Wrangling with Uncertainty in Complex Adaptive Systems of Systems (CASoS) Engineering

or

"Why CASoS Engineering is both an Opportunity and Challenge for Uncertainty Quantification"

Robert Glass

with Arlo Ames, Walter Beyeler, and many others

Sandia National Laboratories

NSF Workshop

"Opportunities and Challenges in Uncertainty Quantification for Complex Interacting systems"

April 13, 2009

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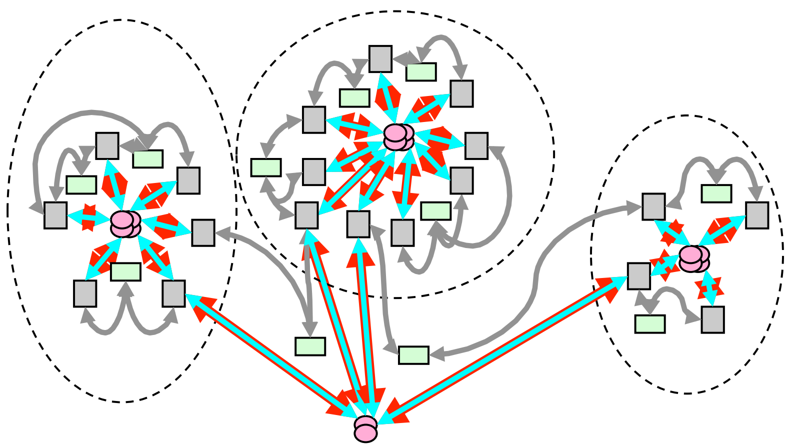
Outline

- What is a CASoS?
- Where does uncertainty arise?
- Engineering within a CASoS: Example of Influenza Pandemic Mitigation Policy Design
- Towards a General CASoS Engineering Framework



What is a CASoS?

- **System:** A system is a set of entities, real or abstract, comprising a whole where each component interacts with or is related to at least one other component and that interact to accomplish some function. Individual components may pursue their own objectives, with or without the intention of contributing to the system function. Any object which has no relation with any other element of the system is not part of that system.
- **System of Systems:** The system is composed of other systems (“of systems”). The other systems are natural to think of as systems in their own right, can’t be replaced by a single entity, and may be enormously complicated.
- **Complex:** The system has behavior involving interrelationships among its elements and these interrelationships can yield emergent behavior that is nonlinear, of greater complexity than the sum of behaviors of its parts, not due to system complication.
- **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.

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Many Examples

- Tropical Rain forest
- Agro-Eco system
- Cities and Megacities (and their
  planet)
- Interdependent infrastructur
  national to global)
- Government and political sy
  economic systems, (local to
  global)… Global Energy Sys

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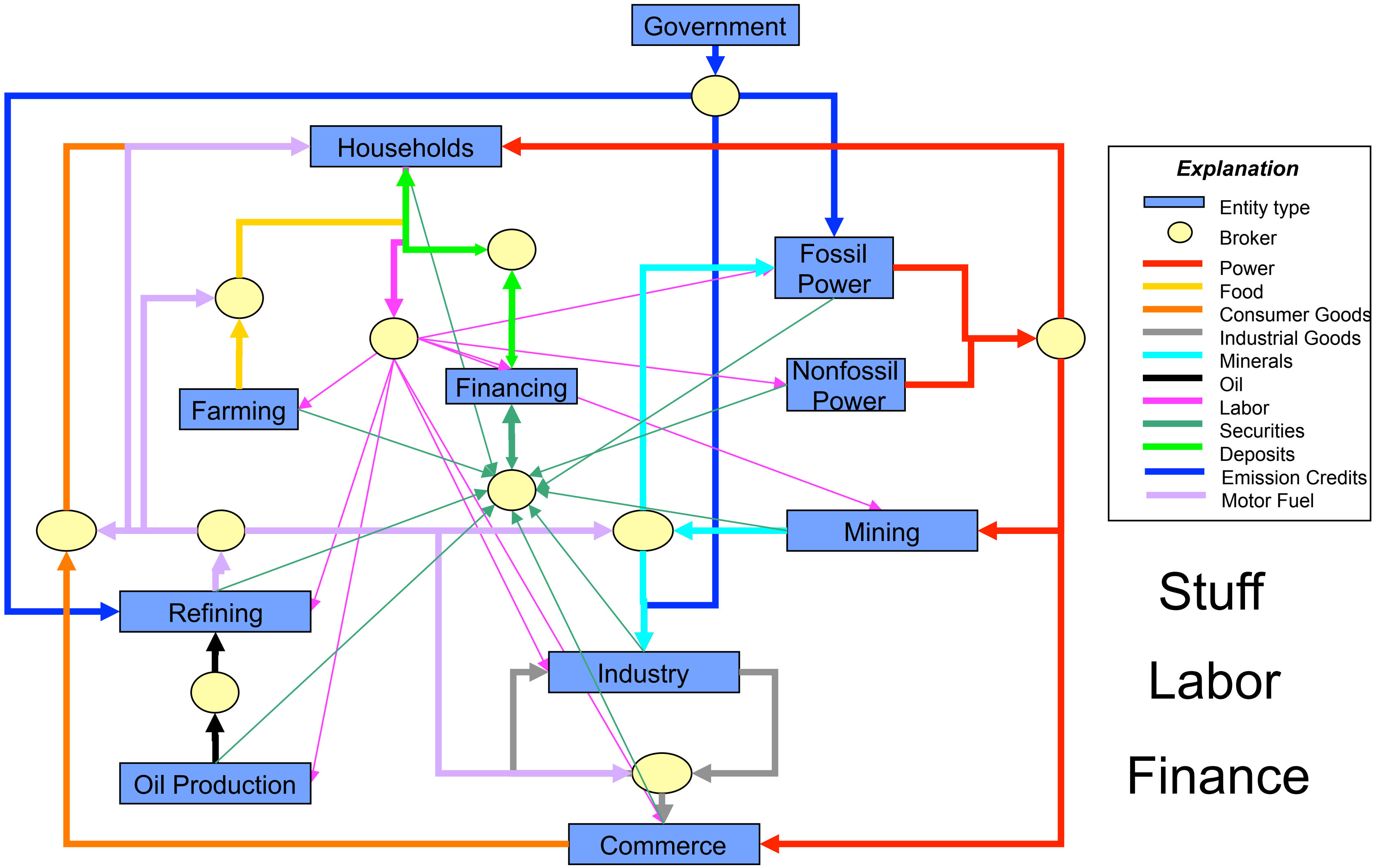
Core Economy within Global Energy System

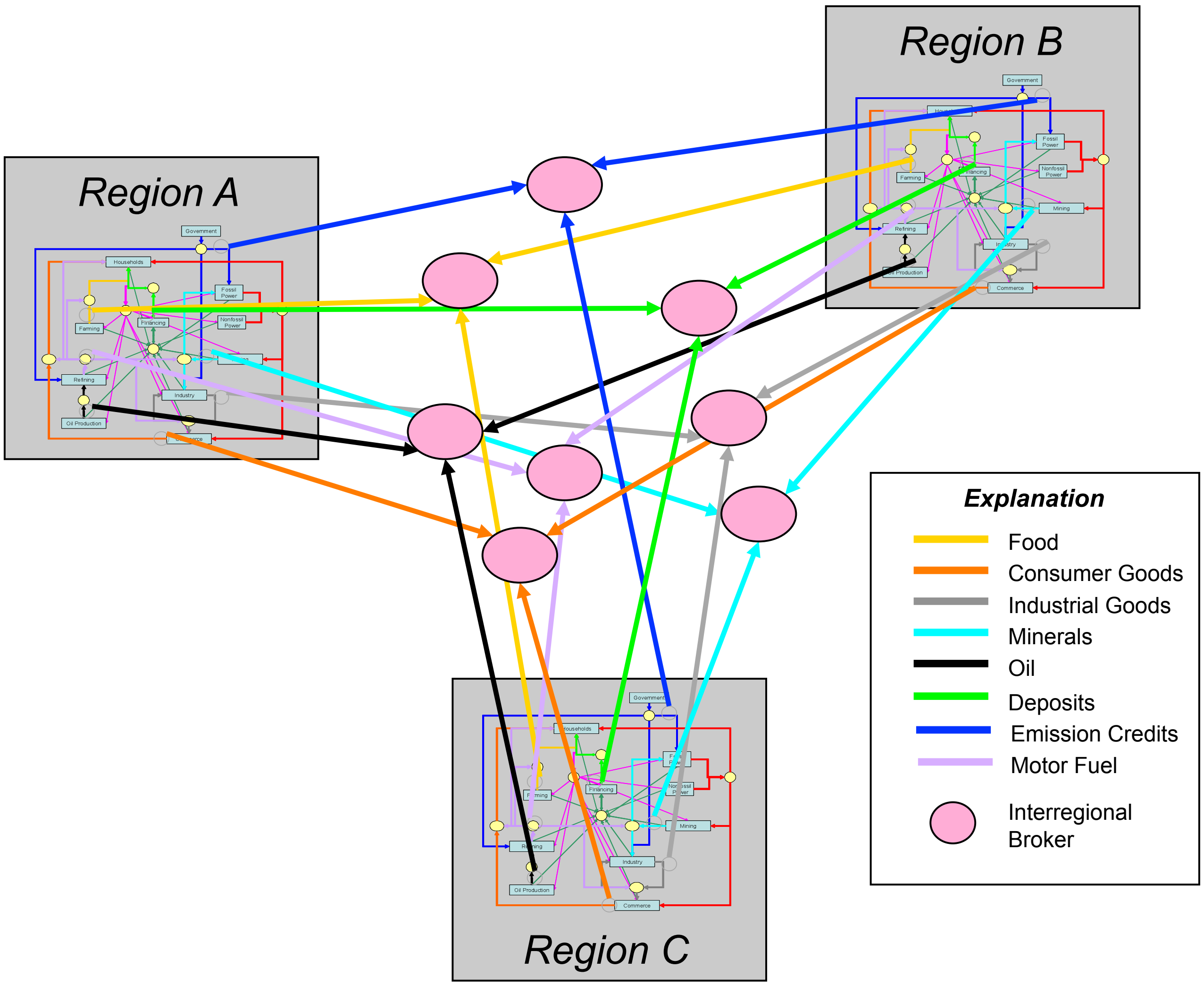


Stuff

Labor

Finance

Trading Blocks composed of Core Economies



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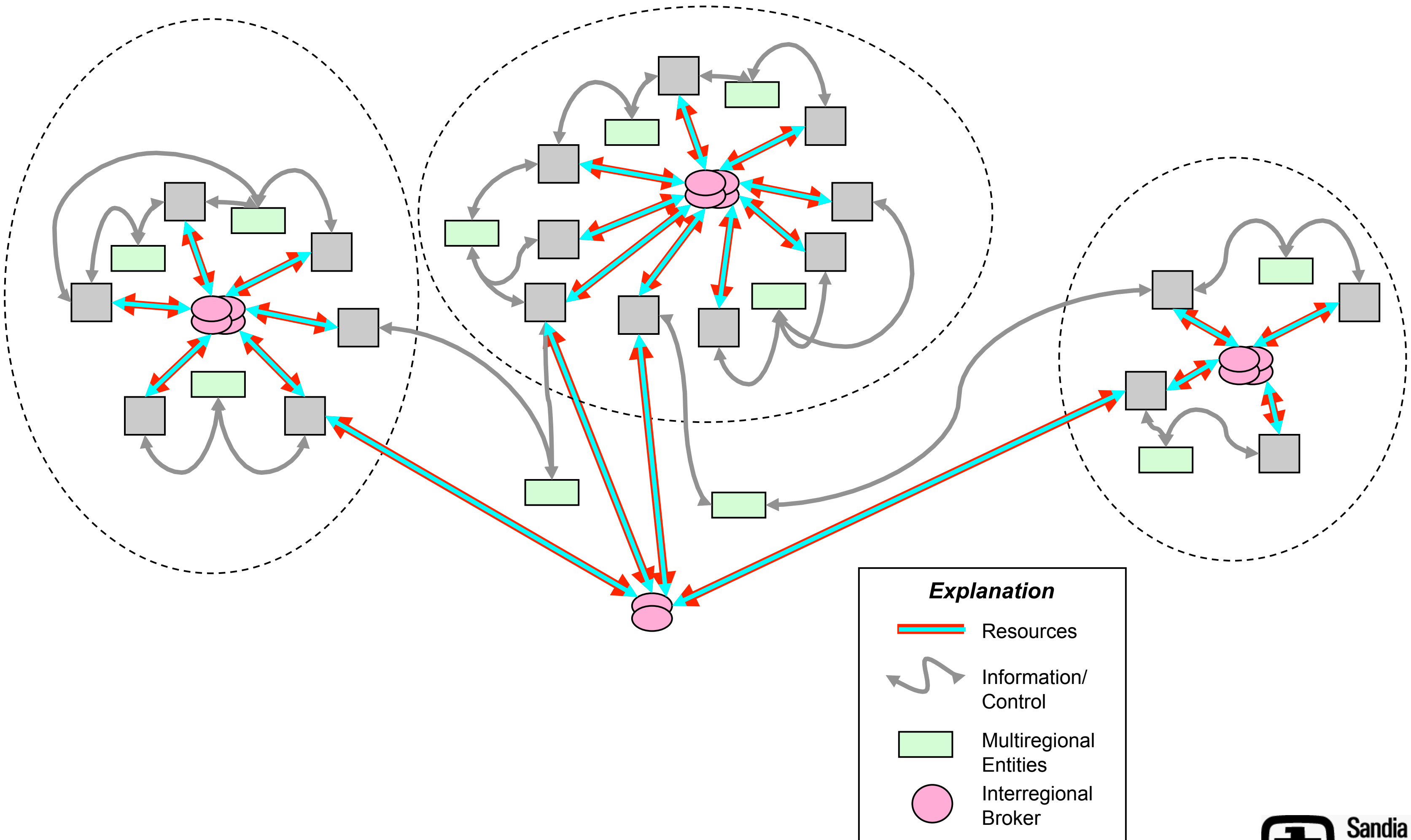
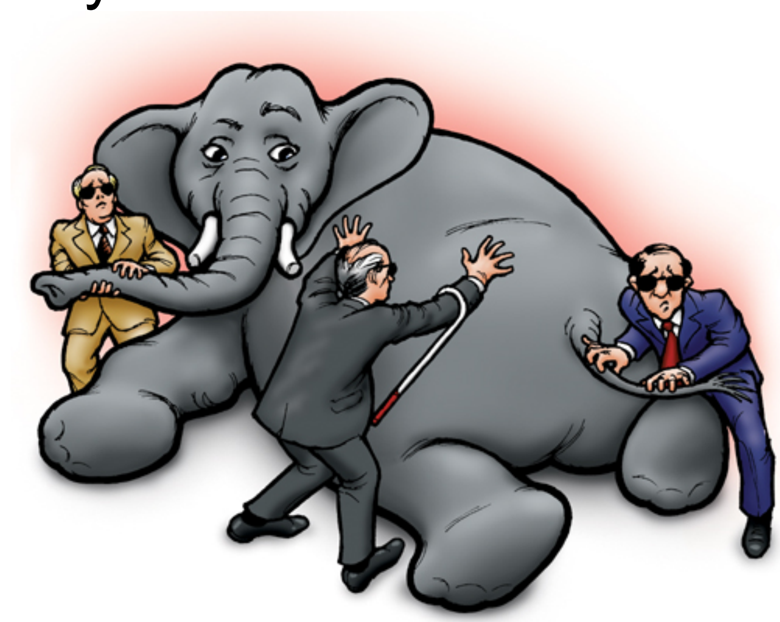
Global Energy System



LOTS of Uncertainty

- Aspects of Complex systems can be unpredictable (e.g. BTW sandpile, …)
- Adaptation, Learning and Innovation
- Conceptual model uncertainty
  - Beyond parameters
  - Beyond IC/BC



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Engineering within a CASoS: Example

Three years ago on Halloween NISAC got a call from DHS. Public health officials worldwide were afraid that the H5NI “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 to avert the carnage?

Chickens being burned in Hanoi

Definition of the 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:** 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

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Analogy with other Complex Systems

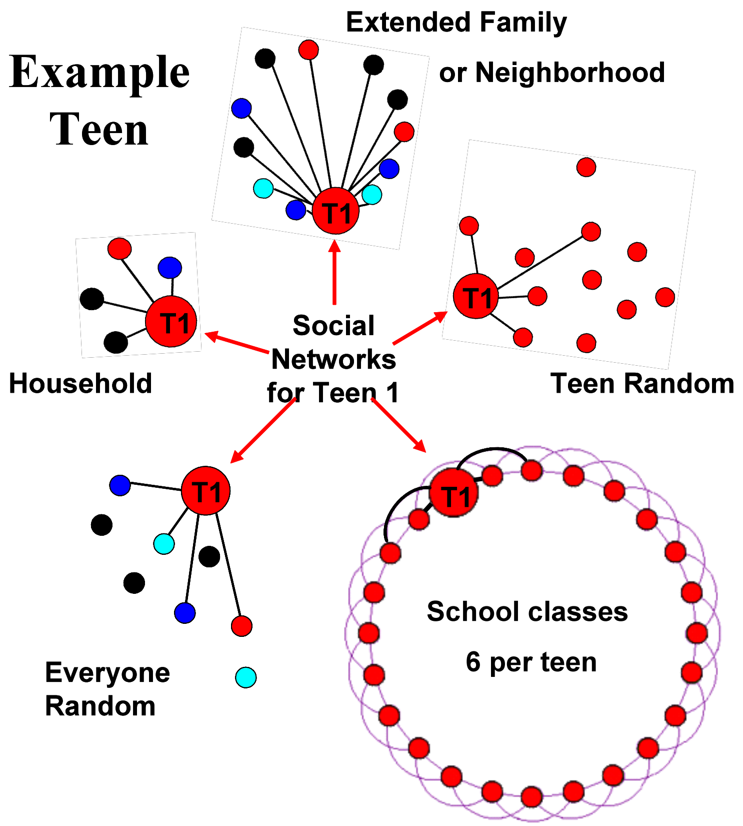
Simple analog:

- **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?

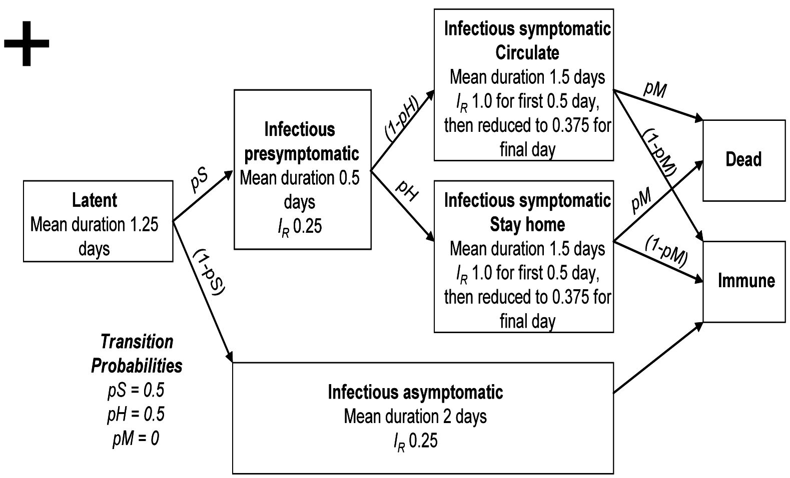
Application of Networked Agent Method to Influenza



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

+

Disease manifestation
(node and link behavior)



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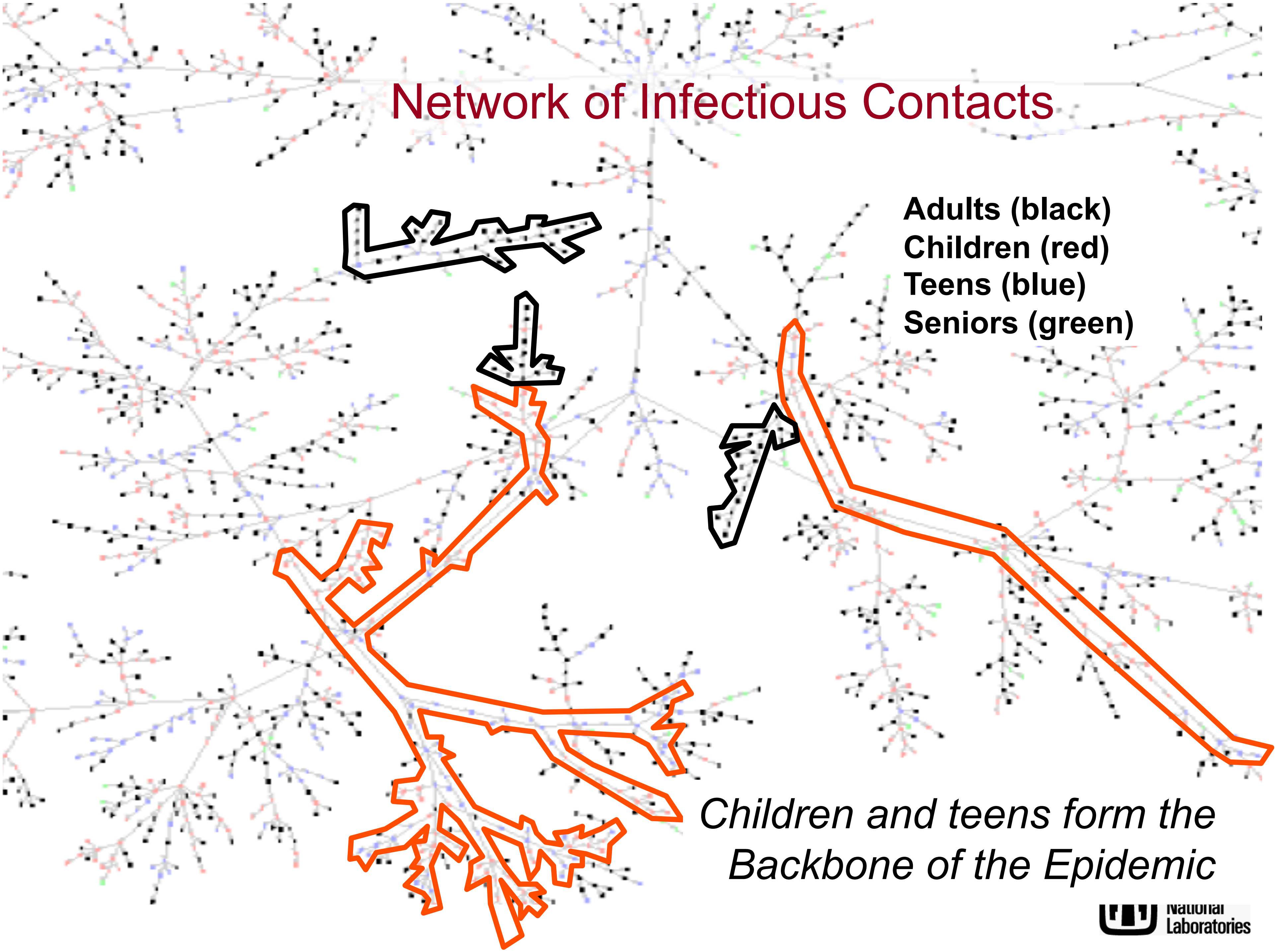
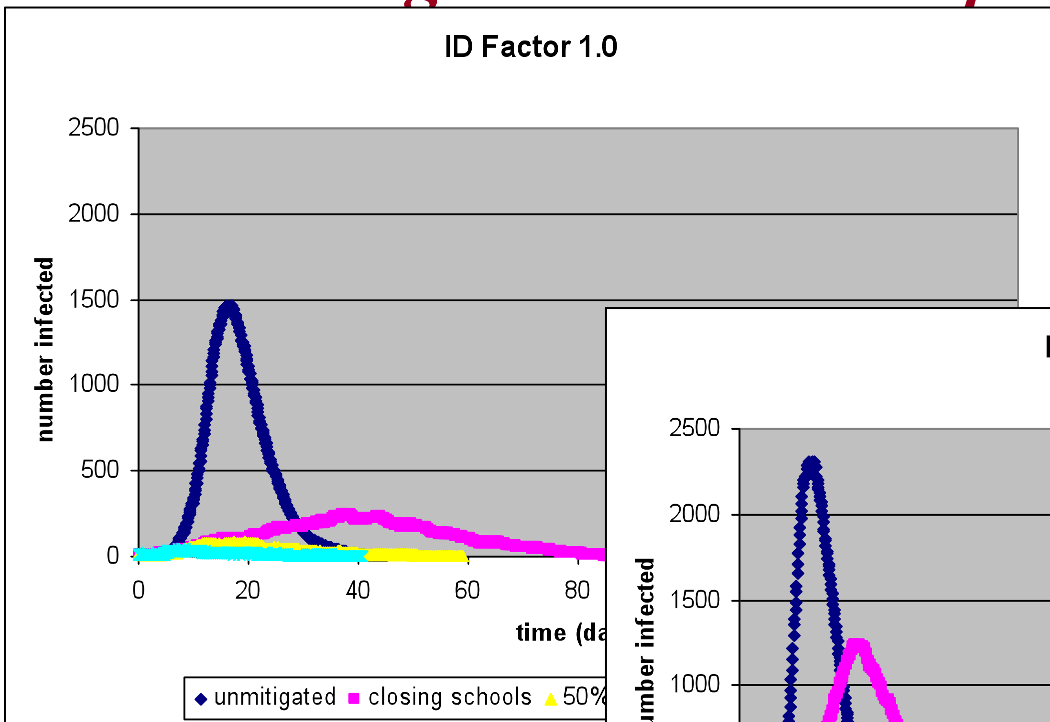
Network of Infectious Contacts

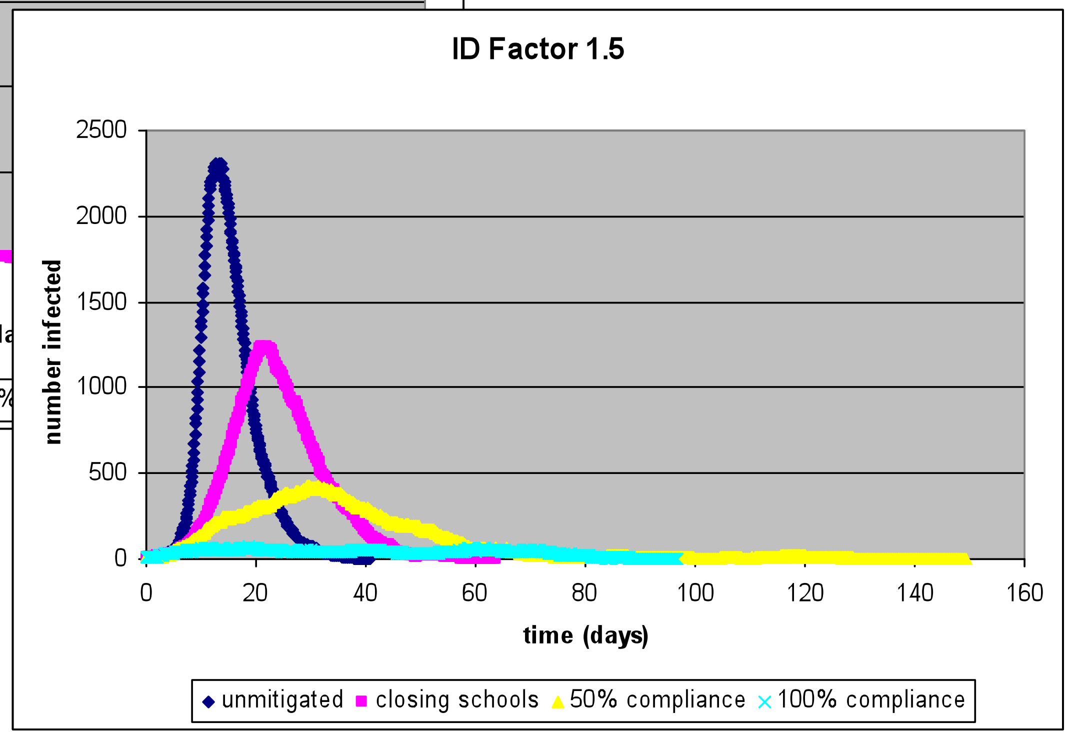


Children and teens form the Backbone of the Epidemic

Closing Schools and Keeping the Kids Home



1958-like



1918-like

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Connected to HSC Pandemic Implementation Plan writing team

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 strategies worked?
- What about adding or “layering” additional strategies including home quarantine, antiviral treatment and prophylaxis, and pre-pandemic vaccine?

We extended the model and put it on Tbird… 10’s of millions of runs later we had the answers to:

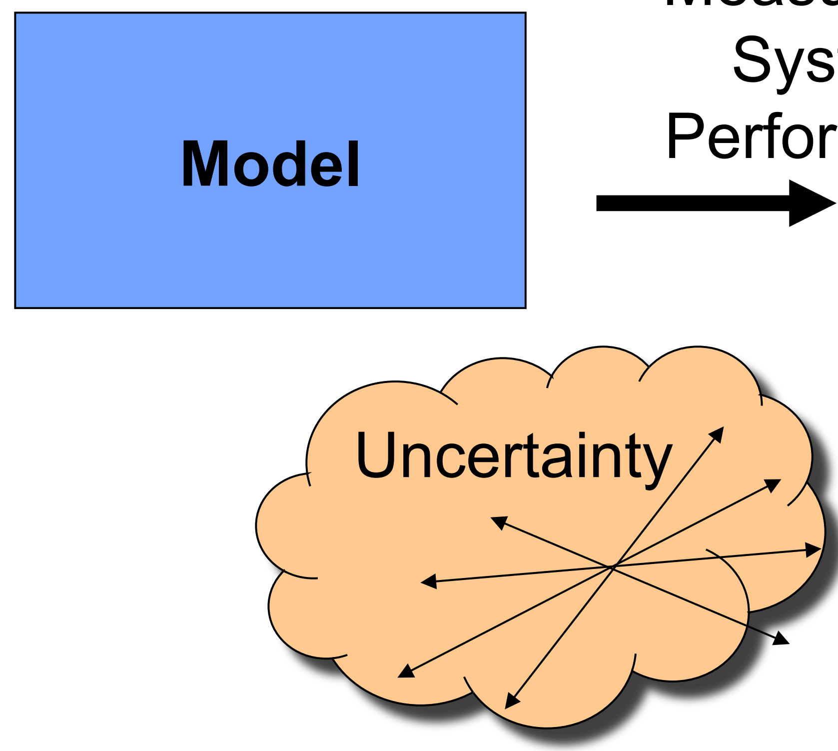
- What is the best mitigation strategy combination? (***choice***)
- How robust is the combination to model assumptions and uncertainty? (***robustness of choice***)
- What is required for the choice to be most effective? (***evolving towards resilience***)

These answers guided the formulation of national pandemic policy, Actualization is still in progress.

Robustness of Choice to Uncertainty

Policies or Actions

Measures of System Performance



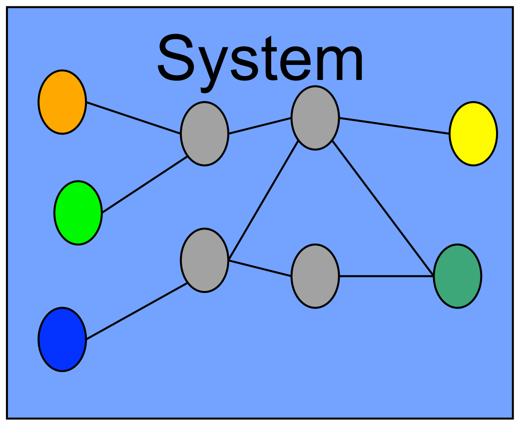
Rank Policies by Performance measures while varying parameters within expected bounds

“Best” policies are those that always rank high, their ***choice is robust to uncertainty***

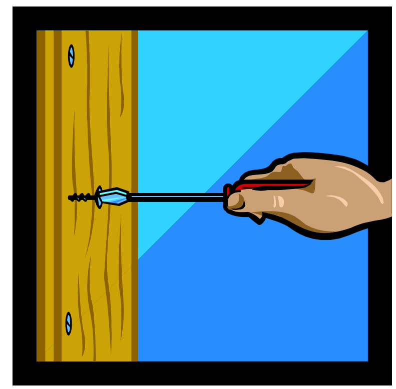
Finding the right model

- There is no general-purpose model of any system
- A model describes a system for a purpose

What to we care about?



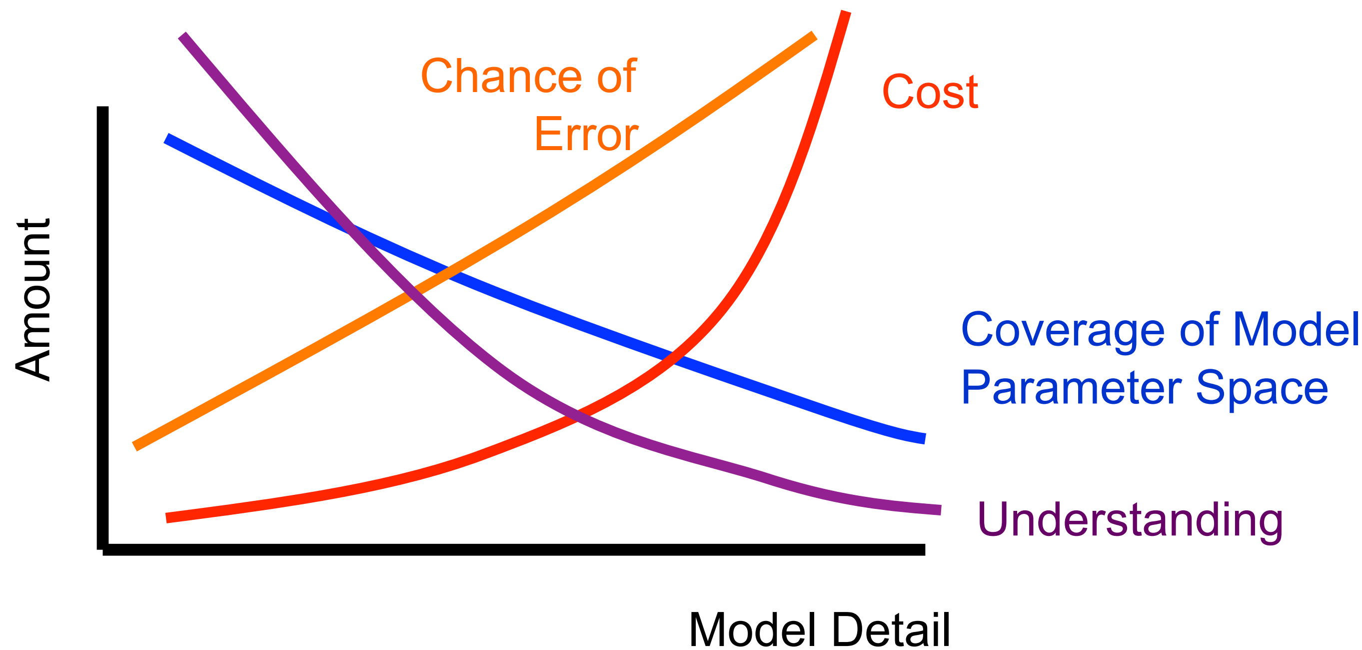
What can we do?



Model

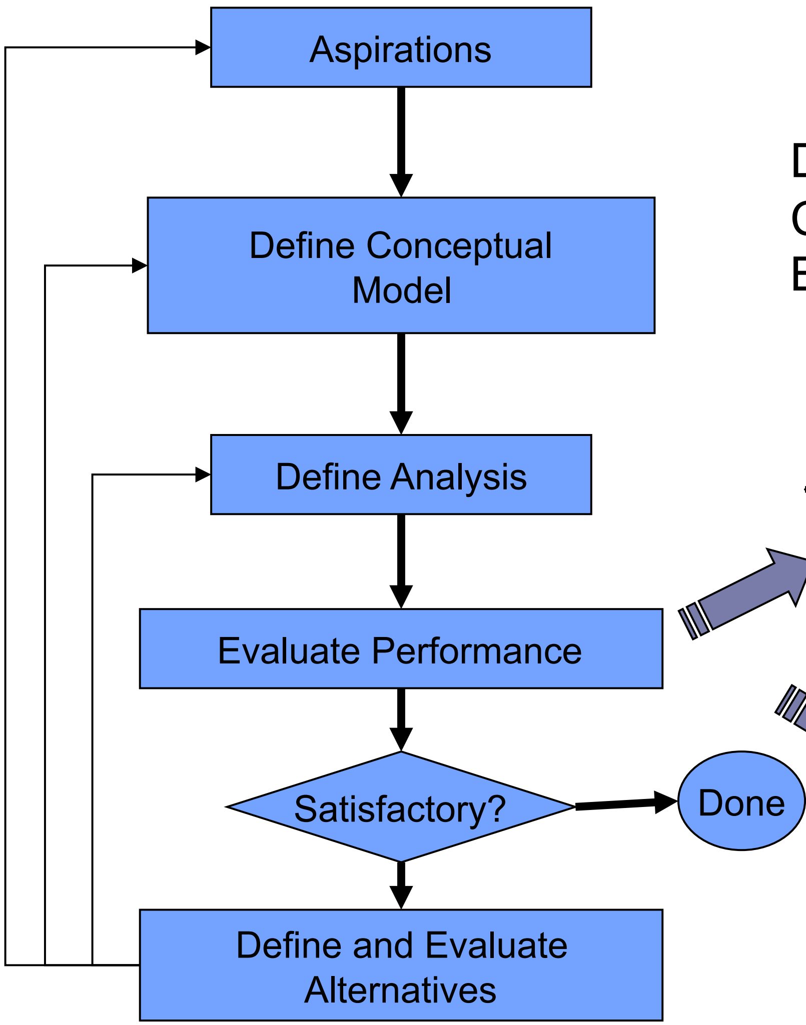
Additional structure and details added *as needed*

Pragmatic Detail : More can be less

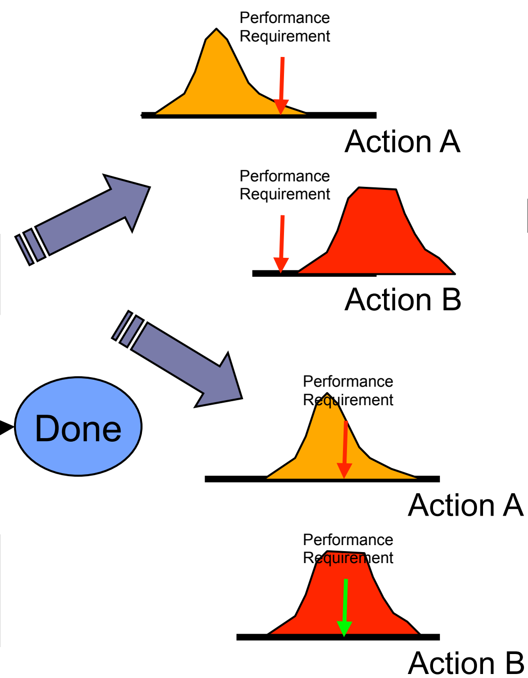


1. Recognize the tradeoff
2. Characterize the uncertainty with every model
3. Buy detail when and where its needed

Model development: an iterative process that uses uncertainty



Decision to refine the model
Can be evaluated on the same
Basis as other actions



Model uncertainty permits distinctions

Model uncertainty obscures important distinctions, and reducing uncertainty has value

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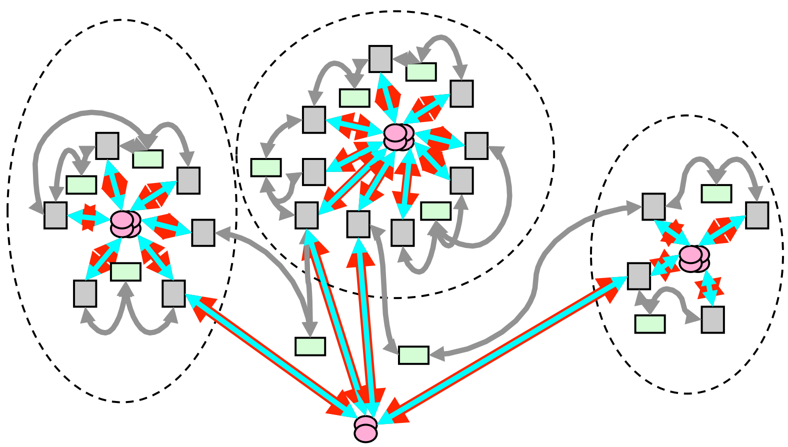
CASoS Engineering:
An Opportunity and Challenge for Uncertainty Quantification



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General CASoS Engineering Framework

- **Define**
  - CASoS of interest and Aspirations,
  - Appropriate methods and theories (analogy, percolation, game theory, networks, agents…)
  - Appropriate conceptual models and required data
- **Design and Test Solutions**
  - What are *feasible choices* within multi-objective space,
  - How *robust* are these choices to uncertainties in assumptions, and
  - Critical enablers that increase system *resilience*
- **Actualize Solutions within the Real World**

An Opportunity and Challenge
For Uncertainty Quantification

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Extra NISAC Related

Resolving Infrastructure Issues Today

Each Critical Infrastructure Insures Its Own Integrity

Oil & Gas

**Communica-
tions**

Water

**Banking
&
Finance**

**Continuity
of
Gov. Services**

**Transpor-
tation**

**Emergency
Services**

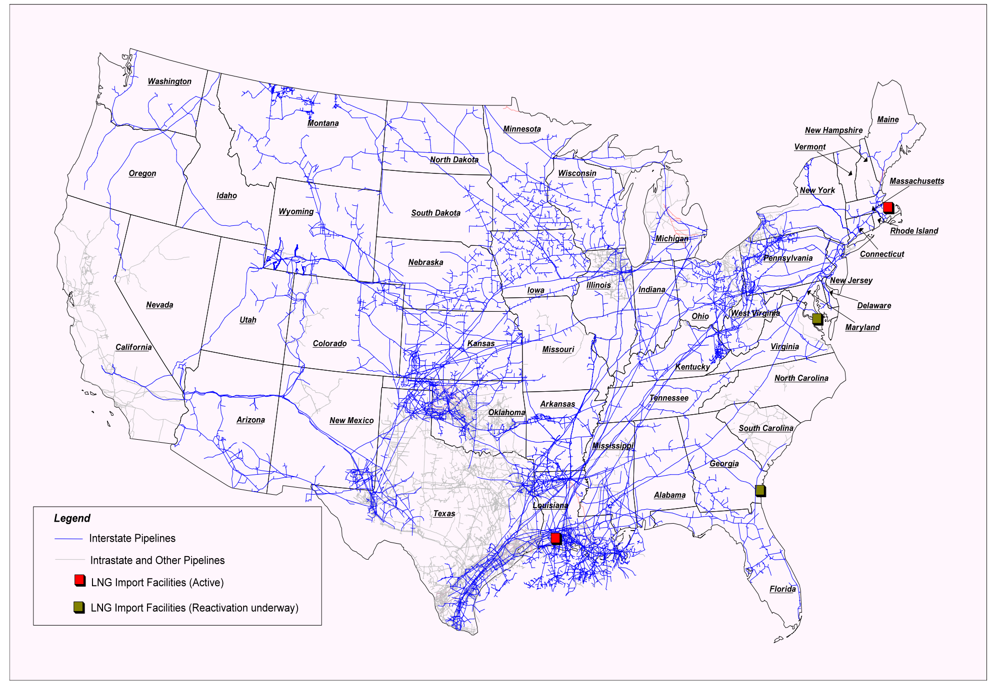
**Electric
Power**

NISAC's Role:

Modeling, simulation, and analysis of critical infrastructures, their interdependencies, system complexities, disruption consequences

A Challenging if not Daunting Task

- Each individual infrastructure is complicated
- Interdependencies are extensive and poorly studied
- Infrastructure is largely privately owned, and data is difficult to acquire
- No single approach to analysis or simulation will address all of the issues



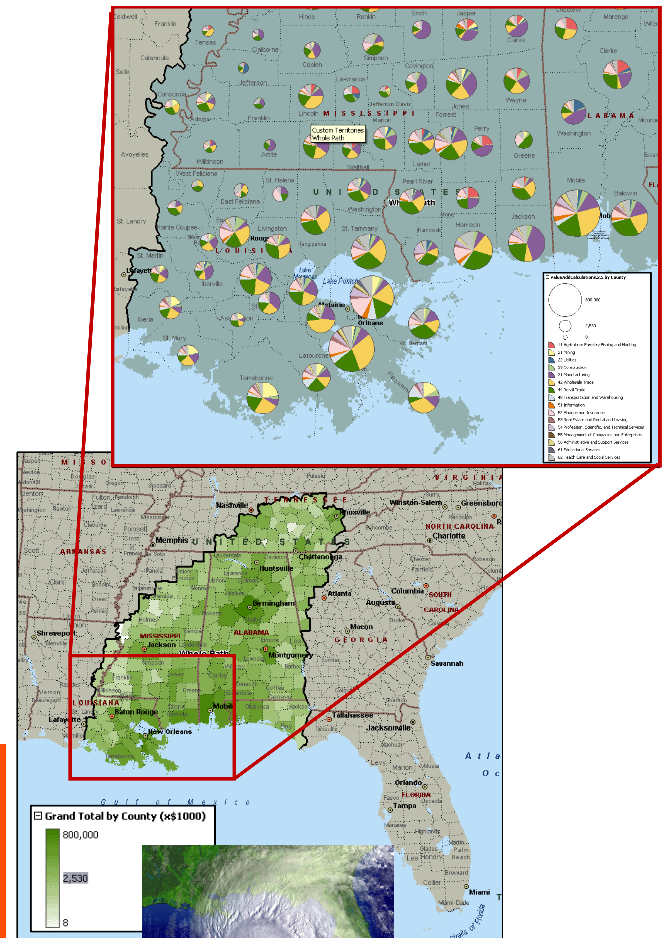
Source: Energy Information Administration, Office of Oil & Gas

Active Refinery Locations,
Crude and Product Pipelines

Example Natural Disaster Analysis: Hurricanes

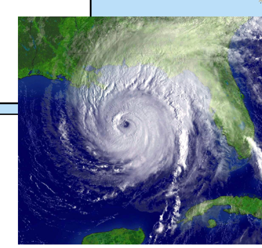
Analyses:

- Damage areas, severity, duration, restoration maps
- Projected economic damage
  - Sectors, dollars
  - Direct, indirect, insured, uninsured
  - Economic restoration costs
- Affected population
- Affected critical infrastructures



Focus of research:

- **Comprehensive evaluation of threat**
- **Design of Robust Mitigation**
- **Evolving Resilience**



Hurricane Ivan

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2003: Advanced Methods and Techniques Investigations (AMTI)

Critical Infrastructures:

- ***Are Complex*:** composed of many parts whose interaction via local rules yields ***emergent structure* (*networks*) *and behavior* (*cascades*)** at larger scales
- ***Grow and adapt*** in response to local-to-global ***policy***
- ***Contain people***
- Are interdependent "***systems of systems***"

Critical infrastructures are Complex Adaptive Systems of Systems: CASoS

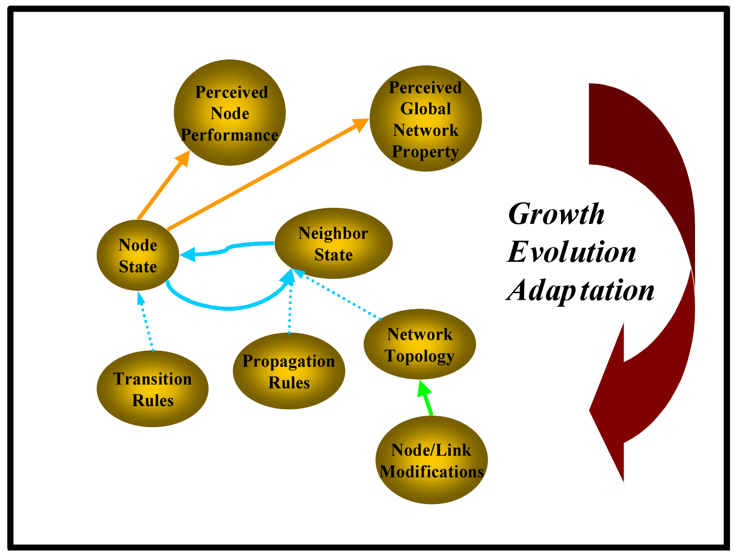
Generalized Method: Networked Agent Modeling

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 from Policy

Connect nodes appropriately to form a system (network)
Connect systems appropriately to form a System of Systems

"Caricatures of reality" that embody well defined assumptions



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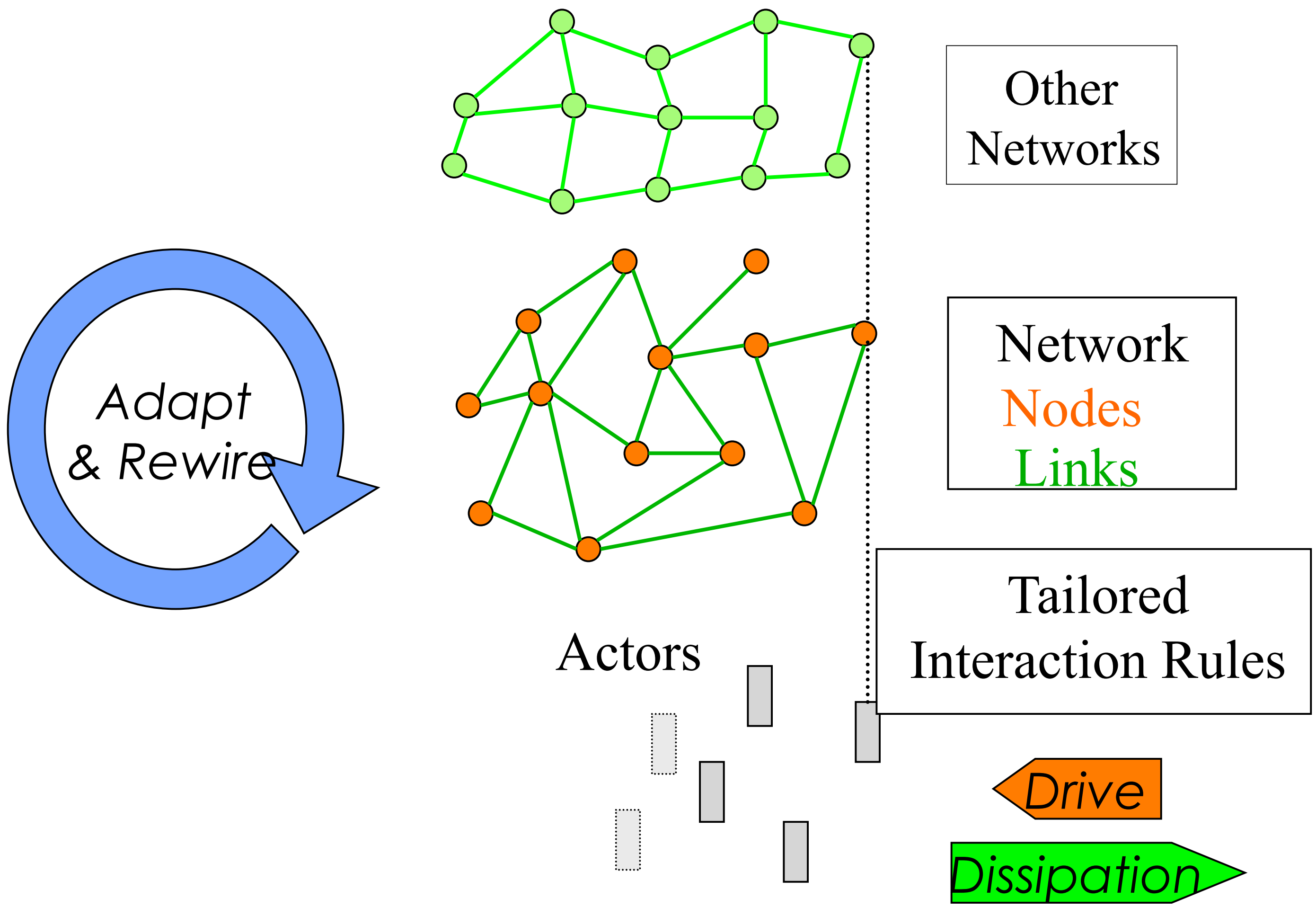
Graphical Depiction: Networked Agent Modeling



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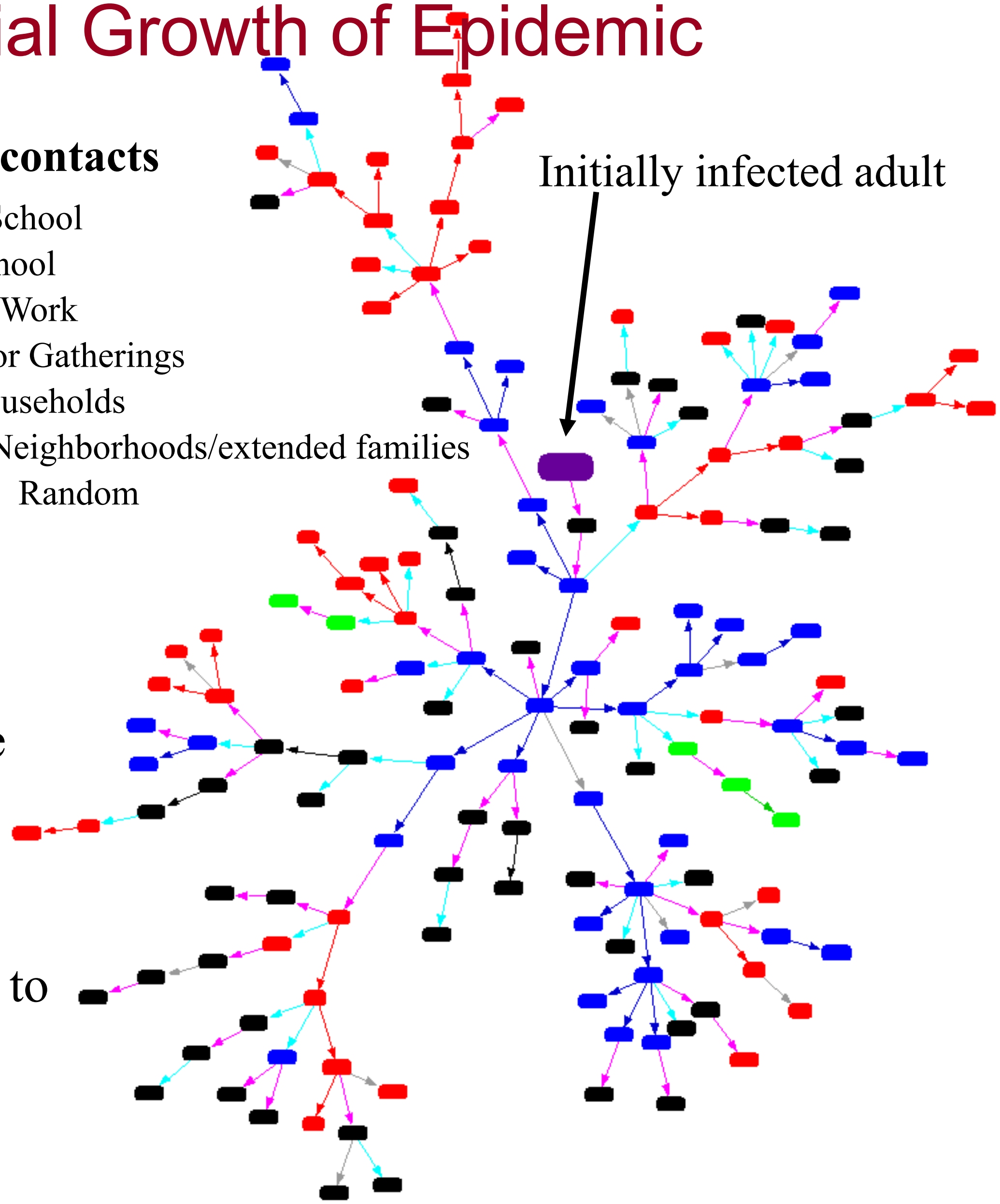
Initial Growth of Epidemic

Infectious contacts

- Children School
- Teens School
- Adults Work
- Senior Gatherings
- Households
- Neighborhoods/extended families
- Random

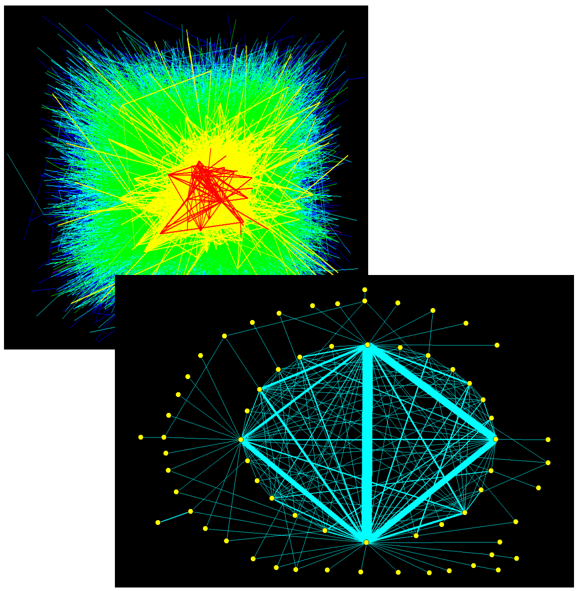
Agents

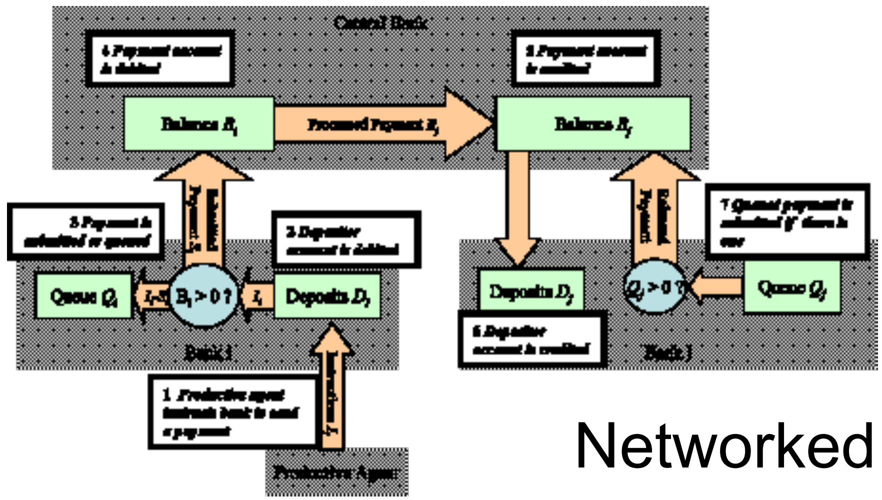
- Initially infected adult
- child
- teenager
- adult
- senior



Tracing the spread of the disease: From the initial seed, two household contacts (light purple arrows) brings influenza to the *High School* (blue arrows) *where it spreads like wildfire.*

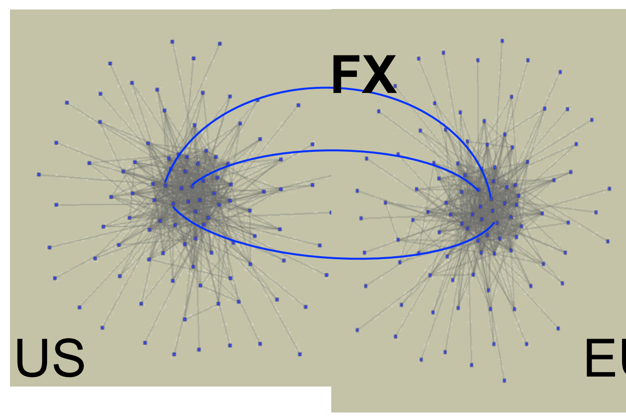
Application: Congestion and Cascades in Payment Systems





Networked ABM

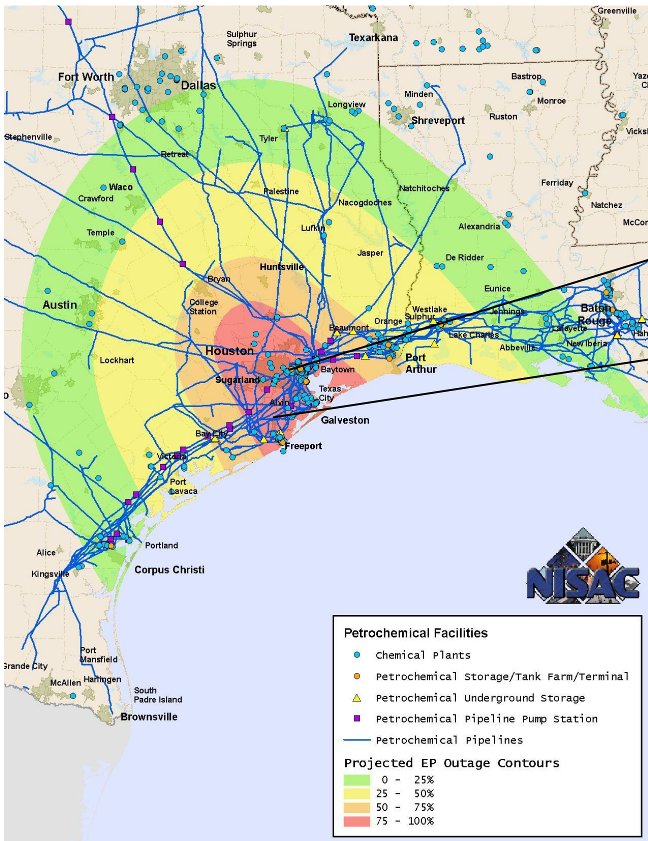
Payment system topology

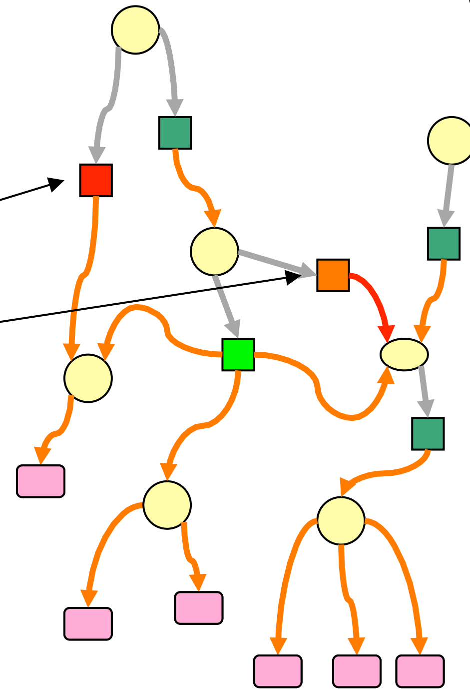


Global interdependencies

Application: Industrial Disruptions

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





Diminished Product Availability

Complexity Primer Slides

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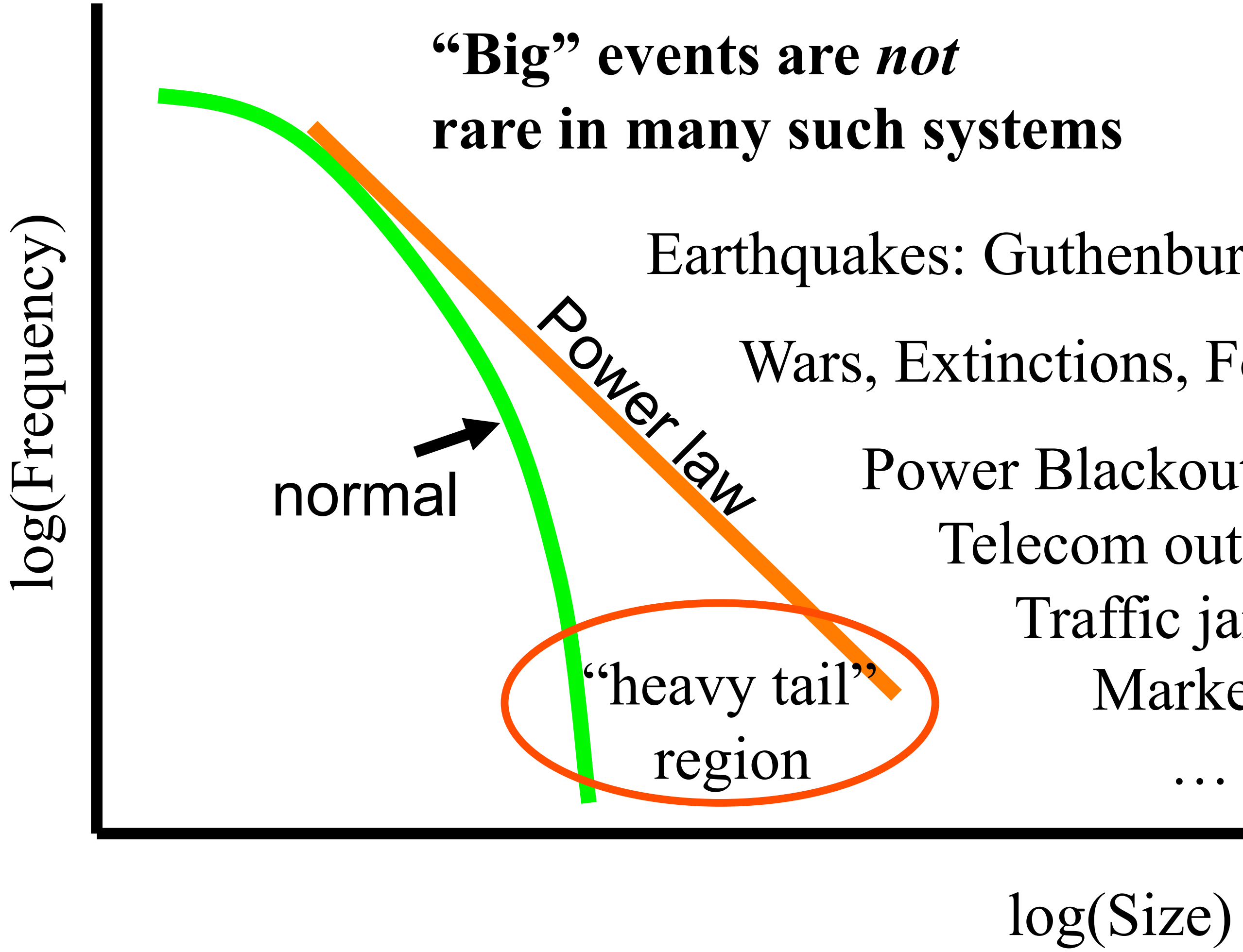
First Stylized Fact: Multi-component Systems often have power-laws & "heavy tails"



Earthquakes: Guthenburg-Richter

Wars, Extinctions, Forest fires

Power Blackouts?

Telecom outages?

Traffic jams?

Market crashes?

… ???

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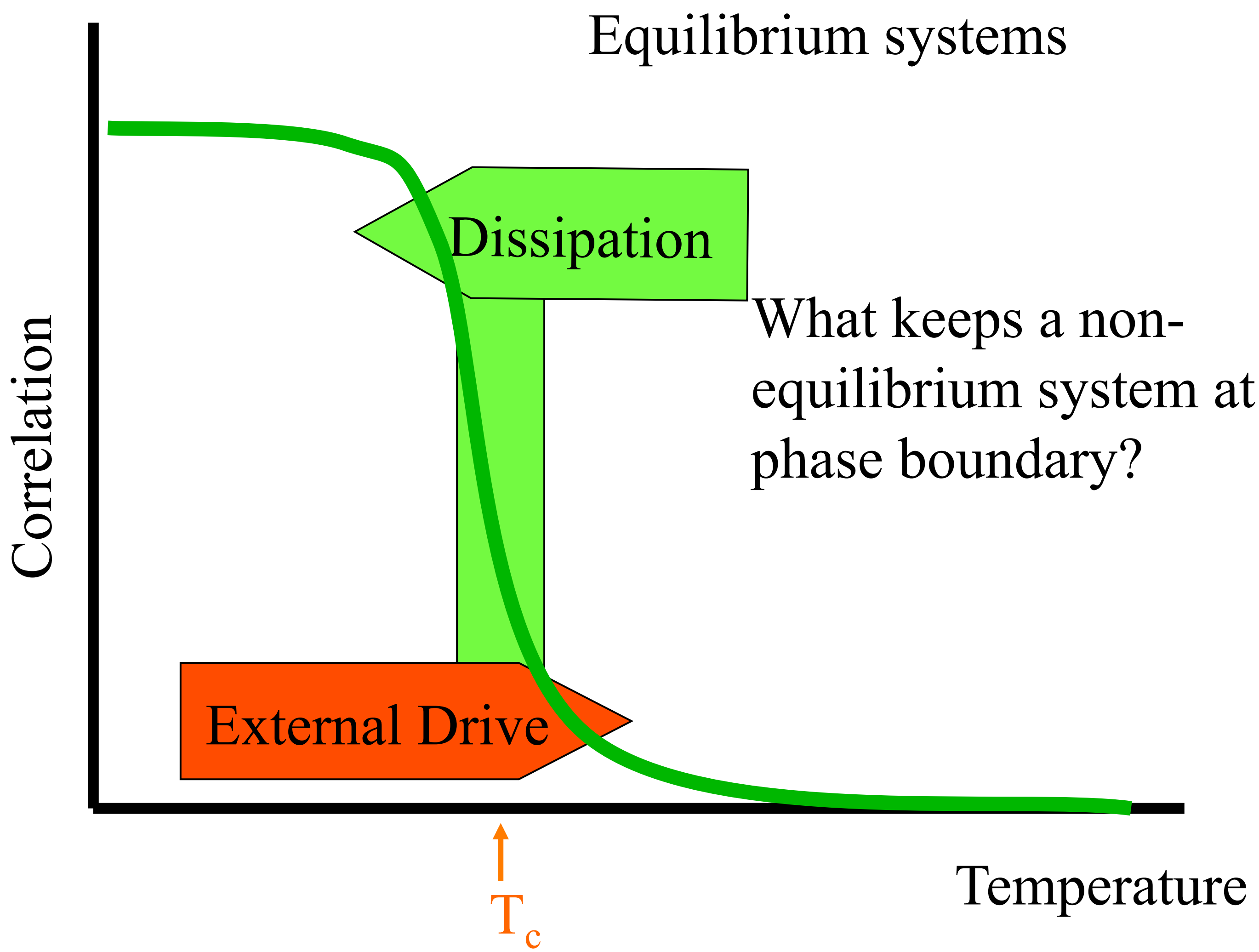
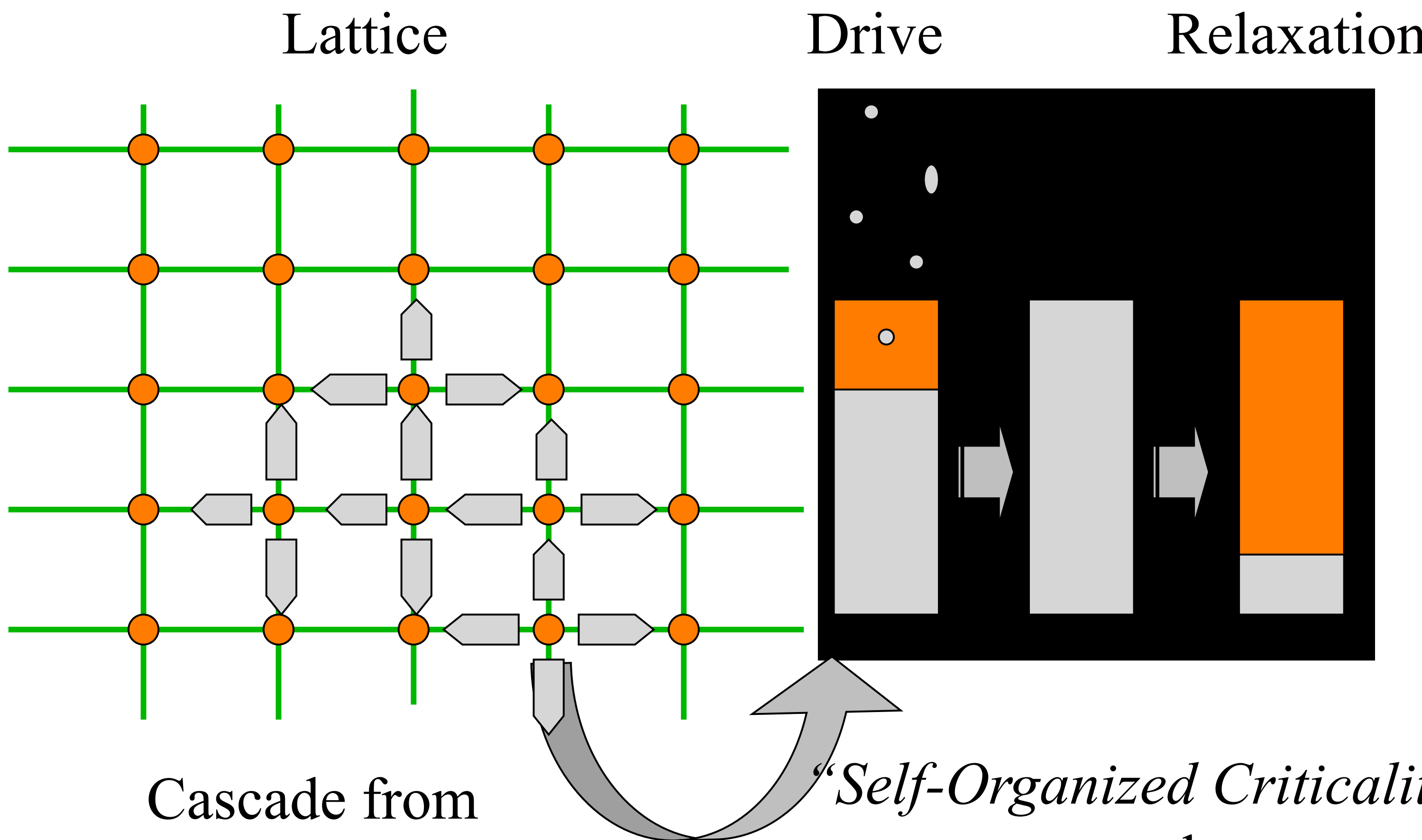
Power Law - Critical behavior - Phase transitions



What keeps a non-equilibrium system at a phase boundary?

1987 Bak, Tang, Wiesenfeld's "Sand-pile" or "Cascade" Model



Cascade from
Local Rules

"Self-Organized Criticality"
power-laws
fractals in space and time
time series unpredictable

Second Stylized Fact: Networks are Ubiquitous in Nature and Infrastructure

Food Web

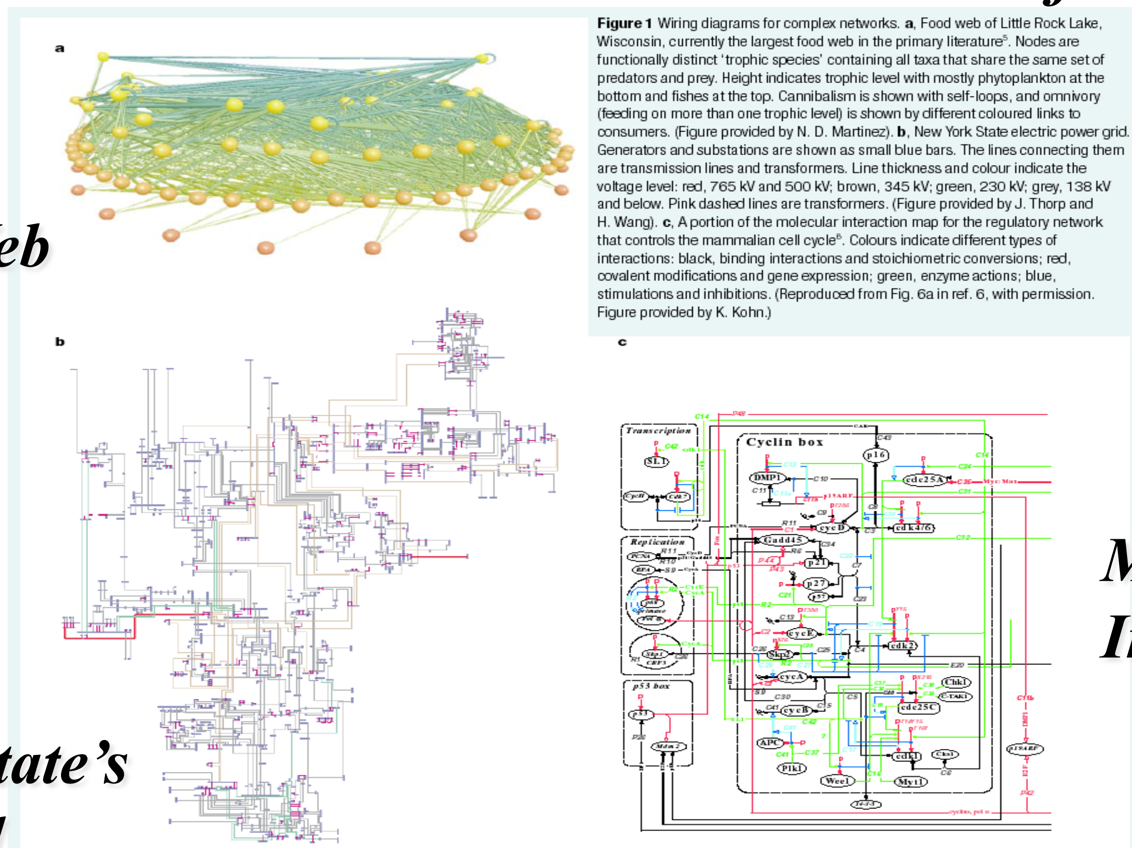


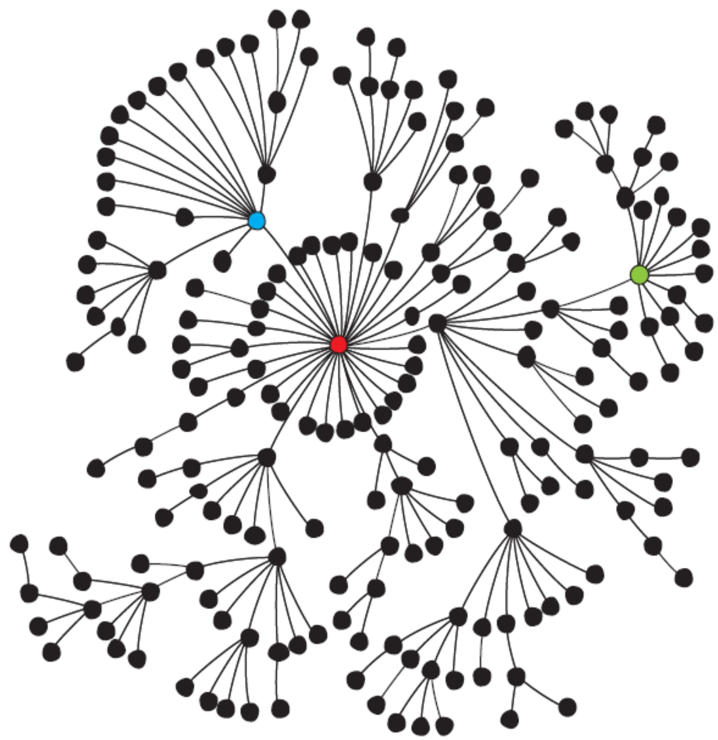
Figure 1 Wiring diagrams for complex networks. **a**, Food web of Little Rock Lake, Wisconsin, currently the largest food web in the primary literature[5]. Nodes are functionally distinct 'trophic species' containing all taxa that share the same set of predators and prey. Height indicates trophic level with mostly phytoplankton at the bottom and fishes at the top. Cannibalism is shown with self-loops, and omnivory (feeding on more than one trophic level) is shown by different coloured links to consumers. (Figure provided by N. D. Martinez). **b**, New York State electric power grid. Generators and substations are shown as small blue bars. The lines connecting them are transmission lines and transformers. Line thickness and colour indicate the voltage level: red, 765 kV and 500 kV; brown, 345 kV; green, 230 kV; grey, 138 kV and below. Pink dashed lines are transformers. (Figure provided by J. Thorp and H. Wang). **c**, A portion of the molecular interaction map for the regulatory network that controls the mammalian cell cycle[6]. Colours indicate different types of interactions: black, binding interactions and stoichiometric conversions; red, covalent modifications and gene expression; green, enzyme actions; blue, stimulations and inhibitions. (Reproduced from Fig. 6a in ref. 6, with permission. Figure provided by K. Kohn.)

Molecular Interaction

New York state's Power Grid

Illustrations of natural and constructed network systems from Strogatz [2001].

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



Simple Preferential attachment model: "*rich get richer*" yields Hierarchical structure with "King-pin" nodes

Properties:

tolerant to random failure…

vulnerable to informed attack

Evolving towards Resilience

- Robustness of choice to uncertainty also shows *those factors that good system performance depends on*, in order:
  - Implementation threshold
  - Compliance
  - Regional mitigation
  - Rescinding threshold
- *Planning and Training* required to push the system where it needs to be (carrots and sticks)
- Because *eliciting appropriate behavior of humans is inherently uncertain* (fatigue, hysteria, false positives), this policy is “interim”, meanwhile:
  - Research to develop broad spectrum vaccine for influenza
  - Resolving supply chain issues for antivirals

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