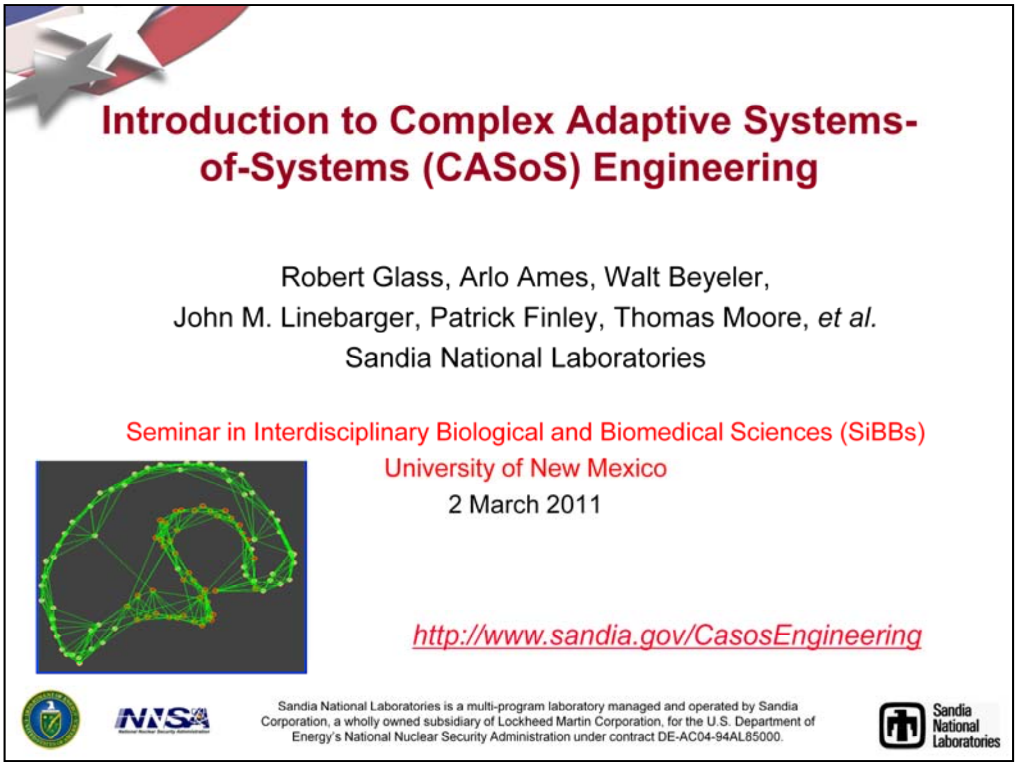

The CASoS Engineering effort at Sandia began in 2003 as part of the National Infrastructure Simulation and Analysis (NISAC) program, in partnership with Los Alamos National Laboratories. NISAC focuses on infrastructure protection, and infrastructures are a CASoS. They are interdependent and are designed by people to be used by people, governed by supply and demand.

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

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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

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The Pandemic story:

-On Halloween 2005 NISAC got a call from DHS. 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. DHS wanted NISAC to put together a briefing package to prepare DHS Sec Chertoff for a White House table top exercise the second week of December.

-President Bush got excited about this issue by reading a book on a plane (or while he was in Crawford in August 2005 on vacation).

The situation that NISAC was charged to investigate was the existence of a pandemic outbreak, but with no supplies of vaccine or antiviral.

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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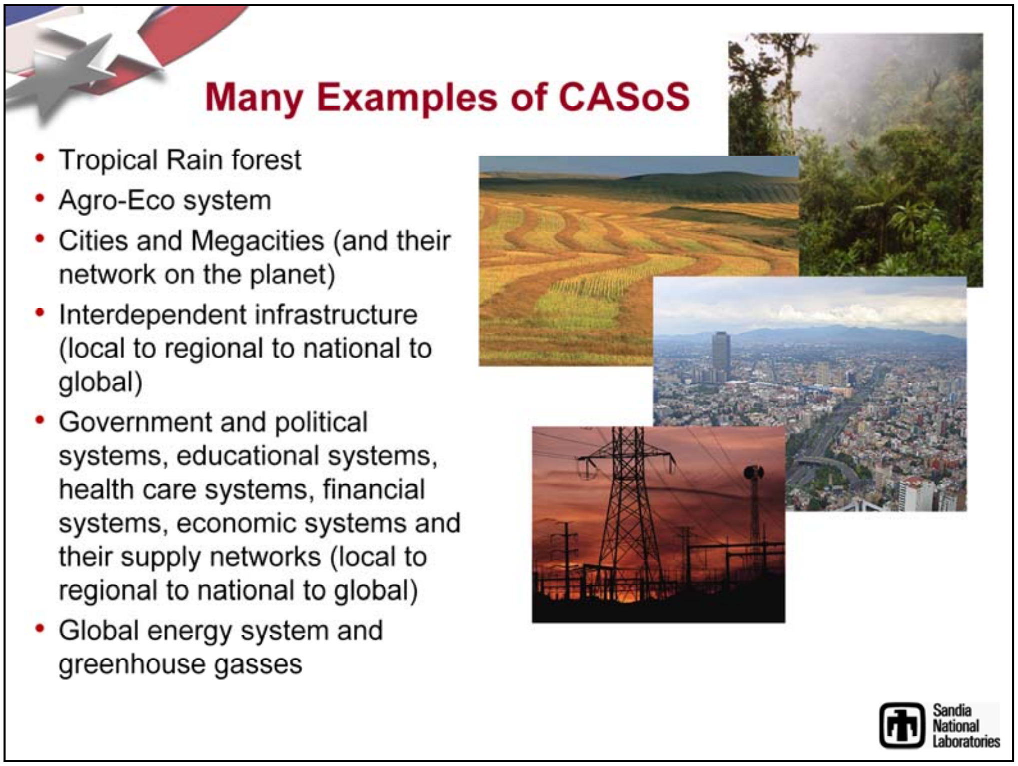
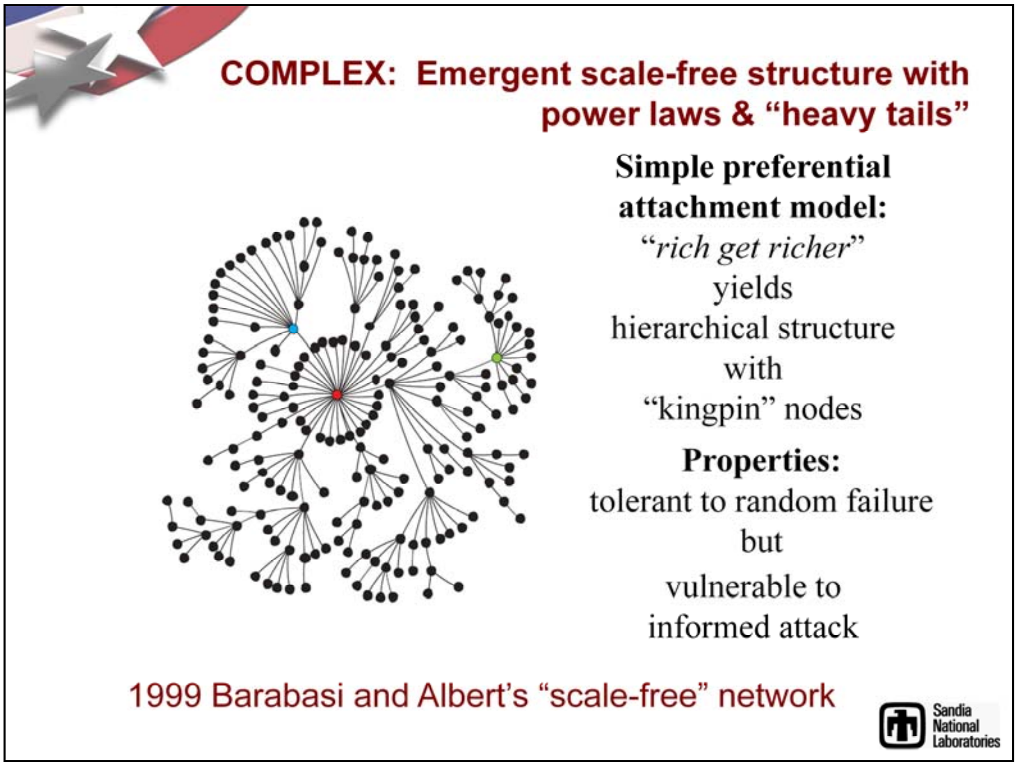


Our goal is to design solutions inside of these systems, or to design them themselves.



Now to define each of the terms in CASoS in turn.

Complex systems are generally characterized by a high degree of interdependency and multiscale variety. Multiscale variety reflects the different patterns of interdependency that are exhibited depending on the scale at which you are looking. The interdependency we see in nature often has a particular structure to it, a scale-free network structure.

Two signatures that we often see in Complex Systems (both of which exhibit a power law):

Scale-free structure (no mean number of nodes; instead, a large number of minimally connected nodes and a small number of extremely connected nodes)

Emergent behavior

Special properties of the scale free network

Scale-free networks can be formed by many different processes or models.

The preferential attachment algorithm of Barabasi and Albert (1999) was used to create the network shown in this slide.

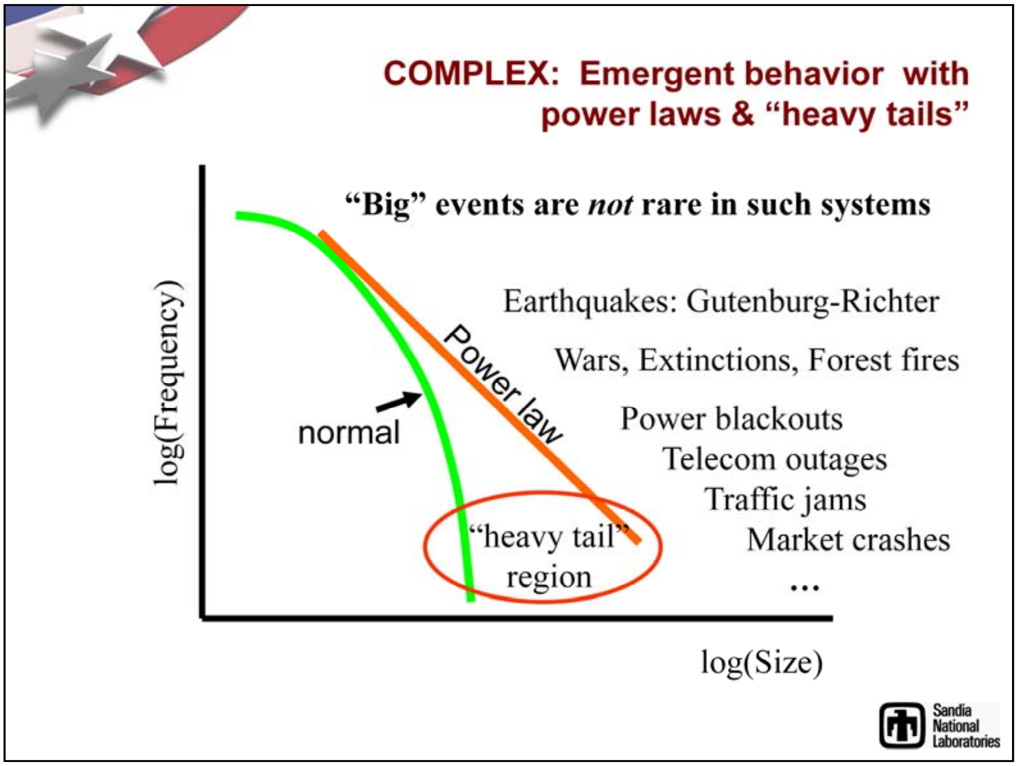
Two additional features that one often finds in real and engineered systems are "**kingpin**" or "**keystone**" nodes (blue) that are critical to the operation of the entire system, and **hierarchies or "tree" structures** where some (or all but one [red]) nodes are subservient to others. Both of these features are found in the scale-free network.

Albert, Jeong and Barabasi (2000) demonstrated the critical properties of such a network: **tolerant to random failure** but **vulnerable to informed attack**. For example, if one chose a node at random to remove from the network in the slide, a degree one node would likely be selected, and its removal would do little to the connectivity at large. But if the red, highest degree node were selected, the network would fragment into many pieces, losing its large-scale connectivity.

References:

Barabasi and Albert, Emergence of Scaling in Random Networks, *Science* **286**: 509–512, 1999.

Albert, R., H. Jeong, A.-L. Barabasi, Error and attack tolerance of complex networks, Nature, **406**: 378-382, 2000.



Second signature often seen in Complex Systems: Emergent behavior

Gutenberg-Richter is a power law that expresses the relationship between the magnitude and the total number of earthquakes in any given region and time period of *at least* that magnitude. For example, for every magnitude 4.0 event there will be 10 magnitude 3.0 quakes and 100 magnitude 2.0 quakes.

First Stylized Fact

Infrastructures are **very large multi-component systems**.

Many multi-component systems exhibit "**heavy tails**" that can often be represented as a **power law** for event frequency as a function of event (or outage) size.

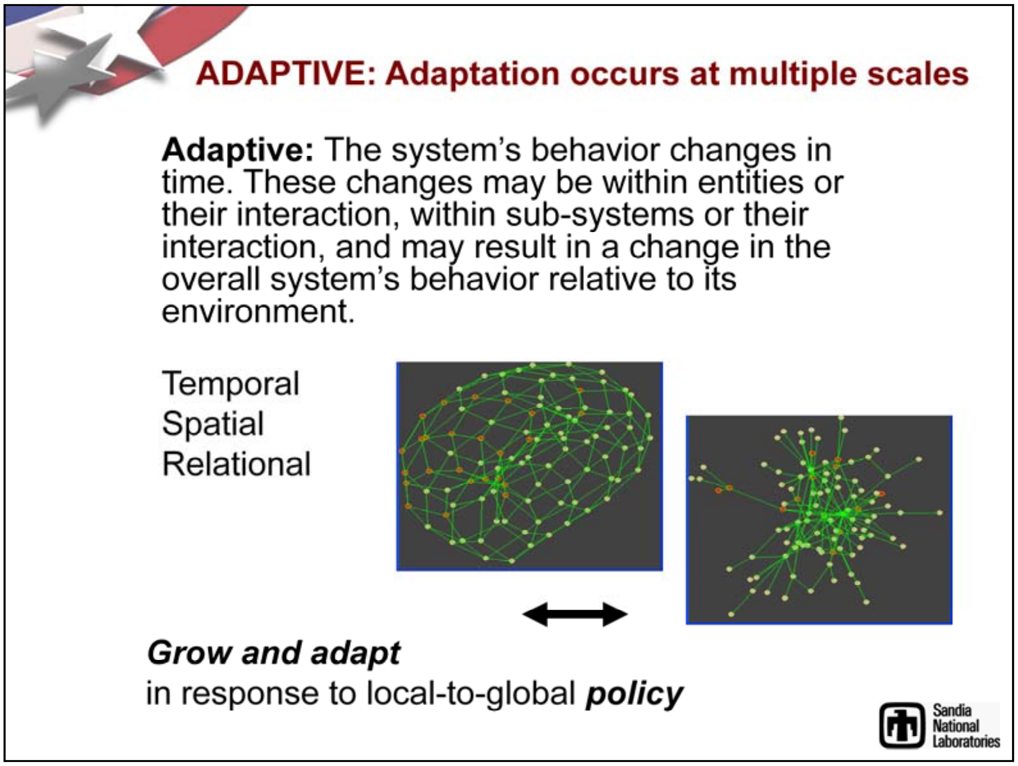
The green curve represents a standard normal distribution while the orange line is a power law. The "**heavy tail**" region of the power-law shows that big events are not rare in such systems.

Power-law behavior is also typical of what has been called "**1/f noise**" found in many natural and anthropogenic systems.

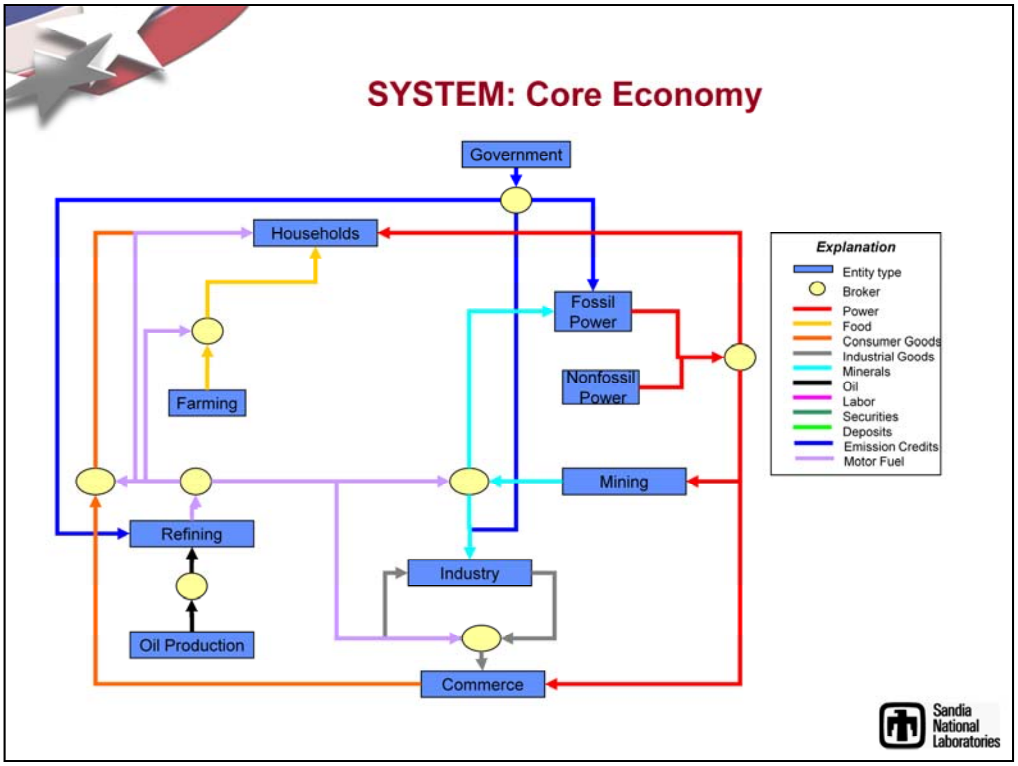
What about infrastructures?

Certainly **Power grid blackouts** have heavy tails, but also **Telecom outages**, **Traffic jams** and **Market crashes** as well.

Note that **roll off** in the power law at both ends occurs in all natural systems of finite size.



Adaptivity can result in temporal, spatial, and relational responses. The structure of the nodes in the system is dynamic and can change and adapt over time, in response to both local and global policy.

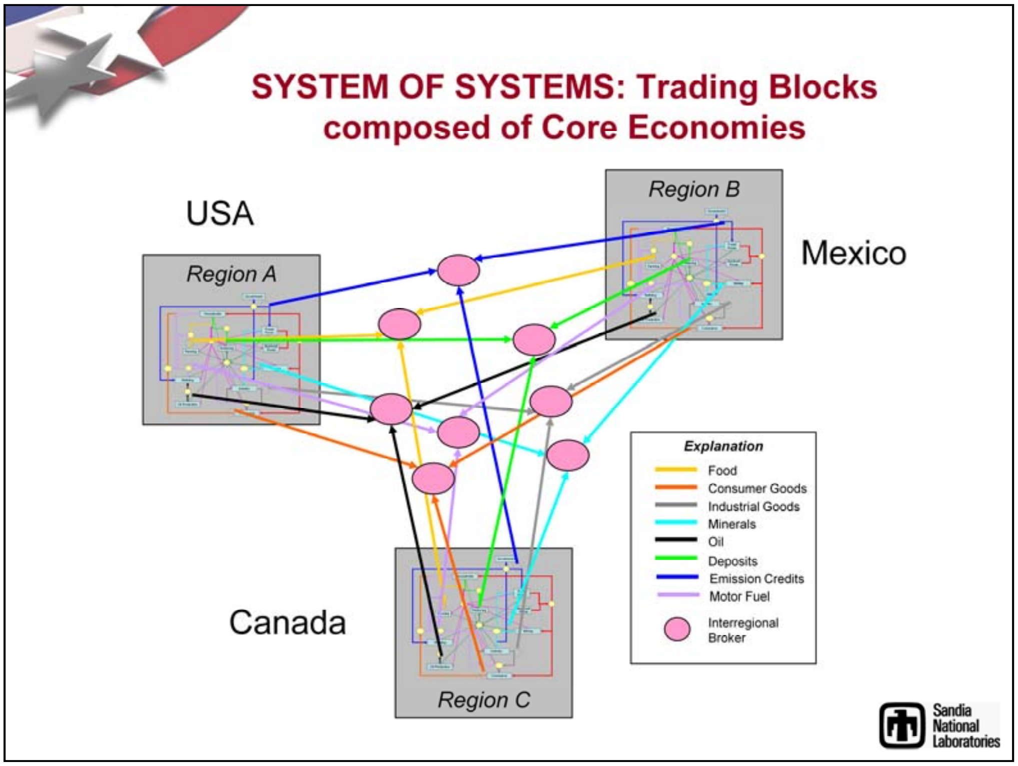


Definition of a System:

"A group of interacting, interrelated, or interdependent elements forming a complex whole" (TheFreeDictionary)

Example of a System

Industry takes raw materials and turns them into products which are consumed by a household.

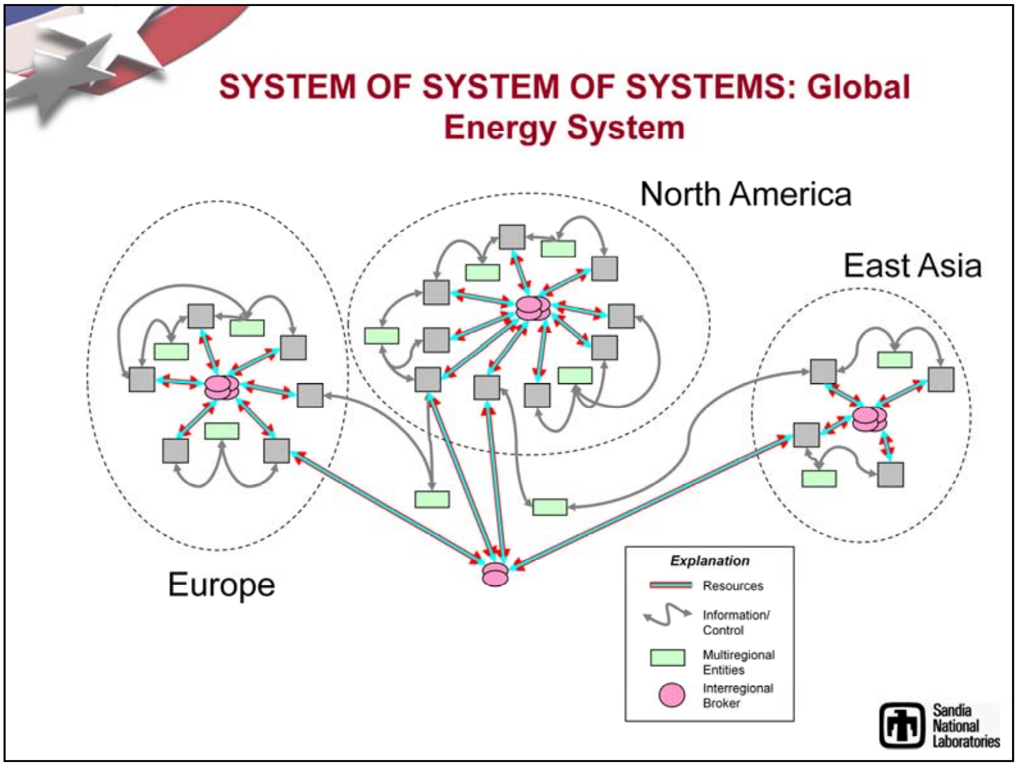


This slide depicts a network of core economies, which constitutes a system-of-systems.

Definition of a System-of-Systems:

"A collection of task-oriented or dedicated systems that pool their resources and capabilities together to obtain a new, more complex, 'meta-system' which offers more functionality and performance than simply the sum of the constituent systems" (Wikipedia)

There are many core economies. This diagram represents NAFTA, which is a hierarchical System-of-Systems.



It doesn't stop there. The Global Energy System is a System of System of Systems.

Our focus is Complex Adaptive Systems-of-Systems

Four fields are being brought together in this work (taking the terms of CASoS piecewise):

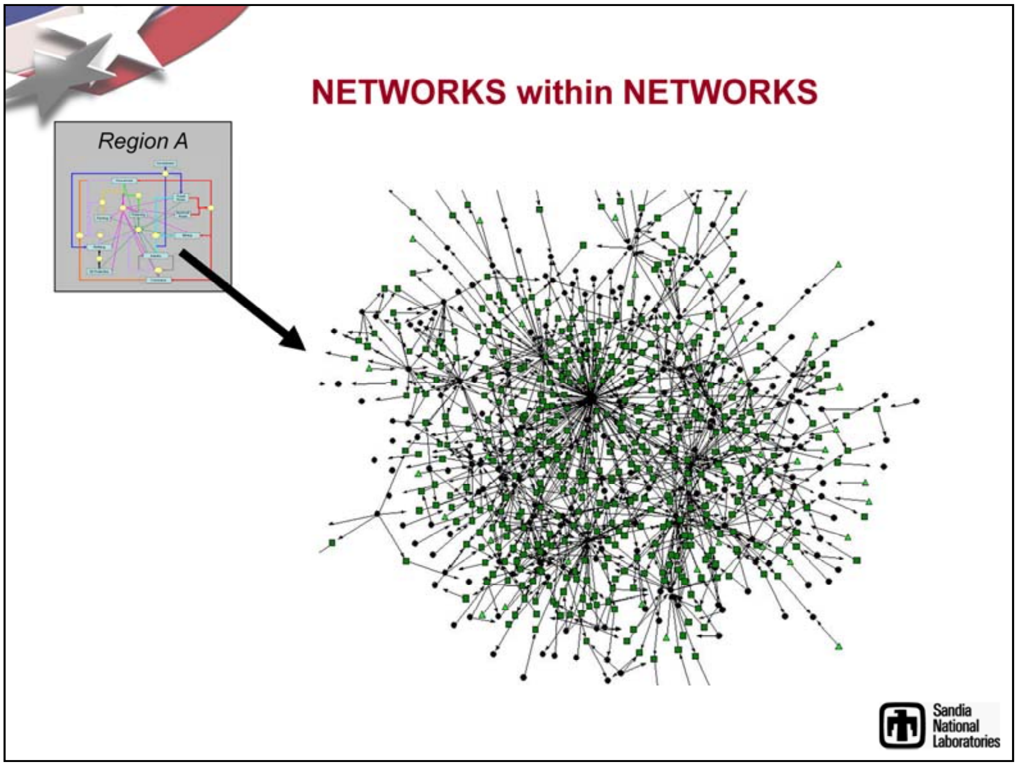
-Systems (people have been studying them for a long time)

-Complexity

-Adaptivity (often in the context of Complex Adaptive Systems)

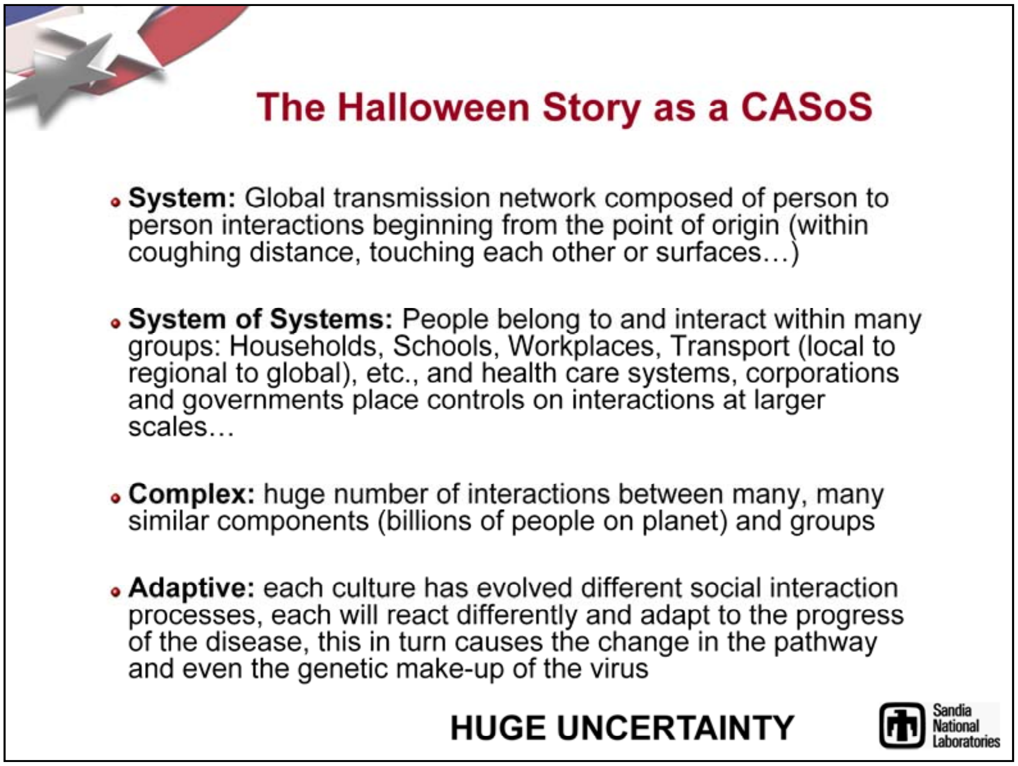
-Systems-of-Systems

They have been studied in isolation, but we put them all together.



The previous slides projected upward, from a system to a system of systems to a system of systems of systems. You can also decompose downward, taking each of the boxes in a system and decomposing them into networks, which are themselves systems-of-systems.

Networks form a SoS as well. If you look into any of the boxes of the SoS you find a network, with critical nodes. Note the kingpin node here in a scale-free network.



NISAC didn't just pull a model off the shelf. They analyzed it de novo and characterized each of its CASoS aspects.

System is a global transmission network that proliferated it among humans once it jumped species. It's a contact network (as opposed to an influence network, for example), because contact of some sort is required for infection propagation.

SoS because of the huge number of groups involved at all levels—cultures, interaction (business) rules, different nations and segmentations and rules

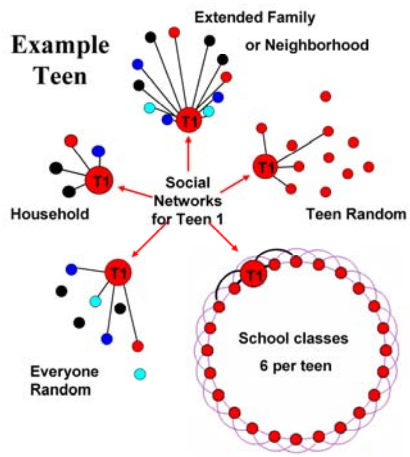
Complex because of the huge amount of interactions among many similar components.

Adaptive because disease changes and different cultures react differently to disease.

The problem as posed exhibited huge uncertainty. How to proceed? Others just took a model off the shelf and dusted it off. NISAC attempted to solve the problem.

How Do We Control This CASoS?

- We map aspirations to solutions via modeling and uncertainty quantification



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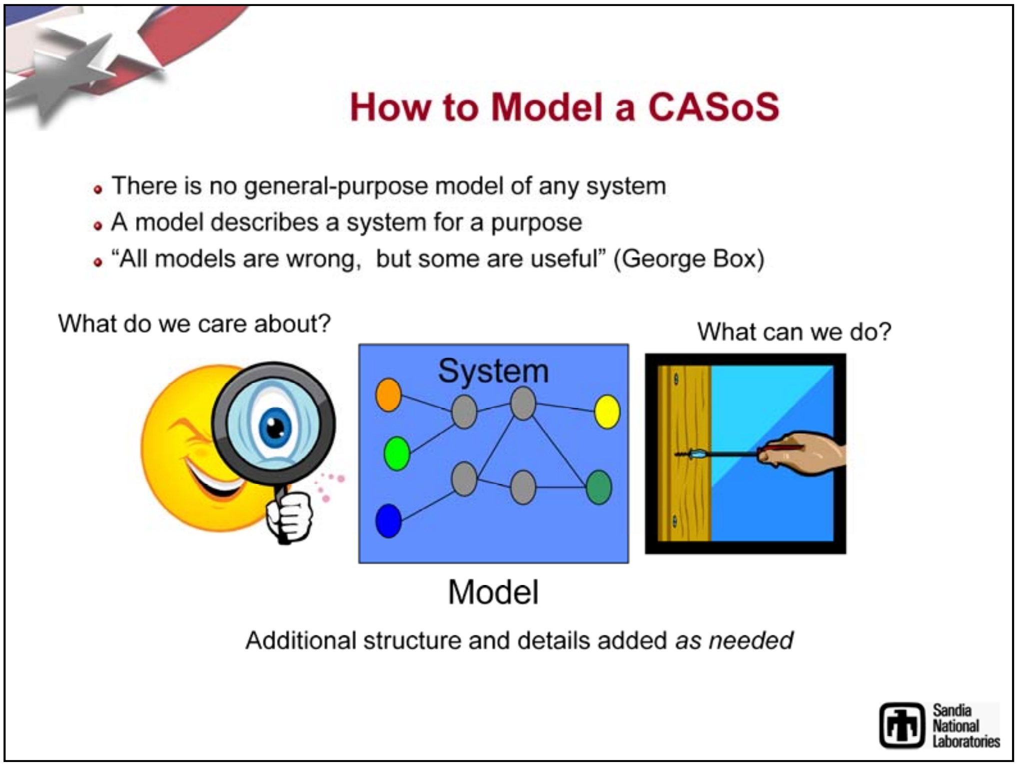


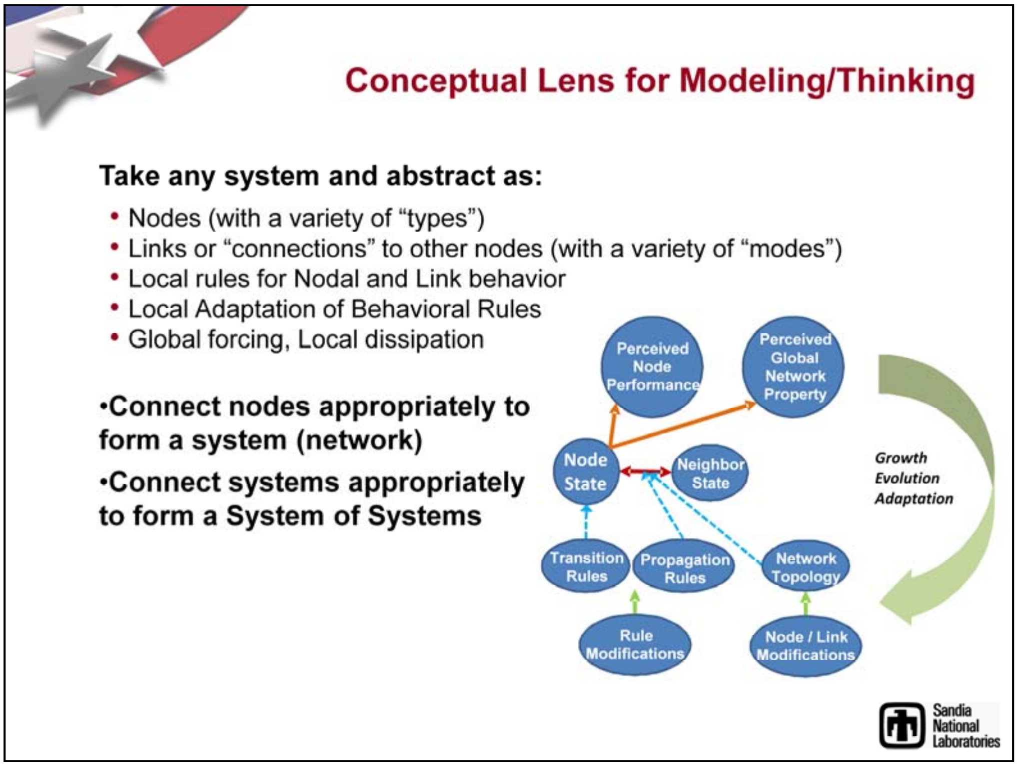
We have learned several things over the last few years.

When it comes to model use and reuse, the understanding is transferrable but the models usually are not. A model is generally purpose-built. Better to re-model than to reorient an existing model.

Here is our process:

1. Define what you care about
2. Define what you can do to influence the things you care about
3. Construct a model that connects the two (i.e., a causal map)
4. Add structure and detail only where needed. Parsimony and economy are good things in modeling.

The conceptual model is the causal model that describes how the things you influence in the system affect the things you care about.



Our methodology: Start with a conceptual lens for modeling and thinking about a CASoS problem. We tend to start by modeling a CASoS with networked agents.

Take any system and abstract it as a set of nodes. Nodes can be people, buildings, etc. Link them together. Links can have various modes of operation.

Local rules for nodal and link behavior can be expressed mathematically. Nodes here are Entities or Agents; what we're doing here is agent-based modeling.

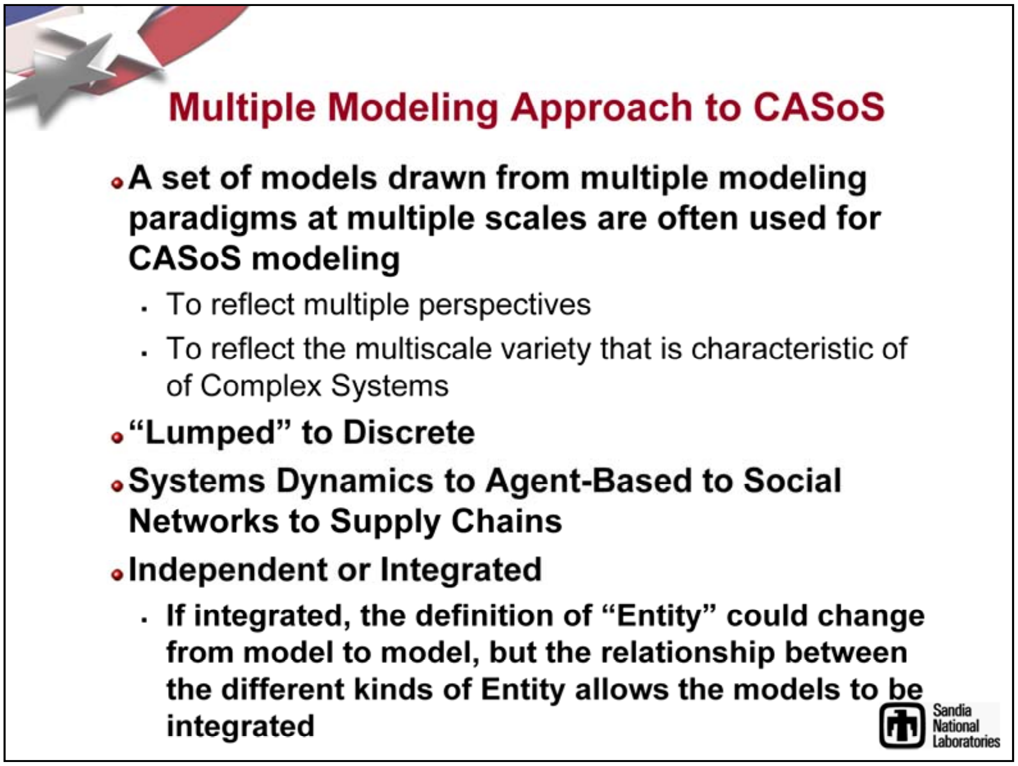
Node state and neighbor state interact. Propagation rules govern the movement of information from neighbor to neighbor, and transition rules govern change in states. Note that there is no centralized control. Perceived Node Performance is at a Local level.

Growth/Evolution/Adaptation modifies the network topology and drive the emergent behavior. Rules can also change over time, not just the topology.

Pretty much anything can be modeled with this approach. Can add global forcing with local dissipation, which allows you to learn from the lessons of sandpile models.

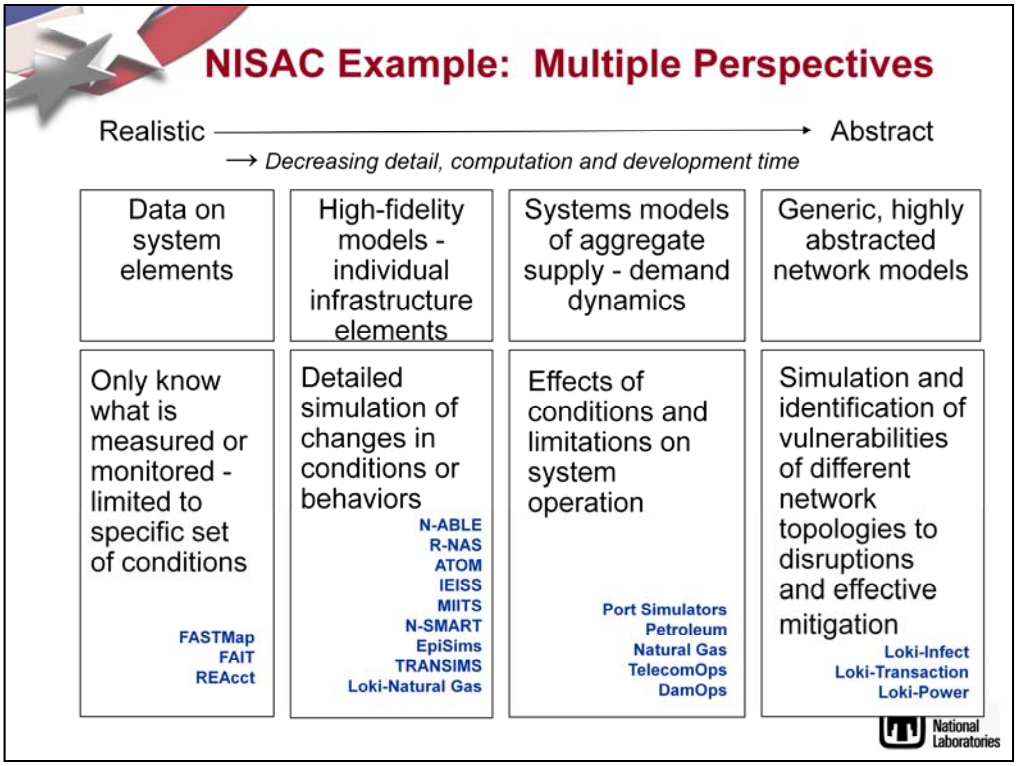
Connecting things up yields a system of systems. We have applied this modeling methodology to a wide range of systems.

This modeling approach has been inspired by Complex Systems but also by Computer Scientists, especially in the area of Agent-Based Modeling.

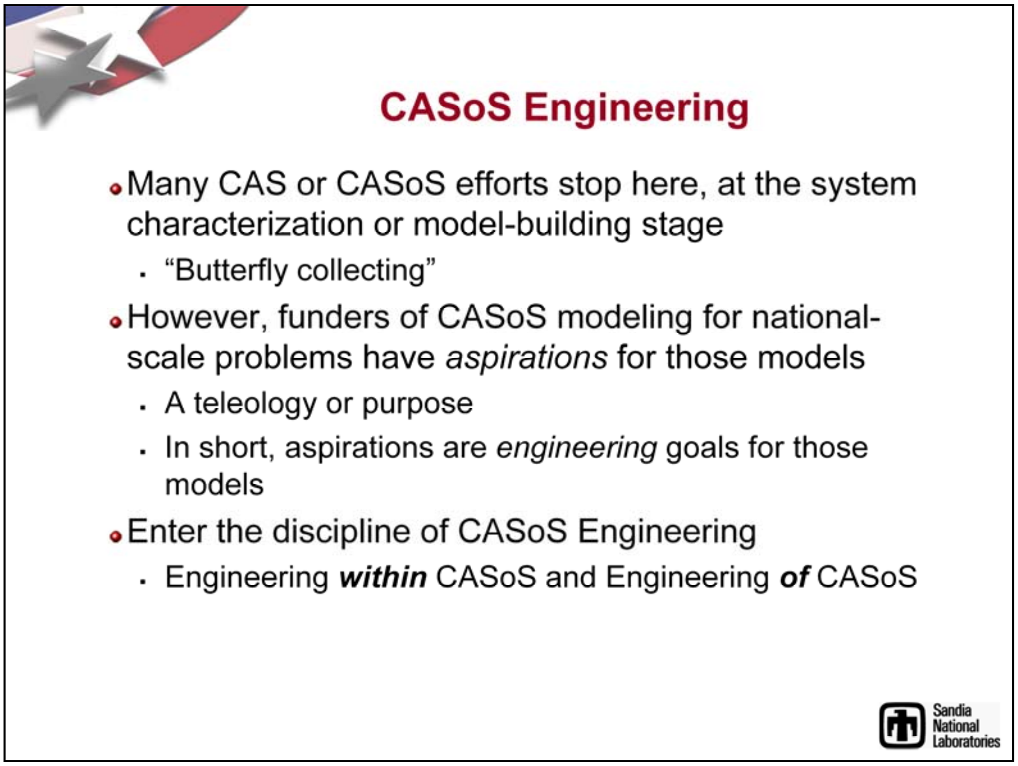


One model is generally not enough to capture a CASoS.

Lumpers vs. splitters. (Note that even this categorization reflects a lumper mentality!)



A table of NISAC codes that look at critical infrastructures from multiple perspectives



"Butterfly collecting" stops at the understanding and behavior characterization stage.

However, national sponsors want us to solve complex adaptive systems-of-systems problems, to design solutions to the problem and not just characterize them.

Funders have aspirations for those models, which are engineering goals.

CASoS Engineering has two aspects: Engineering within CASoS (determining policies to solve CASoS problems) and Engineering of CASoS (actually creating or synthesizing a CASoS to achieve certain properties, such as a resilient national power grid).

We have a teleology, a goal, for the understanding of a CASoS problem – we want to engineer a solution to that problem.

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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Aspirations are a taxonomy of engineering goals for the CASoS.

The kernel of an aspiration is control; the rest are flavors or intermediate manifestations of control. Control implies *intervention* of some sort in the system.

Taxonomy or categorization of Aspirations for the understanding of a CASoS problem, which guide the engineering of solutions. Aspirations start to put the Engineering in CASoS Engineering.

This is the transition to the "so what" question: You've characterized the system as a CASoS; now, so what? What do you want to do with that understanding?

Culminating in the engineering and synthesizing of a CASoS, an artificially synthesized CASoS (like a Green Grid).

Relevant Aspiration for the Halloween Story

- Control (or mitigate)

Source: nmhm.washingtondc.museum

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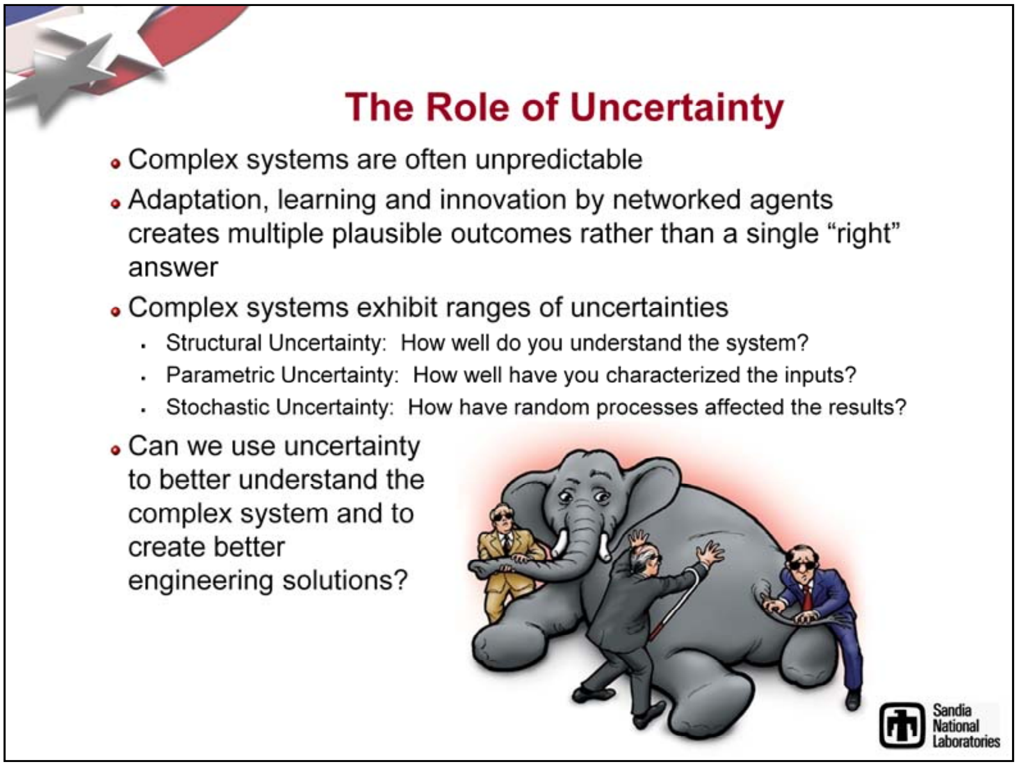
The picture is of a quarantine and treatment area during the 1918 pandemic flu



Where does Uncertainty arise? Goes beyond parametric uncertainty or Initial Conditions/Boundary Conditions uncertainties.

in system conceptualization (blind men describing an elephant)

- where the boundaries are drawn
- what is modeled within (processes)

in conceptual model representation (physics or mathematical representation)

- range of representativeness within parameter space
- behavioral regimes and transitions between
- scale effects

in model parameters

- their definition and measurement
- their values for a given situation

in computational representation

- calculational error
- discrete vs continuum (continuous)
- stochasticity

in dependence on unknown history (hysteretic), initial conditions, boundary conditions

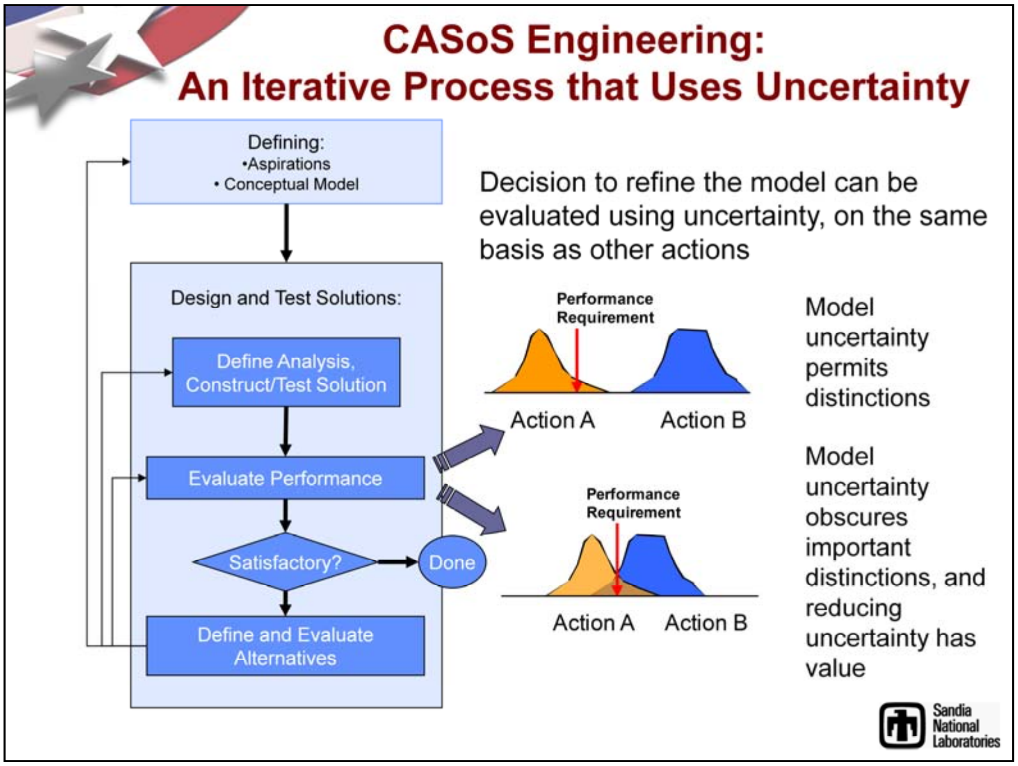
in reactive-adaptive response of both units and collectives (mechanism, time scales)

in what can be predicted and what cannot (in some cases prediction is impossible even with correct model structure and well characterized model parameters)

- chaos
- complex systems
- human systems (Colbaugh’s movie example)

Uncertainty comes from all kinds of places

1. Complex systems have complex signals. You don’t have a mean or variance described; you have a power law instead (e.g., frequency vs. size). This means you can’t go very far analytically.
2. Uncertainty also comes from the changes that the system undergoes due to adaptation, learning, and innovation.
3. There are also conceptual model or structural uncertainties. For example, the infectivity of the disease in the Pandemic Influenza investigation. Also the response of the public to the disease

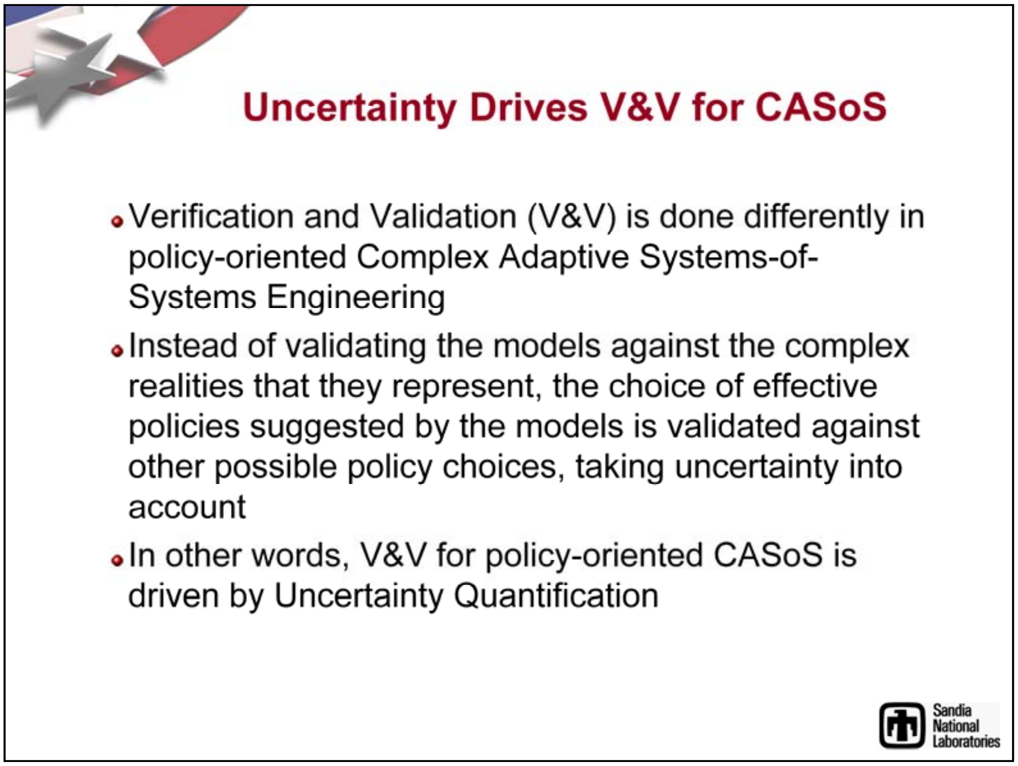


Uncertainty must be considered when building a model in the first place.

Flow diagram for CASoS Engineering. Iteration required for refinement.

Here, we use the same process but we bring in uncertainty. The decision to refine the model can be made considering the uncertainties in parameter space and model space.

In the graphs above, the first pair indicates that you clearly can decide between action A and action B (B gets the nod). (A and B are two different proposed policies.)   However, you can't in the second pair because uncertainty is obscuring the distinction, thus you must go back and find sources of uncertainty and change the model, or just decline to answer that particular policy question.


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
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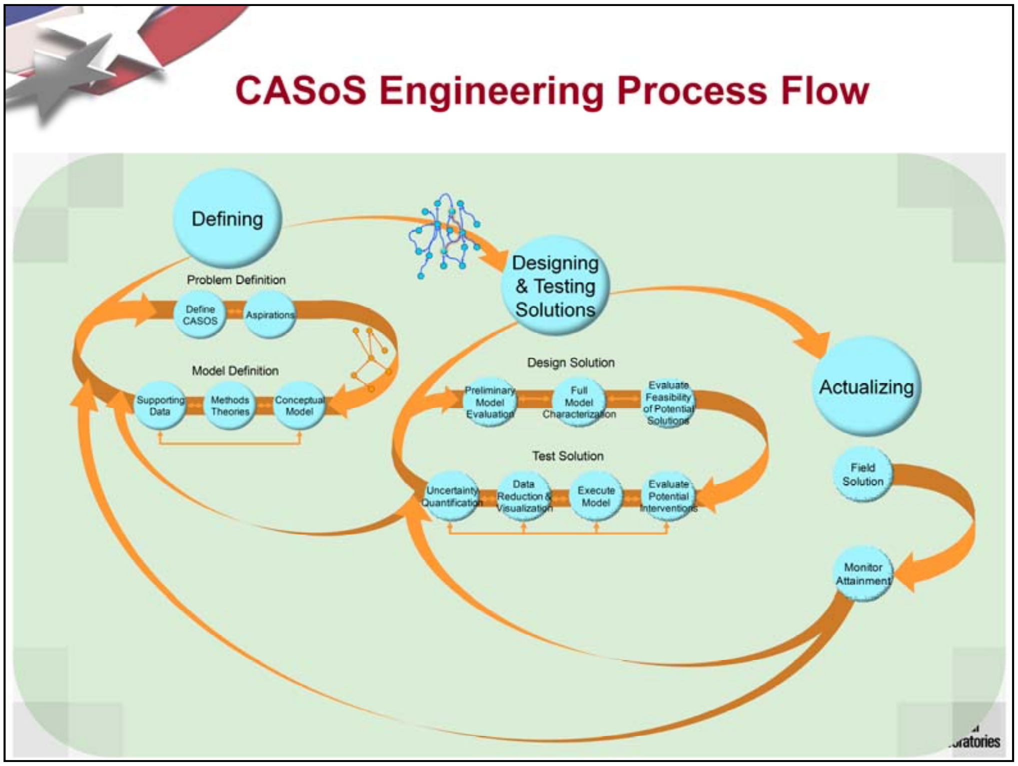
“Data-free” V&V!



Our overall process flow for CASoS Engineering treats CASoS Engineering as itself a complex system, complete with flows, iterations, and feedback loops.

The orange network is a notional conceptual model, that delimits the boundaries of the problem.

The blue network is a more refined and detailed conceptual model, the causal map between what you can influence about the system and the things you care about. It is now in a form such that it is testable, and use it to draw inferences about future states of the system given the interventions that are considered. Ambiguity has been eliminated from this version of the causal model; all the inferences have been specified. This version of the conceptual model can be used to assess consequences of interventions.

Three fundamental decision points occur in this flow graph, one at each stage: Do I iterate through this stage again, move on, or go back?

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

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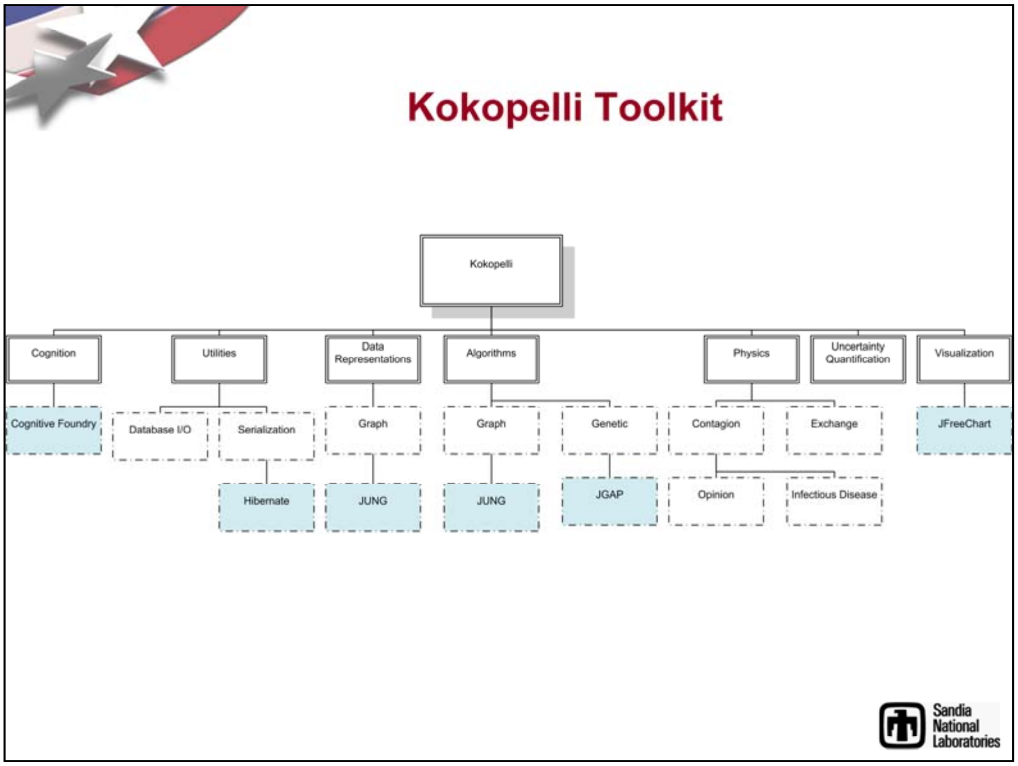
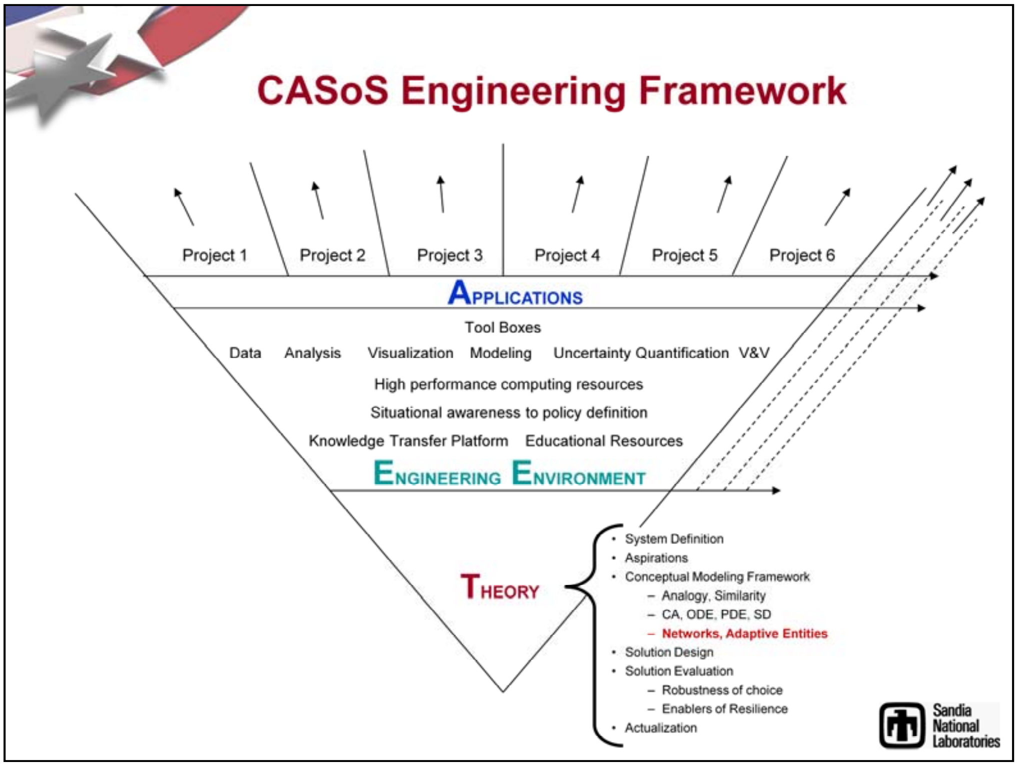
Tools in our CASoS Engineering toolbox



We're developing a comprehensive agent-based toolkit for CASoS Engineering that we plan to make available as open-source

Java-based

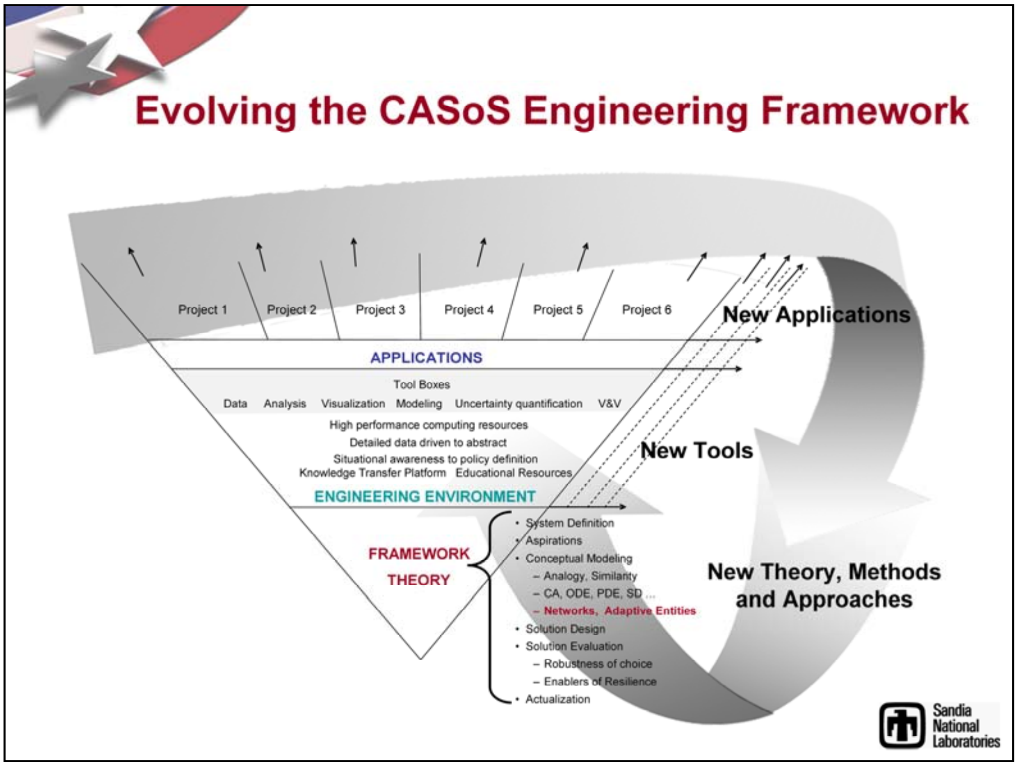
Integrates and supports the CASoS Engineering life-cycle



We’re also developing a three-level framework for CASoS Engineering. The foundational level is the Theory level.

The Theory is implemented computationally by the Engineering Environment level …

… and then applied to various funded application domains in the Application level.



Of course, due to the reality of funding sources, this is the way it *really* works …

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

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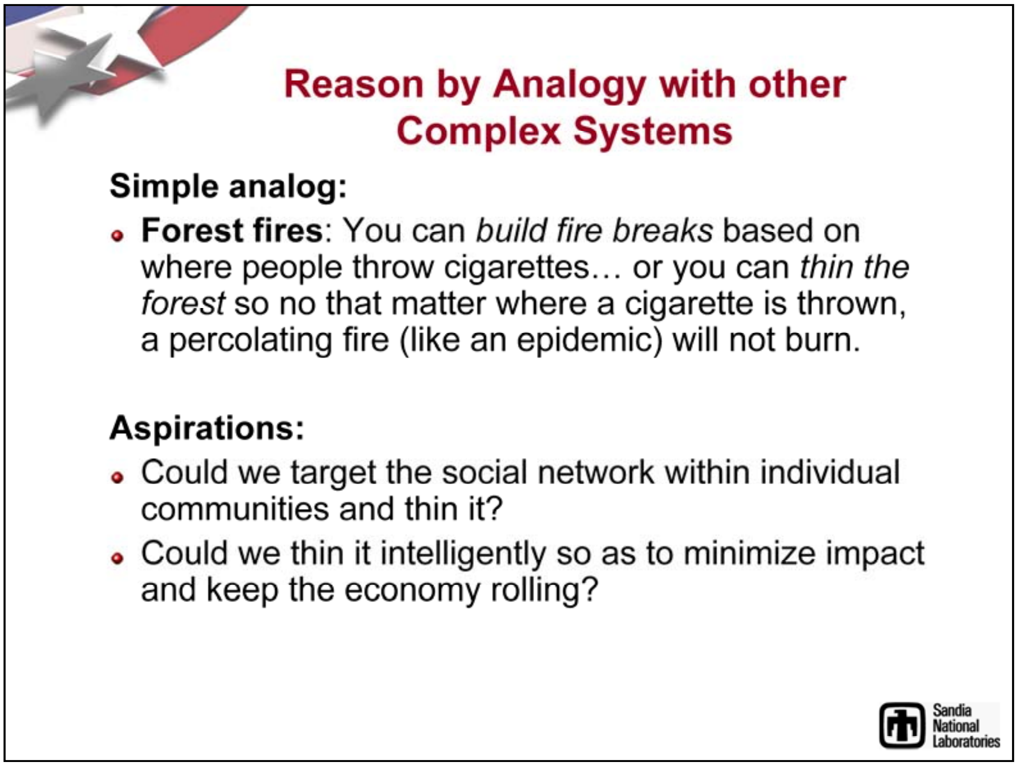
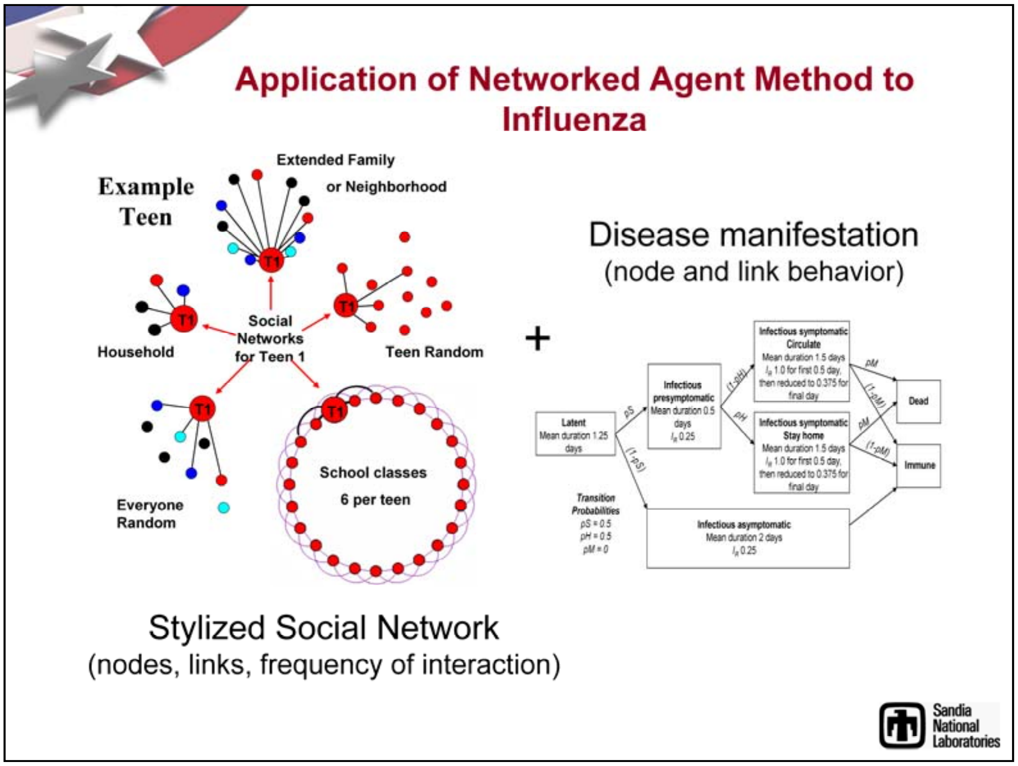


First, we thought of it by analogy. Flu can be caught from neighbors, just like forest fires.

Two approaches to stop a forest fire. One is to build fire breaks. Breaks are great until a spark inevitably spans the break and lights the other side. Cf. HOT (highly optimized tolerance) work by Carson and Doyle, which also yields power law behavior. The other way is to thin the forest, which prevents percolation throughout the entire system. This is a preferred approach, since you don't have to worry about where the spark is coming from—it solves lots of problems. Don't have to close borders.

Epidemics move on a social network. Could a social network be targeted, instead of the nation as a whole (which could involve closing the borders)? Could the network be thinned intelligently to reduce the economic impact?

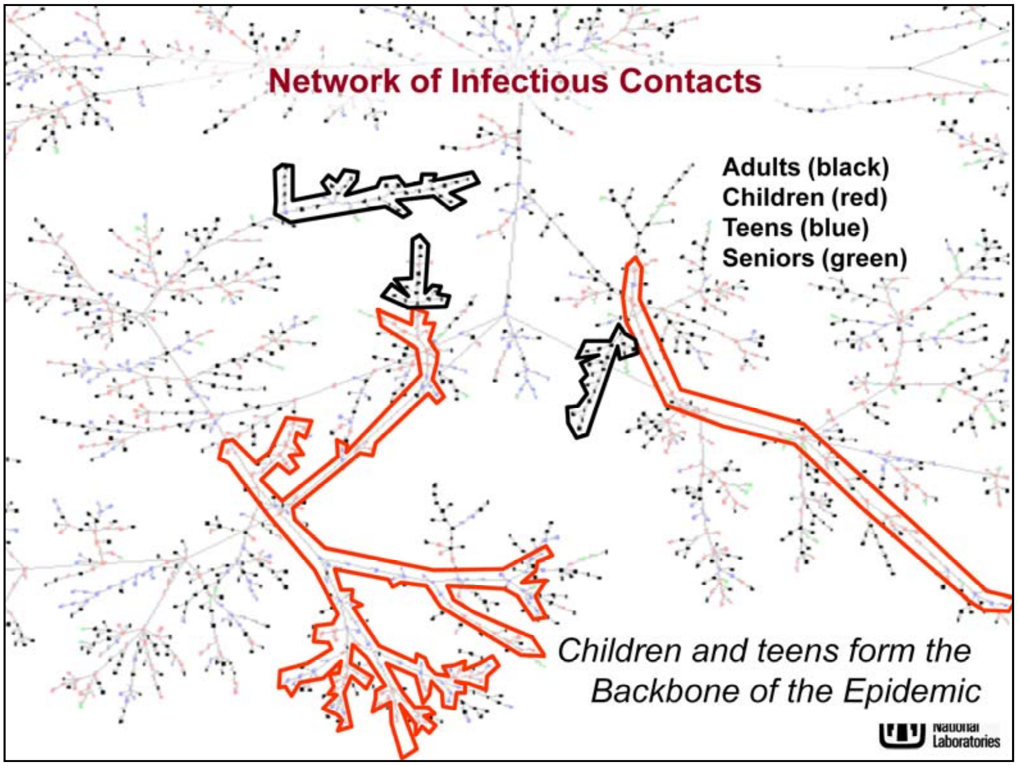


We took our general approach and applied it to the pandemic problem. People were nodes, their interactions were links in the network. Disease would spread along these links from person to person. We put in the appropriate behavior of the disease and the physics of its transmission. We then asked a series of experts: “What are your groups, how big are they, how often do you go to them and for how long, and how many people do you interact with there”. From this general information we constructed a network for a representative community.

Used the conceptual lens presented earlier to model the problem. First built a stylized social network. Bob Glass’s daughter Laura (a ninth grader at the time) conducted interviews and put together a social network model.

Also found a standard infectious disease manifestation model in the literature. The disease spreads between nodes on the network. Putting them together yielded a simple model, parsimonious and economical, that could explain what happens at a local scale. It is also amenable to modification--the pushing of levers and the twisting of dials to change the behavior of the model--to find out what approaches might work.

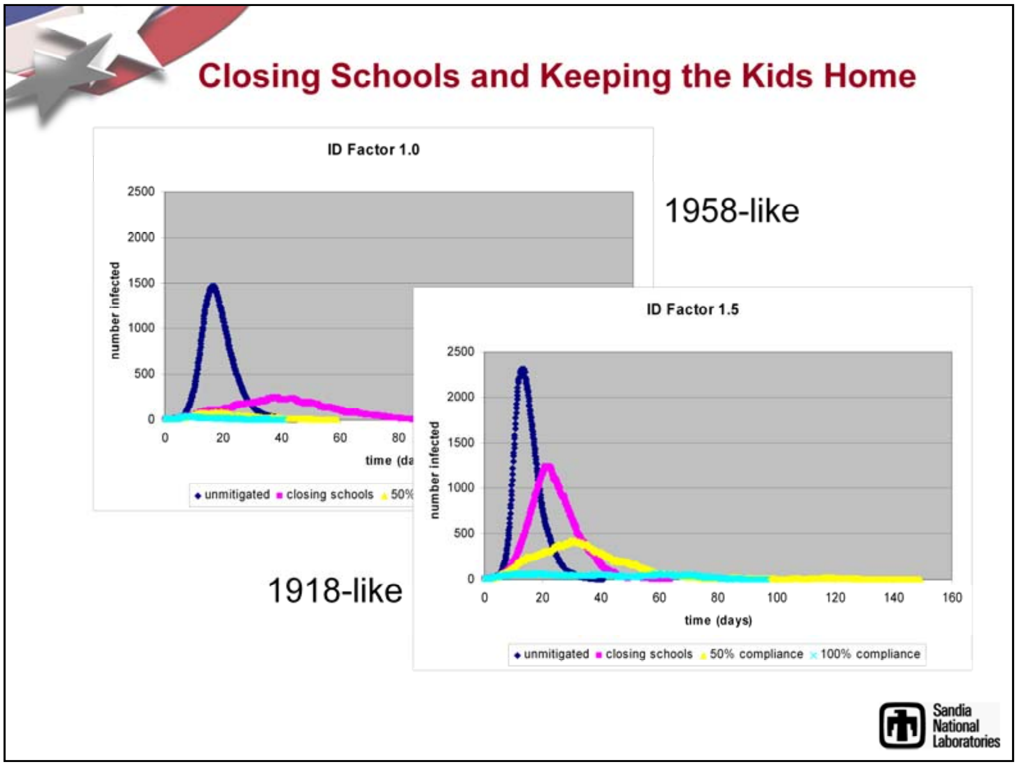
The two parts of the diagram are topology plus physics, a fundamental distinction in CASoS.



By studying the burn path through the small stylized community, we identified children and teens as the culprits. They form the backbone of the epidemic while adults are at the dead ends of the network.

The red zones are the backbone of the infectious portion of the network. Almost all are kids and teenagers, who congregate at schools. (Didn't bring in college students into the model, but they are cooped up less than elementary school children.)

Adults are at the edges of the network, children are in the center of the network of infectious contacts.



So much for the understanding of the problem. Now, what can you do?

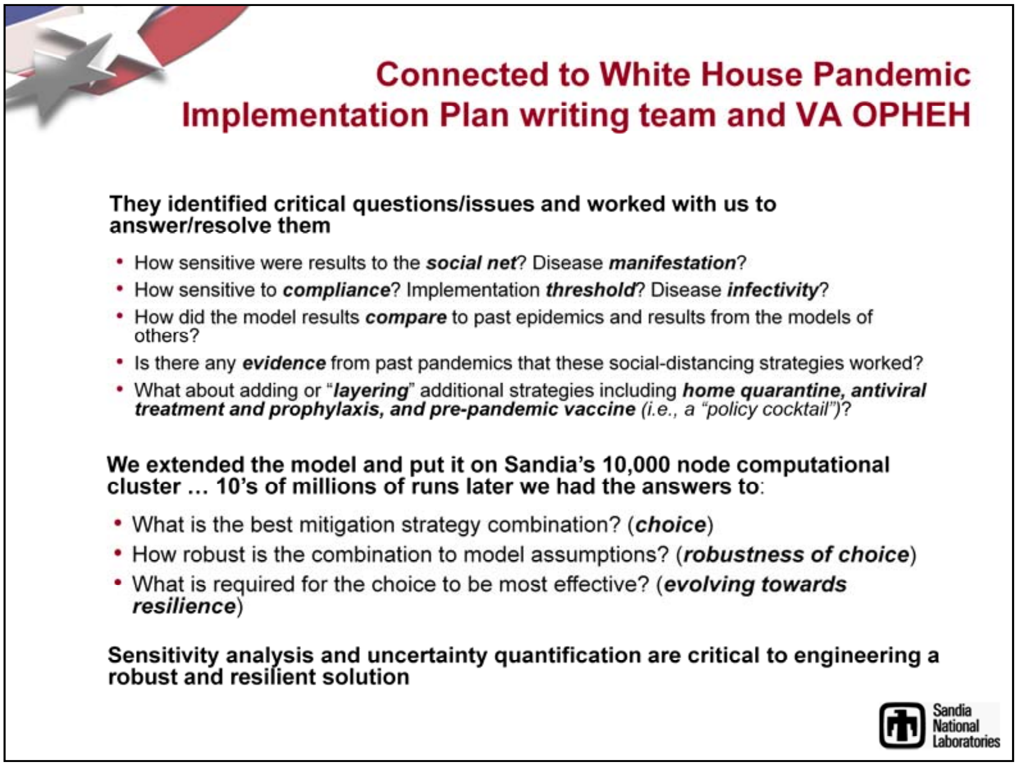
Based on the insight from the previous slide, try closing the schools and keeping the kids at home, since they are at the center of the infectivity network. Also model different levels of compliance with that policy. Don't let them go to the mall or hang out in a neighborhood playground.

Model two versions of the flu, 1918-like and 1958-like. More people get sick in 1918-like flu. The blue line is doing nothing. Closing schools is magenta line; but kids still allowed to do other activities. Yellow and blue lines indicate different levels of compliance with another stipulation, that the kids must stay home.

Goal is to design a solution or policy that solves the problem, *then* worry about how to actually implement that solution or policy.

Found data on how 1958 influenza affected age classes, and modeled that with only one parameter – infectivity. This constituted the physics of the disease propagation. Everything else was rules of thumb. Social network was also stylized. They dialed in the infectivity (e.g., 50% of the population infected) and recovered the percentages infected by age group. For 1918 influenza there was no age band data, only the full curve (70% people getting sick). Also a mortality rate.

Important to connect with the people who really owned the problem. They ended up validating the approach, finding proper data, constructing appropriate social networks, etc. Fundamental issue: are models good and the policies supportable?



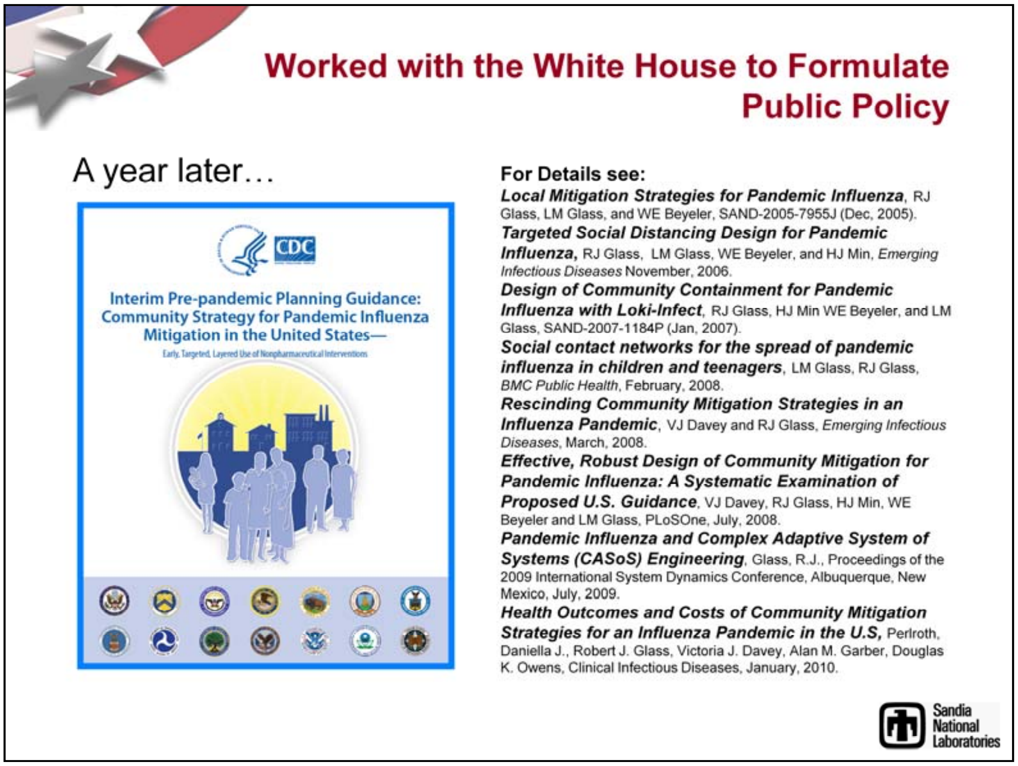
VA OPHEH – Office of Public Health and Environmental Hazards in the Veterans Administration

White House and CDC were very interested in these initial results; others were pushing antiviral solutions (which we didn't have) and didn't create social network models.

Partners expand your view and you go back and extend the model and rerun the results.

SA and UQ vital to finding the best mitigation strategy, to identify robust choices in the context of uncertainty.

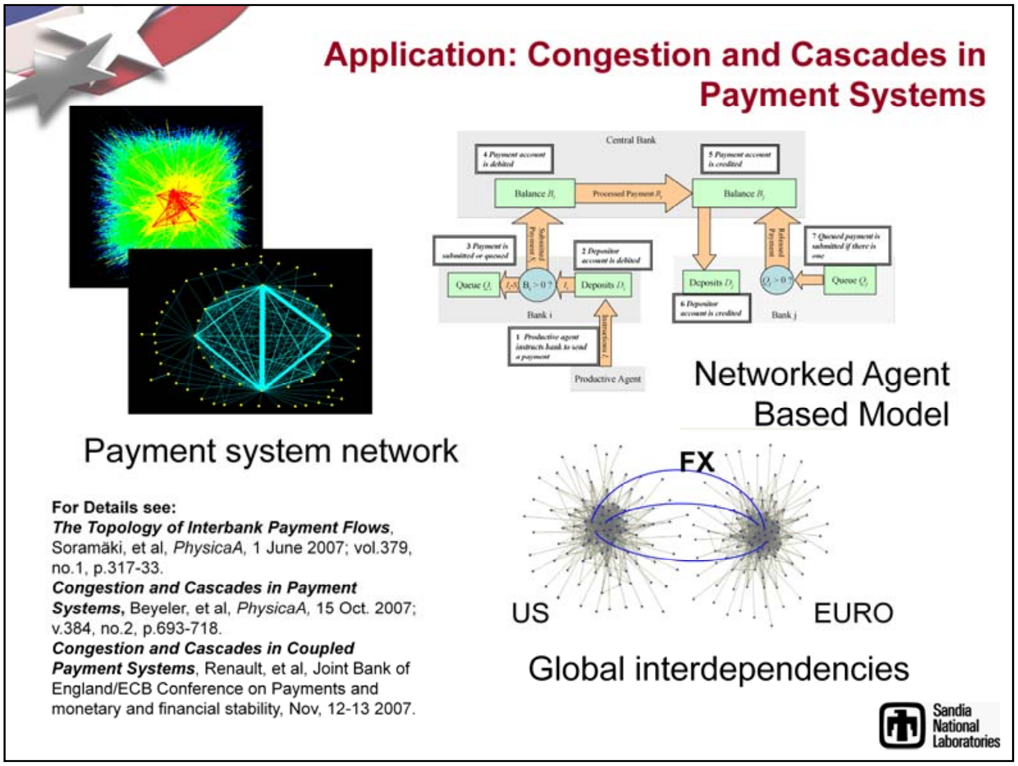
Goal: pick the policy (or synergistic policy cocktail) that is the most robust to uncertainty.



These results became the basis of the CDC's policy, and it was actually tried out during 2009, when they pulled the guidebook off the shelf and started closing schools in the presence of avian influenza. Infectivity of the actual influenza was not very high, so they stopped closing schools and instead used other methods of social distancing.

The 2010 paper looks at infectivity and how to deal with it cost-effectively. Closing schools is extremely costly.

Others [other organizations than Sandia] looked at highly-developed rules and assumed that it would be a 1918-style epidemic, instead of considering a number of infection propagation schedules and potential outcomes.



This approach to CASoS Engineering has been applied to a number of application domains.

FedWire is an example of a payment system, how money moves around the world from bank to bank. In 2007 there was a credit crunch. Movement of funds across the world stopped, and they stopped in payment systems.

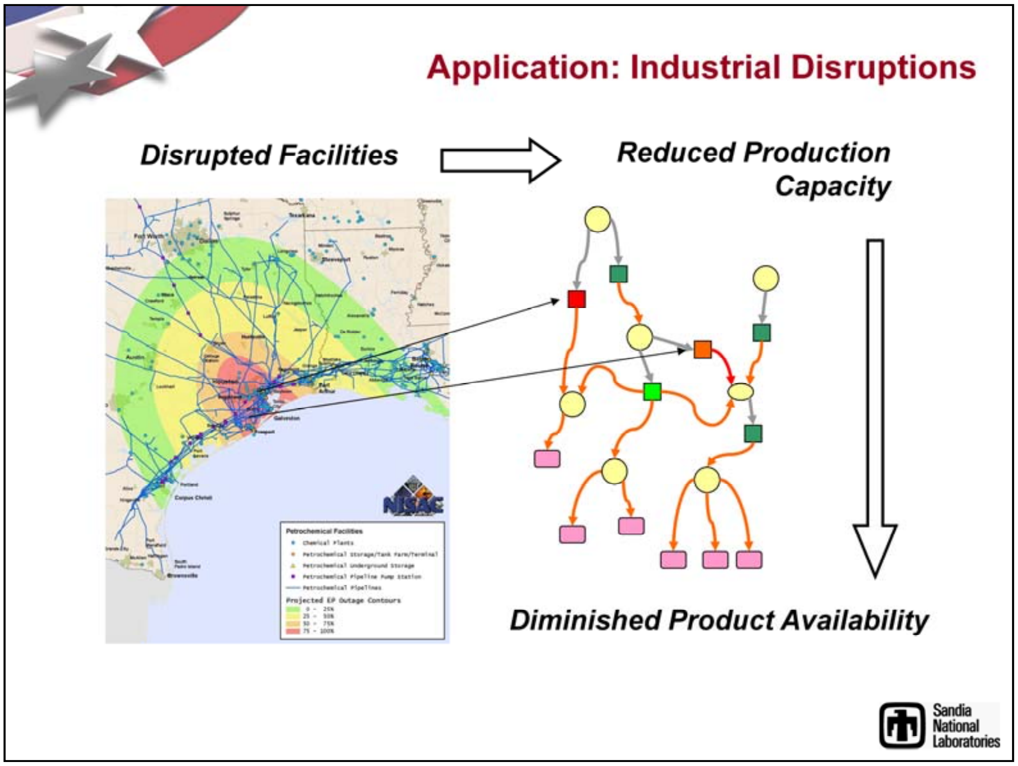
Two primary measures that work together:

Liquidity - how much money is in the bank, at the Fed

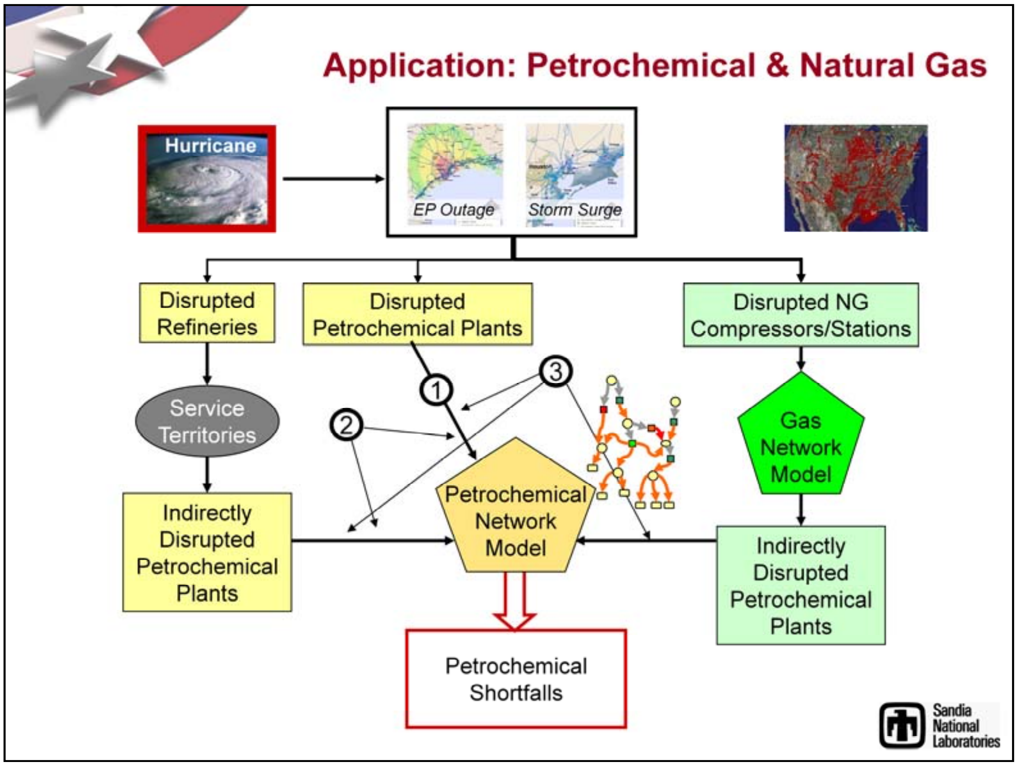
Interest rate – what you will be charged if you need money, for your lack of liquidity

When there is a hiccup the whole system stops. In 2007 they were running at 1/20th of the level they should have been

Also looked how risk transferred to other payment systems, like in Europe

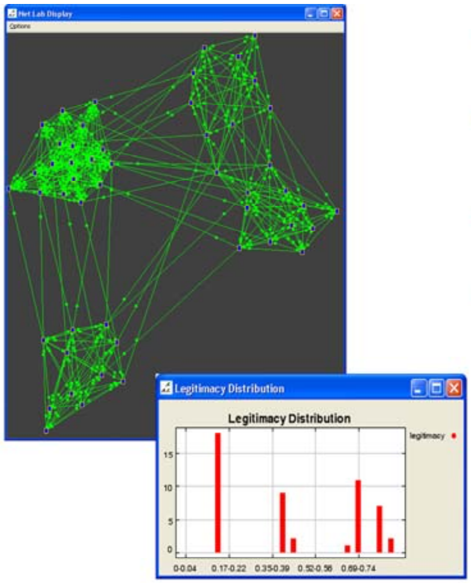


The situation is that a hurricane is moving in. Looking at a national-scale chemical supply chain and the effect of a hurricane on it. Components of the chain shut off, which has both downstream and upstream effects.

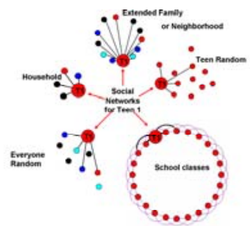


A study of how Petrochemical and Natural Gas systems interrelate and are impacted by a catastrophic event.

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



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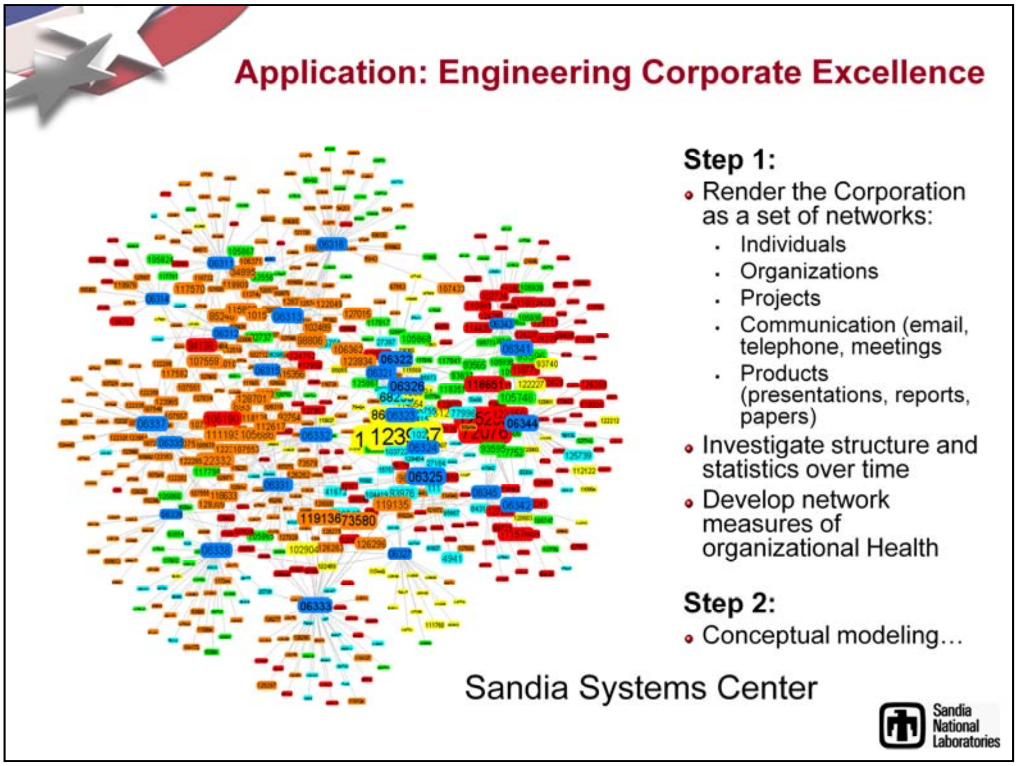
The domain for this work is intelligence analysis



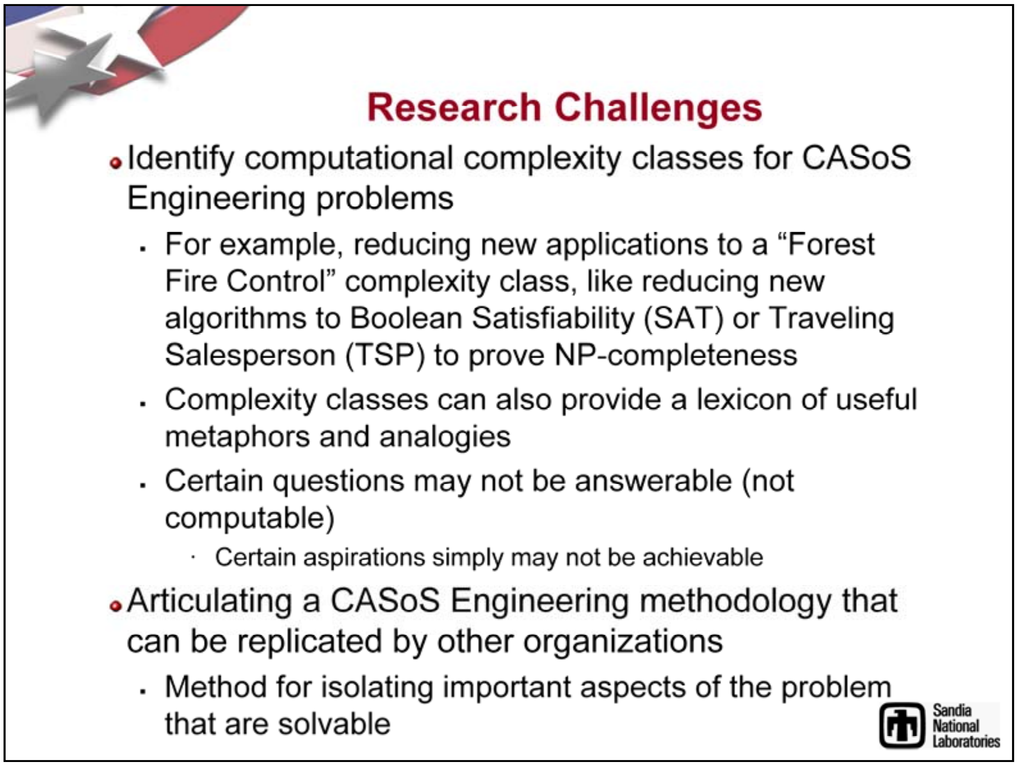
A.K.A. Enterprise Transformation

We're also looking at enterprises and corporations, such as Sandia. Network analysis of enterprises and corporations.

Also VA Health Care network (the largest in the US)

A common goal is to show how one policy outperforms all the others, taking into account uncertainty (both parametric and model uncertainty). Must take behavior of people into account, and this can be generally done without sophisticated cognitive models. Can model what people *will* do, but can model the best thing to do, and the effect of training. Can't really model what will happen, but can determine the best policies and the best training that will implement those policies.

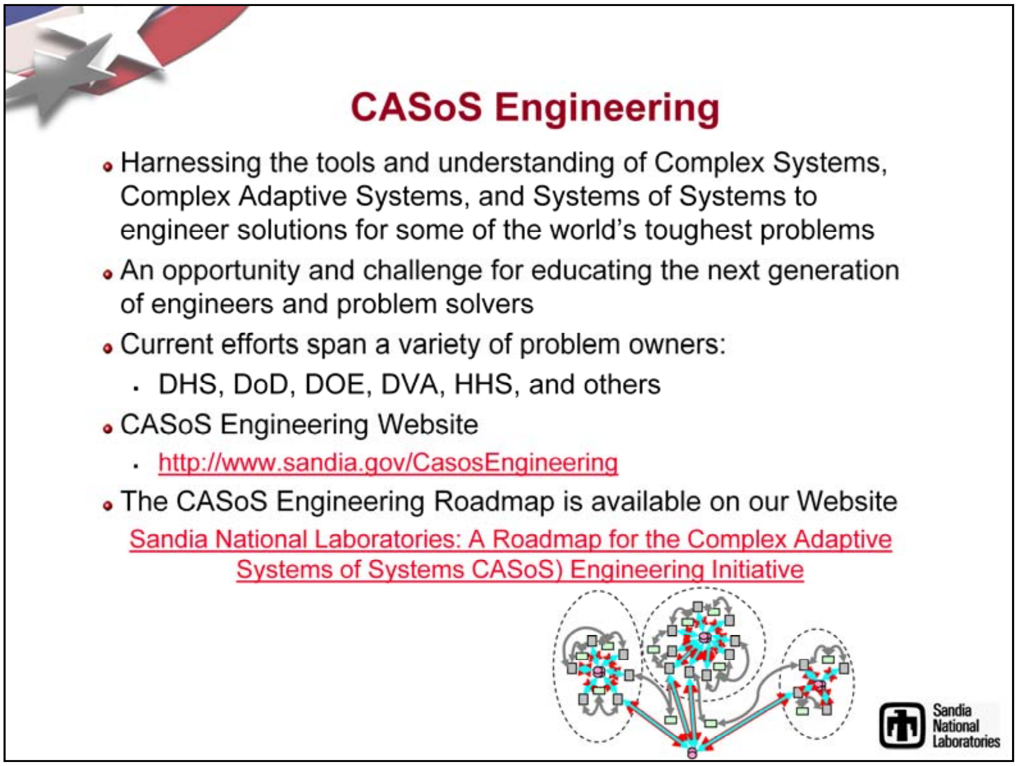
E.g., an effect of the 1918 epidemic is that no one spits anymore because they finally understood how disease was transmitted.



We want to develop a lexicon/vocabulary and a canonical set of CASoS Engineering complexity classes that we can reduce incoming problems to, if possible. We want a classification scheme, a categorization scheme, for canonical CASoS Engineering problems.

There are computability implications as well. For example, certain measures of complex systems simply are not computable (like the mean if it is characterized by a power law). Thus some questions may not be answerable and some aspirations related to those questions may not be achievable.

We need to transition from Art to Engineering by articulating a CASoS Engineering methodology and replicating it somewhere else. Systematized, not cookbook. We'd especially like to systematize our method for how to isolate what aspects of the problem are solvable, and what aspects of the problem can simply be cut out.



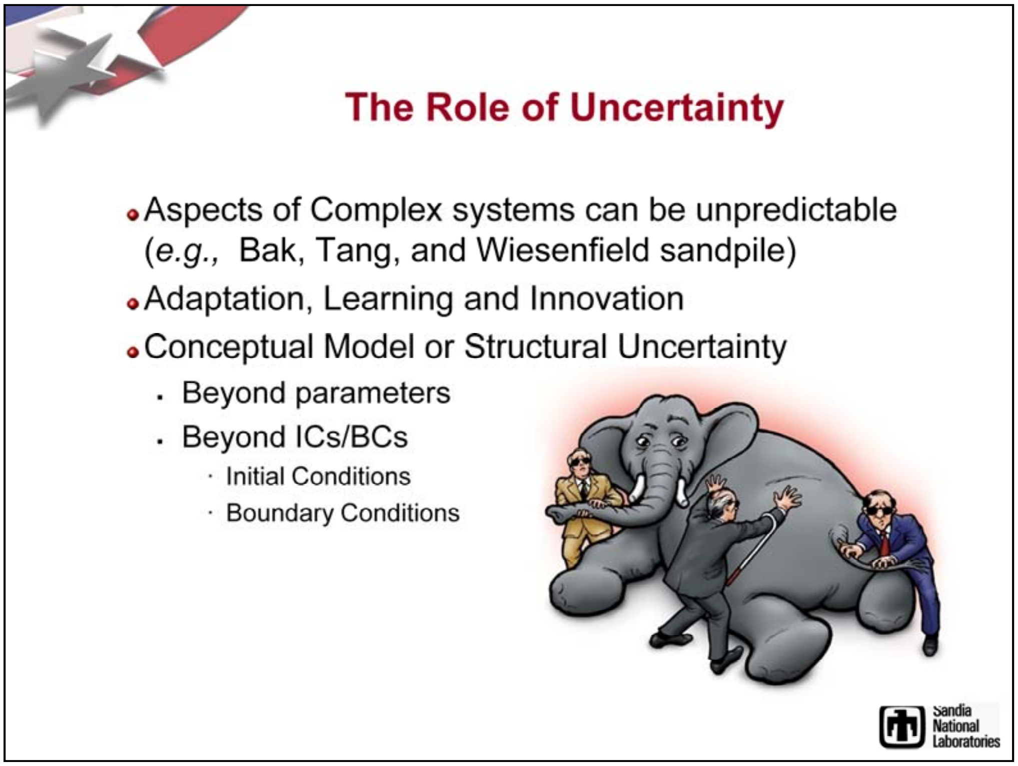
We want to use CASoS Engineering to solve problems that no one has been able to address before. We believe that modeling, the way we have defined it, is the way to go.

Our roadmap is on the Web at the specified link.

We currently have a number of partners in the Federal Government. They are interested in using these approaches to formulate policies to solve the pressing problems in their domain. They are looking to modeling to tell them how good a policy might be before they actually use it. Can they select from policy options in a cost-effective way? What policy cocktail can be constructed/concocted that will solve the problem in the most cost-effective fashion? We believe CASoS Engineering is a good way to go about making those kinds of policy decisions.

We are also working on Green Grid stuff, actually constructing a CASoS.

Q&A



Where does Uncertainty arise?

in system conceptualization (blind men describing an elephant)

- where the boundaries are drawn
- what is modeled within (processes)

in conceptual model representation (physics or mathematical representation)

- range of representativeness within parameter space
- behavioral regimes and transitions between
- scale effects

in model parameters

- their definition and measurement
- their values for a given situation

in computational representation

- calculational error
- discrete vs continuum (continuous)
- stochasticity

in dependence on unknown history (hysteretic), initial conditions, boundary conditions

in reactive-adaptive response of both units and collectives (mechanism, time scales)

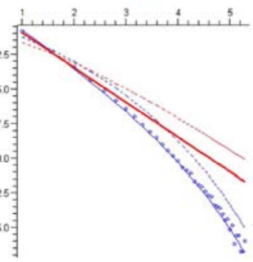
in what can be predicted and what cannot (in some cases prediction is impossible even with correct model structure and well characterized model parameters)

- chaos
- complex systems
- human systems (Colbaugh's movie example)

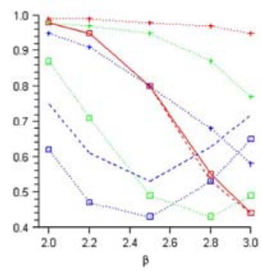
Uncertainty comes from all kinds of places

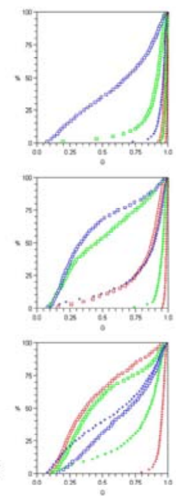
1. Complex systems have complex signals. You don't have a mean or variance described; you have a power law instead (e.g., frequency vs. size). This means you can't go very far analytically.
2. Uncertainty also comes from the changes that the system undergoes due to adaptation, learning, and innovation.
3. There are also conceptual model or structural uncertainties. For example, the infectivity of the disease in the Pandemic Influenza investigation. Also the response of the public to the disease and to instructions. We try to train people to do the right thing, the best thing to do. These

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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