Complexity Science: Implications for Critical Infrastructures

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Why Complexity Science?

Complexity Science – Explores commonalities among 'catastrophes' such as:

- Earthquakes
- Mass extinctions
- Major wars
- Traffic jams
- Major forest fires
- Epidemics
- Revolutions
- Landslides
- Stock market crashes

All of these disasters have something in common: we are unable to fully explain their causes nor predict their precise occurrences and magnitudes. They exhibit behaviors characteristic of systems that are 'complex'.

In recent years, a common underlying theory for complex systems has emerged that suggests there is a natural tendency for such systems to 'self-organize' into what is called the 'critical state'… a state of instability often described as being at the 'edge of order and chaos'. The underlying structure of networks can strongly influence the behavior (e.g., information transfer rate…) and resiliency (e.g., attack vs. error tolerance) of complex system.

There is a growing understanding that such systems often adapt, especially when people are integral to the system, and thus are 'Complex Adaptive Systems'. Here, the two aspects of complex systems, their behavior and underlying network (interaction) structure, are intertwined with feedbacks that allow the system to evolve.

Infrastructures are Complex Adaptive Systems (CAS). CAS methodology provides abstract representations of infrastructures for analysis

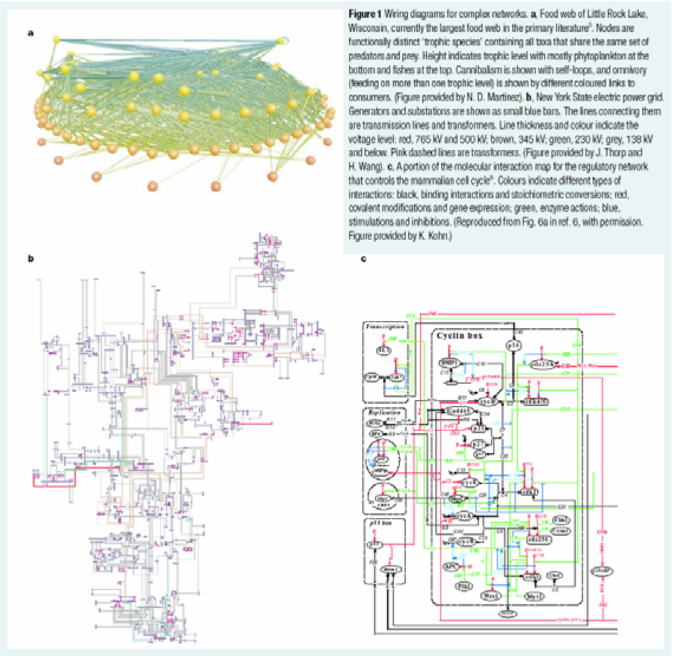
Infrastructures as Complex Adaptive Systems

Real World Examples:

An infrastructure is a network that can be represented as a series of nodes, connected to each other by some form of interaction.

Nodes could be:
- *-Power plants, transformers, power grid users*
- *-Computers and routers on the internet*
- *-Institutions in a financial network*
- *-Transportation hubs (airports)*
- *-Telecommunications hubs*
- *-People in a social network*

Characteristics of such networks:
- *-Connectivity*
- *-Clustering*
- *-Path length (or degrees of separation)*

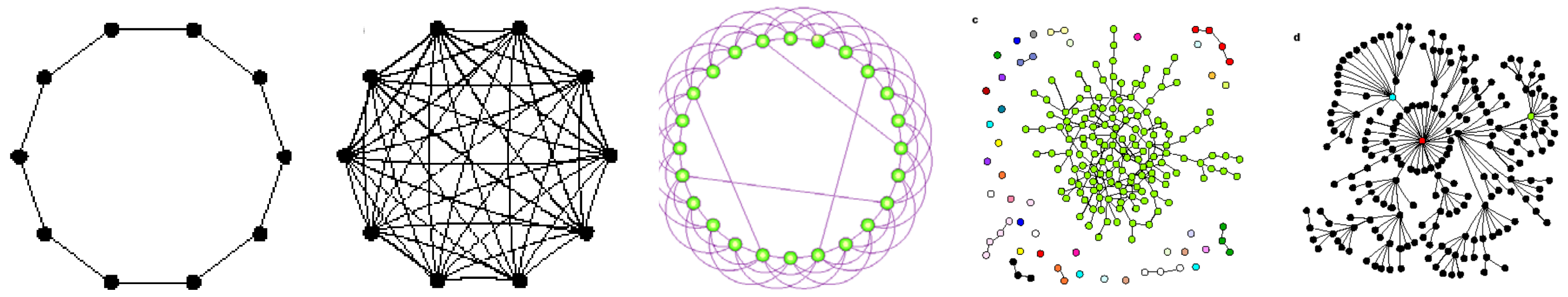


From the work of Strogatz

Network Topology:

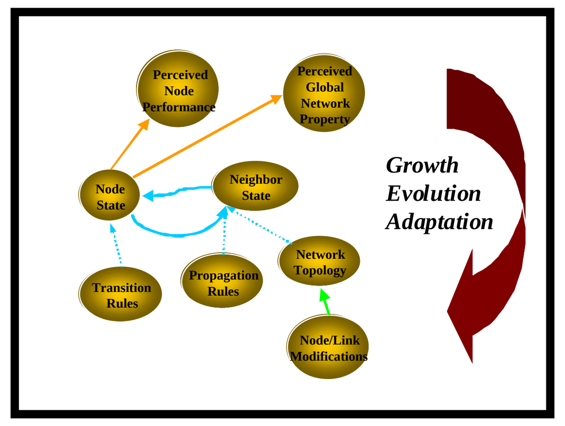
Topological Categorization and Attributes of Networks:
- *-Ordered (highly clustered, long path lengths)*
- *-Random (low clustering, short path lengths)*
- *-Networks between random and ordered (highly clustered, short path lengths)*
- *-Scale-free (highly clustered, short path lengths, power law connectivity distribution)*

Concepts:
- *Small Worlds: Span the spectrum from a single value of connectivity to power-law distributions (with some very influential or well connected nodes …), 'egalitarian to aristocratic'.*
- *Susceptibility to attack vs. error, behavior of scale-free is very different than random or ordered (fishnet).*



Ordered — Ordered+Random — Random — Scale-Free

Adaptation:



Growth, Evolution and Adaptation:
- *-In network topology*
- *-In simple interaction rules*

May be:
- *-Random or focused 'the rich get richer…'*
- *-With constraints (local to global)*

System behavior and system structure are linked and evolve through adaptive feed back

Complex Behavior:

Systems composed of many interacting parts often yield behavior that is not intuitively obvious at the outset… 'the whole is greater than the sum of the parts'

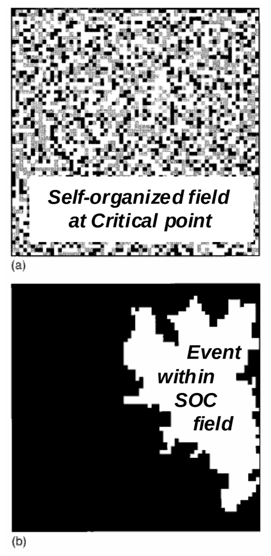
Example:

Node State: Consider the simplest case where the state of a node has only two values. For a physical node (computer, relay, etc.), the node is either on/off, untripped/tripped, etc. For a human node, the state will represent a binary decision, yes/no, act/acquiesce, buy/sell, or a state such as healthy/sick.

Node interaction: When one node changes state, it influences the state of its neighbors, i.e., sends current its way, influences a decision, infects it, etc…

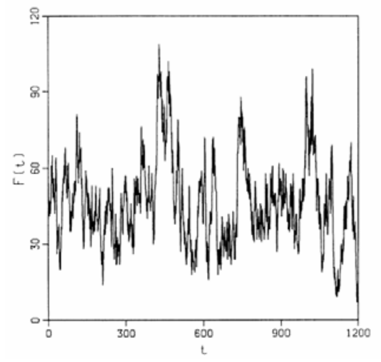
Ensuing Behavior:

Now consider behavior induced by a random fluctuation… We find:
- *Cascade events*
- *Heavy tailed distributions and power laws*

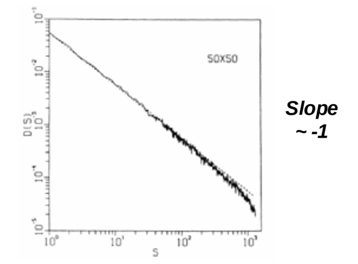


Cascade Behavior

From the work of Bak, Tang, and Wiesenfeld



Time Series of Events



Power-Law Behavior (Frequency vs. Size)

Concepts:
- *System self-organizes into a 'critical state' where events of all sizes can occur at any time and thus are, in some sense, unpredictable.*
- *In general, the details underlying whether a node is in one state or another often don't matter. What matters is that the ultimate behavior of a node is binary and it influences the state of its neighbors.*

Implications

Complexity science provide methods and a framework for simulation and analysis of abstract infrastructures and infrastructure interdependencies. These methods can help us understand both how/why some types of infrastructures will fail and the direction that a given infrastructure must evolve or be 'pushed' to reduce the probability of failure. Such understanding is critical for the reliable operation of the nation's infrastructures.

Areas of Implication include:
- *-categorization of disruptions and vulnerabilities (i.e., error vs attack)*
- *-choice of mitigation strategies and policy to achieve results*
- *-identification of infrastructure interdependencies*
- *-definition of what is predictable and what is not*

Demonstration

Our on-screen demonstration shows Complex Behavior on Complex Networks with a simple abstracted model relevant to power grids, financial markets, propagation of ideas, epidemics, and even earthquakes…

For more details, see the one- page handout on the table.

Further Reading

Readings from the Popular Literature on Complex behavior:
- How Nature Works, *by Per Bak*
- Ubiquity: the Science of History… or Why the World is Simpler than we Think, *by Mark Buchanan*

Readings from the Popular Literature on Complex Networks:
- Nexus: Small Worlds and the Groundbreaking Science of Networks, *by Mark Buchanan*
- Linked: The New Science of Networks, *by Albert-Laszlo Barabasi*

Technical References:
- *Albert, R., H. Jeong, and A.L Barabasi,* Error and Attack Tolerance of Complex Networks, *Nature, 406, 378-382, 2000.*
- *Bak, P., C. Tang, and K. Wiesenfeld,* Self-Organized Criticality: An Explanation of 1/f Noise, *Physical Review Letters, 59:4:381-384, 1987.*
- *Strogatz, S.H.,* Exploring Complex Networks, *Nature, 410, 268-276, 2001.*
- *Sakhtjen, M.L., B.A. Carreras and V.E. Lynch,* Disturbances in a Power Transmission System, *Physical Review Letters, 61:5:4877-4882, 2000.*
- *Watts, D.J.,* A Simple Model of Global Cascades on Random Networks, *Proceedings of the National Academy of Science, 99:9:5766-5771, 2002*

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