Simulation and Analysis of Cascading Failure in Critical Infrastructure

Robert Glass[1], Walt Beyeler[1], Kimmo Soramäki[2], Morten Bech[3] and Jeffrey Arnold[3]

[1]Sandia National Laboratories
[2]European Central Bank
[3]Federal Reserve Bank of New York

Los Alamos

NISAC

Sandia National Laboratories

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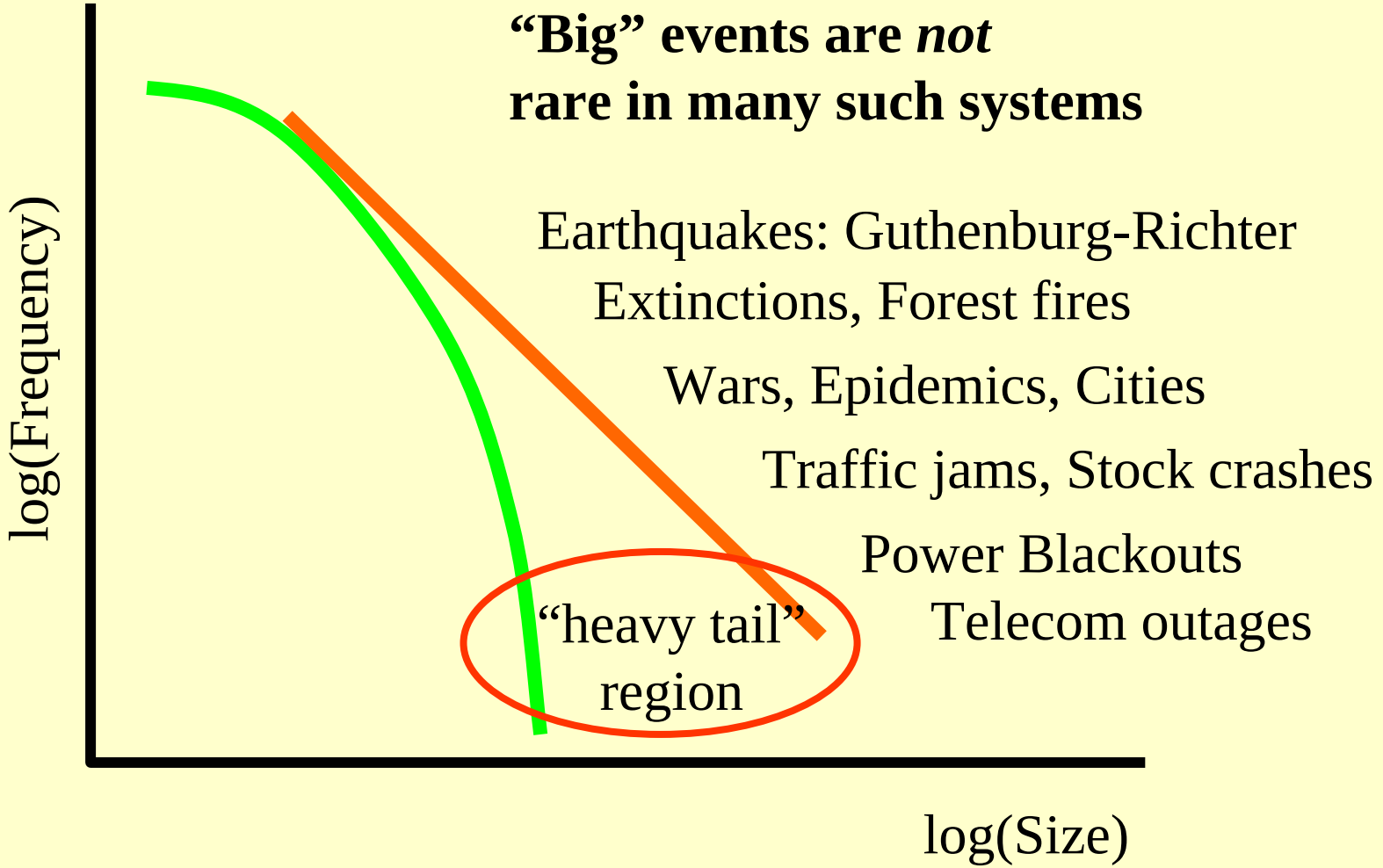
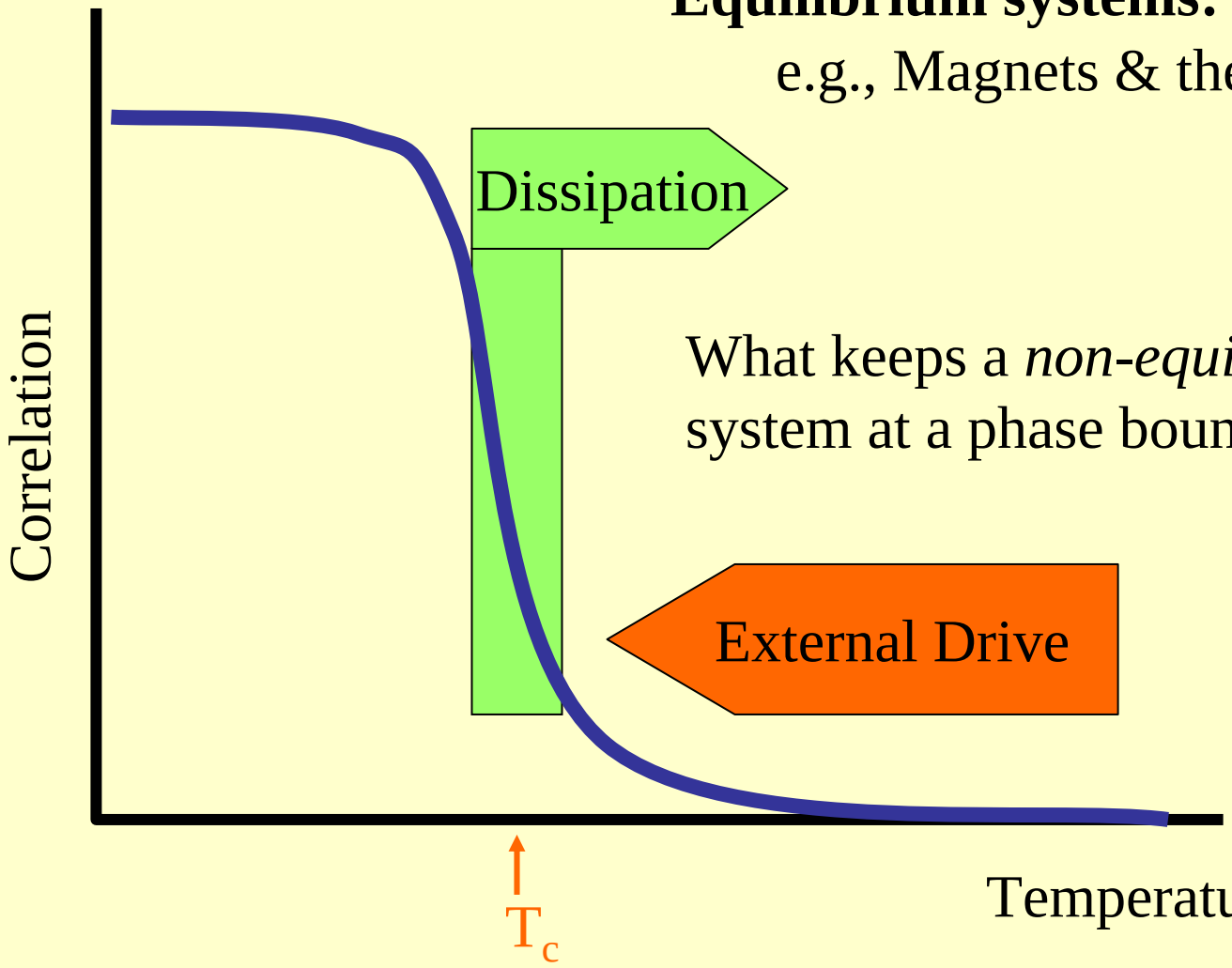
First Stylized Fact: Multi-component Systems often have power-laws & "heavy tails"



Power Law - Critical behavior – Phase transitions

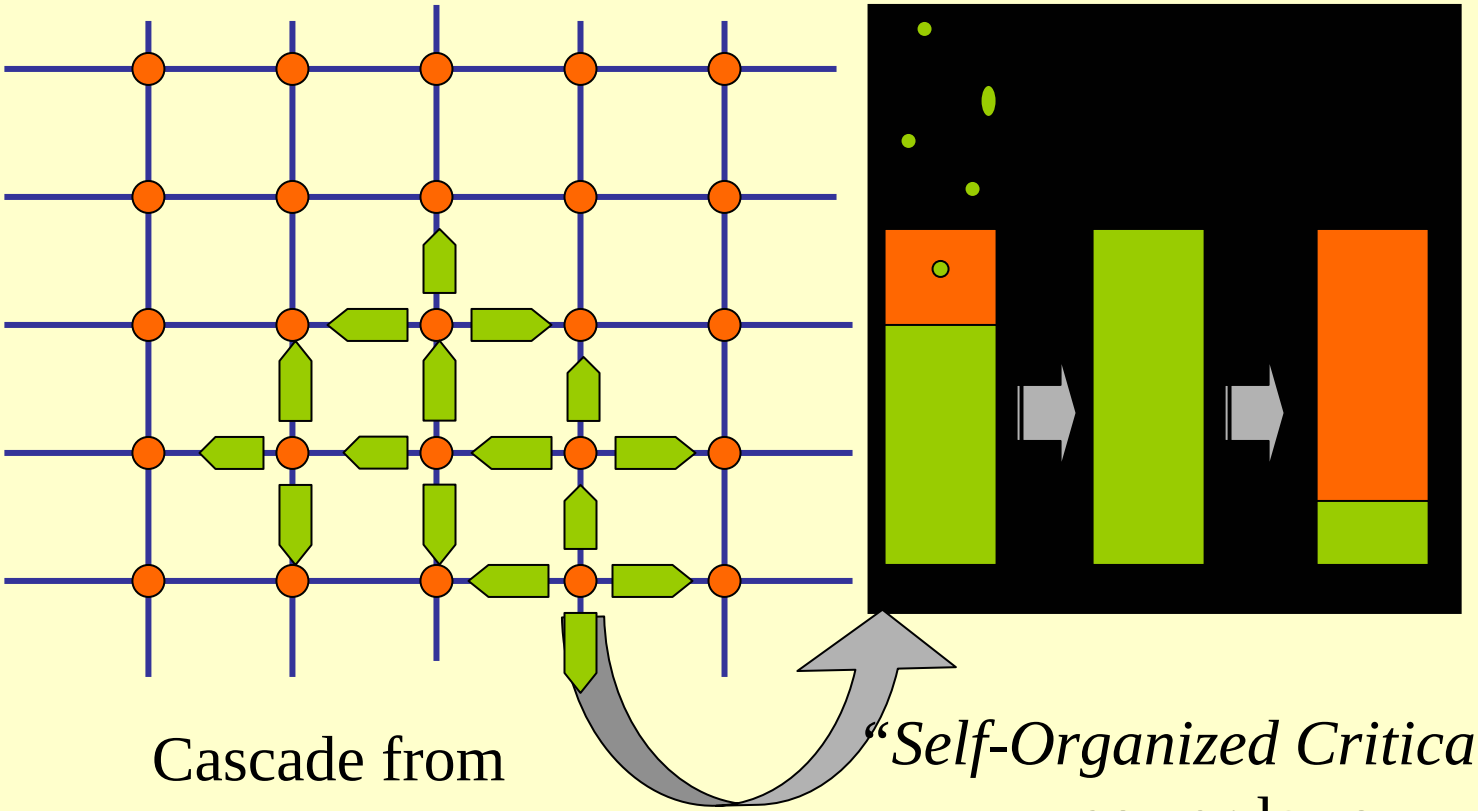
Equilibrium systems:

e.g., Magnets & the Curie point



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

Second Stylized Fact: Networks are Ubiquitous

Food Web

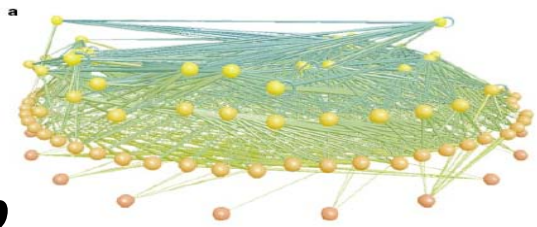
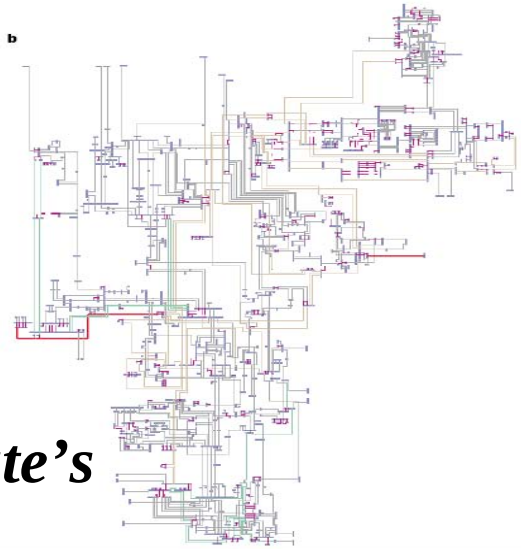
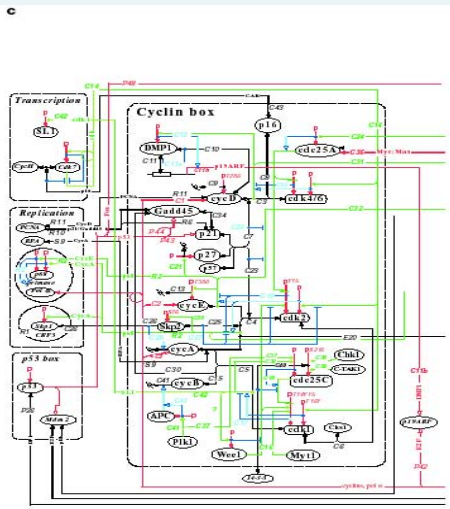


Figure 1 Wiring diagrams for complex networks. **a**, Food web of Little Rock Lake, Wisconsin, currently the largest food web in the primary literature[5]. Nodes are functionally distinct 'trophic species' containing all taxa that share the same set of predators and prey. Height indicates trophic level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





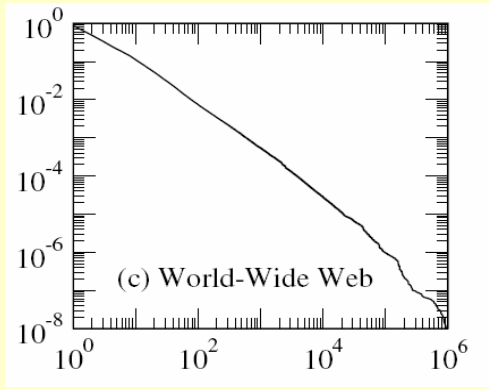
Molecular Interaction

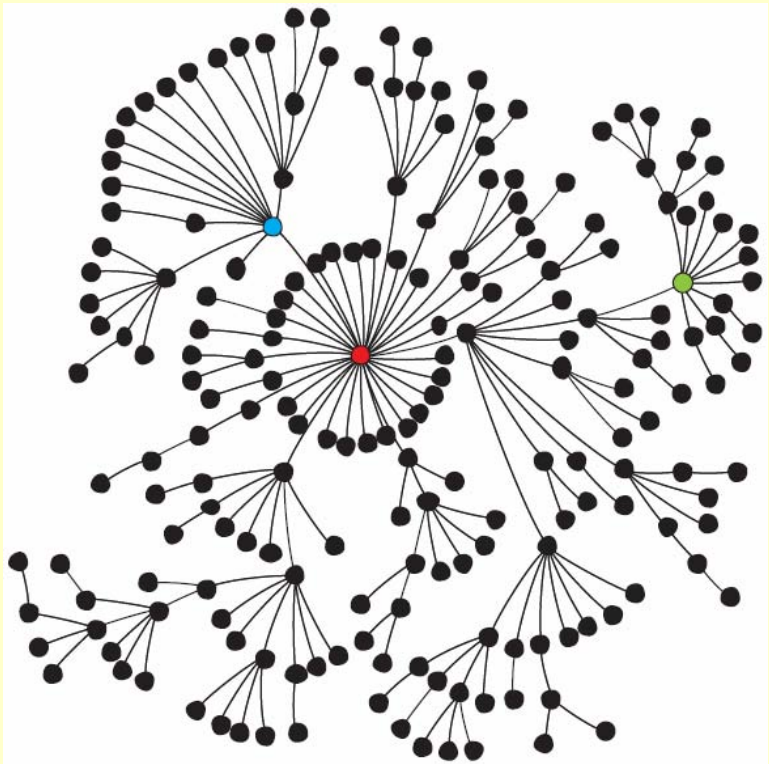
New York state's Power Grid

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

Special properties of the "Scale-free" network

Power-law degree distribution





Hierarchical with
"King-pin" nodes

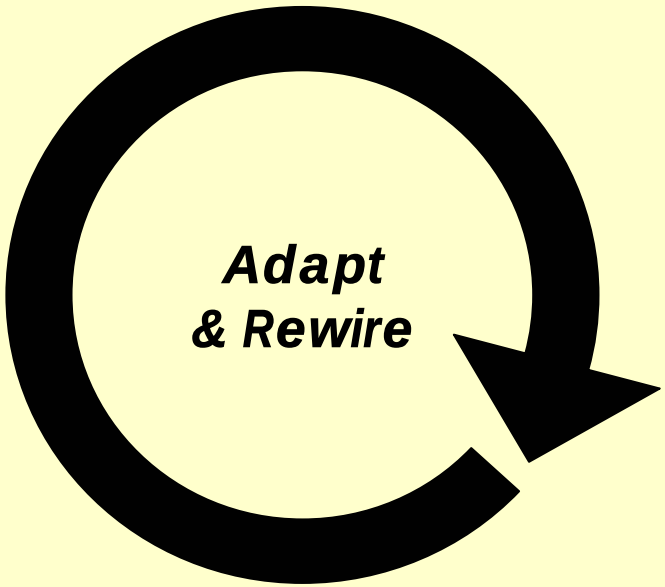
Properties:
vulnerable to
informed attack…

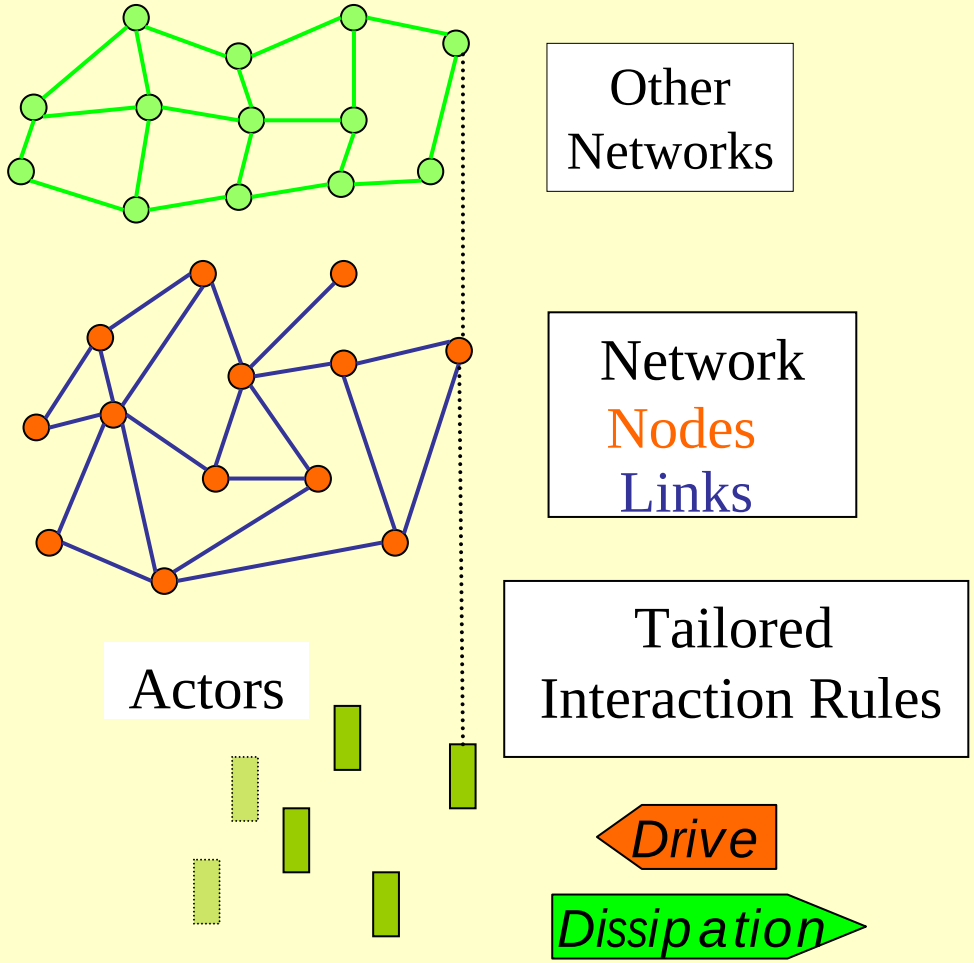
tolerant to random failure

Our Conceptual Approach: Rules ON Networks for Bottoms up Simulation of Infrastructures

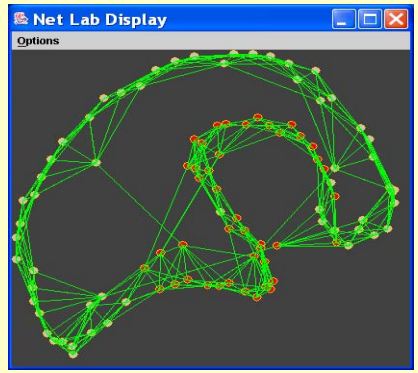
PolyNet

Built in Repast





Development & Applications



Abstract Studies

Stylized Physical Infrastructure Applications:

High Voltage Electric Power Grids

Payment and Banking Systems

Information Networks

Physical + SCADA + Market + Policy Forcing

Stylized Social Applications:

Epidemics

Social/Report Network Evolution

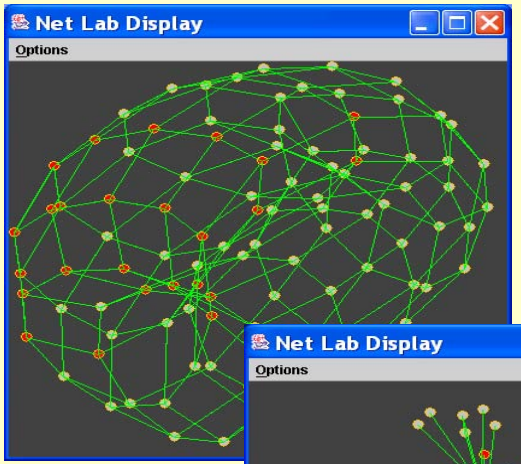
Self-organized Terrorist/Extremist groups

Crisis and recovery from WMD & Bio attacks

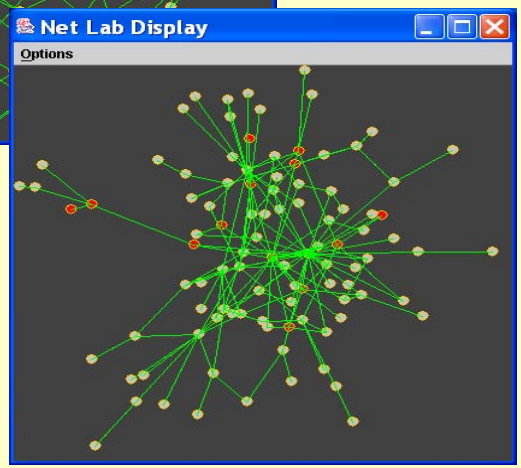
Where we are headed:

Combined Physical-Human "Infrastructure" Systems

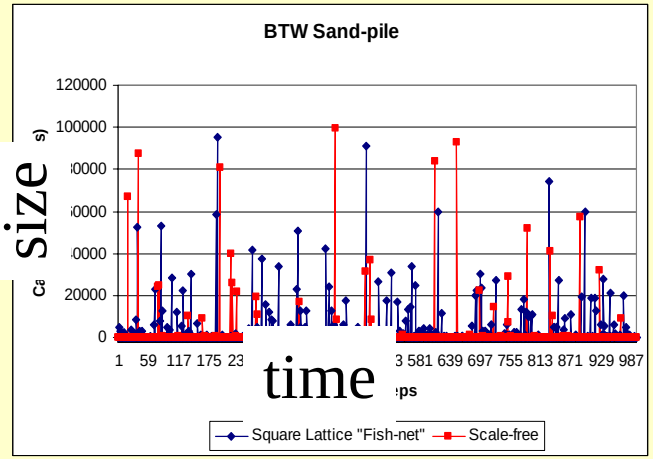
BTW sand-pile on varied topology

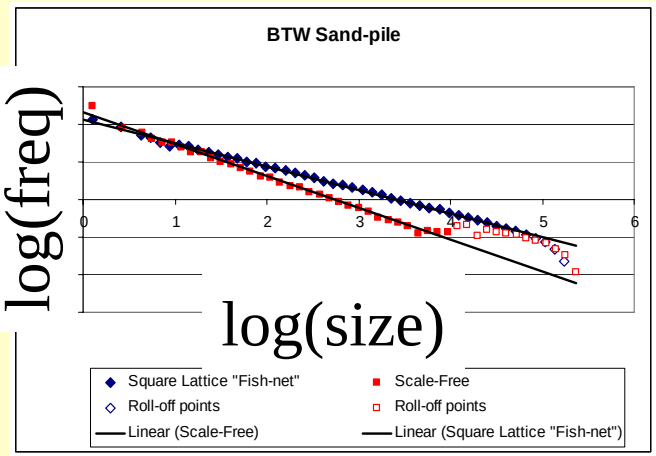


Fish-net
or Donut



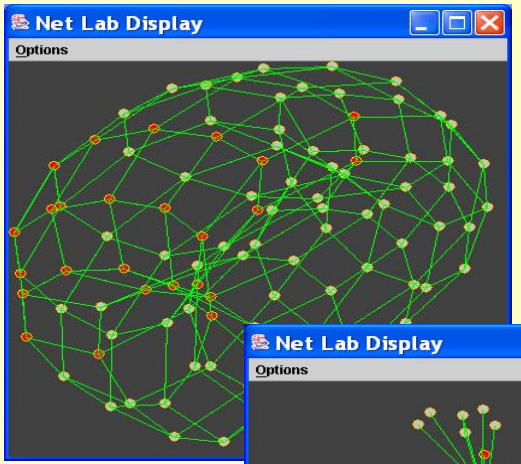
Scale-free





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

Cascading Blackouts



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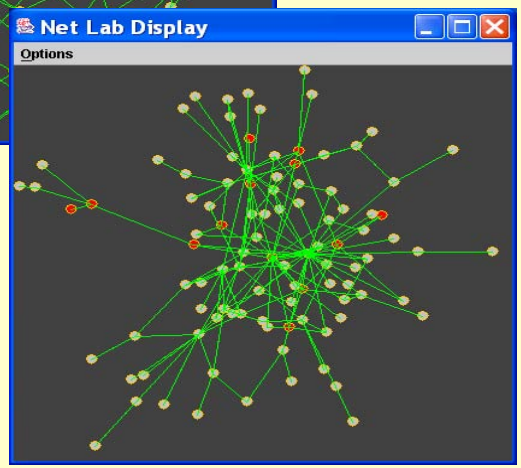
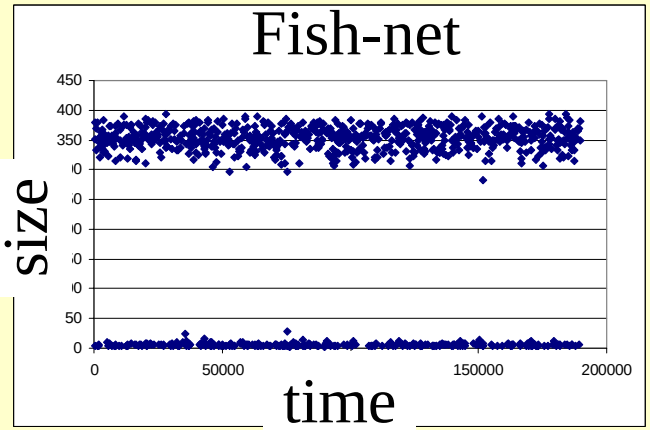
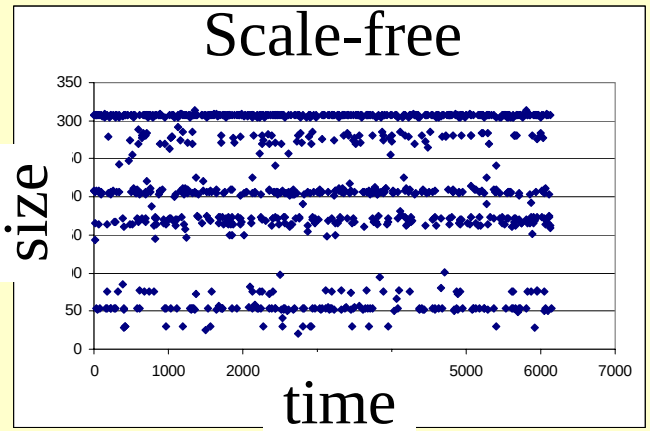


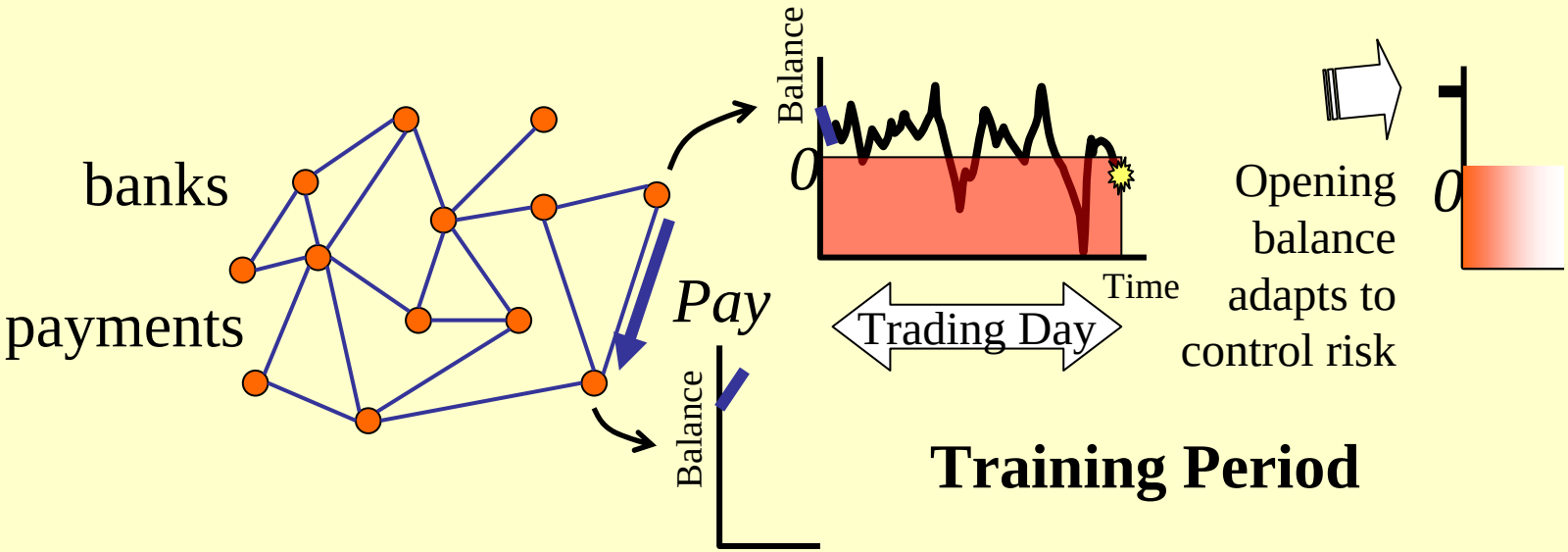
Scale-free



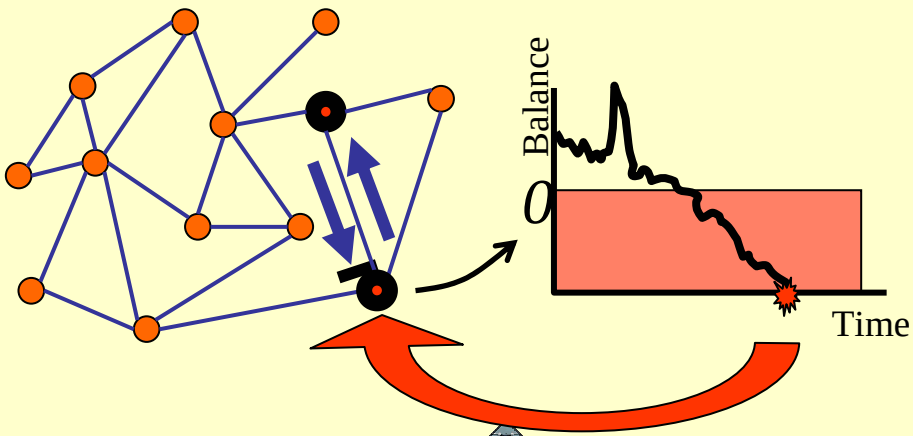


Sources, sinks, relay stations, 400 nodes
DC circuit analogy, load, safety factors
Random transactions between sources and sinks

Cascading Liquidity Loss within Payment Systems



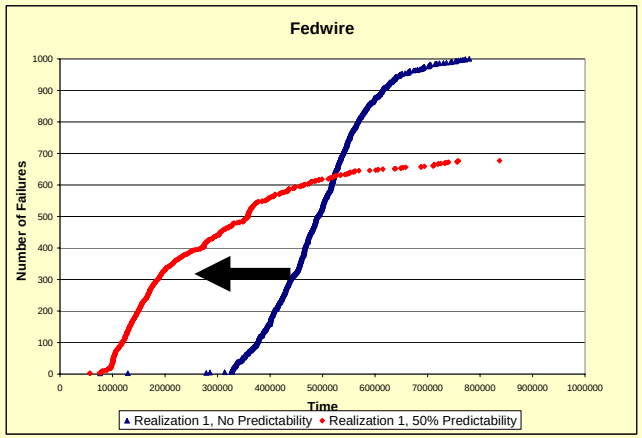
Cascading Period



Cascading Liquidity in Scale-free Network

Patterned Transactions

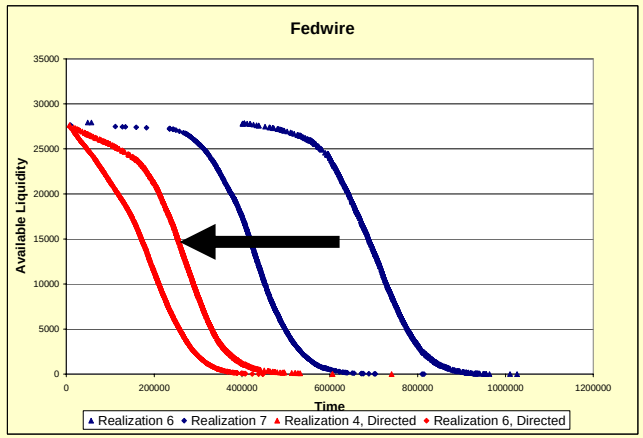
bank defaults



time

Random removal vs Attack of the Highest Degree node

liquidity



time

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Cascading Infectious Diseases

Agent classes

- Kids
- Teens
- Adults
- Seniors

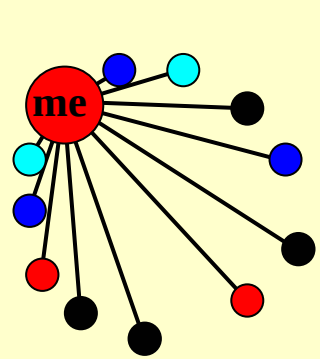
Class Specific Parameters

- Infectivity
- Mortality
- Immunity
- Etc.

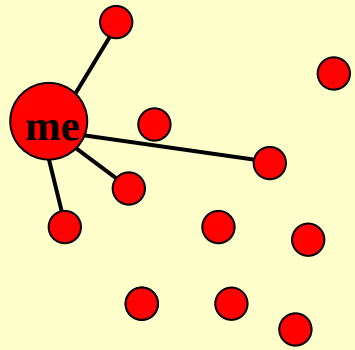
Parameters can change when Symptomatic

Teen Laura Glass's Groups

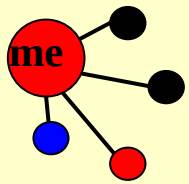
Links & Frequency



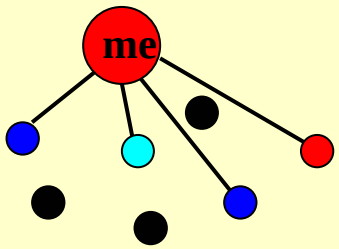
Extended Family



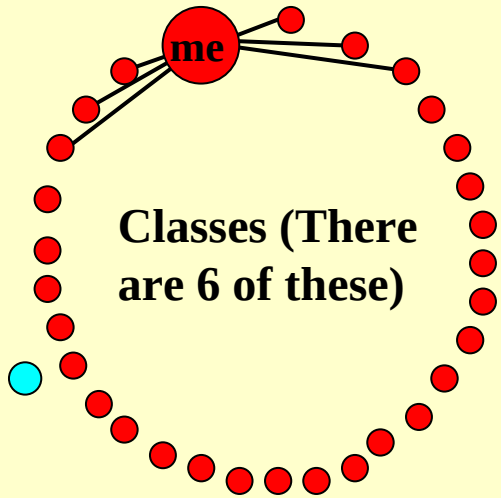
Teen Extra



Nuclear Family

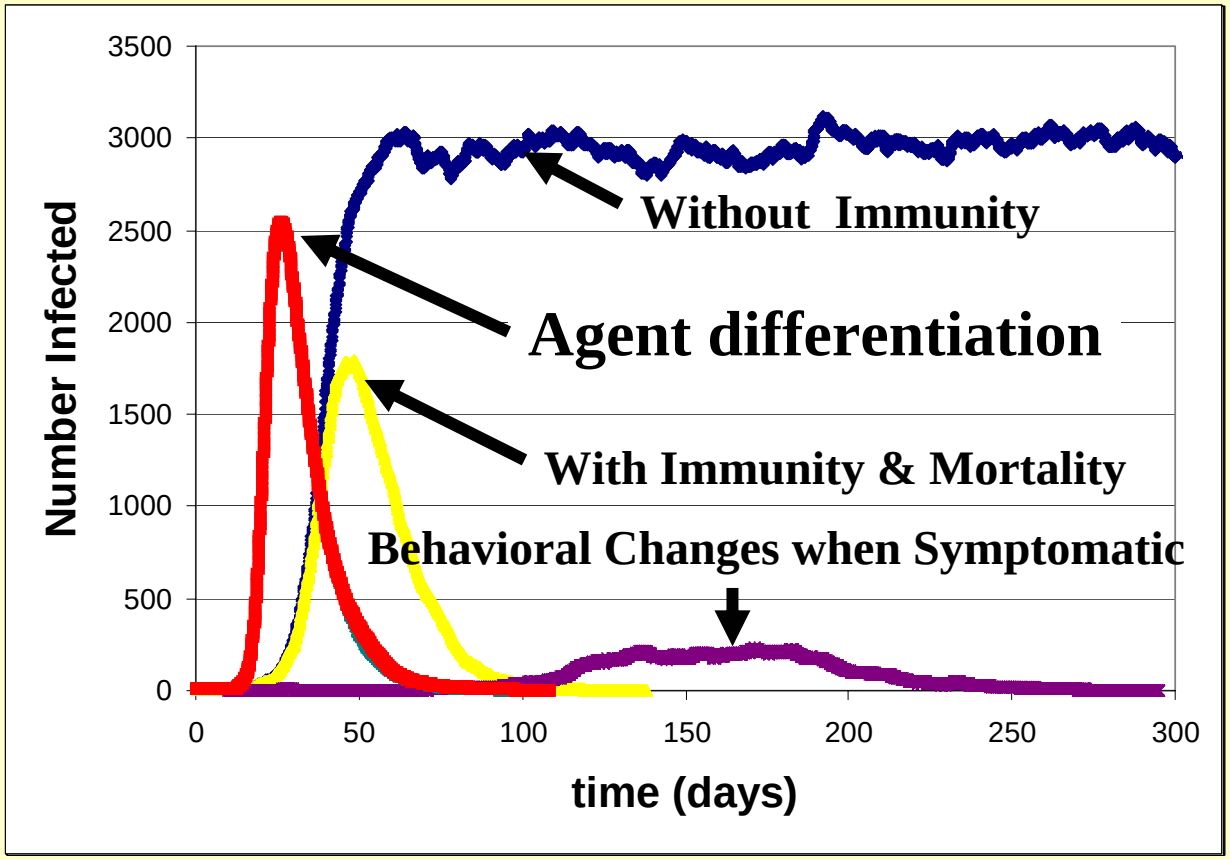


Everyone



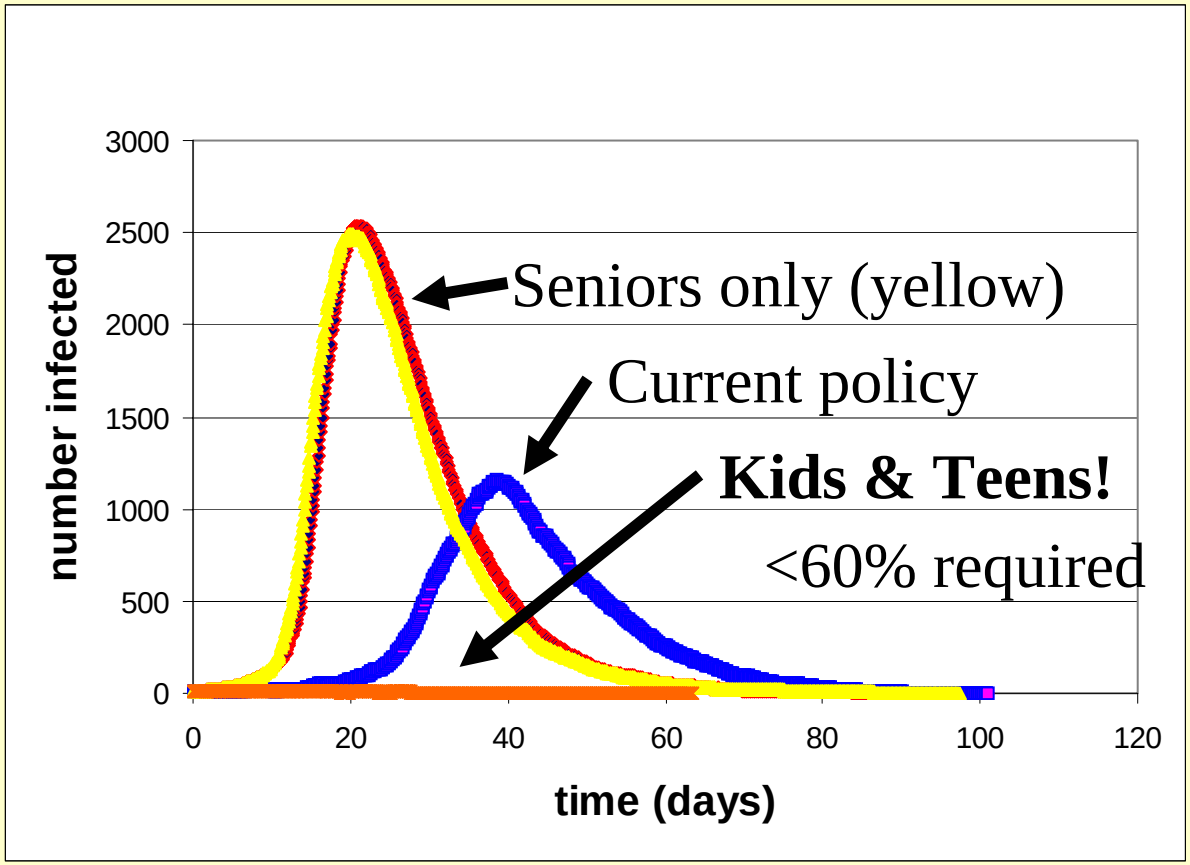
Classes (There are 6 of these)

Influenza Epidemic in Structured Village of 10,000: Increasing Realism



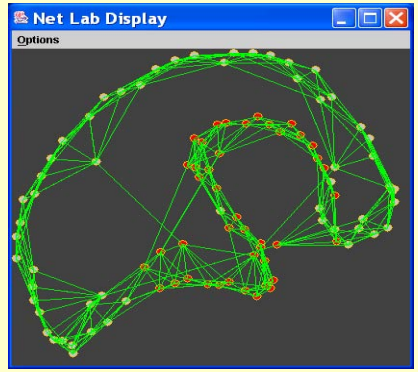
Structure: Heterogeneous Network + Like with Like

Flu Epidemic Mitigation: Vaccination Strategies



Network Structure + Physics of Transmission Process Allows Effective Mitigation Design

General Remarks:



Concepts from Complexity Science are valuable and allow a simulation approach for critical infrastructures that is flexible and has wide ranging applications

Focus on **POLICY**

Developmental directions

Detailed applications with Domain experts

Generalization/Abstraction

Encapsulation/Integration
-NABLE
-BOF simulator

Tools/Insight for Rapid deployment