety of “types”)
- Links or “connections” to other nodes (with a variety of “modes”)
- Local rules for Nodal and Link behavior
- Local Adaptation of Behavioral Rules
- Global forcing, Local dissipation

•Connect nodes appropriately to form a system (network)

•Connect systems appropriately to form a System of Systems



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Multiple Modeling Approach to CASoS

- **A set of models drawn from multiple modeling paradigms at multiple scales are often used for CASoS modeling**
  - To reflect multiple perspectives
  - To reflect the multiscale variety that is characteristic of of Complex Systems
- **"Lumped" to Discrete**
- **Systems Dynamics to Agent-Based to Social Networks to Supply Chains**
- **Independent or Integrated**
  - **If integrated, the definition of "Entity" could change from model to model, but the relationship between the different kinds of Entity allows the models to be integrated**

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NISAC Example: Multiple Perspectives

Realistic → Abstract

→ *Decreasing detail, computation and development time*

Data on system elements	High-fidelity models - individual infrastructure elements	Systems models of aggregate supply - demand dynamics	Generic, highly abstracted network models
Only know what is measured or monitored - limited to specific set of conditions **FASTMap** **FAIT** **REAcct**	Detailed simulation of changes in conditions or behaviors **N-ABLE** **R-NAS** **ATOM** **IEISS** **MIITS** **N-SMART** **EpiSims** **TRANSIMS** **Loki-Natural Gas**	Effects of conditions and limitations on system operation **Port Simulators** **Petroleum** **Natural Gas** **TelecomOps** **DamOps**	Simulation and identification of vulnerabilities of different network topologies to disruptions and effective mitigation **Loki-Infect** **Loki-Transaction** **Loki-Power**

CASoS Engineering

- Many CAS or CASoS efforts stop here, at the system characterization or model-building stage
  - "Butterfly collecting"
- However, funders of CASoS modeling for national-scale problems have *aspirations* for those models
  - A teleology or purpose
  - In short, aspirations are *engineering* goals for those models
- Enter the discipline of CASoS Engineering
  - Engineering ***within*** CASoS and Engineering ***of*** CASoS

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CASoS Engineering Aspirations

From an engineering perspective, *Aspirations* fall into a set of clearly identified categories:

- **Predict** the evolution of the system and, in particular, the results of events (*e.g.,* perturbations of a variety of qualities and quantities) with direct and consequential changes in system health.
- **Prevent or Cause** an event to occur.
- **Prepare** elements of the system for impending events (*e.g.*, minimize/maximize influence).
- **Monitor** important aspects of a system to record the response of the system to events.
- **Recover or Change** in response to events.
- **Control** system behavior to avoid or steer the system towards specified regimes through the design of appropriate incentives and feedback.
- **Design** an artificial CASoS.

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Relevant Aspiration for the Halloween Story

- Control (or mitigate)

Source: nmhm.washingtondc.museum

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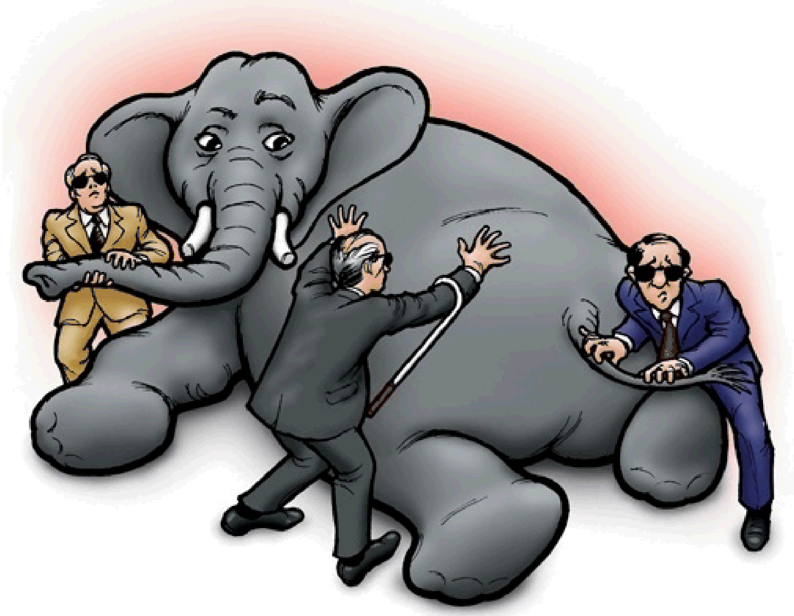
The Role of Uncertainty

- Complex systems are often unpredictable
- Adaptation, learning and innovation by networked agents creates multiple plausible outcomes rather than a single “right” answer
- Complex systems exhibit ranges of uncertainties
  - Structural Uncertainty: How well do you understand the system?
  - Parametric Uncertainty: How well have you characterized the inputs?
  - Stochastic Uncertainty: How have random processes affected the results?
- Can we use uncertainty to better understand the complex system and to create better engineering solutions?



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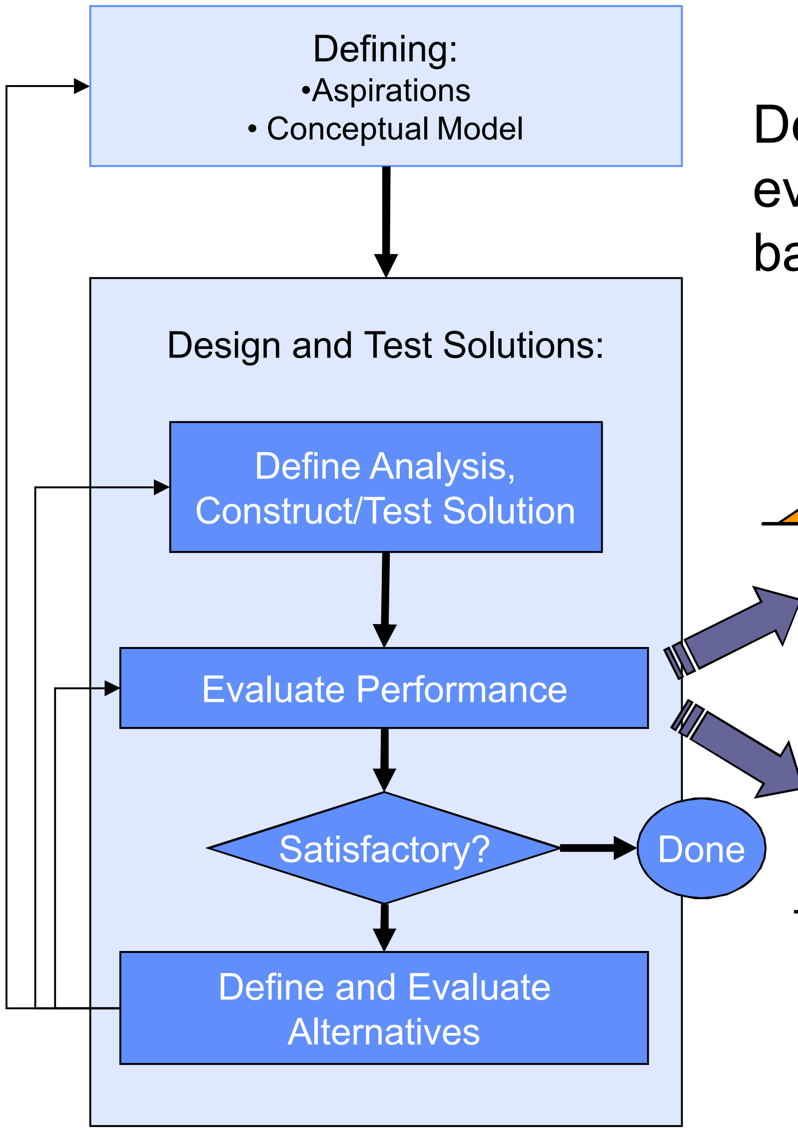
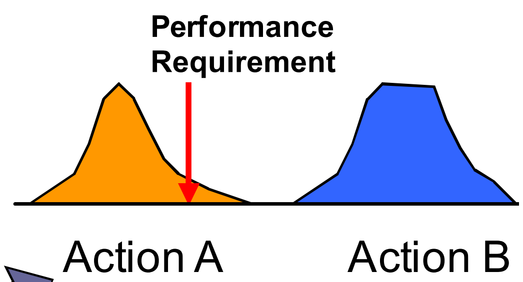
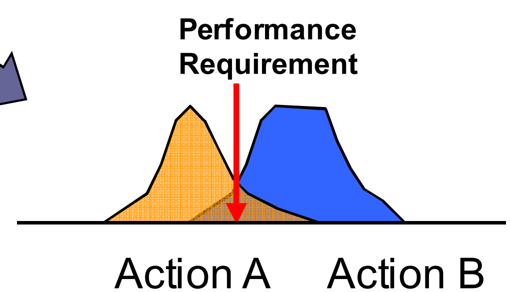
CASoS Engineering: An Iterative Process that Uses Uncertainty



Decision to refine the model can be evaluated using uncertainty, on the same basis as other actions



Model uncertainty permits distinctions

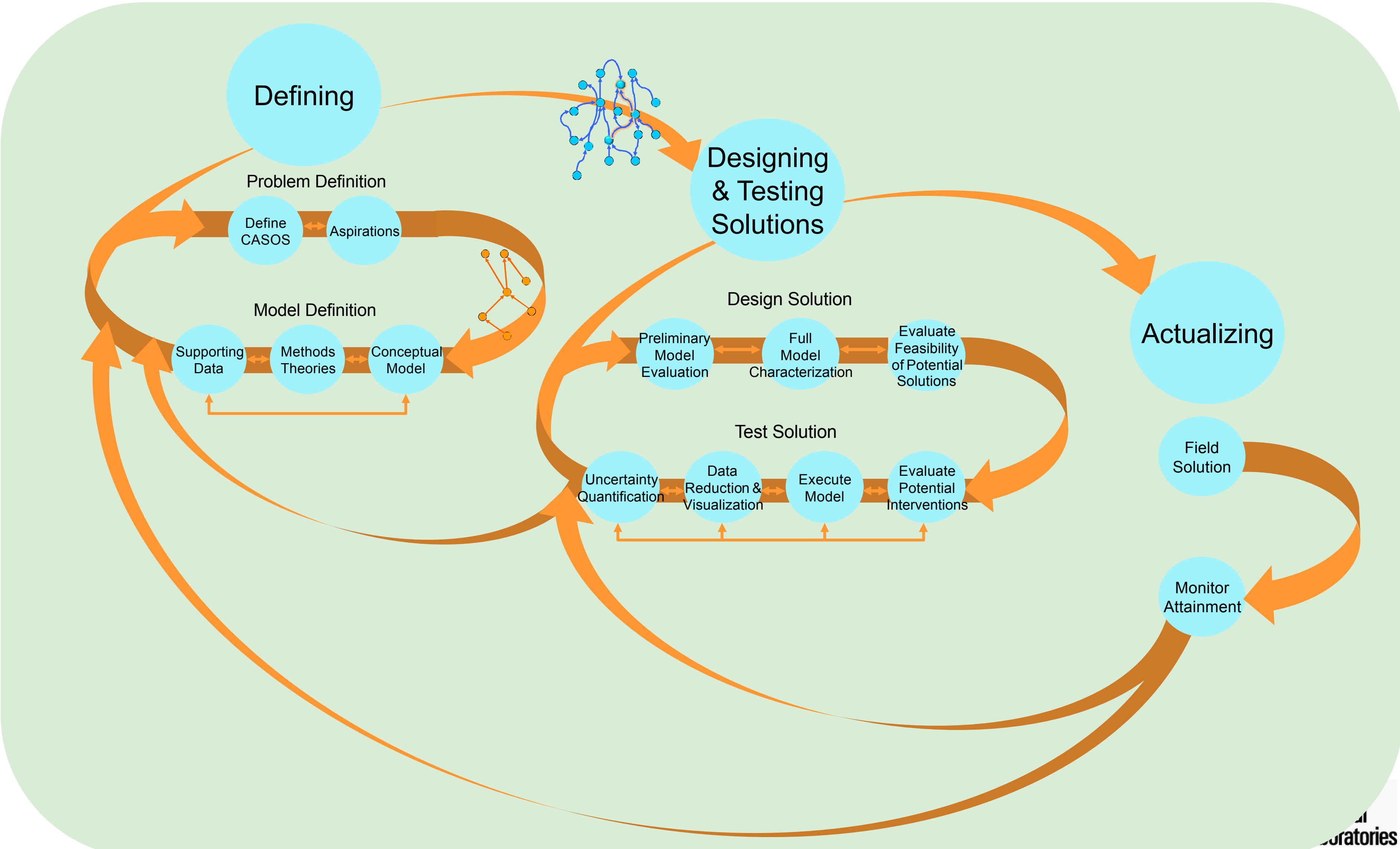


Model uncertainty obscures important distinctions, and reducing uncertainty has value

Uncertainty Drives V&V for CASoS

- Verification and Validation (V&V) is done differently in policy-oriented Complex Adaptive Systems-of-Systems Engineering
- Instead of validating the models against the complex realities that they represent, the choice of effective policies suggested by the models is validated against other possible policy choices, taking uncertainty into account
- In other words, V&V for policy-oriented CASoS is driven by Uncertainty Quantification

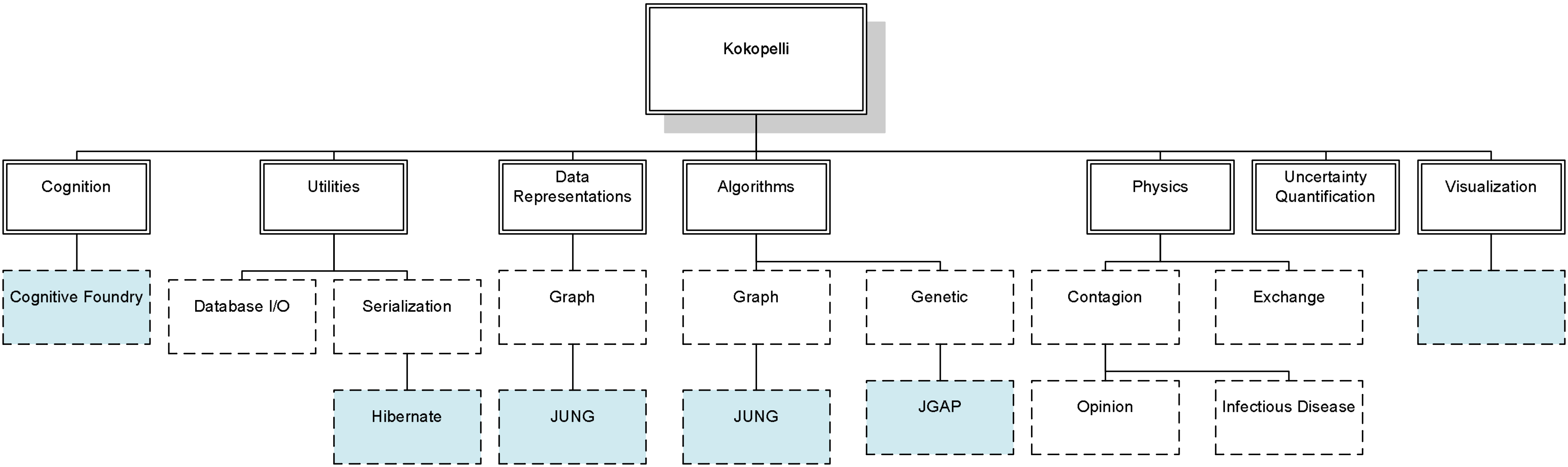
CASoS Engineering Process Flow



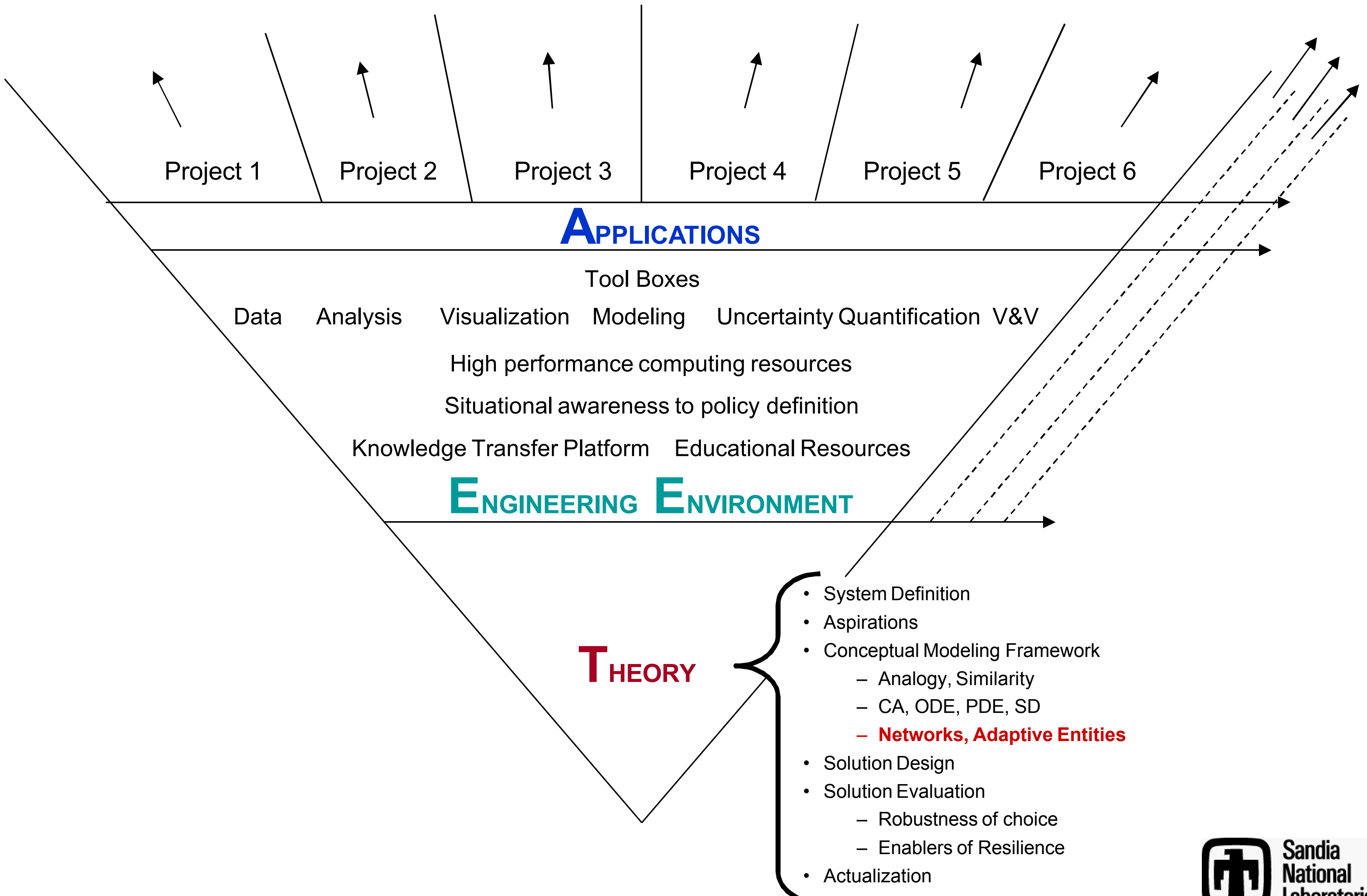
CASoS Engineering Tools

- **Modeling Tools**
  - Systems Dynamics modeling
  - Agent-based modeling
  - Discrete-event modeling
  - Markov modeling
  - Cellular Automata
  - State Machines
- **Algorithmic tools**
  - Genetic algorithms
  - Simulated Annealing
  - Ant Colony Optimization
- **Conceptual Tools**
  - Control theory
  - Chaos theory
  - Game theory
  - Innovation theory
- **Analytical Tools**
  - Bifurcation Analysis
  - Uncertainty Quantification
  - Verification and Validation

Kokopelli Toolkit



CASoS Engineering Framework



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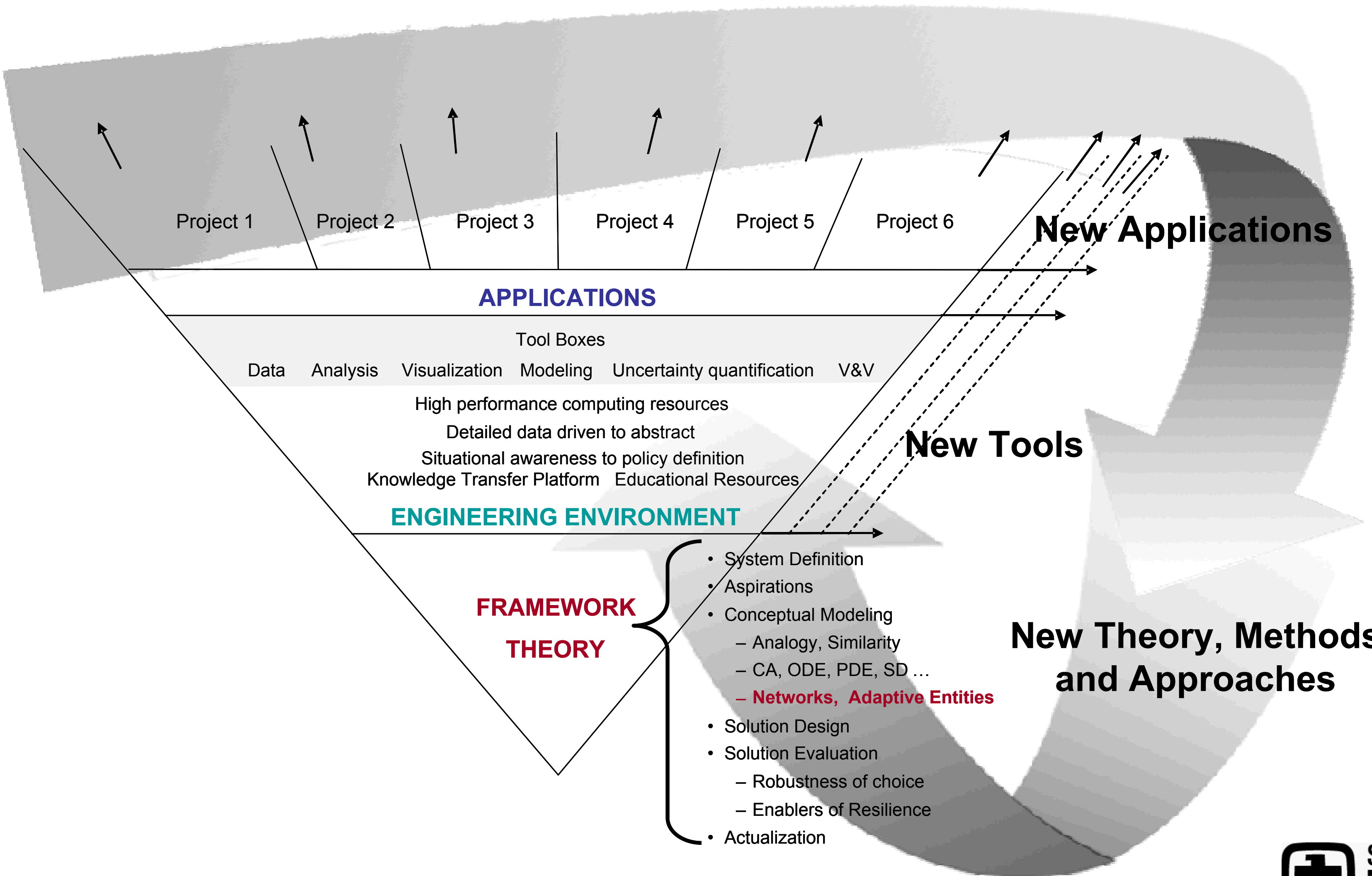
Evolving the CASoS Engineering Framework



SO … HOW DID WE ENGINEER A SOLUTION TO THE HALLOWEEN STORY?

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Reason by Analogy with other Complex Systems

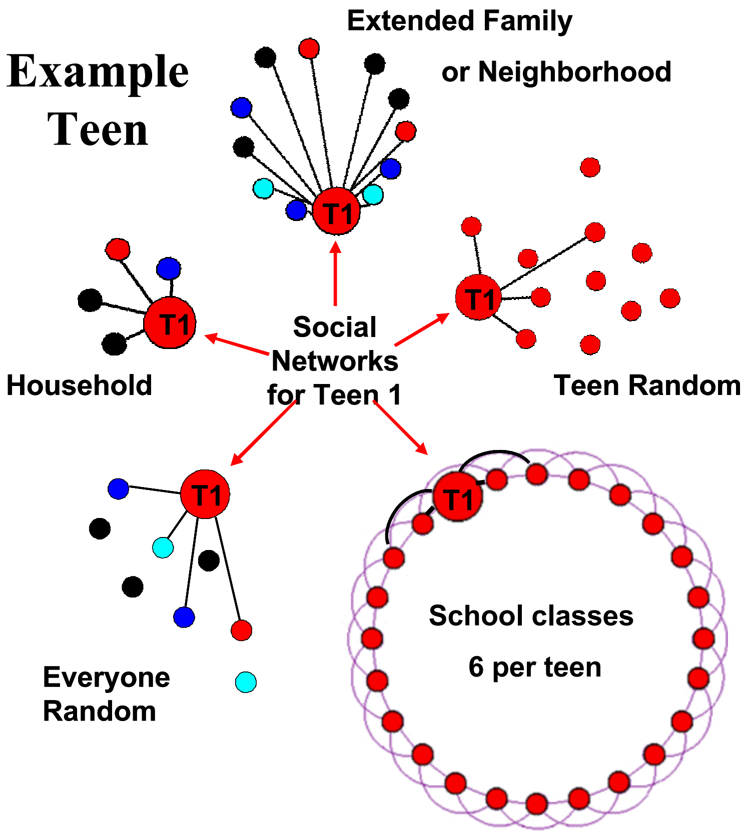
Simple analog:

- **Forest fires**: You can *build fire breaks* based on where people throw cigarettes… or you can *thin the forest* so no that matter where a cigarette is thrown, a percolating fire (like an epidemic) will not burn.

Aspirations:

- Could we target the social network within individual communities and thin it?
- Could we thin it intelligently so as to minimize impact and keep the economy rolling?

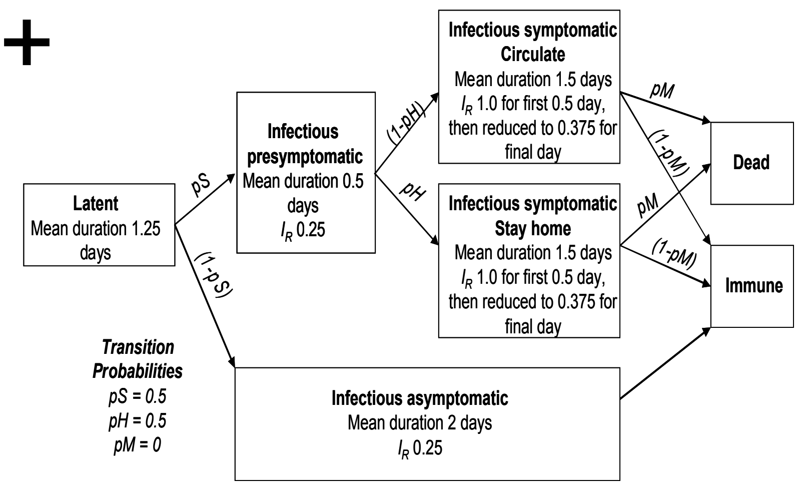
Application of Networked Agent Method to Influenza



Stylized Social Network
(nodes, links, frequency of interaction)

+

Disease manifestation
(node and link behavior)



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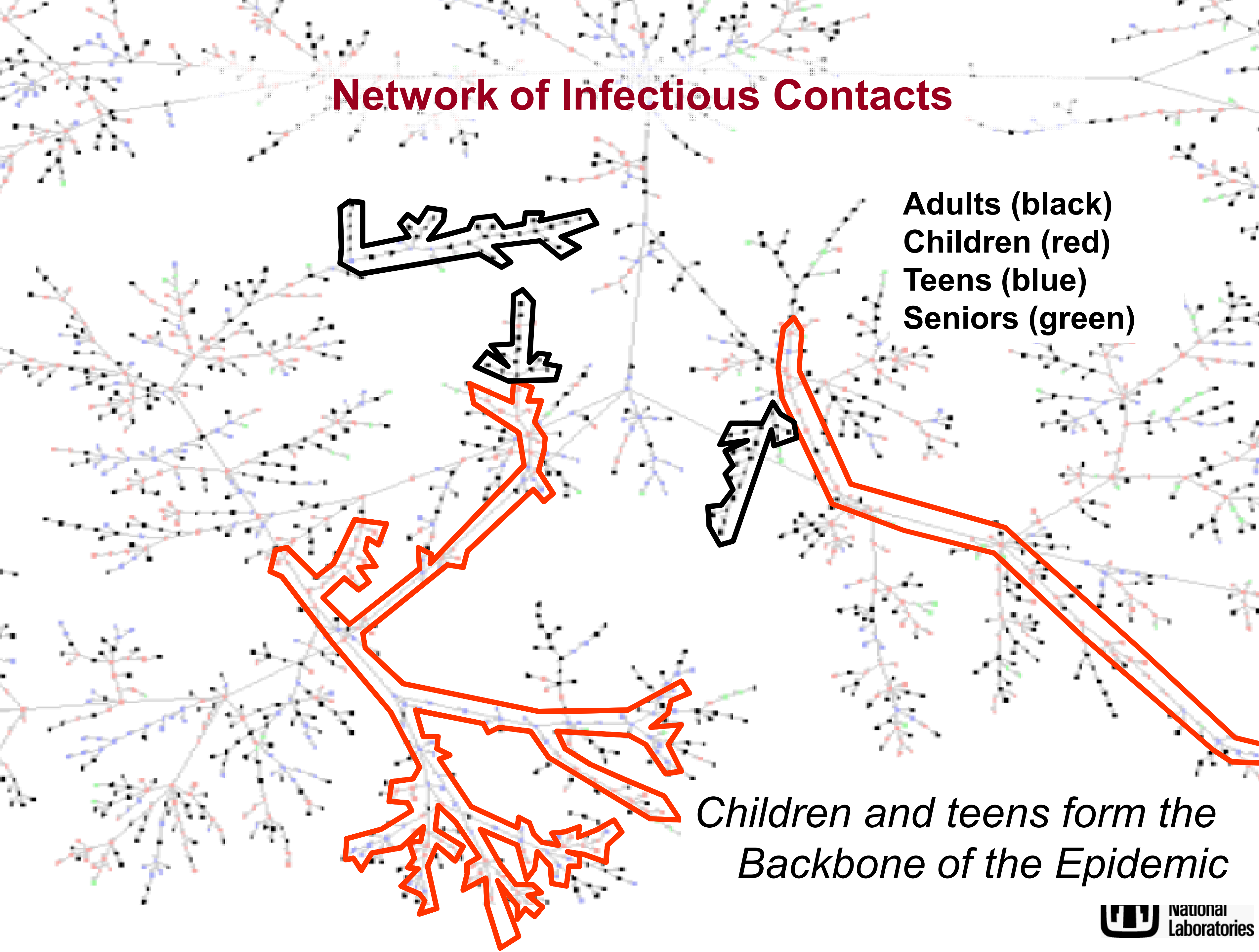
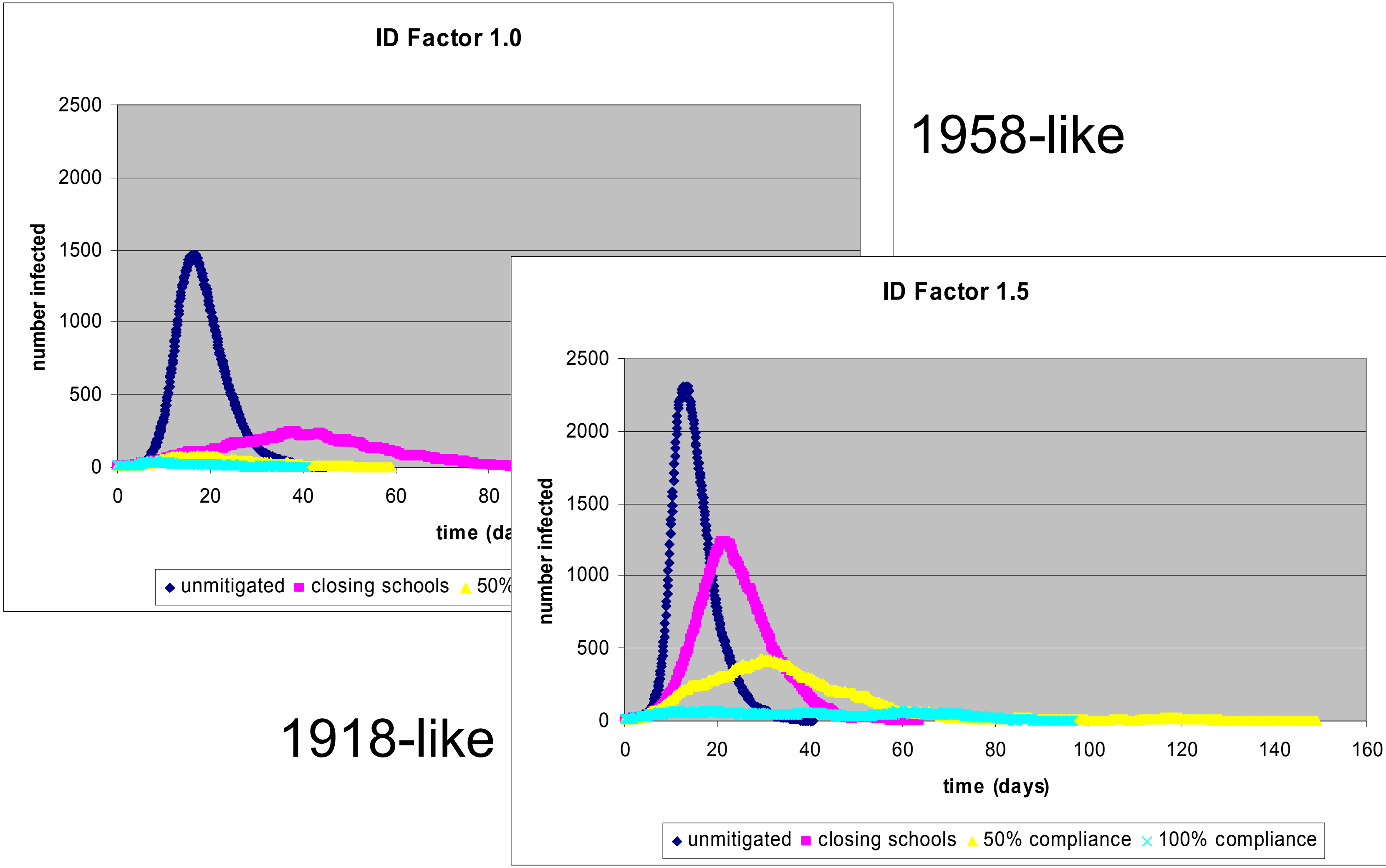
Network of Infectious Contacts



Closing Schools and Keeping the Kids Home

1958-like



1918-like

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Connected to White House Pandemic Implementation Plan writing team and VA OPHEH

They identified critical questions/issues and worked with us to answer/resolve them

- How sensitive were results to the ***social net***? Disease ***manifestation***?
- How sensitive to ***compliance***? Implementation ***threshold***? Disease ***infectivity***?
- How did the model results ***compare*** to past epidemics and results from the models of others?
- Is there any ***evidence*** from past pandemics that these social-distancing strategies worked?
- What about adding or "***layering***" additional strategies including ***home quarantine, antiviral treatment and prophylaxis, and pre-pandemic vaccine*** *(i.e., a "policy cocktail")*?

We extended the model and put it on Sandia's 10,000 node computational cluster … 10's of millions of runs later we had the answers to:

- What is the best mitigation strategy combination? (***choice***)
- How robust is the combination to model assumptions? (***robustness of choice***)
- What is required for the choice to be most effective? (***evolving towards resilience***)

Sensitivity analysis and uncertainty quantification are critical to engineering a robust and resilient solution

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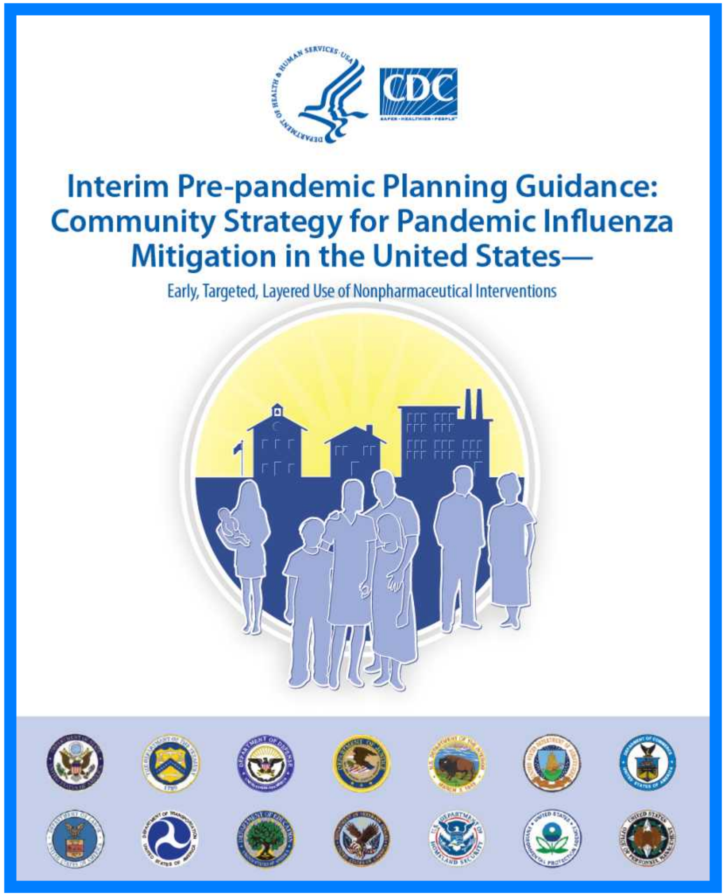
Worked with the White House to Formulate Public Policy

A year later…



For Details see:

Local Mitigation Strategies for Pandemic Influenza, RJ Glass, LM Glass, and WE Beyeler, SAND-2005-7955J (Dec, 2005).

Targeted Social Distancing Design for Pandemic Influenza, RJ Glass, LM Glass, WE Beyeler, and HJ Min, *Emerging Infectious Diseases* November, 2006.

Design of Community Containment for Pandemic Influenza with Loki-Infect, RJ Glass, HJ Min WE Beyeler, and LM Glass, SAND-2007-1184P (Jan, 2007).

Social contact networks for the spread of pandemic influenza in children and teenagers, LM Glass, RJ Glass, *BMC Public Health*, February, 2008.

Rescinding Community Mitigation Strategies in an Influenza Pandemic, VJ Davey and RJ Glass, *Emerging Infectious Diseases*, March, 2008.

Effective, Robust Design of Community Mitigation for Pandemic Influenza: A Systematic Examination of Proposed U.S. Guidance, VJ Davey, RJ Glass, HJ Min, WE Beyeler and LM Glass, PLoSOne, July, 2008.

Pandemic Influenza and Complex Adaptive System of Systems (CASoS) Engineering, Glass, R.J., Proceedings of the 2009 International System Dynamics Conference, Albuquerque, New Mexico, July, 2009.

Health Outcomes and Costs of Community Mitigation Strategies for an Influenza Pandemic in the U.S, Perlroth, Daniella J., Robert J. Glass, Victoria J. Davey, Alan M. Garber, Douglas K. Owens, Clinical Infectious Diseases, January, 2010.

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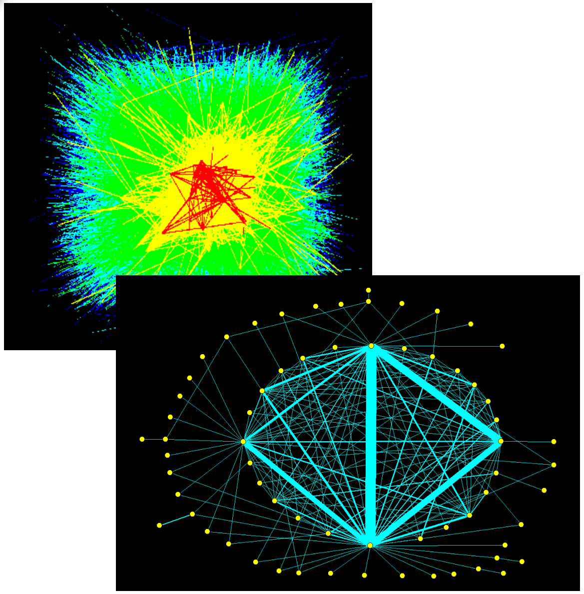
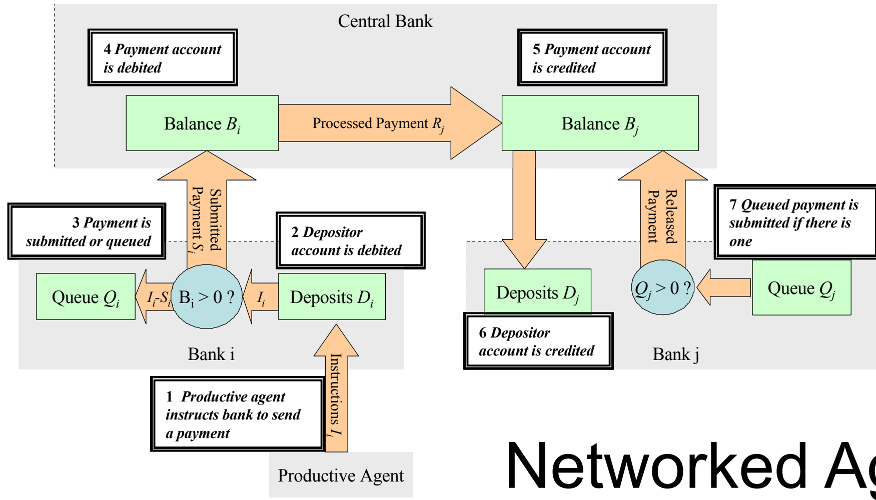
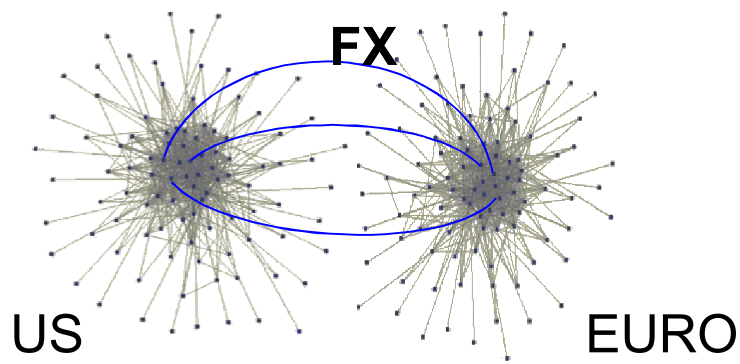
Application: Congestion and Cascades in Payment Systems



Payment system network



Networked Agent Based Model



Global interdependencies

For Details see:
The Topology of Interbank Payment Flows, Soramäki, et al, *PhysicaA,* 1 June 2007; vol.379, no.1, p.317-33.
Congestion and Cascades in Payment Systems, Beyeler, et al, *PhysicaA,* 15 Oct. 2007; v.384, no.2, p.693-718.
Congestion and Cascades in Coupled Payment Systems, Renault, et al, Joint Bank of England/ECB Conference on Payments and monetary and financial stability, Nov, 12-13 2007.

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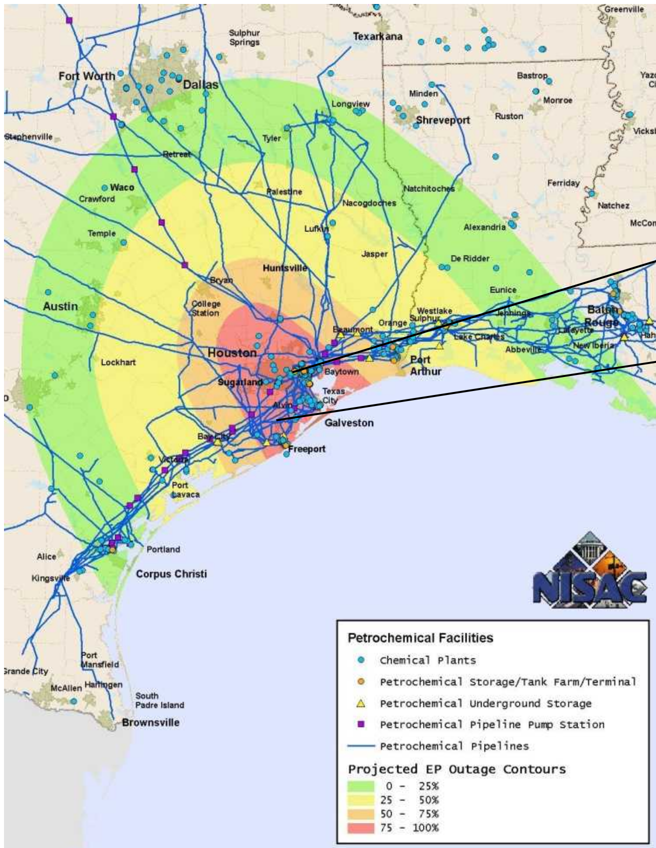
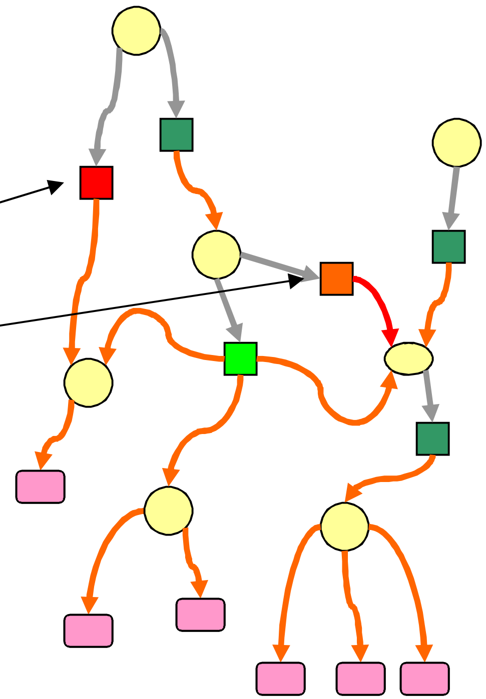
Application: Industrial Disruptions

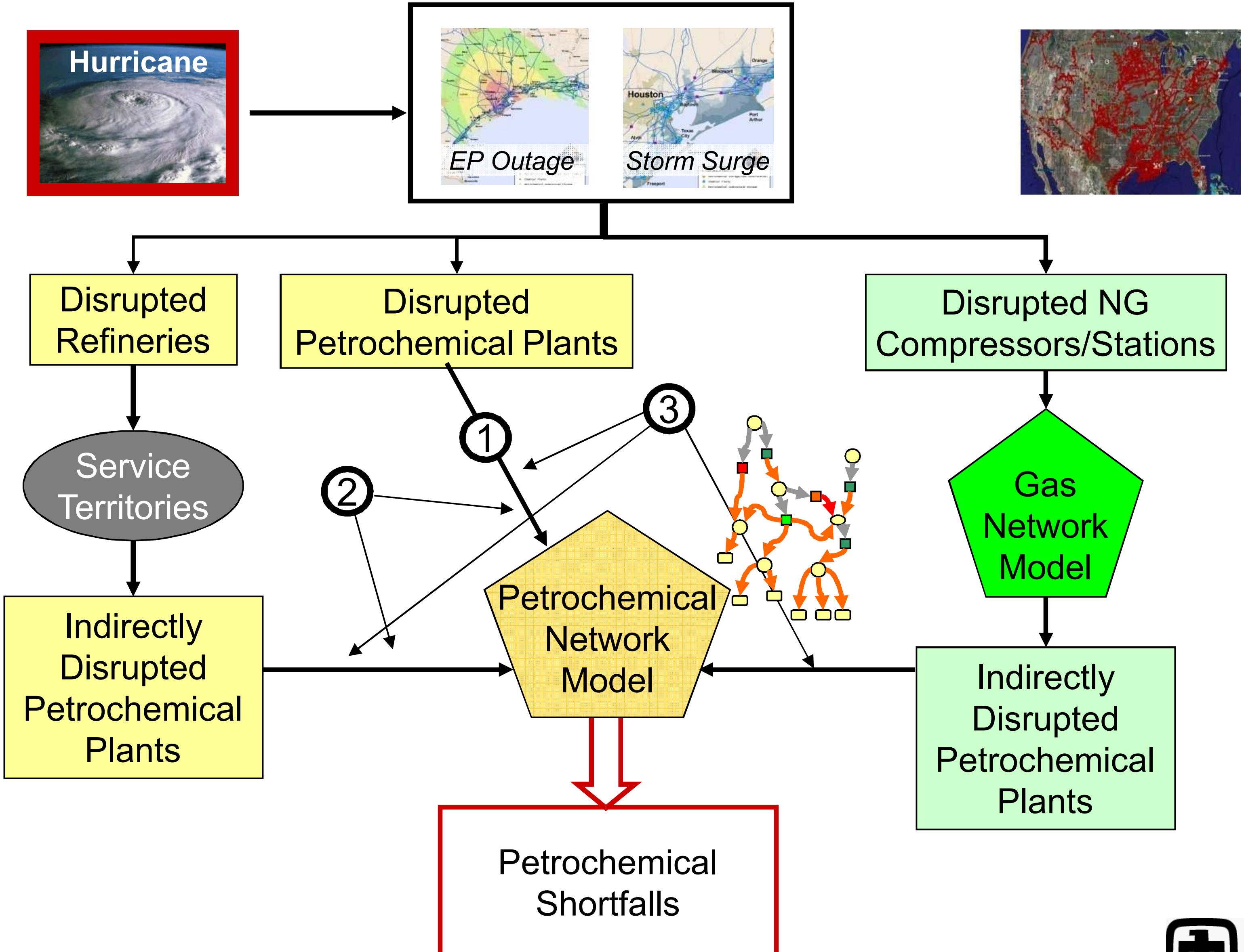
Disrupted Facilities → ***Reduced Production Capacity***





Diminished Product Availability

Application: Petrochemical & Natural Gas



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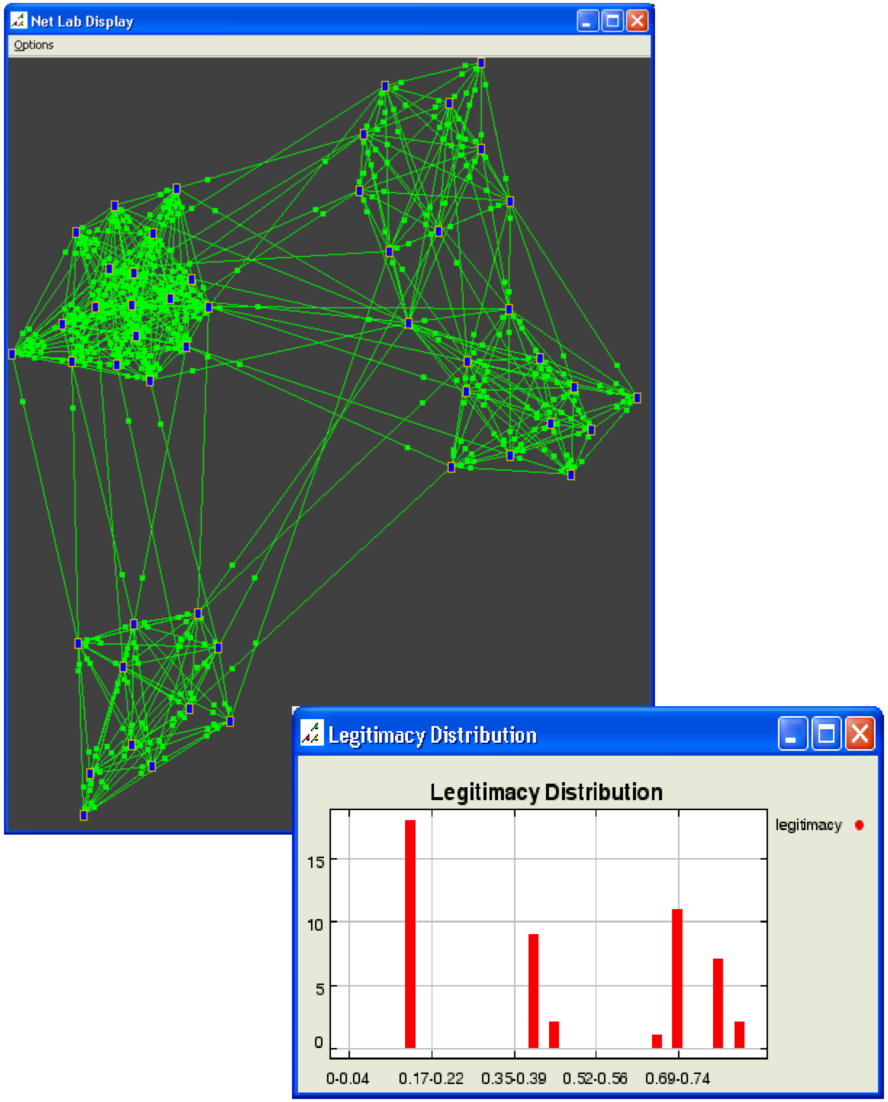
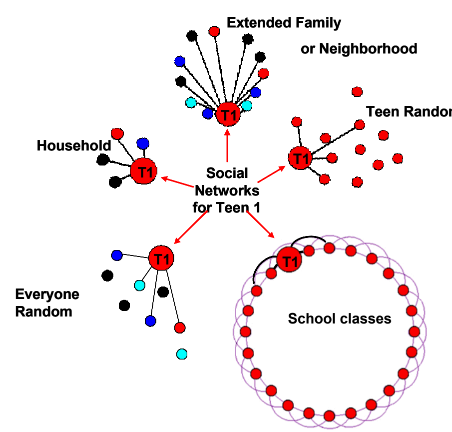
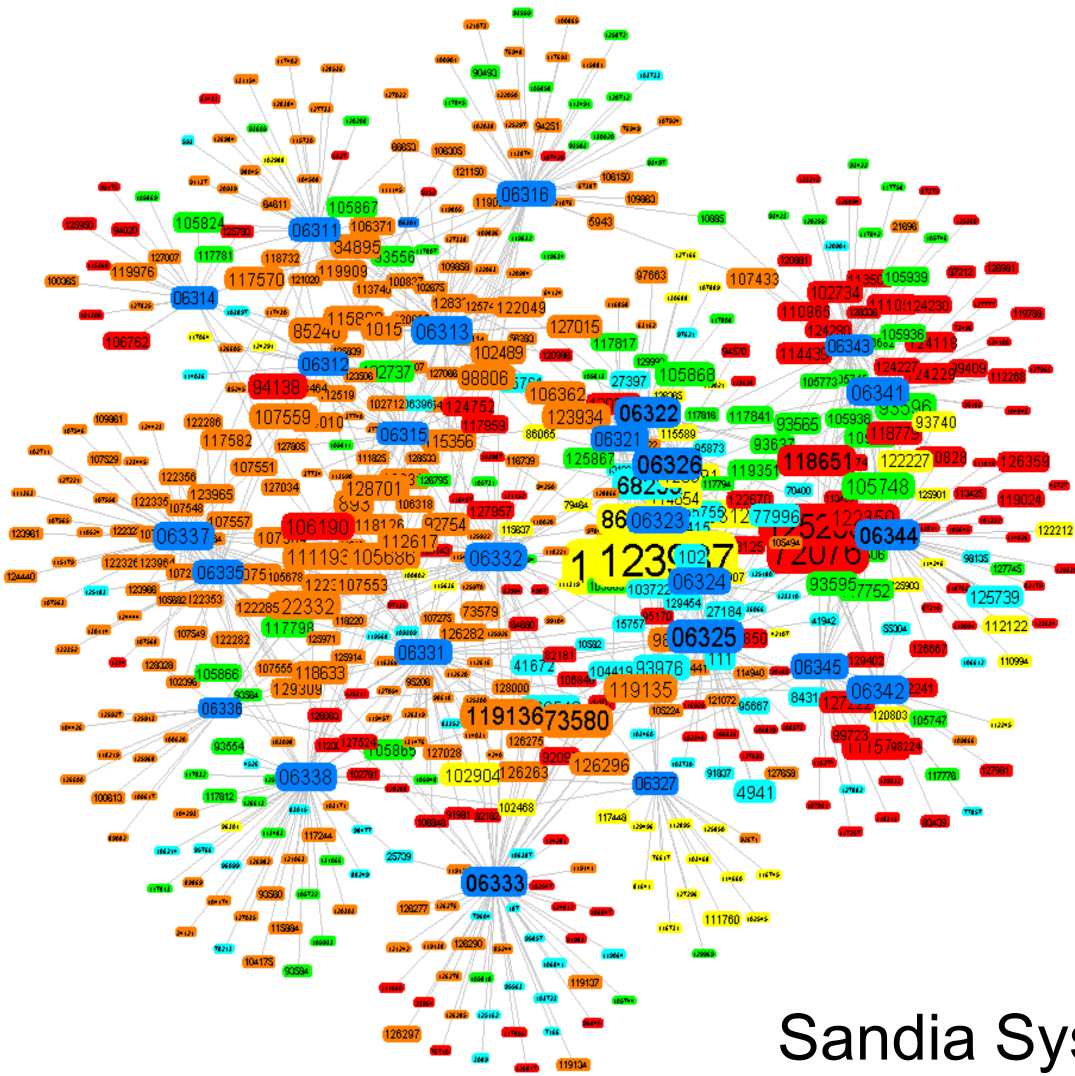
Application: Group Formation and Fragmentation



- Step 1: Opinion dynamics: tolerance, growing together, antagonism
- Step 2: Implementation of states with different behaviors (active, passive)
- Consider self organized extremist group formation, activation, dissipation
- **Application:** Initialization of network representative of community of interest



Application: Engineering Corporate Excellence



Step 1:

- Render the Corporation as a set of networks:
  - Individuals
  - Organizations
  - Projects
  - Communication (email, telephone, meetings
  - Products (presentations, reports, papers)
- Investigate structure and statistics over time
- Develop network measures of organizational Health

Step 2:

- Conceptual modeling…

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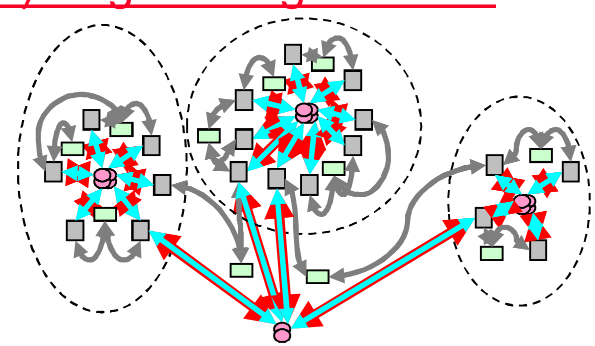
Research Challenges

- Identify computational complexity classes for CASoS Engineering problems
  - For example, reducing new applications to a "Forest Fire Control" complexity class, like reducing new algorithms to Boolean Satisfiability (SAT) or Traveling Salesperson (TSP) to prove NP-completeness
  - Complexity classes can also provide a lexicon of useful metaphors and analogies
  - Certain questions may not be answerable (not computable)
    - Certain aspirations simply may not be achievable
- Articulating a CASoS Engineering methodology that can be replicated by other organizations
  - Method for isolating important aspects of the problem that are solvable

CASoS Engineering

- Harnessing the tools and understanding of Complex Systems, Complex Adaptive Systems, and Systems of Systems to engineer solutions for some of the world's toughest problems
- An opportunity and challenge for educating the next generation of engineers and problem solvers
- Current efforts span a variety of problem owners:
  - DHS, DoD, DOE, DVA, HHS, and others
- CASoS Engineering Website
  - http://www.sandia.gov/CasosEngineering
- The CASoS Engineering Roadmap is available on our Website

Sandia National Laboratories: A Roadmap for the Complex Adaptive Systems of Systems CASoS) Engineering Initiative



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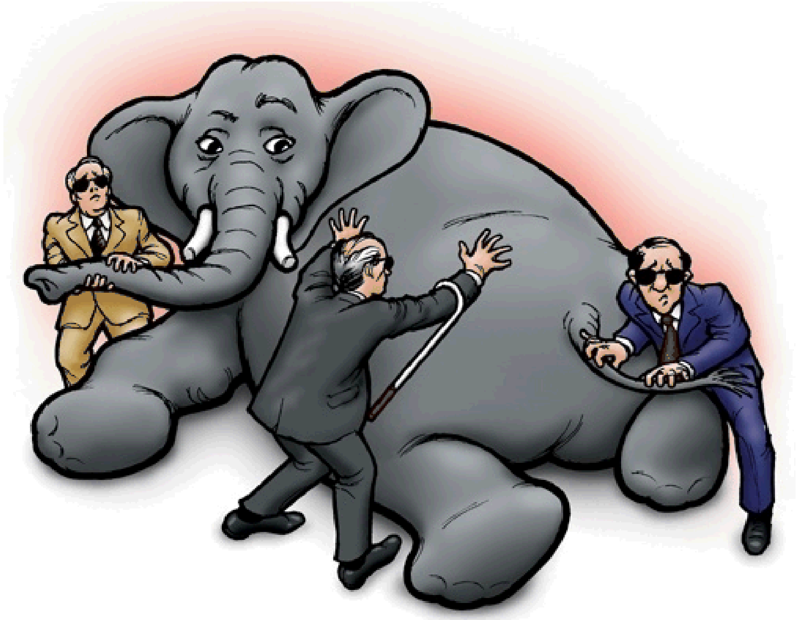
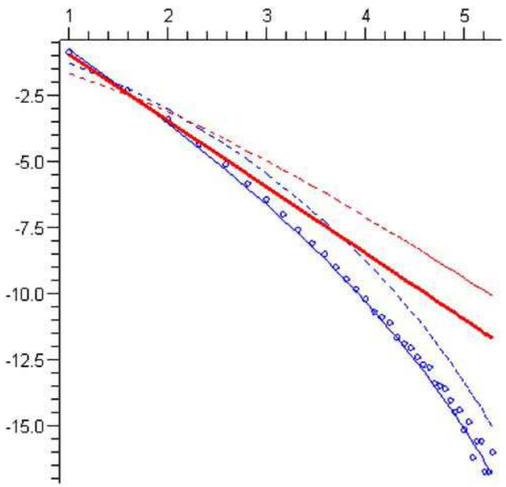
Q&A

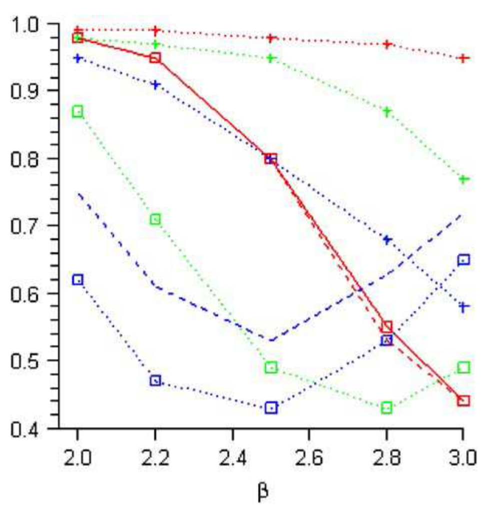
The Role of Uncertainty

- Aspects of Complex systems can be unpredictable (*e.g.,* Bak, Tang, and Wiesenfield sandpile)
- Adaptation, Learning and Innovation
- Conceptual Model or Structural Uncertainty
  - Beyond parameters
  - Beyond ICs/BCs
    - Initial Conditions
    - Boundary Conditions

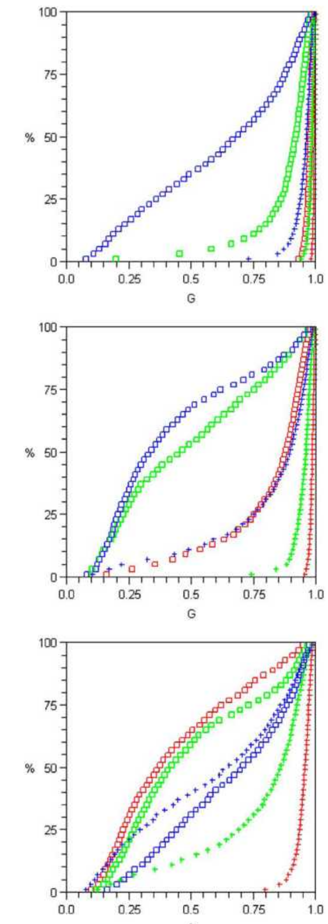


Application: Sensitivity of the Resilience of Congested Random Networks to Cascade Failure





- Studied the effect of network topology on the resilience of congested networks to cascade failure, by varying rolloff and offset characteristics
- $\exp(-\rho x)(\varphi + x)^{-\beta}$
  - This truncated power-law distribution describes many systems and models, including the degree distribution of finite random graphs
- Research Question: How sensitive is the resilience of such networks to rolloff (ρ) and offset (φ)?
- Research Results
  - Rolloff makes networks less resilient because the network is more sparse and tree-like
  - Offset makes networks more resilient because the network gains more edges and cycles
- Reference: R. A. LaViolette *et al.*, Physica A 368 (2006), p. 287-293



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