Designing Solutions in an Interdependent World: CASoS Engineering

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Complex Adaptive Infrastructures and Behavioral Systems

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NISAC

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

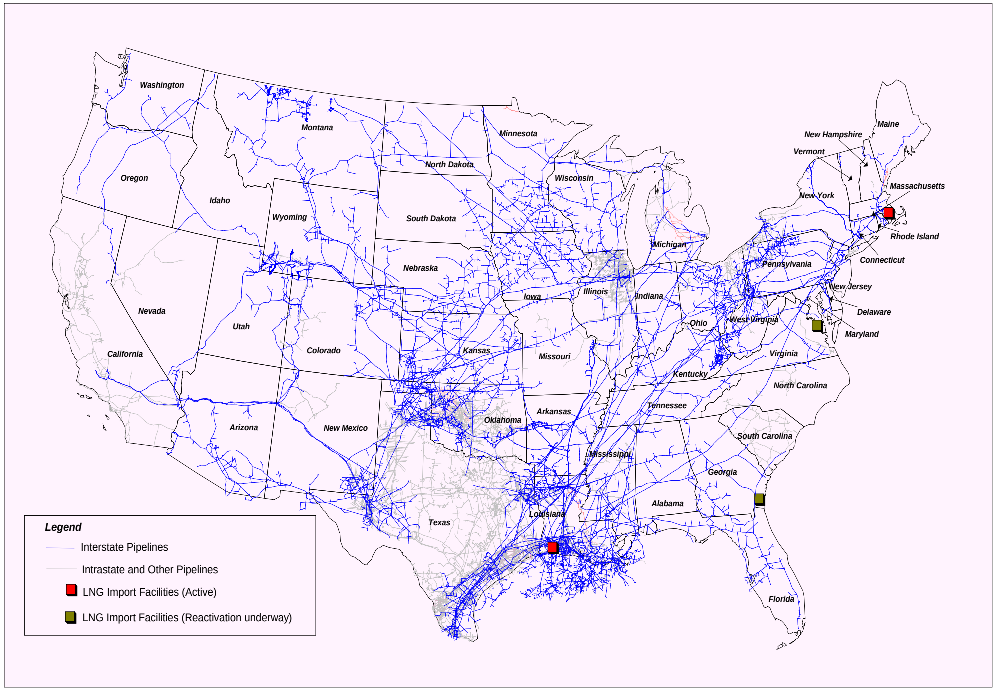
Electric Power

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

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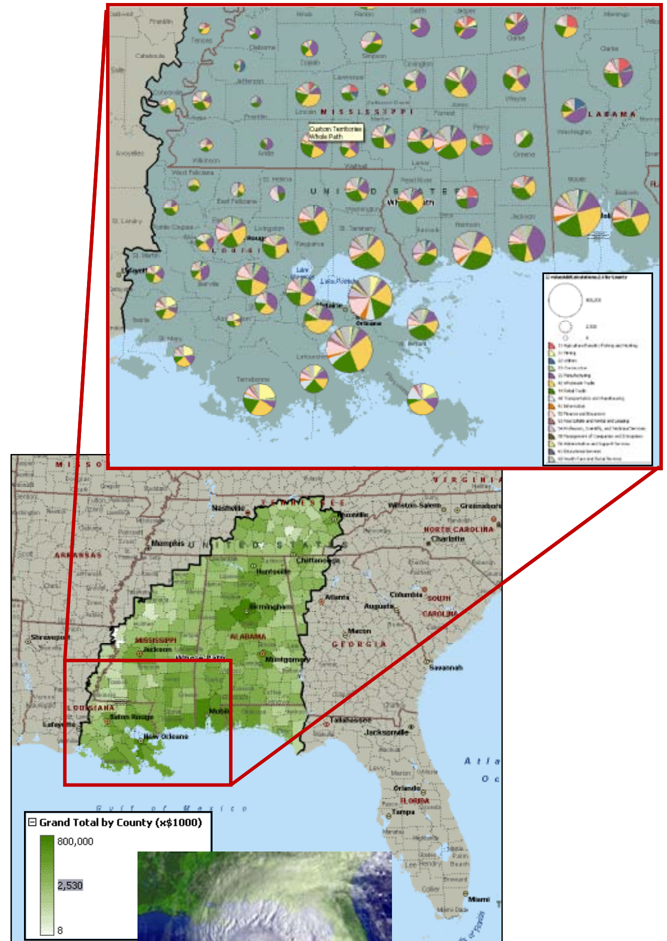
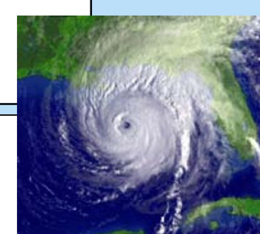
Example Natural Disaster Analysis: Hurricanes

Analyses:

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





Hurricane Ivan

Focus of research:

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

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

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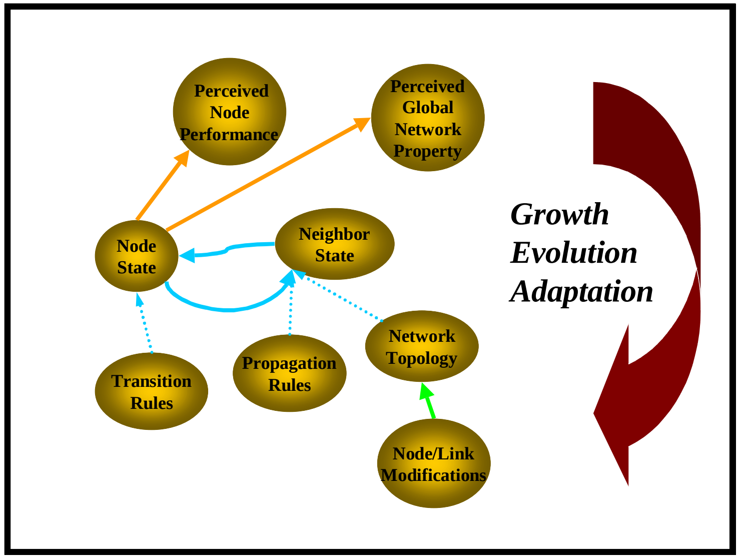
Generalized Method: Networked Agent Modeling

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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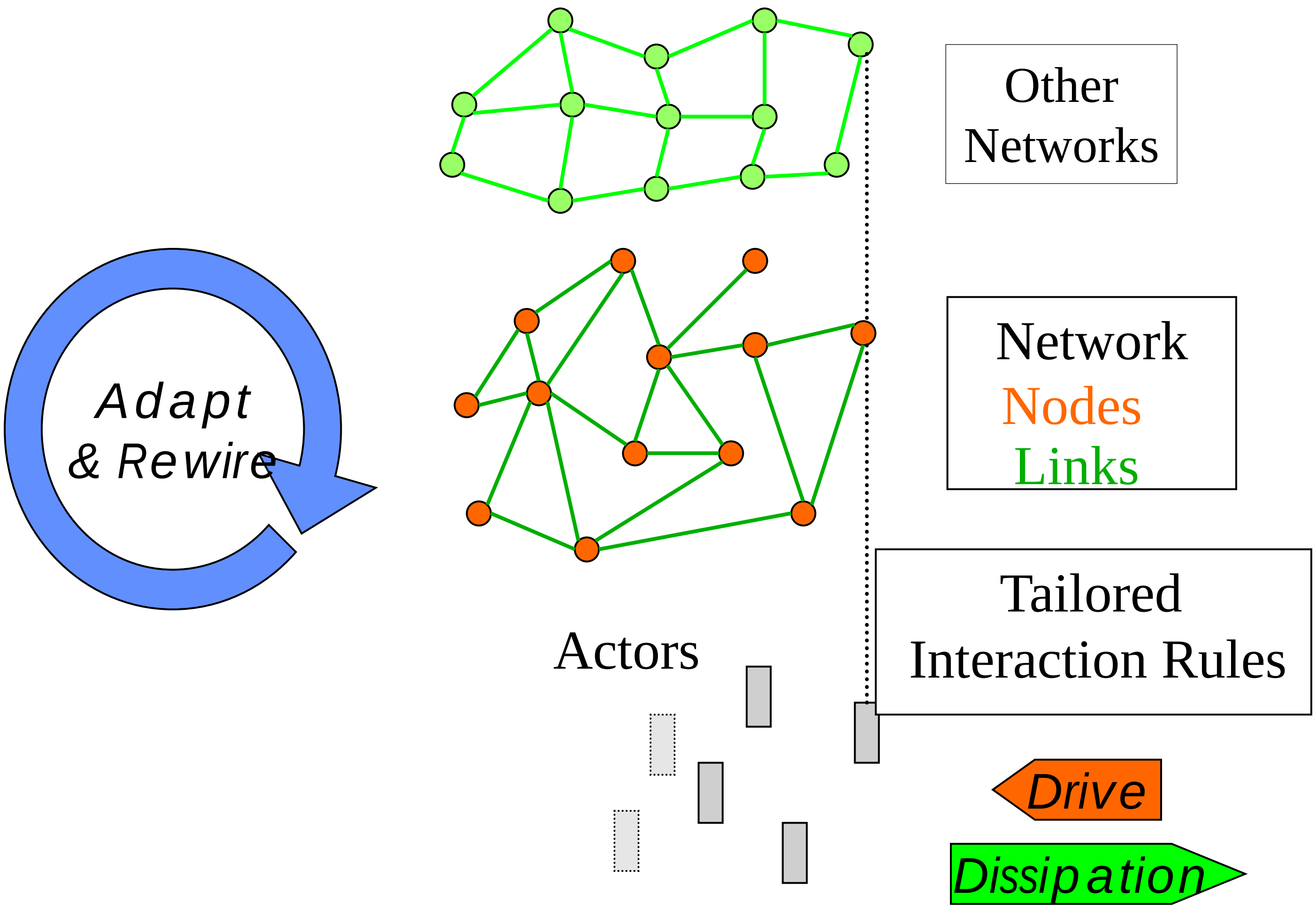
Graphical Depiction: Networked Agent Modeling



CASoS Engineering

- **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**

Example Application: Pandemic Influenza

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

This is a CASoS Problem

- **System:** Global transmission network composed of person to person interactions (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

Analogy with other CASoS

Two Simple analogs:

- **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.
- **Power grid blackouts**: The spread of a pandemic is a cascade that runs on the interactions among people, the social network, instead of the wires of a power-grid.

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

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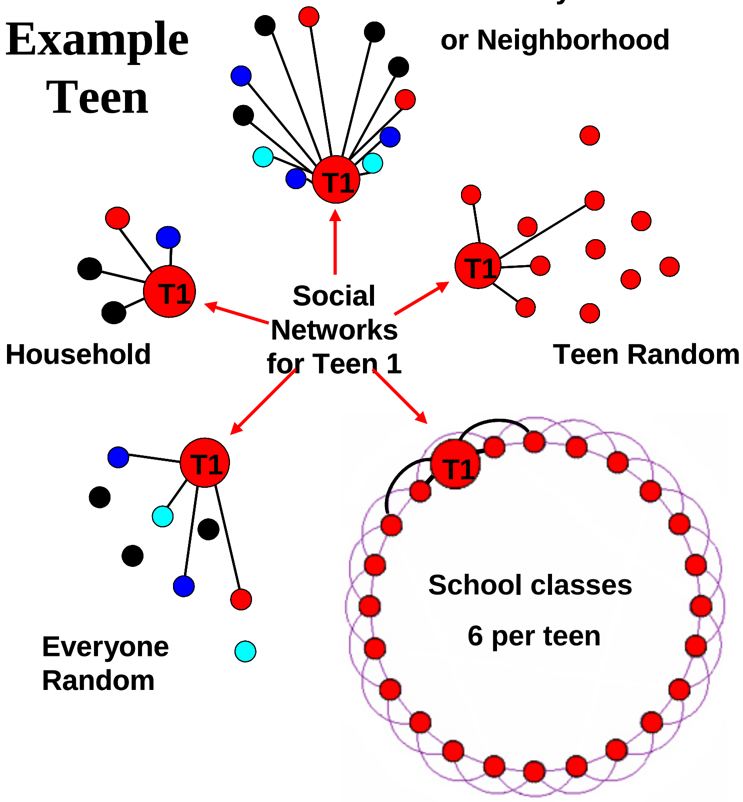
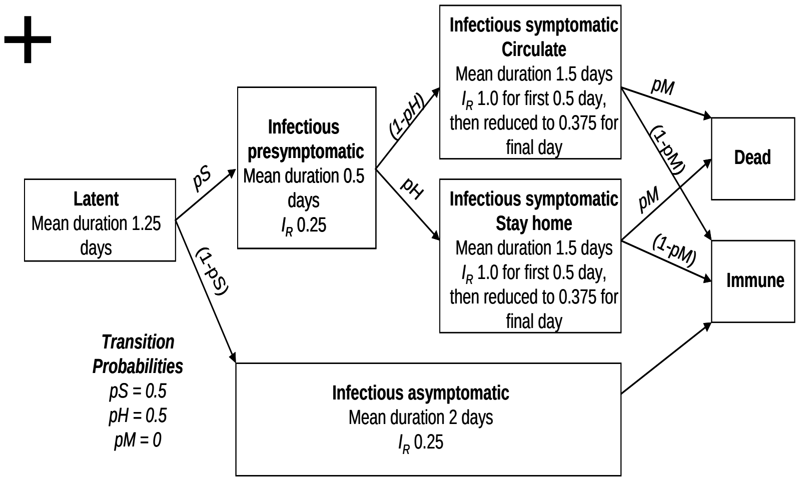
Application of Networked Agent Method to Influenza



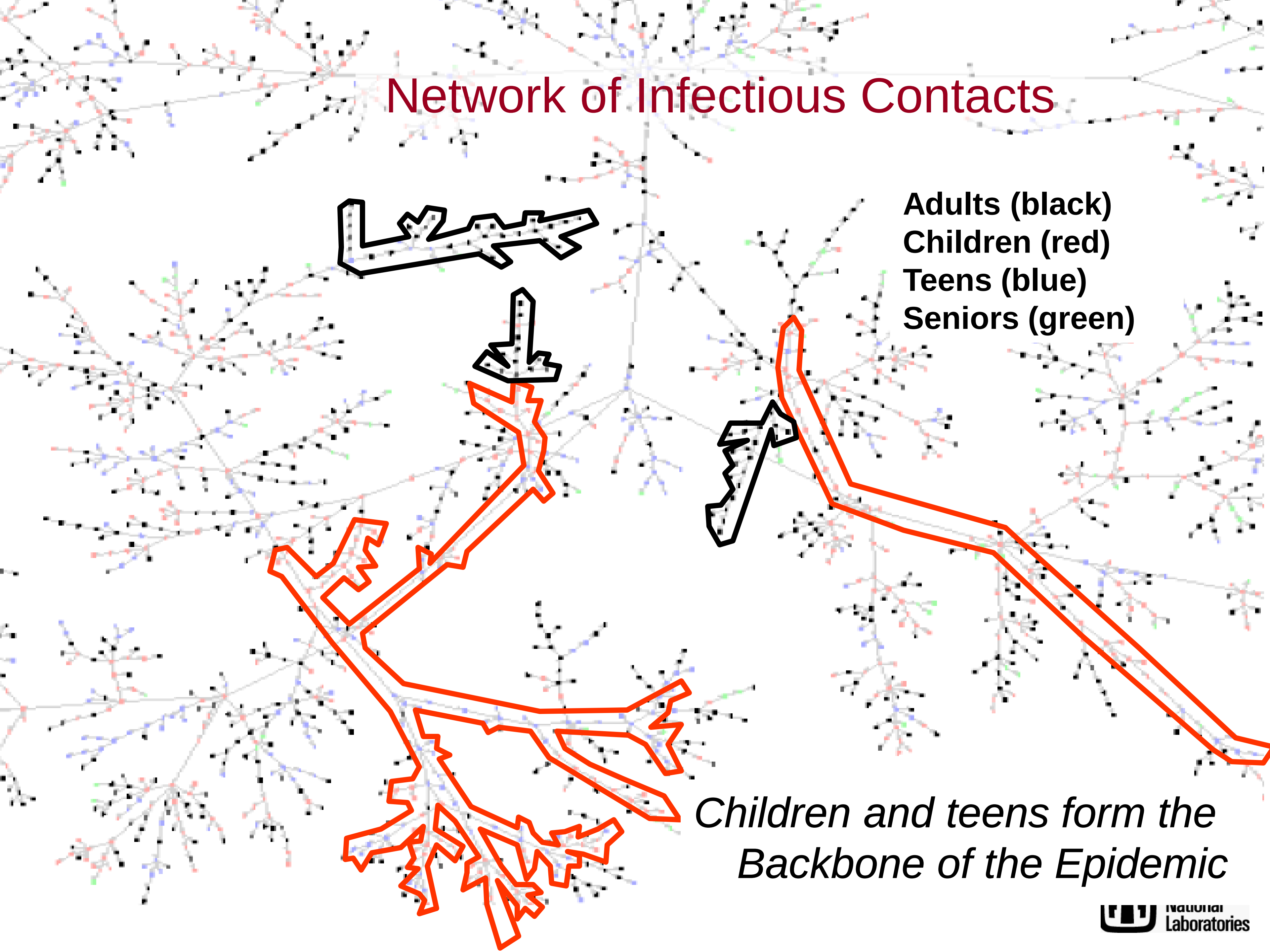
Stylized Social Network
(nodes, links, frequency of interaction)

+

Disease manifestation
(node and link behavior)



Network of Infectious Contacts



Children and teens form the Backbone of the Epidemic

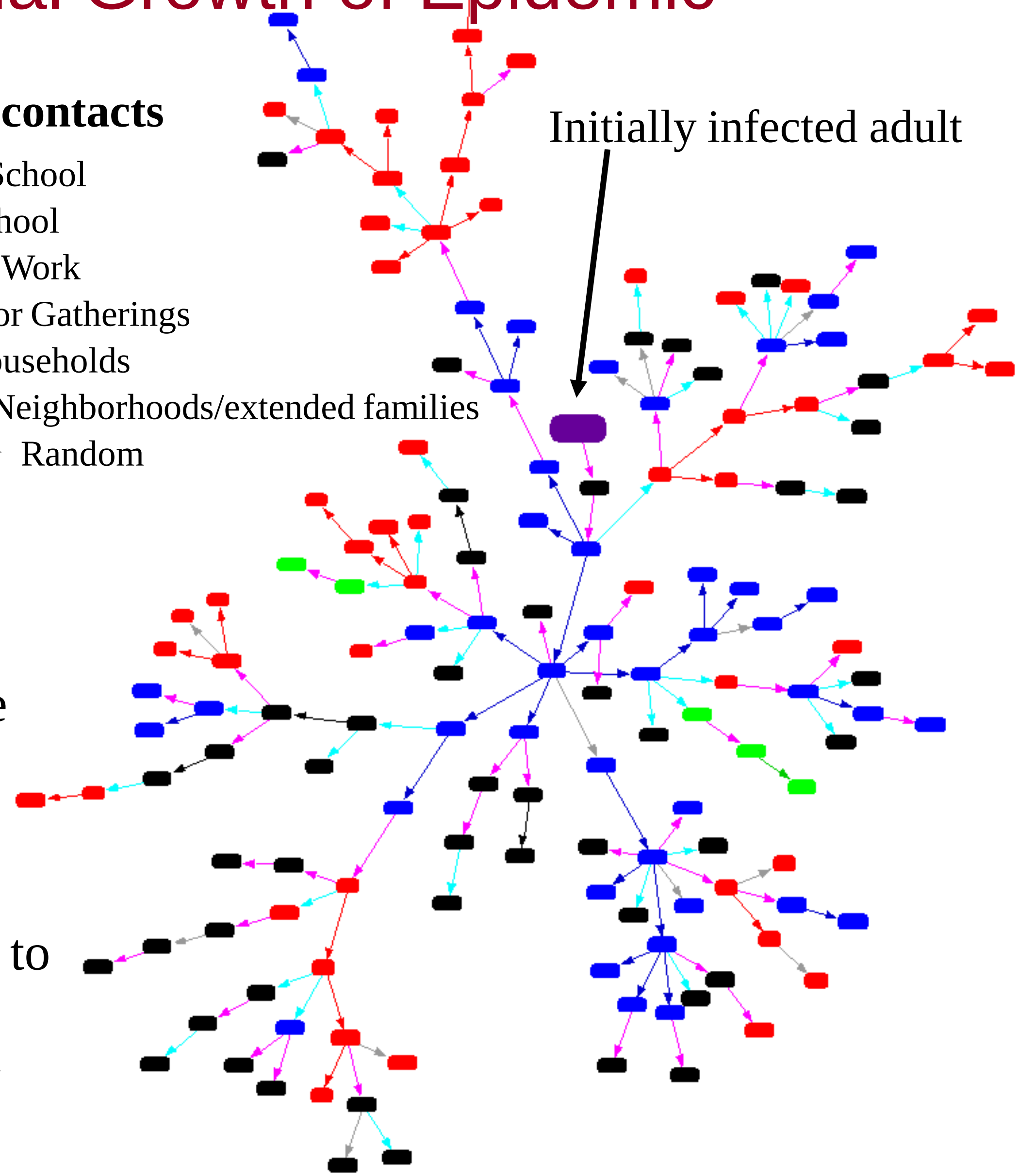
Initial Growth of Epidemic

Infectious contacts

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

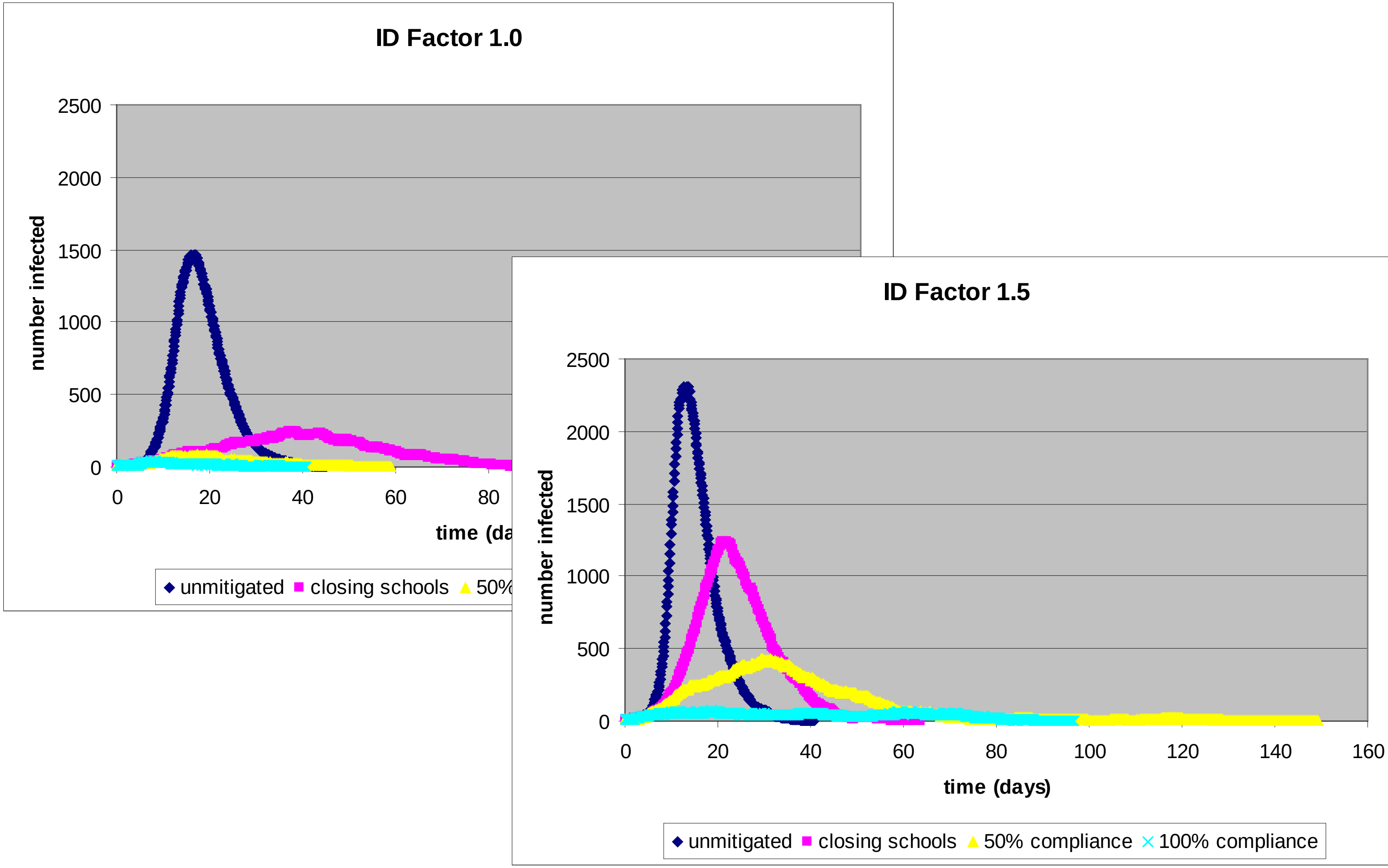
Agents

- 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.*

Closing Schools and Keeping the Kids Home



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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? (***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.

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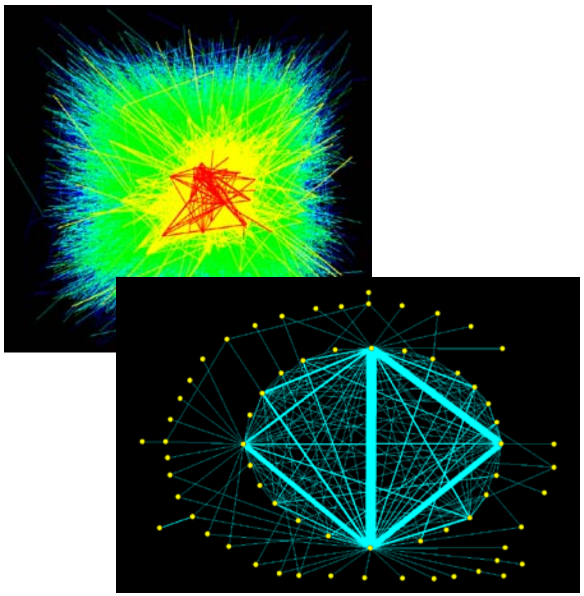
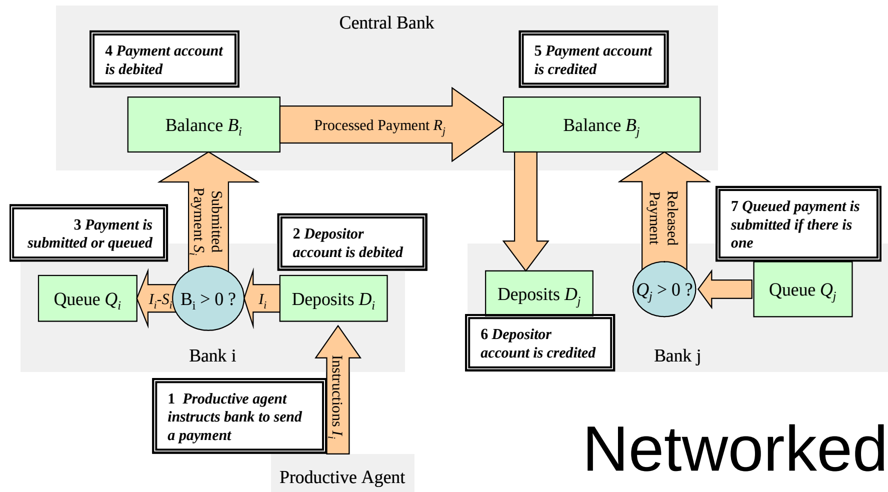
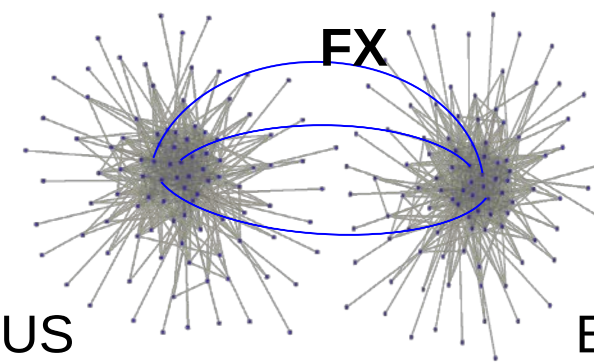
Application: Congestion and Cascades in Payment Systems



Payment system topology



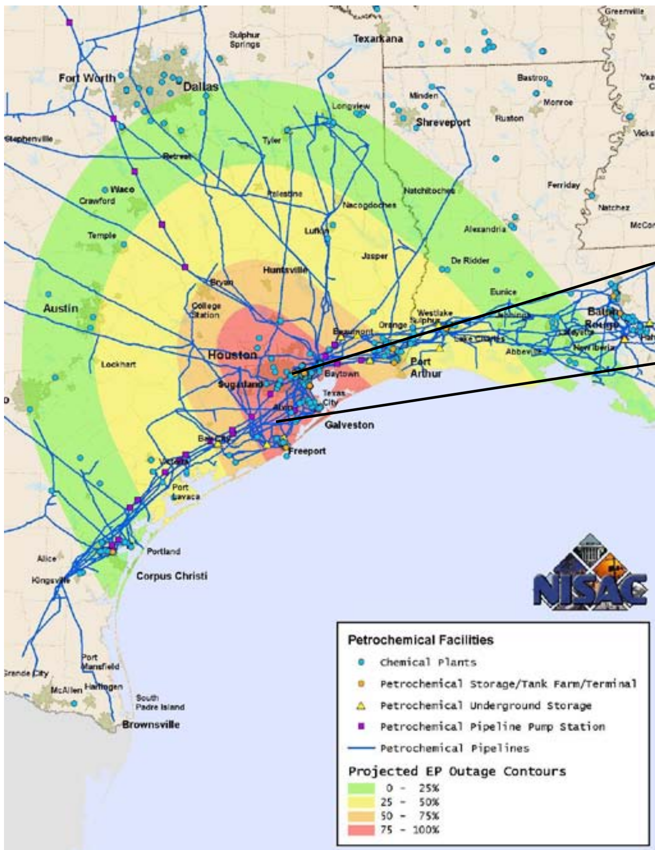
Networked ABM

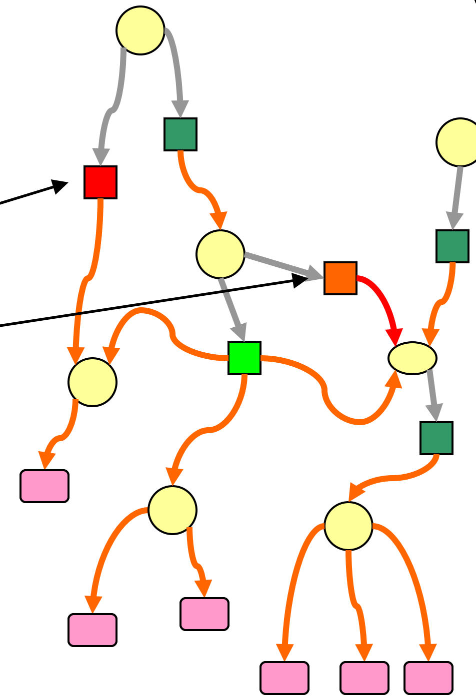


Global interdependencies

Application: Industrial Disruptions

Disrupted Facilities ⇒ ***Reduced Production Capacity***





Diminished Product Availability

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MEGACITIES

- Megacities are CASoS with many interdependent Systems… and CASoS Engineering can be applied
  - Design sub-systems
  - Design policy
- Networked Agent Conceptualization should be a powerful method
- Specific examples we have worked on could be adapted to Megacity Engineering

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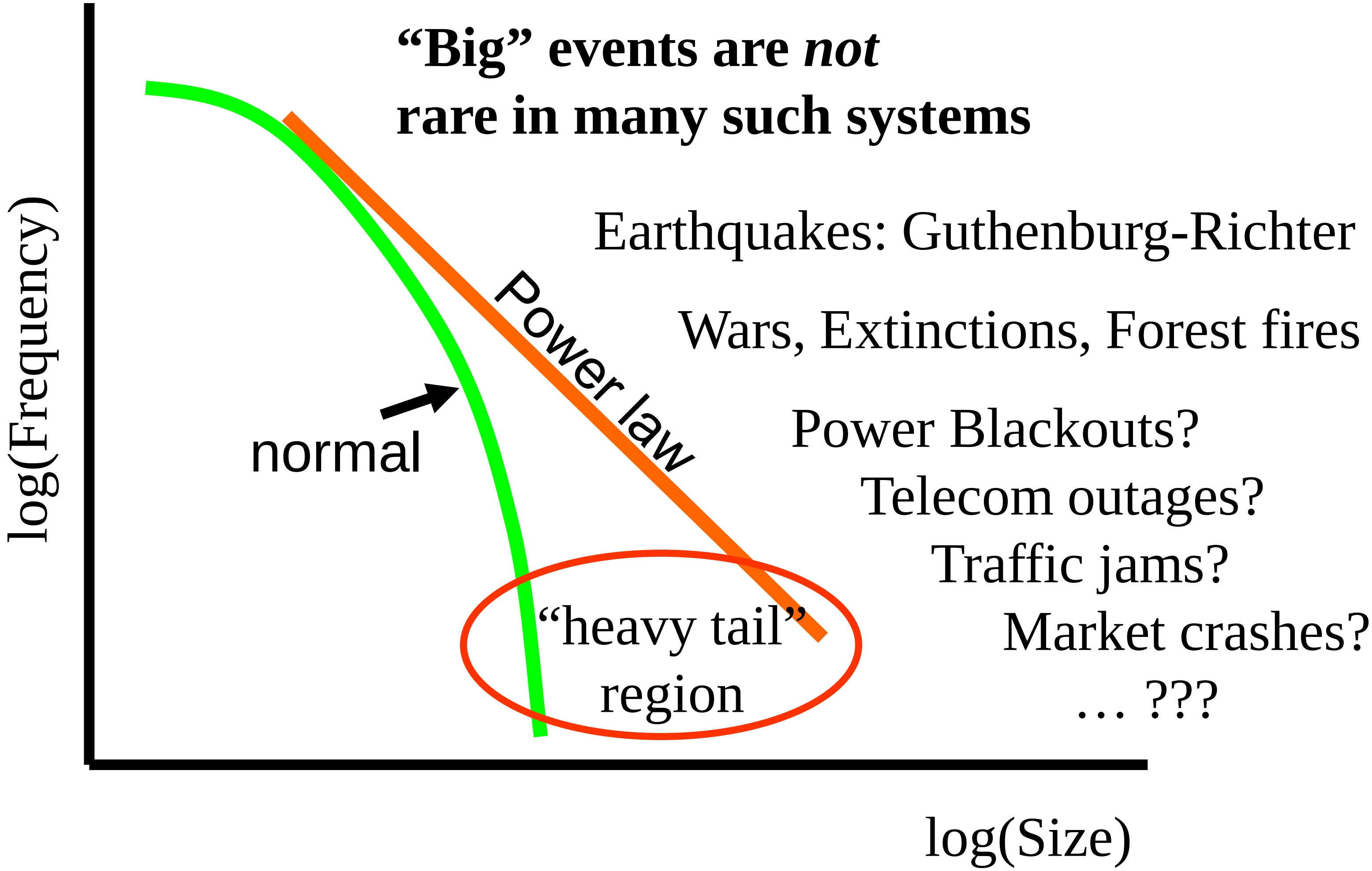
Two Thoughts for MEGACITIES

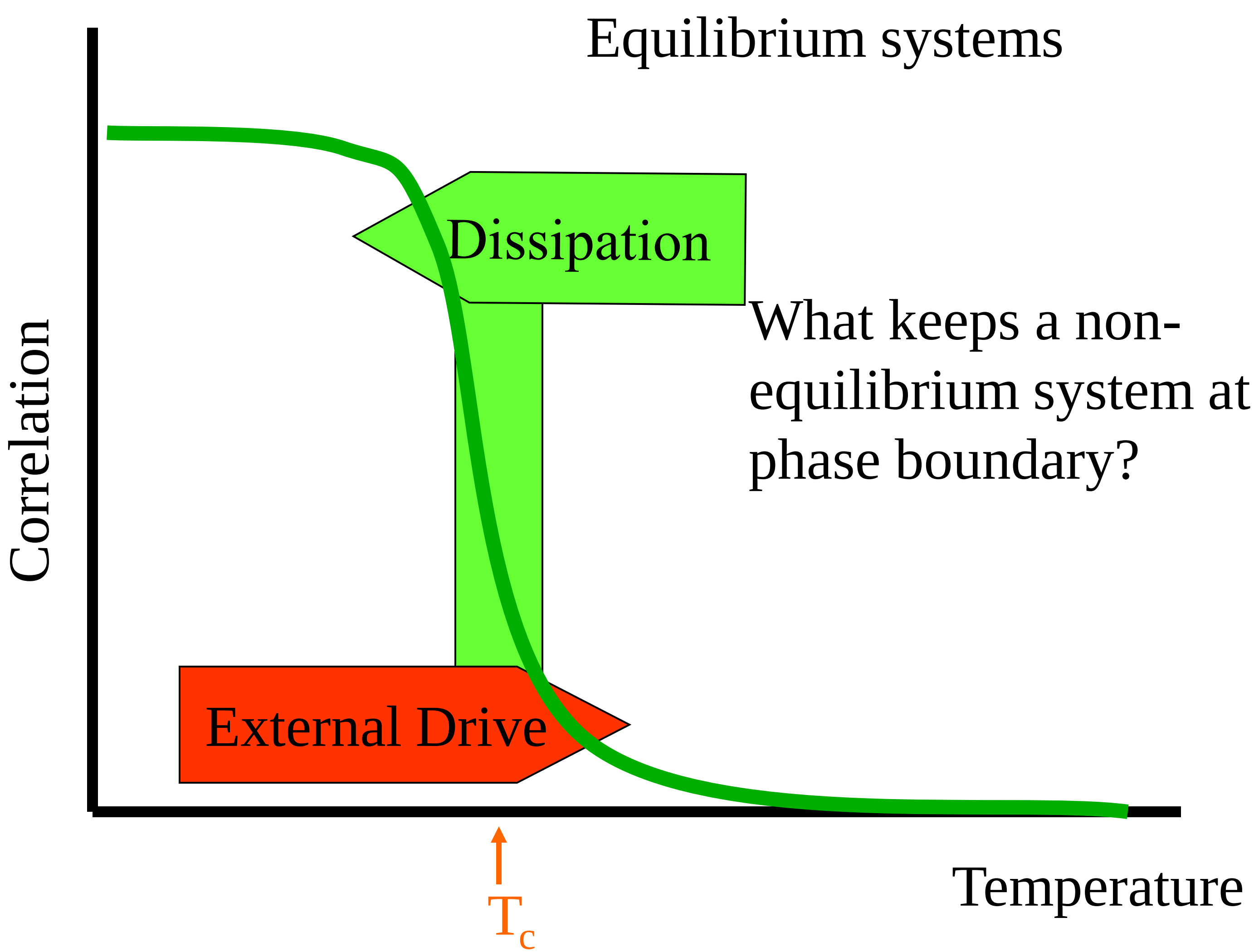
- Global view: Megacities as a set of entities that interact locally and within global context, set goals, develop niches, form alliances, etc… research towards understanding the global ecology of cities
- Local View: Evolving land, energy, and water use into the future as a function of policy using ABMs, example: John Bolte's work that considered Alternative Futures for the Willamette River Basin (Oregon State)

Complexity Primer Slides

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



Power Law - Critical behavior - Phase transitions



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

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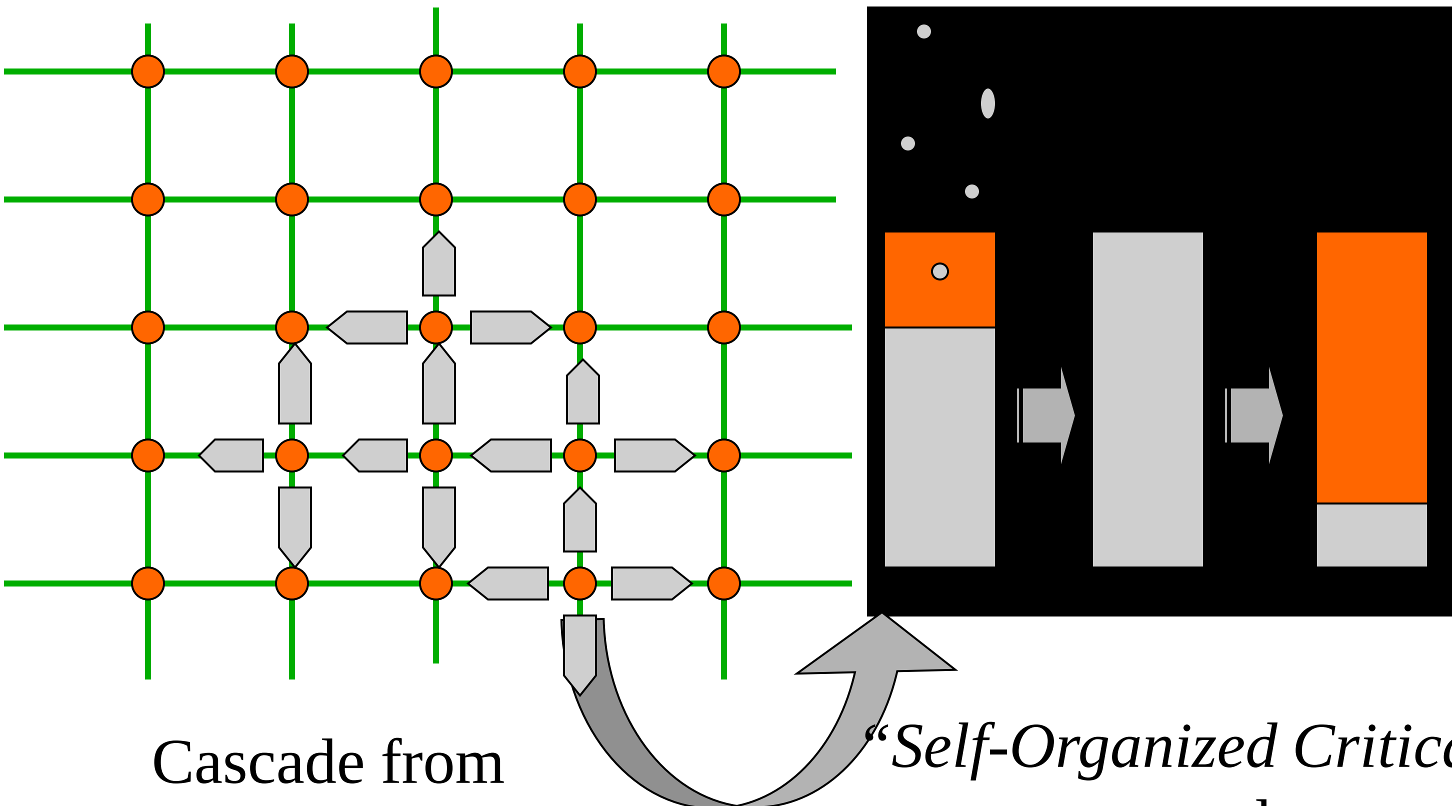
1987 Bak, Tang, Wiesenfeld's "Sand-pile" or "Cascade" Model

Lattice Drive Relaxation



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

Molecular Interaction

New York state's Power Grid

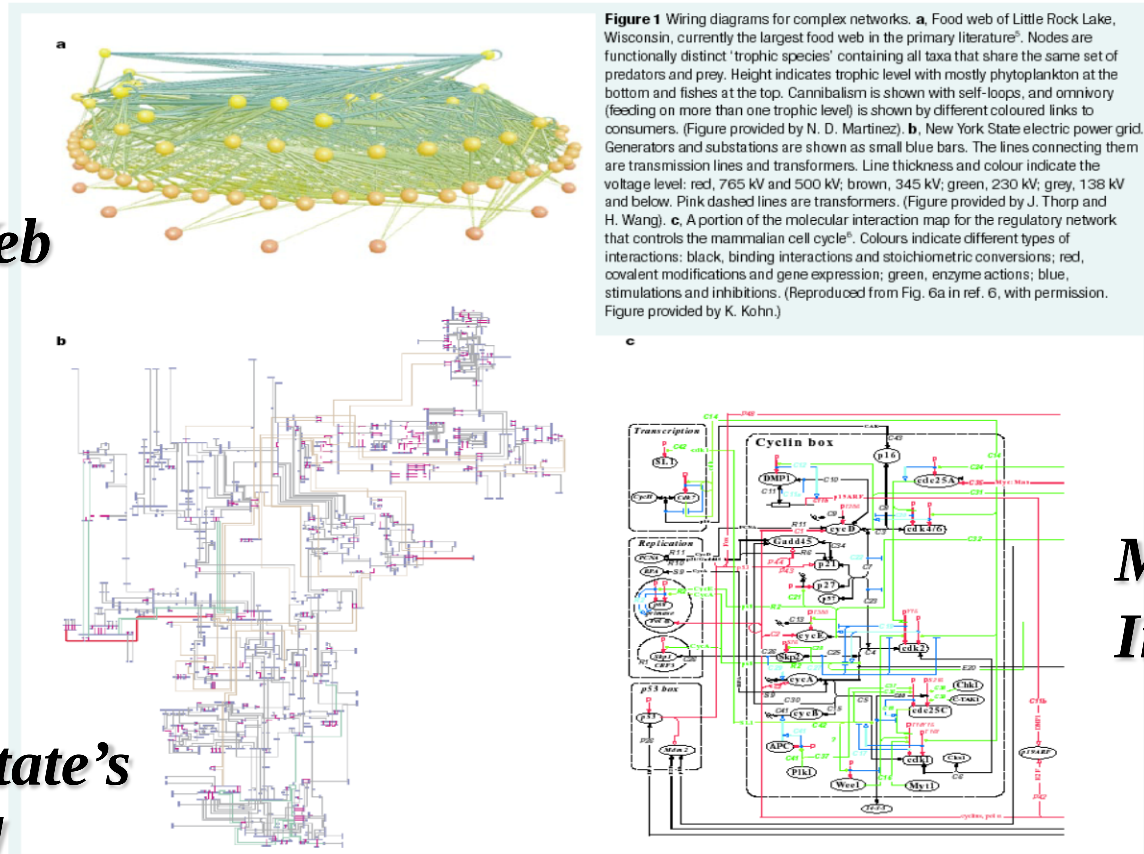
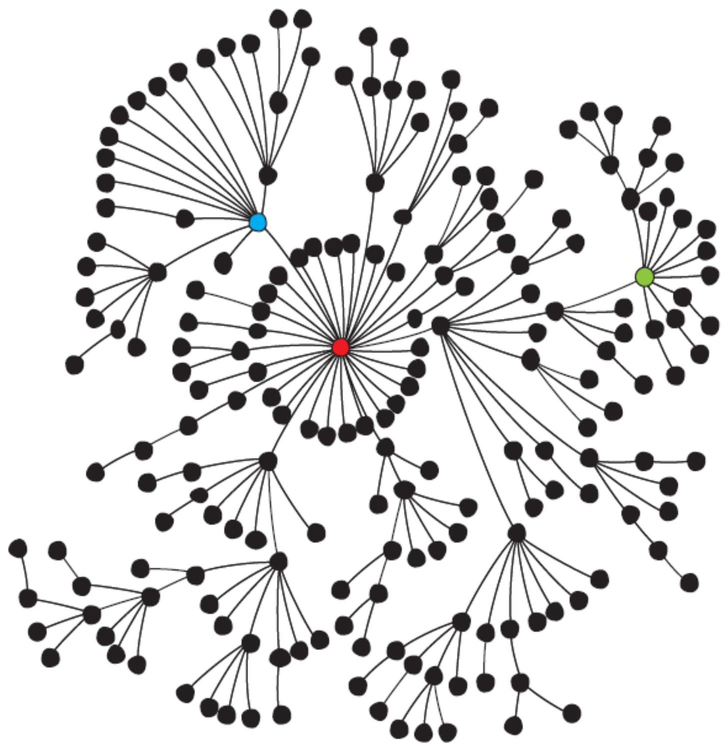


Figure 1 Wiring diagrams for complex networks. **a**, Food web of Little Rock Lake, Wisconsin, currently the largest food web in the primary literature[5]. Nodes are functionally distinct 'trophic species' containing all taxa that share the same set of predators and prey. Height indicates trophic level 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.)

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