Office of Infrastructure Protection (IP)

National Infrastructure Simulation and Analysis Center (NISAC)

Complex Adaptive Systems of Systems (CASoS) Engineering

DHS Economic Roundtable

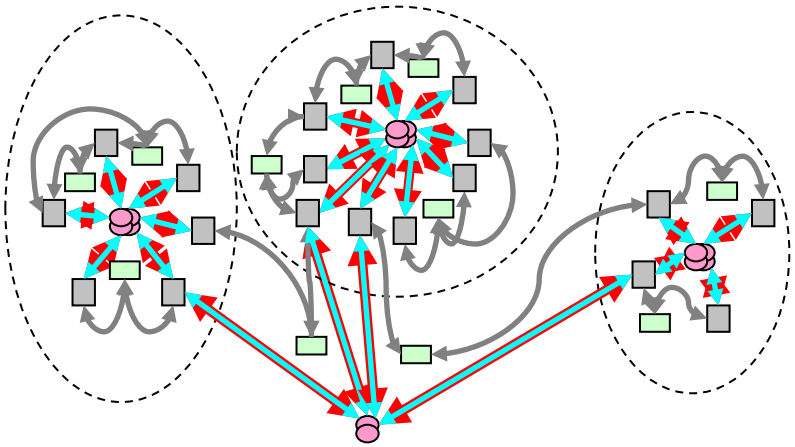
April 17, 2009

Homeland Security

UNCLASSIFIED

Outline

- **Beginnings, Definitions and Examples**
- **General approach for modeling CASoS**
- **Engineering within a CASoS: Example of Influenza Pandemic Mitigation Policy Design**
- **Important Insights for CASoS Engineering**
- **Initial development for the Global Financial System**



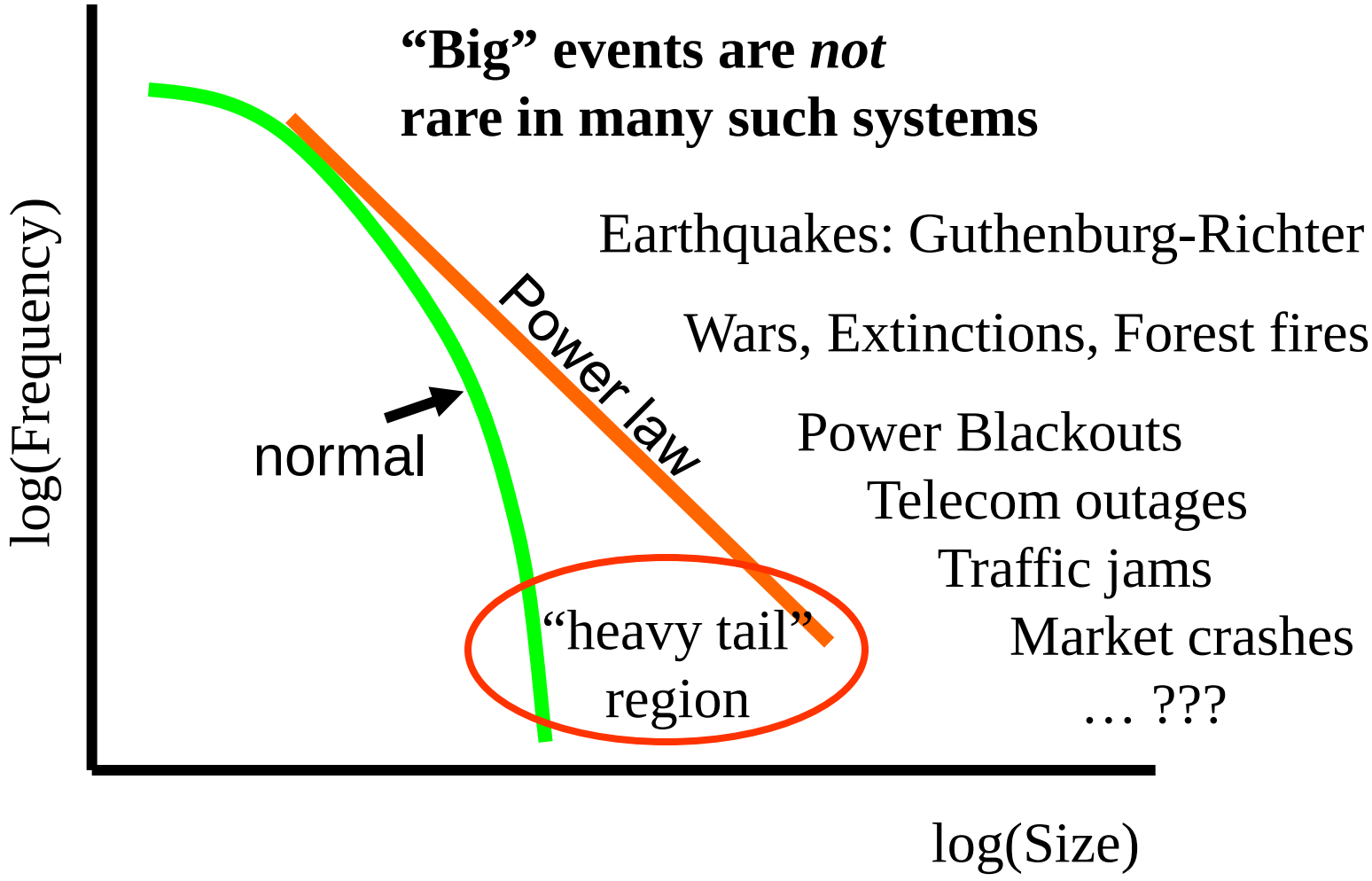
2003: Advanced Methods and Techniques Investigations (AMTI)

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

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



Second Stylized Fact: Networks are Ubiquitous

Food Web

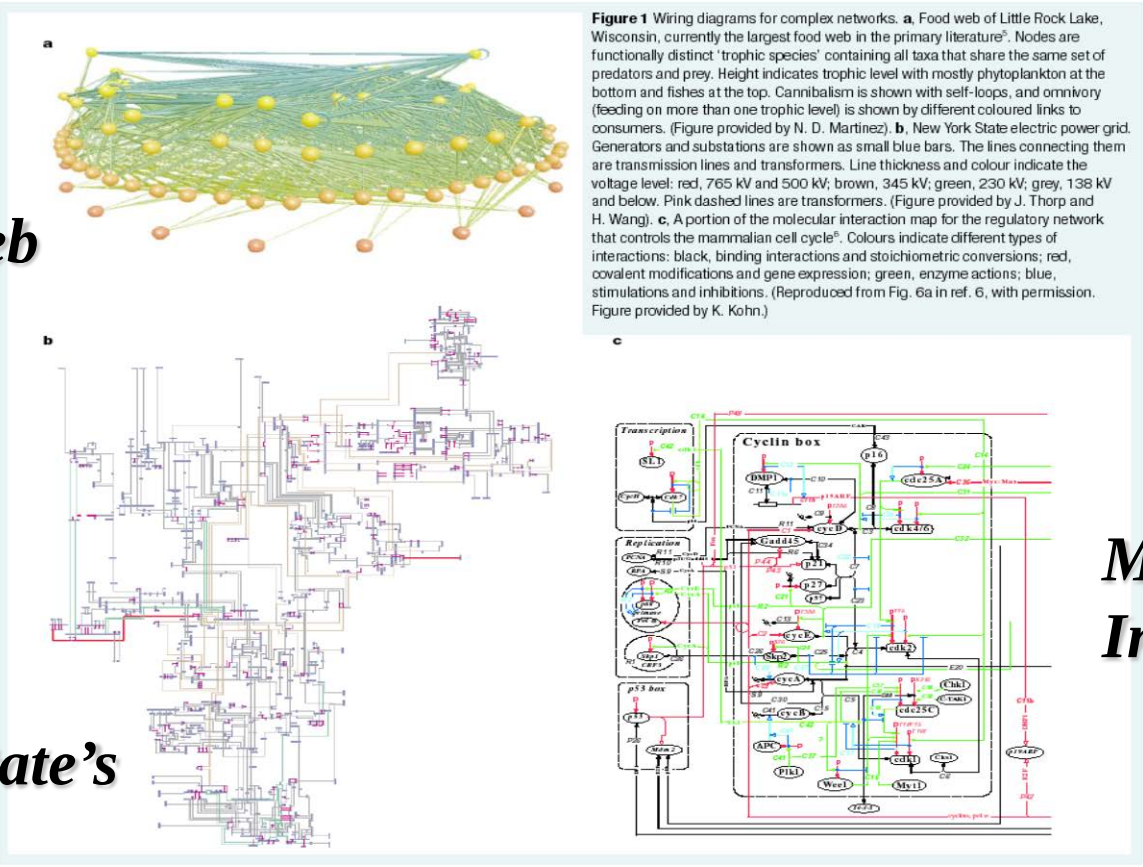


Figure 1 Wiring diagrams for complex networks. **a**, Food web of Little Rock Lake, Wisconsin, currently the largest food web in the primary literature[5]. Nodes are functionally distinct 'trophic species' containing all taxa that share the same set of predators and prey. Height indicates trophic level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

New York state's Power Grid

Molecular Interaction

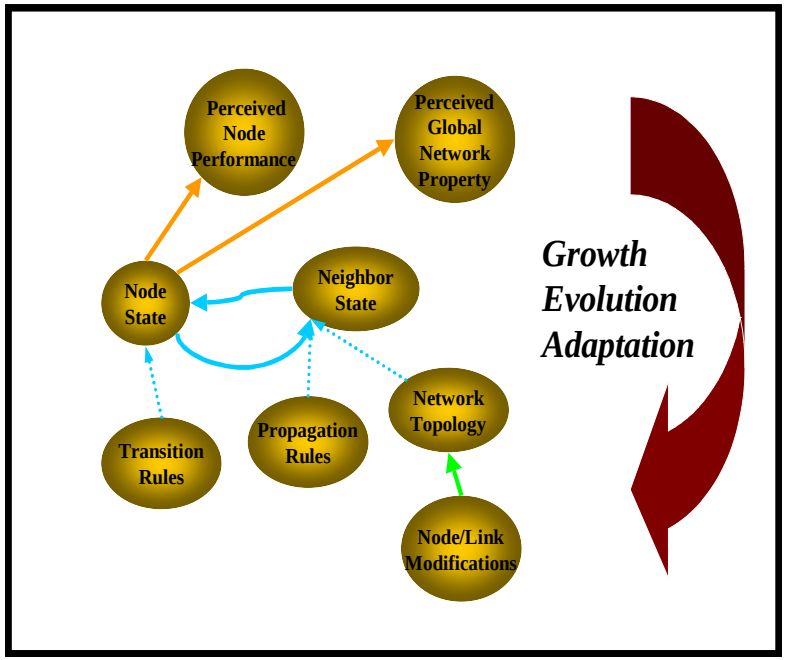
Illustrations of natural and constructed network systems from Strogatz [2001].

Generalized Method: Networks of Entities

Take any system and Abstract as:

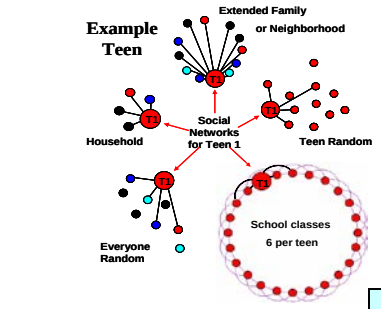
- **Nodes (“Entities” with a variety of “types”)**
- **Links or “connections” to other nodes (with a variety of “modes”)**
- **Local rules for Nodal and Link behavior**
- **Local Adaptation of Behavioral Rules**
- **“Global” forcing from Policy**

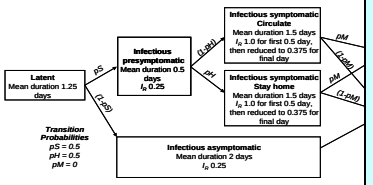
Connect nodes appropriately to form a system (network)
Connect systems appropriately to form a System of Systems



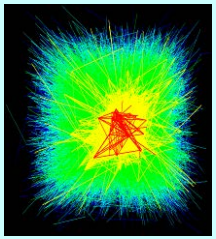
NISAC Applications

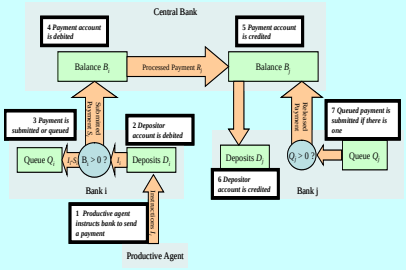
Infectious Disease Spread



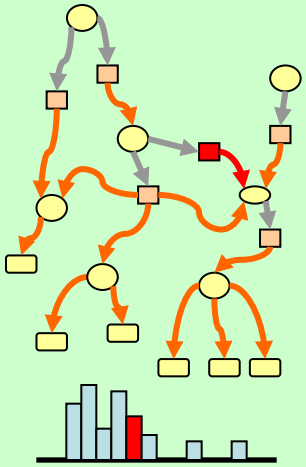


Banking Interactions



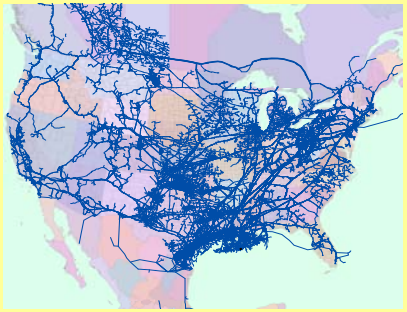


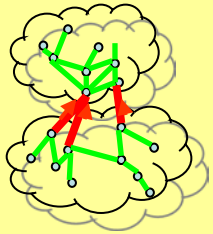
Petrochemical Interdependencies



Capacity

Natural Gas Transmission





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

Defining 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

Analogy with other Complex Systems

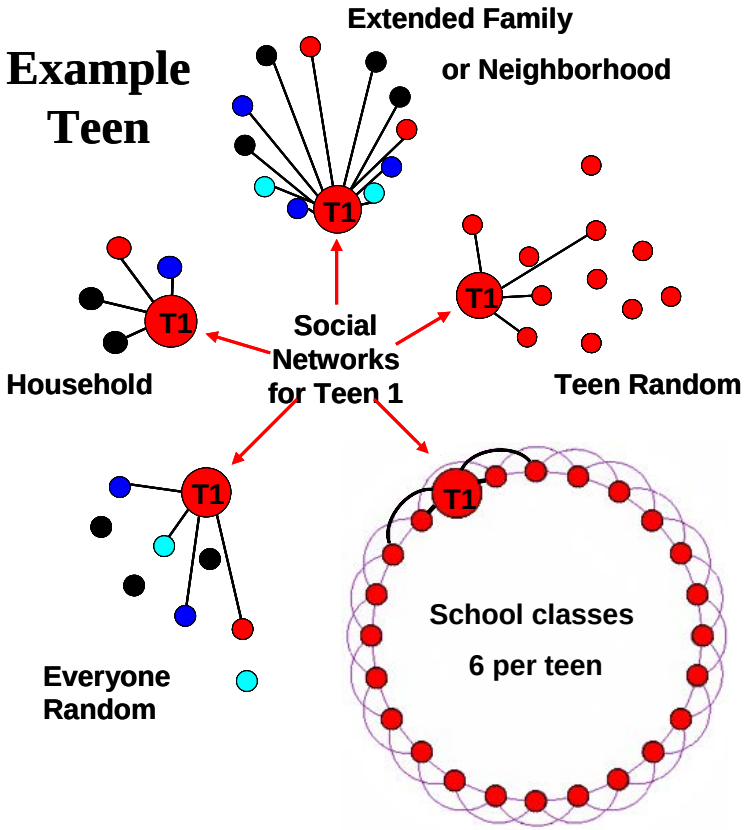
Simple analog:

- 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?**

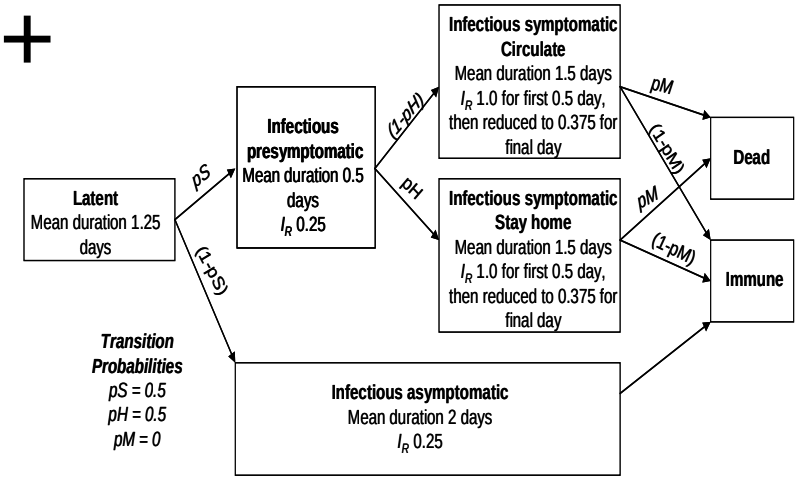
Application of Networked Agent Method



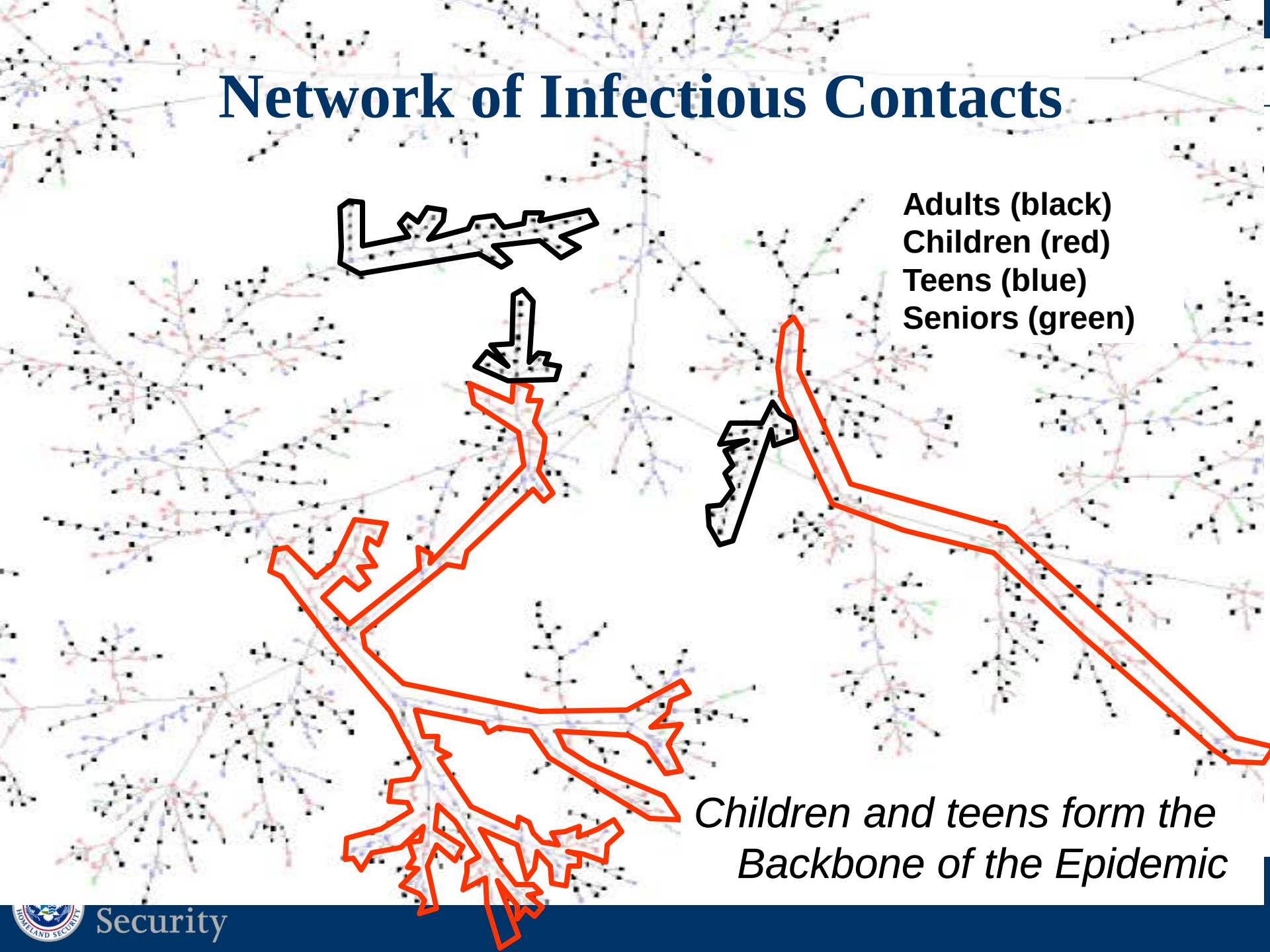
Stylized Social Network
(nodes, links, frequency of interaction)

+

Disease manifestation
(node and link behavior)

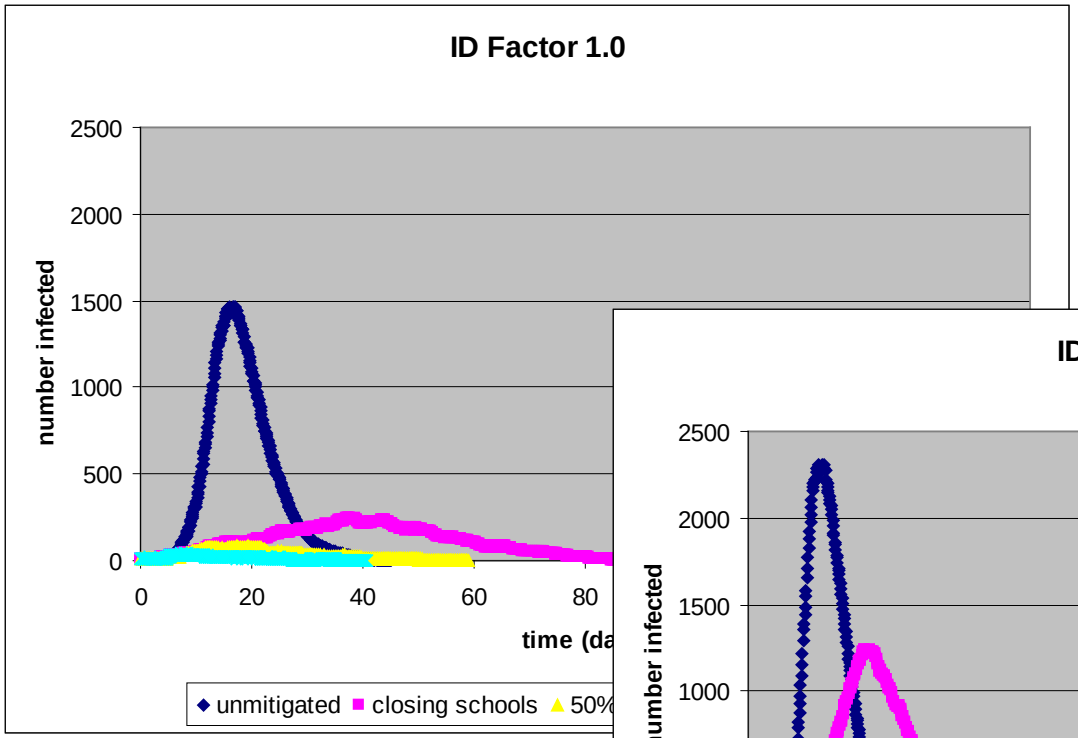


Network of Infectious Contacts

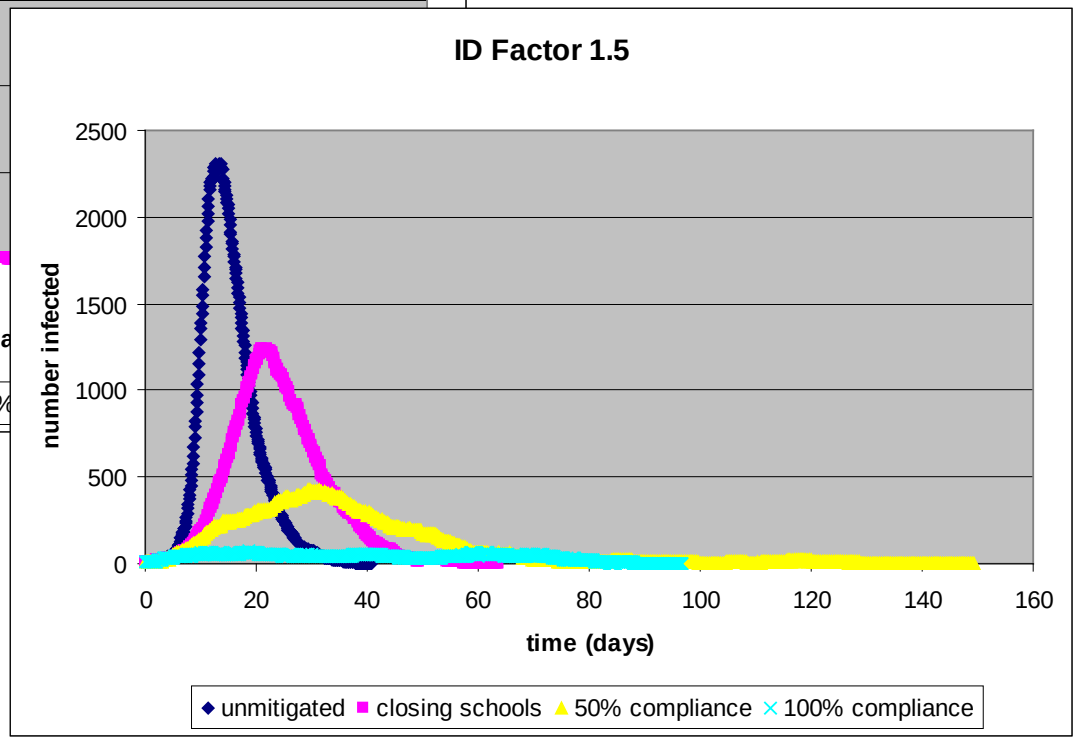


Children and teens form the Backbone of the Epidemic

Closing Schools and Keeping the Kids Home



1958-like



1918-like

Worked with the HSC to formulate Public Policy

A year later…

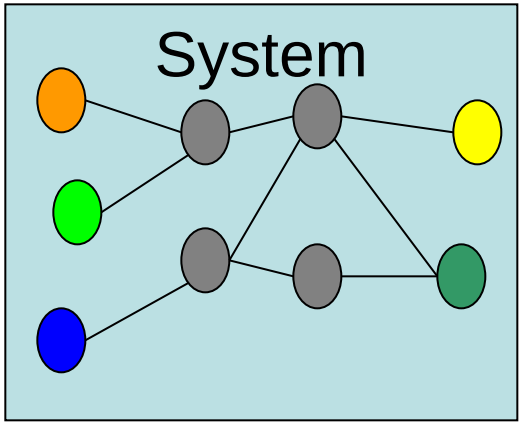
Interim Pre-pandemic Planning Guidance: Community Strategy for Pandemic Influenza Mitigation in the United States—

Early, Targeted, Layered Use of Nonpharmaceutical Interventions

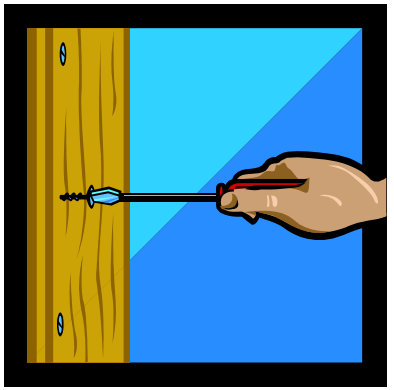
Model? Build the right one

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

What to we care about?



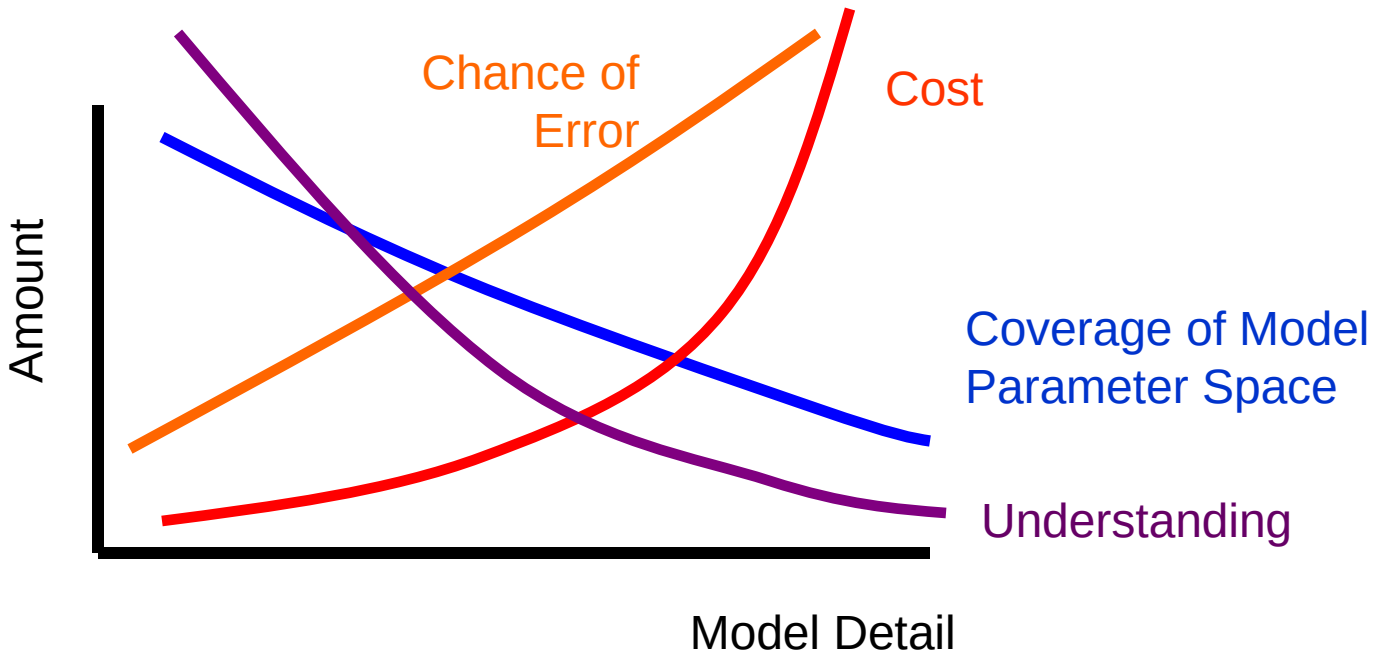
What can we do?



Model

Additional structure and details added *as needed*

Detail? More can be less



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

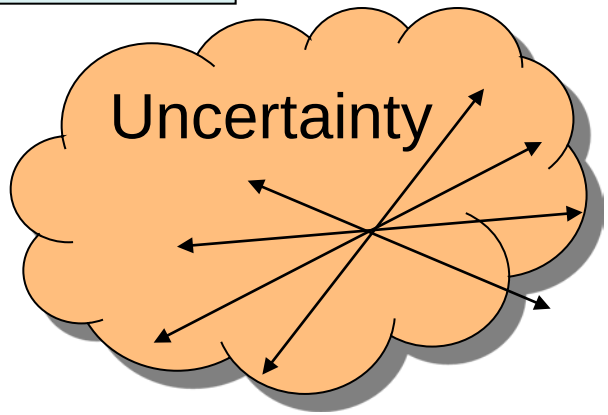
Uncertainty? Focus on robustness of Choice

Policies or Actions

Model

Measures of System Performance

Rank Policies by Performance measures while varying parameters within expected bounds

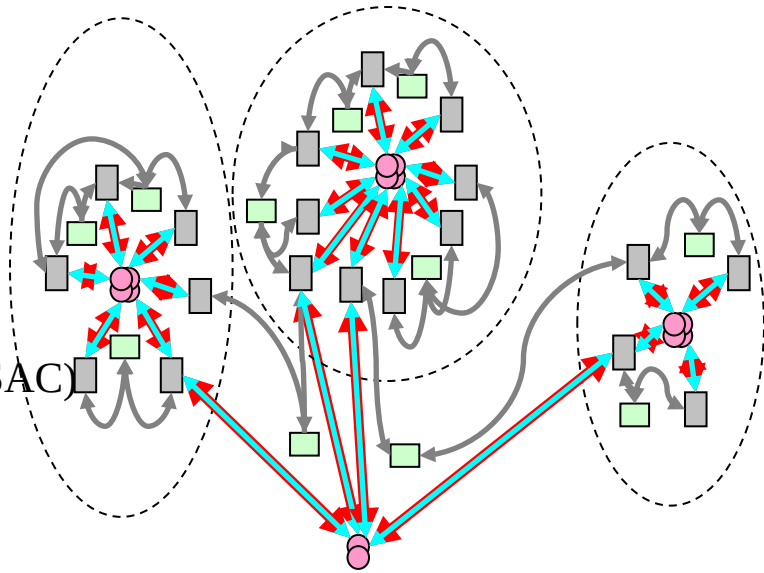


"Best" policies are those that always rank high, their ***choice is robust to uncertainty***

CASoS Engineering

- **Harnassing the tools and understanding of Complex Systems, Complex Adaptive Systems, and Systems of Systems to Engineer solutions for some of the worlds biggest, toughest problems: The CASoS Engineering Initiative**

- **Current efforts across a variety of Funders:**
  - Global Financial System (NISAC)
  - Global Energy System (DOE)
  - Health Care Systems (VA)
  - Cascading in Multi-Network Infrastructure (DOE)
  - Building out the critical national infrastructures (NISAC)



Causes of instability

- **Typical pattern of financial crises:**
  - Displacement followed by asset inflation
  - Credit expansion
  - Asset price leveling and collapse
  - Default

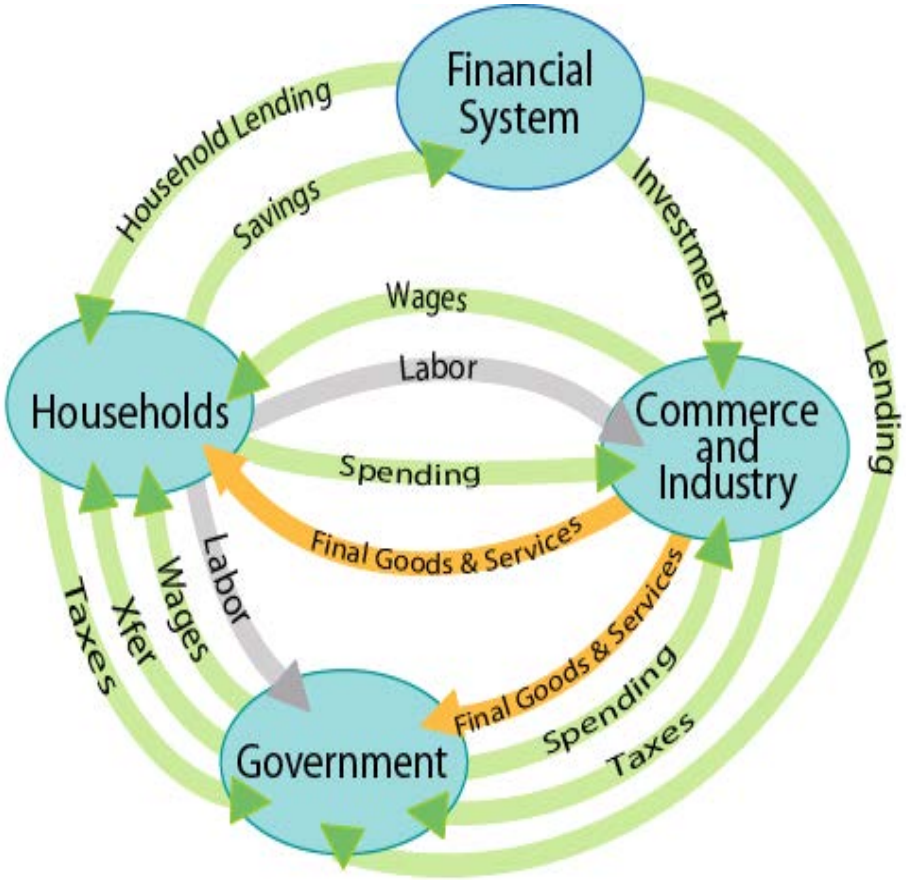
"Details proliferate; structure abides" - Charles P. Kindleberger

- **Most markets at most times are dominated by negative feedbacks**
- **Sometime *reinforcing* feedbacks predominate**
- **Basic feature: price movements change expectations in a way that fosters stronger movements in the same direction**
- **Financial systems are rife with such structures**

Modeling global financial instability

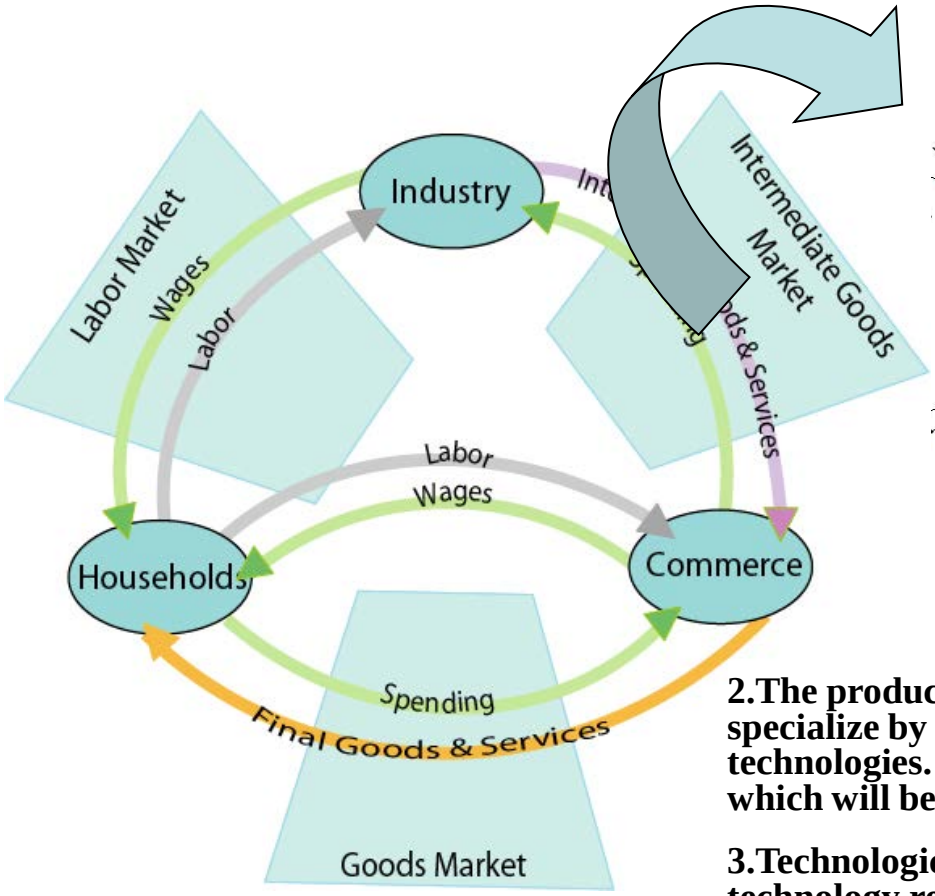
- **Details of global finance are fiendishly complicated and dynamic, and there will always be destabilizing feedbacks in financial systems. Models are unlikely to be able to predict the next collapse.**
- **CASoS engineering framework leads to appropriately focused analyses:**
  - Goals: Moderate the episodic crises that occur in financial systems, as measured by
    - Production
    - Employment
  - Controls:
    - Countercyclical policies (asset prices, spreads,…)
    - Adaptive capital requirements
    - Exchanges for new financial instruments
    - …

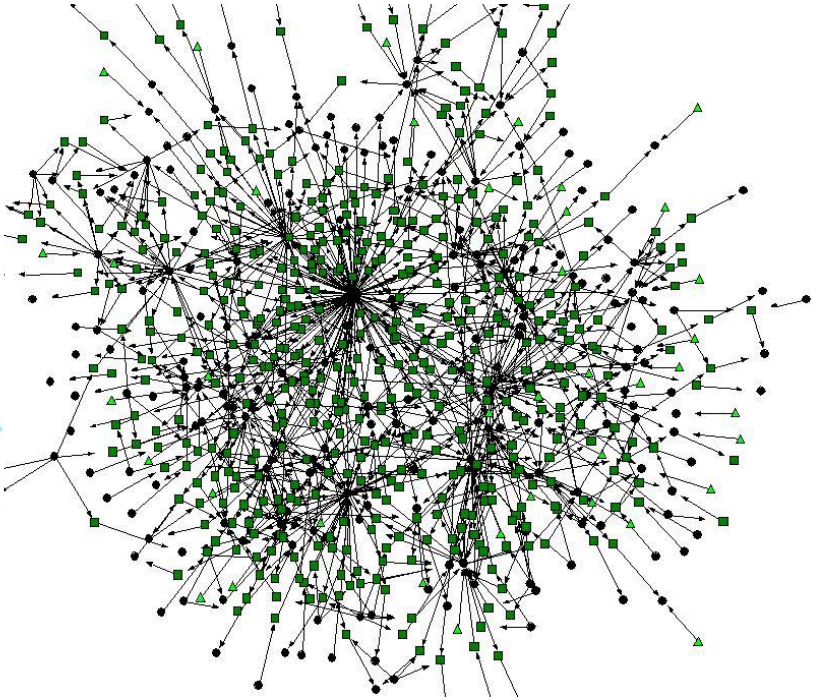
Economic context of finance



- **Intermediation is the key role of finance**
- **Risk perception is essential:**
  - Anticipated performance of allocation to different sectors
  - Counterparty reliability
- **Innovation is essential:**
  - Creates new investment opportunities with uncertain prospects
  - Financial innovation is a feature of many crises.

Staged implementation I

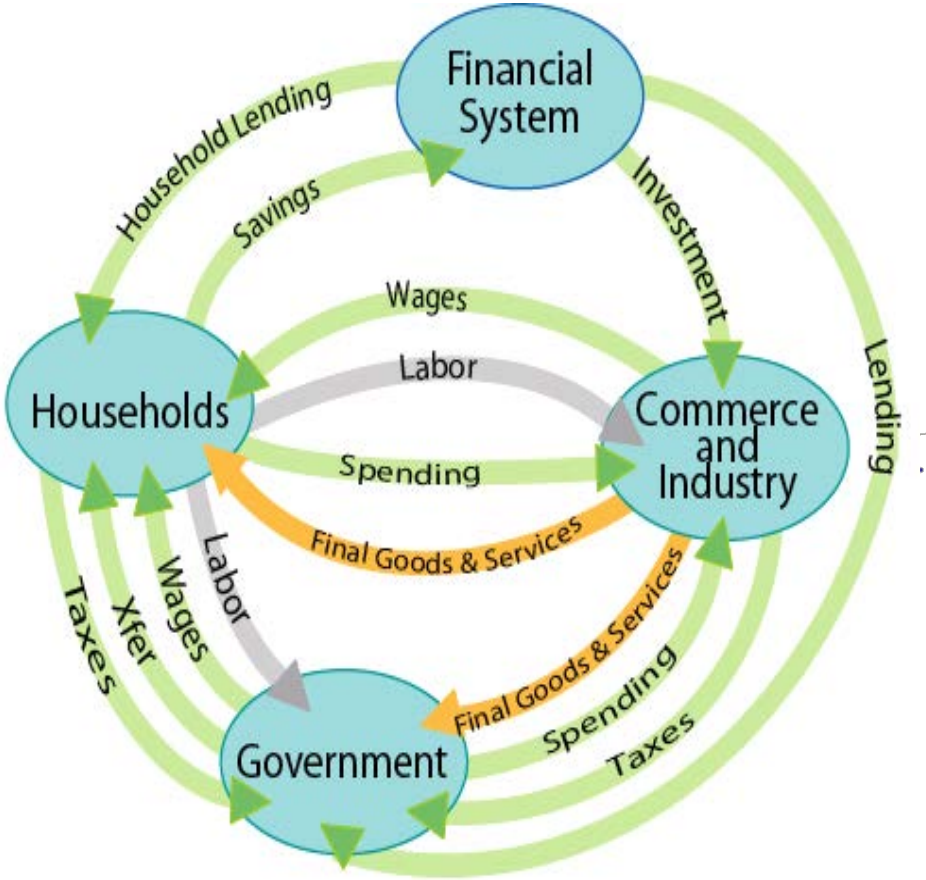




2.The productive sector (commerce and industry) is allowed to specialize by implementing one of a set of randomly-generated technologies. Each technology will employ one or more inputs, one of which will be labor, and produce one or more outputs.

3.Technological improvement (via drift in the coefficients of firms' technology reactions) and disruption (via mutations in firms' reactions to include newly-created resources as inputs or catalysts) is added. Expansion is funded only from retained earnings.

Staged implementation II



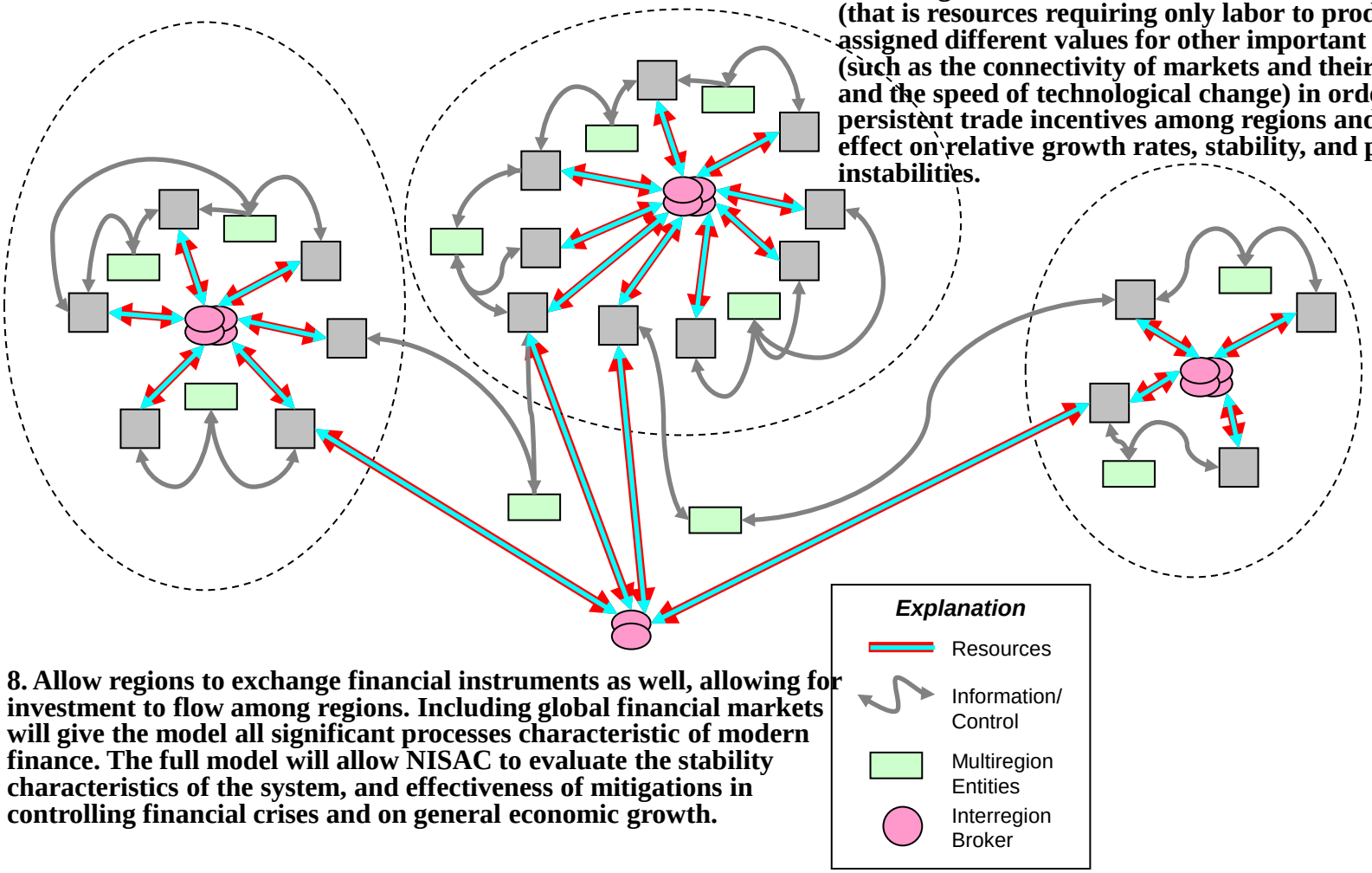
4. A government sector is added as employer and consumer, funded by taxes on transactions. By including this sector, demand and production patterns should shift because the services provided by government (for example, infrastructure, defense and law enforcement) are implicit in the operation of the economy.

5. A basic financial layer is added in which firms, governments, and households can become indebted. Initially only lending is implemented because, unlike equity, debt is available to all entities (households, firms of any size)

6.Add equity markets, allowing firms of a certain size to issue publicly-traded stock. This introduces the second major mechanism for firms to raise capital. Equity shares are another kind of contract, in which the initial purchase gives the buyer a claim on a future revenue stream from dividends.

Staged implementation III

7. Replicate for multiple regions which can exchange goods. These regions will have different endowments of basic resources (that is resources requiring only labor to produce), and may be assigned different values for other important initial parameters (such as the connectivity of markets and their transaction costs, and the speed of technological change) in order to create persistent trade incentives among regions and to study their effect on relative growth rates, stability, and propagation of instabilities.



8. Allow regions to exchange financial instruments as well, allowing for investment to flow among regions. Including global financial markets will give the model all significant processes characteristic of modern finance. The full model will allow NISAC to evaluate the stability characteristics of the system, and effectiveness of mitigations in controlling financial crises and on general economic growth.

References in Banking and Finance

Publications

- A General Engineering Framework for the Definition, Design, Testing and Actualization of Solutions within Complex Adaptive Systems of Systems (CASoS) with Application to the Global Energy System (GES), Robert J. Glass, Arlo L. Ames, Walter E. Beyeler, Bernard Zak, David A. Schoenwald, Sean A. McKenna, Stephen H. Conrad , S. Louise Maffitt, Sandia National Laboratories SAND 2008-7952, December 2008
- The Payments System and the Market of Interbank Funds, Morten L. Bech, Walter E. Beyeler, Robert J. Glass, and Kimmo Soramäki, Part 4 in New Directions for Understanding Systemic Risk, Economic Policy Review, Federal Reserve Bank of New York, 2007, .
- Congestion and Cascades in Interdependent Payment Systems, Fabien Renault, Walter E. Beyeler, Robert J. Glass, Kimmo Soramäki, Morten L. Bech, Submitted to International Journal of Central Banking, 2009 .
- New Approaches for Payment System Simulation Research, Kimmo Soramäki, Walter E. Beyeler, Morten Bech, and Robert J. Glass in: Simulation studies of liquidity needs, risks and efficiency in payment networks, Proceedings from the Bank of Finland Payment and Settlement System Seminars 2005-2006, Harry Leinonen ed., (Bank of Finland Studies E:39/2007)
- Congestion and cascades in payment systems (2007-7271), Walter E. Beyeler, Robert J. Glass, Morten Bech and Kimmo Soramäki, Physica A, 15 Oct. 2007; v.384, no.2, p.693-718, accepted May 2007 (also available from Elsevier B.V. /Physica A)
- The Topology of Interbank Payment Flows, Kimmo Soramaki, Morten L. Bech, Jeffrey Arnold, Robert J. Glass, Walter E. Beyeler, Physica A: Statistical Mechanics and Its Applications, June 2007; vol.379, no.1, p.317-33.(also available from Elsevier B.V. /Physica A)
- Congestion and Cascades in Payment Systems, Walter E. Beyeler, Robert J. Glass, Morten L. Bech, Kimmo Soramaki, Federal Reserve Board of New York Staff report, July 2006
- The Topology of Interbank Payment Flows (2006-1984 J), Soramäki, K, ML Bech, J Arnold, RJ Glass, and WE Beyeler, Federal Reserve Bank of New York Staff Reports, no. 243, March 2006
- Advanced Simulation for Analysis of Critical Infrastructure: Abstract Cascades, the Electric power grid, and Fedwire (2004-4239), Robert J. Glass, Walt E. Beyeler, and Kevin L. Stamber
- Defining Research and Development Directions for Modeling and Simulation of Complex, Interdependent Adaptive Infrastructures (2003-1778), Robert J Glass, Walter E Beyeler, Stephen H Conrad, Nancy S Brodsky, Paul G Kaplan, and Theresa J Brown

References (continued)

Conference Papers and Presentations

- Joint Bank of France / European Central Bank Conference on Liquidity in interdependent transfer systems, Paris, 9-10 June 2008
- *Performance and Resilience to liquidity disruptions in interdependent RTGS payment systems* , F. Renault, WE Beyeler, RJ Glass, K. Soramäki and ML Bech
- Modeling Critical Infrastructures with Networked Agent-based Approaches, RJ Glass and WE Beyeler (also presented at Lawrence Livermore, March 2008)
- Joint Bank of England & European Central Bank Conference on Payments and monetary and financial stability, November 2007
- *Congestion and Cascades in Coupled Payment Systems* (paper), F. Renault, WE Beyeler, RJ Glass, K. Soramäki and ML Bech
- International Society of Dynamic Games Workshop, Rabat, Morocco September 2007
- Effect of Learning and Market Structure on Price Level and Volatility in a Simple Market, WE Beyeler, K Soramäki and RJ Glass
- Bank of Finland 5th Payment and Settlement Simulation Seminar and Workshop. Helsinki, Finland, August 2007
- *Congestion and Cascades in Coupled Payment Systems*, WE Beyeler, RJ Glass
- Bank of Finland 4th Payment and Settlement Simulation Seminar and Workshop, Helsinki, Finland, August 2006
- *Network Topology and Payment System Resilience - first results*, K Soramaki, WE Beyeler, ML Bech, RJ Glass
- *Congestion and Cascades in Payment Systems*, WE Beyeler, K Soramaki, ML Bech, RJ Glass
- The National Academy of Sciences of the National Academies/ The Federal Reserve Bank of New York: New Directions for Understanding Systemic Risk, New York City, May 2006
- *Contagion, Cascades and Disruptions to the Interbank Payment System* (2005-4915 C), ML Bech, WE Beyeler, RJ Glass, K Soramaki
- Bank of Finland 3rd Payment and Settlement Simulation Seminar and Workshop, Helsinki, Finland, August 2005
- Network relationships and network models in payment systems, K Soramaki, ML Bech, J Arnold, WE Beyeler, RJ Glass
- Modeling Banks' Payment Submittal Decisions, WE Beyeler, K Soramaki, ML Bech, RJ Glass
- Simulation and Analysis of Cascading Failure in Critical Infrastructure, RJ Glass, WE Beyeler, K Soramaki, ML Bech, J Arnold
- Working Together: R&D Partnerships in Homeland Security Conference, May 2005
- *Complexity Science: Implications for Critical Infrastructures*, RJ Glass, WE Beyeler, SH Conrad, PG Kaplan, TJ Brown

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- **See our web site for other work: http://www.sandia.gov/nisac/amti.html**


NISAC

Extra Slides

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.

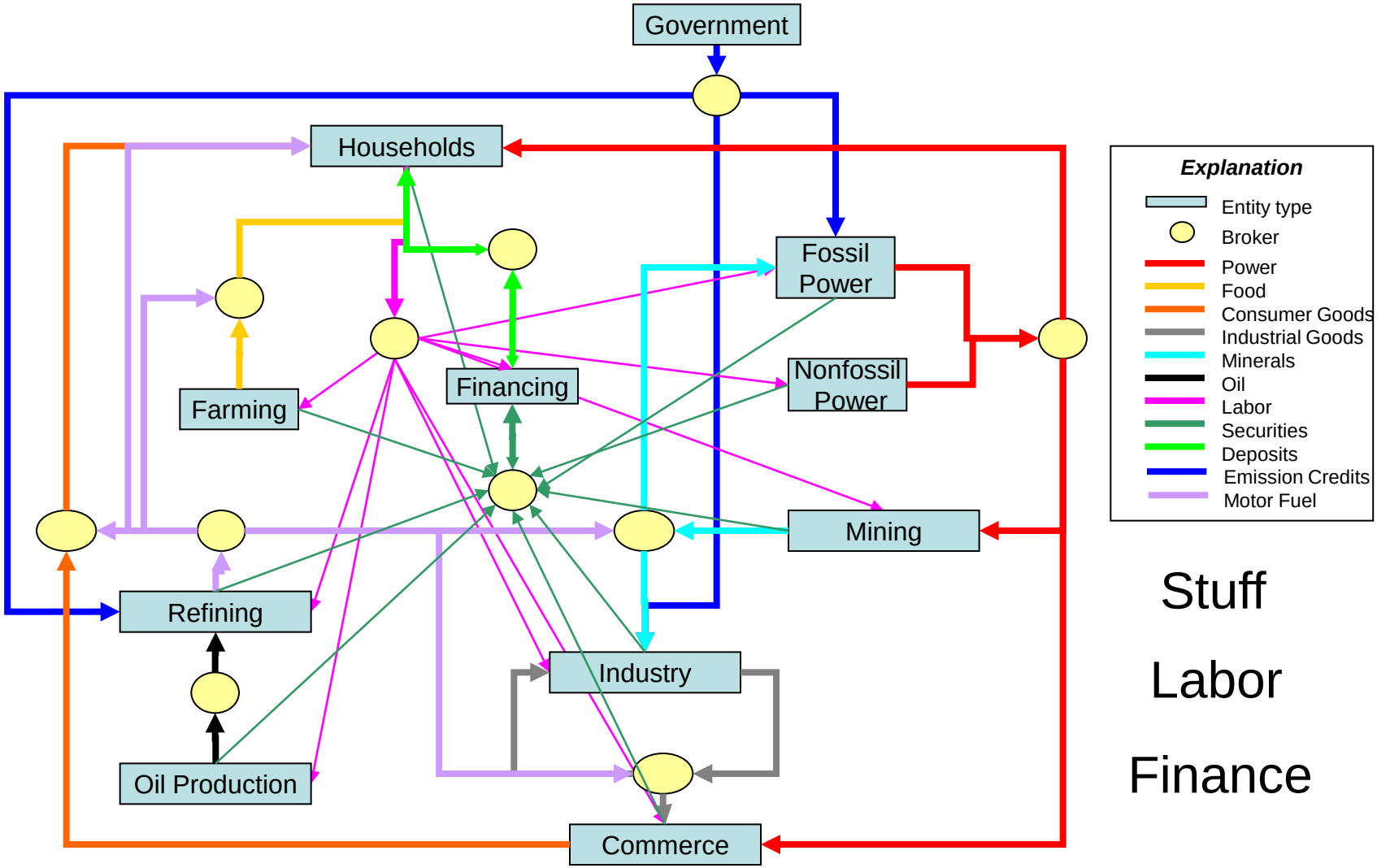
General CASoS Engineering Framework

- 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

Summary

- **Financial systems are driven by perceptions of risk and value**
- **These perceptions are shaped by experience with the performance of the system**
- **The resulting feedback is often destabilizing**
- **Specific predictions are impossible, but the CASoS framework allows us to use models to inform decisions**

Core Economy within Global Energy System

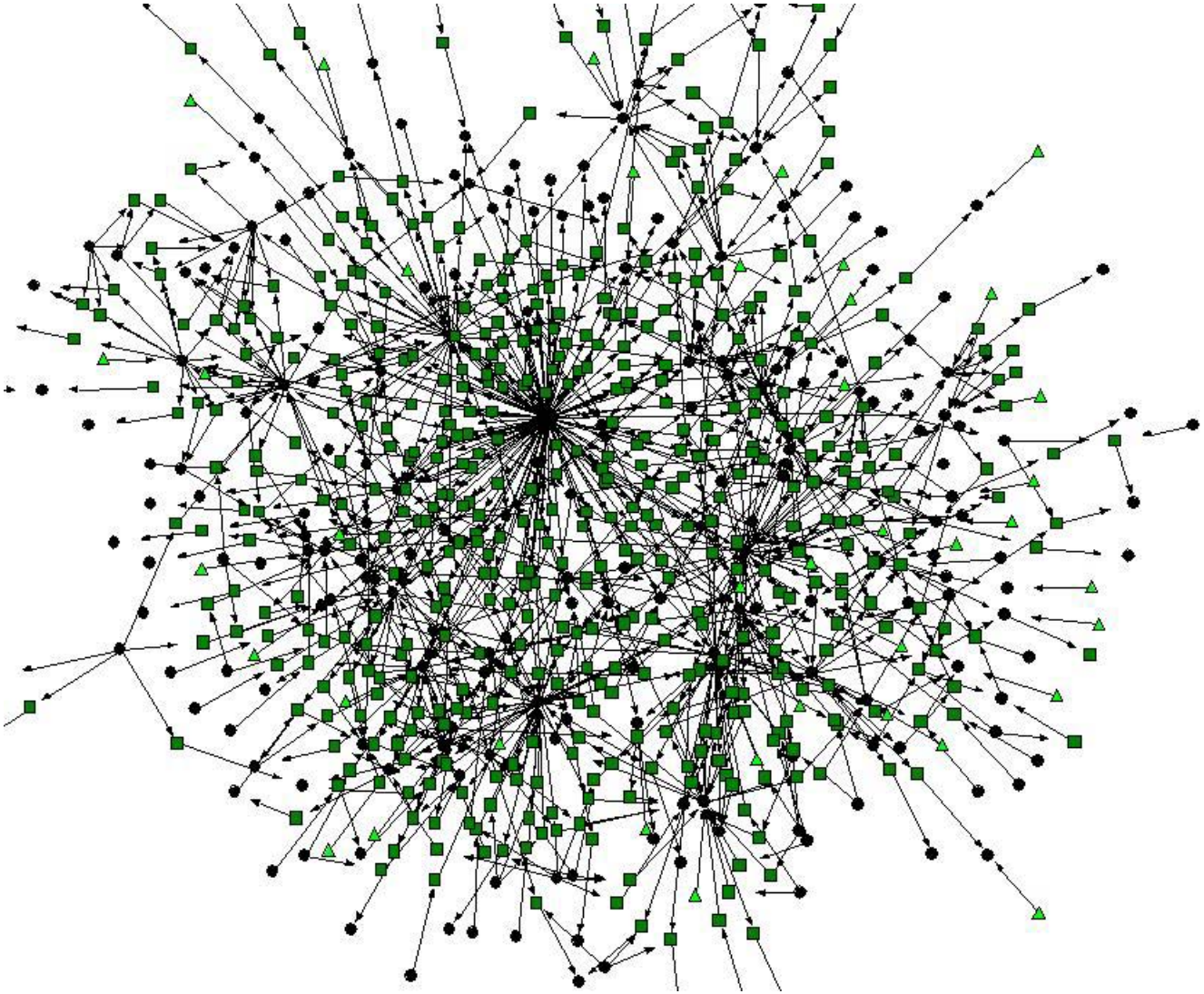


Stuff

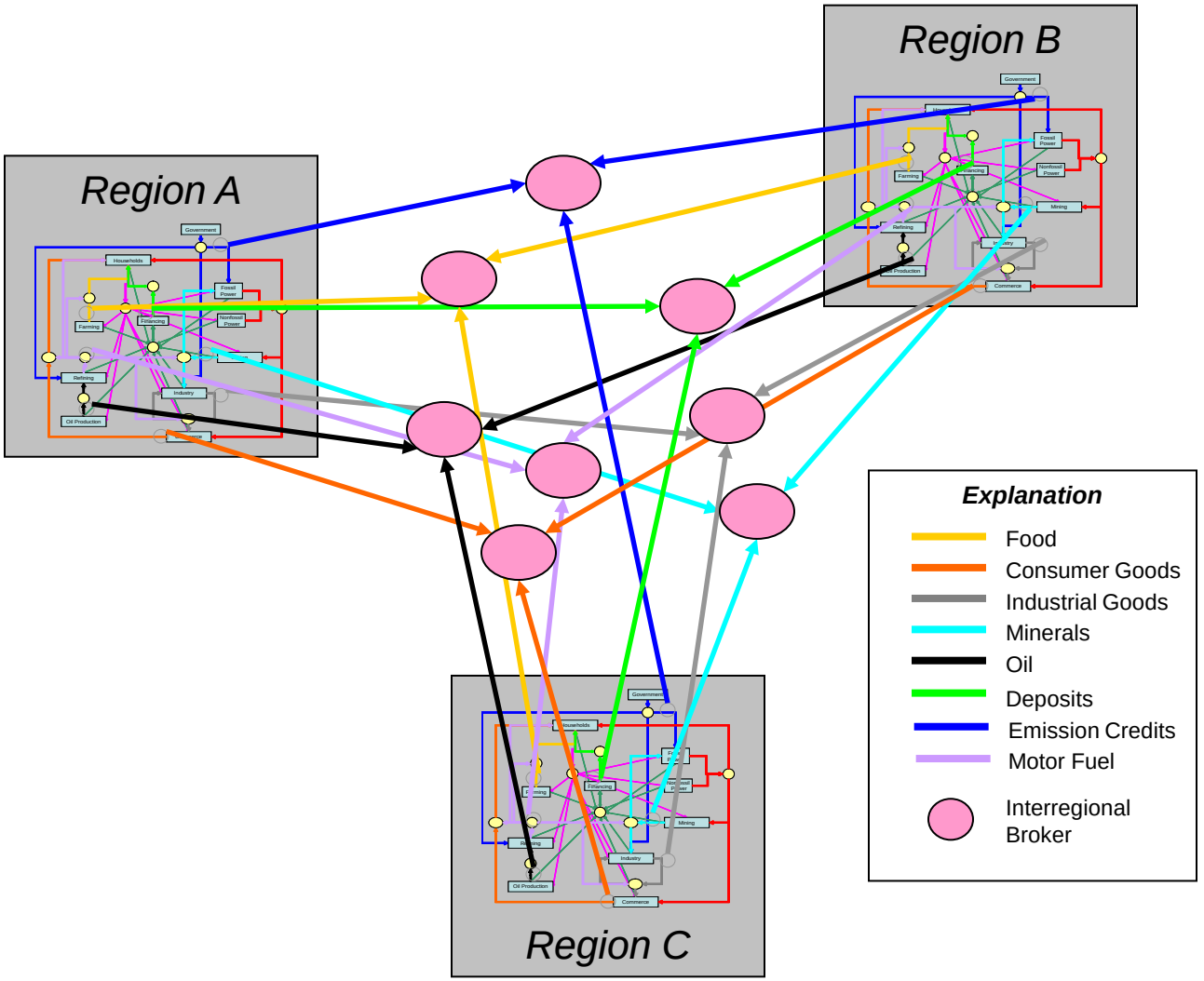
Labor

Finance

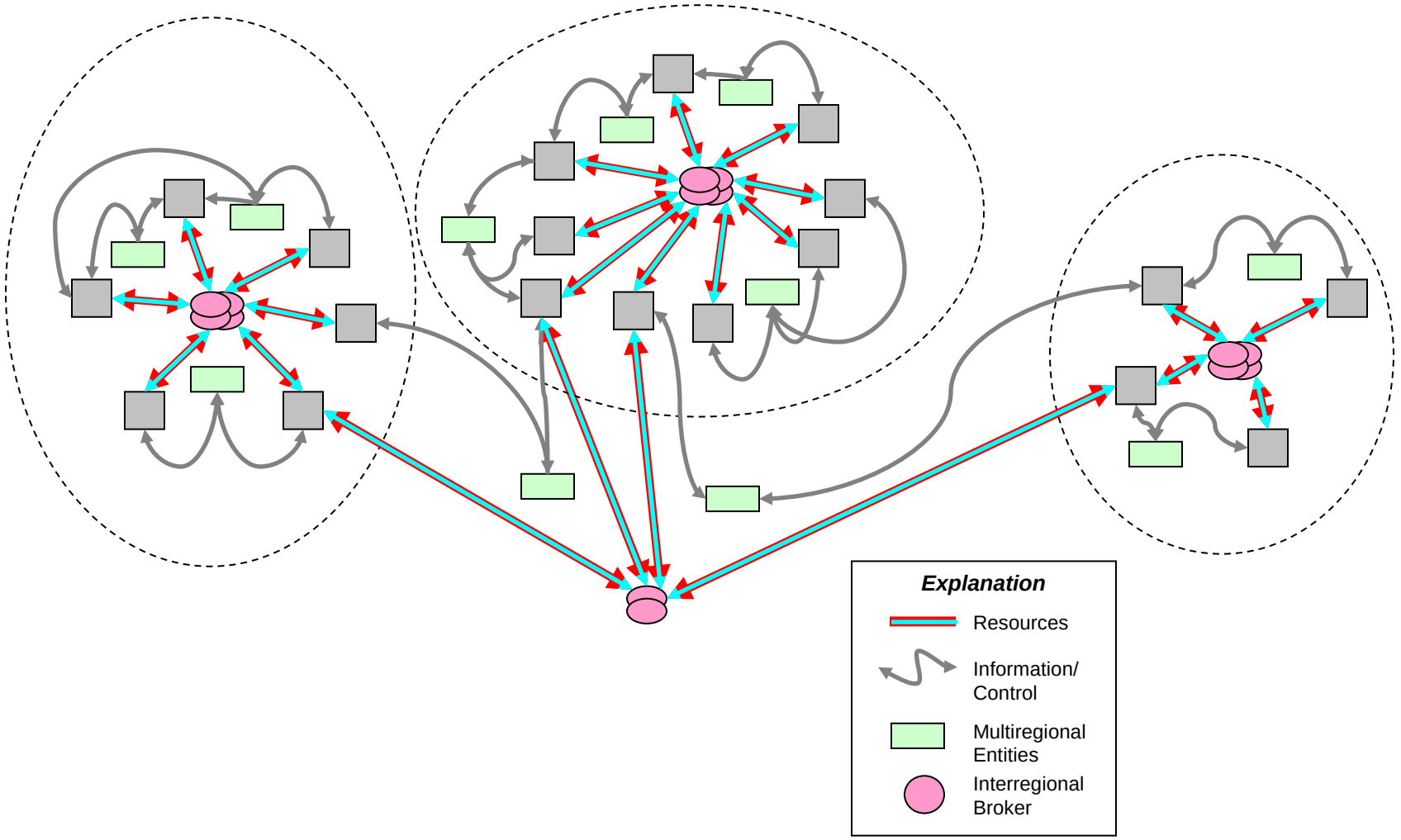
Within an entity type…



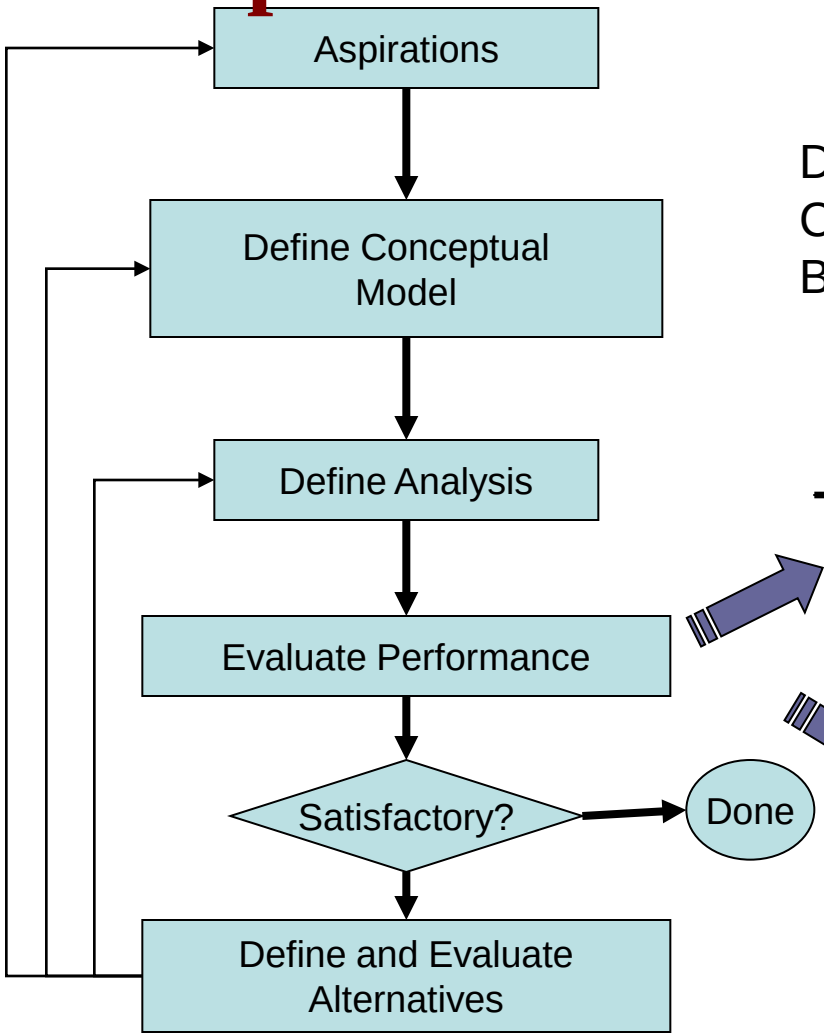
Trading Blocks composed of Core Economies



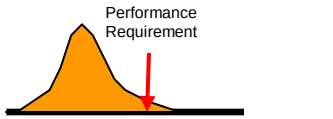
Global Energy System

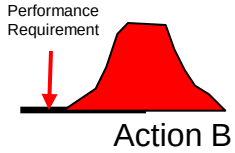


Model development: an iterative process that uses uncertainty

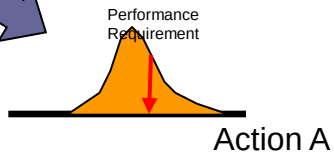


Decision to refine the model
Can be evaluated on the same
Basis as other actions





Model uncertainty permits distinctions



Model uncertainty obscures important distinctions, and reducing uncertainty has value

Many Examples of CASoS

- **Tropical Rain forests**
- **Agro-Eco systems**
- **Cities and Megacities (and their ne**
- **Interdependent infrast**
- **Government and politi**
  energy systems (local t

Extra NISAC Related

Resolving Infrastructure Issues Today

Each Critical Infrastructure Insures Its Own Integrity

Oil & Gas

Communica-tions

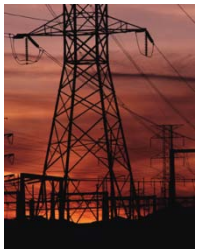
Water

Banking & Finance

Continuity of Gov. Services

Transpor-tation

Emergency Services



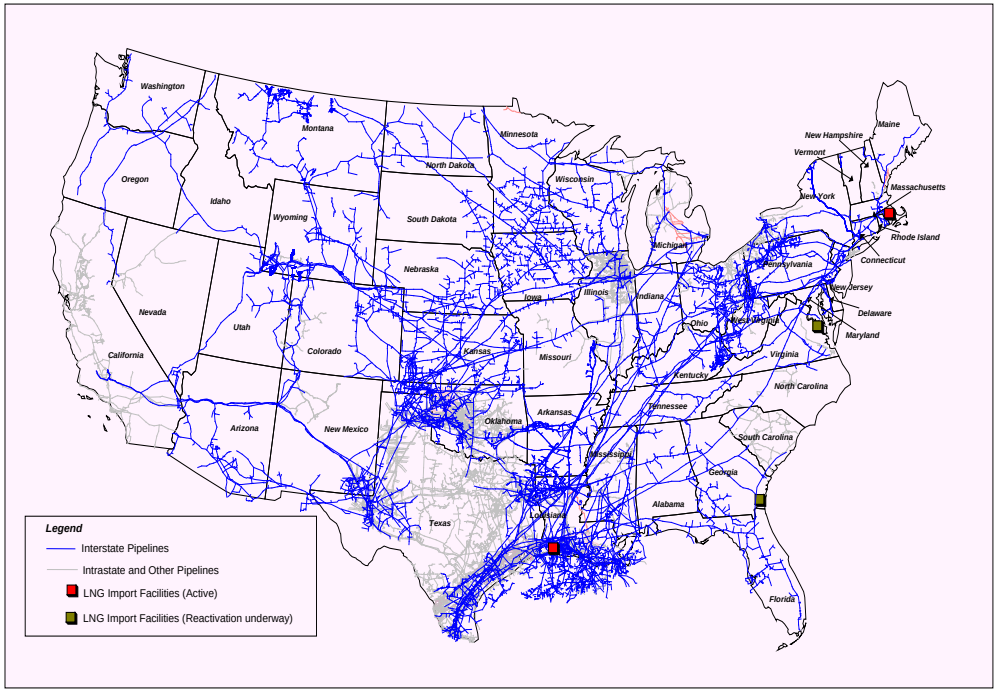
Electric Power

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



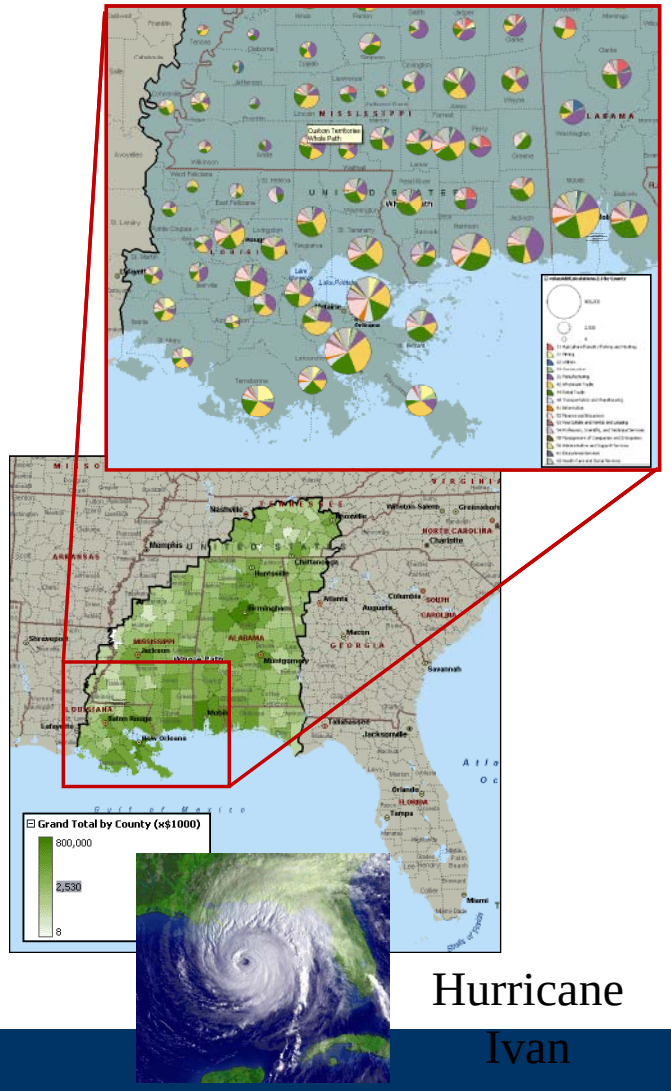
Source: Energy Information Administration, Office of Oil & Gas

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**



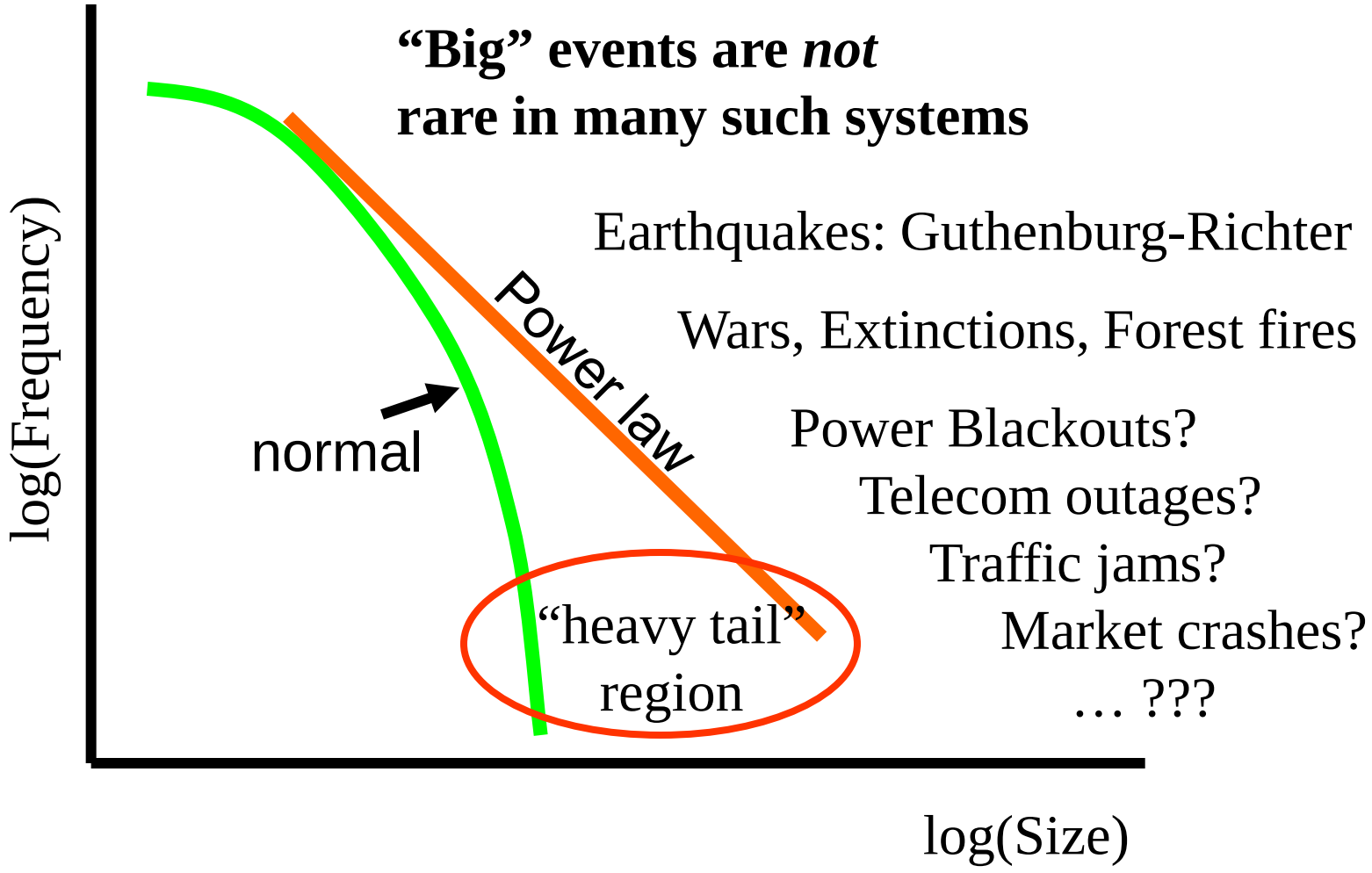
Hurricane Ivan

Focus of research:

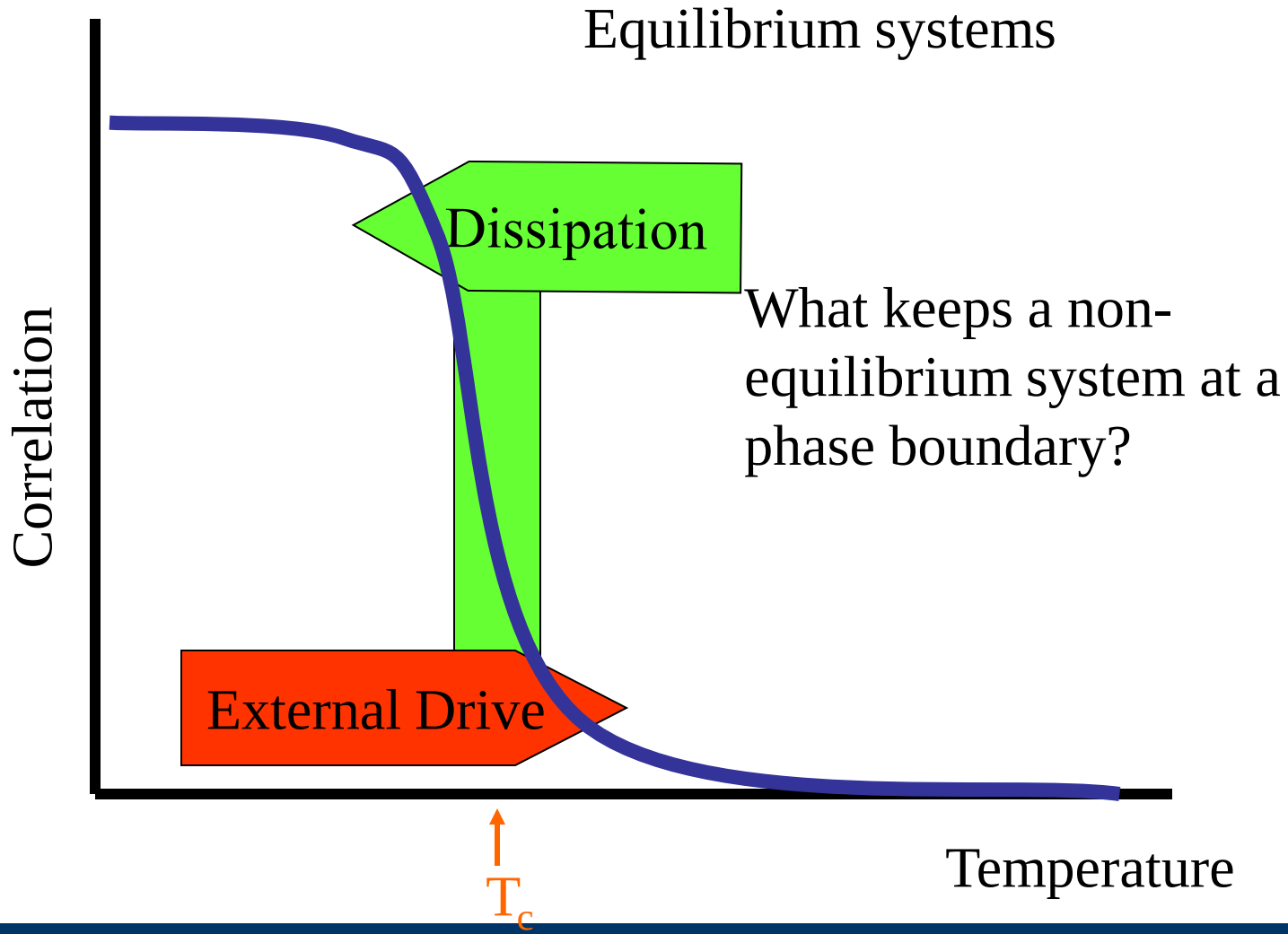
- **Comprehensive evaluation of threat**
- **Design of Robust Mitigation**
- **Evolving Resilience**

Complexity Primer Slides

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



Power Law - Critical behavior - Phase transitions

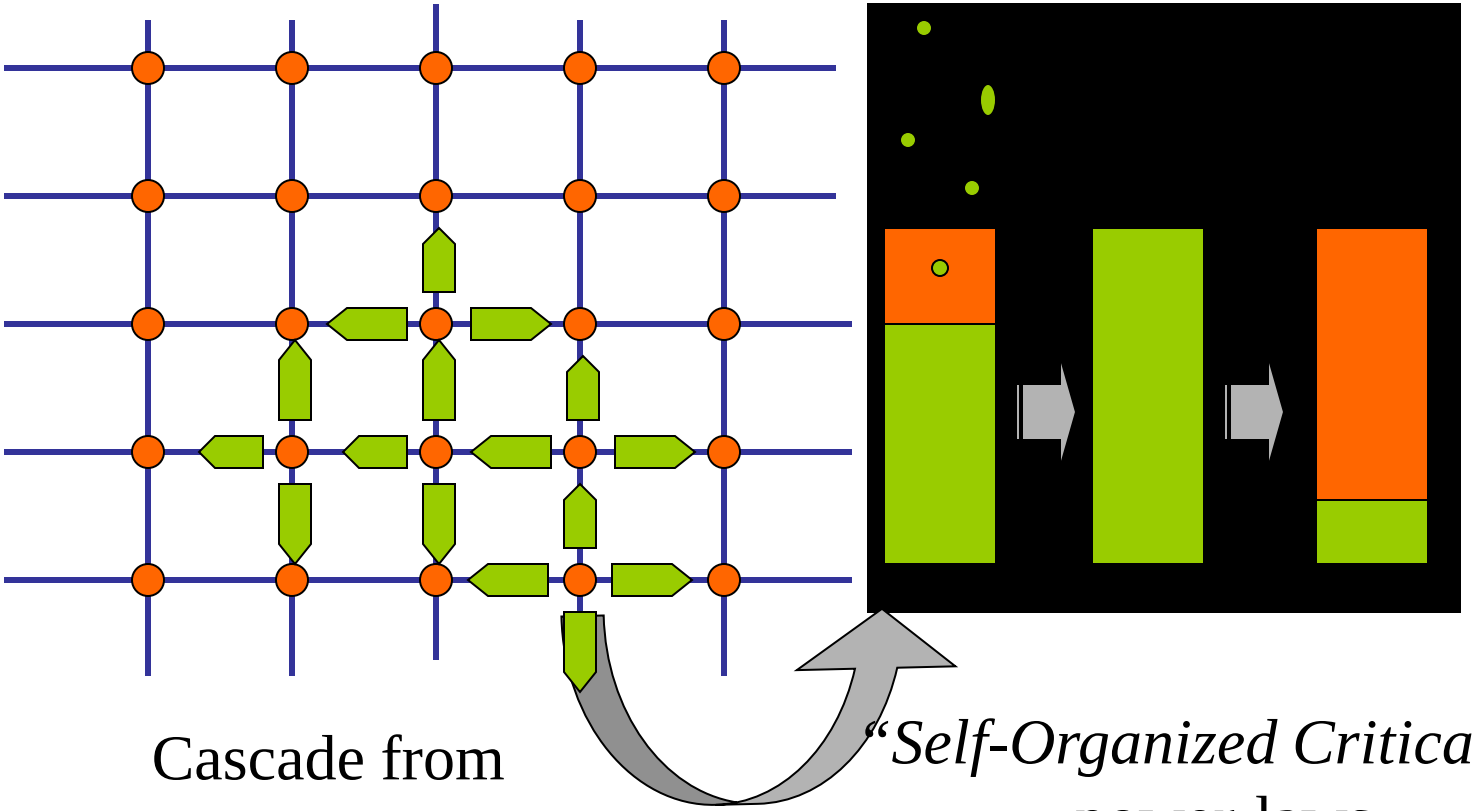


1987 Bak, Tang, Wiesenfeld's "Sand-pile" or "Cascade" Model

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

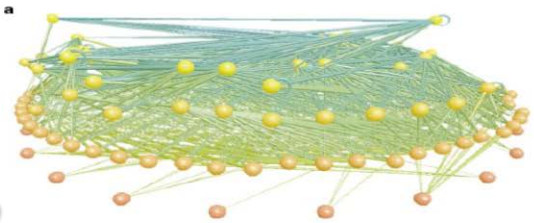
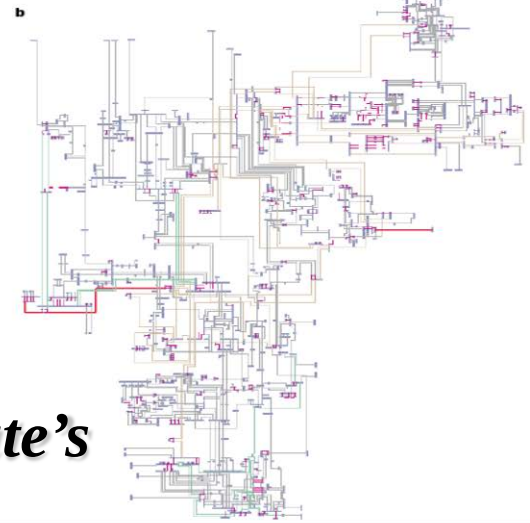
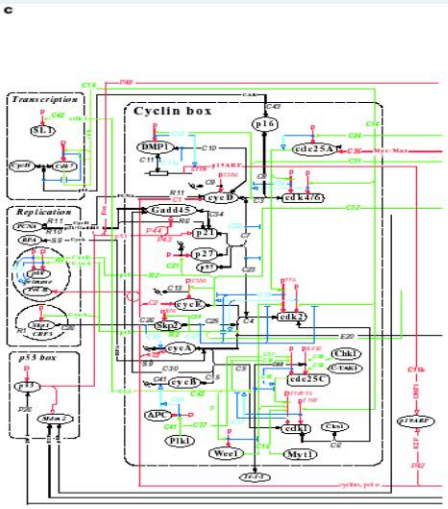


Figure 1 Wiring diagrams for complex networks. **a**, Food web of Little Rock Lake, Wisconsin, currently the largest food web in the primary literature[5]. Nodes are functionally distinct 'trophic species' containing all taxa that share the same set of predators and prey. Height indicates trophic level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



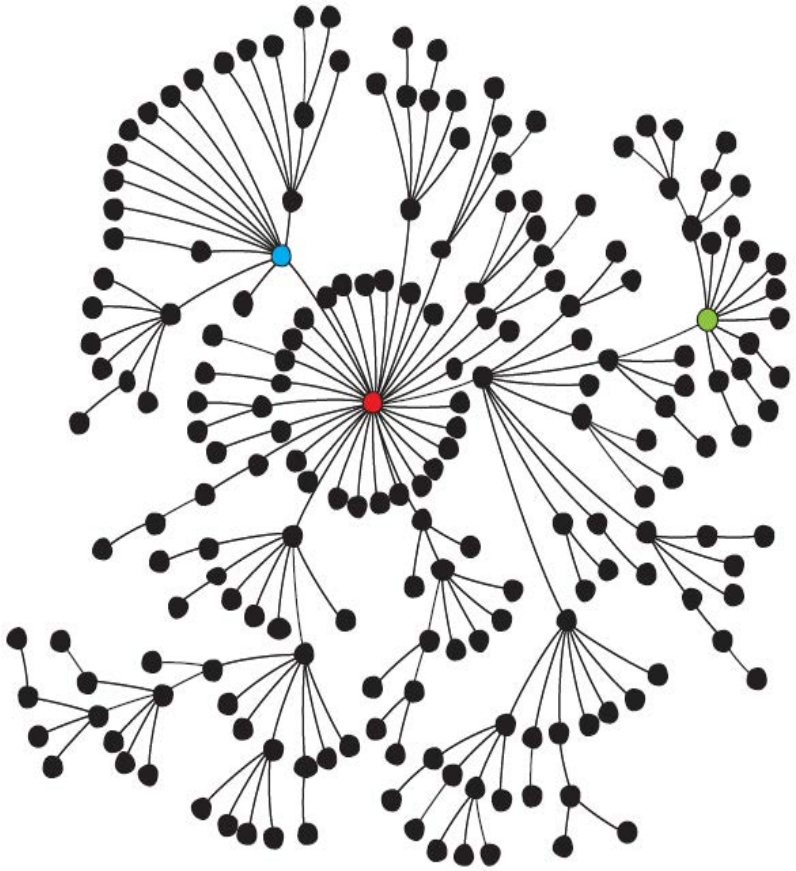


Molecular Interaction

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

Graphical Depiction: Networked Entities