CE693: Adv. Computer Networking

L-13 Network Topology

Acknowledgments: Lecture slides are from the graduate level Computer Networks course thought by Srinivasan Seshan at CMU. When slides are obtained from other sources, a a reference will be noted on the bottom of that slide. A full list of references is provided on the last slide.

Today's Lecture

- Structural generators
- Power laws
- HOT graphs
- Assigned reading
  - On Power-Law Relationships of the Internet Topology
  - A First Principles Approach to Understanding the Internet's Router-level Topology

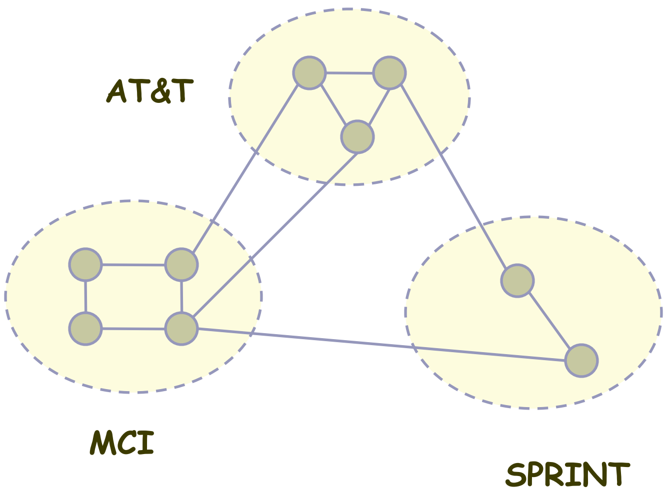
Outline

- Motivation/Background
- Power Laws
- Optimization Models

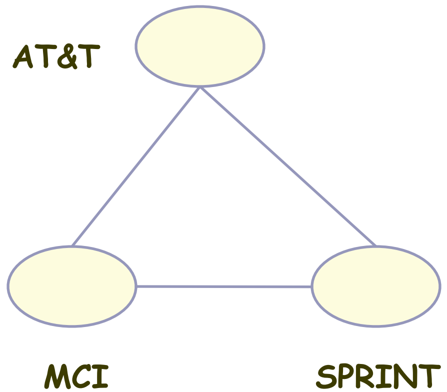
Why study topology?

- Correctness of network protocols typically independent of topology
- Performance of networks critically dependent on topology
  - e.g., convergence of route information
- Internet impossible to replicate
- Modeling of topology needed to generate test topologies

Internet topologies



Router level



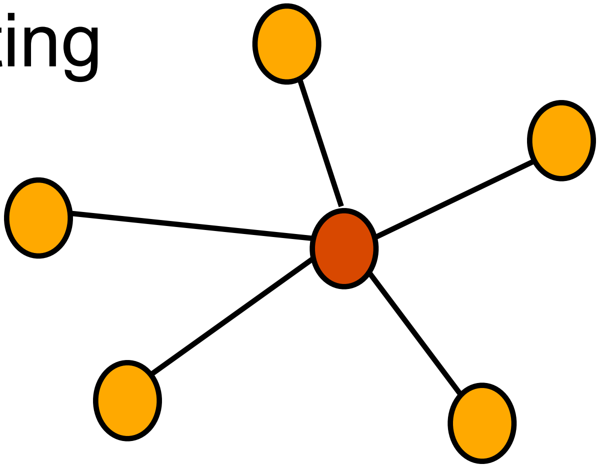
Autonomous System (AS) level

More on topologies..

- Router level topologies reflect physical connectivity between nodes
  - Inferred from tools like *traceroute* or well known public measurement projects like Mercator and Skitter
- AS graph reflects a peering relationship between two providers/clients
  - Inferred from inter-domain routers that run BGP and publlic projects like Oregon Route Views
- Inferring both is difficult, and often inaccurate

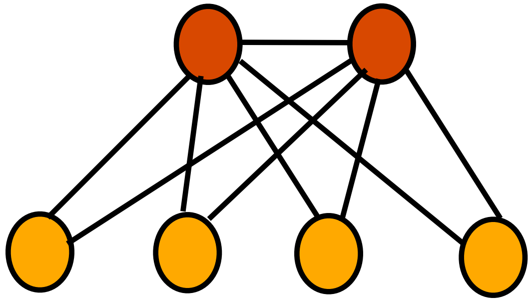
Hub-and-Spoke Topology

- Single hub node
  - Common in enterprise networks
  - Main location and satellite sites
  - Simple design and trivial routing
- Problems
  - Single point of failure
  - Bandwidth limitations
  - High delay between sites
  - Costs to backhaul to hub

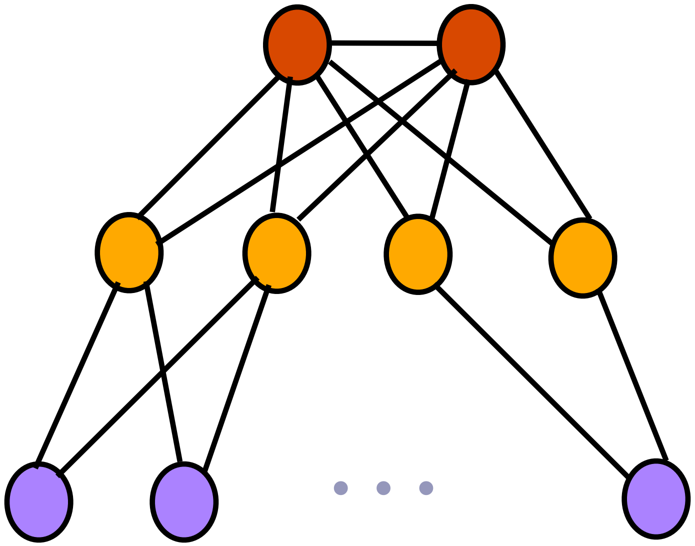


Simple Alternatives to Hub-and-Spoke

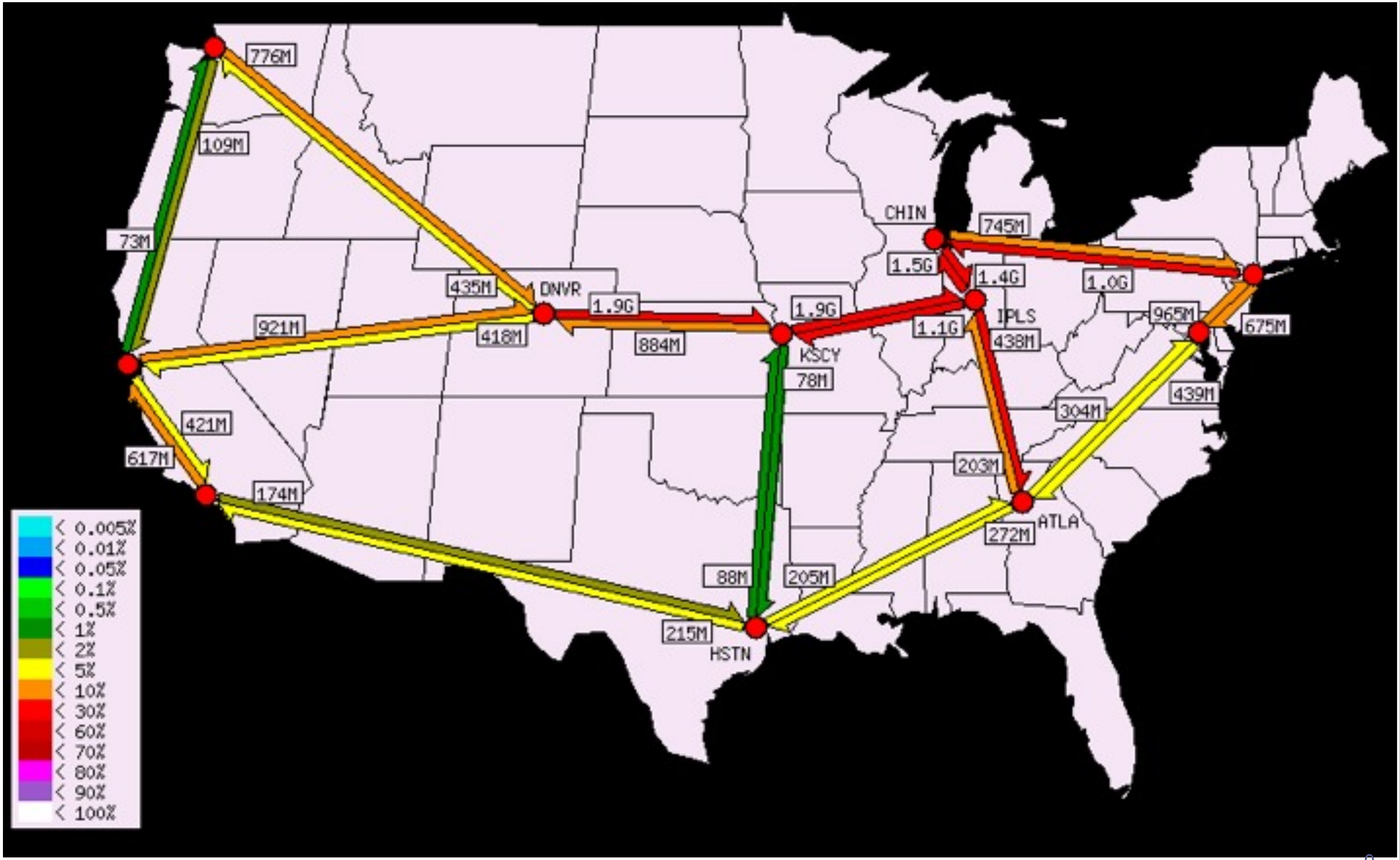
- Dual hub-and-spoke
  - Higher reliability
  - Higher cost
  - Good building block

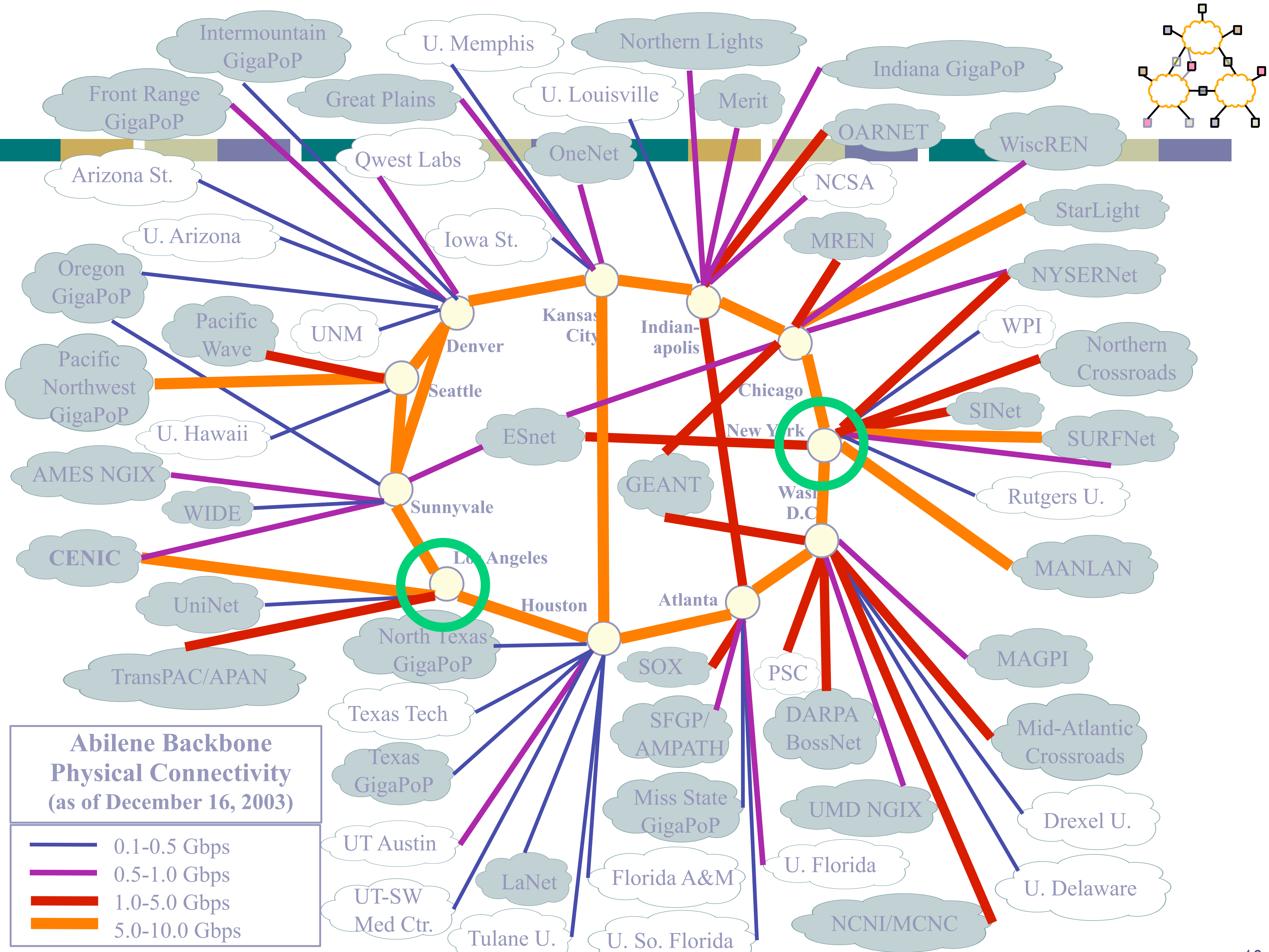


- Levels of hierarchy
  - Reduce backhaul cost
  - Aggregate the bandwidth
  - Shorter site-to-site delay



Abilene Internet2 Backbone

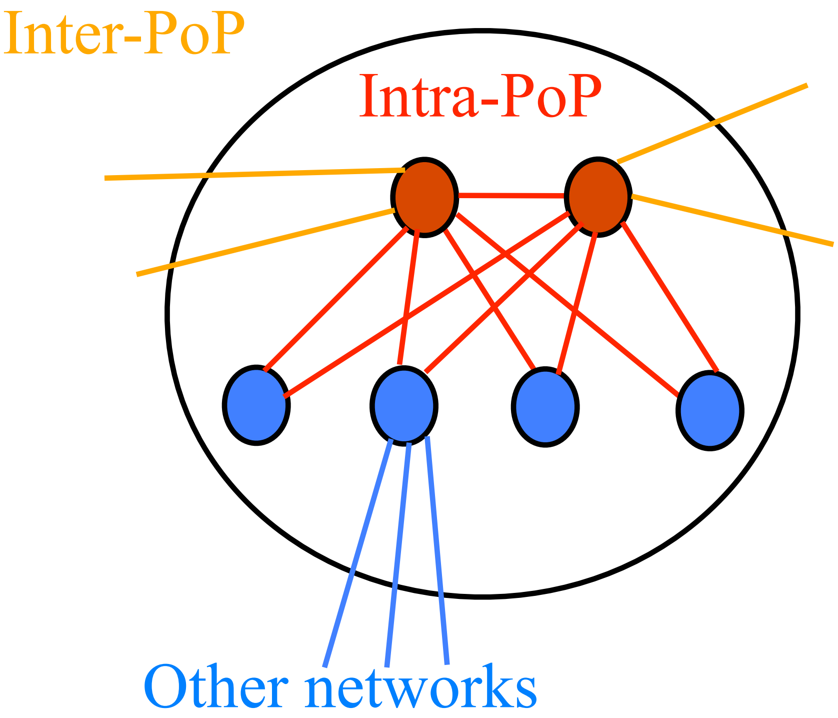




Abilene Backbone Physical Connectivity (as of December 16, 2003)

Points-of-Presence (PoPs)

- Inter-PoP links
  - Long distances
  - High bandwidth
- Intra-PoP links
  - Short cables between racks or floors
  - Aggregated bandwidth
- Links to other networks
  - Wide range of media and bandwidth



Deciding Where to Locate Nodes and Links

- Placing Points-of-Presence (PoPs)
  - Large population of potential customers
  - Other providers or exchange points
  - Cost and availability of real-estate
  - Mostly in major metropolitan areas
- Placing links between PoPs
  - Already fiber in the ground
  - Needed to limit propagation delay
  - Needed to handle the traffic load

Trends in Topology Modeling

Observation

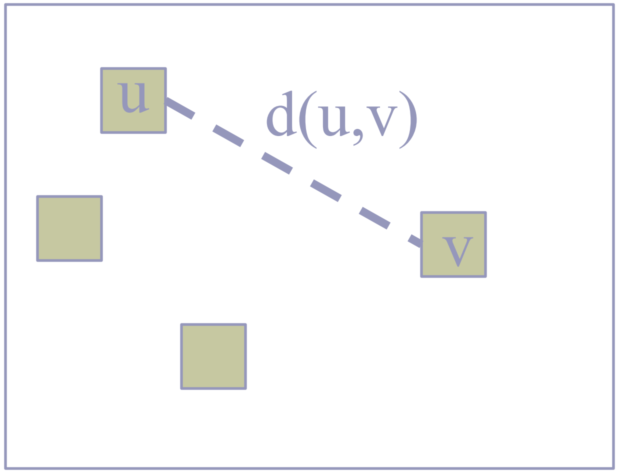
- Long-range links are expensive
- Real networks are not random, but have obvious hierarchy
- Internet topologies exhibit power law degree distributions (Faloutsos et al., 1999)
- Physical networks have hard technological (and economic) constraints.

Modeling Approach

- Random graph (Waxman88)
- Structural models (GT-ITM Calvert/Zegura, 1996)
- Degree-based models replicate power-law degree sequences
- Optimization-driven models topologies consistent with design tradeoffs of network engineers

Waxman model (Waxman 1988)

- Router level model
- Nodes placed at random in 2-d space with dimension L
- Probability of edge (u,v):
  - ae^{-d/(bL)}, where d is Euclidean distance (u,v), a and b are constants
- Models locality

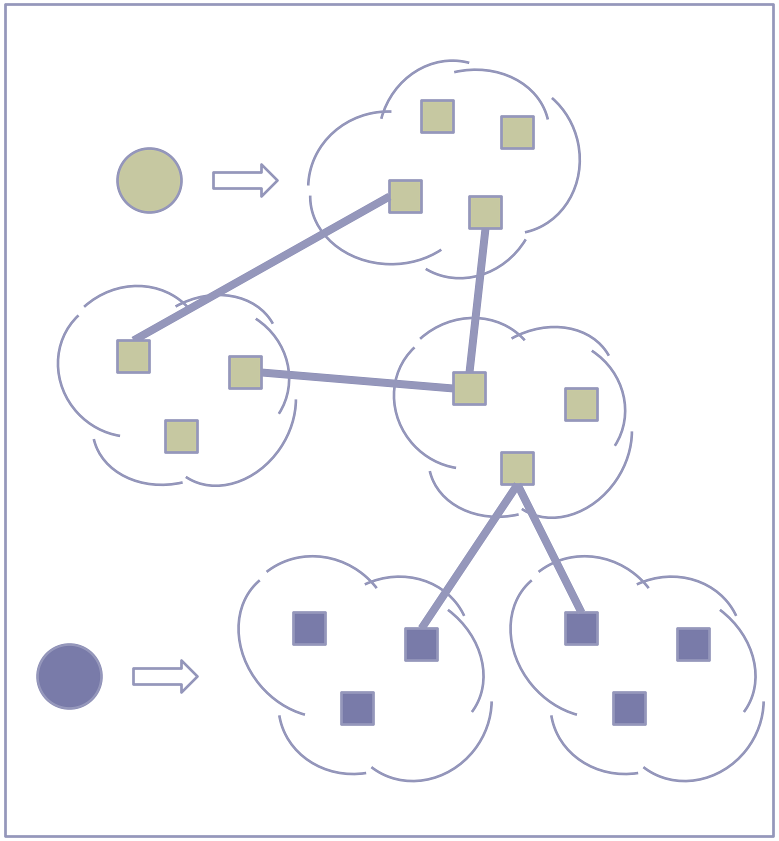


Real world topologies

- Real networks exhibit
  - Hierarchical structure
  - Specialized nodes (transit, stub..)
  - Connectivity requirements
  - Redundancy
- Characteristics incorporated into the Georgia Tech Internetwork Topology Models (GT-ITM) simulator (E. Zegura, K.Calvert and M.J. Donahoo, 1995)

Transit-stub model (Zegura 1997)

- Router level model
- Transit domains
  - placed in 2-d space
  - populated with routers
  - connected to each other
- Stub domains
  - placed in 2-d space
  - populated with routers
  - connected to transit domains
- Models hierarchy



So…are we done?

- No!
- In 1999, Faloutsos, Faloutsos and Faloutsos published a paper, demonstrating power law relationships in Internet graphs
- Specifically, the node degree distribution exhibited power laws

That Changed Everything…..

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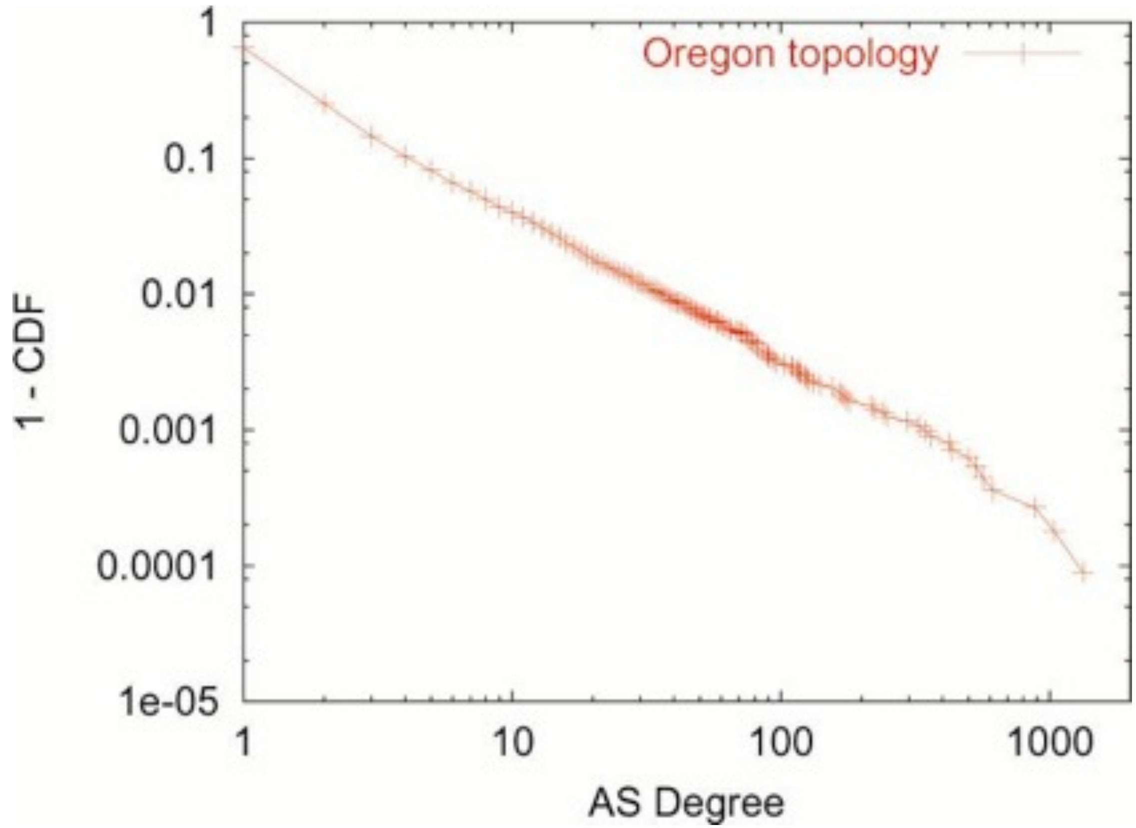
Power laws in AS level topology

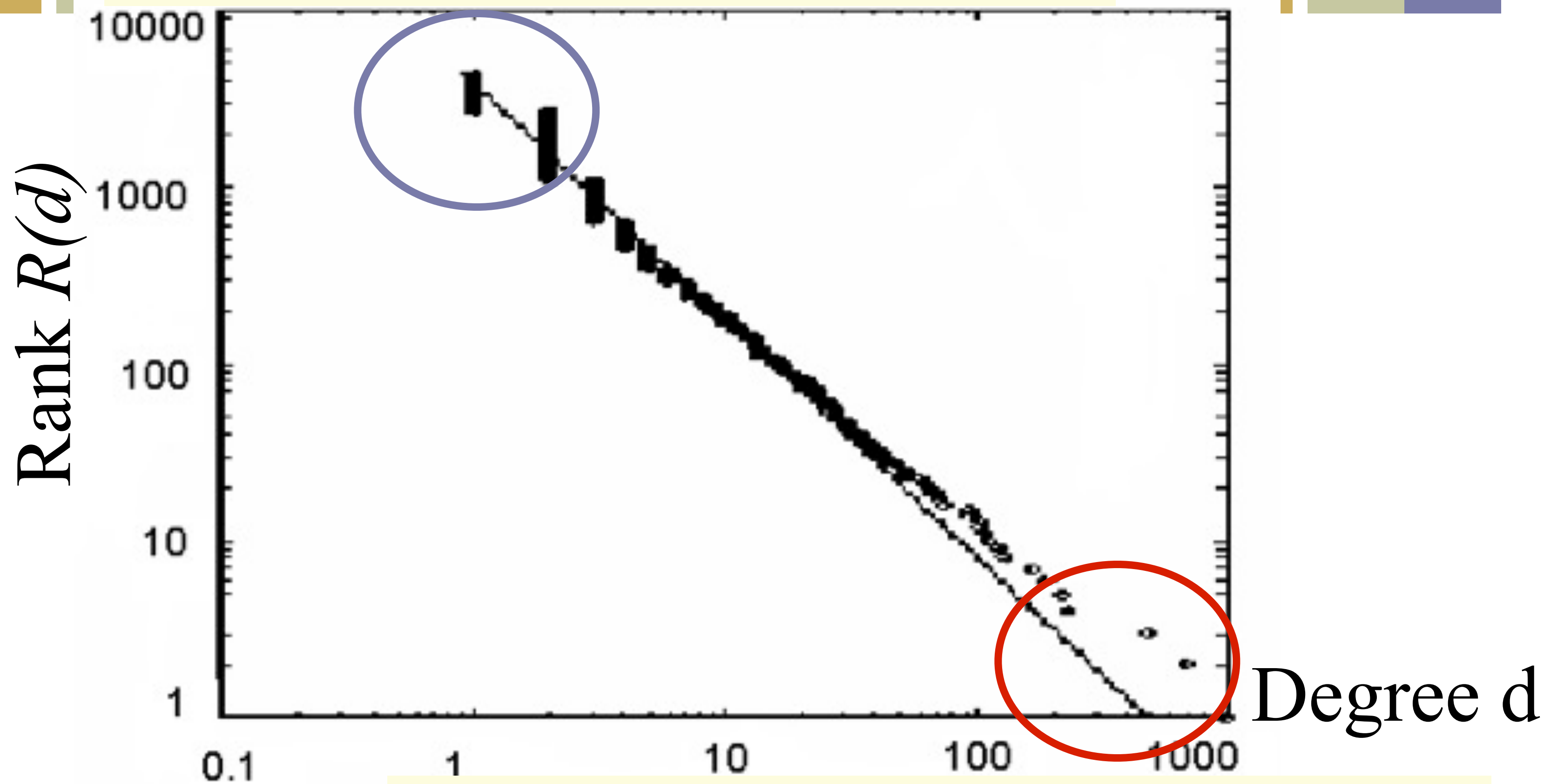


Power Laws and Internet Topology

Source: Faloutsos et al. (1999)

Most nodes have few connections

R(d) = P (D>d) x #nodes



A few nodes have lots of connections

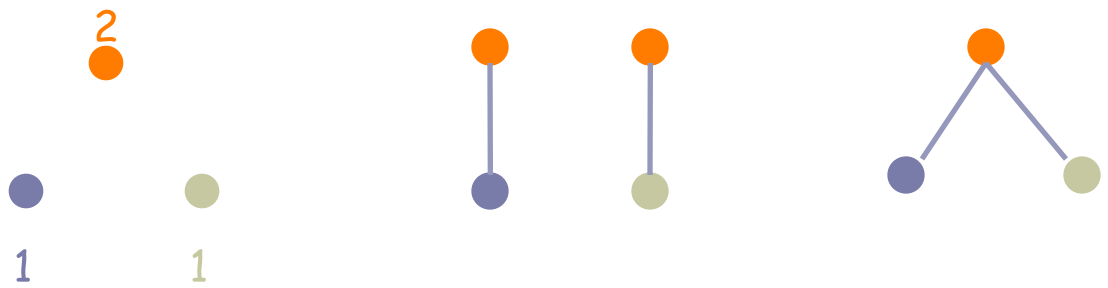
- Router-level graph & Autonomous System (AS) graph
- Led to active research in *degree-based* network models

GT-ITM abandoned..

- GT-ITM did not give power law degree graphs
- New topology generators and explanation for power law degrees were sought
- Focus of generators to match degree distribution of observed graph

Power law random graph (PLRG)

- Operations
  - assign degrees to nodes drawn from power law distribution
  - create kv copies of node v; kv degree of v.
  - randomly match nodes in pool
  - aggregate edges

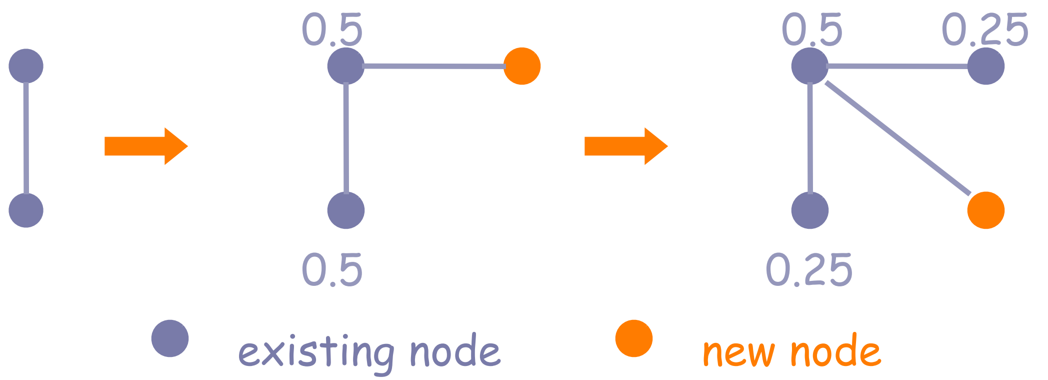


may be disconnected, contain multiple edges, self-loops

- contains unique giant component for right choice of parameters

Barabasi model: fixed exponent

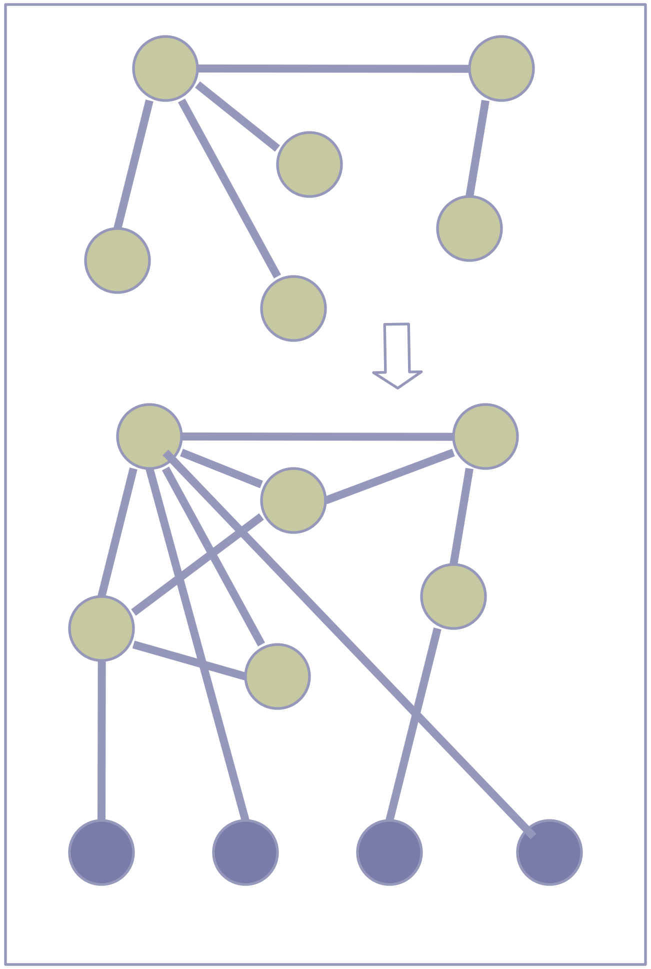
- incremental growth
  - initially, m0 nodes
  - step: add new node i with m edges
- linear preferential attachment
  - connect to node i with probability ki / ∑ kj



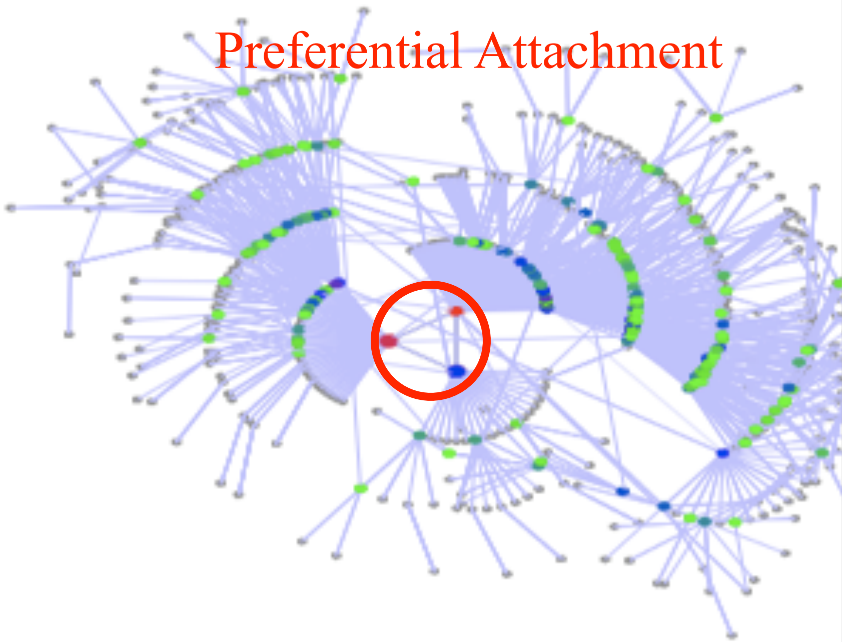
may contain multi-edges, self-loops

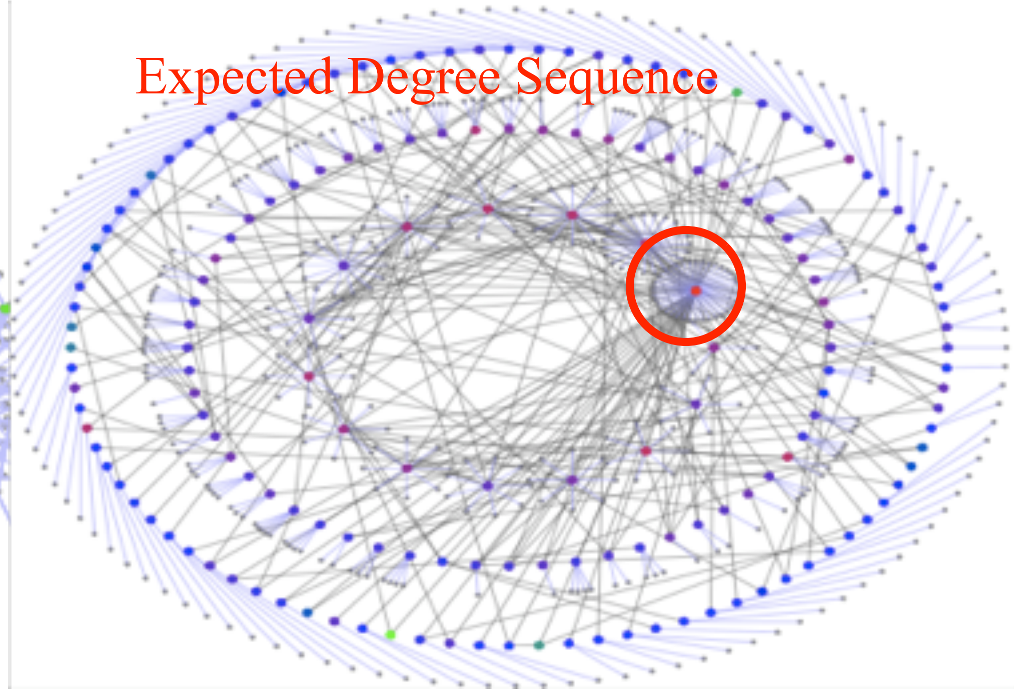
Inet (Jin 2000)

- Generate degree sequence
- Build spanning tree over nodes with degree larger than 1, using preferential connectivity
  - randomly select node u not in tree
  - join u to existing node v with probability $d(v)/\Sigma d(w)$
- Connect degree 1 nodes using preferential connectivity
- Add remaining edges using preferential connectivity



Features of Degree-Based Models





- Degree sequence follows a power law (by construction)
- High-degree nodes correspond to highly connected central “hubs”, which are crucial to the system
- Achilles’ heel: robust to random failure, fragile to specific attack

Does Internet graph have these properties?

- No…(There is no Memphis!)
- Emphasis on degree distribution - structure ignored
- Real Internet very structured
- Evolution of graph is highly constrained

Problem With Power Law

- ... but they're descriptive models!

- No correct physical explanation, need an understanding of:
  - the driving force behind deployment
  - the driving force behind growth

Outline

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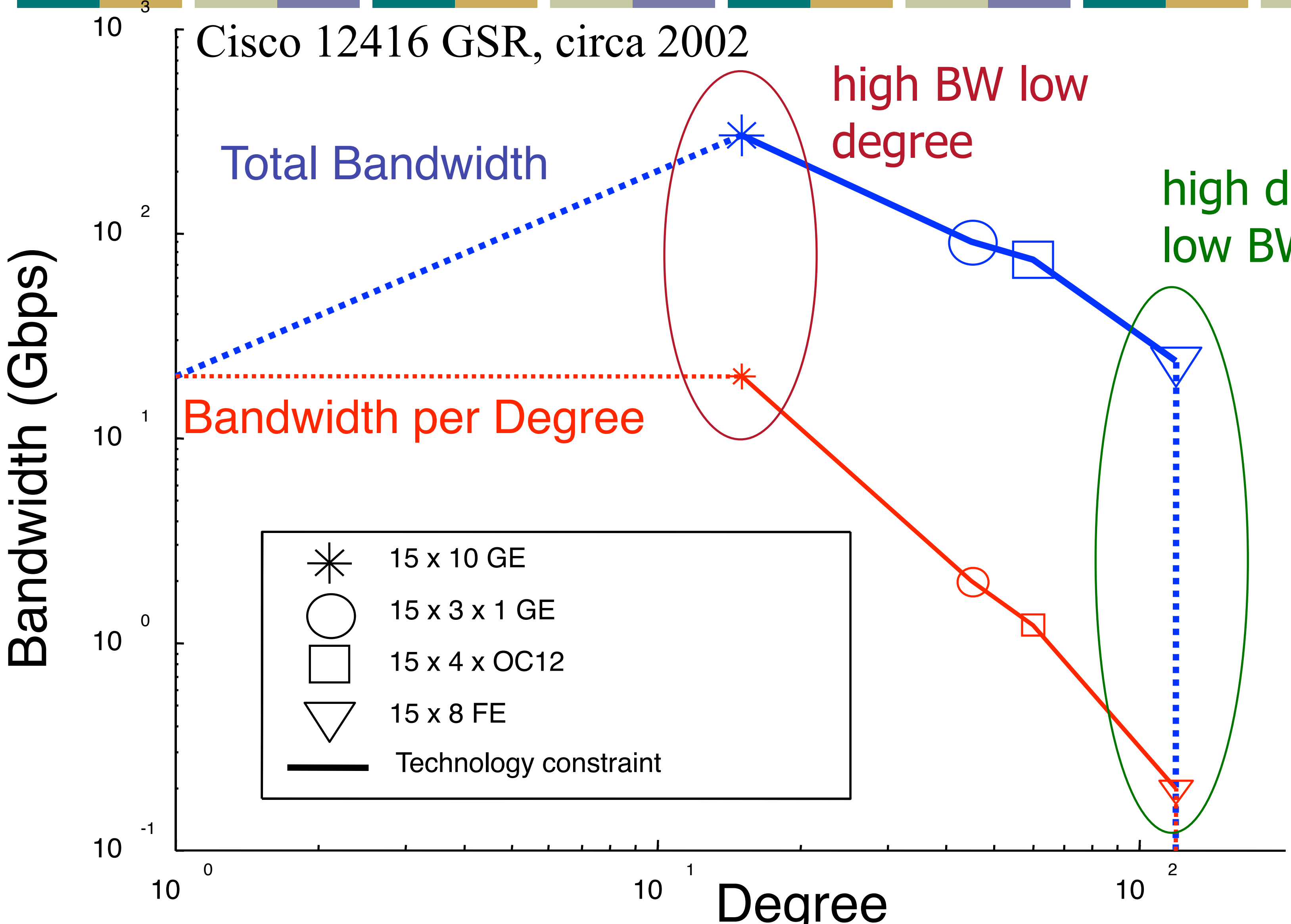
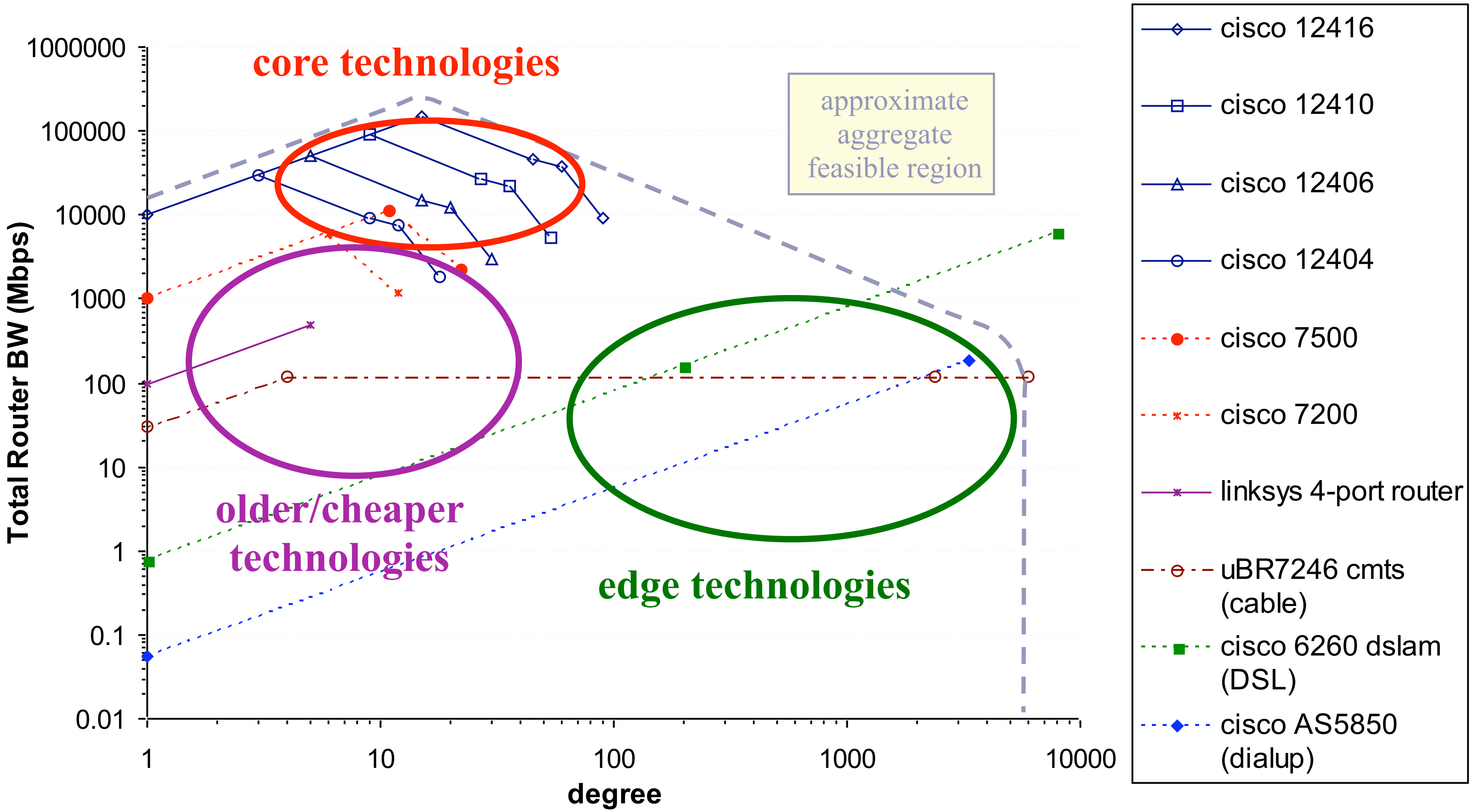
Li et al.

- Consider the explicit design of the Internet
  - Annotated network graphs (capacity, bandwidth)
  - Technological and economic limitations
  - Network performance
- Seek a theory for Internet topology that is explanatory and not merely descriptive.
  - Explain high variability in network connectivity
  - Ability to match large scale statistics (e.g. power laws) is only secondary evidence

Router Technology Constraint

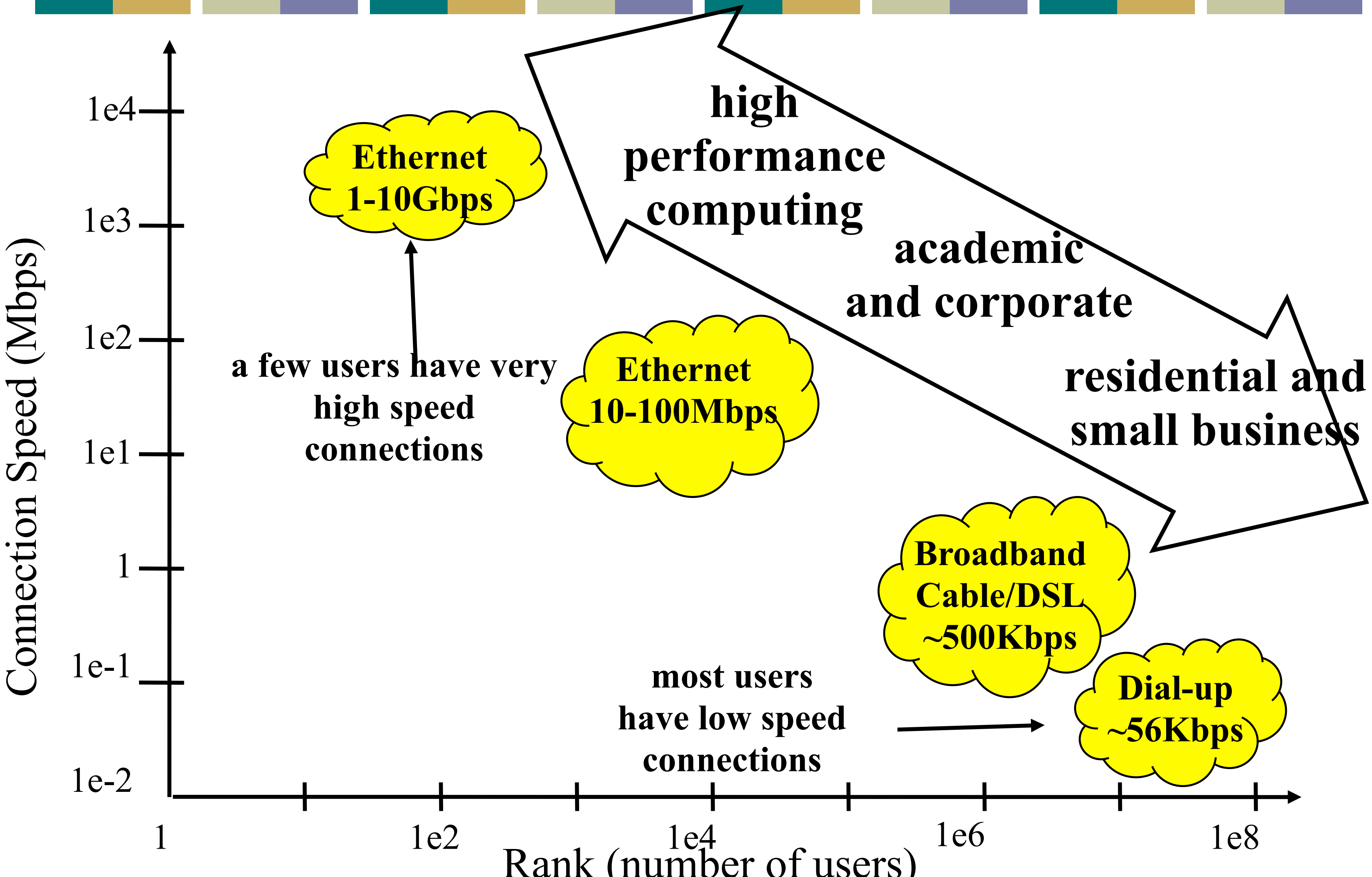


Aggregate Router Feasibility

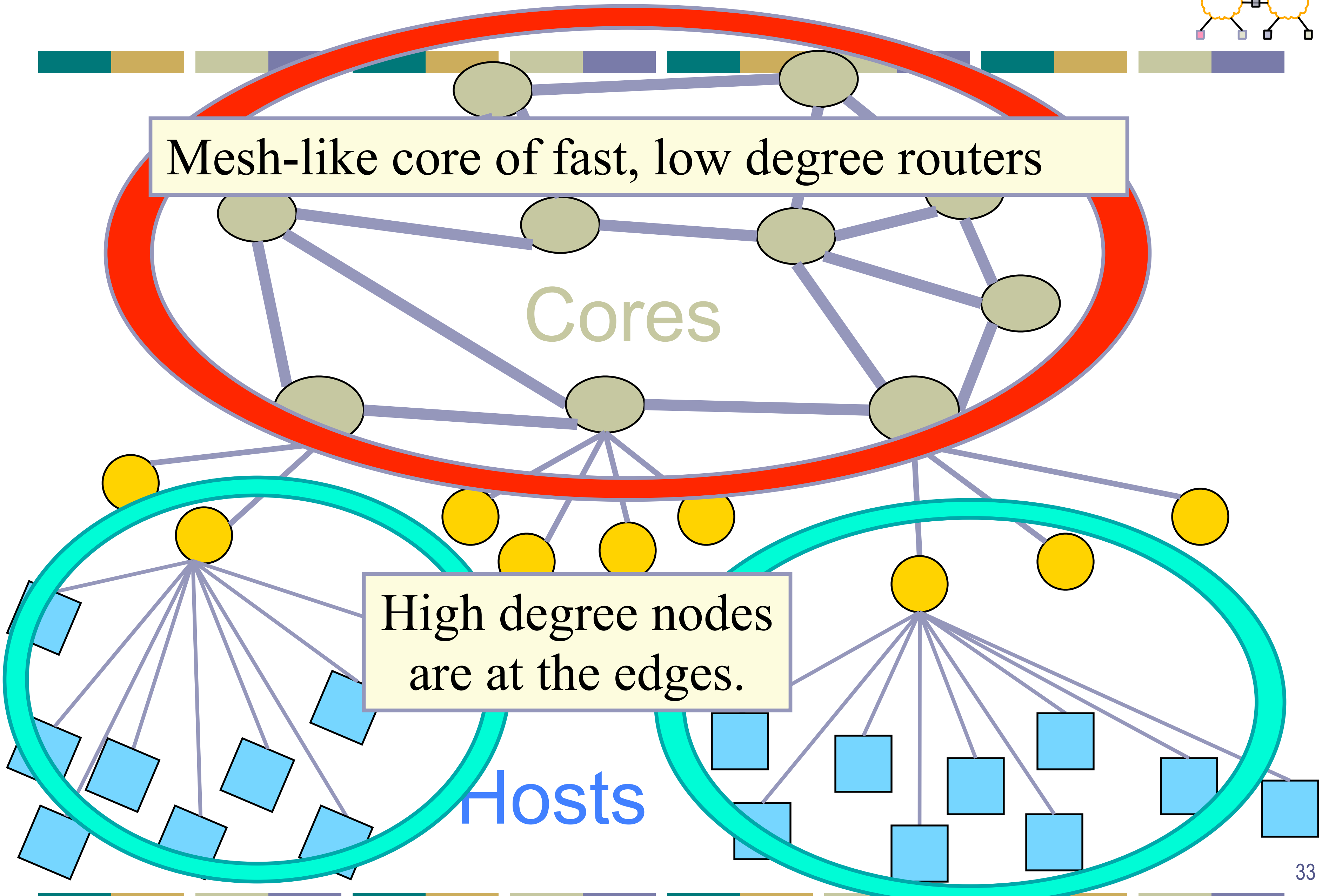


Source: Cisco Product Catalog, June 2002

Variability in End-User Bandwidths



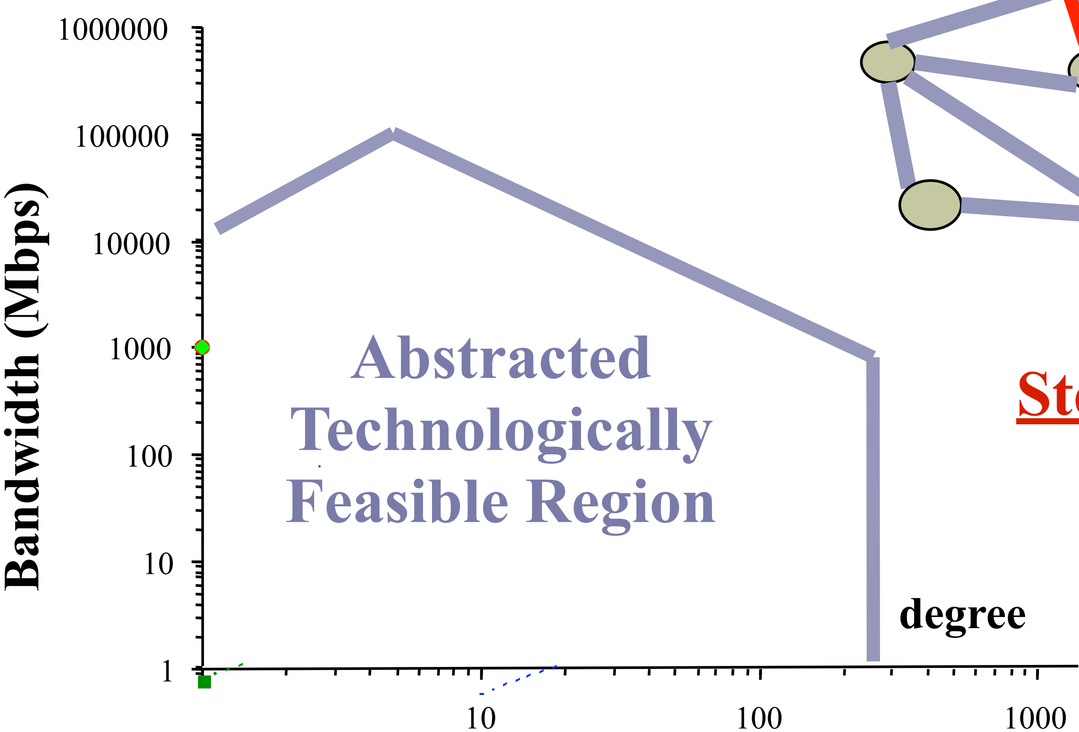
Heuristically Optimal Topology



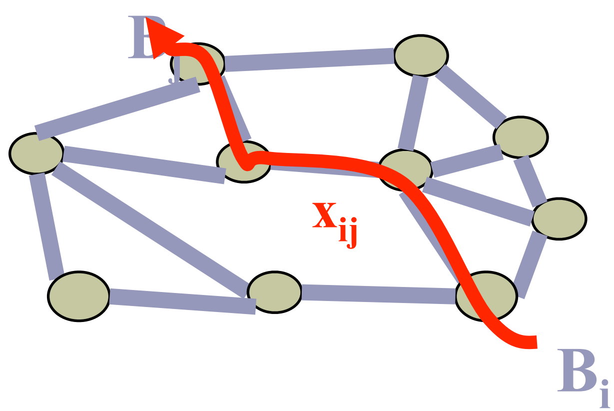
Comparison Metric: Network Performance

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



$$x_{ij} \propto B_i B_j$$

Step 3: Compute max flow

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

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

Likelihood-Related Metric

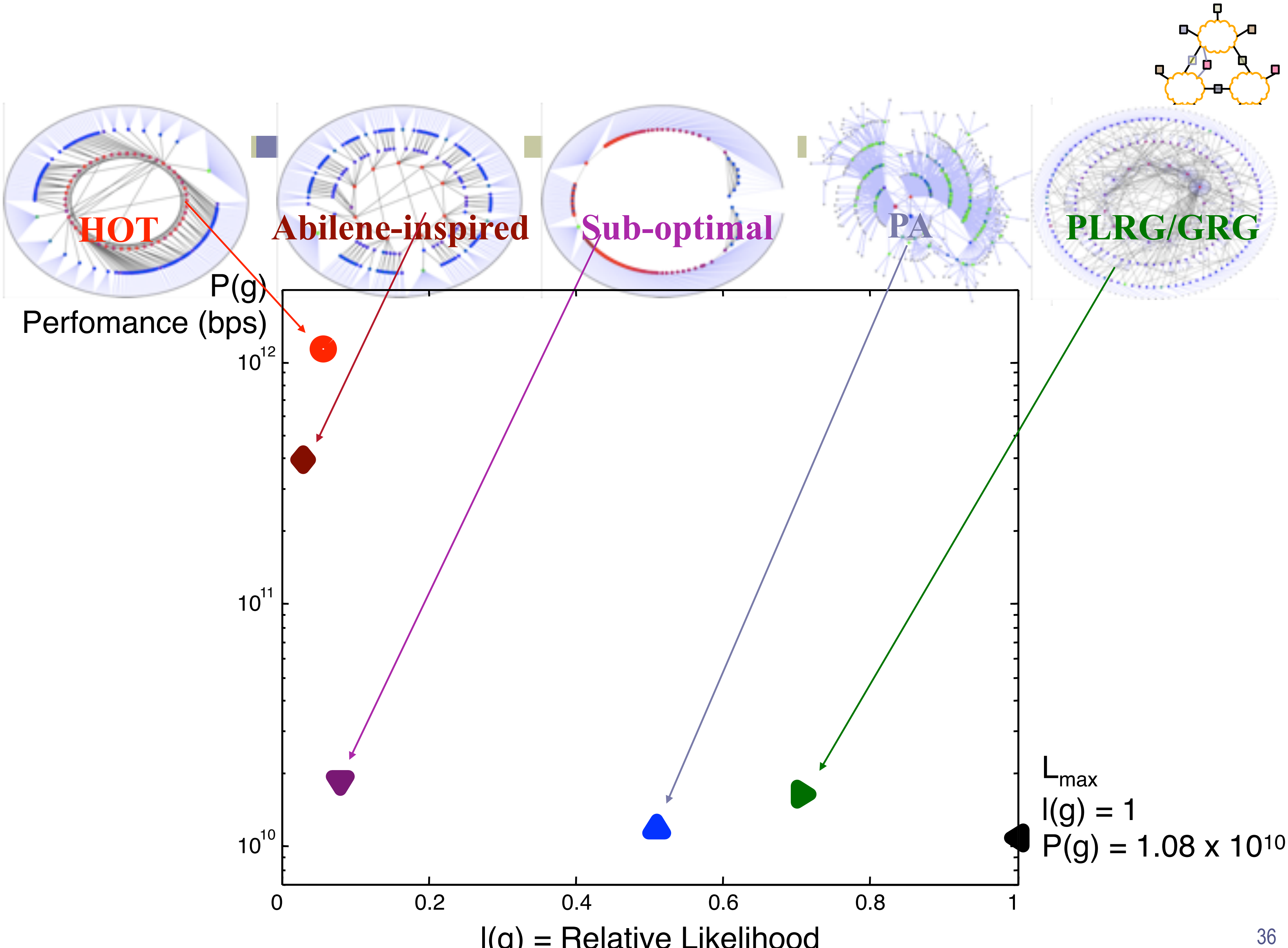
Define the metric $L(g) = \sum_{\substack{i,j \\ connected}} d_i d_j$ (d_i = degree of node i)

- Easily computed for any graph
- Depends on the structure of the graph, not the generation mechanism
- Measures how "hub-like" the network core is

- For graphs resulting from probabilistic construction (e.g. PLRG/GRG),

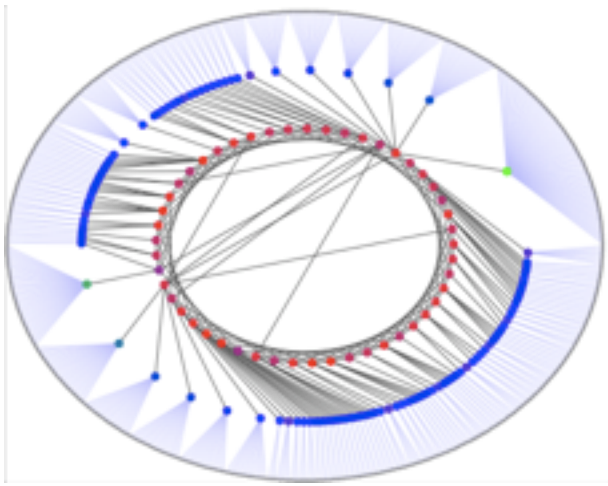
  LogLikelihood (LLH) $\propto L(g)$

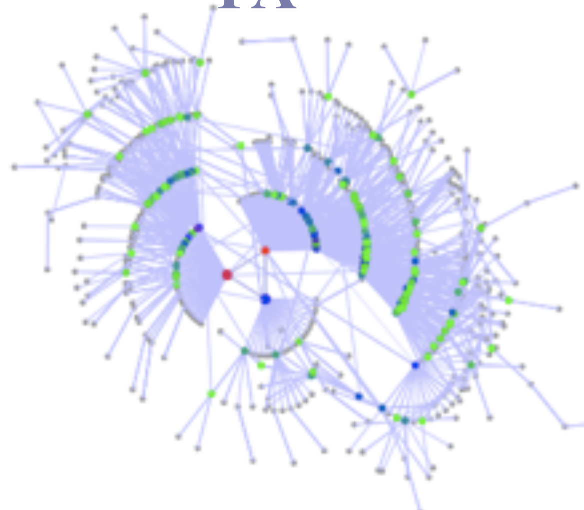
- <u>Interpretation</u>: How likely is a particular graph (having given node degree distribution) to be constructed?


HOT
Abilene-inspired
Sub-optimal
PA
PLRG/GRG
P(g)
Perfomance (bps)
10^{12}
10^{11}
10^{10}
0
0.2
0.4
0.6
0.8
1
I(g) = Relative Likelihood
L_{max}
$l(g) = 1$
$P(g) = 1.08 \times 10^{10}$

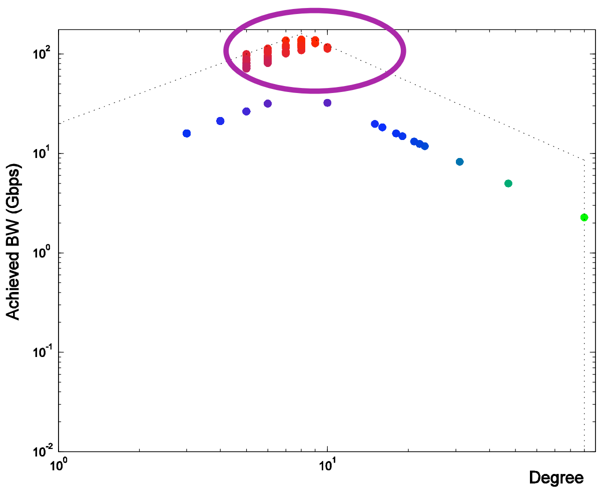
Structure Determines Performance

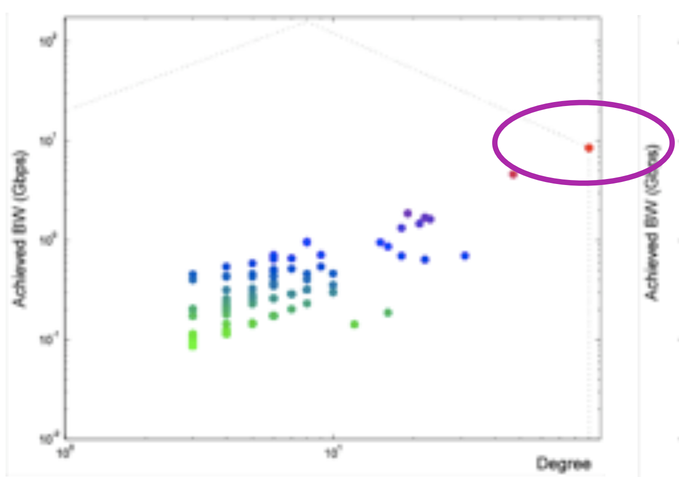
HOT | **PA** | **PLRG/GRG**

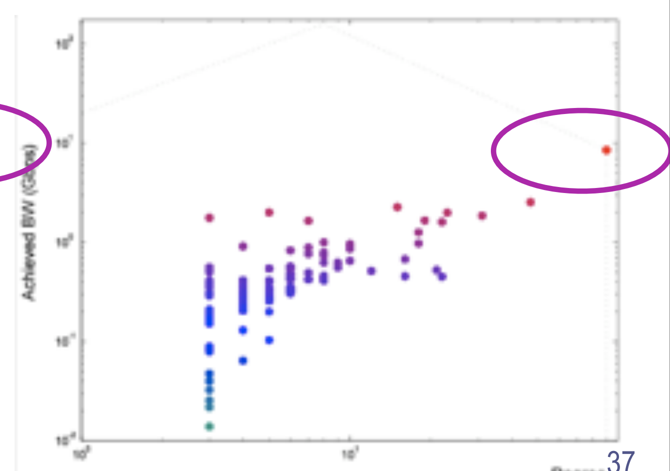




$P(g) = 1.13 \times 10^{12}$ | **$P(g) = 1.19 \times 10^{10}$** | **$P(g) = 1.64 \times 10^{10}$**







Summary Network Topology

- Faloutsos^3 [SIGCOMM99] on Internet topology
  - Observed many “power laws” in the Internet structure
    - Router level connections, AS-level connections, neighborhood sizes
  - Power law observation refuted later, Lakhina [INFOCOM00]

- Inspired many degree-based topology generators
  - Compared properties of generated graphs with those of measured graphs to validate generator
  - What is wrong with these topologies? Li et al [SIGCOMM04]
    - Many graphs with similar distribution have different properties
    - Random graph generation models don’t have network-intrinsic meaning
    - Should look at fundamental trade-offs to understand topology
      - Technology constraints and economic trade-offs
    - Graphs arising out of such generation better explain topology and its properties, but are unlikely to be generated by random processes!

The elephant in the room…

- How good is the underlying data on which these studies are based?
- E.g., sampling bias → traceroute of shortest paths on random graph can produce power-law distribution [Lakhina03]
  - Similar issues with AS-level view
- Router level data is very noisy

Better Measurements?

- Rocketfuel [sigcomm02]
  - Better router alias resolution
  - Detailed maps based on multiple viewpoints
- RouteViews and BGP collection efforts

Next Lecture

- Overlay networks
- Challenges in deploying new protocols
- Required readings:
  - Active network vision and reality: lessons from a capsule-based system
- Optional readings:
  - Resilient Overlay Networks
  - Future Internet Architecture: Clean-Slate Versus Evolutionary Research