Large Complex Systems
- Examples
- Questions?

Power Laws are Ubiquitous in Complex Systems
- Power law (heavy-tailed) distributions
- 100+ years of repeated observations of power laws
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What is a large complex system?

- Basically, any system with millions, billions or more interacting components

What are typical examples?

- Computer networks: the Internet, World Wide Web, wireless networks
- Integrated circuits
- Massively parallel computers
- The brain circuitry: the most complex computer of all
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Why emphasizing these systems now?

- The engineered systems are approaching the same level of complexity as the natural ones (e.g., biological).
- The remaining problems in natural systems often involve system level issues (e.g., systems biology).
- The accumulated scientific knowledge and technology (computational power) seems ready to tackle these problems.

Common issues and properties

- Scalability
  - The systems of today, e.g. wireless networks, should operate in the future on much larger scale.
  - Small inefficiencies may accumulate and deteriorate the performance of the system as a whole.
  - Optimal designs for small systems may not be optimal for the large ones since their complexities may become prohibitively large.
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  - Some existing designs may be inadequate (e.g., retransmissions in the communications context)
  - We should be able to learn some design principles from nature

- Multiple spatial and temporal scales
  - Different dynamics on different scales
  - New analytical/mathematical tools may be needed

- Statistical invariants
  - Power law (heavy-tailed) distributions are universally observed
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2. Power Laws are Ubiquitous in Complex Systems
   - Power law (heavy-tailed) distributions
   - 100+ years of repeated observations of power laws
   - What are the origins?
   - Why do we care?
A random variable $X$ has a power law tail if

for $\alpha > 0$

$$P[X > x] \sim \frac{H}{x^\alpha}$$

or

$$\log P[X > x] \approx -\alpha \log x$$

**Figure:** Size vs rank of the 135 largest U.S. cities in 1991, Gabaix (1999).
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Power law distribution is a straight line on the log-log plot.
Sample path characteristic of power laws

- Large values occur frequently

Sample path of power law versus exponential distribution.

**Figure:** Distribution of video scenes, Jelenković et al. (1997).
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100+ years of repeated observations of power laws

Distribution of income

- Starting with Pareto (1897)

World income distribution

Figure: Zipf’s plot of the 30th-85th percentiles of the world income distribution (GDP per capita) in 1960 and 1997.
Neuron spiking time-series

Figure: Power law inter-spike distribution in depressed rats, Bershadskii (2001).
File sizes

Figure: Distribution of computer files in COMET lab at Columbia University ($\alpha = 1.44$), Jelenković and Momčilović (2001)
Figure: Distributions of the number of pages and visitors per Web site.
Power law random graphs

Power law connectivity of complex networks came as a surprise to researchers accustomed to the traditional random networks.

Traditional random graph - Erdos-Renyi model
VS scale free graph - Barabási model

Figure: Concentrated degree distribution (Poisson)

Figure: Power law degree distribution
Graphs of Internet topology and interacting proteins in yeast

Figure: Image credit: Internet Mapping Project of Lumeta Corporation; Scientific American
Albert László Barabási et al.: The Architecture of Complexity. From the Diameter of the WWW to the Structure of the Cell (power-point presentation) (http://www.nd.edu/~networks/papers.htm)

\[ P(k) \sim k^{-\gamma} \quad (\gamma = 3) \]
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Are these observations merely a big coincidence?
Are there universal mathematical laws governing these phenomena?

Our recent research

- Proportional growth situations almost invariably result in power laws (Jelenković and Tan 2006/07)
- Retransmissions in communications networks may result in power law delays and even in zero throughput (Jelenković and Tan 2006/07)
- Still a number of unexplained phenomena, e.g.:
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**Power laws in finite population ALOHA**

- $M$ - finite number of users; random backoffs
- Short data units (packets) $\{L_i\}$
- Most of the access protocols, especially in wireless networks, are based on this mechanism

**Diagram:**
- $N$ - number of retransmissions between 2 successes
- $T$ - time between 2 successful transmissions
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\[L_1\] \[L_2\] \[\vdots\] \[L_M\]

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Example (Average data $\ll$ backoff $\Rightarrow$ positive throughput?)

- $M = 3$ - users (small number)
- Short packets (on average)
- Large backoffs (on average)
- Everything should work fine?

**Surprise**

$\alpha \approx 0.83 < 1 \Rightarrow 0$ throughput

Jelenković and Tan 2007 (Best Student Paper Award)
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For communication networks:

- Re-examining retransmission protocols to prevent large delays
- Designing new control mechanisms specifically optimized for power law traffic
- Power law topology: resilience to (targeted or random) attacks
- Using power law topology to design better communication protocols and information storage/content distribution mechanisms, etc.

For other areas:

- Economy, biology, etc.

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