Lecture 2 Outline

- Typologies of architectures (classification or taxonomy)
  - Context (or domain of knowledge)
  - Functional (object-process)
  - Structural
- Network Analysis Activity and the improvement of models
- Terms and Definitions
  - Engineering Systems
  - Network Analysis (graph theory)
- Research Front Issues

How to Learn

- We will learn more about such architecture/structure by examining a wide variety of systems such as biological, sociological, economic at a variety of levels in addition to the technological and organizational systems of most direct interest to us, because
- These systems are similar in many ways, perhaps more than we think
- Since we want to influence structure (not just accept it as we are interested in ***design***), we will also explore how structure is determined by looking at system typologies and constraints that influence or determine the structure
- We will use network methods - a choice of level of abstraction

Systems *Context* Typology I

- Technical Systems
  - Power-oriented (e.g., cars, aircraft, their engines, etc.)
  - Information-oriented
    - Physically realized: e.g., telephone network, Internet
    - Non-physical: e.g., software, mathematical systems (Macsyma, Mathematica)
- Organizations (of humans)
  - Teams
  - Hierarchies
  - Networks
- Social/economic "systems"
  - Markets
  - Social Classes
  - Social networks like coauthors, citation lists, e-mails, terrorists
  - Behaviors: e.g., rumors, diseases, herd mentality
- Biological systems
  - Cells
  - Animal body plans
  - The process and role of evolution

Systems *Context* Typology II

- Overtly designed
  - Can be an architect
  - A design strategy is practical
  - Products, product families
  - Cars, airplanes
  - Bell System
  - Organizations
  - Centrally-planned economies

- Infrastructures
  - Architect not common
  - Protocols and standards are crucial
  - Design strategy may or may not be practical
  - May be designed when small
  - Usually grow with less direction from a common strategy when large
  - Regional electric grids
  - City streets
  - Federal highway system

- Natural systems
  - No architect
  - Follow laws of physics
  - Respond to context
  - Change, develop
  - Differentiate or speciate
  - Interact hierarchically, synergistically, exploitatively
  - Cells, organisms, food webs, ecological systems
  - *Friendship groupings?*
  - *Co-author networks?*

In all cases, legacy (similar to path dependency) <u>is possibly a dominant influence</u>

Systems Typology : Complex Systems *Functional* Classification Matrix from Magee and de Weck

Process/Operand	Matter (M)	Energy (E)	Information (I)	Value (V)
Transform or Process (1)	**GE Polycarbonate Manufacturing Plant**	**Pilgrim Nuclear Power Plant**	**Intel Pentium V**	**N/A**
Transport or Distribute (2)	**FedEx Package Delivery**	**US Power Grid System**	**AT&T Telecommunica tion Network**	**Intl Banking System**
Store or House (3)	**Three Gorge Dam**	**Three Gorge Dam**	**Boston Public Library (T)**	**Banking Systems**
Exchange or Trade (4)	**eBay Trading System (T)**	**Energy Markets**	**Reuters News Agency (T)**	**NASDAQ Trading System (T)**
Control or Regulate (5)	**Health Care System of France**	**Atomic Energy Commission**	**International Standards Organization**	**US Federal Reserve (T)**

Some Things Do Not Have Architectures with Internal Structure

- Random Networks
- Perfect gases
- Crowds of people
- Their behavior can still be analyzed *–indeed they are usually easier to analyze than real systems*. Thus, they often form a baseline for comparison to things that do have architectures with significant structure

Structural Typology

- Totally regular
  - Grids/crystals
  - Pure Trees
  - Layered trees
  - Star graphs
- Deterministic methods used

- Real things
  - The ones we are interested in
- New methods or adaptations of existing methods needed

- No internal structure
  - Perfect gases
  - Crowds of people
  - Classical economics with invisible hand
- Stochastic methods used

- Less regular
  - -“Hub and spokes”
  - -“Small Worlds”
  - -Communities
  - -Clusters
  - -Motifs

Comments on Typologies: Attributes of Effective Classification

- Standards for Taxonomy
  - ***Collectively Exhaustive and Mutually Exclusive***
  - ***Internally Homogeneous***
  - Stability
  - Understandable Representation and Naming

- None of the approaches just reviewed really fulfill these criteria. Interestingly (more later in course), ***no categorizations*** of man made systems have ever been found that fulfill these criteria. ***Natural systems categorizations have been found that do fulfill*** these criteria (Linnaeus and Mendeleyev) and these have even been the basis of future successful predictions.

What has been going on recently in "The New Science of Networks"?

- The ***Physicists and their friends*** have come to this area strongly starting with the paper in Nature by Watts and Strogatz in 1998
- The publications started with a few per year and now have reached 1000's per year in various journals (plus 3 books).

Papers with "Complex Networks" in Title

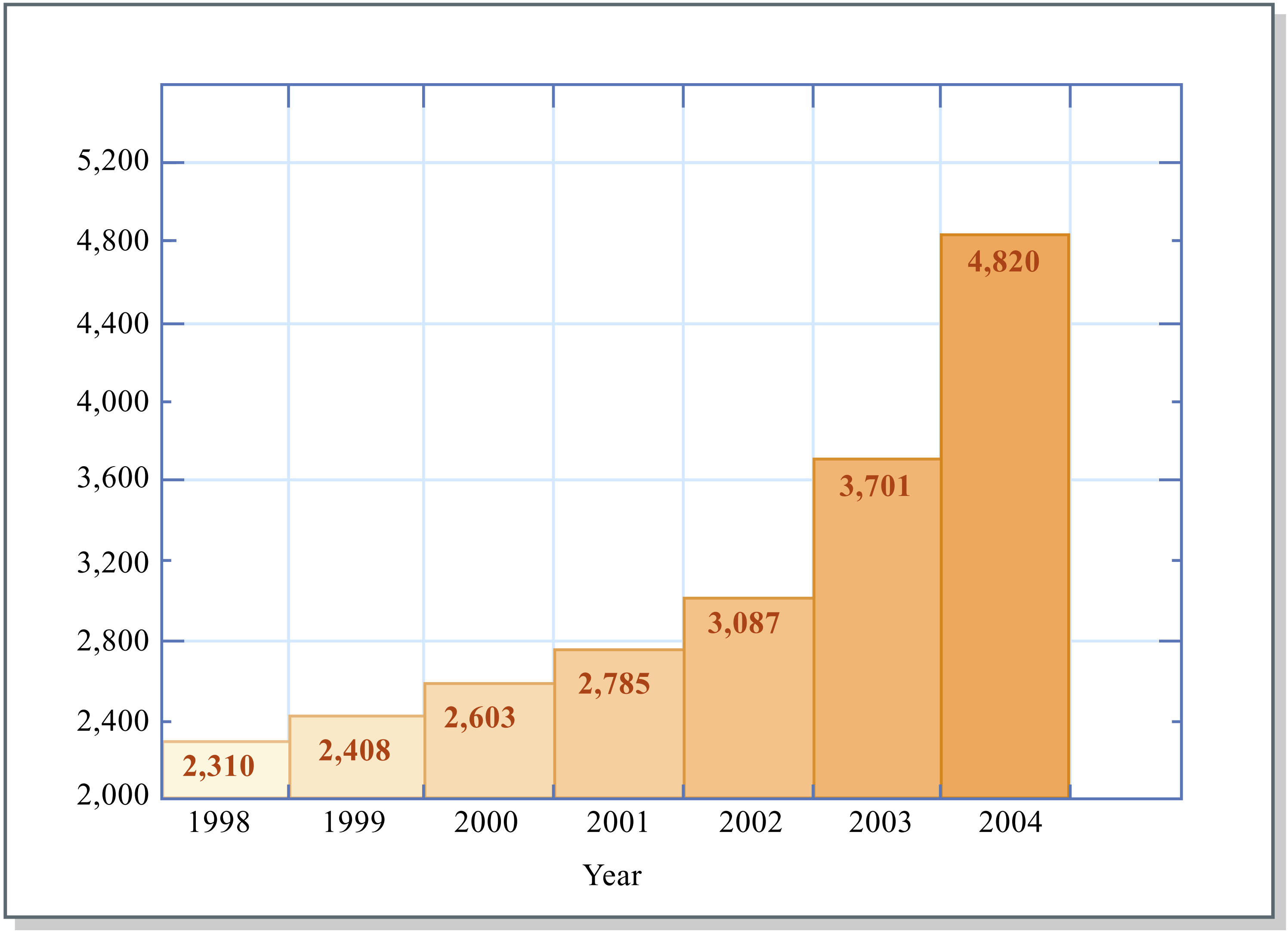


Figure by MIT OCW. Adapted from: Introduction to Complex Networks: Modeling, Control and Synchronization. Briefing by Guanrong Chen, director, Centre for Chaos Control and Synchronization, City University of Hong Kong, to the First Chinese Conference on Complex Networks, Wuhan, China, April 2005.

Magazines with major article on Networks

- Circuits and Systems
- Science
- New Scientist
- Nature
- Nature Reviews
- Proteomics

What has been going on recently in "The New Science of Networks"?

- The ***Physicists and their friends*** have come to this area strongly starting with the paper in Nature by Watts and Strogatz in 1998
- The publications started with a few per year and now have reached 1000's per year in various journals (plus 3 books).
- All of the effort builds upon work done by sociologists and Operations Researchers over the preceding 40 or more years.
- Strong activities now exist at a variety of academic institutions:
  - The University of Michigan
  - Oxford University
  - The Sante Fe Institute
  - Columbia University
  - Notre Dame University
  - Many others

Why might *We* (who are interested in design, management, behavior, etc. of complex systems) care?

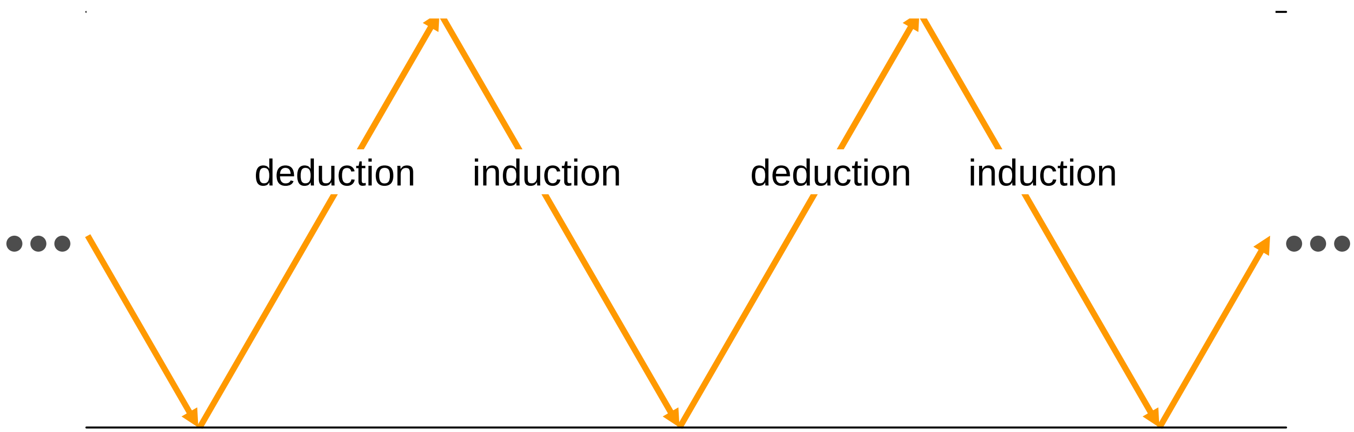
- A strong mathematical basis is being established for developing relatively tractable models of large-scale complex systems
  - *We* need more modeling tools that are useful for large-scale systems with many elements, interactions and complex behaviors
- Quantifiable metrics are being developed that may be of use in predicting behavior of complex large-scale systems
  - *We* need such metrics as they would be valuable in designing and managing our systems
- Algorithms for extracting information from complex systems are being developed and these can improve "observability" of such systems.
- New visual representations for complex systems are being developed

Comparative Progress in Understanding and performance: CLM objective/subjective observations

- 1940-2000 improvement
  - Small-scale electro-mechanical systems (x40-100)
  - Energy transformation systems (x 10-20)
  - Information processing systems (x 10^5 to 10^7)
  - Cosmology (x 30-100)
  - Paleontology (x 50)
  - Organizational theory and practice (x ***1.1 to 2***)
  - Economic systems (x ***1.1 to 2***)
  - Complex large-scale socio-technological systems (?)
- Possible reasons for large differences for ***organization issues***
  - Lack of attention by deep thinkers
  - Low utilization of mathematical tools
  - "Hardness" of problem particularly ***human intent***
  - ***Difficulties with detailed quantitative observation to improve models (hiding of data, privacy etc.)***

The Iterative Learning Process

Objectively obtained quantitative data (facts, phenomena)



hypothesis (model, theory that can be disproved)

As this process matures,
what new can the models accomplish?

The major accomplishment will be the rapid facilitation of a transition to engineering (vs. craft approaches) for the design of complex social/ technological systems

What is needed to greatly improve the *practice* of complex social/ technological system design?

- The major opportunity is to transition from the "pre-engineering" (experiential or craft) approach now widely used to a solid (post 1870 at least) engineering approach to these design problems. ***What does this entail?***
- If you are doing work where ***all*** factors involved are quantitatively and accurately determined from mathematical approaches, you are possibly doing accounting or actuarial work but you are *not doing engineering design* because you are not doing creative work.
- If you are pursuing a creative end but are using ***no*** quantitative methods developed from a scientific perspective, you are possibly a sculptor or a painter but are *certainly not an engineer*
- The critical need to greatly accelerate the rate of improvement in practice is ***objective methods for quantitative observation*** to develop reliable and well-understood "simple" models.

Terms and Definitions

- System
- Function
- Performance
- Properties or characteristics
  - Complexity, uncertainty, emergence
- Ilities - often have life-cycle importance
  - Flexibility
  - Robustness
  - Sustainability
  - Others?

Form and Function

- Function
  - (narrow) what the system does, as opposed to Performance and Ilities
  - (broad) combines function, performance and ilities
- What is the relationship between Form and Function?

Other System Characteristics

- Complexity
- Uncertainty
- Emergence
- Various definitions have been proposed

What are the relationships, especially trade-offs, between forms, functions, ilities, performance and these characteristics?

Network Analysis Terminology

Network Analysis Essentials

- Network Analysis (or Science?) consists of a relatively simple way (Euler was first) of modeling or representing a system
  - Each Element (or subsystem or) is a ***node***
  - The relationship between nodes (elements or) is a ***link***
- The appeal of generality of application is based upon the very simple model for a system described by this representation combined with the mathematics of graph theory for quantifying various aspects of such models.
- A limitation for widespread utility is the simplicity
- The research front is where people are sacrificing as little simplicity as possible while making the models reflect more reality and thus have increased utility

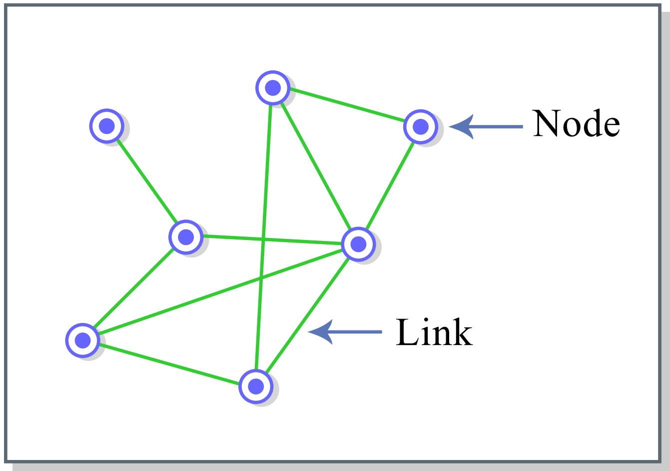


Figure by MIT OCW.

Network Analysis Terminology

- **Node** = Vertex (Element, Component, Subsystem, Agent?)
- **Link** = Edge (Relationship, Interaction, Interface?,Flow?)
- **Random, rewiring,**
- **Degree** (average degree, degree distribution)
- **Path Length** (Path)
- **Size, density, sparseness, Connectivity**
- **Community =** Clique, (cluster?, module?), **modularity**
- **Degree Correlation Coefficient**
- **Centrality, Prestige, closeness, proximity, Betweenness, Assortative Mixing, Homophily**
- **Motifs =** Patterns
- **Self-similarity, Scale-Free?, Scale Rich?**
- **Preferential Attachment**
- **Metrics, Constraints**

Metrics (as used in this class)

- A network analysis metric is a ***quantitative characteristic*** of a system that is derived from ***representing the observed system as a network*** (and applying graph theory or other means of quantitative calculation)

Network metrics

- Size
- Density of interactions, sparseness
- Path Length –dependence on size

Image removed due to copyright reasons.

Network Metrics I

- n, the number of nodes
- m, the number of links
- m/n is the average degree <k> as the number of links on a given node, k, is the degree.
- m/[(n)(n-1)] or <k>/(n-1)is the "sparseness" or normalized interconnection "density"
- Path length, *l*

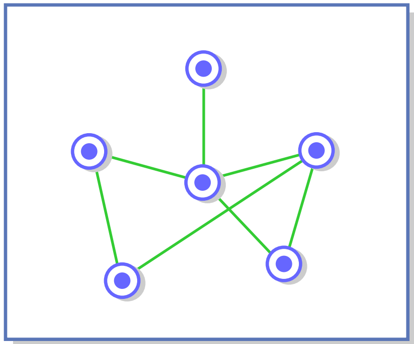
$$l = \frac{1}{\frac{1}{2}n(n-1)} \sum_{i \geq j} d_{ij}$$

  - "Small Worlds"
  - In a "Small World", *l* is *relatively* small
  - And at given <k>, *l* ~ to *ln n or less rapid rise is taken to mean "Small World" (**where clustering is high**)*

Important topics at the “Research Front”

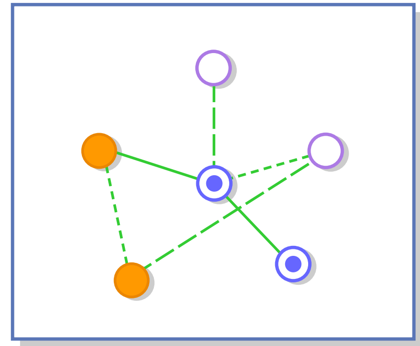
- How useful are the models and metrics that exist for architectural or structural attributes in the case of Engineering Systems (high complexity and **heterogeneity**)?
- Can we quantify important properties such as flexibility and find analytical relationships to some structural metrics?
- Can we invent models and metrics for **heterogeneous** systems that are more useful indicators of important “properties of real systems”?

Figures by MIT OCW.



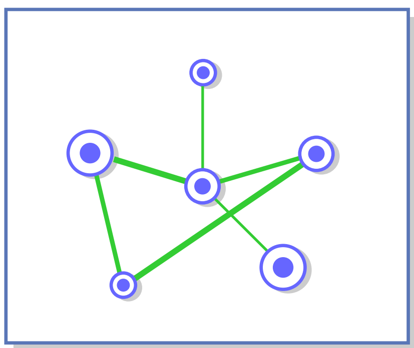
A

An undirected network with only a single type of node and a single type of link



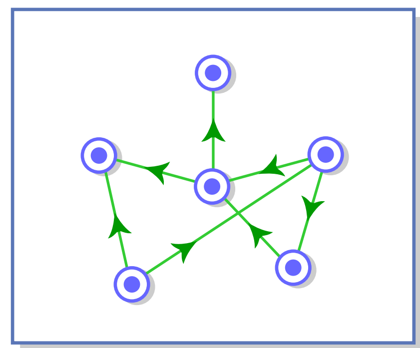
B

A network with a number of discrete node and link types



C

A network with varying node and link weights



D

A directed network in which each link has a direction

VARIOUS CLASSES OF NETWORKS

Missing are networks that have nodes with multiple functions and that have multiple types of links. For example, nodes that transform energy and also calculate and that have links that pass information, control signals, energy, etc.

See Newman, M. E. J. "The Structure and Function of Complex Networks." *SIAM Review* 45, no. 2 (2003): 167–256. Society for Industrial and Applied Mathematics.

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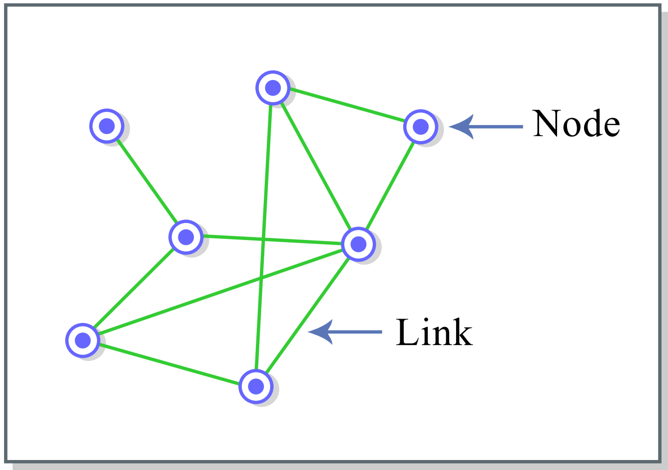

Figure by MIT OCW.

More Research Front Topics

- To what extent are intuitively important aspects of architecture quantifiable and measurable?
- Are there useful paradigms, patterns, principles or other lessons from natural systems that researchers on real system architectures can use - and how can they be used?
- Assuming we know what functions, performance, and ilities we want, what methods can be used to create a suitable architecture?
- Assuming we know what architecture we want, what are the most effective ways of influencing the architecture of complex, evolving engineering systems?

Lecture 2 Outline

- Typologies of architectures (classification or taxonomy)
  - Context (or domain of knowledge)
  - Functional (object-process)
  - Structural
- Models and their improvement-network analysis activity
- Terms and Definitions
  - Engineering Systems
  - Network Analysis (graph theory)
- Research Front Issues
- → Comments on assignment #1