# Internet Topology

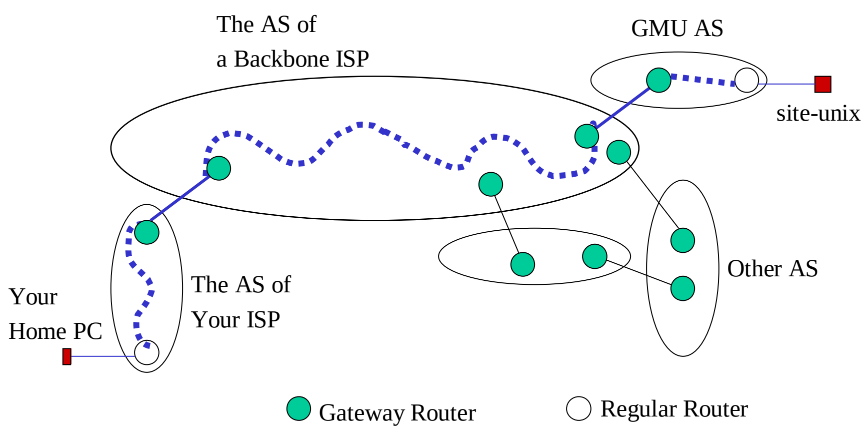




# A Review of Internet Routing

- The Internet is divided into Autonomous Systems (**AS**).
- Each AS comprises the routers and networks governed by a single administration authority.
  - GMU campus,
  - A regional/backbone ISP,
- Routing occurs at two levels
  - Intra-AS routing
  - Inter-AS routing

# Two-Level Routing of the Internet






- Intra-AS topologies are difficult to obtain because of the reluctance of service providers.
- The inter-AS Internet topology can obtained by analyzing the routing information collected by BGP.
  - In the AS-level topology, each node of the graph represents an entire AS and an edge between two AS represents connectivity between the two AS by one or more link.

## Random Graph Generation

- Many facets of the Internet performance depends on the topology of the Internet.
- Suppose we wish to predict the performance of Internet routing in year 2005.
- We can extrapolate the size of the Internet in 2005 according to its growth history.
- But, how do we know future Internet topologies ?
- One possibility is to investigate our subject using a large number of random graphs, hoping that the average will not be biased.



## Random Model

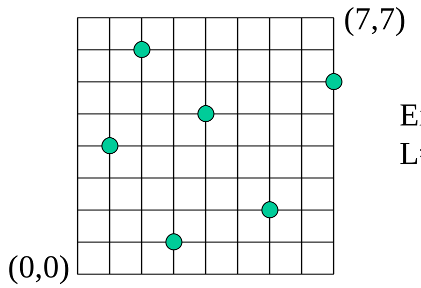
- Given N nodes, there are at most N(N-1)/2 edges.
- We wish to generate a graph with average node degree D.
  - We need ND/2 edges
- The probability for an edge to be selected is

$$P=D/(N-1)$$

- Note that the resultant graph may not be connected; you may need to try several times to produce a connected graph.

## Waxman Model

- Create an L×L grid and select N points in the grid.




Example
L=8 and N=6

- The probability of the link between two vertices u and v is given by

$$P(u,v) = \alpha \times e^{-dist(u,v)/(\beta L)}$$

where $0 < \alpha, \beta \leq 1$ are two constants.

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## Discussion

- Parameter $\alpha$ determines the density of the graph.
  - The larger the $\alpha$, the denser the graph.
  - However, the exact value of $\alpha$ to produce a desired average degree $D$ must be determined by trial and error.
- Parameter $\beta$ controls the locality of edges.
  - The smaller the $\beta$, the more we prefer short links.
- Again, you may need to try several times to produce a connected graph.

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## Hierarchical Model

- ❑ A connected random graph is first generated using the Waxman model.
  - – This is the AS-level topology.
  - – Each node represents an entire **Transit domain** (an ISP AS).
- ❑ Each transit domain node is expanded to form another connected random graph, representing the backbone topology of that domain.
- ❑ For each node in a transit domain, a number of connected random graphs are generated, representing **Stub domains** (customer AS) that are attached to the transit node.



## Properties of Internet Topologies

- ❑ The topology of the Internet varies (or precisely grows) over time.
  - – How do we evaluate a new protocol in the Internet ?
  - – If we use the present topology, do the results hold in the future ?
  - – We need to generate a large number of random graphs that are of the size of a projected Internet size and "similar" to the present Internet.
  - – Question is, "similar" in what sense ?

## Internet Topologic Properties Size and Density

- The Internet has been growing steadily.
  - In Nov. 1997, we have 3015 AS nodes with average degree 3.42.
  - In Sept. 2001, we have 11927 AS nodes with average degree 4.61.
- It is expected that we will exhaust AS ID space ($2^{16}$) by the end of 2005.
- The Internet is growing rapidly *in size* but at a much slower rate *in density*.
- What other properties of Internet topologies are known ?



## Power Law 1

- Given a Internet topology, we sort its nodes in decreasing order of their degrees.
- For a node $v$, let $d_v$ be its degree and $r_v$ be its rank after sorting. We notice

$$d_v \propto r_v^R$$

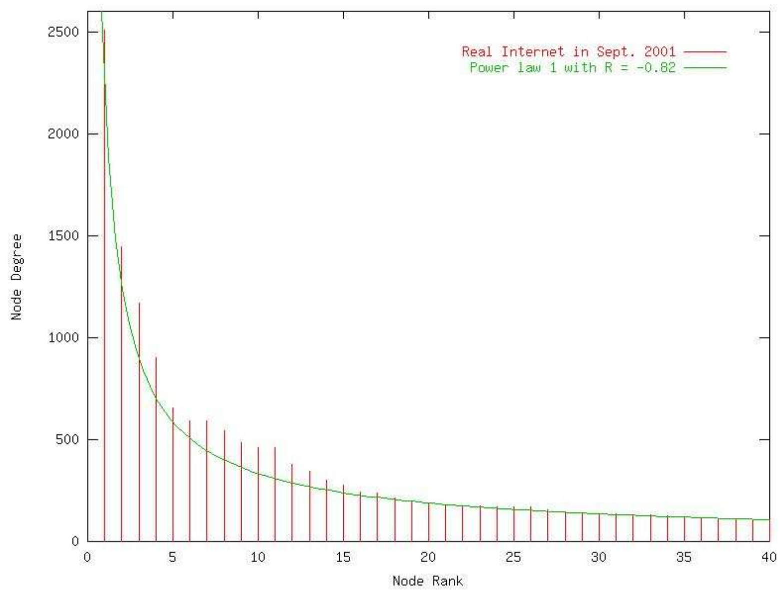
- $R$ is a constant called the rank exponent.
- In Nov 1997, R = -0.74. In Dec. 1998, R = -0.81.
- This property has been verified from 1997 to 2000.

## Further Observations

- Assuming that the degree of the $N$-th ranked node is 1, we have
  - $d_N = C \times N^R = 1$
  - $C = 1 / (N^R)$
- That is, $d_v = \frac{1}{N^R} r_v^R$
- It can also be shown that $E = \frac{1}{2(R+1)}(1 - \frac{1}{N^{R+1}})N$



## Theory versus Reality



## Power Law 2

- Let $f_d$ be the frequency (the number of nodes) of a given degree $d$. We notice

$$f_d \propto d^O$$

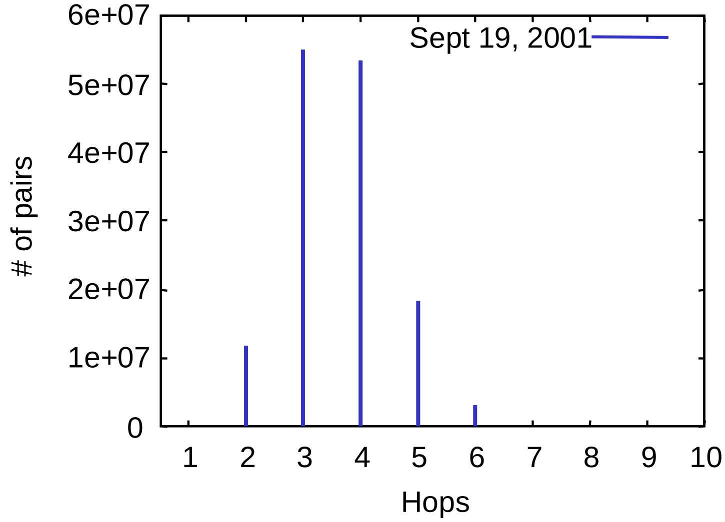
- $O$ is a constant called the degree exponent.
- The values of $O$ remained virtually constant from 1997 to 1998, at around –2.18.



## Distances

- The diameter of the Internet at the AS level is only 10.
  - The diameter of a network is the largest distance in terms of hops between any two nodes in the network.
  - Given the size of the Internet, this is somewhat surprising.
- Define $P(h)$ be the number of pairs of nodes that are $h$ hops apart.
  - By definition $P(0)$ is the number of nodes in the network.

## AS Distances in Sept. 2001






## Discussions

- Internet topologies are not your average random graphs.
- The distribution of degrees/edges among nodes is highly biased.
  - A small number of nodes possess large degrees (hundreds to 2.5 thousands in 2001) while the majority of nodes are of small degrees (1 or 2).
- The distances among nodes are amazingly small.
  - Most of the nodes are within 5 hops from each other.

# Open Issues

- What are the implications of the power law properties ?
- How do we generate “random” graphs that satisfy power laws ?
- Do existing power laws capture the essence of Internet topologies ?
  - In another word, are there other important properties unknown ?
- How about intra-AS topologies ?