Network thinking in Complex Systems

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Beyond Reductionism: Network Thinking

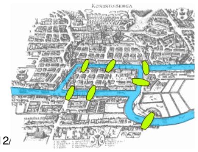
- Success in scientific understanding in 20th century owe to Reductionism
- To move ahead we need to look beyond!
- Systems in various domains exhibit properties not captured by reductionism
- Reductionist approach has ignored the emergent properties of (complex) systems!
- System > (sum of its parts)

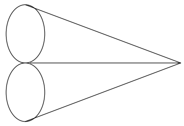
Network Approach

- Understanding how various parts of a system are *linked* with each other may tell us the dynamics of the system as a whole and how the system evolves with time

How it all began?

- Euler's solution to *Seven Bridges of Königsberg* Problem: The birth of Graph Theory
- Necessary condition for the existence of Eulerian cycles is that all vertices in the graph have an even degree





Networks hide Emergent Properties

- Networks or graphs have properties hidden in their construction which limit or enhance our ability to do things with them [1]
- Small changes in graph's topology can emerge new properties

Random Graphs

- One can obtain a random graph by starting with a set of *n* vertices and adding edges between them at random (eg: with the use of dice, random number generator, etc)
- Erdős–Rényi model: Set an edge between each pair of nodes with equal probability, independently of the other edges.
- Random Graphs give rise to Giant Cluster where everything is connected with everything else – "Community Formation"

Random Graphs contd…

- An important result: As the average number of links per node increases beyond the critical one, the number of nodes left out of Giant Cluster decrease exponentially
- Discussion: Do you think the world is structured in form of Random Graphs? If not, why not?

2/12/2008 7

Problem with Random Graphs

- Assumptions of Random Graphs can be unrealistic in real situations
- There is more order in the world as predicted by Erdős–Rényi model
- Random Graphs are at the verge of chance
- There are hidden rules which may give a network topology much better than chance as we will see later…

2/12/2008 8

World is Small

- We have more friends than one needs to keep connected!
- 6 degrees of separation: Stanley Milgram Study
- The strength of weak ties: Mark Granovetter Study
- Weak graphs are connected by weak ties called acquaintance
- Weak ties play important role – From spreading rumors to getting job [1]
- Weak ties are like help links for our ability to know and communicate with the outside world
- Society is not a Random Network!!

2/12/2008 9

Self Organization

- How crickets organize their chirping?
- How Mexican waves form?
- What defines the pattern in the flying birds?
- What about swarm of bees and ant colonies?
- Complex systems have capability to organize themselves as they evolve with time. But there are rules which govern such dynamics. Network theory may help define those rules

2/12/2008 10

Small-world phenomenon

- Duncan J. Watts and Steven H. Strogatz showed that networks from both the natural and manmade world, such as the neural network of C. elegans and power grids, exhibit the small-world property (*Nature, 1998*).
- Connectors and Hubs (important constituents of small worlds) : Malcom Gladwell Study
- Range of scores in Gladwell Study (9 - 118)
- Social butterflies or social hubs

2/12/2008 11

Importance of hubs

- Hubs appear in large complex networks
- Hubs create short path between any 2 nodes in a network
- Telemarketing firms: Hubs in telephone networks
- Amazon, Yahoo, Google, MSN: Hubs in World Wide Web (Yahoo is reachable in 2-3 (mean) clicks from any site)
- Hub like nature of P53 protein is key to understanding the process behind cancer at Molecular level
- Hubs are not Accidents!

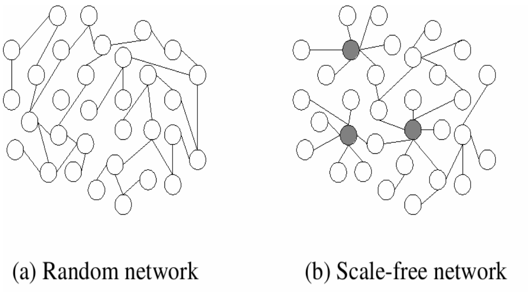
2/12/2008 12

Scale Free Distribution

- In scale-free networks, some nodes act as "highly connected hubs", although most nodes are of low degree.
- Most of the real world networks are Scale Free
- Scale Free Networks follow Power Law
- Network growth and preferential attachment have been shown to create networks with power law degree distributions (Barabasi et al, 1999).

2/12/2008 13

Random vs Scale Free



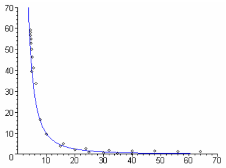
2/12/2008 14

Power law degree distribution

- A power law relationship is defined as

$$P(k) \sim k^{-\gamma},$$

- Below on x axis we have the number of links and on Y axis we have the number of nodes with k links



2/12/2008 15

Disorder to order

- Real Networks are far from random
- Power law appear at Phase transition
- From Gaussian to Power law i.e., from Disorder to Order
- Power laws can be defined as signature of SO in complex systems [1]
- Why Power Laws: 80/20 rule, rich gets richer, preferential attachment

2/12/2008 16

Scale Free does not solve everything!

- Rich gets richer model (seniority and preferential attachment): It ignores aging
- Google violates Scale free model (Scale Free model has no room for late comers)
- Other issues: fitness of nodes – fitter will acquire links more quickly
- Environment is competitive, fitness play a key role
- Fitness breaks and makes hubs
- Power law says that all nodes follow same dynamics rule but nodes have different dynamics and as such they all are different
- Real world networks are rapidly evolving dynamical systems

2/12/2008 17

Bose Einstein Condensate Analogy

- Incorporating fitness in Scale Free Model results in equations similar to those describing Bose Einstein Condensate in Statistical Mechanics where high fitness of a node is analogues to low energy level
- Example: Microsoft (winner takes all!!)

2/12/2008 18

Robustness of Scale Free Networks

- Distinguishing feature of SFN is the existence of hubs, few highly connected nodes
- Failure does not discriminate between nodes but affect small nodes and larges nodes with equal probability
- Small nodes have high probability to get dismantled (since they exist in large nos) as compared to hubs (low nos)

Contd…

- Decimation of hubs may lead to a break down
- Example: Shut down Google, Live, Yahoo and Altavista. Can you guess where all the traffic for search will head to?? Small service providers will be flooded with traffic and may break down!!
- In SFN, remove just small no of hubs and network will break in small isolated pieces

Directed vs Undirected Networks

- Directed: www, food webs etc
- Undirected: Protein, Citation Networks
- It is difficult to study directed networks since you can search only in one direction
- Problems with directed networks: Example www
- Other problems: Finding communities on web is an NP complete problem
- Many problems in Graph theory reduce to NP complete problems (TSP). Does this offer a problem in studying networks?

Cell and Protein Networks

- Water, ATP, ADP acts as hubs in cellular networks
- Cancer Research: P53 gene act as tumor suppressor
- Cell is like an internet, P53 is also a network
- Mutation in P53 turns cell cancerous and kill organism
- Disrupt cellular network and kill Cancer!! Will it work???

Contd…

- Cell is controlled by complex network with small world properties
- Why drugs have side effects?
- Metabolic, gene regulatory and protein-protein interaction networks all have an approximately power-law degree distribution (Debatable!!)

Protein-protein networks

- Most of the highly connected proteins in the protein interaction network are 3 times more likely to be essential for survival than were the weekly connected proteins (Jeong et al)
- More highly connected proteins evolve slowly and are less likely to be lost over evolutionary time
- -ve correlation: Highly connected nodes are less likely to be connected to other highly connected nodes than one would expect by chance (Maslov & Sheppen)
- Network structures contain large no of small, local motifs
- Challenge: How evolutionary forces shape network structure, in turn, determines organismal function [2]

Metabolic Networks

- Position of gene within the network structure is an important unit of analysis
- Metabolic networks are highly robust to damage
- How gene regulatory networks shape patterns of development?
- Example: In ant castes where wings are produced, gene regulation for wing development has been conserved over several hundred million years. Among castes that do not produce wings, a different regulatory gene was disrupted in each of four species (Abouheif & Wray)

Food Webs

- How food webs determine the stability of the community?
- How stable the community will be in face of fluctuations in density, invasion of new species and long term persistence of the community under non-linear population dynamics?
- Studies show that degree distribution is not poisson.
- Studies also disagree over the fact that distribution is controlled by Power Laws. Why??

Community Stability and Network Robustness

- Exploring what happens when we remove or alter nodes in the network
- Studies show that the removal of the most connected species causes more secondary extinctions than does the random removal of species (Dunne et al, 2002)

Dynamics of biological networks

- Rough power law distribution can emerge simply through a neutral model of the repeated duplication and loss of genes, which creates a kind of preferential attachment (Wagner)
- Network with power laws still differ in terms of clustering, motif frequency, nestedness and fractal structure [2]
- Genetic networks do not function in the same way as the information exchanging nodes on the internet.
- How to map the quantitative and functional relationship that define biological networks??

More about variation in biological networks

- Most of these networks are in fact samples of the full network in question. Samples from SFN are not SFN and converse is also true.
- Real food webs are not randomly assembled. Recent studies suggest 2 degrees of separation – 95% of species are typically within three links of each other

Open Questions

- Why biological networks differ from all others?
- Is it because most of the network analysis of biological networks is done by physicists who ignore important biological functions?
- Do we need any other approach? Or something revolutionary with the network approach?

Other things to ponder

- Terrorist networks: They are extremely self organized and scattered
- Can network analysis may give us clues to potential terrorist attack?
- Terrorist organizations like Al Queda are highly distributed. One can't get rid of them by just shutting down people like Osama Bin Laden and other his close allies [1].
- Can we predict their activity pattern by have a network of their part activities?

Who's who?

Who's who?

Who's who?

Who's who?

References

- [1] Barabási, Albert-László *Linked: How Everything is Connected to Everything Else*, 2004
- [2] Network thinking in ecology and evolution, (Prolux et al, 2005)
- [3] Network structure and the biology of populations, (Robert M. May, 2006)

Thank You

2/12/2008 37