The Role of Design in the Internet and Other Complex Systems

David Alderson
February 10, 2004

Joint work with
J. Doyle, W. Willinger, and L. Li
My challenge

Use models of Internet topology as a case study to illustrate many of the themes of this week

– “How to make complex systems still complex but experimentally accessible?”
– Importance/interpretation of high variability in complex systems
– Modeling debate: design vs. randomness
– Understanding the “robust, yet fragile” aspects of the Internet
– “Closing the loop” between modeling and analysis
– Similarity to models in biology?
The Internet as a Case Study

• To the user, it creates the illusion of a simple, robust, homogeneous resource enabling endless varieties and types of technologies, physical infrastructures, virtual networks, and applications (heterogeneous).
• Its complexity is starting to approach that of simple biological systems
• Our understanding of the underlying technology together with the ability to perform detailed measurements means that most conjectures about its large-scale properties can be unambiguously resolved, though often not without substantial effort.
A Theory for the Internet?

General Approach:
Use an engineering design perspective to understand, explain the complex structure observed.

Take a single layer in isolation and assume that the other layers are handled near optimally.
A Theory for the Internet?

If TCP/AQM is the answer, what is the question?

Primal/dual model of TCP/AQM congestion control…
A Theory for the Internet?

If the current topology of the Internet is the answer, what is the question?
The Internet hourglass

Applications

Web
FTP
Mail
News
Video
Audio
ping
napster

Transport protocols

TCP
SCTP
UDP
ICMP

IP

Link technologies

Ethernet
802.11
Power lines
ATM
Optical
Satellite
Bluetooth
The Internet hourglass

Applications

Web, FTP, Mail, News, Video, Audio, ping, napster

TCP

IP

Link technologies:
Ethernet, 802.11, Power lines, ATM, Optical, Satellit, Bluetooth
The Internet hourglass

Everything on IP

TCP

IP

IP on everything

Web  FTP  Mail  ping  napster

Ethernet  802.11  Bluetooth

Satellite
Network protocols.

Files

HTTP

TCP

IP

Packets

Sources

Links
Hosts

Routers

packets

Hosts

Routers
Modeling Network Topology

Why does it matter?

1. Performance evaluation of protocols
2. Provisioning
   - Topology constrains the applications and services that run on top of it
3. Understanding large-scale properties
   - Reliability and robustness to accidents, failures, and attacks on network components
4. Insight into other network systems
   - To the extent that the network model is “universal”
Topology Modeling

• Direct inspection generally not possible
• Recent trend: generative models follow empirical measurement studies
• But…
  – So many things to measure
  – Incredible variability in so many aspects
  – How to determine what matters?
The Internet

• Full of “high variability”
  – Link bandwidth: Kbps – Gbps
  – File sizes: a few bytes – Mega/Gigabytes
  – Flows: a few packets – 100,000+ packets
  – In/out-degree (Web graph): 1 – 100,000+
  – Delay: Milliseconds – seconds and beyond

• How should we think about the incredible scaling ability of the Internet?

• Is there something “universal” about its structure?
Topology Modeling

• Direct inspection generally not possible
• Recent trend: generative models follow empirical measurement studies
• But…
  – So many things to measure
  – Incredible variability in so many aspects
  – How to determine what matters?

• We will focus on router-level topology
Router-Level Topology

- Nodes are machines (routers or hosts) running IP protocol
- Measurements taken from traceroute experiments that infer topology from traffic sent over network
- Subject to sampling errors and bias
- Requires careful interpretation
Power Laws and Internet Topology

A few nodes have lots of connections

Most nodes have few connections


• How to account for high variability in node degree?
• Can we develop an explanatory model for the current network topology?
Power laws are ubiquitous

• This is no surprise, and requires no “special” explanation.
• Gaussians (“Normal”) distributions are attractors for averaging (e.g Central Limit Theorem) so are also ubiquitous.
• Power laws are attractors for averaging too, but are also the only distributions invariant under maximizing, marginalization, and mixtures.
• For high variability data subject to these operations, power laws should be expected (Power laws as “more normal than Normal”?)
20th Century’s 100 largest disasters worldwide

Log(rank)

Log(size)

- **Natural ($100B)**
- **Technological ($10B)**

US Power outages (10M of customers)
20th Century’s 100 largest disasters worldwide

- Technological ($10B)
- Natural ($100B)

US Power outages (10M of customers, 1985-1997)

Slope = -1 (\(\alpha=1\))
US Power outages
(10M of customers, 1985-1997)

Slope = -1
(α=1)

A large event is not inconsistent with statistics.
Our Perspective

• Must consider the explicit design of the Internet
  – Protocol layers on top of a physical infrastructure
  – Physical infrastructure constrained by technological and economic limitations
  – Emphasis on network performance
  – Critical role of feedback at all levels

• We seek a theory for Internet topology that is explanatory and not merely descriptive.

• Consider the ability to match large scale statistics (e.g. power laws) as secondary evidence of having accounted for key factors affecting design
HOT

Highly Optimized Tolerance
Heavily Organized Tradeoffs
Heuristically

• Based on ideas of Carlson and Doyle
• Complex structure (including power laws) of highly engineered technology (and biological) systems is viewed as the natural by-product of tradeoffs between system-specific objectives and constraints
• Non-generic, highly engineered configurations are extremely unlikely to occur by chance
What factors dominate network design?

- Economic constraints
  - User demands
  - Link costs
  - Equipment costs
- Technology constraints
  - Router capacity
  - Link capacity
Internet End-User Bandwidths

How to build a network that satisfies these end user demands?
**Economic Constraints**

- Network operators have a limited budget to construct and maintain their networks
- Links are tremendously expensive
- Tremendous drive to operate network so that traffic shares the same links
  - Enabling technology: multiplexing
  - Resulting feature: traffic aggregation at edges
  - Diversity of technologies at network edge (Ethernet, DSL, broadband cable, wireless) is evidence of the drive to provide connectivity and aggregation using many media types
Heuristically Optimal Network

Mesh-like core of fast, low degree routers

High degree nodes are at the edges.
Heuristically Optimal Network

Claim: economic considerations alone yield

- Mesh-like core of high-speed, low degree routers
- High degree, low-speed nodes at the edge

- Is this consistent with technology capability?
- Is this consistent with real network design?
Cisco 12000 Series Routers

- Modular in design, creating flexibility in configuration.
- Router capacity is constrained by the number and speed of line cards inserted in each slot.

<table>
<thead>
<tr>
<th>Chassis</th>
<th>Rack size</th>
<th>Slots</th>
<th>Switching Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>12416</td>
<td>Full</td>
<td>16</td>
<td>320 Gbps</td>
</tr>
<tr>
<td>12410</td>
<td>1/2</td>
<td>10</td>
<td>200 Gbps</td>
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<tr>
<td>12406</td>
<td>1/4</td>
<td>6</td>
<td>120 Gbps</td>
</tr>
<tr>
<td>12404</td>
<td>1/8</td>
<td>4</td>
<td>80 Gbps</td>
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</tbody>
</table>

Source: www.cisco.com
Cisco 12000 Series Routers

Technology constrains the number and capacity of line cards that can be installed, creating a feasible region.
Cisco 12000 Series Routers


(http://techmall.dis.wa.gov/masterContracts/intranet/routers_switches.asp)
Sprint backbone
Backbone topology of both Abilene and CENIC are both built as a mesh of high speed, low degree routers.

As one moves from the core out toward the edge, connectivity gets higher, and speeds get lower.
Heuristically Optimal Network

• Mesh-like core of high-speed, low degree routers
• High degree, low-speed nodes at the edge

• Claim: consistent with drivers of topology design
  – Economic considerations (traffic aggregation)
  – End user demands
• Claim: consistent with technology constraints
• Claim: consistent with real observed networks

Question: How could anyone imagine anything else?
Two *opposite* views of complexity

**Physics:**
- Pattern formation by reaction/diffusion
- Edge-of-chaos
- Order for free
- Self-organized criticality
- Phase transitions
- Scale-free networks
- Equilibrium, linear
- Nonlinear, heavy tails as exotica

**Engineering and math:**
- Constraints
- Tradeoffs
- Structure
- Organization
- Optimality
- Robustness/fragility
- Verification
- Far from equilibrium
- Nonlinear, heavy tails as tool
Models of Internet Topology

- Random graphs [Waxman ’88]
- Explicit hierarchy [Calvert/Zegura ’96]
- Power laws [Faloutsos ³ ’99]

Figure 3: The rank plots. Log-log plot of the outdegree $d_v$ versus the rank $r_v$ in the sequence of decreasing outdegree.
Random Networks

Two methods for generating random networks having power law distributions in node degree

• Preferential attachment ("scale-free" networks)
  – Inspired by statistical physics
  – Barabasi et al.; 1999

• Power Law Random Graph (PLRG)
  – Inspired by graph theory
  – Aiello, Chung, and Lu; 2000

Common features:

• Ignore all system-specific details
• Central core of high-degree, hub-like nodes
Summary of Scale-Free Story

• Fact: Scale-free networks have roughly power law degree distributions

• Claim:
  – If the Internet has power law degree distribution
  – Then it must be scale-free (oops)
  – Therefore, it has the properties of a scale-free network
One of the most-read papers ever on the Internet!
"The reason this is so is because there are a couple of very big nodes and all messages are going through them. But if someone maliciously takes down the biggest nodes you can harm the system in incredible ways. You can very easily destroy the function of the Internet," he added.

Barabasi, whose research is published in the science journal Nature, compared the structure of the Internet to the airline network of the United States.
13. Accurately Modeling the Internet Topology, arXiv

Abstract: To model the behavior of a network it is crucial to obtain a good description of the topology because structure affects function. When studying the topological properties of the Internet, we found out that there are two mechanisms which are necessary for the growth of the Internet: a nonlinear preferential growth mechanism, where the growth is described by a positive-feedback mechanism, and the appearance of new links between already existing nodes. We show that the Positive-Feedback Preference (PFP) model, which is based on the above mechanisms, reproduces the topological properties of the Internet such as: degree distribution, (rich-club connectivity), shortest path length, neighbor clustering, network rectangle coefficient), disassortative mixing (nearest-neighbors average degree), and information flow pattern (betweenness centrality). We believe that these growth mechanisms require further study because they provide a novel insight into the evolutionary dynamics of networks.

* [38] Accurately Modeling the Internet Topology, Shi Zhou, Raul J. Mondragon, arXiv 2004-02-05, arXiv
Key Points

• The scale-free story is based critically on the implied relationship between power laws and a network structure that has highly connected “central hubs”
  – Not all networks with power law degree distributions have properties of scale free networks. (The Internet is just one example!)
  – Building a model to replicate power law data is no more than curve fitting (descriptive, not explanatory)

• The scale-free models ignore all system-specific details in making their claims
  – Ignore architecture (e.g. hardware, protocol stack)
  – Ignore objectives (e.g. performance)
  – Ignore constraints (e.g. geography, economics)
End Result

The scale-free claims of the Internet are not merely wrong, they suggest properties that are the opposite of the real thing.

Fundamental difference:
random vs. designed
Internet topologies

nodes = routers
edges = links

25 interior routers
818 end systems

“scale-rich” vs. scale-free

How to characterize / compare these two networks?

- Low degree mesh-like core
- High degree hub-like core

identical power-law degrees

rank

$10^0$ $10^1$
Network Performance

Given realistic technology constraints on routers, how well is the network able to carry traffic?

Step 1: Constrain to be feasible

Step 2: Compute traffic demand

Step 3: Compute max flow $\alpha$

$$\max_{\alpha} \sum_{i,j} x_{ij} = \max \sum_{i,j} \alpha B_i B_j$$

s.t. $$\sum_{i,j: k \in r_{ij}} x_{ij} \leq B_k, \forall k$$
Network Likelihood

How likely is a particular graph (having given node degree distribution) to be constructed?

- Notion of likelihood depends on defining an appropriate probability space for random graphs.
- Many methods (all based on probabilistic preferential attachment) for randomly generating graphs having power law degree distributions:
  - Power Law Random Graph (PLRG) [Aiello et al.]
  - Random rewiring (Markov chains)

In both cases, LogLikelihood (LLH) $\propto \sum_{i,j}^{\text{connected}} d_id_j$
Likelihood

Fast

Performance

Slow

Why such striking differences with same node degree distribution?
**HOT scale-rich**
- Core: Mesh-like, low degree
- Edge: High degree
- Robust to random $\Delta$
- Robust to “attack”

**Scale-free**
- Core: Hub-like, high degree
- Edge: Low degree
- Robust to random $\Delta$
- Fragile to “attack”

+ objectives and constraints

- High performance
- Low link costs
- Unlikely, rare, designed
- Destroyed by rewiring
- Similar to real Internet

- Low performance
- High link costs
- Highly likely, generic
- Preserved by rewiring
- Opposite of real Internet
Hierarchical Scale-Free (HSF)

Low Likelihood
Low Performance

Hierarchical Scale-Free (HSF)

Most Likely
The only functional biological or technological networks are highly organized, robust, efficient, and very unlikely to arise by random.
Carriers

Amino acids
Nucleotides
Fatty acids And Lipids
Cofactors

Nutrients
Catabolism

Precursors
Biosynthesis

Bowtie architecture
\[ S_1 + ATP \rightarrow S_2 + ADP \]
\[ S_3 + NADH \leftrightarrow S_4 + NAD \]

**Stoichiometry Matrix**

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<thead>
<tr>
<th></th>
<th>( S_1 )</th>
<th>( S_2 )</th>
<th>( S_3 )</th>
<th>( S_4 )</th>
<th>( ATP )</th>
<th>( ADP )</th>
<th>( NADH )</th>
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</table>
• WT is highly organized, structured
• Simple reactions
• Long assembly lines
• Universal common carriers
• Precursors and carriers are universal common currencies
• Randomly rewire to get “scale-free” version
• Preserve
  • degree
  • carrier and enzyme
• Destroys structure
• Only one useful pathway remains
Carriers

precursors  amino acids

Wild type  Random

GLC  DPG  PGL  PGC  RL5P  X5P  6PG  MAL  CIT  ICIT  SUC  FUM
G6P  F6P  T3P  3PG  PEP  R5P  E4P  PYR  OA  AKG  SUCOA
PRPP  DAH  DQT  DHS  SME  S5P  PSM  CHO  AN  NAN  CD5  IGP
PPN  HPP  BAP  ASS  HSE  PHS  DHD  PIP  SAK  SDP  DPI  MDP
PHP  PPS  ASE
GLN  GLU  SER  TRP  ASP  TYR  THR  LYS  CYS  GLY  ASN
PI  NAD  NADH  ADP  ATP  NADP  NADPH  CO2  COA  COO  H2O  PPI  AMP  ATP  NH3  AC  THF  MTH  H2S
“Closing the loop”

Modeling

Analysis

Measurement.arrow

Validation
Internet Routing Technologies

Degree (number of connections)

Total Router Bandwidth (Mbps)

- Core Routers
- High-End Gateways
- Older Cheaper Technology
- Access Edge Routers Shared Media

Abstracted Feasible Region
Internet Routing Technologies

- Core Routers
- High-End Gateways
- Older Cheaper Technology
- Access Edge Routers
- Shared Media

Per link bandwidth

Degree (number of connections)

Total Router Bandwidth (Mbps)
Internet Link Speeds

- **Dial-up**: ~56Kbps
- **Cable Broadband**: ~500Kbps
- **DSL**: ~500Kbps
- **Local Area Ethernet**: 10-100Mbps
- **Core/Edge Routers**: 1Gbps
- **Core Routers**: 10Gbps

Bandwidth / Link (Mbps) vs. Degree (number of connections)