

15-744: Computer Networking

L-14 Network Topology



Today's Lecture



- Structural generators
- Power laws, HOT graphs, ..
- Assigned reading
 - A First Principles Approach to Understanding the Internet's Router-level Topology
 - Measuring ISP Topologies with Rocketfuel (2 sections)
- Optional reading:
 - On Power-Law Relationships of the Internet Topology

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Outline



- Motivation/Background
- Power Laws
- Optimization Models
- Measuring Topology

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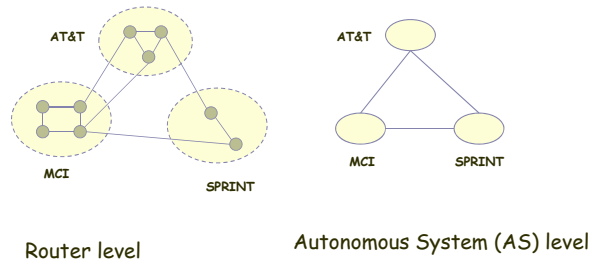
Why study topology?



- **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

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Internet topologies



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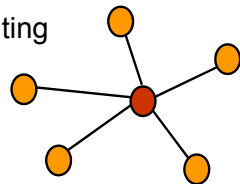
More on topologies..

- 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 public projects like Oregon Route Views
- Inferring both is difficult, and often **inaccurate**

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Hub-and-Spoke Topology

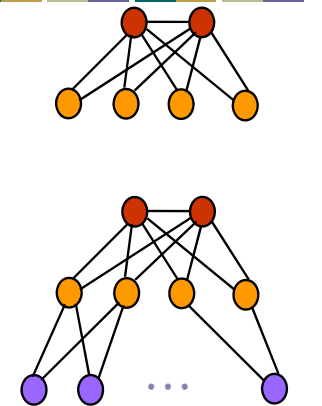
- Single hub node
 - Common in enterprise networks
 - Main location and satellite sites
 - Simple design and trivial routing
- Problems
 - Single point of failure
 - Bandwidth limitations
 - High delay between sites
 - Costs to backhaul to hub



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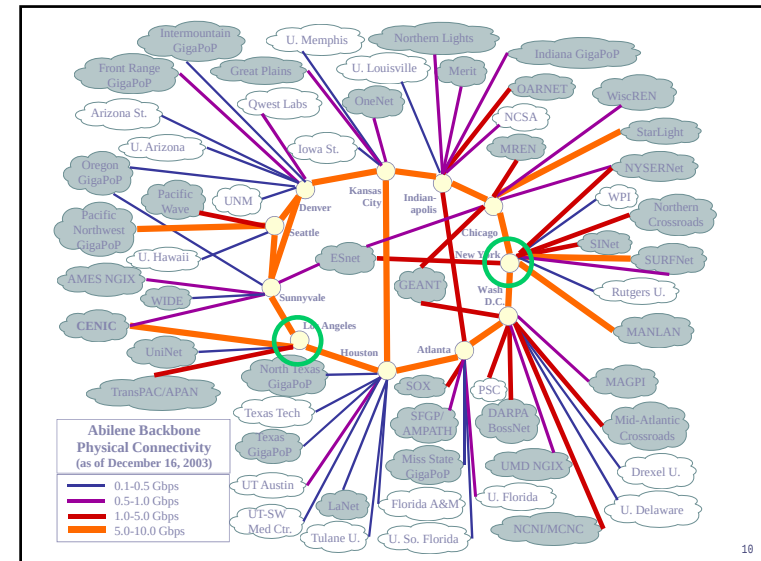
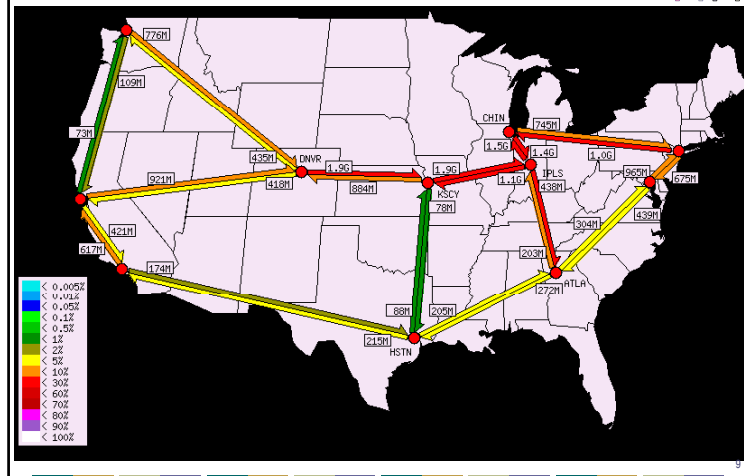
Simple Alternatives to Hub-and-Spoke

- 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



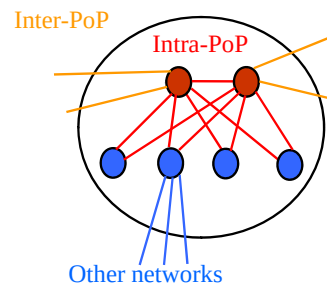
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Abilene Internet2 Backbone



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

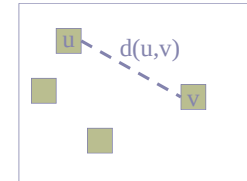
- Random graph (Waxman88)
- Structural models (GT-ITM Calvert/Zegura, 1996)
- Degree-based models replicate power-law degree sequences
- Optimization-driven models topologies consistent with design tradeoffs of network engineers

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Waxman model (Waxman 1988)



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



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Real world topologies



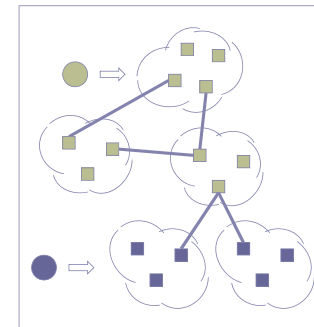
- Real networks exhibit
 - Hierarchical structure
 - Specialized nodes (transit, stub..)
 - Connectivity requirements
 - Redundancy
- Characteristics incorporated into the Georgia Tech Internetwork Topology Models (GT-ITM) simulator (E. Zegura, K. Calvert and M.J. Donahoo, 1995)

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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



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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.....

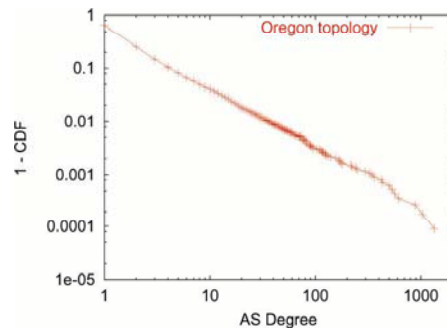
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Outline

- Motivation/Background
- **Power Laws**
 - Slides John Dickerson
- Optimization Models
- Measuring Topology

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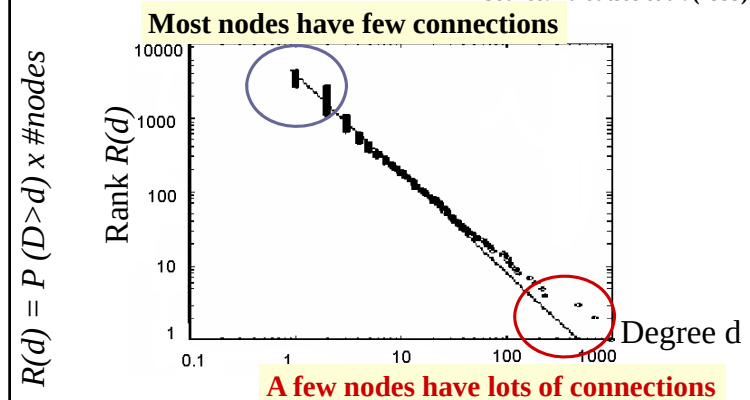
Power laws in AS level topology



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Power Laws and Internet Topology

Source: Faloutsos et al. (1999)



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

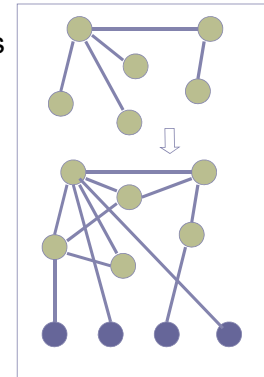
GT-ITM abandoned..

- 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

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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 $d(v)/\sum d(w)$
- Connect degree 1 nodes using preferential connectivity
- Add remaining edges using preferential connectivity



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Power law random graph (PLRG)

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

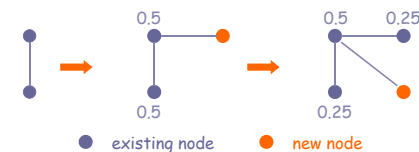


- may be disconnected, contain multiple edges, self-loops
- contains unique giant component for right choice of parameters

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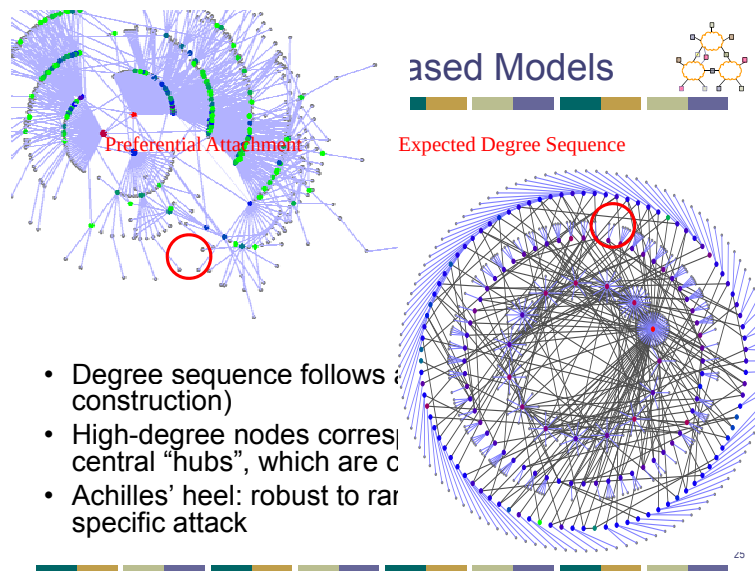
Barabasi model: fixed exponent

- incremental growth
 - initially, m_0 nodes
 - step: add new node i with m edges
- linear preferential attachment
 - connect to node i with probability $k_i / \sum k_j$



may contain multi-edges, self-loops

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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

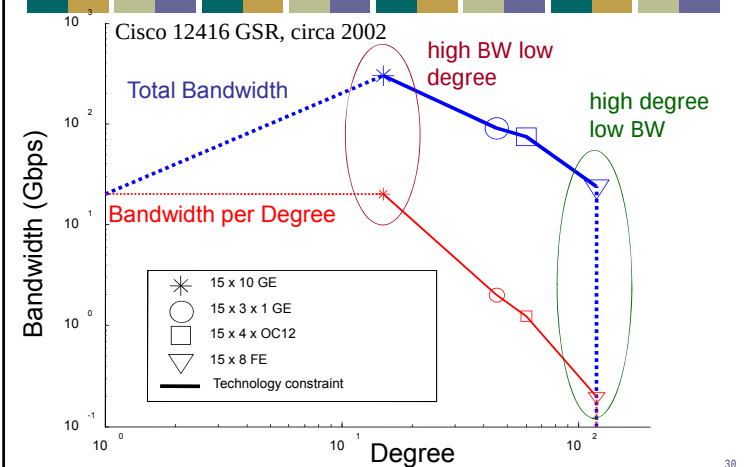
- Motivation/Background
- Power Laws
- **Optimization Models**
- Measuring Topology

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

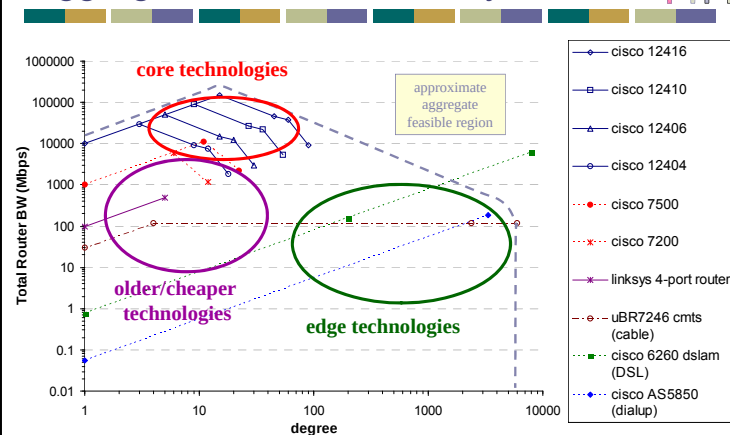
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Router Technology Constraint



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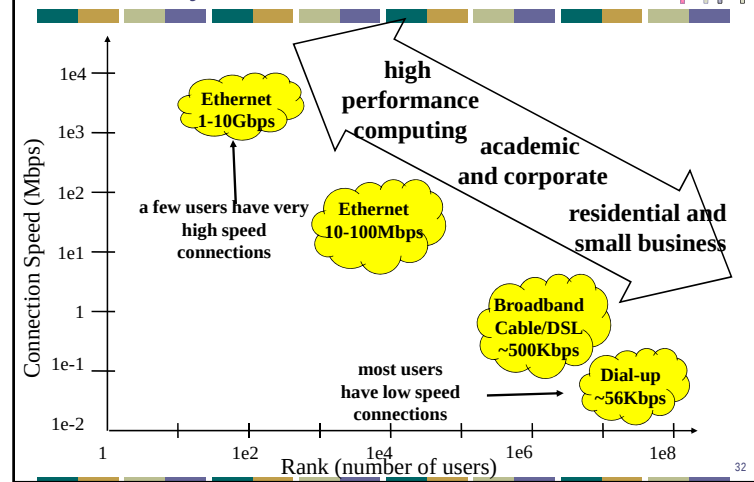
Aggregate Router Feasibility



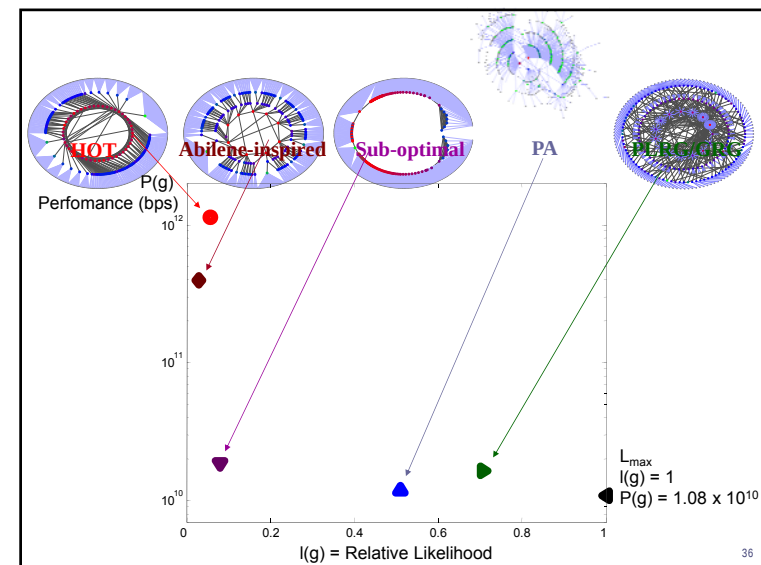
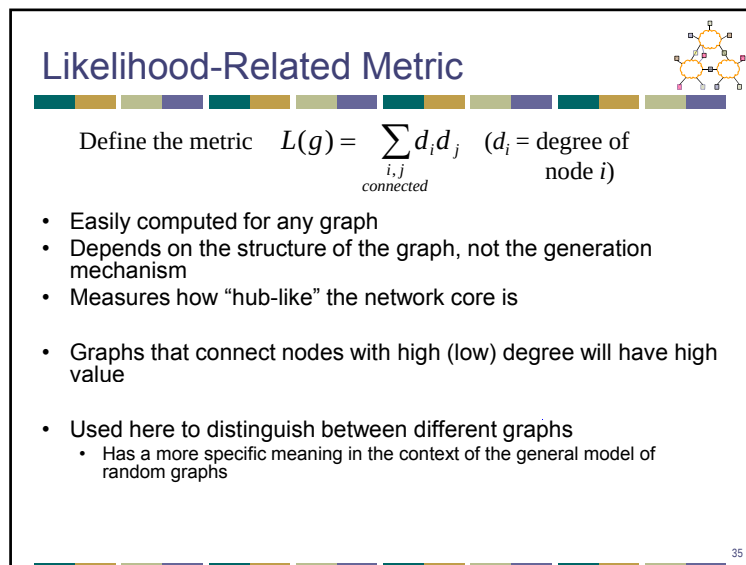
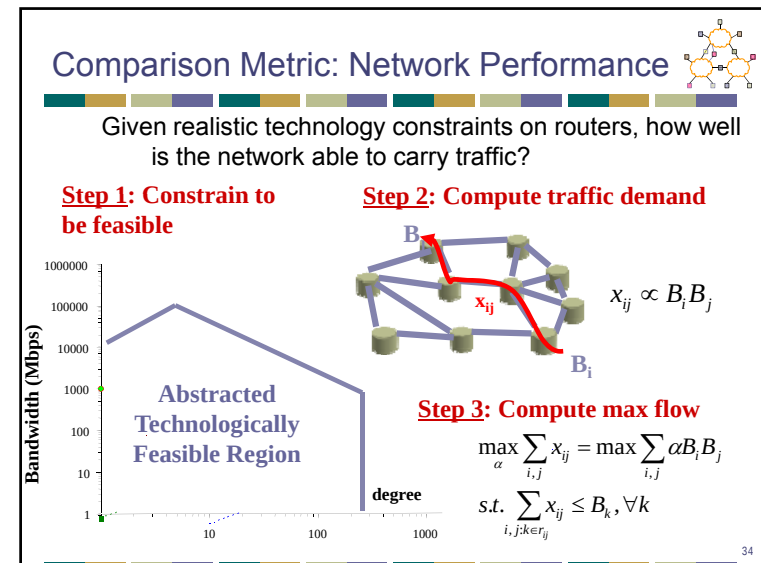
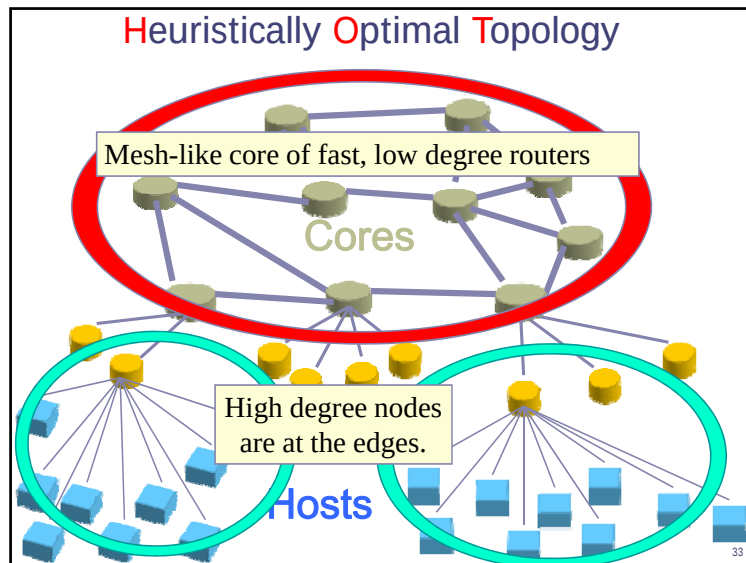
Source: Cisco Product Catalog, June 2002

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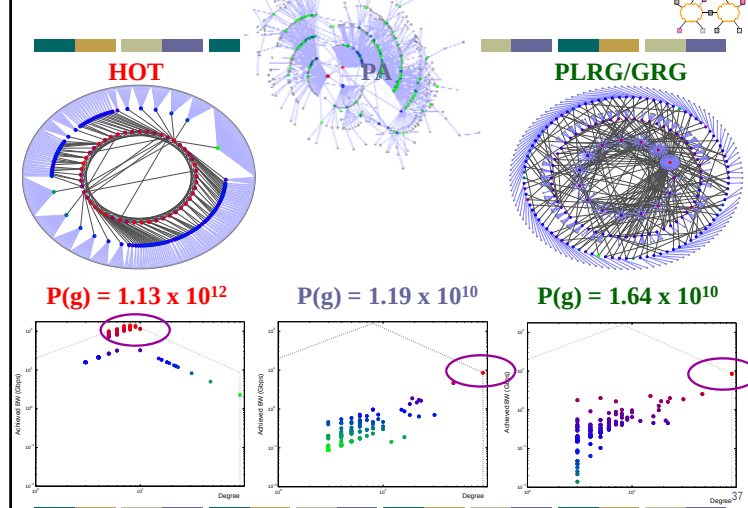
Variability in End-User Bandwidths



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Structure Determines Performance



Outline

- Motivation/Background
- Power Laws
- Optimization Models
- **Measuring Topology**
 - **Slides John Wright**

Summary Network Topology

- Faloutsos³ [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!

Announcements

- No lecture Friday and Monday
- Next course segment is on overlay networks and future Internet architecture
 - Readings are up to date for the semester
 - May need to reshuffle final few lectures a bit
- Project update: good progress but need to become more concrete quickly
 - What will be your initial results?
 - Timeline for the remaining seven weeks?
 - Short reports on status by Oct 28 (e-mail)