“Lies, Damned Lies, and Statistics:”

Preferential Attachment-type Network Models of the Internet

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Acknowledgments

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Recap: What “Network Science” says about the Internet

- **Measurements**
  - Router-level: large-scale traceroute experiments
  - AS-level: BGP-based, traceroute-based, WHOIS
  - WWW: large-scale web crawling experiments

- **Inference**
  - (Exclusive) focus on node degree distribution
  - Inferred node degree distributions follow a power law

- **Modeling**
  - Preferential attachment-type growth model
    - Incremental growth
    - Preferential attachment: \( p(k) \approx \text{degree of node } k \)
  - There exist many variants of this basic PA model
Recap: What “Network Science” says about the Internet (cont)

• Key features of PA-type models
  – Randomness enters via attachment mechanism
  – Exhibit power law node degree distributions with or without exponential cutoffs

• Model validation
  – The model “fits the data ...”
  – Reproduces observed node degree distribution

• Highly publicized claims about Internet topology
  – High-degree nodes form a hub-like core
  – Fragile/vulnerable to targeted node removal
  – Achilles’ heel
  – Zero epidemic threshold
Basic Question

Do the available Internet-related connectivity measurements and their analysis support the sort of claims that can be found in the existing complex networks literature?

Key Issues

• What about data hygiene?
• What about statistical rigor?
• What about model validation?
The Internet: The User Perspective

my computer

router

router

nature
The Internet is a LAYERED Network

The perception of the Internet as a simple, user-friendly, and robust system is enabled by FEEDBACK and other CONTROLS that operate both WITHIN LAYERS and ACROSS LAYERS.

These ARCHITECTURAL DETAILS (protocols, interfaces, etc.) are MOST ESSENTIAL to the nature of the Internet.
Internet Architecture: Vertical Decomposition

Benefits:
- Each layer can evolve independently
- Substitutes, complements

Requirements:
1. Each layer follows the rules
2. Every other layer does “good enough” with its implementation
Internet Architecture: Horizontal Decomposition

Horizonal decomposition
Each level is decentralized and asynchronous

Benefit: Individual components can fail (provided that they “fail off”) without disrupting the network.
The Internet hourglass

Applications

Transport protocols
TCP  SCTP  UDP  ICMP

IP

Link technologies
The Internet hourglass

Everything on IP

IP on everything

Courtesy Hari Balakrishnan
Internet Connectivity/Topology

- Consider a (vertical) layer of the Internet hourglass
- Expand it horizontally
- Give layer-specific meaning to “nodes” and “links”
"nodes" "links"
The Many Facets of Internet Connectivity/Topology

- Web graph
- Email graph
- P2P graph
- and many others ...
- Autonomous System (AS) or AS-level ecosystem
- IP-level connectivity (i.e., layer 3)
- Router-level connectivity (i.e., layer 2)
Internet Connectivity/Topology

virtual

dynamic

physical

static

TCP

IP

Transmission

Ethernet, ATM, POS, WDM, ...

WWW, Email, Napster, FTP, ...

Applications
On Measuring Internet Connectivity

- No central agency/repository
- Economic incentive for ISPs to obscure network structure
- Direct inspection is typically not possible
- Based on measurement experiments, hacks
- Mismatch between what we want to measure and can measure
- Specific examples covered in this talk
  - Physical connectivity (ISP router-level topology)
  - Logical connectivity (Internet AS-level topology)
Back to our Basic Question

Do the available Internet-related connectivity measurements and their analysis support the sort of claims that can be found in the existing complex networks literature?

Key Issues

• What about data hygiene?
• What about statistical rigor?
• What about model validation?
On Data Hygiene
On Measuring the Internet’s Router-level Topology

- **traceroute** tool
  - Discovers compliant (i.e., IP) routers along path between selected network host computers

- Large-scale traceroute experiments
  - Pansiot and Grad (router-level map from around 1995)
  - Cheswick and Burch (mapping project 1997--)
  - Mercator (router-level maps from around 1999 by R. Govindan and H. Tangmunarunkit)
  - Skitter (ongoing mapping project by CAIDA folks)
  - Rocketfuel (state-of-the-art router-level maps of individual ISPs by UW folks)
  - Dimes (EU project)
http://research.lumeta.com/ches/map/
http://www.caida.org/tools/measurement.skitter/
HOWEVER: Problems with existing measurements

- traceroute-based measurements are ambiguous
  - traceroute is strictly about IP-level connectivity
  - traceroute cannot distinguish between high connectivity nodes that are for real and that are fake and due to underlying Layer 2 (e.g., Ethernet, ATM) or Layer 2.5 technologies (e.g., MPLS)
The Internet: The Engineering Perspective

my computer -> router -> router -> web server

HTTP
TCP
IP
LINK
Illusion of a fully-meshed Network due to use of MPLS

http://www.cs.washington.edu/research/networking/rocketfuel/
www.savvis.net
managed IP and hosting company
founded 1995
offering “private IP with ATM at core”

This “node” is an entire network! (not just a router)
HOWEVER: Problems with existing measurements

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  - traceroute is strictly about IP-level connectivity
  - traceroute cannot distinguish between high connectivity nodes that are for real and that are fake and due to underlying Layer 2 (e.g., Ethernet, ATM) or Layer 2.5 technologies (e.g., MPLS)

• traceroute-based measurements are inaccurate
  - Requires some guesswork in deciding which IP addresses/interface cards refer to the same router (“alias resolution” problem)

• traceroute-based measurements are incomplete/biased
  - IP-level connectivity is more easily/accurately inferred the closer the routers are to the traceroute source(s)
  - Node degree distribution is inferred to be of the power-law type even when the actual distribution is not
On Statistical Rigor
How to lie with statistics …

Given: Samples from an exponential distribution
Want: Claim power law behavior
Recipe: Use size-frequency plots!

Given: Samples from a Pareto distribution with $\alpha=1.0$
Want: Claim power law with $\alpha=1.5$
Recipe: Use size-frequency plots!
Size-Frequency vs. Size-Rank Plots
or
Non-cumulative vs. Cumulative

\[ \alpha + 1 = 1.5 \]

\[ \alpha = 0.5 \]

\[ \alpha = 1.0 \]
Exponential Scaling

\( Y^e \) appears (incorrectly) to be exponential
Noncumulative Size-Frequency

raw MERCATOR data

Binned Size-Frequency

a common reporting technique

without 2 largest nodes

exponential in tail...
On Model Validation
Taking Model validation more serious ...

- Mathematical Modeling 101
  - For one and the same observed phenomenon, there are usually many different explanations/models
  - All models are wrong, but some are “damned lies”
- Model validation ≠ data fitting
  - The ability to reproduce a few graph statistics does not constitute “serious” model validation
  - Which of the observed properties does a proposed model have to satisfy before it is deemed “valid”?
- What constitutes “serious” model validation?
  - There is more to networks than connectivity
  - Meaning of “node” and “link”
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>
</tr>
<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>
</tr>
</tbody>
</table>

Source: www.cisco.com
Router Technology Constraint

Cisco 12416 GSR, circa 2002

- Total Bandwidth
- Degree
- Bandwidth (Gbps)
- Technology constraint

- High BW low degree
- High degree low BW

- 15 x 1-port 10 GE
- 15 x 3-port 1 GE
- 15 x 4-port OC12
- 15 x 8-port FE
Back to the Basic Question:

Do the available Internet-related connectivity measurements and their analysis support the sort of claims that can be found in the existing complex networks literature?

Short Answer:

No!
Network Science and the Internet: “Lies, damned lies and statistics”

- Power-law (scale-free) node degree distribution
  - Example of “how to lie with statistics”
- Preferential attachment-type models
  - (White) lies ...
- Highly popularized claims (e.g., Achilles’ heel, fragile/vulnerable to targeted node removal, zero epidemic threshold)
  - Damned lies ...
  - These claims are not “controversial” – they are simply wrong!
- Bad analysis of bad data = bad models (“damned lies”)

“Bad [models] are potentially important: they can be used to stir up public outrage or fear; they can distort our understanding of our world; and they can lead us to make poor policy choices.” (J. Best)
The “Math” Perspective of the Internet

• Assumption
  – Node degree distributions follow a power-law

• Rigorous model definition/formulation
  – Preferential attachment-type models

• Rigorous proofs
  – Achilles’ heel
  – Fragile/vulnerable to targeted node removal
  – Zero epidemic threshold

• End result is the same
  – Rigorous analysis of bad model = “damned lies”
How to avoid such Fallacies?

• Taking model validation more serious

• Applying an engineering perspective to engineered systems
Internet Modeling: An Engineering Perspective

- ISPs design their router-level topology for a purpose, namely to carry an expected traffic demand.
- Surely, the way an ISP designs its physical infrastructure is not the result of a series of coin tosses ...
- Randomness enters in terms of uncertainty in traffic demands.
- ISPs are constrained in what they can afford to build, operate, and maintain (economics).
- The “nodes” and “links” are physical things that have hard constraints (technology).
- Decisions of ISPs are driven by objectives (performance) and reflect tradeoffs between what is feasible and what is desirable (heuristic optimization).
- Power laws: Full of sound and fury, signifying nothing!
Heuristically Optimized Topologies (HOT)

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

Step 1: Constrain to be feasible

Step 2: pick traffic demand model

\[ x_{ij} \propto B_i B_j \]

Step 3: Compute max flow

\[
\max_{\alpha} \sum_{i,j} x_{ij} = \max_{i,j} \sum \alpha B_i B_j \\
\text{s.t. } \sum_{i,j; k \in r_{ij}} x_{ij} \leq B_k, \forall k
\]
HOT model

Preferential Attachment

node rank

node degree
HOT-type Network Models

• Very recent alternatives to PA-type models
  – Extremely unlikely to occur at random

• Key features of HOT models
  – Consistent with existing ISP router-level topologies
  – Consistent with existing technologies
  – Consistent with (complementary) measurements
  – Node degree distribution is a non-issue

• Same story for AS-level Internet topology
  – Surely, deciding on whether or not to establish what type of peering relationship and with whom is not the outcome of a series of chance experiments conducted by the different ASs, but is largely based on economic arguments.
  – First HOT-type model by Chang et al. (2006)
Litmus Test for Newly Proposed Network Models

- Make node degree distribution a non-issue
  - Good reasons
    - High-quality data but low variability (e.g., exponential)
    - Low-quality data
    - High-quality data and high variability (e.g., power-laws)
  - PA-type models
    - dead on arrival
  - Only reasonable alternative
    - Bring in and rely on domain knowledge
- What new kinds of measurements does the proposed model suggest for the purpose of model validation
  - PA-type models: none
  - HOT models: get data on existing router technology
Some Implications of this Engineering Perspective

• New paradigm for network modeling
  – Network modeling ≠ data fitting
  – Node degree distribution is a non-issue

• Constrained optimization formulation
  – Optimization of tradeoffs between multiple functional objectives of networks
  – Subject to constraints on their components
  – With an explicit source of uncertainty (in the environment) against which solutions must be tolerant or robust
Further Implications of this Engineering Perspective

- Dynamics of graphs
  - Evolution of connectivity structures
  - Evolution of (internal) node/link structure
- Dynamics over graphs
  - Traffic dynamics (bytes, packets, flows, ...)
- Challenging feedback problem
  - Traffic dynamics/routing impacts network structure
  - Network structure impacts traffic dynamics/routing
- Can’t (shouldn’t) model connectivity without traffic
- Robustness/fragility considerations only make sense in the context of the broader system, i.e., protocol stack
  - Router-level: Inter-AS routing protocol
  - AS-level: Intra-AS routing protocol
Further Implications of this Engineering Perspective (cont.)

• Key question #1: What is the network as whole trying to achieve?
  – Internet router-level: see earlier
  – Internet AS-level: ?
  – WWW, P2P: ??
  – Social Networks: ???
Here are two project teams, the gray links indicate project-related interactions. Which team is from a Fortune 500 company and which is from Al Qaeda?
Further Implications of this Engineering Perspective (cont.)

• Key question #1: What is the network as whole trying to achieve?
  – Internet router-level: see earlier
  – Internet AS-level: ?
  – WWW, P2P: ??
  – Social Networks: ???

• Key question #2: How is the network trying to achieve its objective?
  - Decentralized, distributed
  - Duality gap (“price of anarchy”)
A Reminder

- Past: Modeling in the presence of high-quality data
  - “All models are wrong ... but some are useful” (G.E.P. Box)

- Future: Modeling in the presence of highly ambiguous data
  - Take the ambiguities in the data into account
  - “When exactitude is elusive, it is better to be approximately right than certifiably wrong.” (B.B. Mandelbrot)
http://hot.caltech.edu/topology.html


