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NATIONAL INFRASTRUCTURE SIMULATION & ANALYSIS CENTER

Modeling Critical Infrastructures with Networked Agent-based Approaches

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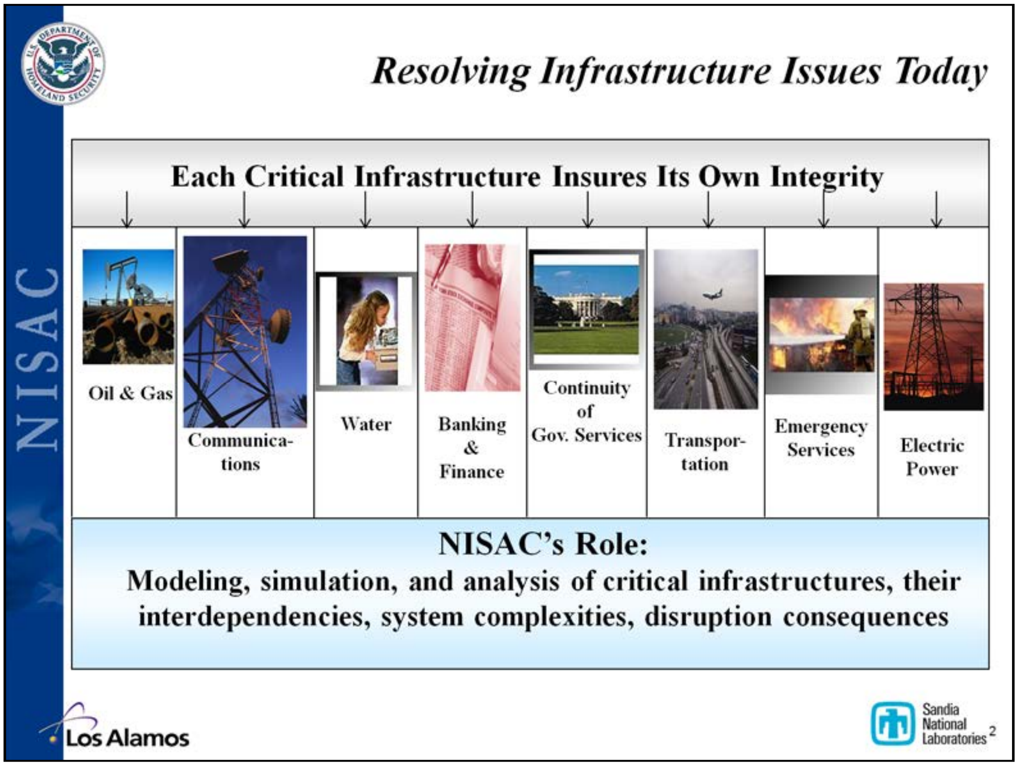
Advanced Methods and Techniques Investigations (AMTI)
National Infrastructure Simulation and Analysis Center (NISAC)
Sandia National Laboratories



NISAC analyses focus on the such things as projecting the consequences of disruptions in infrastructure services and changes in security policy (power outages, hurricanes, floods, terrorist attacks, security measures, etc.). NISAC combines simulation of the various infrastructures with perturbations (natural and anthropogenic) along with disease and economic models to evaluate consequences to public health, economics of the region, their distribution and duration.

A major focus of NISAC is understanding **interdependencies**, quantifying their effects and identifying effective strategies for reducing the potential consequences. We are focused on how and when a perturbation spills over or **cascades** from one infrastructure to another. We use coupled network models, agent-based simulation tools and system dynamics models with feedbacks within and between infrastructures to try to model and understand this process, evaluate consequences, and ultimately suggest mitigation strategies that minimize the compounded effects.

Of course, there's a lot of integration that you have to do to play this game.

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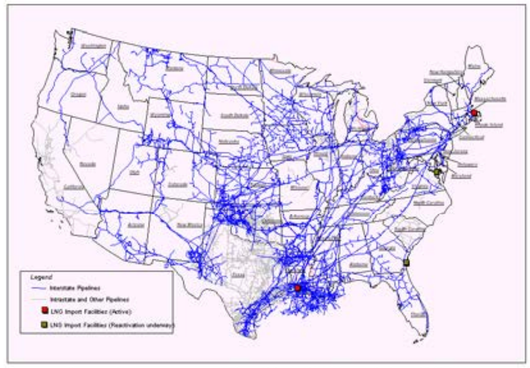
A Challenging if not Daunting Task

- 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

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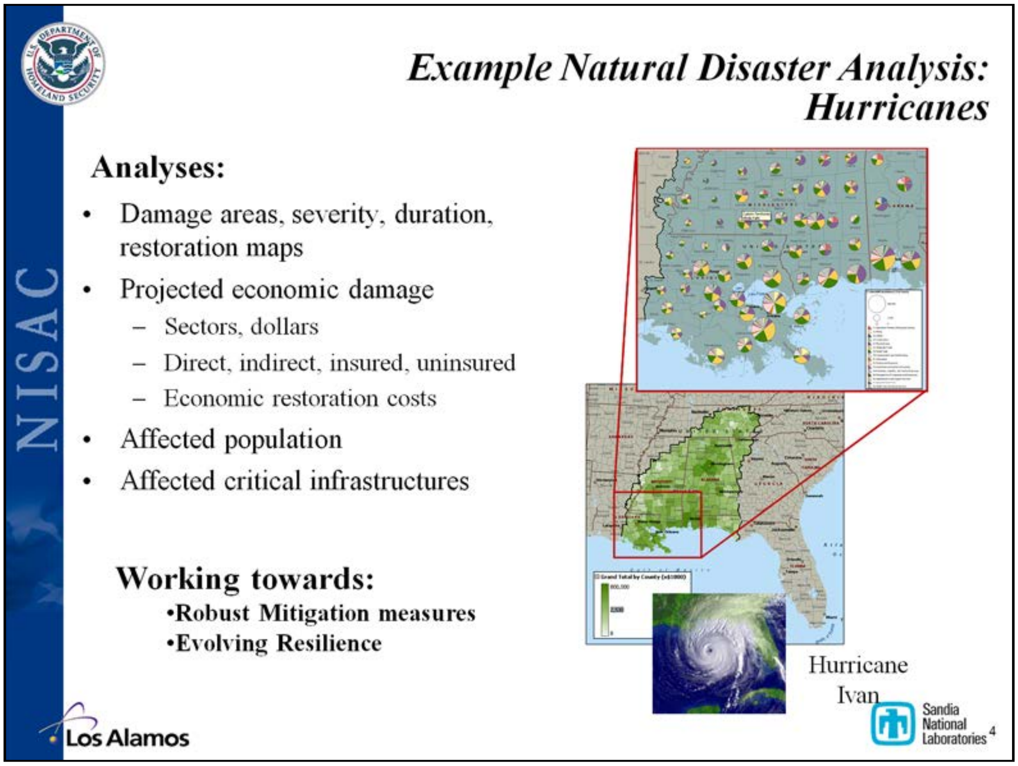

Business sales losses during the outage may total $10-15 billion, although most of this is likely recoverable (increased sales before and after the hurricane)

Total direct impact losses ($8-13 billion) are partially covered by insurance, and Federal disaster relief but not all losses will be recoverable (uninsured property damage, food spoilage, hotel and restaurant services, lost inventory, tourism, etc.)

Indirect impacts from losses in this state will likely affect the rest of the region and nation and will increase total permanent losses (ex. airlines, freight, downstream businesses, etc.)

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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***

Critical infrastructures are Complex Adaptive Systems

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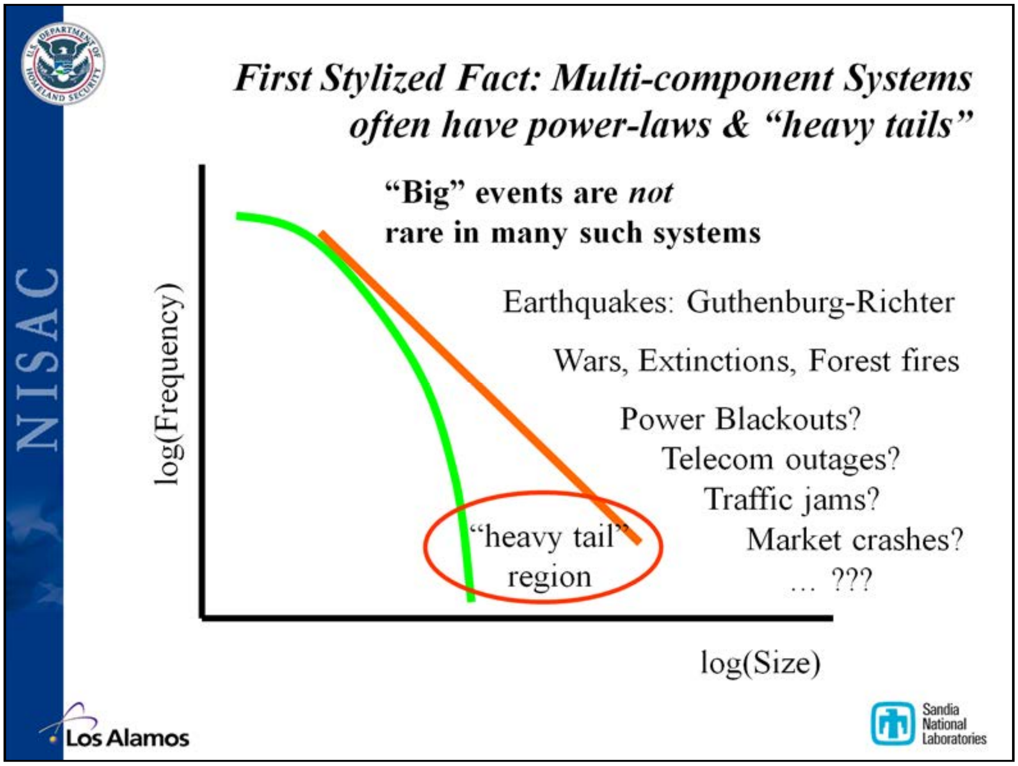


First Stylized Fact

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.

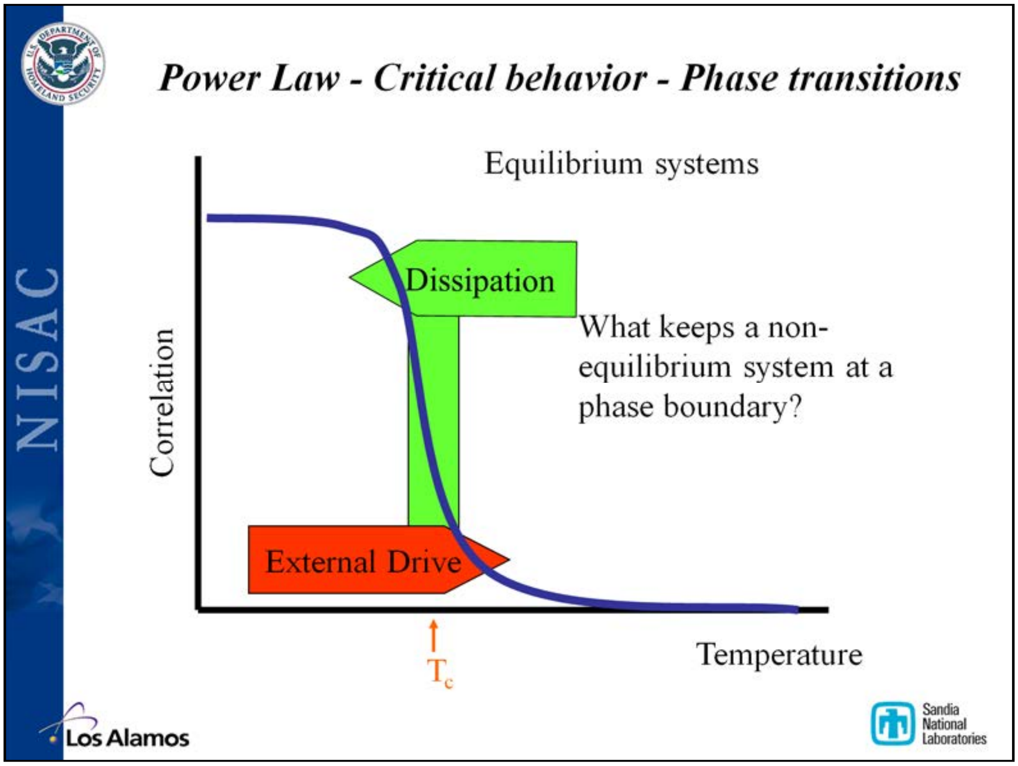
The green curve represents a standard normal distribution while the orange line is a power law. The "**heavy tail**" region of the power-law shows that big events are not rare in such systems.

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.



What is behind this power-law behavior?

In **equilibrium** systems, **power-laws** are correlated with **critical behavior** as often found at **phase transition boundaries**.

Phase transitions occur at specific **critical points**, Tc, and systems generally must be tuned to be there.

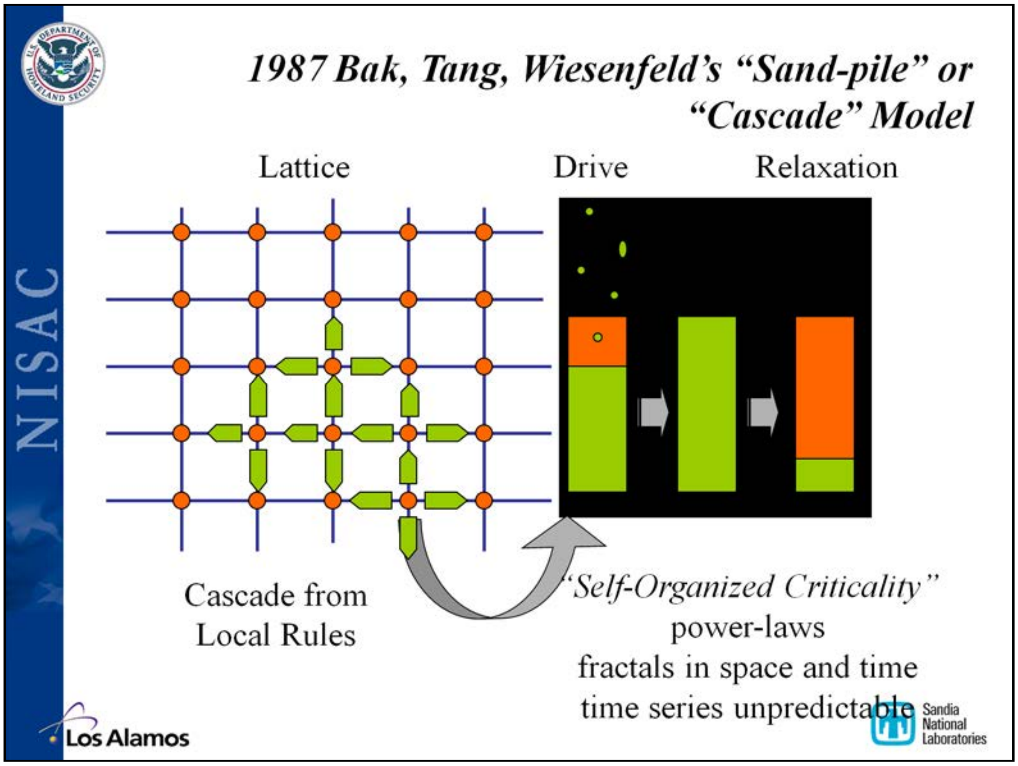
A magnet is a classic example where below the Curie point it behaves collectively (as a magnet) but above, does not.

Percolation theory has been developed to understand system behavior at the critical point where spatial-temporal fractals and power laws emerge.

What about **non-equilibrium** systems?

Many non-equilibrium systems (e.g. BTW sand-pile in the next slide) **maintain themselves in a critical state**. This can occur through the interaction of a driving process which pushes the system in one direction, and a dissipating process which only becomes effective because of properties that emerge (perhaps via long-range correlations) at the phase transition boundary.

For non-equilibrium systems to behave this way, they must be **placed and maintained within an energy gradient**.



BTW Sand-pile or Cascade model

In 1987, **Bak, Tang, and Wiesnefeld** formulated a very simple model that generates **cascades** with power-law distributions within a multi-component system from **simple local rules** operating on a square lattice within a slow random drive: the **BTW sand-pile**.

In the BTW sand-pile, a grain of sand is added to a site chosen at random within a two dimensional square lattice. When the number of grains at a site exceeds 4, it distributes a grain of sand to each of its non-diagonal neighbors. If any of these sites are pushed over their thresholds, they too distribute their sand grains and thus contribute to the cascade. Sand is removed from the domain when it encounters the edge of the network.

Model relies on a **separation of time scales** such that the **drive** is very slow relative to the **relaxation** process. Thus cascades evolve to completion before additional sand is applied.

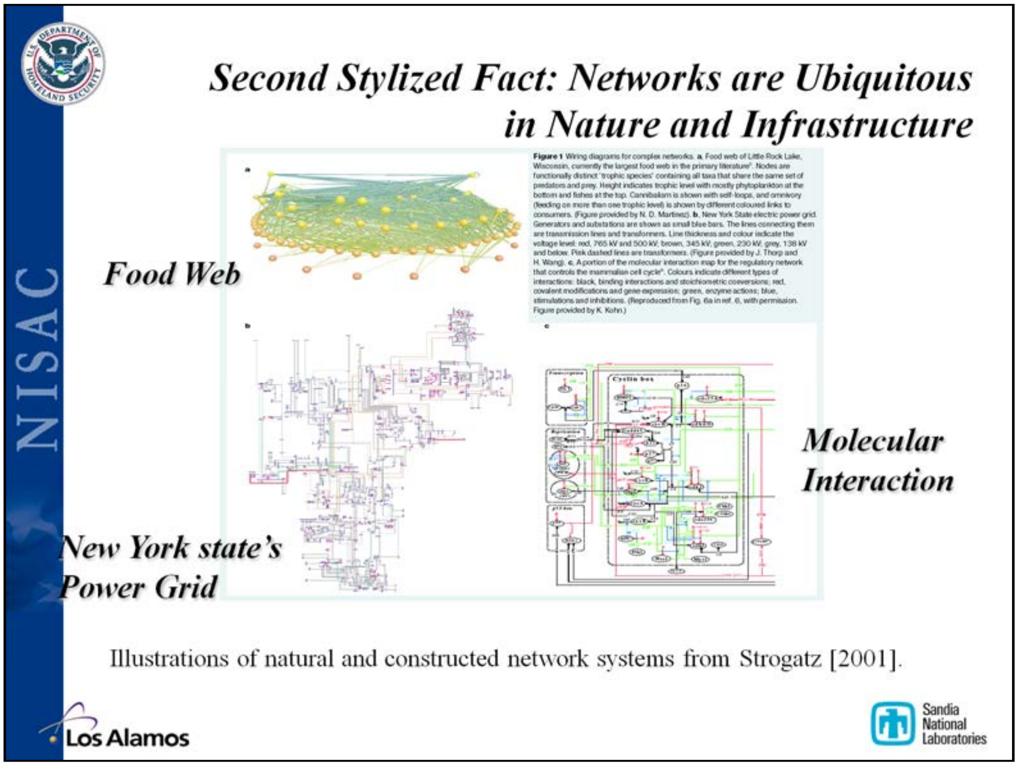
Dissipative system: for the original BTW sand-pile, dissipation occurs only at the boundaries where sand is lost. However, dissipation can occur within the local rule as well (i.e., friction).

This simple model based on local rules creates a state of **Self Organized Criticality** with power law distributions for cascades and fractals in space and time.

Since it's introduction, this simple model has been modified and applied in nearly every scientific field and the original paper has been referenced over 2000 times.

References:

Bak, P., C. Tang, and K. Wiesenfeld, Self-organized criticality: An explanation of 1/f noise, Physical Review Letters, 59:4:381-384, 1987.



Second Stylized Fact

Another important feature of many natural and man made systems are that components are linked into **complex and often ramified networks**.

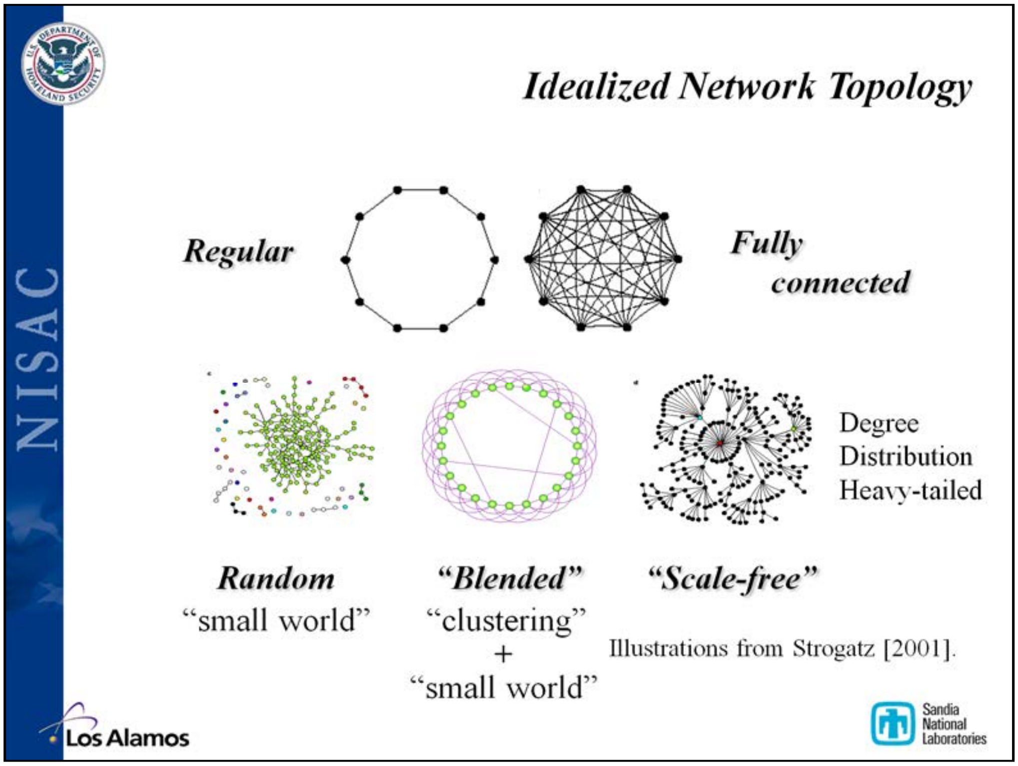
Designed by evolution or by man, **networks are ubiquitous**. Here are three examples from Strogatz (2001).

Nearly every system can be formulated and analyzed as a network!

We find: King pins, keystone species, critical nodes, critical reactions, rate determining steps…

References:

Strogatz, S.H., Exploring Complex networks, Nature, 410:268-276, 2001.



Idealized Network Topology

Graph theorists have generated and explored the properties of many idealized network topologies thus allowing us to identify and classify attributes.

At one end of the spectrum are **perfectly ordered, regular lattices**: crystals are an example.

Regular lattices have the property of "**clustering**", that is, your neighbors are often connected to each other.

At the other end of the spectrum are **disordered, random networks**, first studied by Erdos and Renyi (1959). Such networks are formed by joining two nodes at random and then repeating this selection and joining process over and over until a specified link density is achieved. Random networks have what is called the "**small world**" property, that is, it takes just a few steps within the network to go from one place to another. However, random networks are devoid of clustering.

Blending a Ring lattice with a Random network yields both the small world characteristic and clustering. This was first proposed by Watts and Strogatz (1998) as representative of many social networks.

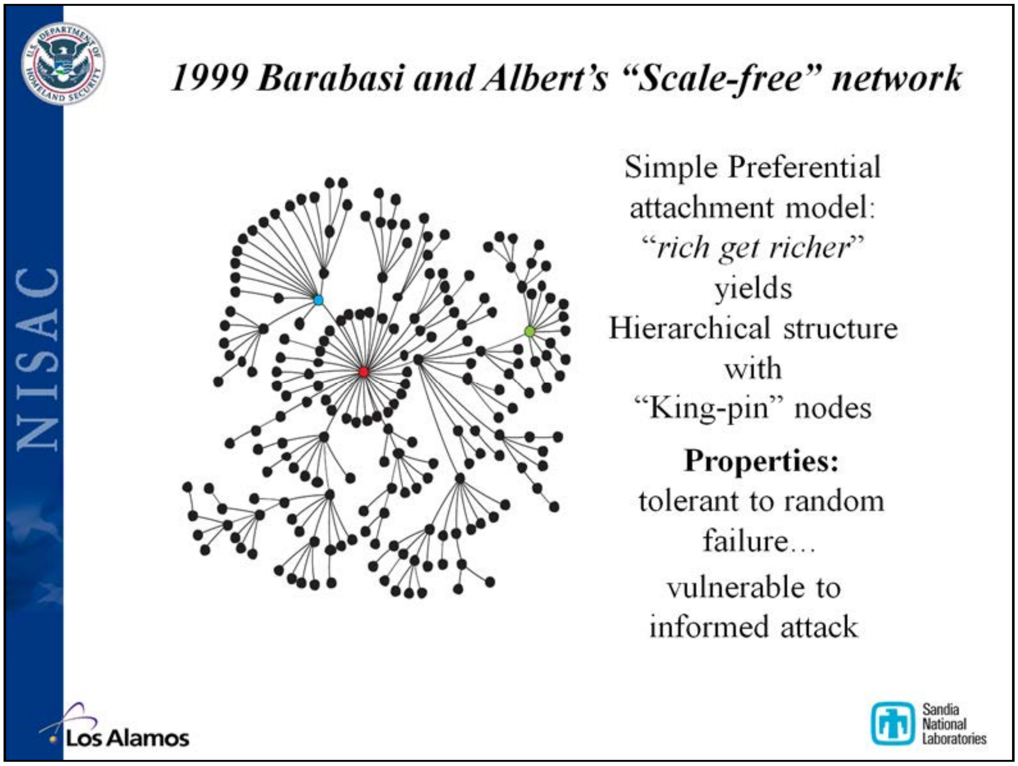
In many naturally occurring networks, one finds a power-law or near power-law for the **nodal degree distribution** such that a significant number of highly connected nodes exist (i.e., a heavy tail). Networks with this power-law distribution have fractal properties and are often called **scale-free** (Barabasi and Albert, 1999).

References:

Erdos, P., and A. Renyi, On Random Graphs, I, Publicationes Mathematicae (Debrecen), 6:290-297, 1959.

Watts, D.J., and S.H. Strogatz, Collective dynamics of 'small world' networks, Nature, 393:440-442, 1998.

Barabasi, A.-L., and R. Albert, Emergence of scaling in random networks, Science, 286:5439:509-512, 1999.



Special properties of the scale free network

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

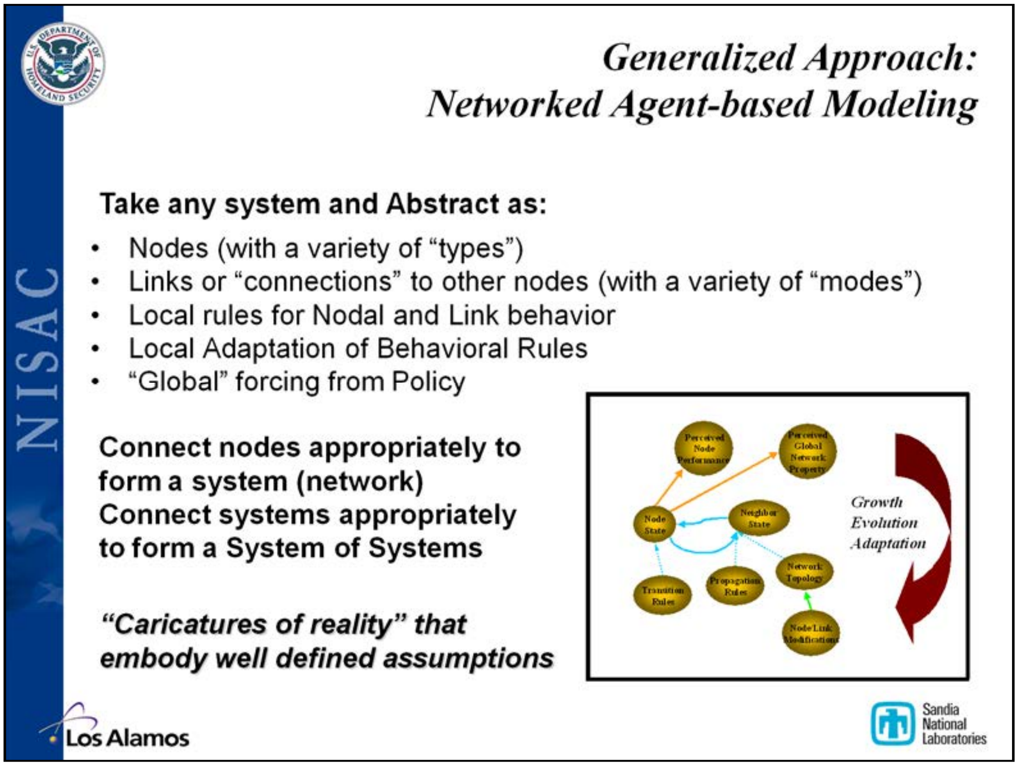
The preferential attachment algorithm of Barabasi and Albert (1999) was used to create the network shown in this slide.

Two additional features that one often finds in real and engineered systems are "**king-pin**" or "**key stone**" nodes that are critical to the operation of the entire system, and **hierarchies or "tree" structures** where some (or all but one) 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, loosing its large scale connectivity.

References:

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



-Three years earlier, a bunch of the early NISAC folks and I began an effort to bring in the understanding being built in the emerging field of CAS and apply it to infrastructures.

Infrastructures were at least CAS… and through our roadmap effort this past summer, we see they are really CASoS.

-By the time the call came on Halloween, **we had developed a generic approach to think about and model any system, infrastructure or otherwise, as a series of nodes connected within a network.** The nodes could be anything, power stations, resources, people and the connections could be, power-lines, supply chains, interactions. The nodes and the links could have any specified behavior (discrete or continuous) and this behavior could adapt or evolve in time and links within the network could form or break.

Towards a Complexity Science Basis for Infrastructure Modeling and Analysis

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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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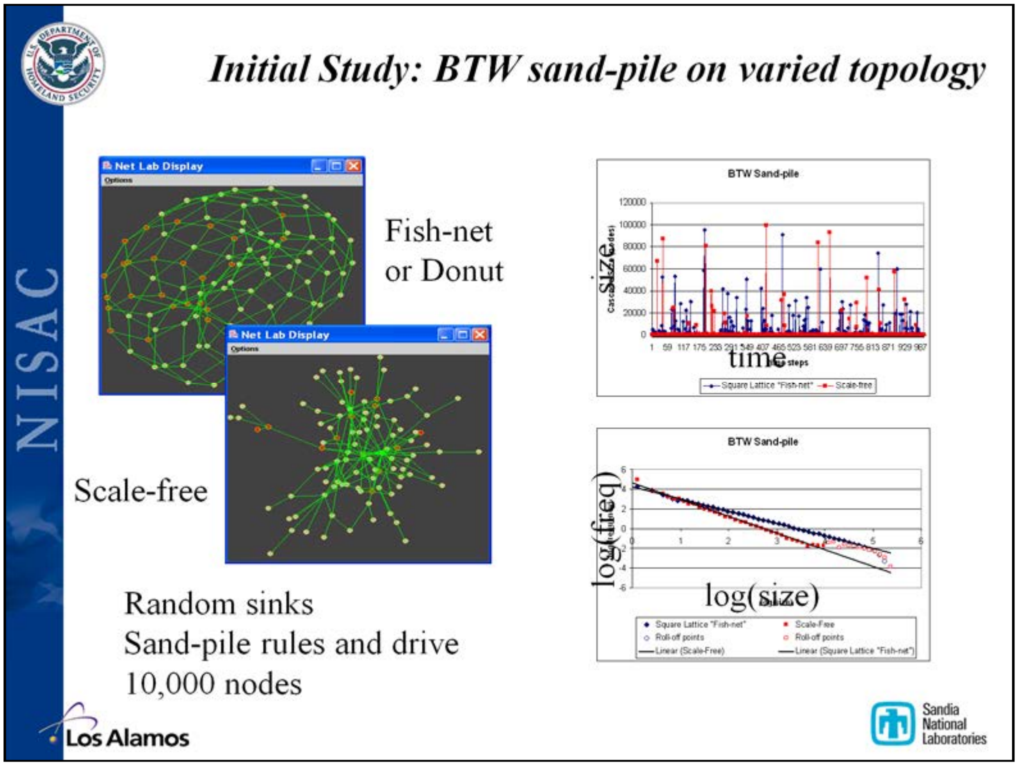


Abstract Example: BTW sand-pile on varied topology

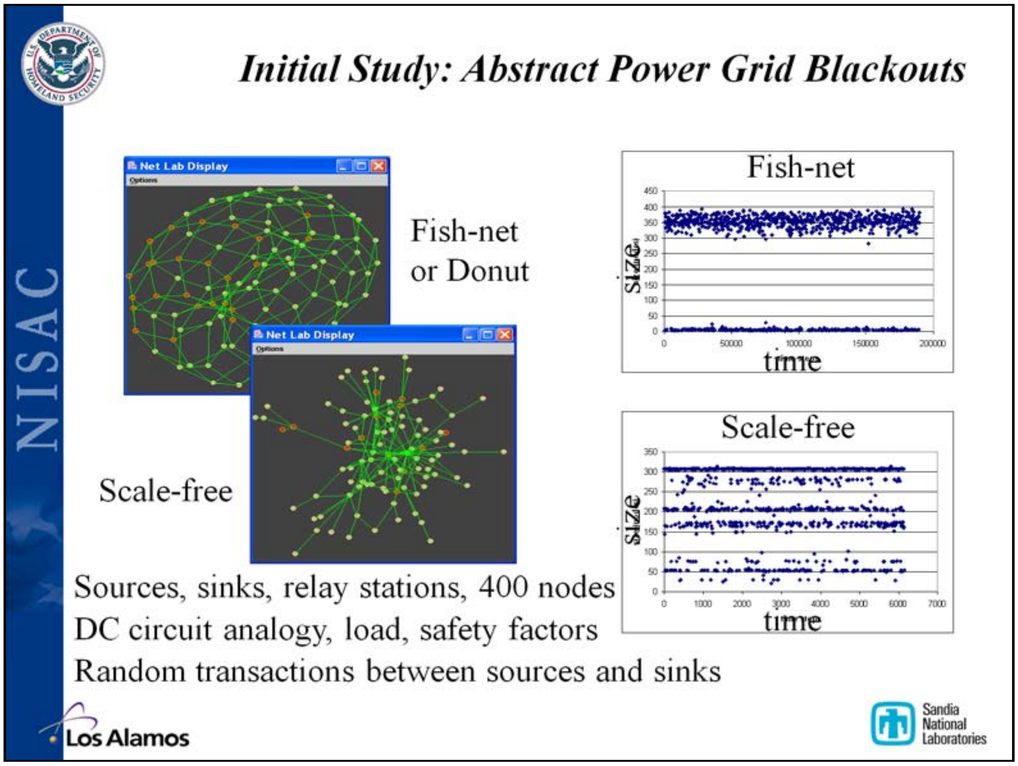
To generalize the BTW sand-pile and apply it to arbitrary network topologies, let us consider grains of sand to represent units of "**energy**", E, and specify a constant threshold value across all sites, Ec, at which a site changes state and distributes one unit of E to each of its neighboring sites. Let us also choose a small number of randomly distributed sites within the network to act as **sinks** that absorb all E distributed to them. These sites play the role of the **edges** of the original BTW sand-pile and allow closed networks to be considered. In this generalized form, we can now apply the BTW sand-pile to any network topology.

Example BTW sand-pile simulations for **10,000 node** problems for fish-net and scale-free stylized network exhibit time series that are **highly erratic** (see **top right plot**). In the plot, cascade size (defined by the number of times nodes in the network are pushed about threshold and distribute E) is shown in time defined by the number of unit additions of E to the network. The time between cascades appears to be random and the size of the cascade unpredictable. Cascade size distributions for each network type (see **lower right plot**) exhibit the **typical BTW sand-pile power-law** with eventual exponential "roll-off" at large values. The **power-law is indicative of self-organized criticality** while the roll-off reflects the finite size of the simulation. We see that the exponent of the power-law (slope of the line) is dependent on the network topology.

The BTW sand-pile considers **simple local nearest neighbor interactions** between nodes and models a transmission process within a network that is fast relative to the addition of accumulating perturbations. As it stands, such a model may have application to a variety of situations of importance in the analysis of critical infrastructures. However, the constraints of the BTW sand-pile can be relaxed or replaced with others quite generally within **Polynet** and thus transform the model in many directions. In the remainder of the talk, we explore such transformations in context of three applications: the electric power grid, a payment system, and the spread of an infectious disease.

Reference:

Glass, R.J., W.E. Beyeler, K.L. Stamber, Advanced simulation for analysis of critical infrastructure: Abstract cascades, the electric power grid, and Fedwire, 18 pages (SNL paper SAND 2004-4239).



Application 1: Cascading Blackouts

A Stylized power grid is represented by ideal networks that “bracket” what we find in real systems: **regular fish-net lattice** and **scale-free**. Nodes represent **sources**, **sinks**, and **relays stations** for electricity. Sources and sinks are assigned **representative values for power grids**. **DC circuit analogy** is solved on the network to yield **loads** at each node and then nodes are given failure loads specified by a uniform **safety factor representative of grid design**. The system is driven by a **random, unregulated market** where pairs of sources and sinks are chosen at random to buy and sell electricity. After each transaction, load is recalculated within the network. This sequence continues until a node is pushed above failure threshold. The failed node is then removed, load is recalculated, nodes which are now pushed above threshold then fail and are removed, etc. The resulting **load based cascade** is followed to its completion. Following a cascade, the network is placed at its initial condition and random transactions are once again accumulated until the next cascade occurs, etc.

Cascade size (number of nodes that fail) as a function of time (transactions) for two example networks each containing 400 nodes are shown in the plots on the right.

Fishnet: Cascades are either very small, or near the size of the system

Scale-free: sets of cascades occur that are specific to a given network realization and determined by the specifics of the network topology, natural breaks occur that fragment the system when cascades occur.

Also note that the **time scales for the two networks are over 2 orders of magnitude different** suggesting the **fish-net to be much more robust to market perturbations than the scale-free** (i.e., it can accumulate many more perturbations before cascading)

References:

Glass, R.J., W.E. Beyeler, K.L. Stamber, Advanced simulation for analysis of critical infrastructure: Abstract cascades, the electric power grid, and Fedwire, 18 pages (SNL paper SAND 2004-4239).

August 2003 Blackout…

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

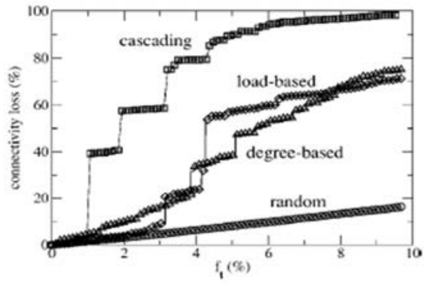


FIG. 4. Connectivity loss in the power grid due to the removal of nodes corresponding to transmission substations. We remove a fraction f_t of transmission nodes with four different algorithms: randomly (circles), in the decreasing order of their degrees (triangles) or loads (diamonds), and by recalculating 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.

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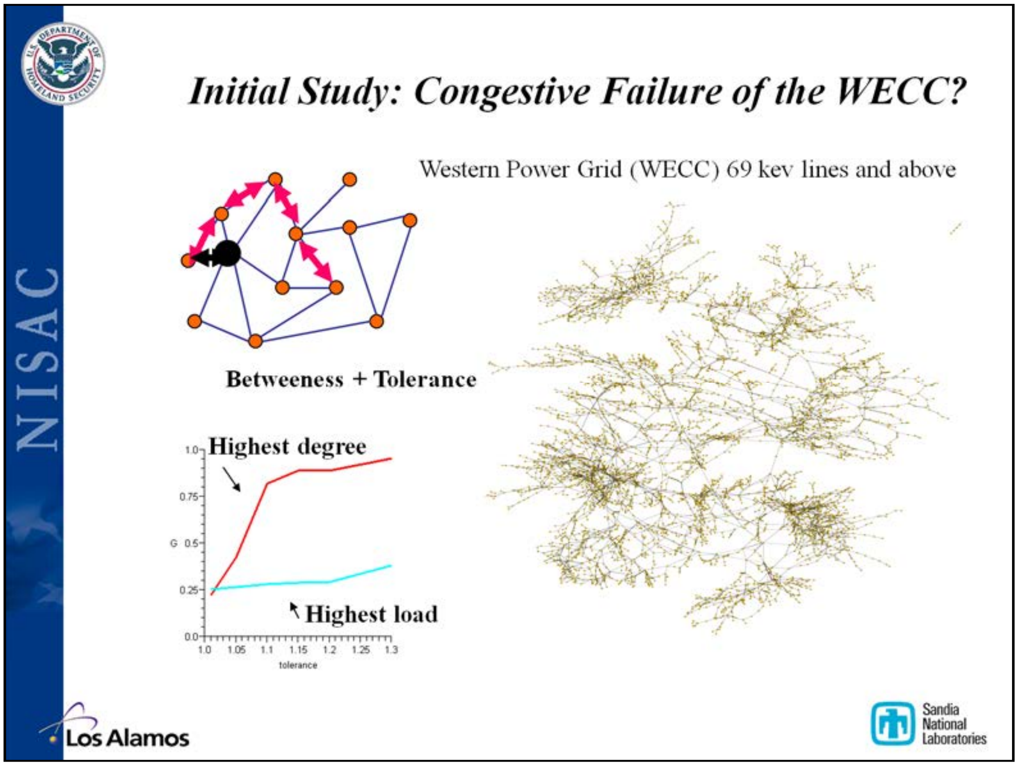

WECC comprises the entire Western Interconnection. With a footprint of 1.8 million square miles and members operating in 14 states in the Western U.S., two Canadian provinces, and Baja Norte, Mexico, WECC is the largest geographically of the eight NERC regions.

WECC's mission of maintaining a reliable electric power system in the Western Interconnection and assuring open and nondiscriminatory transmission access among members is accomplished through thousands of hours of labor contributed by WECC's 159 members. The work of the membership is supported by a staff of 24.

WECC members represent the entire spectrum of bulk electricity users and are divided into five member classes: large transmission owners, small transmission owners, electric line of business entities that do no operate transmission, end users, and state and provincial regulators. Each member has an equal voice in the organization through the standards development process and through representation on WECC's hybrid Stakeholder/Independent Board of Directors.

Loki Toolkit: Modeling and Analysis

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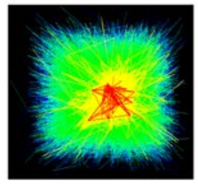
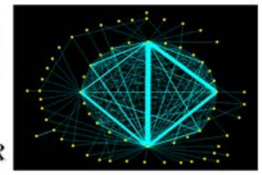
Applications VERY Important





Re-Past & Jung → Polynet → LOKI

LOKI → NET GENERATOR, NET ANALYZER, GENERALIZED BEHAVIOR, POWER, GAS, INFECT, PAYMENT, OPINION, SOCIAL, CONTRACT ...

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

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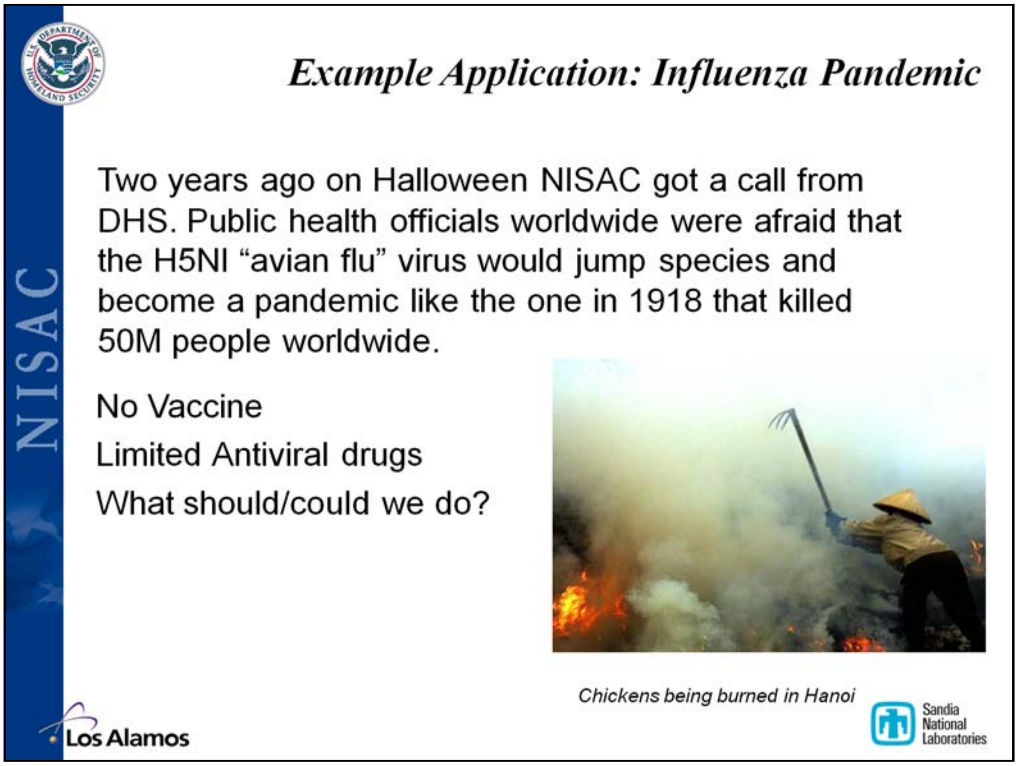
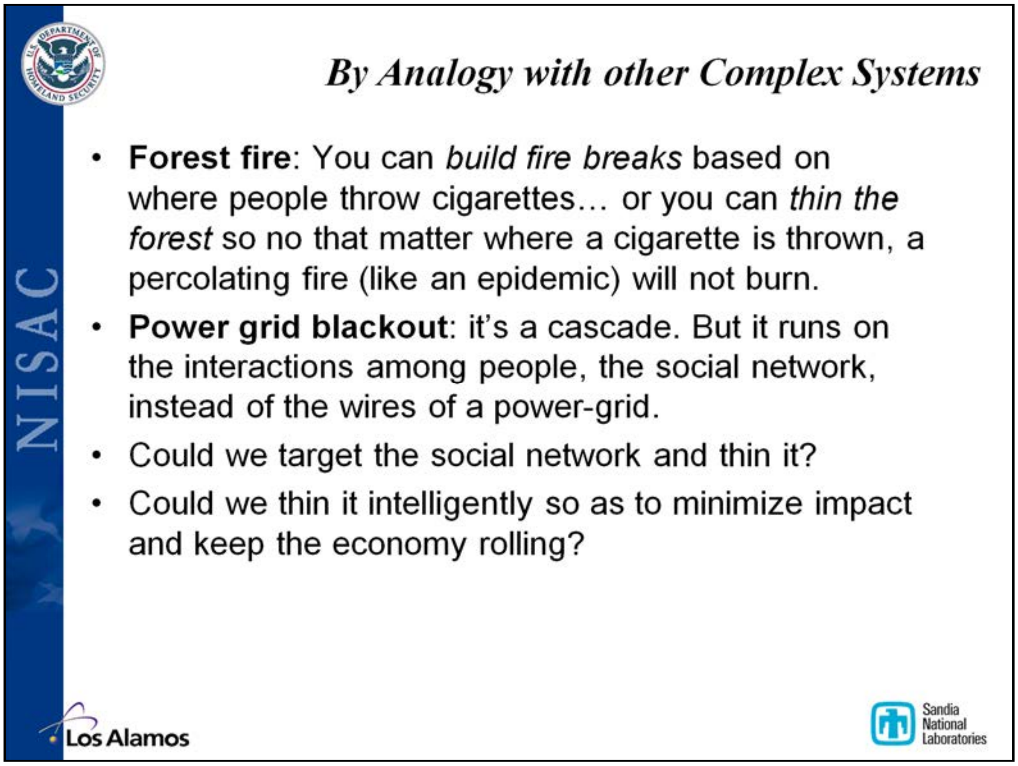


The Pandemic story:

-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. 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.



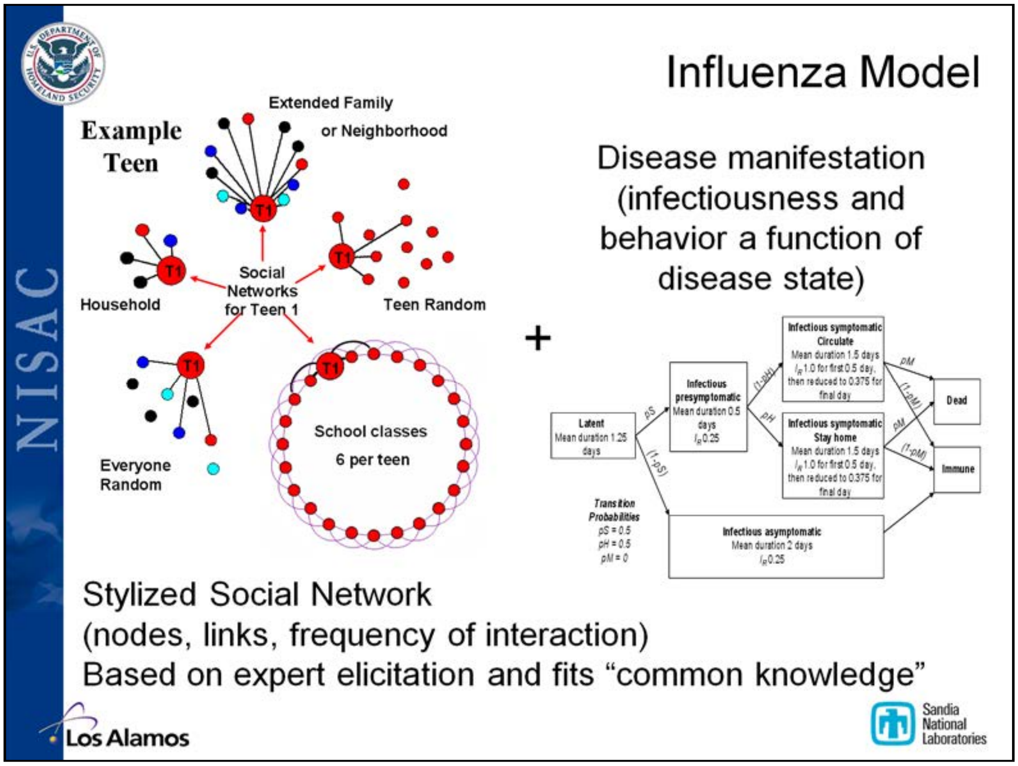
-Pandemic RIGHT NOW. No vaccine. The rest of the world had taken all the stockpiles of antiviral that would be generated for the next 5 years and the US had none.

-What could the US do? What could we at SNL do?

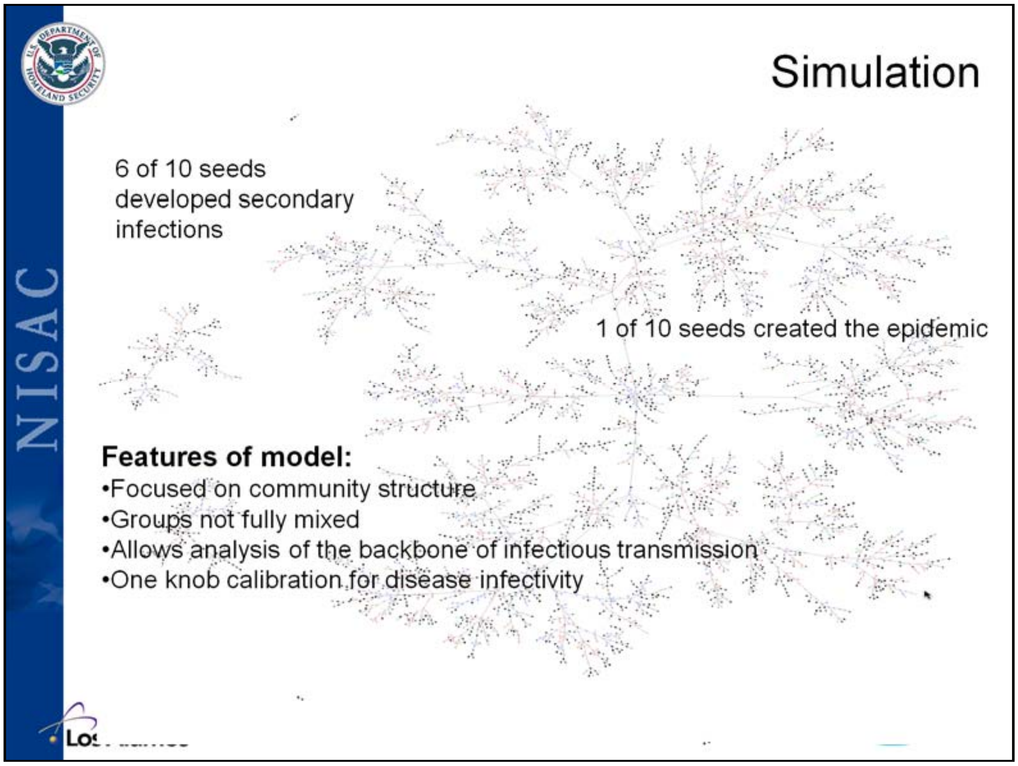
-A pandemic is just like a forest fire. You can build fire breaks based on where people throw cigarettes (this yields HOT)… or you can thin the forest so no that matter where a cigarette is thrown, a percolating fire (like an epidemic) will not burn.

-A pandemic is also just like a power grid blackout… it's a cascade. But it runs on the interactions people, the social network, instead of the wires of a power-grid. Could we target the social network and take it apart? (Of course, everyone could just stay home for six months while waiting for a vaccine.) Could we take it apart intelligently so as to minimize impact and keep the economy rolling?

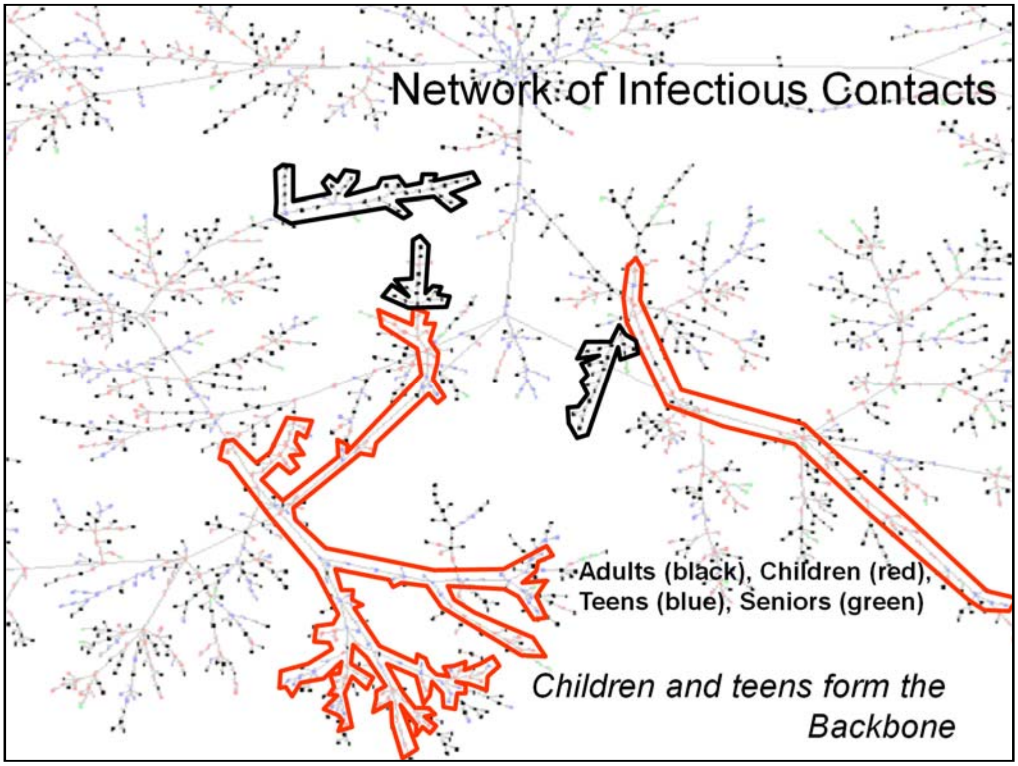
-PROBLEM DEFINTION: stop an epidemic with the least social burden.



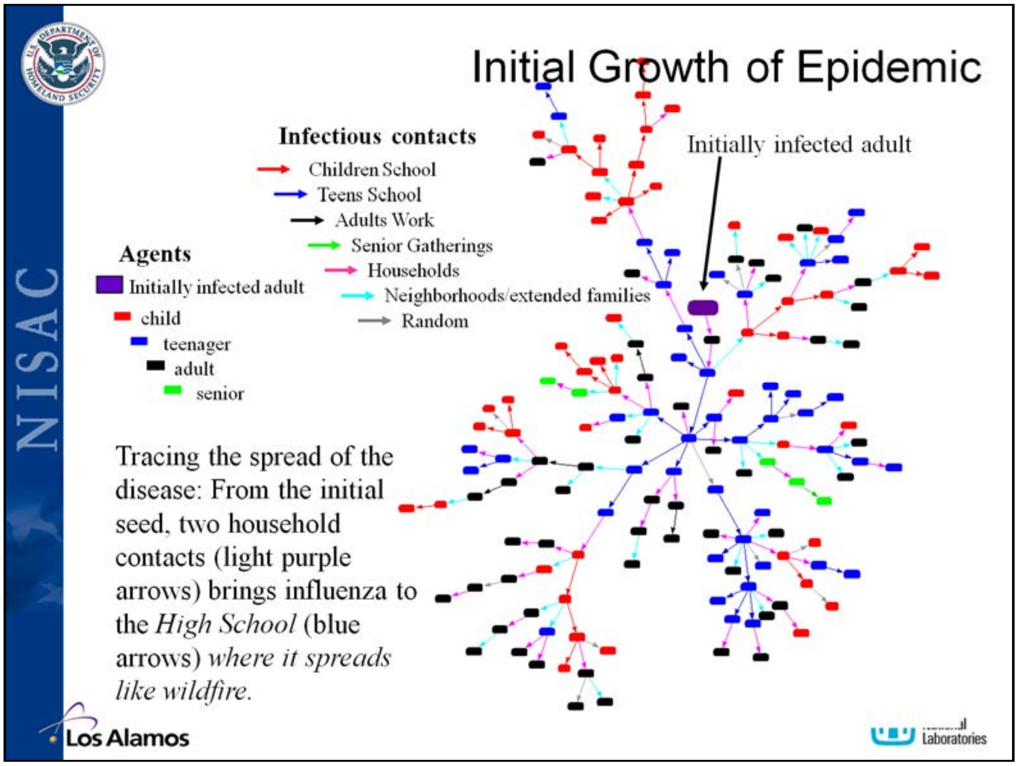
-We took our general approach and applied it to the pandemic problem. People were nodes, their interactions were links in the network. Disease would spread along these links from person to person. We put in the appropriate behavior of the disease and the physics of it’s transmission. We then asked a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



-We ran the model and it hit the numbers from past pandemics without calibration (other's required this calibration). We had the right node and link behavior, the right network, we had the right "physics".

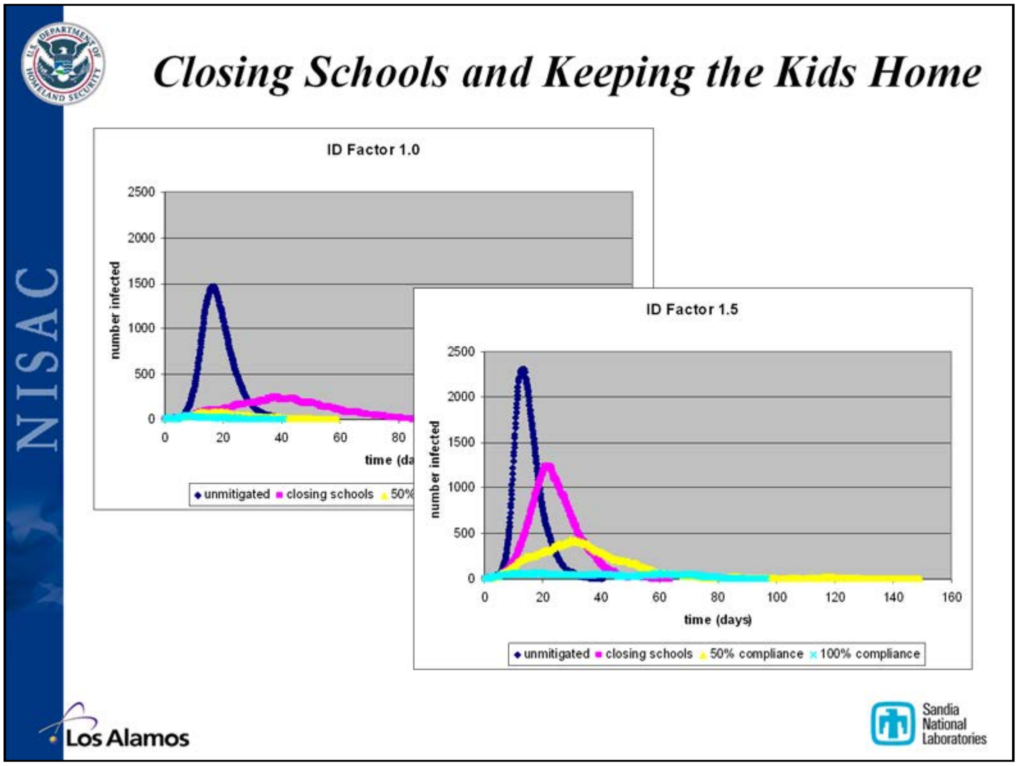


-By studying the burn path through the small community, we identified children and teens as the culprits. They form the backbone of the epidemic while adults are at the dead ends of the network.



-And the critical location for the spread was in the schools. We then targeted these groups: we closed the schools. If the kids and teens were allowed to adapt and go to the mall it actually made things worse. But if we kept them primarily at home, we could knock the local epidemic out.

-PROBLEM SOLUTION: Close the schools and keep the kids and teens at home.


Closing Schools and Keeping the Kids Home
ID Factor 1.0
number infected
time (days)
unmitigated
closing schools
50%
ID Factor 1.5
number infected
time (days)
unmitigated
closing schools
50% compliance
100% compliance
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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***)

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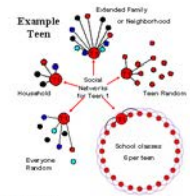
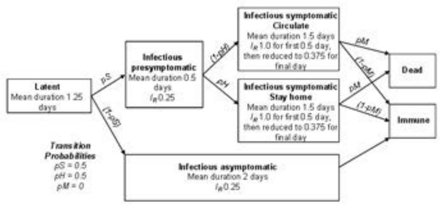
Effective, Robust Design of Community Containment for Pandemic Influenza



- **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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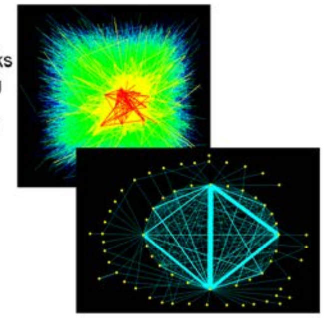
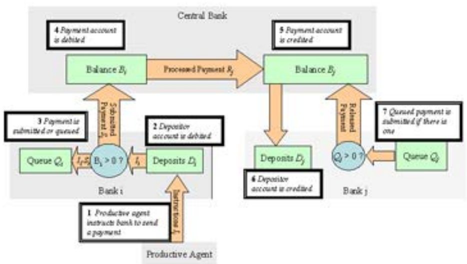
Application: Congestion and Cascades in Payment Systems



- **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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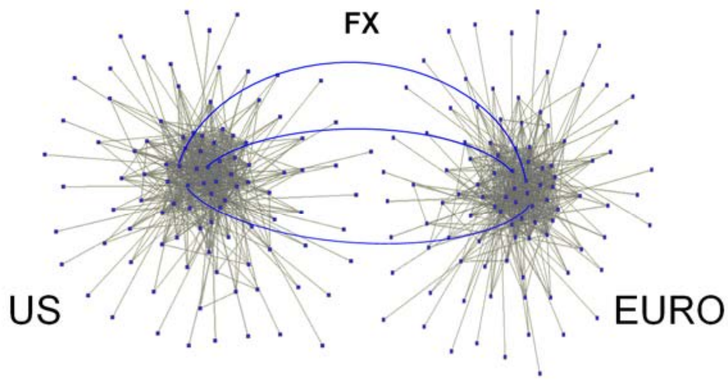
Application: Coupled Payment Systems



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.

Abstract: Generalized Congestive Cascading

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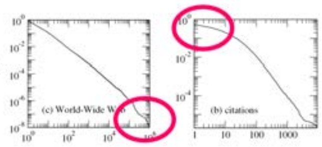
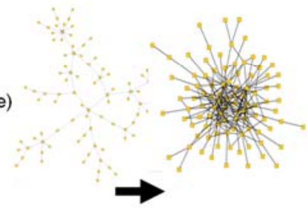
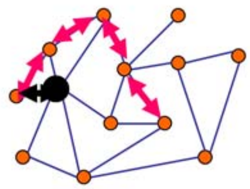
- **Network topology:**
  - Random networks with power law degree distribution
  - Exponent of powerlaw systematically varied
  - Rolloff at low and high values and truncation at high values controlled systematically
- **Rules:**
  - Every node talks to every other along shortest path
  - Calculate load 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.

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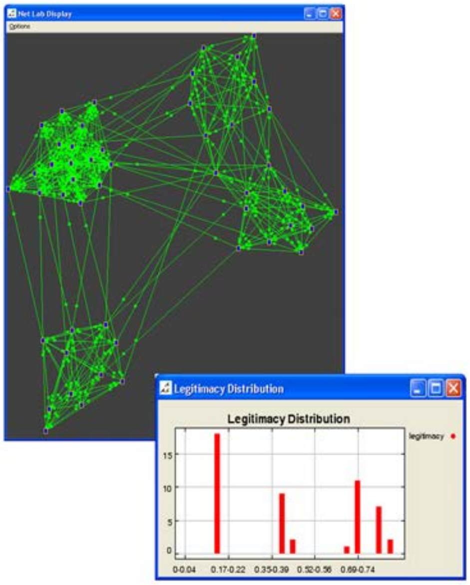
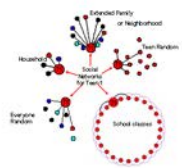
Abstract: Group Formation and Fragmentation



- 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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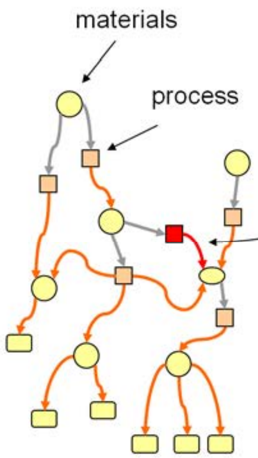
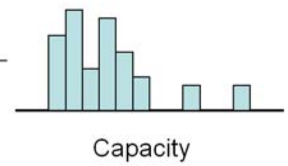
Application: Petrol- Chemical Supply chains



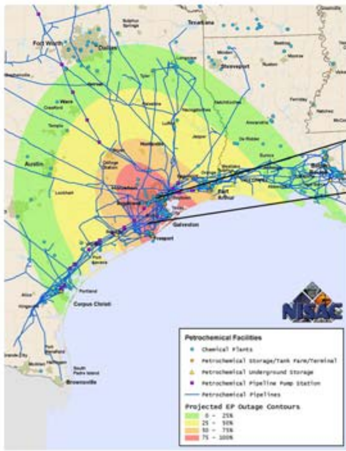
Each process/product link has a *population* of associated producing firms

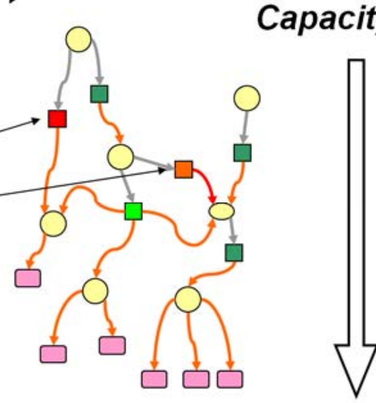


What if an average firm fails?
What if the largest fails?
Scenario Analysis: What if a natural disaster strikes a region?

Scenario Analysis

Disrupted Facilities ⇨ ***Reduced Production Capacity***





Diminished Product Availability

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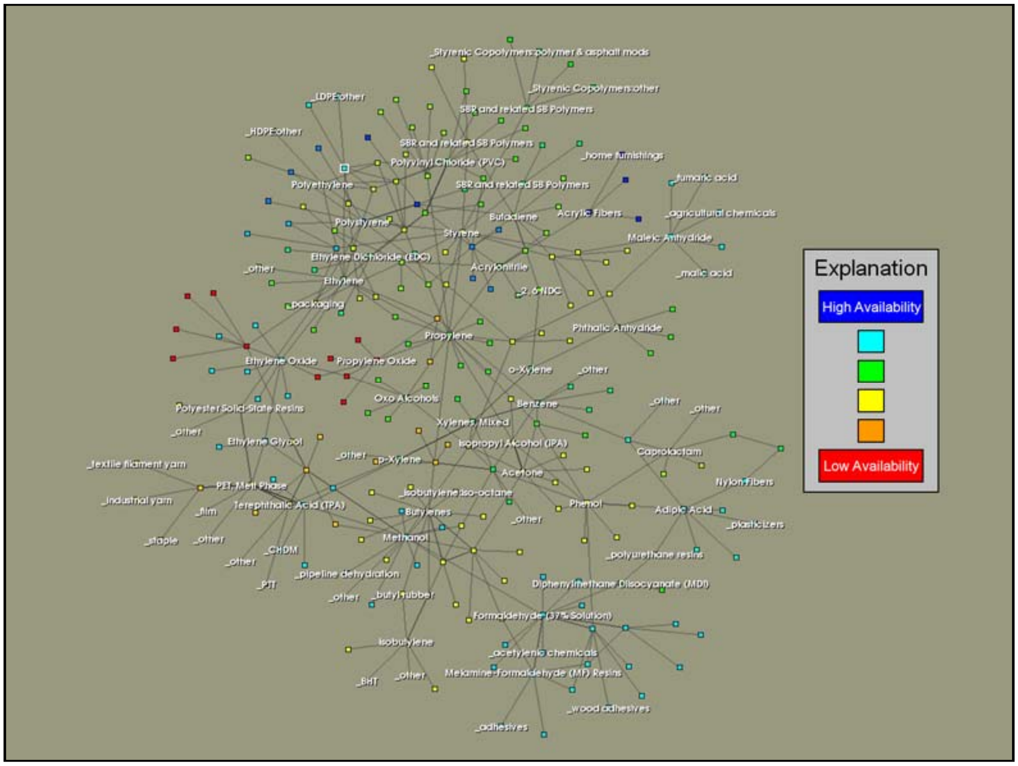

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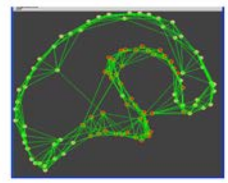
Summary & Future Directions

- 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)

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