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Modeling Critical Infrastructures with Networked Agent-based Approaches

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Sandia National Laboratories

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Resolving Infrastructure Issues Today

Each Critical Infrastructure Insures Its Own Integrity

Oil & Gas

Communica-tions

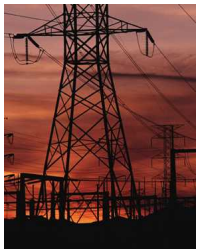
Water

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

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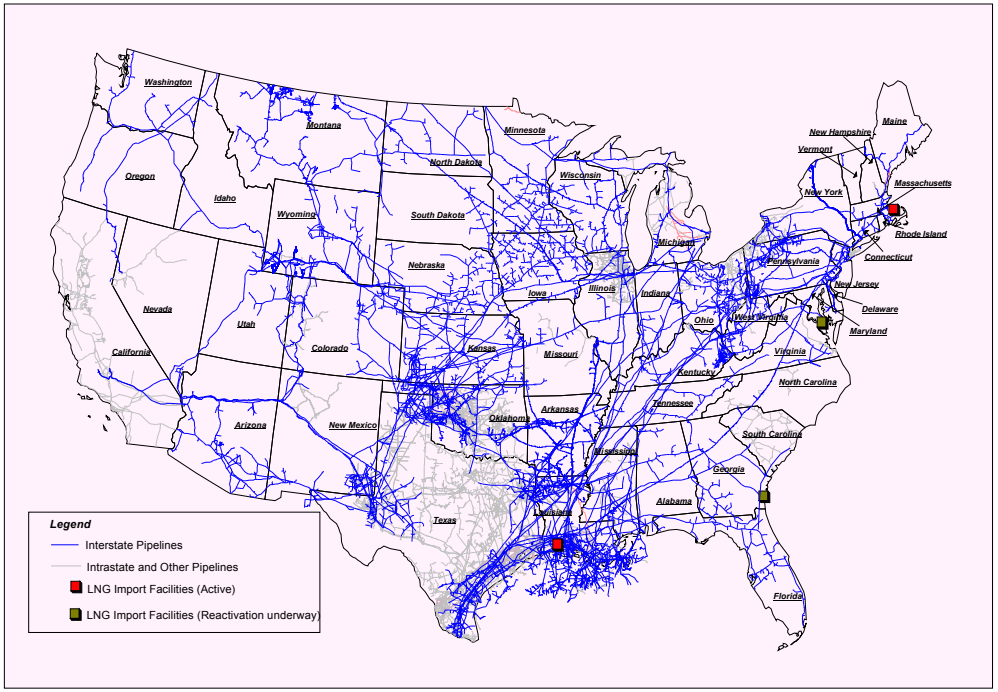
A Challenging if not Daunting Task

- 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

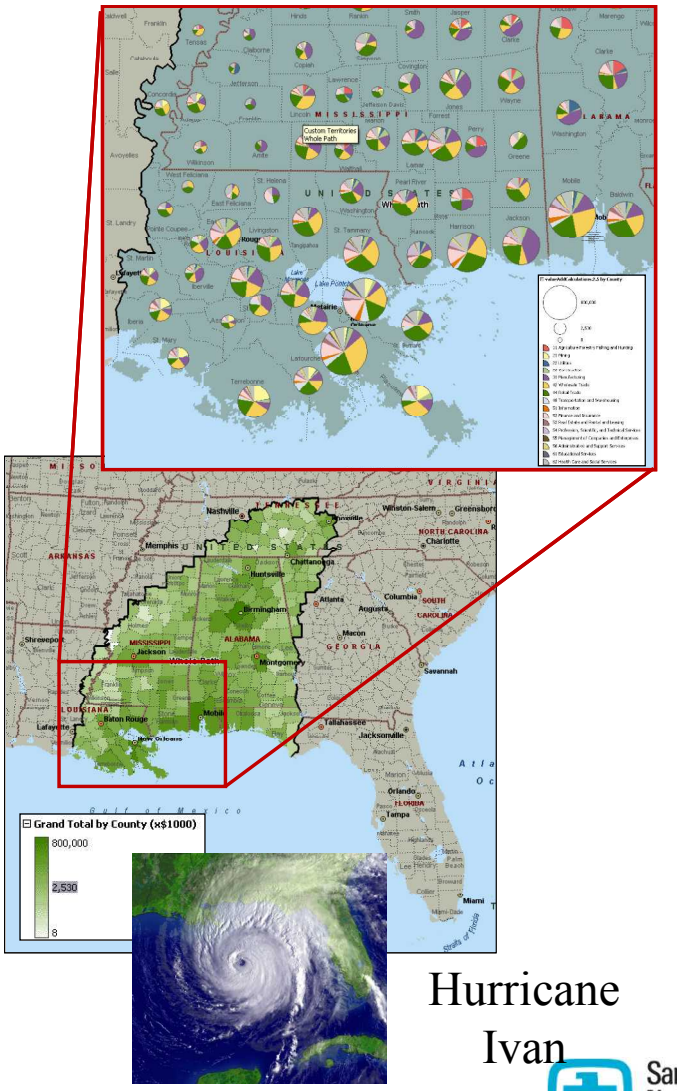
Example Natural Disaster Analysis: Hurricanes

Analyses:

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

Working towards:

- **Robust Mitigation measures**
- **Evolving Resilience**



Hurricane Ivan

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***

Critical infrastructures are Complex Adaptive Systems

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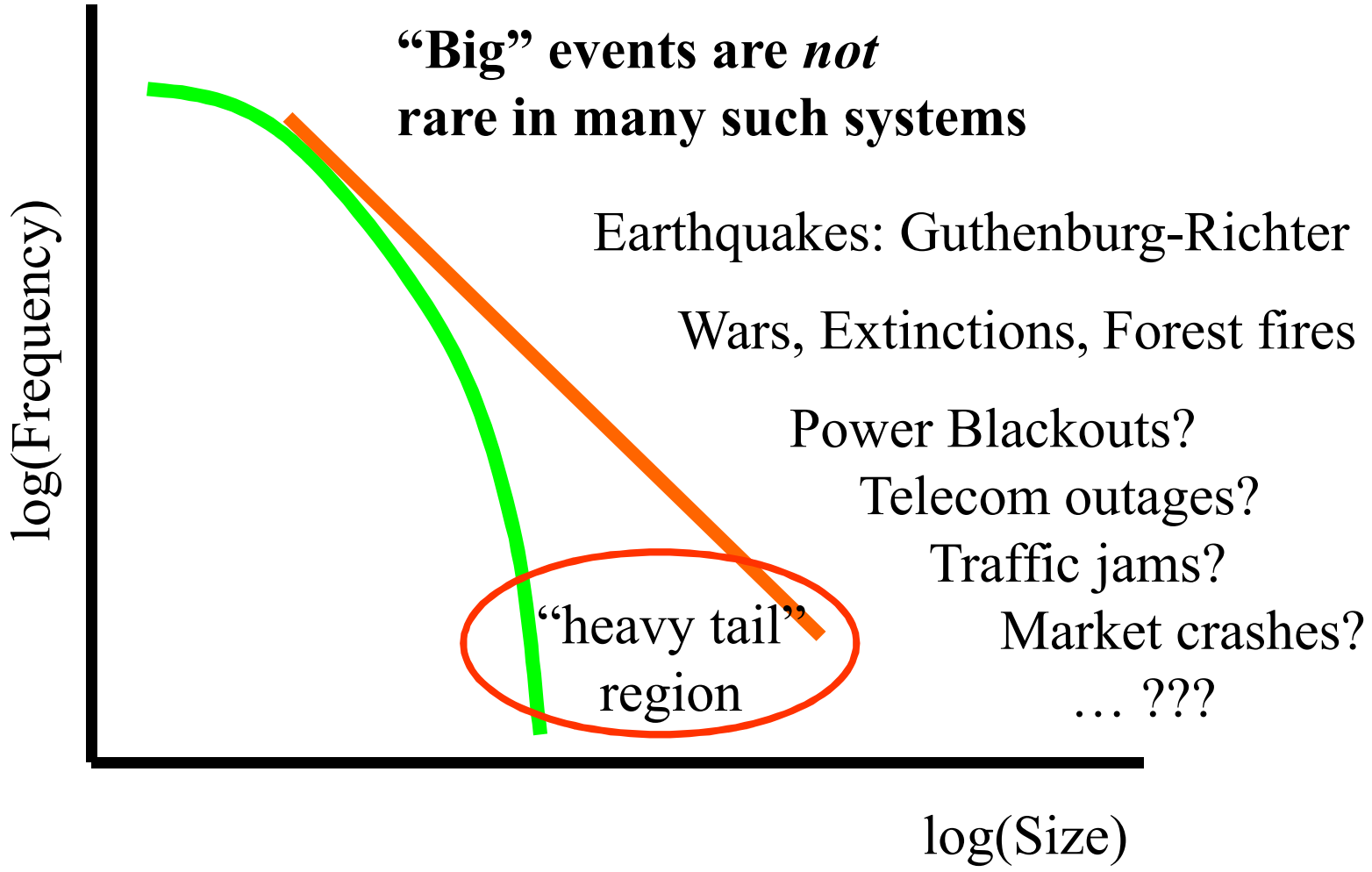
First Stylized Fact: Multi-component Systems often have power-laws & "heavy tails"



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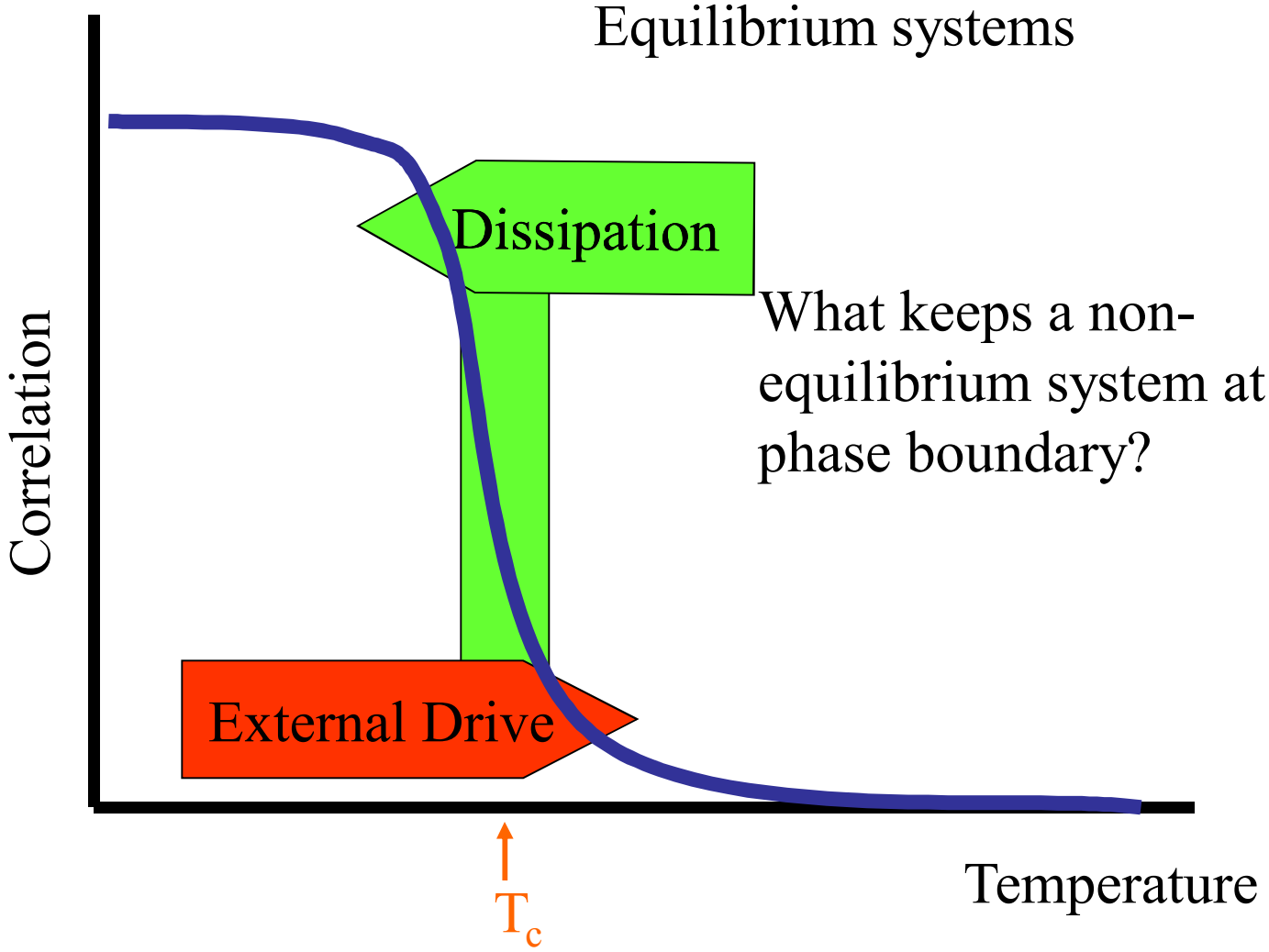
Power Law - Critical behavior - Phase transitions



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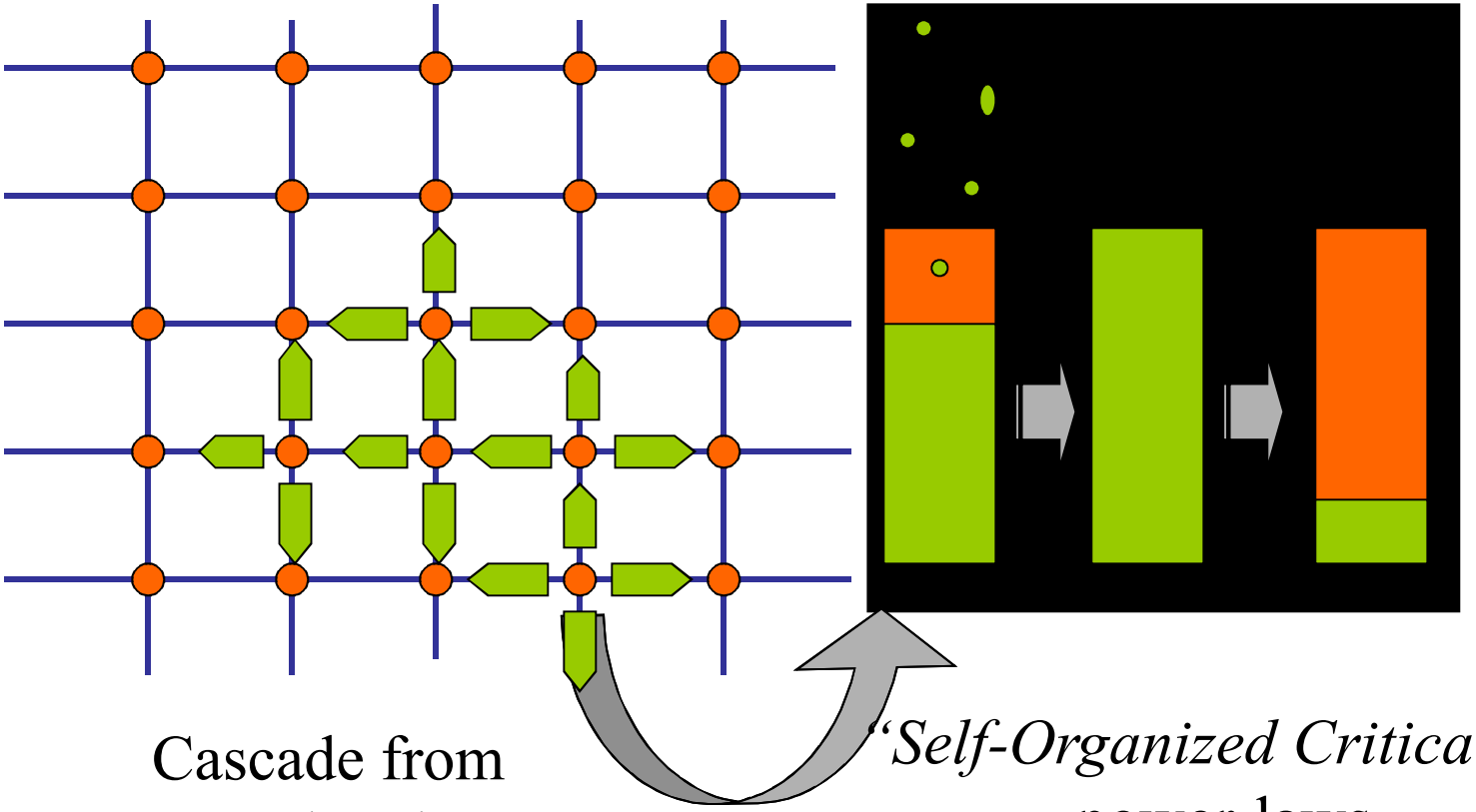
1987 Bak, Tang, Wiesenfeld's "Sand-pile" or "Cascade" Model

Lattice

Drive

Relaxation



Cascade from
Local Rules

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

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Second Stylized Fact: Networks are Ubiquitous in Nature and Infrastructure

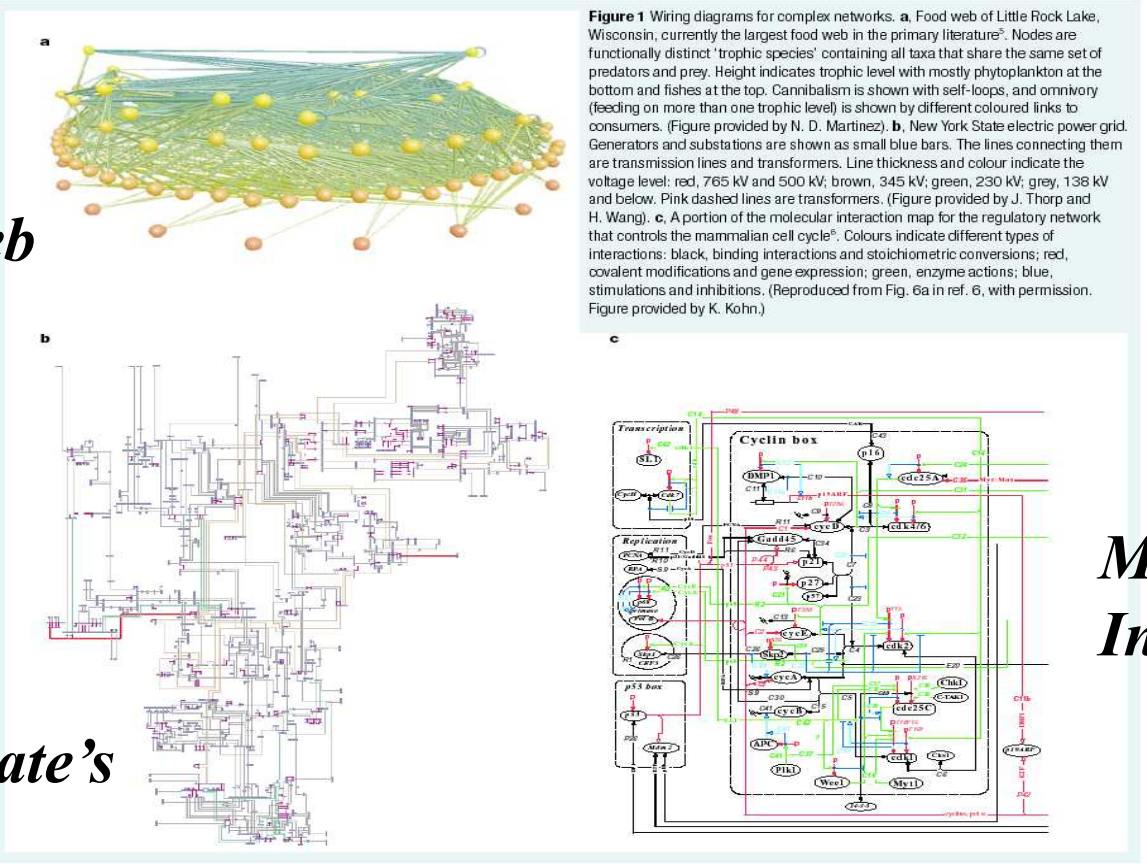

Figure 1 Wiring diagrams for complex networks. **a**, Food web of Little Rock Lake, Wisconsin, currently the largest food web in the primary literature[5]. Nodes are functionally distinct 'trophic species' containing all taxa that share the same set of predators and prey. Height indicates trophic level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

Food Web

Molecular Interaction

New York state's Power Grid

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

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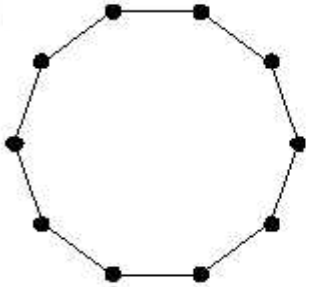
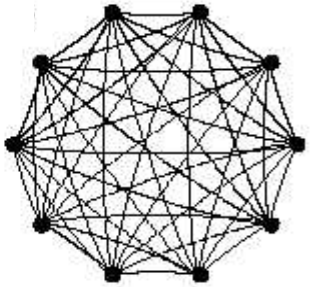
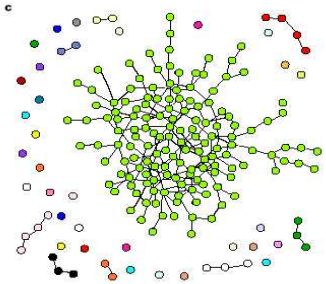
Idealized Network Topology

Regular

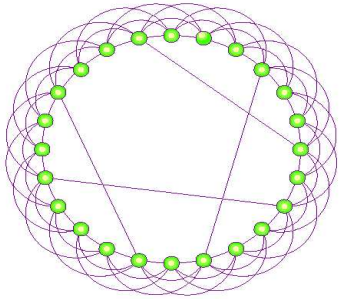




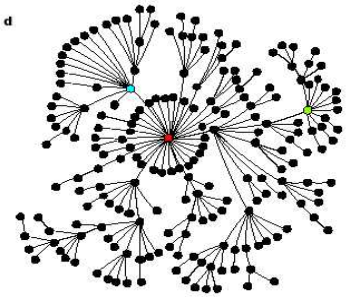
Fully connected



Random
"small world"



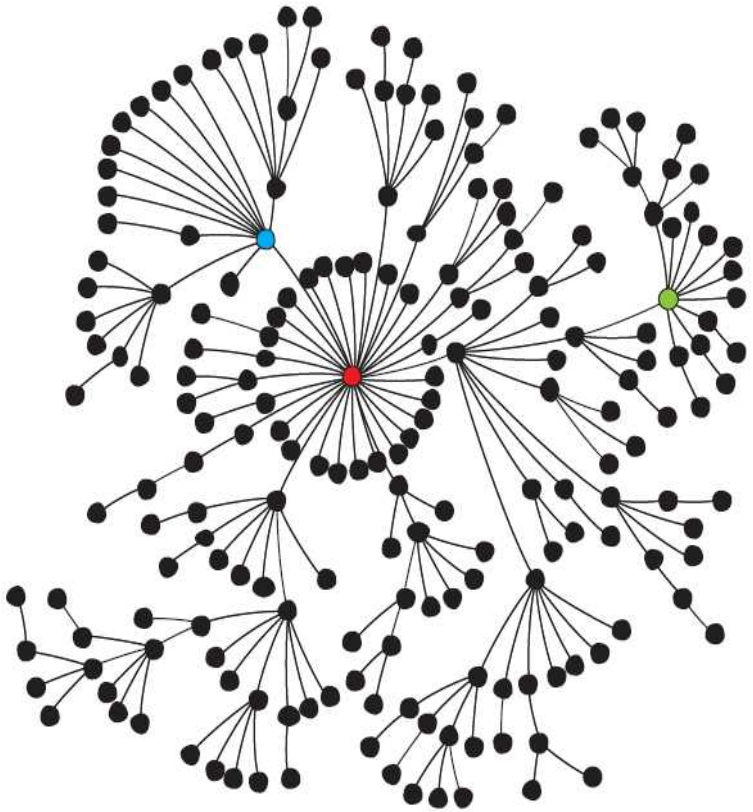
"Blended"
"clustering"
+
"small world"



"Scale-free"
Degree Distribution Heavy-tailed

Illustrations 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

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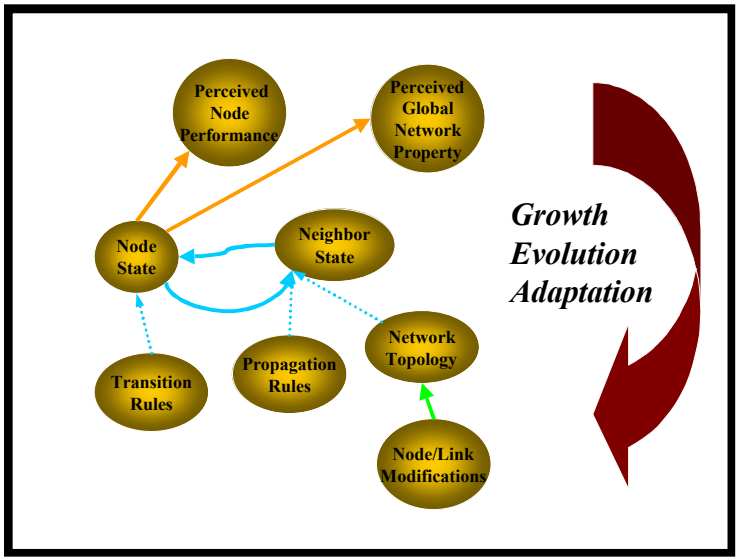
Generalized Approach: Networked Agent-based Modeling

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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Towards a Complexity Science Basis for Infrastructure Modeling and Analysis

Systematically consider:

- Local rules for nodes and links (vary physics)
- Networks (vary topology)
- Robustness to perturbations
- Robustness of control measures (mitigation strategies)
- Feedback, learning, growth, adaptation
- Evolution of resilience
- Extend to multiple networks with interdependency

Study the behavior of models to develop a theory of infrastructures

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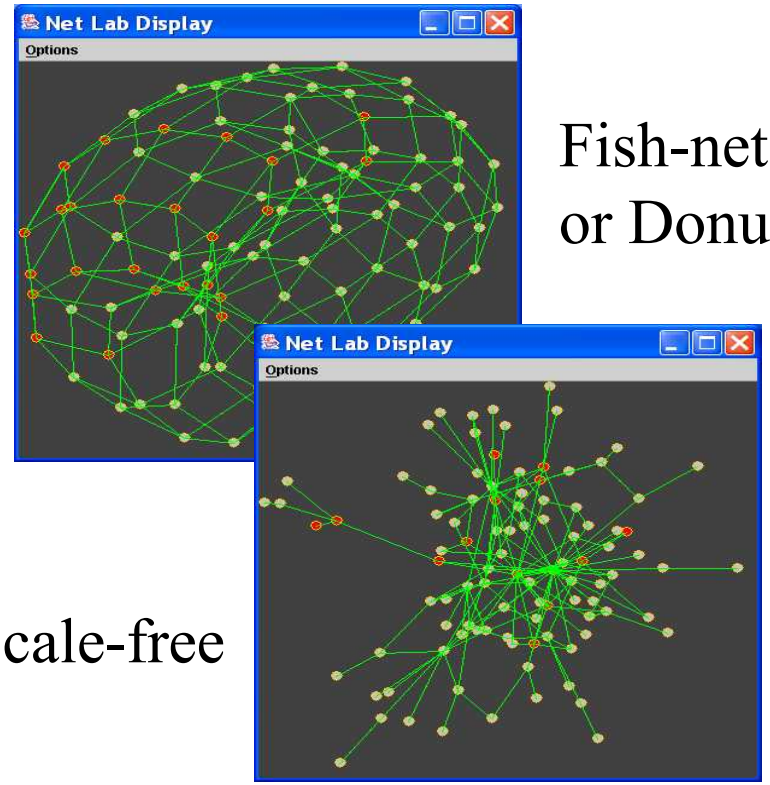
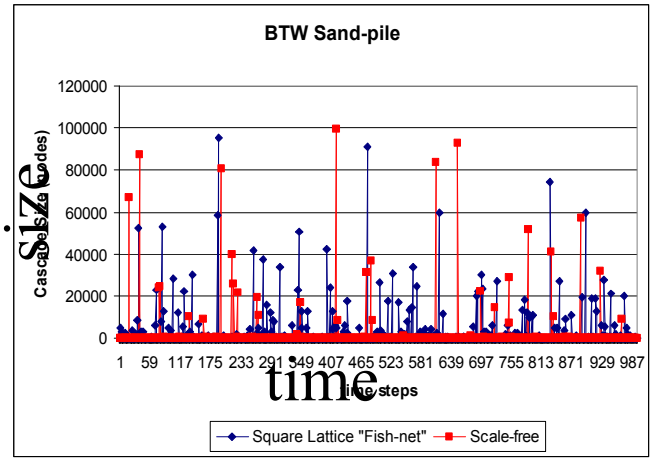
Initial Study: BTW sand-pile on varied topology



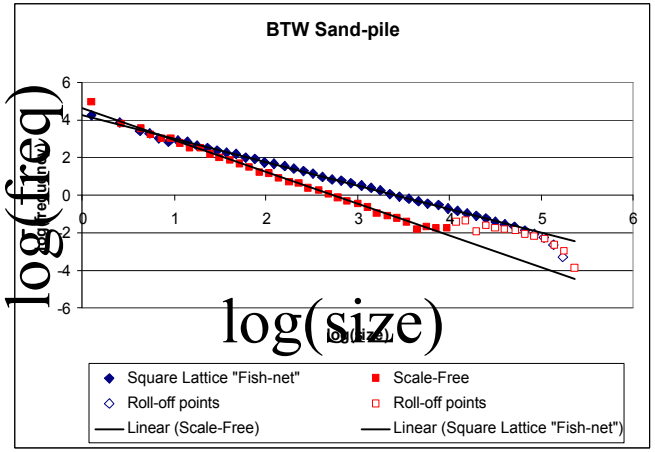
Fish-net
or Donut

Scale-free



size

time



log(freq)

log(size)

Random sinks
Sand-pile rules and drive
10,000 nodes

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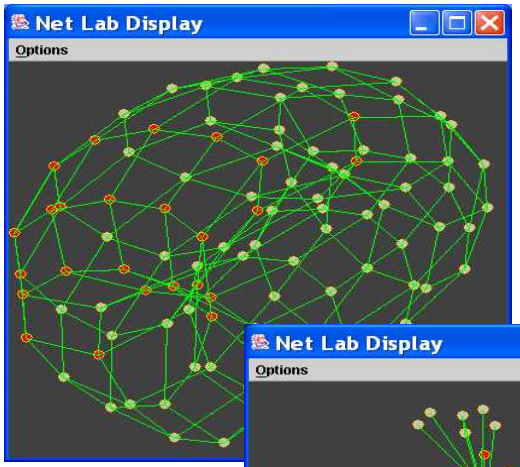
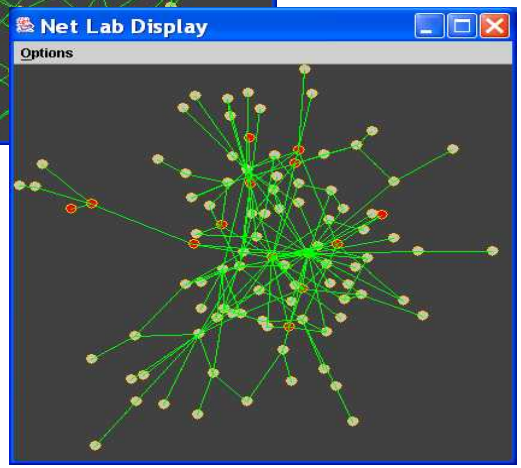
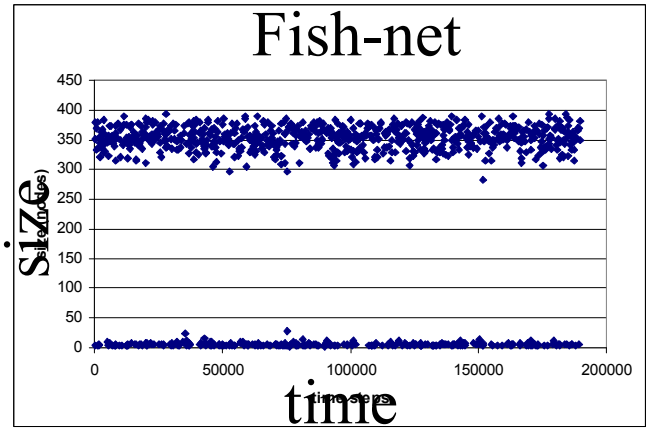
Initial Study: Abstract Power Grid Blackouts

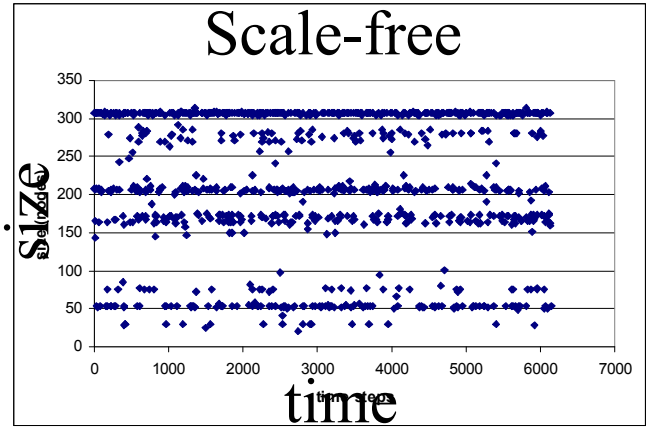


Fish-net
or Donut



Scale-free





Sources, sinks, relay stations, 400 nodes

DC circuit analogy, load, safety factors

Random transactions between sources and sinks

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August 2003 Blackout…

Albert et al., Phys Rev E, 2004, Vulnerability of the NA Power Grid

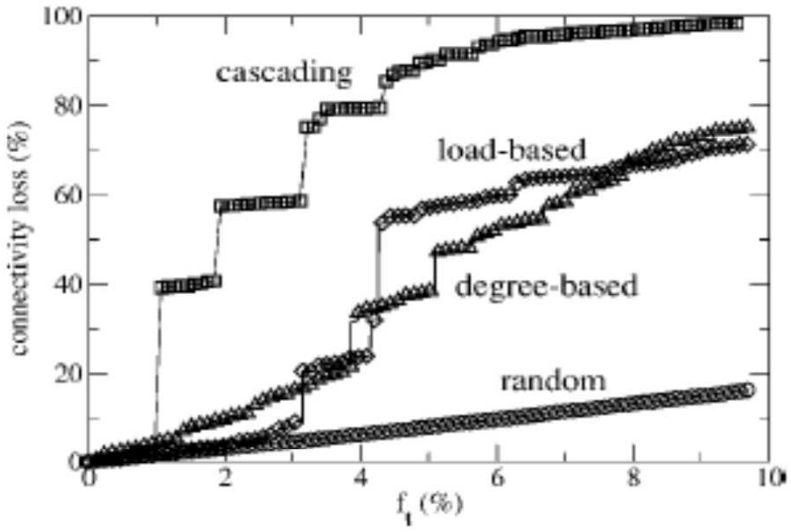
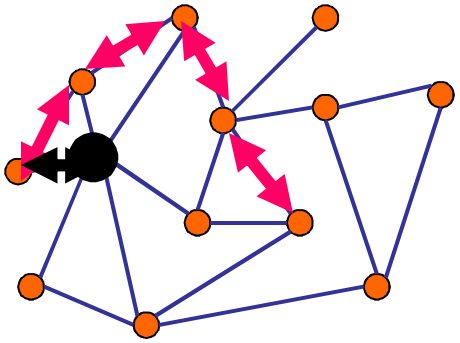
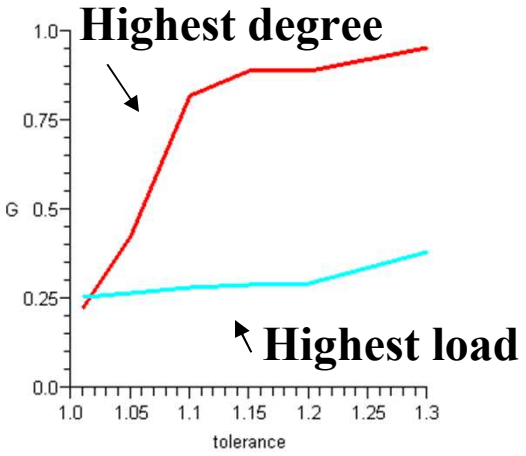


FIG. 4. Connectivity loss in the power grid due to the removal of nodes corresponding to transmission substations. We remove a fraction f_t of transmission nodes with four different algorithms: randomly (circles), in the decreasing order of their degrees (triangles) or loads (diamonds), and by recalculating the load every ten steps and removing the ten nodes with highest load (squares). The curves corresponding to random and degree-based node removal were averaged over ten runs. The load-based and cascading removal curves represent a single run.

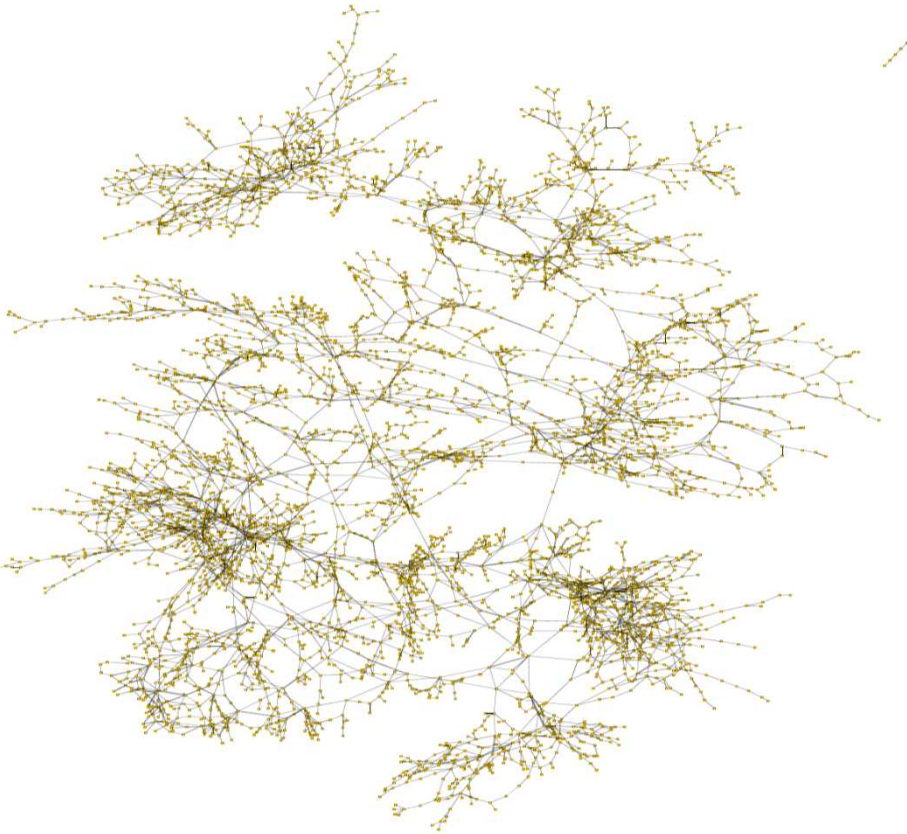
Initial Study: Congestive Failure of the WECC?



Betweeness + Tolerance



Western Power Grid (WECC) 69 kev lines and above



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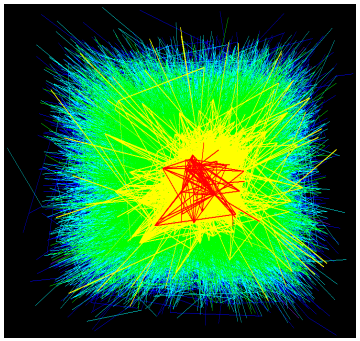
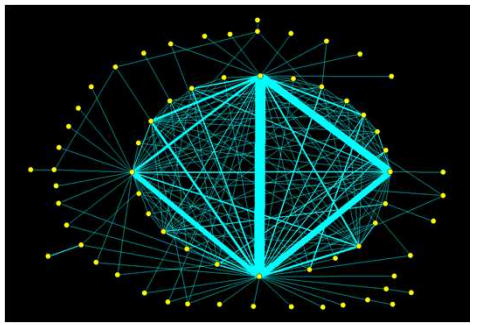
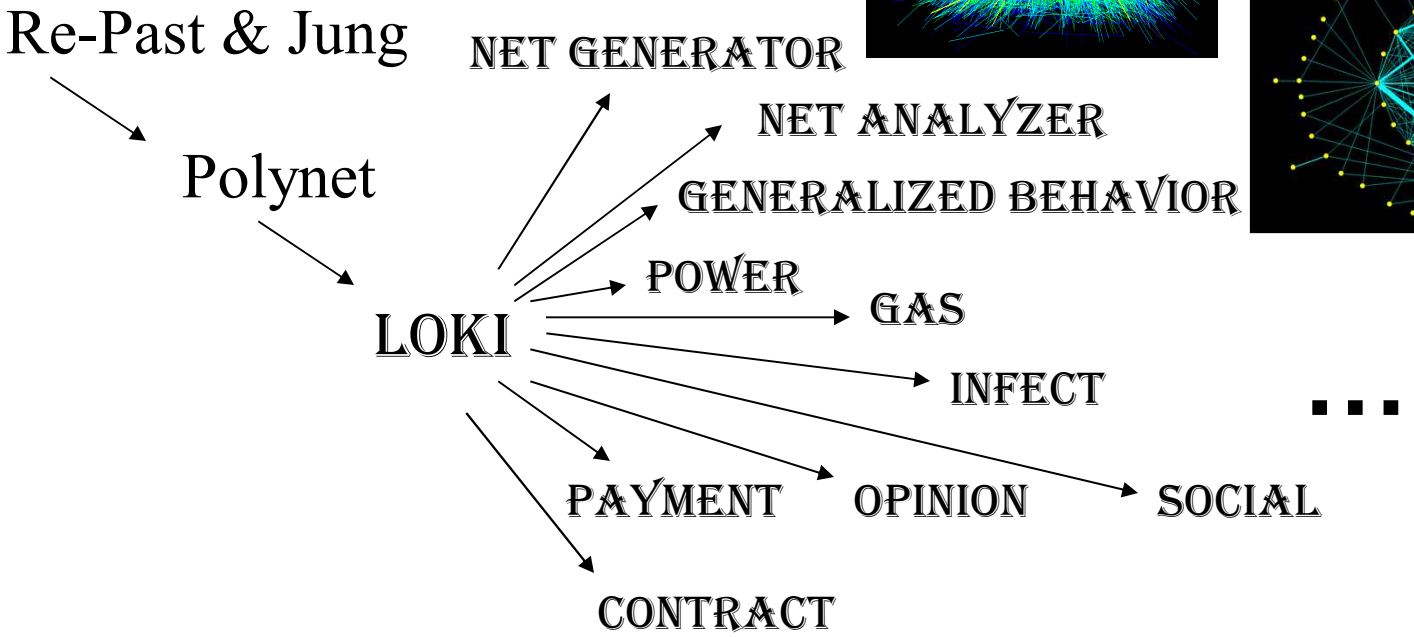
Loki Toolkit: Modeling and Analysis

Applications VERY Important







Modeling and analysis of multiple interdependent networks of agents,
e.g., Physical+SCADA+Market+Policy Forcing

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Example Application: Influenza Pandemic

Two 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.

No Vaccine

Limited Antiviral drugs

What should/could we do?

Chickens being burned in Hanoi

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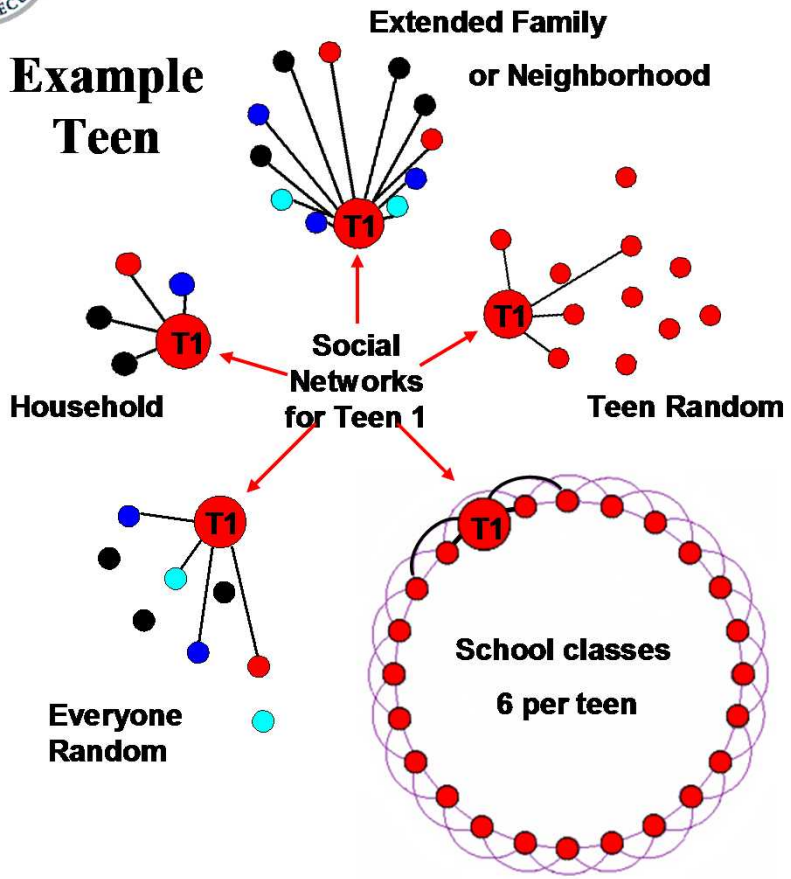
By Analogy with other Complex Systems

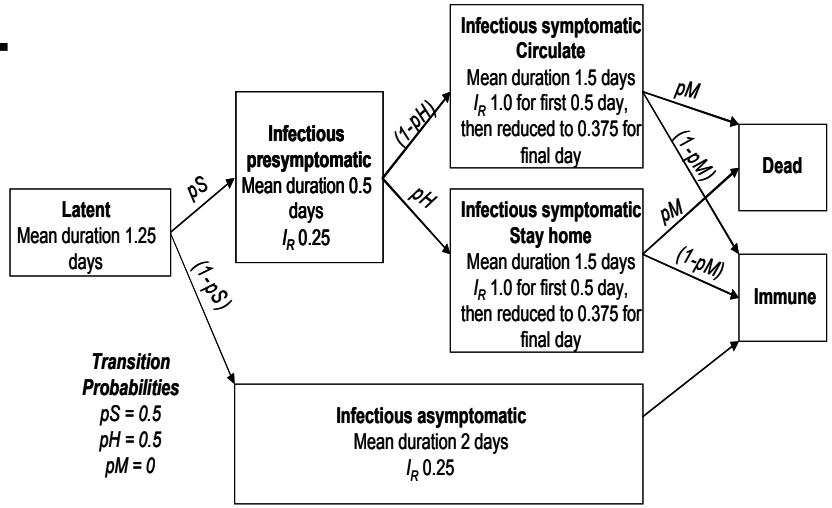
- **Forest fire**: You can *build fire breaks* based on where people throw cigarettes… or you can *thin the forest* so no that matter where a cigarette is thrown, a percolating fire (like an epidemic) will not burn.
- **Power grid blackout**: it's a cascade. But it runs on the interactions among people, 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?

Influenza Model



Disease manifestation (infectiousness and behavior a function of disease state)

+



Stylized Social Network
(nodes, links, frequency of interaction)
Based on expert elicitation and fits “common knowledge”

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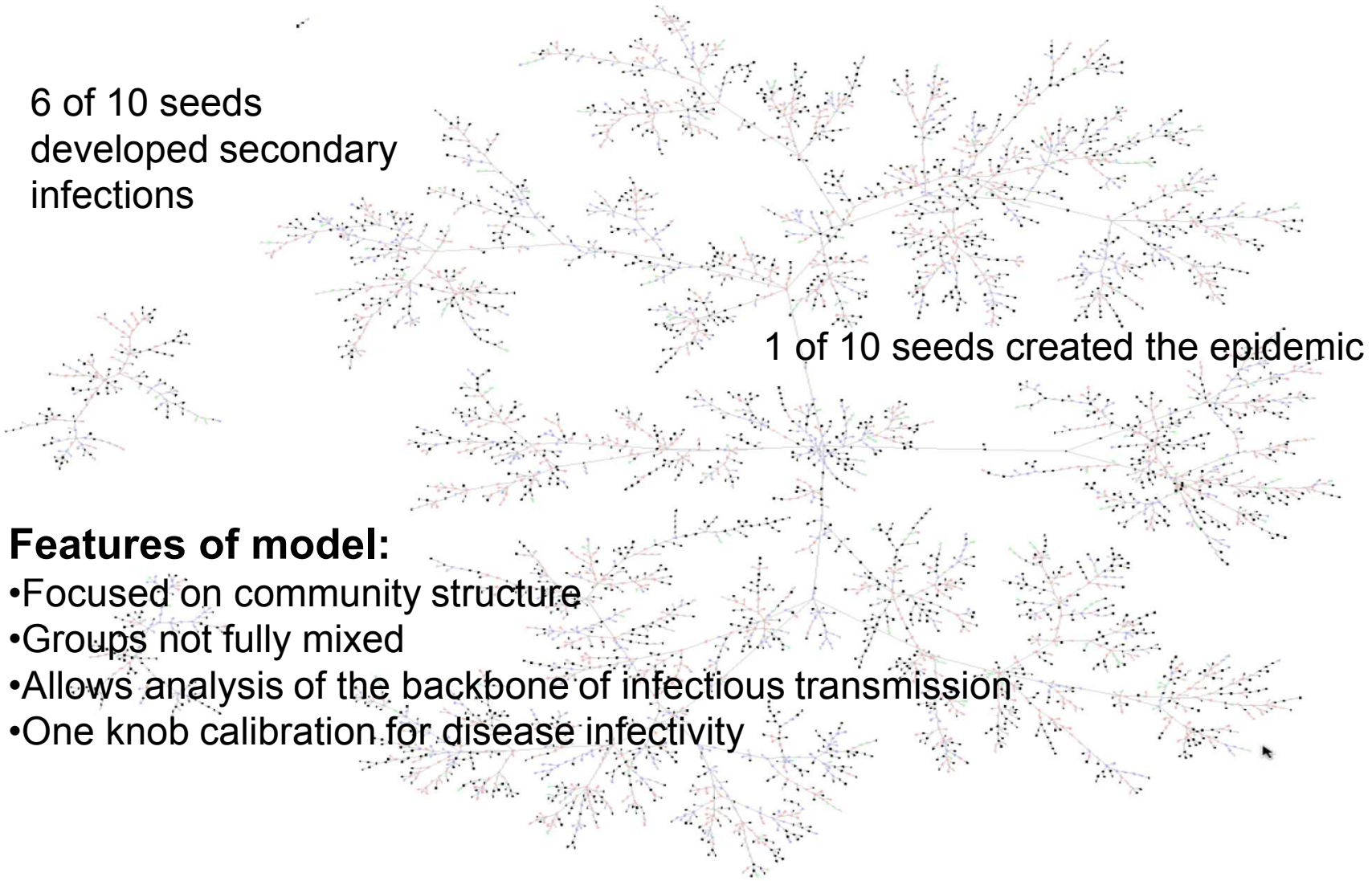
Simulation

6 of 10 seeds developed secondary infections

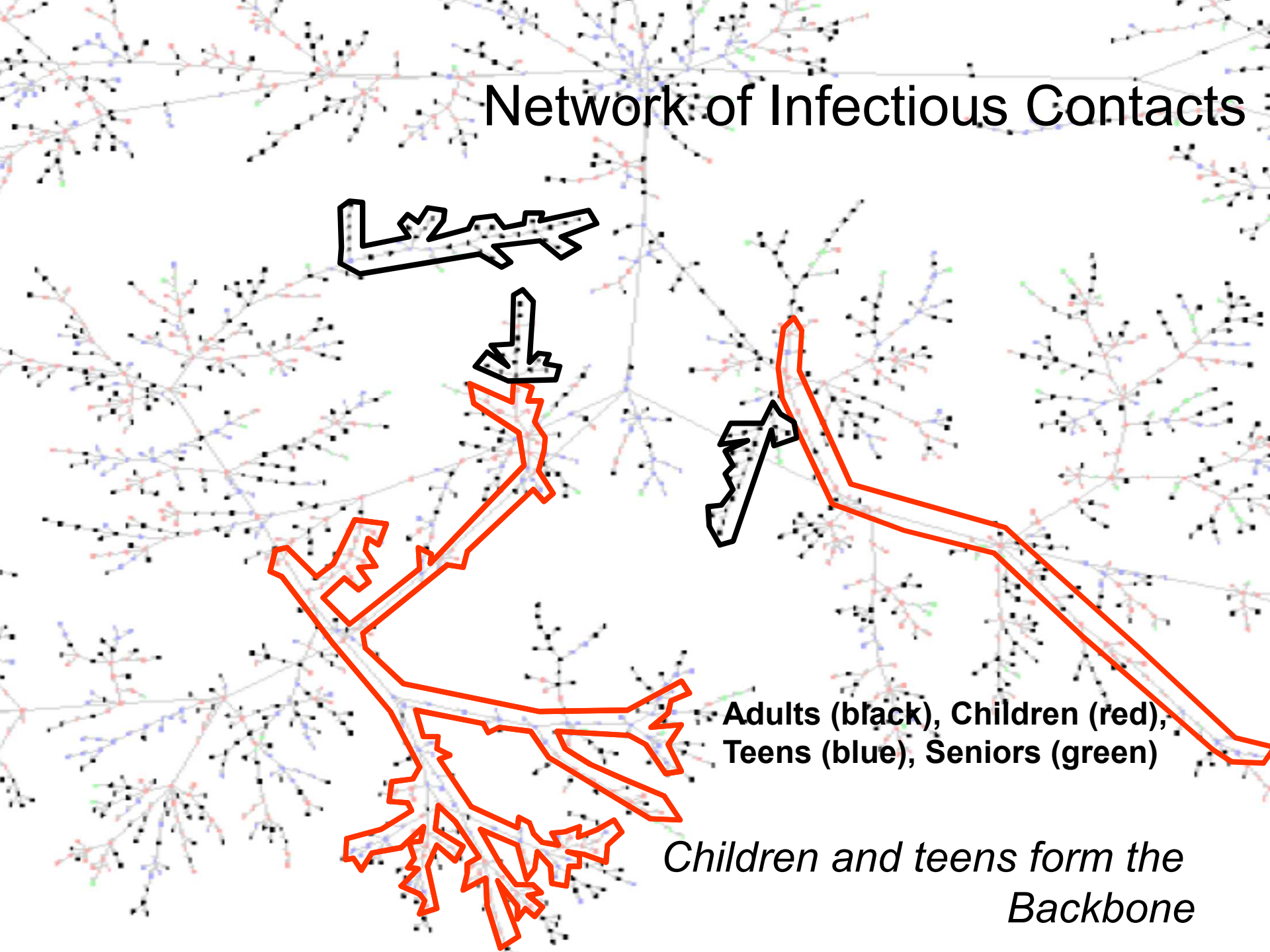


1 of 10 seeds created the epidemic

Features of model:

- Focused on community structure
- Groups not fully mixed
- Allows analysis of the backbone of infectious transmission
- One knob calibration for disease infectivity

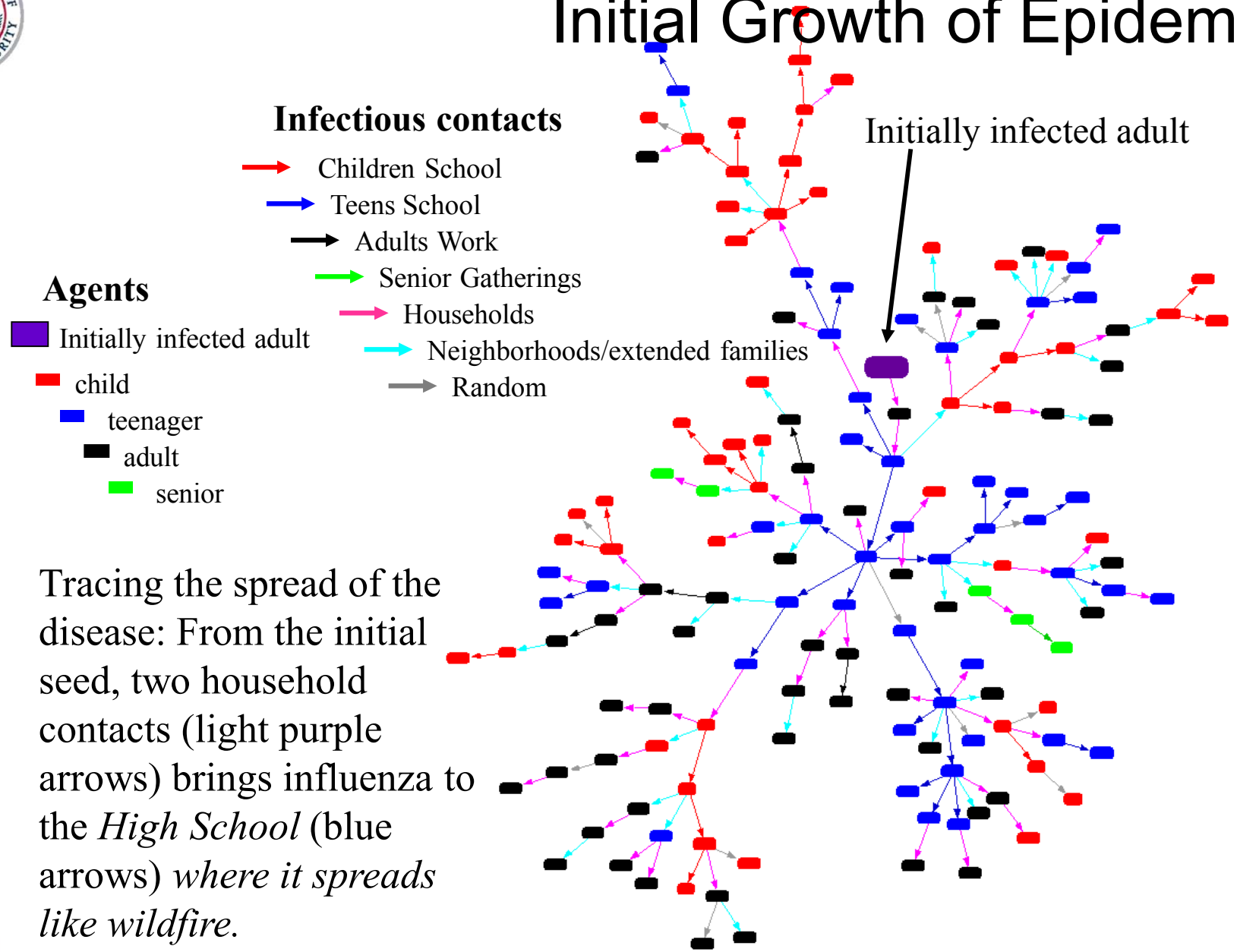
Network of Infectious Contacts



Adults (black), Children (red), Teens (blue), Seniors (green)

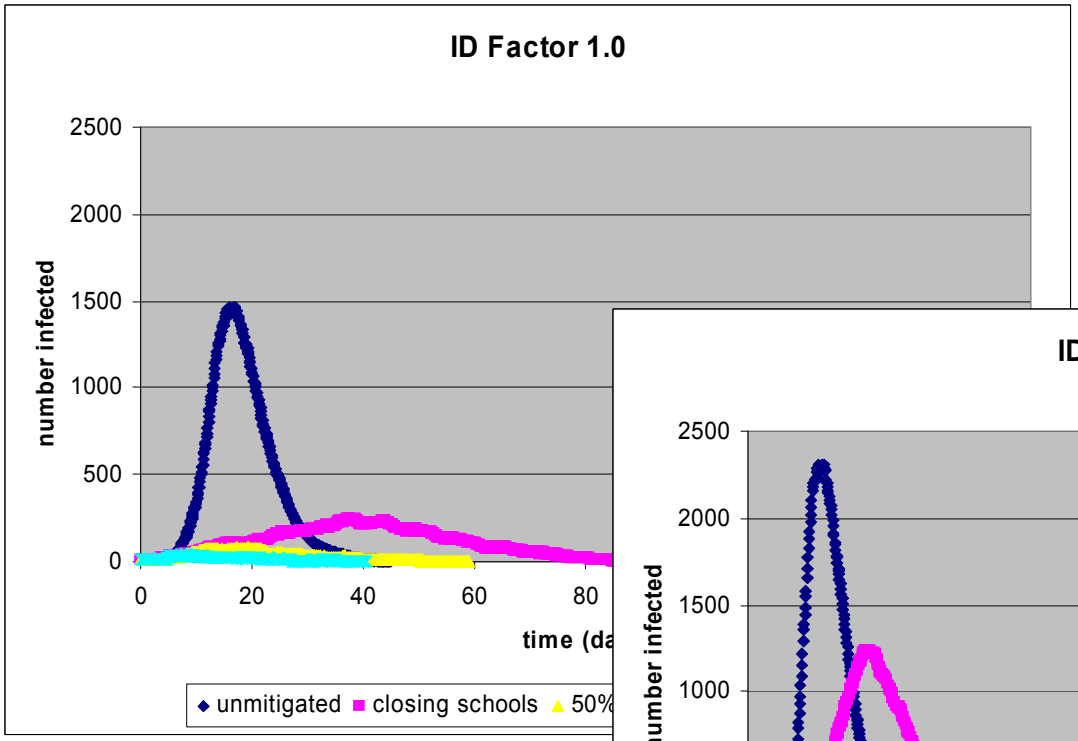
Children and teens form the Backbone

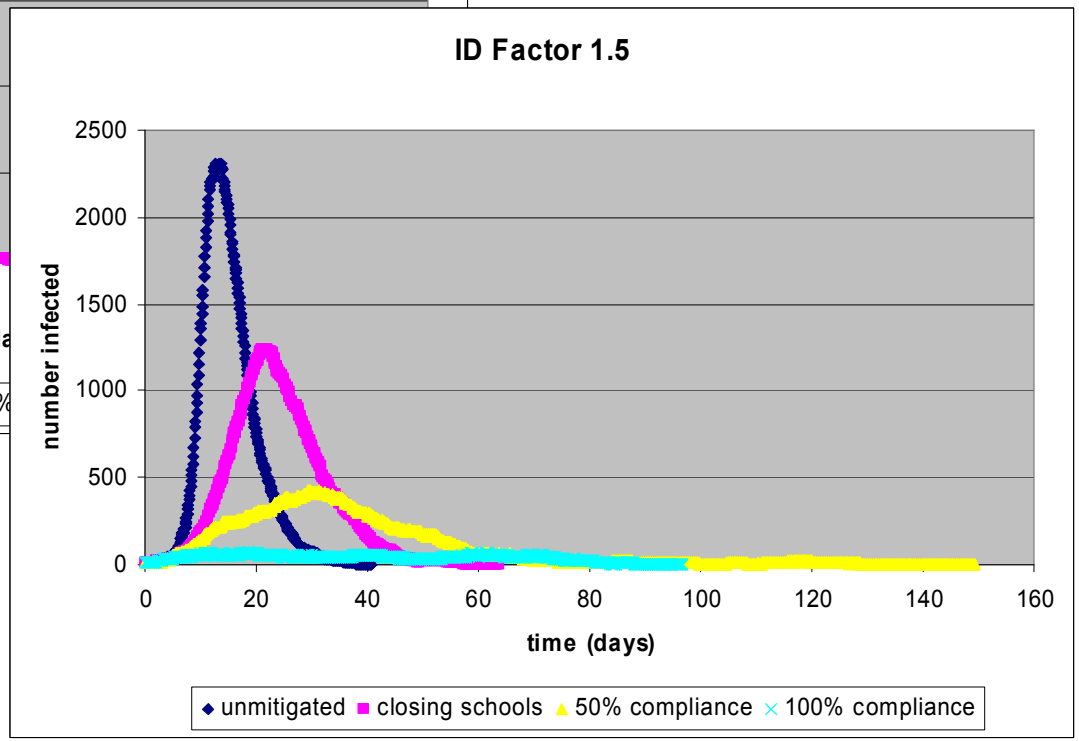
Initial Growth of Epidemic



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

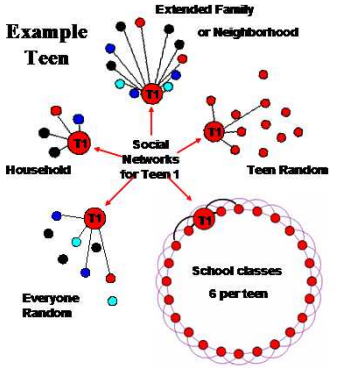
- How sensitive were results to the social net? Disease manifestation?
- How sensitive to compliance? Implementation threshold? Disease infectivity?
- How did the model results compare to past epidemics and results from the models of others?
- Is there any evidence from past pandemics that these strategies worked?
- What about adding or “layering” additional strategies including home quarantine, antiviral treatment and prophylaxis, and pre-pandemic vaccine?

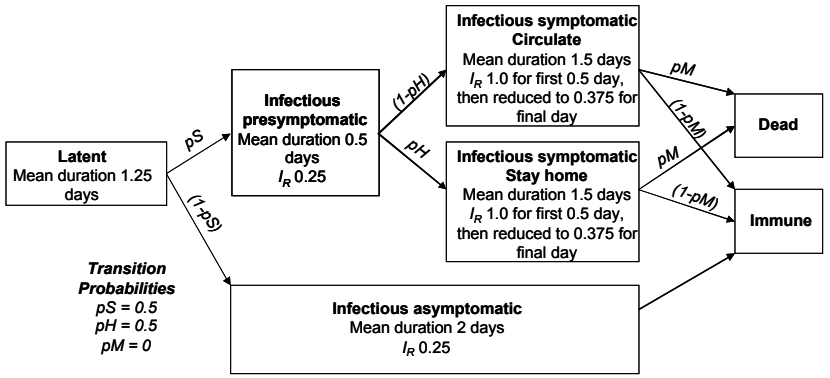
We extended the model and put it on Tbird… 10’s of millions of runs later we had the answers to:

- 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***)

Effective, Robust Design of Community Containment for Pandemic Influenza

- **Explicit social contact network:**
  - Stylized US community of 10000 (Census, 2000)
  - Agents: Child18%, Teen11%, Adult 59%, Senior 12%
  - Groups with explicit sub networks: Households, school classes, businesses, neighborhoods/extended families, clubs, senior gatherings, random
  - Household adult stays home to tend sick or sent home from school children in the family
- **Influenza disease manifestation:**
  - scaled normal flu, (Ferguson-like, ~viral shedding)
  - *pSymptomatic* = 0.5, *pHome* = *pDiagnosis* = 0.8
  - Children 1.5 and Teens 1.25 times more infectious & susceptible than adults & seniors
  - Added 7 day recovery period for symptomatic (ill)





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.

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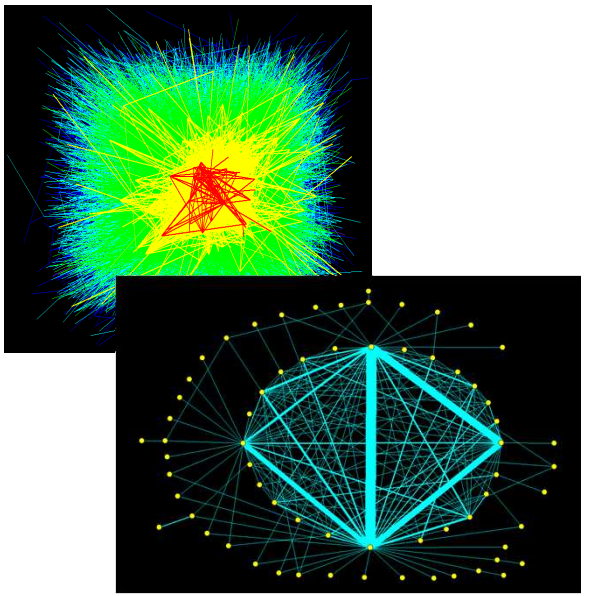
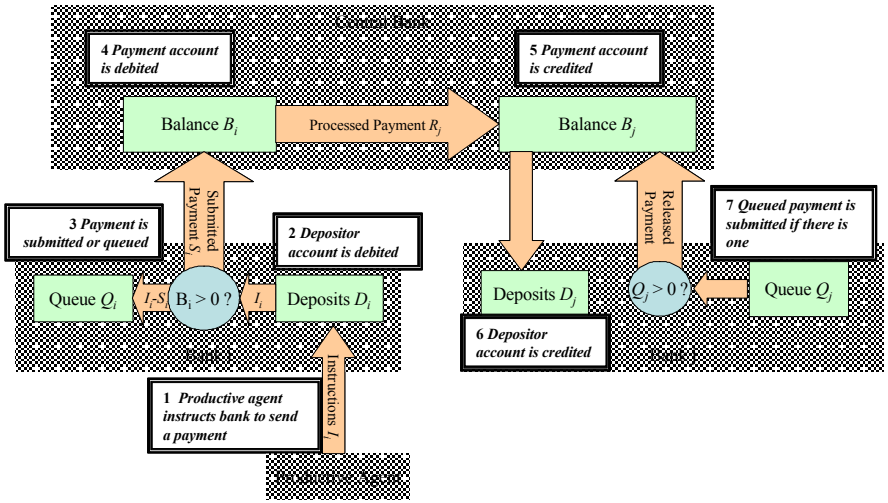
Application: Congestion and Cascades in Payment Systems

- **Network defined by Fedwire transaction data:**
  - Payments among more than 6500 large commercial banks
  - Typical daily traffic: more than 350,000 payments totaling more than $1 trillion
  - Node degree and numbers of payments follow power-lay distributions
- **Bank behavior controlled by system liquidity:**
  - Payments activity is funded by initial account balances, incoming payments, and market transactions
  - Payments are queued pending funding
  - Queued payments are submitted promptly when funding becomes available





For Details see:

The Topology of Interbank Payment Flows, Kimmo Soramäki, Morten L. Bech, Jeffrey Arnold, Robert J. Glass and Walter E. Beyeler, *PhysicaA,* 1 June 2007; vol.379, no.1, p.317-33.

***Congestion and Cascades in Payment Systems*,** Walter E. Beyeler, Robert J. Glass, Morten Bech, Kimmo Soramäki, *PhysicaA,* 15 Oct. 2007; v.384, no.2, p.693-718.

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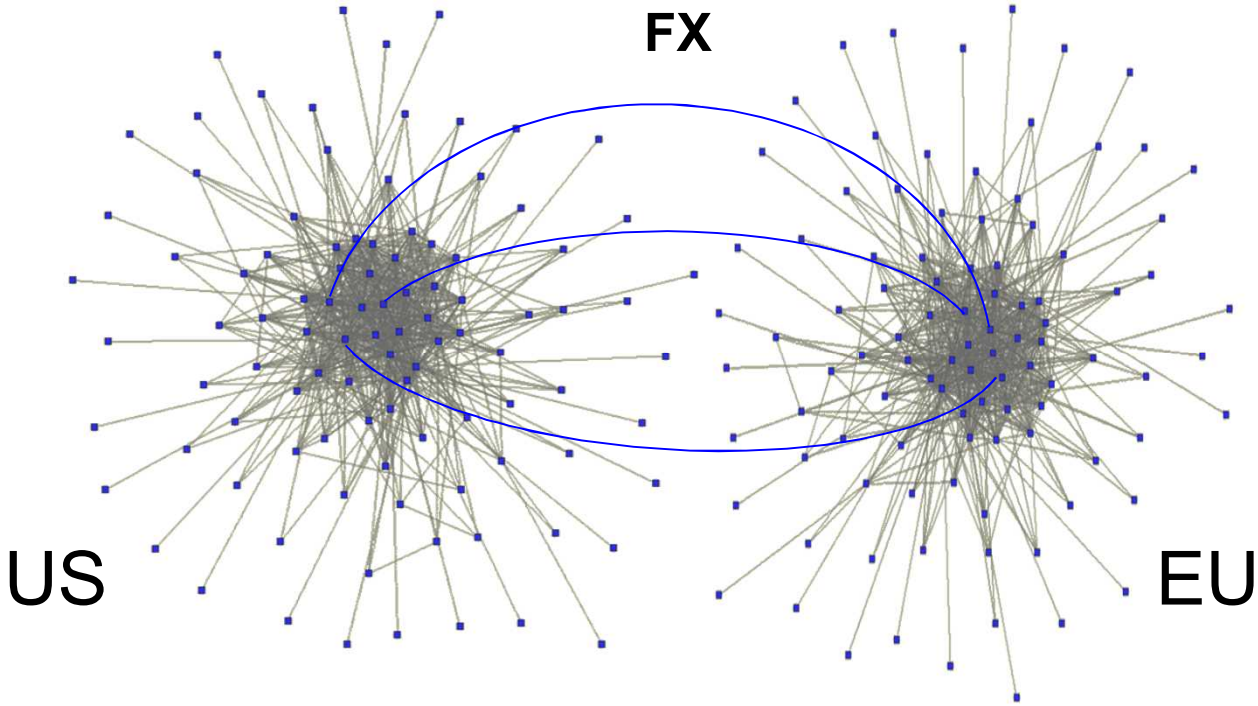
Application: Coupled Payment Systems



For Details See:
Congestion and Cascades in Coupled Payment Systems, Renault, F., W.E. Beyeler, R.J. Glass, K. Soramäki and M.L. Bech, Joint Bank of England/ECB Conference on Payments and monetary and financial stability, Nov, 12-13 2007.

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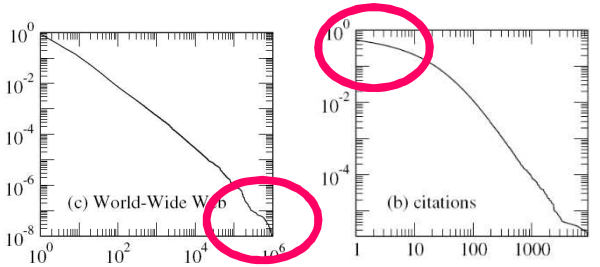
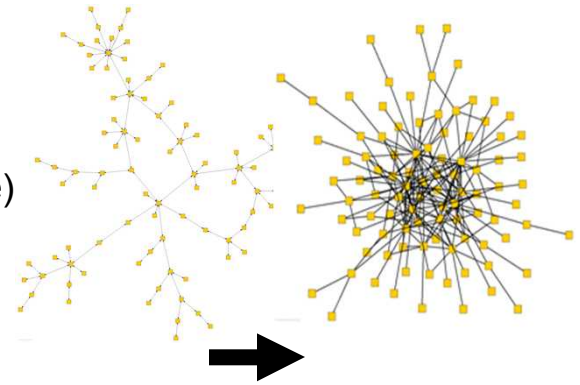
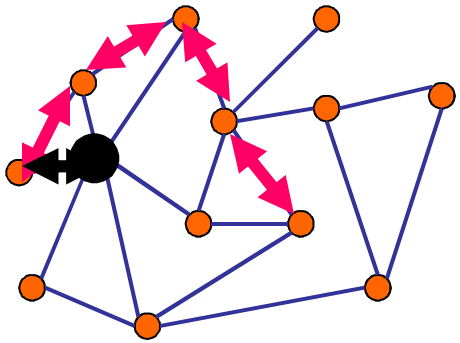
Abstract: Generalized Congestive Cascading

- **Network topology:**
  - Random networks with power law degree distribution
  - Exponent of powerlaw systematically varied
  - Rolloff at low and high values and truncation at high values controlled systematically
- **Rules:**
  - Every node talks to every other along shortest path
  - Calculate load as the betweeness centrality given by the number of paths that go through a node
  - Calculate Capacity of each node as (Tolerance * initial load)
  - ***Attack:*** Choose a node and remove (say, highest degree)
  - ***Redistribute***: if a node is pushed above its capacity, it fails, is removed, and the cascade continues

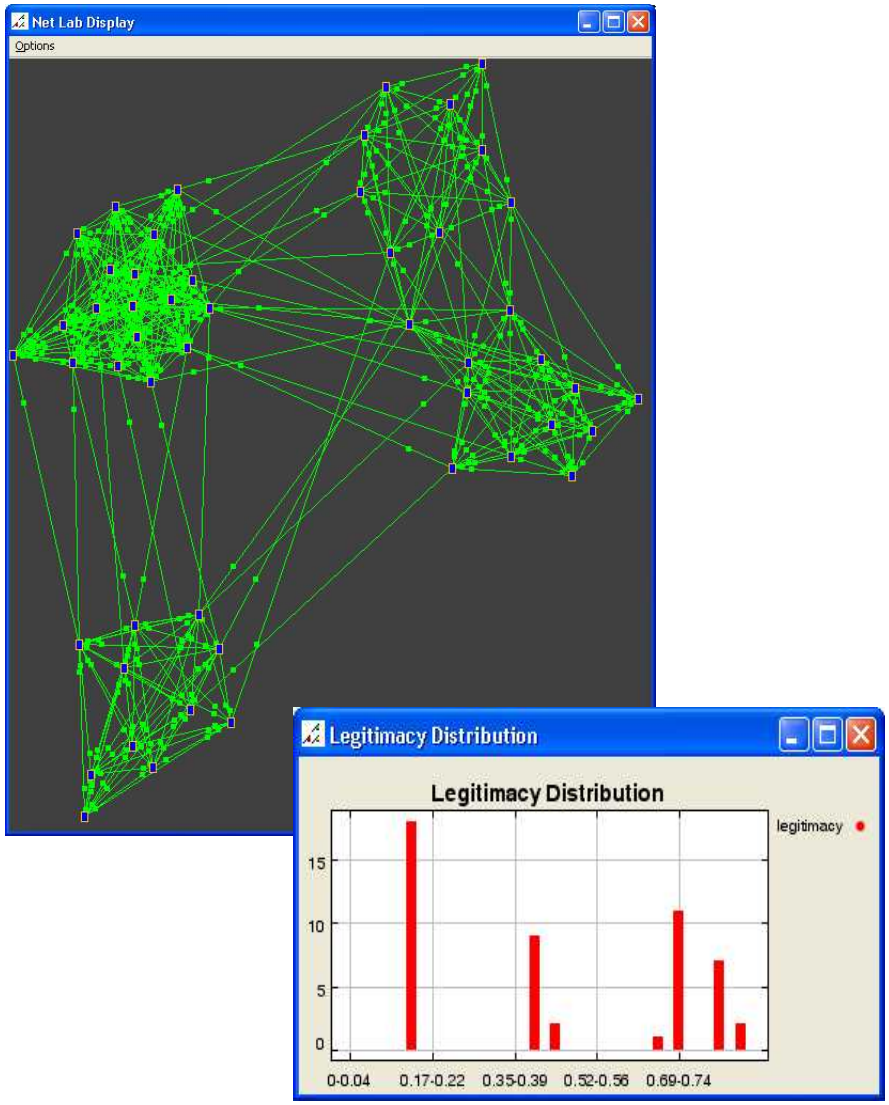




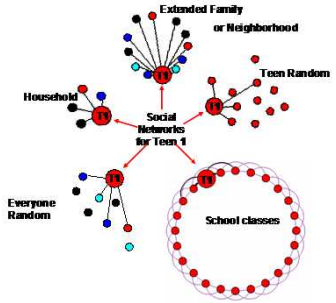


For Some Details see:
LaViolette, R.A., W.E. Beyeler, R.J. Glass, K.L. Stamber, and H.Link, Sensitivity of the resilience of congested random networks to rolloff and offset in truncated power-law degree distributions, Physica A; 1 Aug. 2006; vol.368, no.1, p.287-93.

Abstract: 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 to be representative of community of interest



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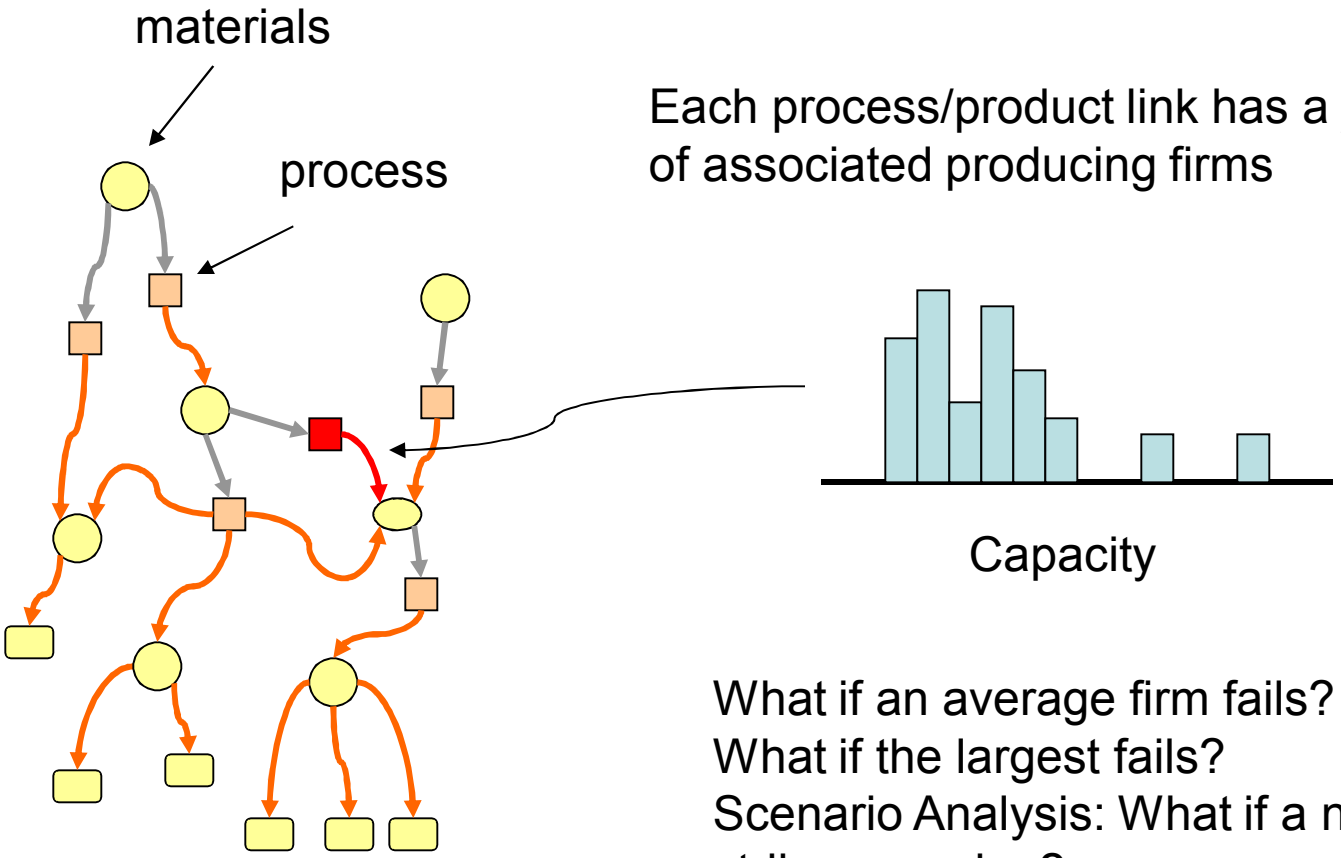
Application: Petrol- Chemical Supply chains

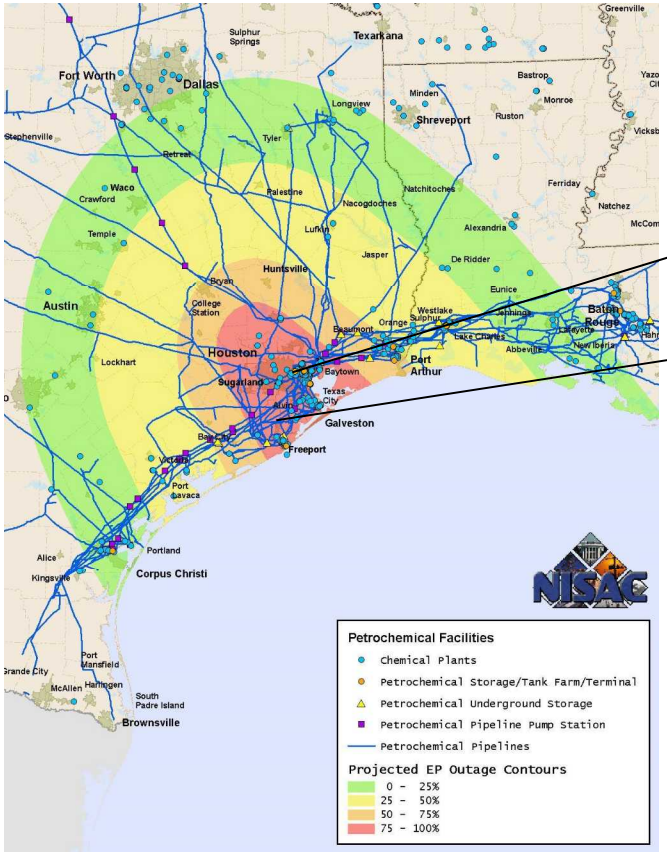


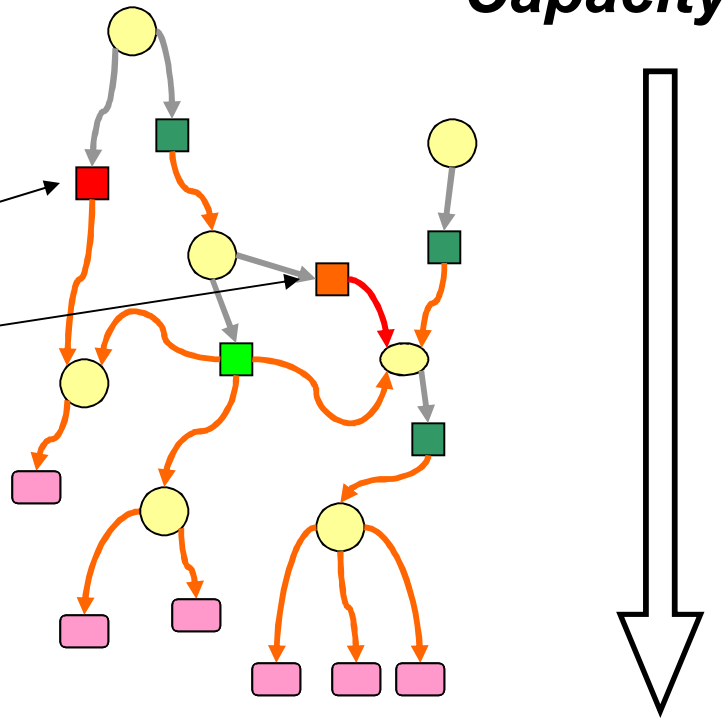
Each process/product link has a *population* of associated producing firms

What if an average firm fails?
What if the largest fails?
Scenario Analysis: What if a natural disaster strikes a region?

Scenario Analysis

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





Diminished Product Availability

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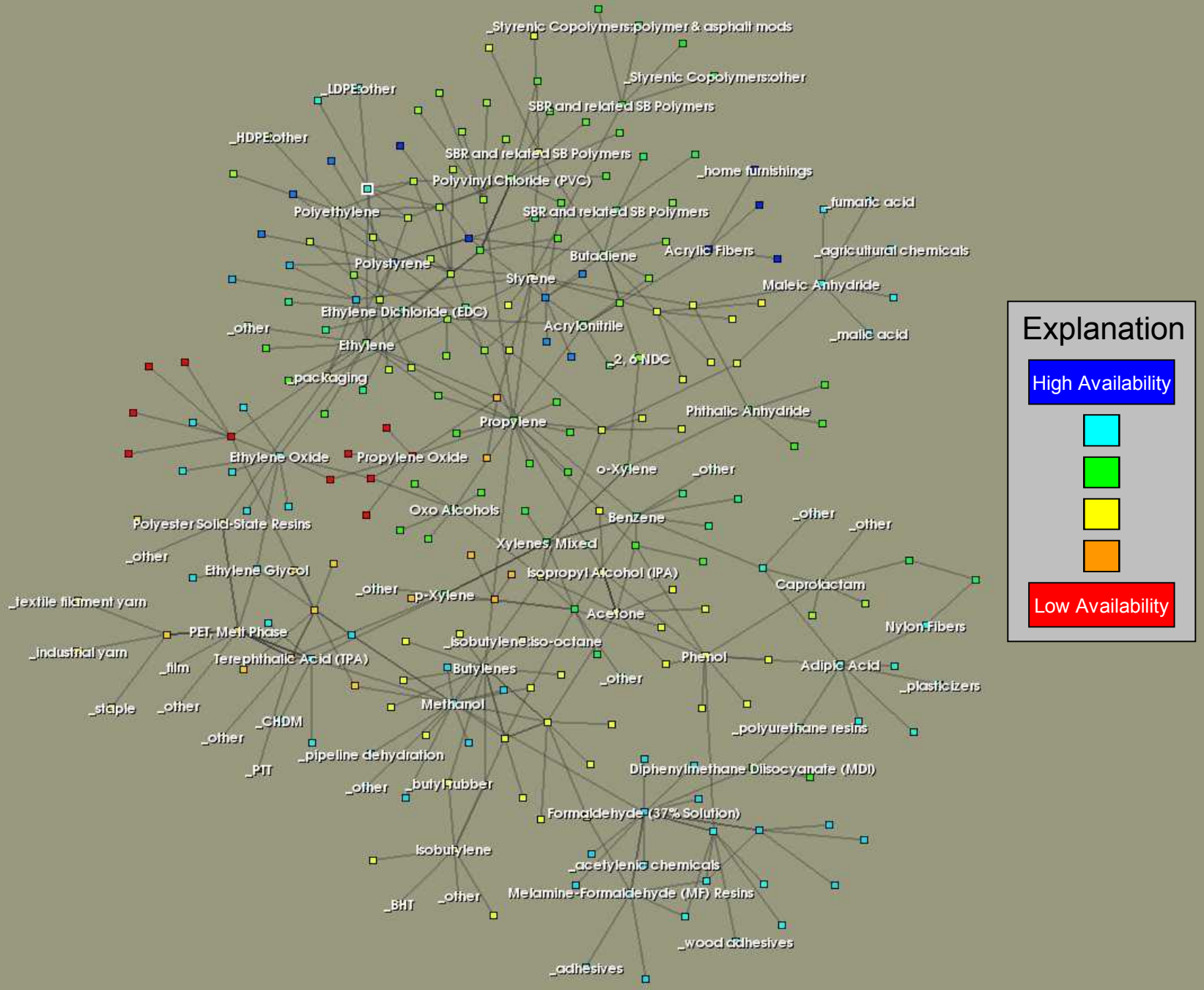
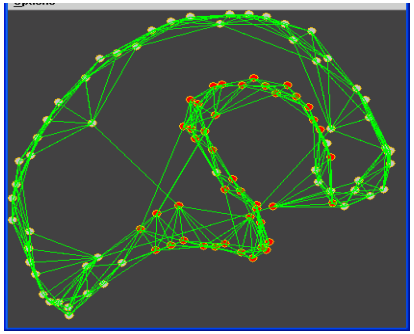

_Styrenic Copolymers:polymer & asphalt mods
_Styrenic Copolymers:other
_LDPE:other
SBR and related SB Polymers
_HDPE:other
SBR and related SB Polymers
_home furnishings
Polyvinyl Chloride (PVC)
_fumaric acid
Polyethylene
SBR and related SB Polymers
Acrylic Fibers
_agricultural chemicals
Butadiene
Polystyrene
Styrene
Maleic Anhydride
Ethylene Dichloride (EDC)
_other
Acrylonitrile
_malic acid
Ethylene
2, 6-NDC
_packaging
Phthalic Anhydride
Propylene
Ethylene Oxide
Propylene Oxide
o-Xylene
_other
Oxo Alcohols
Benzene
_other
_other
Polyester Solid-State Resins
Xylenes, Mixed
_other
Ethylene Glycol
Isopropyl Alcohol (IPA)
Caprolactam
_other
p-Xylene
_textile filament yarn
Acetone
Nylon Fibers
PET, Melt Phase
_isobutylene/iso-octane
_industrial yarn
Phenol
Adipic Acid
Terephthalic Acid (TPA)
_film
Butylenes
_other
_plasticizers
_staple
_other
Methanol
_CHDM
_polyurethane resins
_other
_pipeline dehydration
Diphenylmethane Diisocyanate (MDI)
_PTT
_other
_butyl rubber
Formaldehyde (37% Solution)
Isobutylene
_acetylenic chemicals
_BHT
_other
Melamine-Formaldehyde (MF) Resins
_wood adhesives
_adhesives
Explanation
High Availability
Low Availability

Summary & Future Directions

- Generic approach, many possible applications
- Data driven systems underway this year:
  - Chem industry
  - Natural gas and petroleum products
  - Power Grids
  - People



- Understanding and incorporating adaptation
- Extend to multiply connected networks to get at interdependency
- ***Back to Basics***: Build systematic understanding of the combination of link and nodal behavior and network topology
- CASoS: Complex Adaptive Systems of Systems

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Collaborators

- ***NISAC:*** Theresa Brown and many others
- ***SNL Loki Toolkit:*** Tu-Tach Quach, Rich Detry, Leo Bynum, and others
- ***Infectious diseases:*** Vicky Davey and Carter Mecher (Dept of Veterans Affairs), Richard Hatchett and Hillery Harvey (NIAID-NIH), Laura Glass (Albuquerque Public Schools), Jason Min
- ***Payment Systems:*** Kimmo Soramaki (ECB), Morten Bech (NYFRB), Fabien Renault (BoF)
- ***Power Grid:*** Randall LaViolette, Ben Cook, Bryan Richardson, Keven Stamber
- ***Chem Industry:*** Sue Downes and others
- ***Natural Gas:*** Jim Ellison and others
- ***Social:*** George Backus, Rich Colbaugh, Sarah Glass (Albuquerque Public Schools)