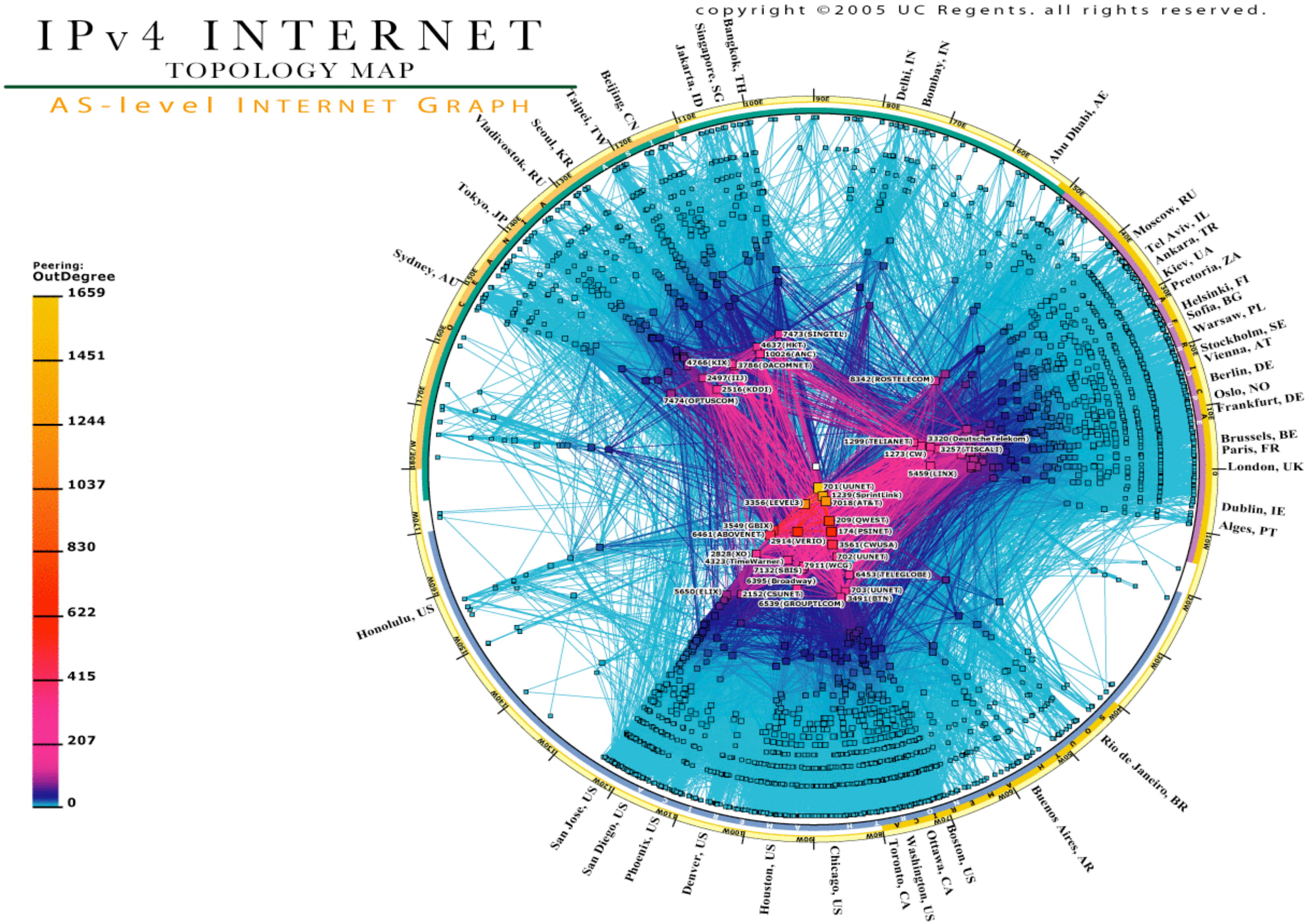
Modeling and Generating Internet Topology


IPv4 INTERNET
TOPOLOGY MAP
AS-level INTERNET GRAPH
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Peering:
OutDegree
1659
1451
1244
1037
830
622
415
207
0
Singapore, SG
Bangkok, TH
Jakarta, ID
Beijing, CN
Taipei, TW
Seoul, KR
Vladivostok, RU
Tokyo, JP
Sydney, AU
Delhi, IN
Bombay, IN
Abu Dhabi, AE
Moscow, RU
Tel Aviv, IL
Ankara, TR
Kiev, UA
Pretoria, ZA
Helsinki, FI
Sofia, BG
Warsaw, PL
Stockholm, SE
Vienna, AT
Berlin, DE
Oslo, NO
Frankfurt, DE
Brussels, BE
Paris, FR
London, UK
Dublin, IE
Alges, PT
Rio de Janeiro, BR
Buenos Aires, AR
Boston, US
Ottawa, CA
Washington, US
Toronto, CA
Chicago, US
Houston, US
Denver, US
Phoenix, US
San Diego, US
San Jose, US
Honolulu, US

Can we characterize the Internet's Topology?

How to generate realistic Internet topology for simulations?

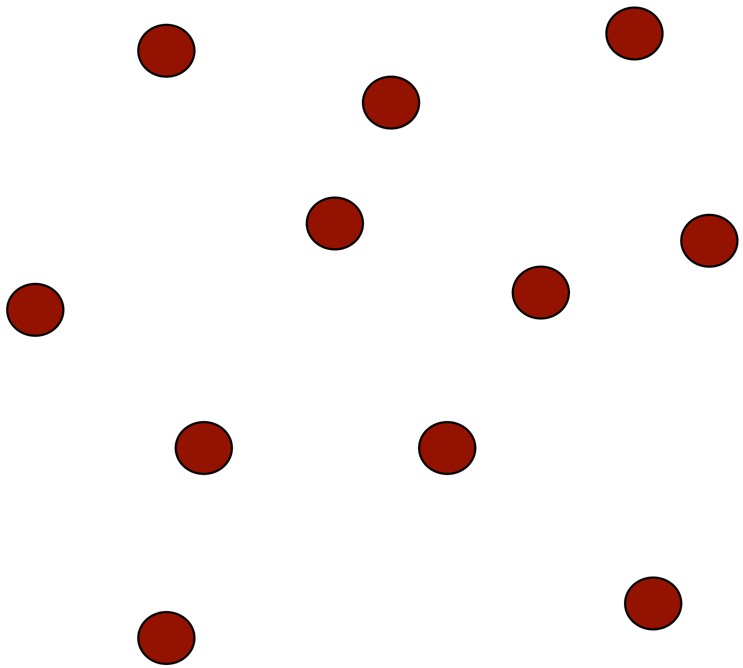
Model Internet as a Graph

Router-Level, node = router edge = 1-hop link

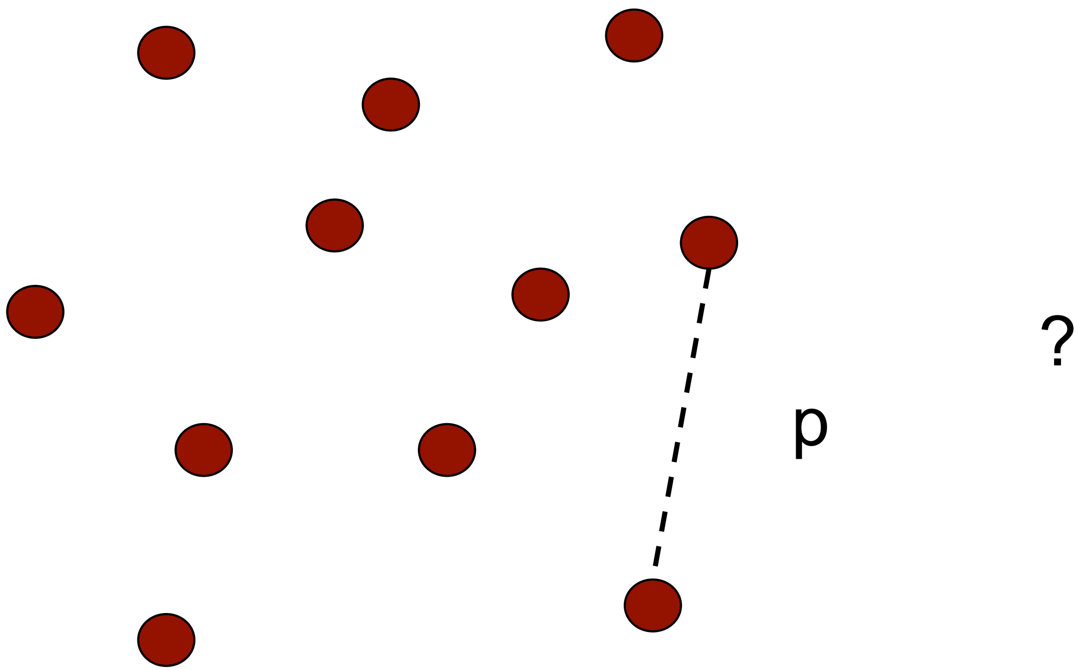
AS-Level,
node = AS domain
edge = Peering

Generating Random Graph

Randomly generate points on a plane

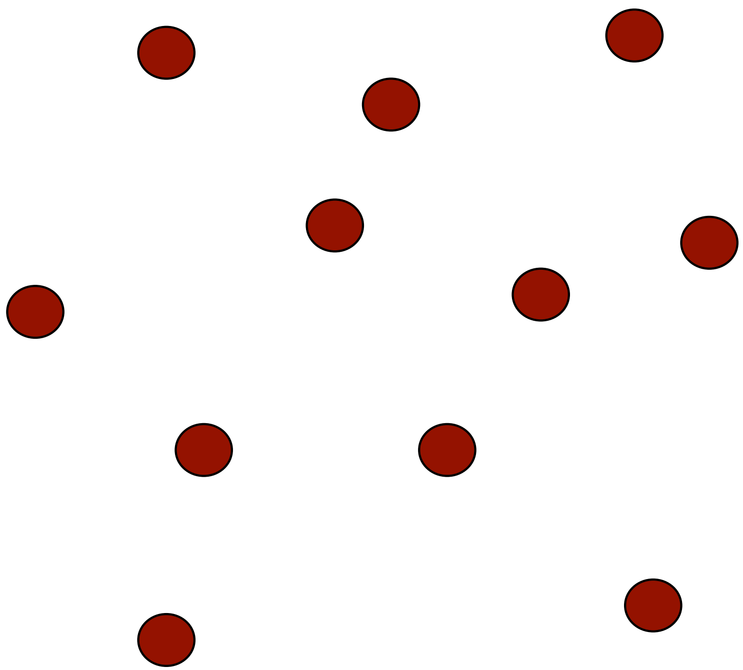


Connects two nodes with fixed probability p

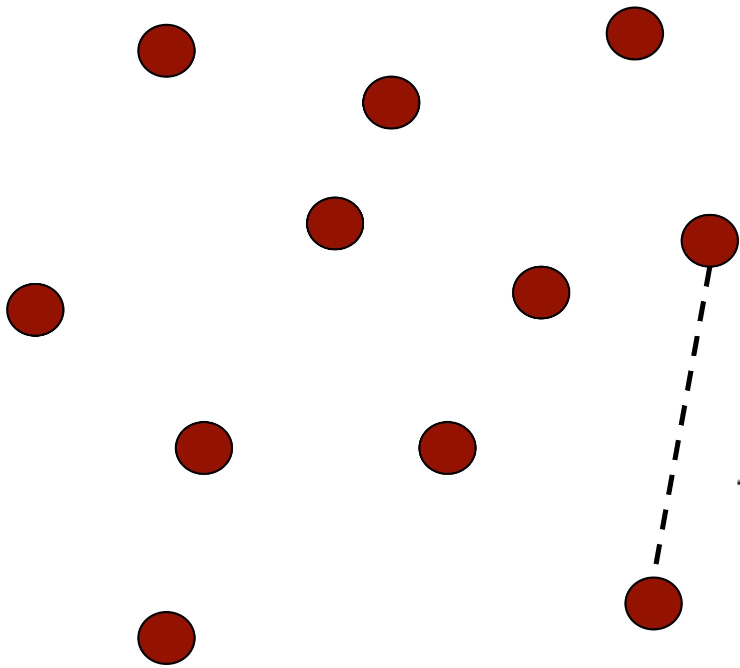


Waxman's Method

Randomly generate points on a plane



Connects two points with probability P(u,v)



?

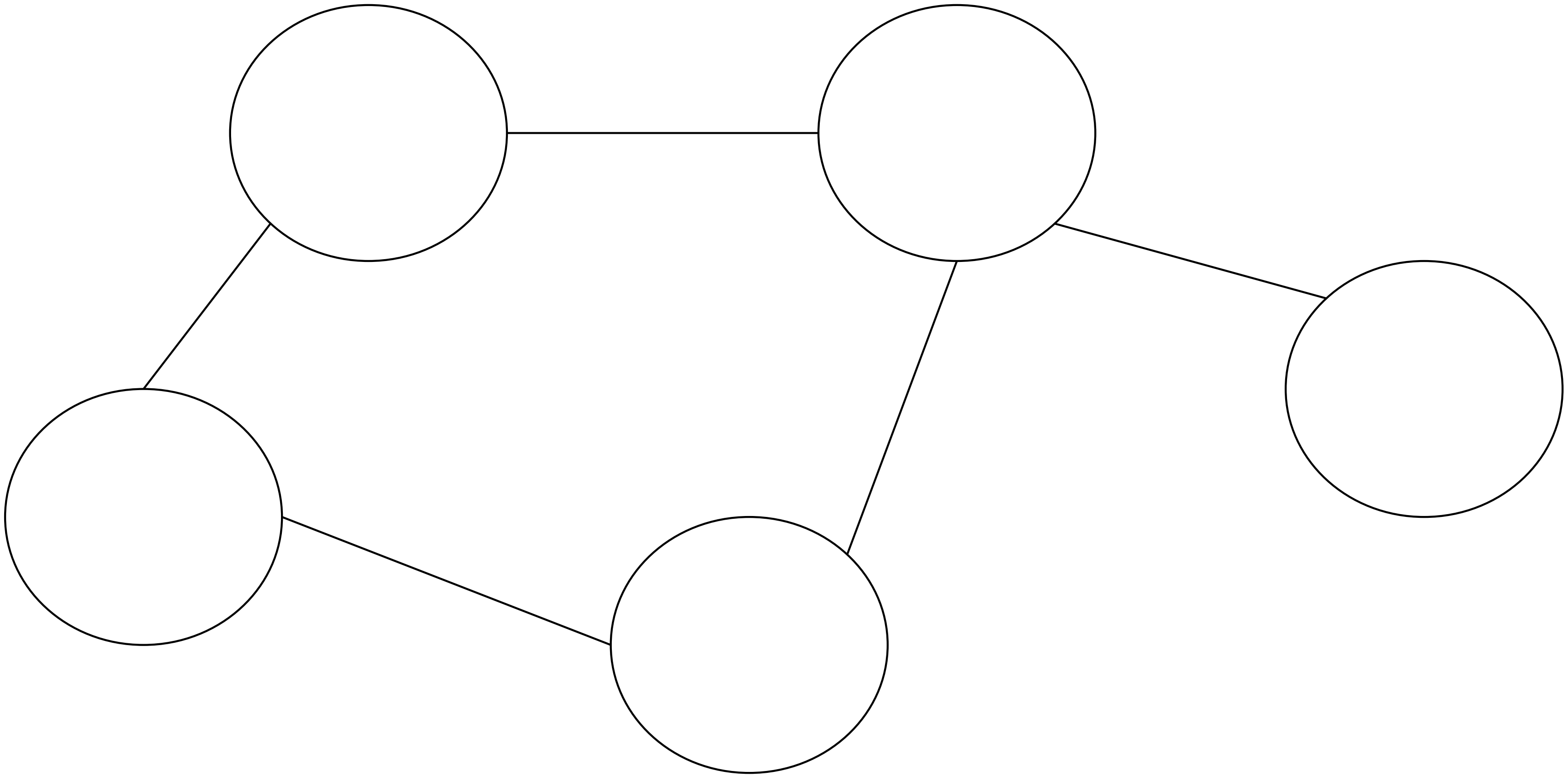
$$P(u,v) = \alpha e^{\frac{-d(u,v)}{\beta L}}$$

L: maximum distance
d(u,v): distance between u and v

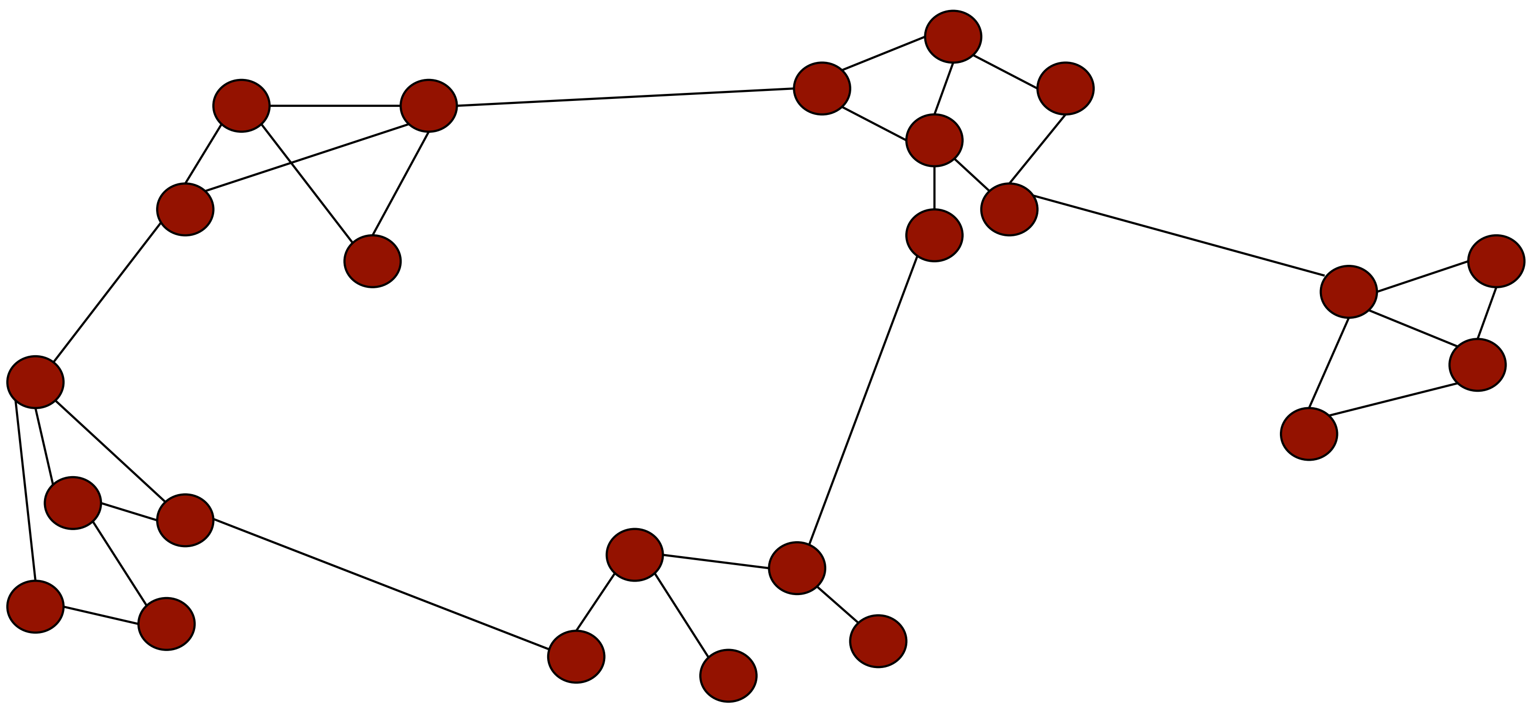
Model locality but not the structure of Internet

Transit-Stub Method

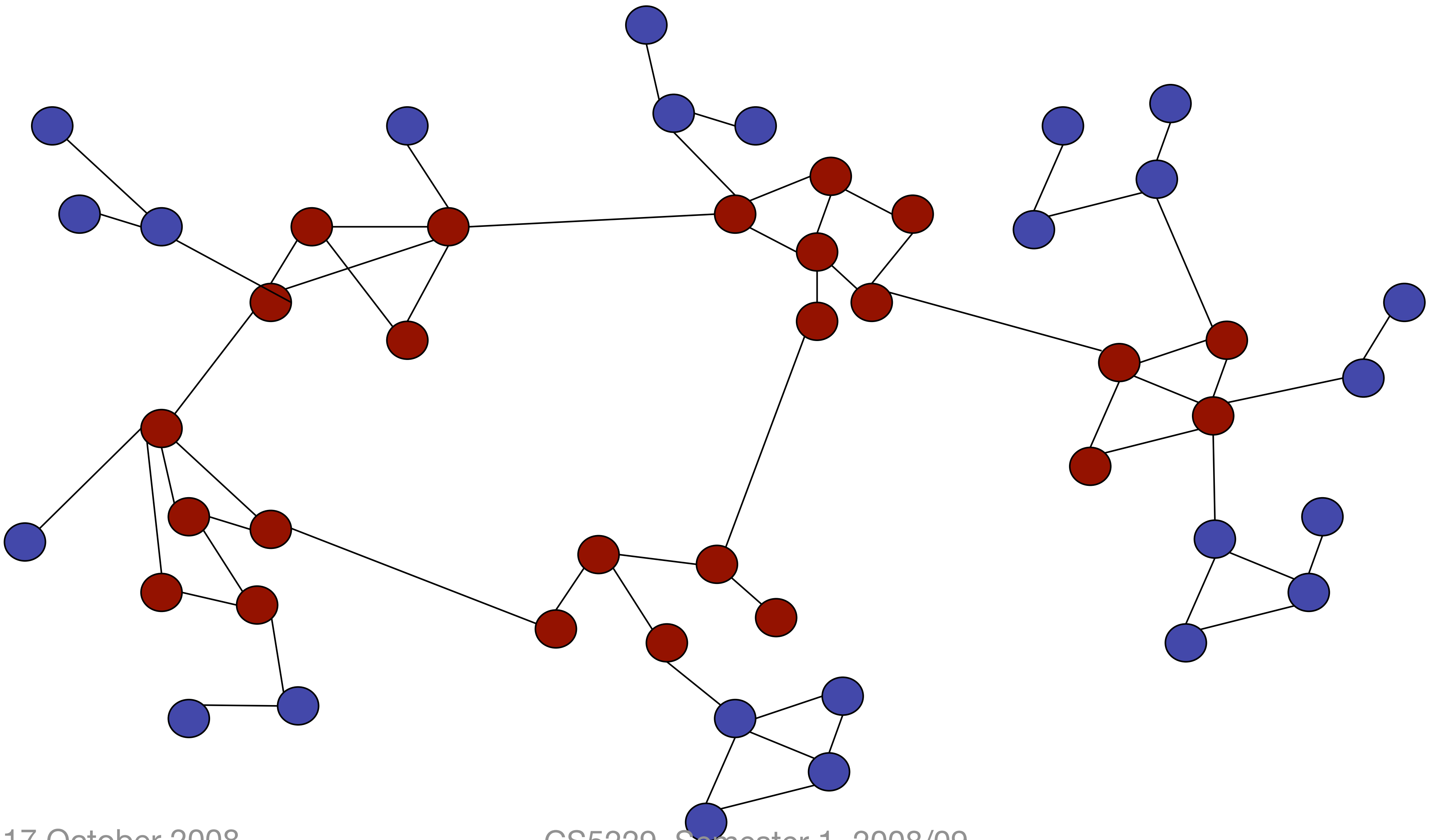
Randomly generate a graph using Waxman's method



Each node is expanded to form a random graph (transit domain)



Connect stub domains to the transit domain.



Looks good, but is it close to the real thing?

“On Power-Law Relationships of the Internet Topology”

The Faloutsos brothers, SIGCOMM ‘99

Use four traces of Internet topology collected between 97-98

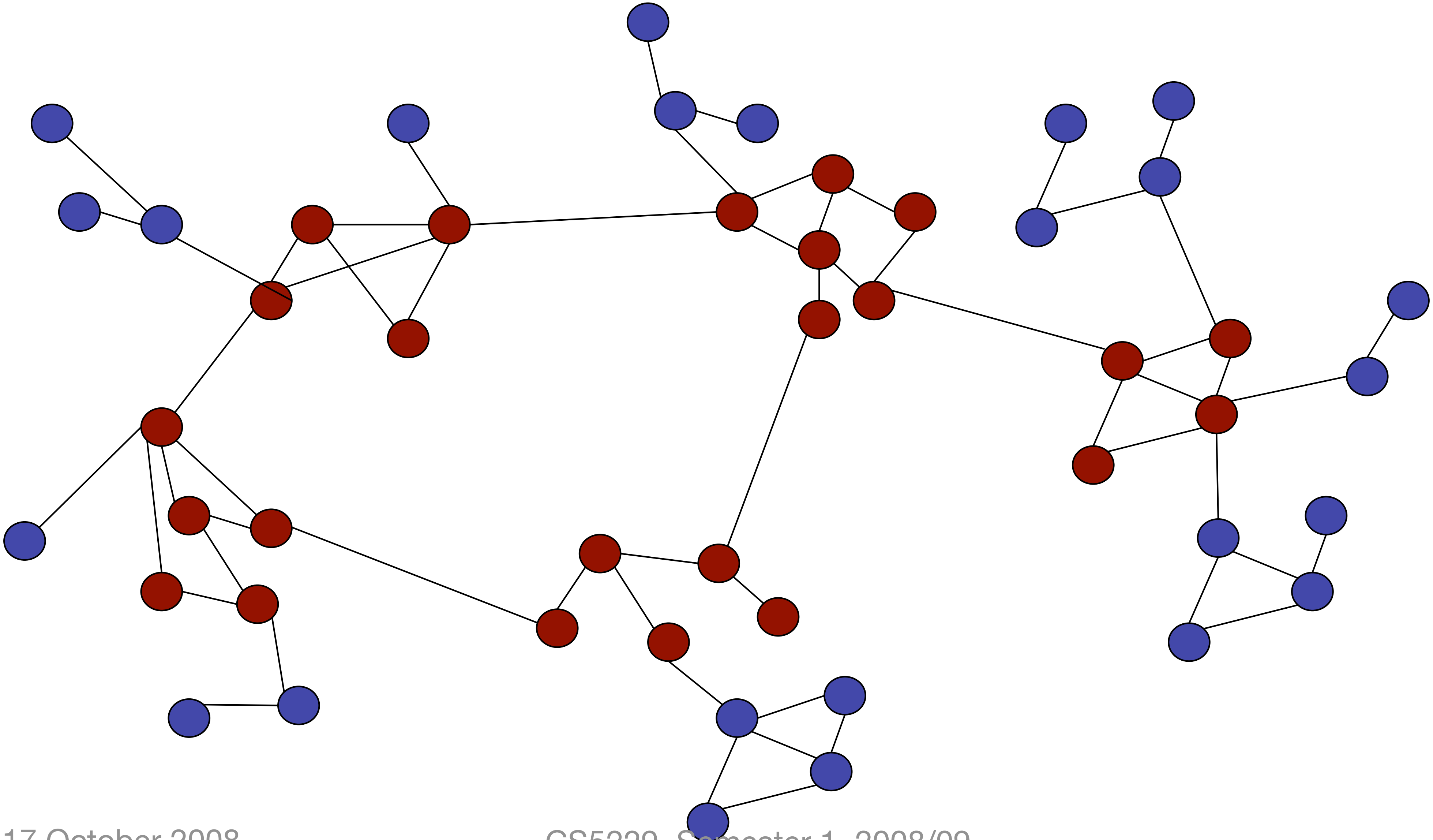
AS-Level Topology

Time	Num of Nodes	Num of Edges	Max outdegre e	Average outdegre e
Nov 97	3015	5156	590	3.42
Apr 98	3520	6432	745	3.65
Dec 98	4398	8256	979	3.76

Router-Level Topology

1995	3888	5012	2.57

Observations: the graphs can be decomposed into two components: trees and core.



40-50%

of the nodes are in trees

3

maximum depth of trees

1

depth of >80% of the trees

Time	Num of Nodes	Num of Edges	Max outdegree	Average outdegree
Nov 97	3015	5156	590	3.42
Apr 98	3520	6432	745	3.65
Dec 98	4398	8256	979	3.76

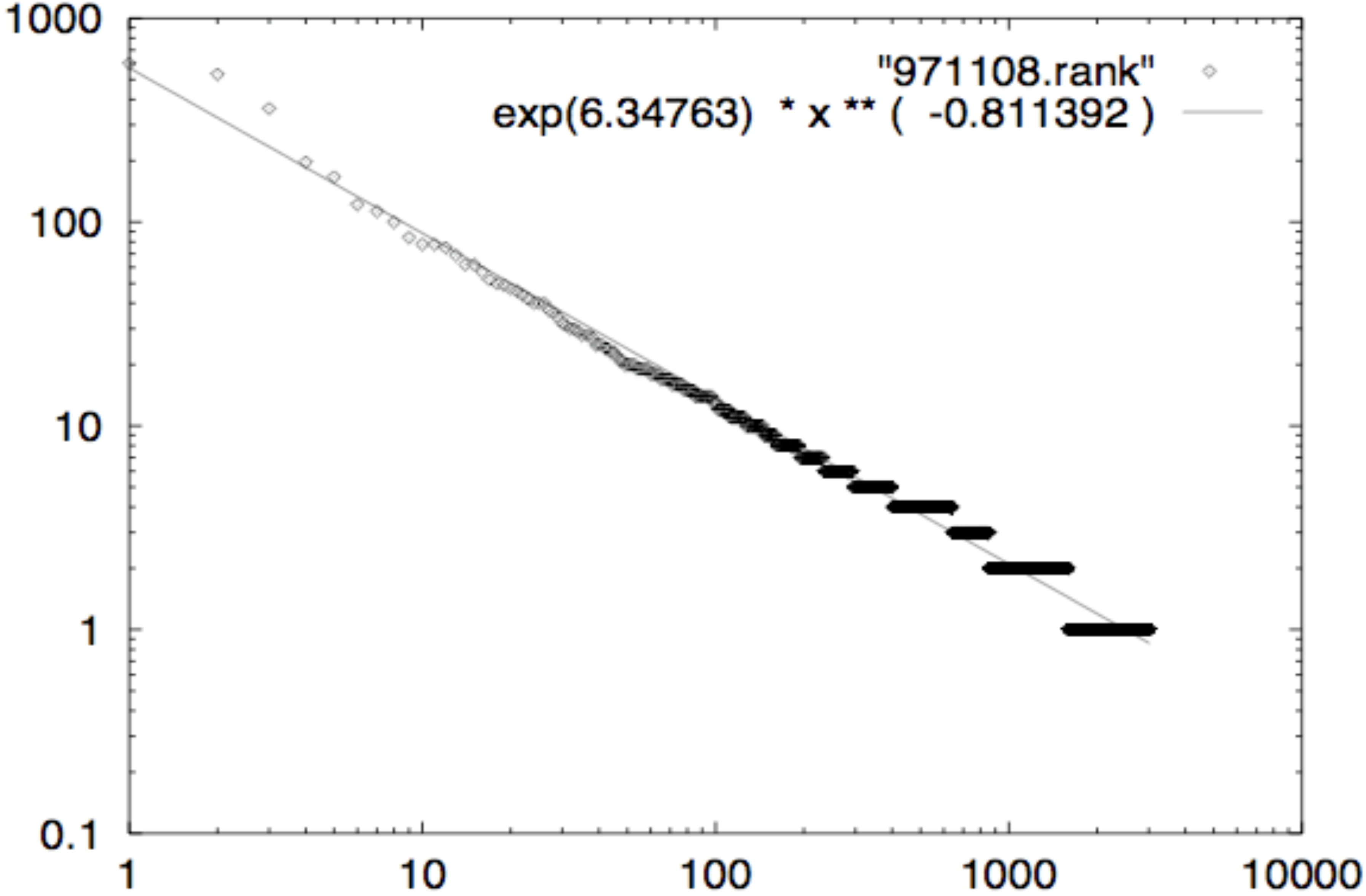
out-degree is highly skewed!

Let

d_v be the **out-degree** of a node, and

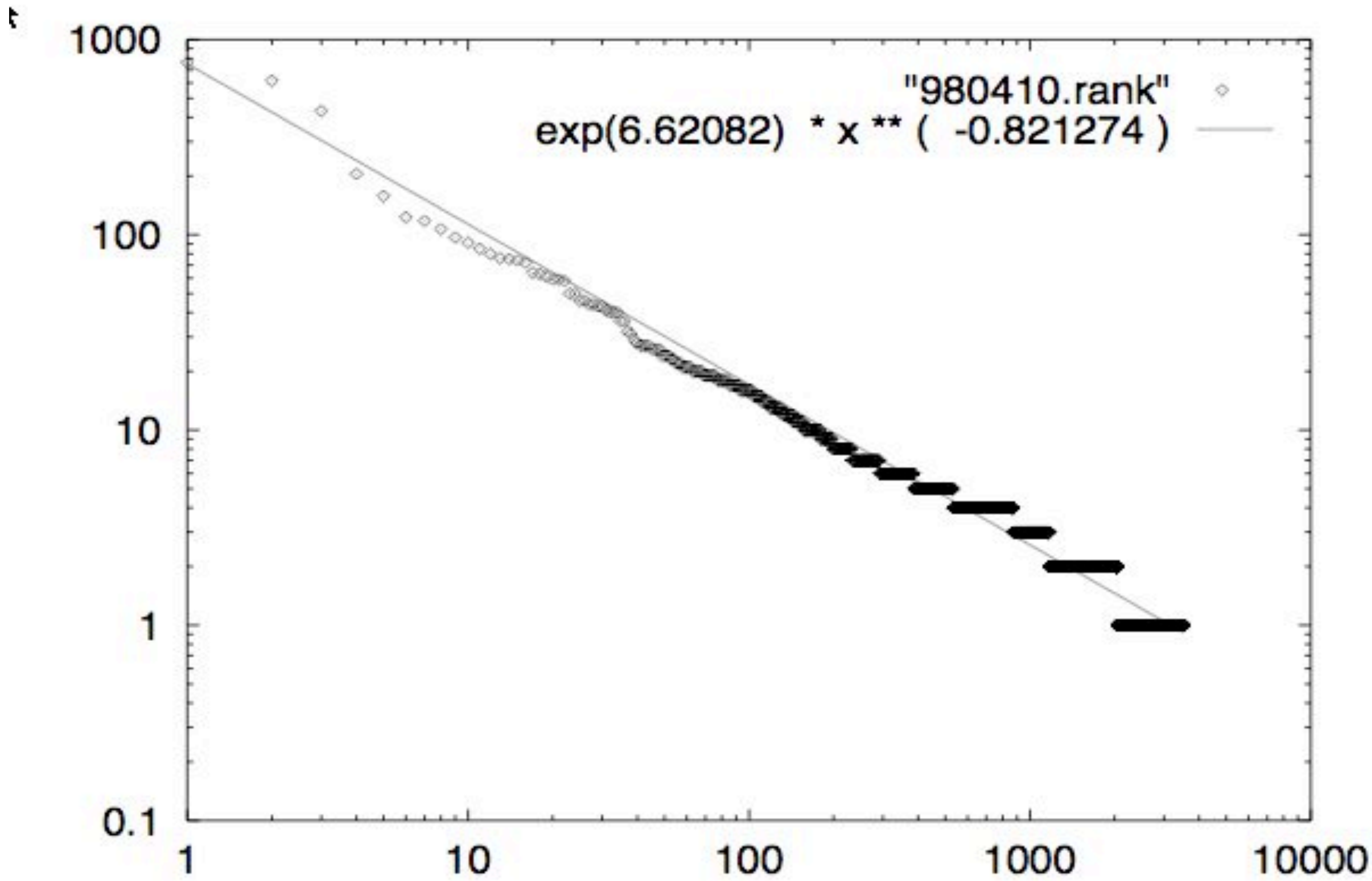
r_v be the **rank** of a node (i.e., index in the order of decreasing outdegree)

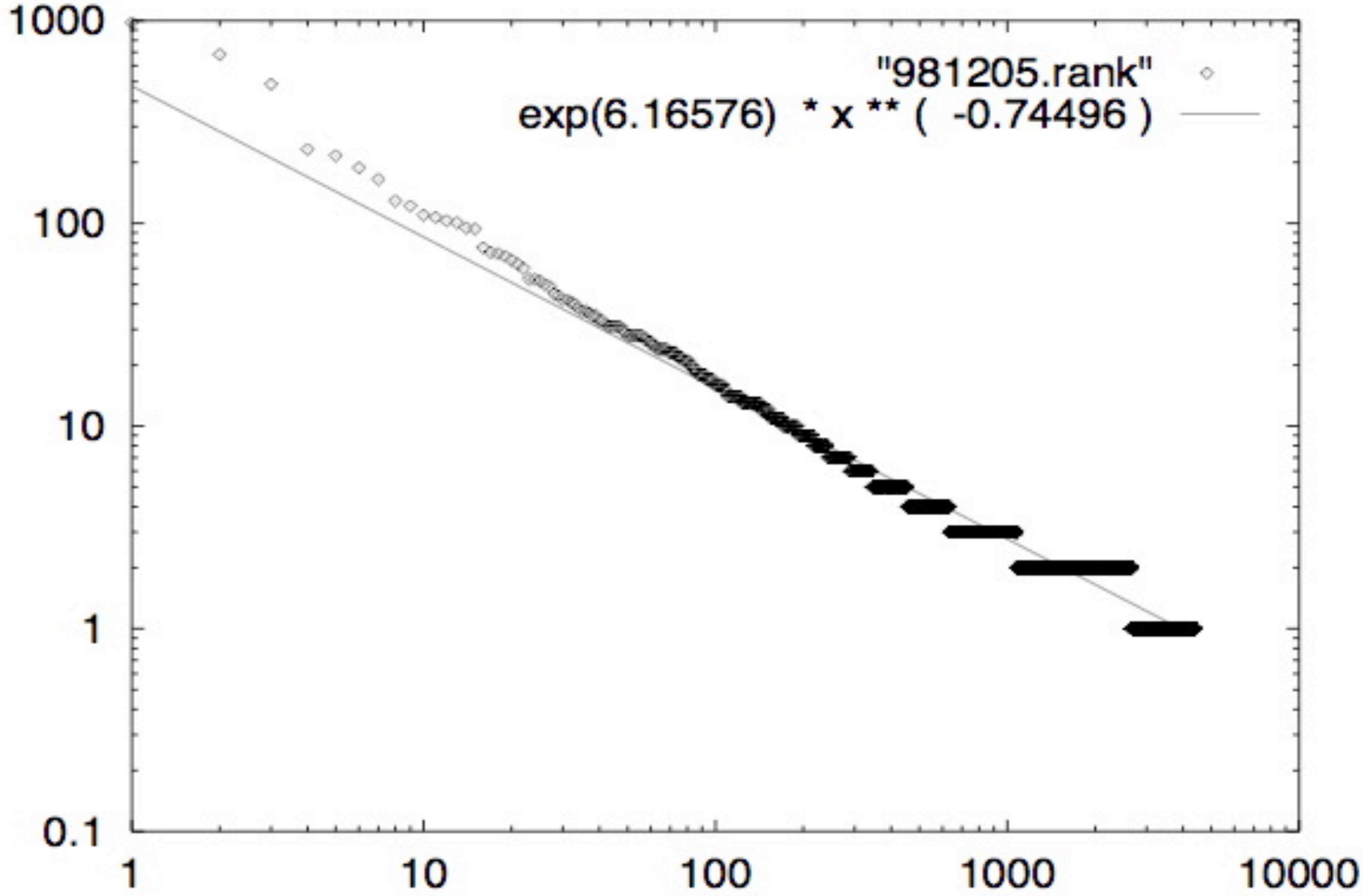
Plot d_v versus r_v on log-log scale



"971108.rank"
exp(6.34763) * x ** (-0.811392)
1000
100
10
1
0.1
1
10
100
1000
10000

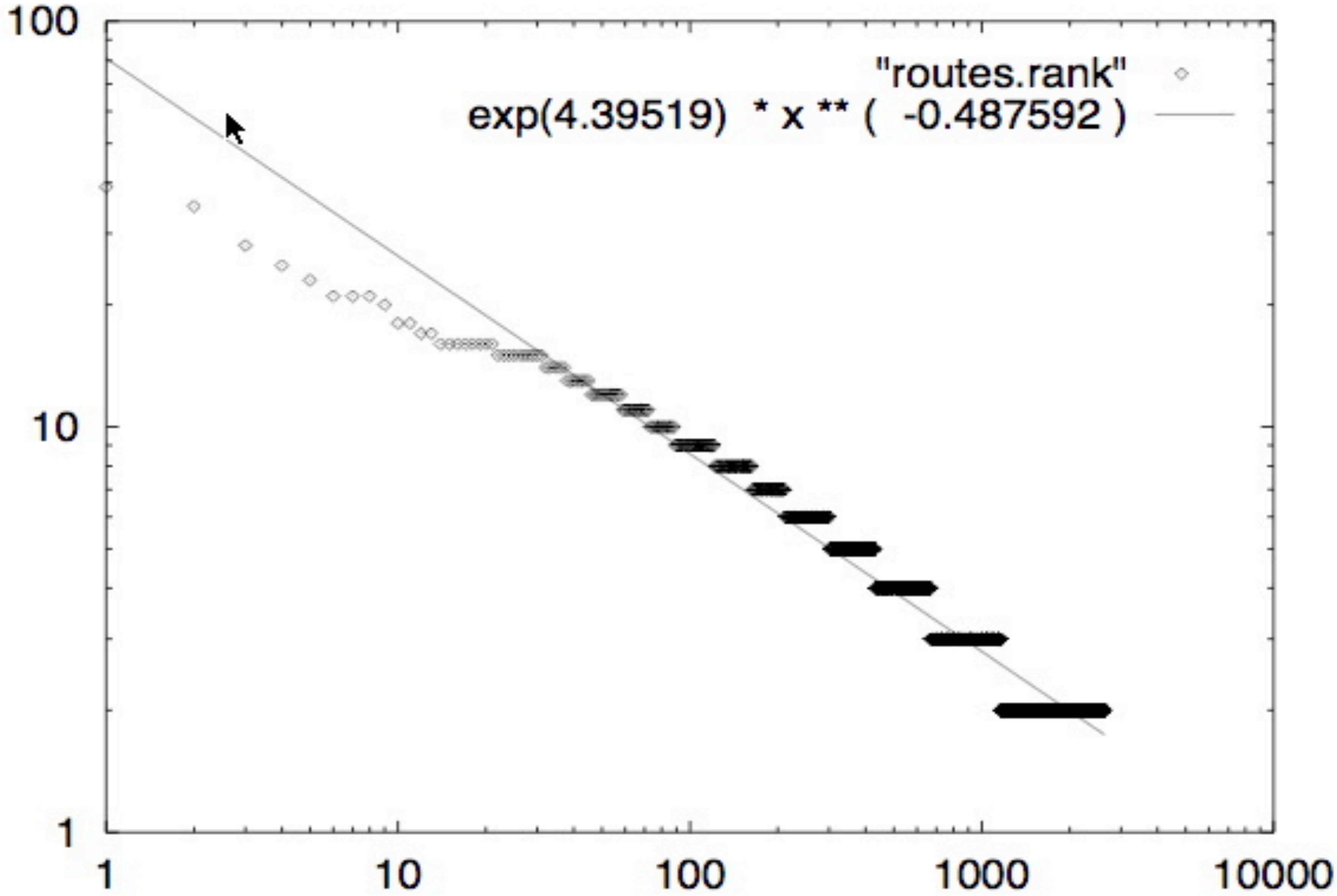
(a) Int-11-97


"980410.rank"
exp(6.62082) * x ** (-0.821274)
1000
100
10
1
0.1
1
10
100
1000
10000
(b) Int-04-98



1000
100
10
1
0.1
1
10
100
1000
10000
"981205.rank"
exp(6.16576) * x ** (-0.74496)

(a) Int-12-98



(b) Rout-95

$$\log d_v = \mathcal{R} \log r_v + c$$

$$d_v \propto r_v^{\mathcal{R}}$$

Rank Exponent

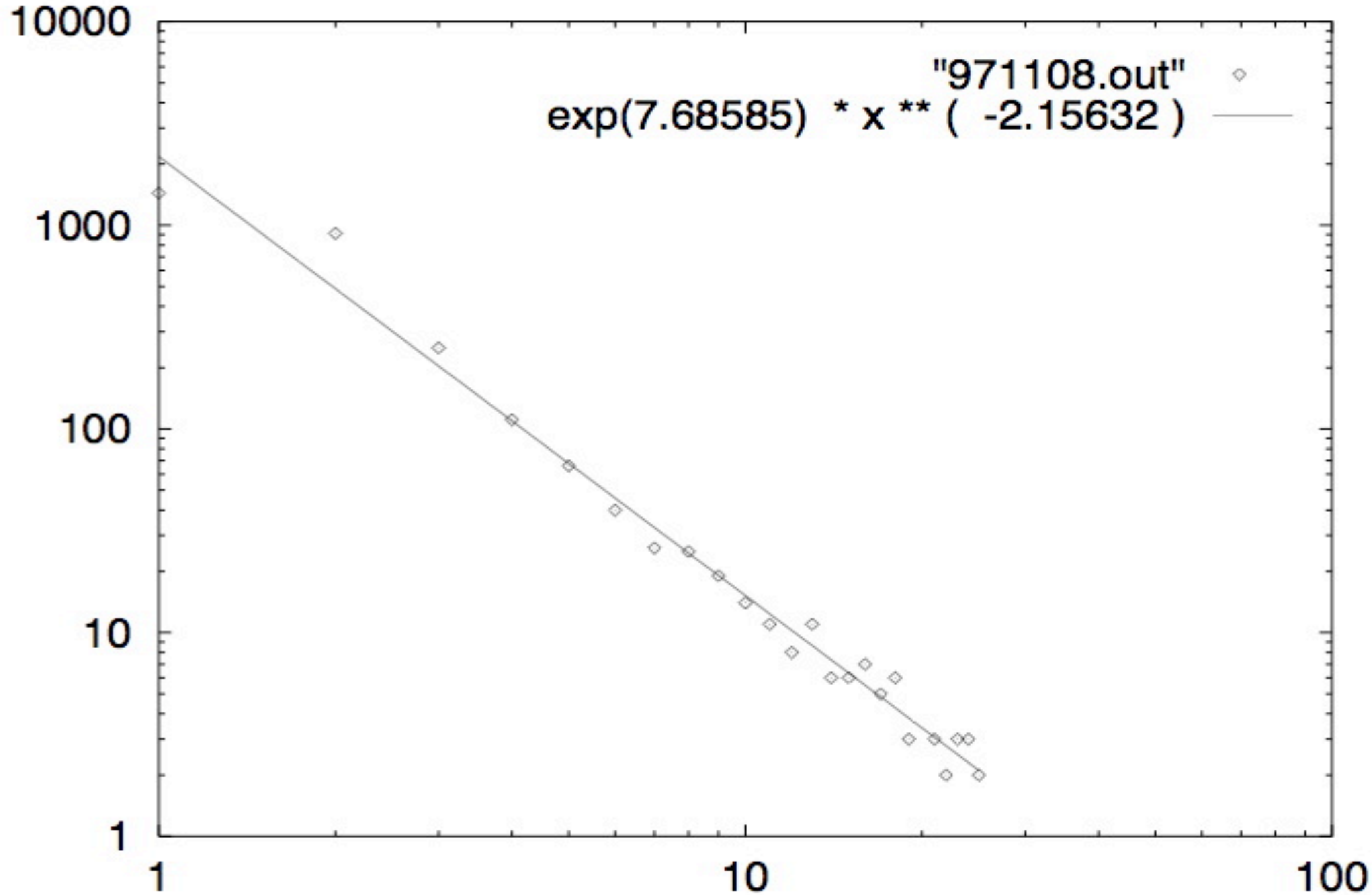
Lemma 1: $d_v = \frac{1}{N^R} r_v^{\mathcal{R}}$

Lemma 2: $E = \frac{N}{2(\mathcal{R}+1)}\left(1 - \frac{1}{N^{\mathcal{R}+1}}\right)$

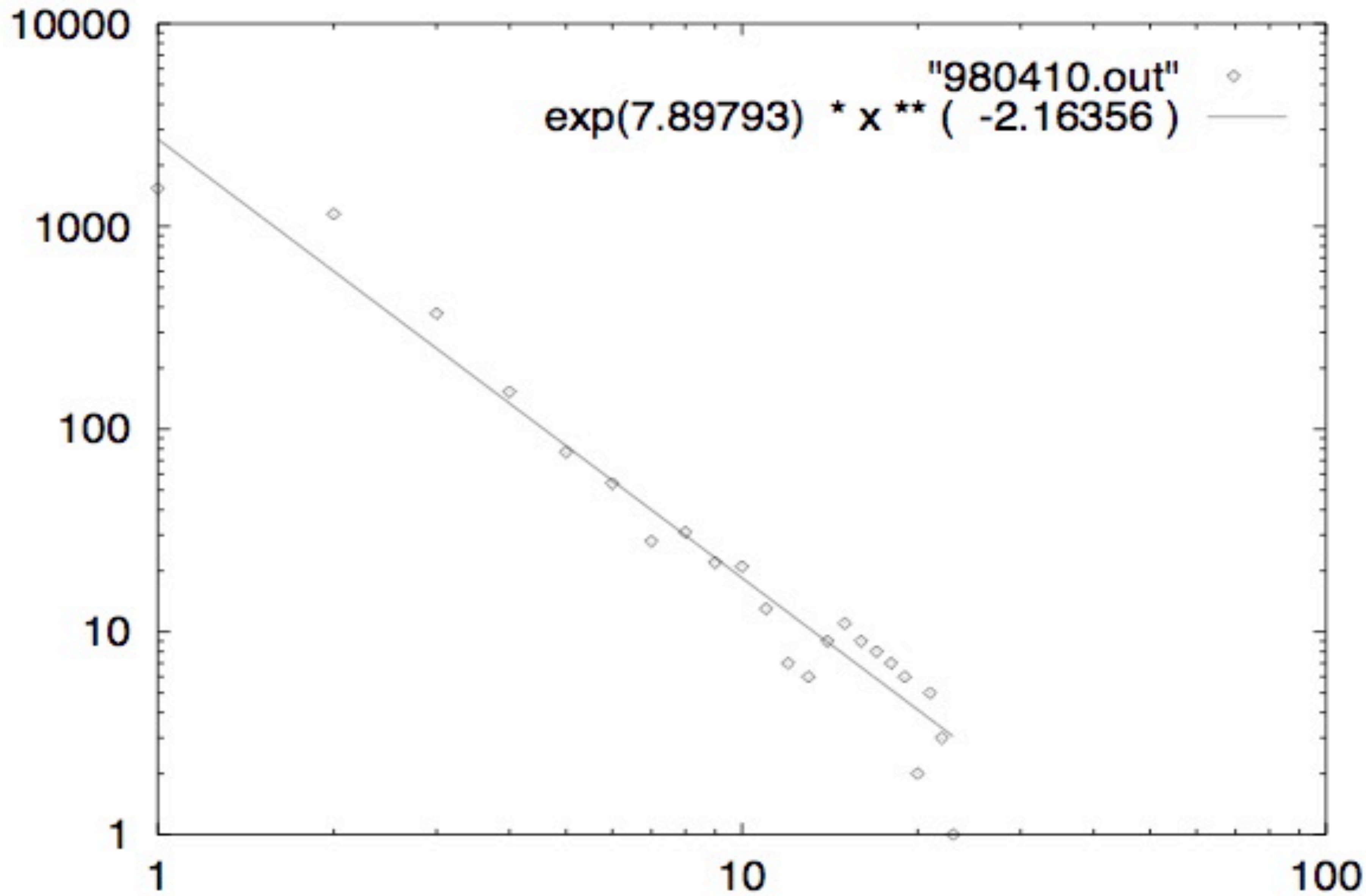
Let

$\mathbf{f_d}$ be the **number of nodes** with out-degree d

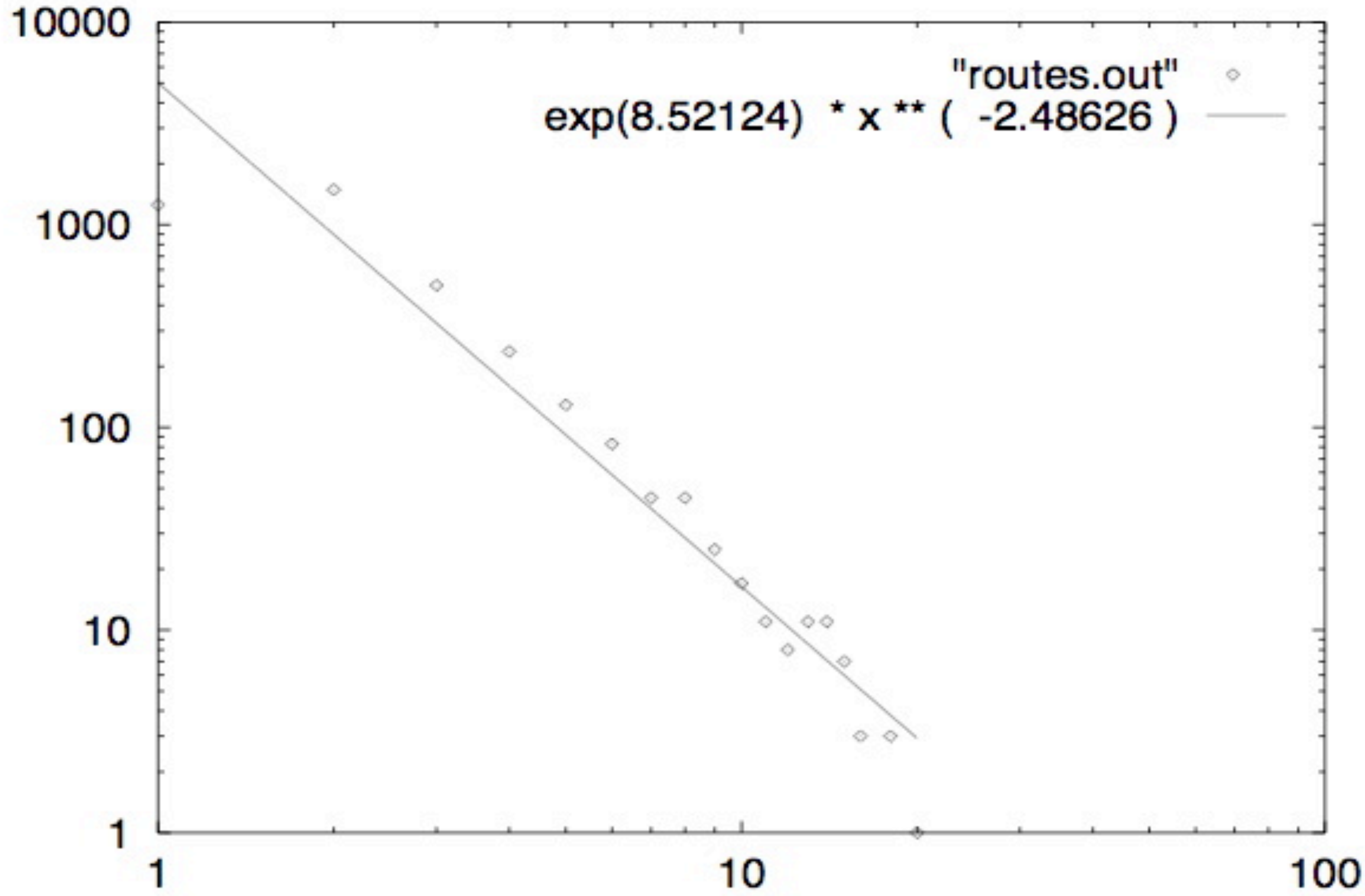
Plot f_d versus d on log-log scale



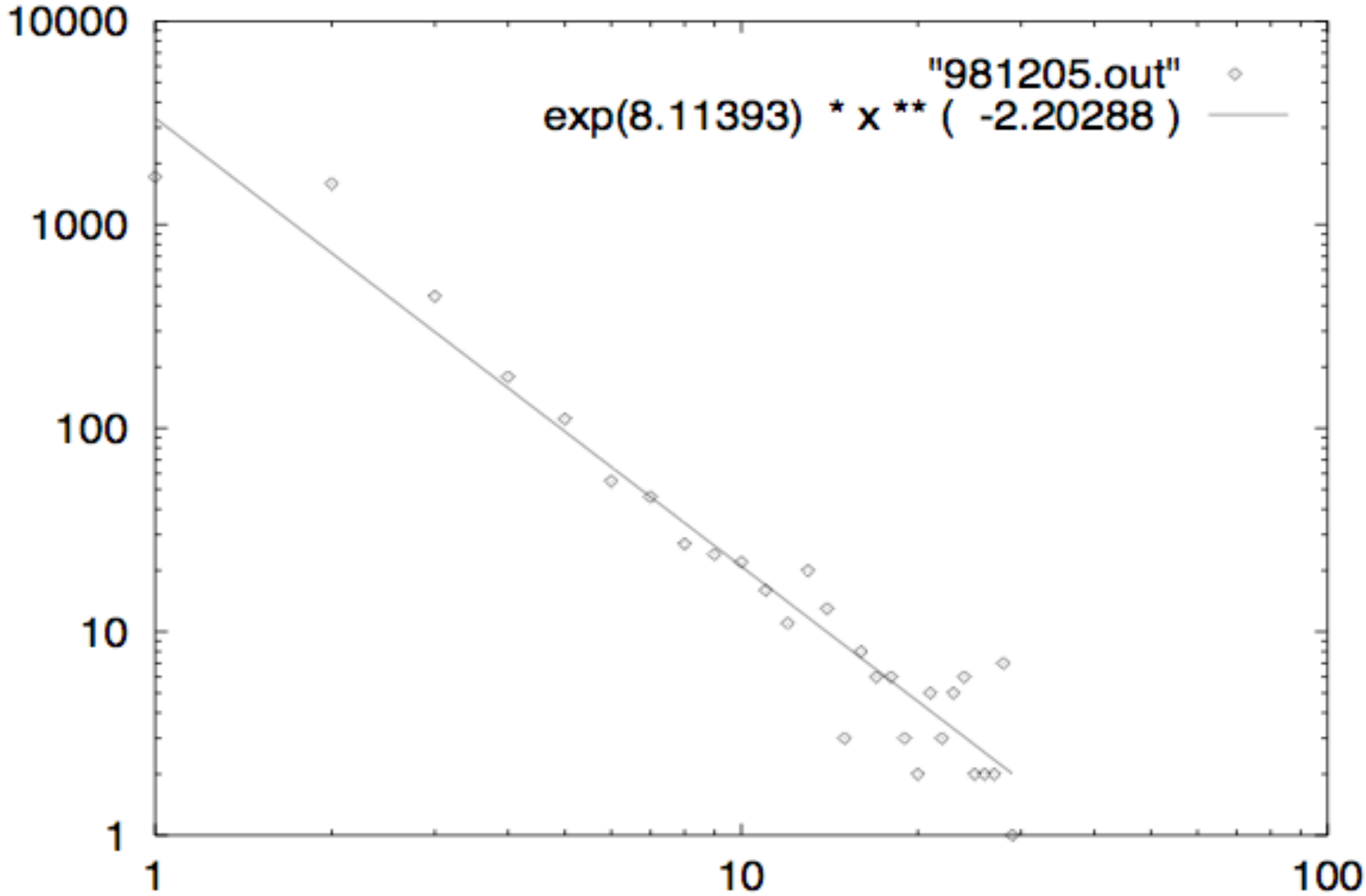
(a) Int-11-97



(b) Int-04-98



(b) Rout-95



(a) Int-12-98

$$f_d \propto d^{\mathcal{O}}$$

“few connects to many,
many connects to few”

On the Effectiveness of Route-Based Packet Filtering for Distributed DoS Attack Prevention in Power-Law Internets*

Kihong Park† Heejo Lee‡
Network Systems Lab
Department of Computer Sciences
Purdue University
West Lafayette, IN 47907
{park,hlee}@cs.purdue.edu

that cannot be proactively curtailed are extremely sparse so that their origin can be localized—i.e., IP traceback—to within a small, constant number of candidate sites. We show that the two proactive and reactive performance effects can be achieved by implementing route-based filtering on less than 20% of Internet autonomous system (AS) sites. Second, we show that the two complementary performance measures are dependent on the properties of the underlying AS graph. In particular, we show that the power-law structure of Internet AS topology leads to connectivity properties which are crucial in facilitating the observed performance effects.

Let

P(h) be the **number of node pairs** within h hops of each other
(include self-pairs, count every pair twice)

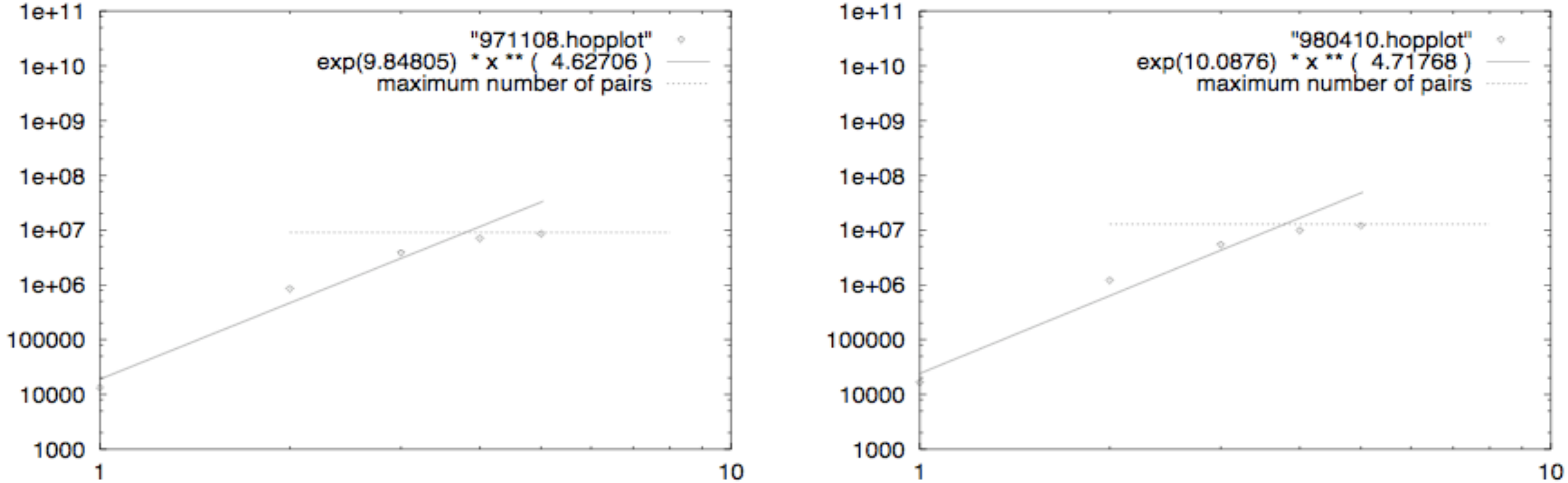
$$P(0) = N$$

$$P(1) = N + 2E$$

$$P(\delta) = N^2$$

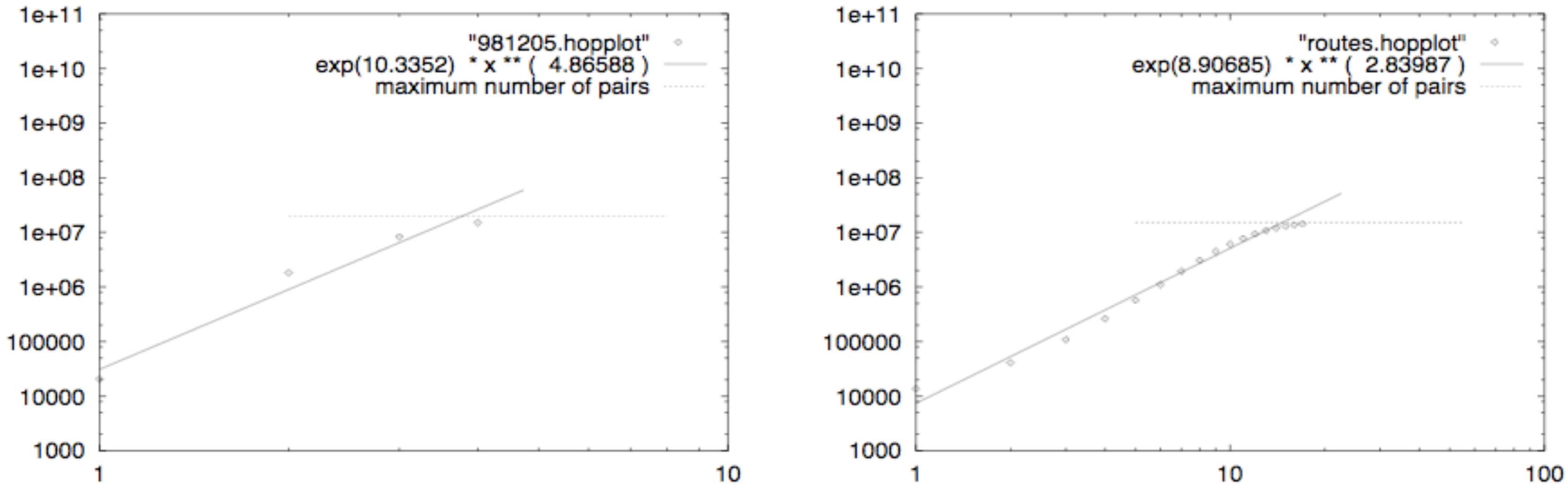
where δ is the diameter of the graph

Plot P(h) versus h on log-log scale



(a) Int-11-97 (b) Int-04-98

Figure 7: The hop-plots: Log-log plots of the number of pairs of nodes $P(h)$ within h hops versus the number of hops h.



(a) Int-12-98 (b) Rout-95

Figure 8: The hop-plots: Log-log plots of the number of pairs of nodes $P(h)$ within h hops versus the number of hops h.

$$P(h) \propto h^{\mathcal{H}}, h \ll \delta$$

$$P(h) = \begin{cases} (N + 2E)h^{\mathcal{H}} & h \ll \delta \\ N^2 & h \geq \delta \end{cases}$$

$$P(\delta_{ef}) = N^2$$

IX TELECOMMUNICATIONS FORUM TELFOR 2001, Belgrade, 20-22.11.2001.

MODELING PEER-TO-PEER NETWORK TOPOLOGIES THROUGH "SMALL-WORLD" MODELS AND POWER LAWS

Mihajlo Jovanović
ECECS Department, University of Cincinnati
Cincinnati, OH 45221

$$\delta_{ef} = \left(\frac{N^2}{N + 2E} \right)^{1/H}$$

Substituting the values for the Gnutella topology snapshot from December 28, 2000, we get that, during that time, a more cost-effective value for the maximum TTL would have been 4 (instead of 7, which is the default specified by the Gnutella protocol).

IV CRAWLER ARCHITECTURE

Gnutella is a highly dynamic network in which topology is constantly changing as hosts join and leave the network, establish new connections, and close the existing ones. Therefore discovering topology of the Gnutella network

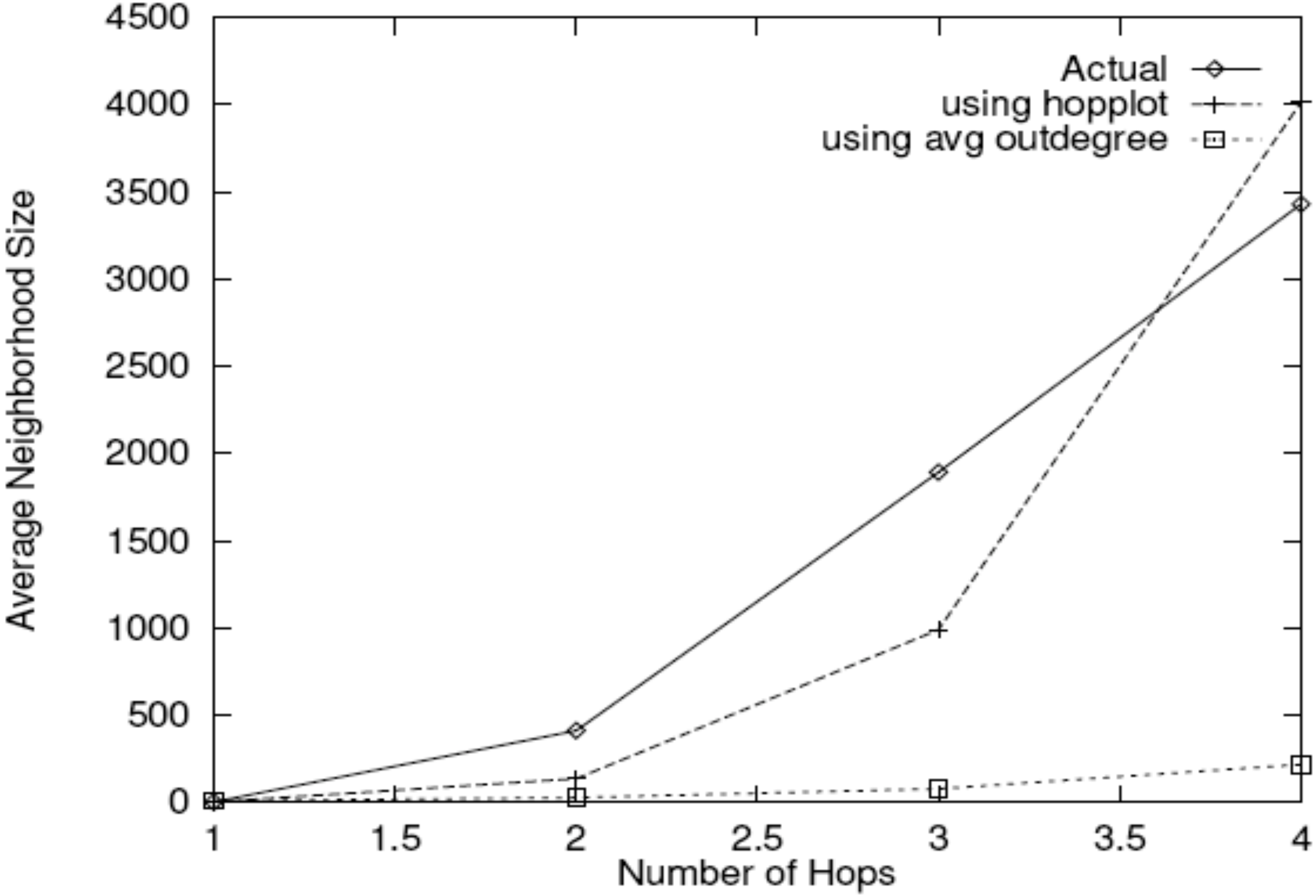
proto
messa
messa
effect
comb
obtai
exper
the c
circui
perfo
that t
will
applic

Average Number of Nodes within h Hops

$$NN(h) = \frac{P(h) - N}{N}$$

Average Number of Nodes within h Hops
(using average degree)

$$NN(h) = \bar{d}(\bar{d} - 1)^h$$



Actual
using hopplot
using avg outdegree
Average Neighborhood Size
Number of Hops
4500
4000
3500
3000
2500
2000
1500
1000
500
0
1
1.5
2
2.5
3
3.5
4

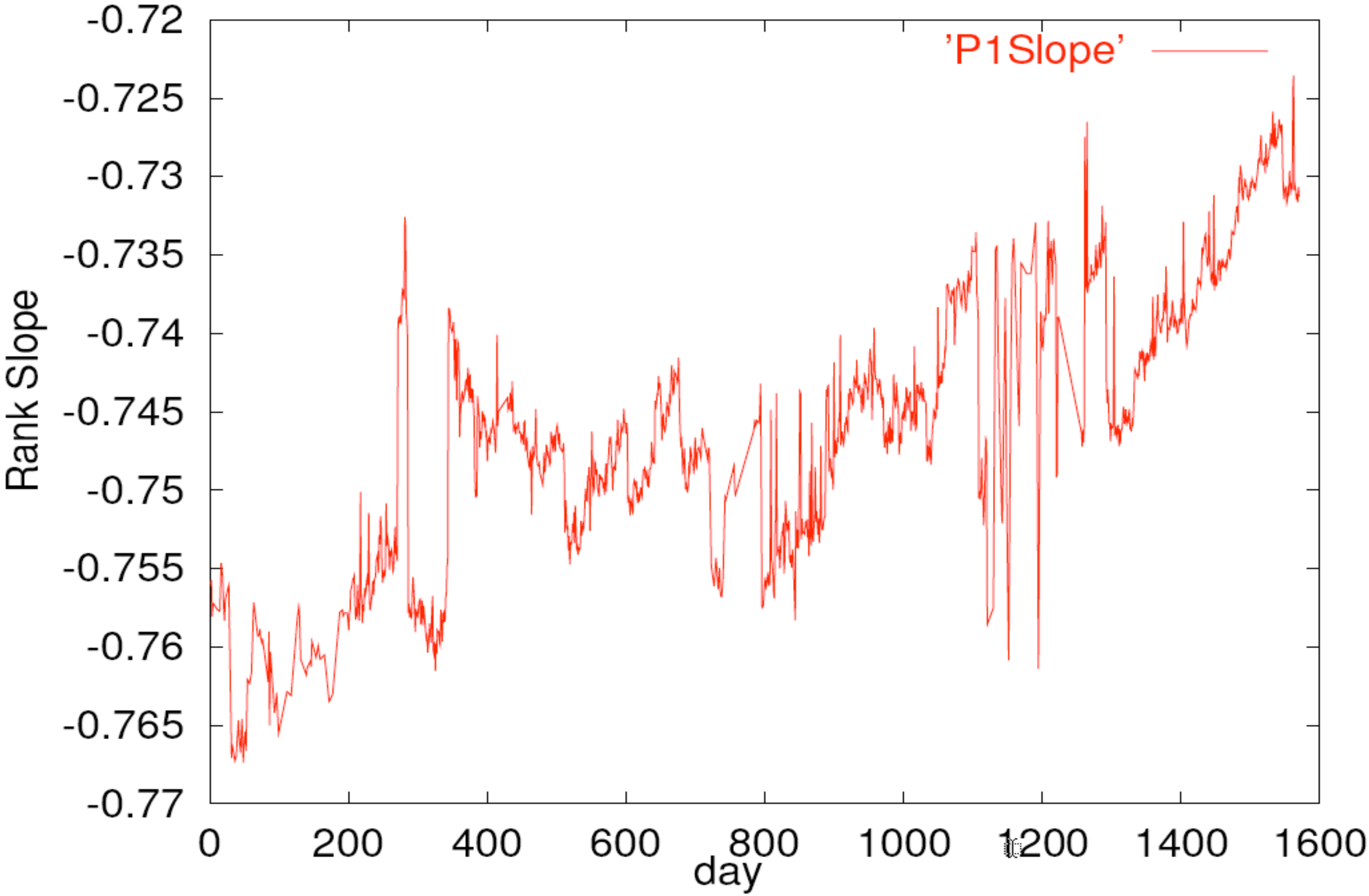
$$d_v \propto r_v^{\mathcal{R}}$$

$$f_d \propto d^{\mathcal{O}}$$

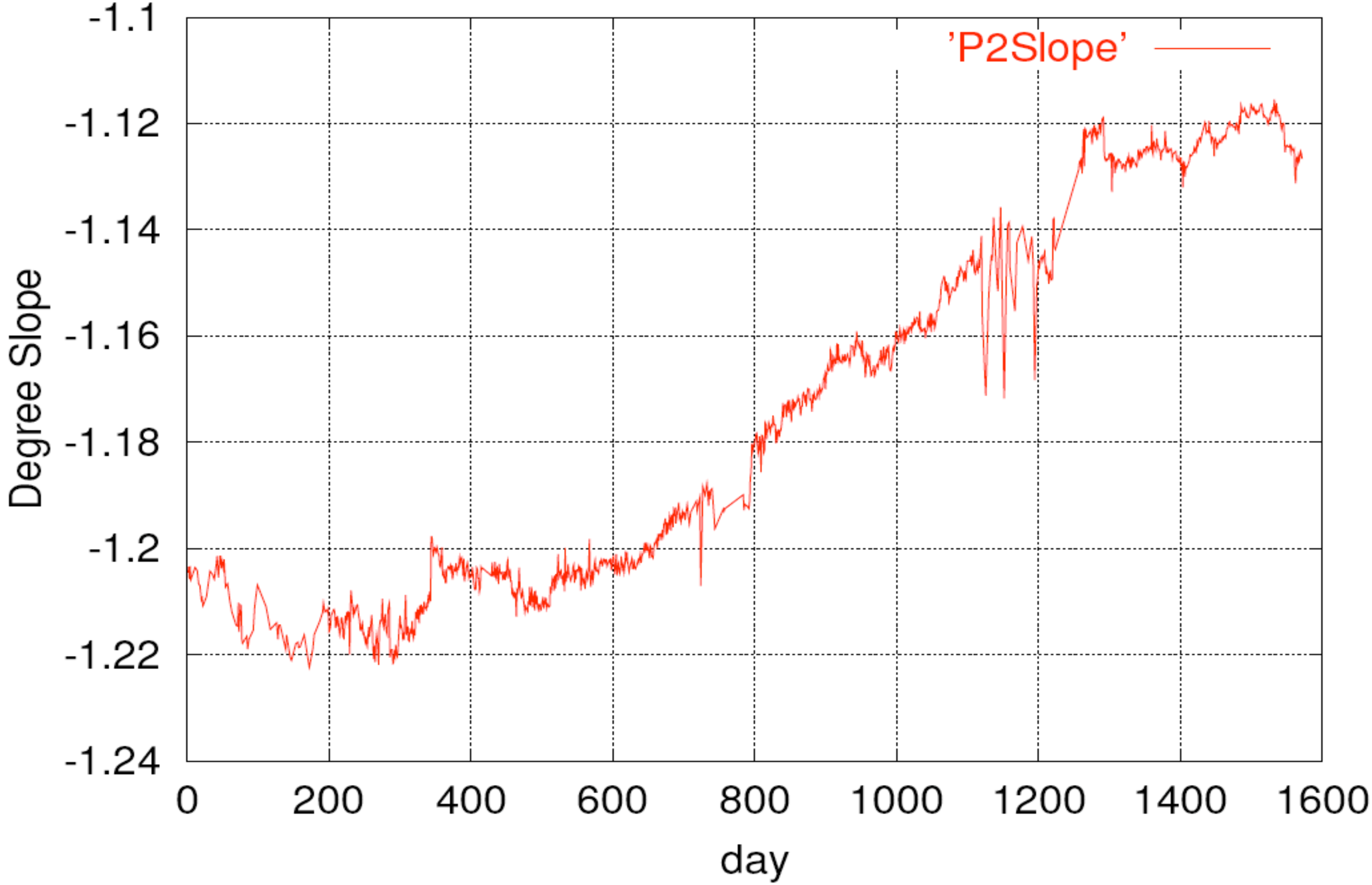
$$P(h) \propto h^{\mathcal{H}}, h \ll \delta$$

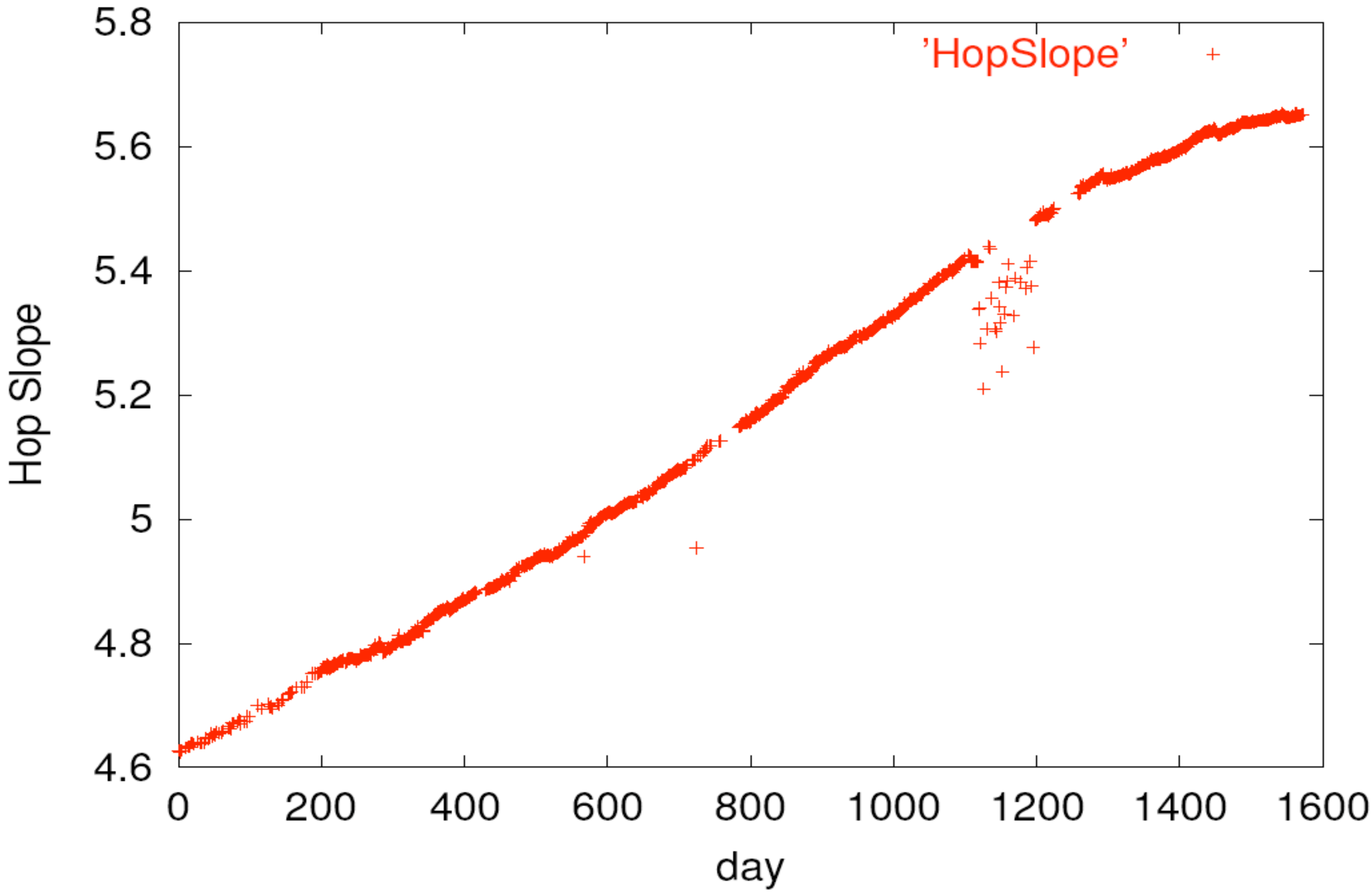
It holds in 97-98.
What about later?

“Power-Laws and the AS-Level Internet Topology”
G. Siganos and the Faloutsos brothers, IEEE/ACM TON



'P1Slope'
Rank Slope
day
-0.72
-0.725
-0.73
-0.735
-0.74
-0.745
-0.75
-0.755
-0.76
-0.765
-0.77
0
200
400
600
800
1000
1200
1400
1600


'P2Slope'
Degree Slope
-1.1
-1.12
-1.14
-1.16
-1.18
-1.2
-1.22
-1.24
0
200
400
600
800
1000
1200
1400
1600
day



5.8
5.6
5.4
5.2
5
4.8
4.6
Hop Slope
0
200
400
600
800
1000
1200
1400
1600
day
'HopSlope'

Do topologies generated by Waxman and Transit-Stub exhibit Power Law?

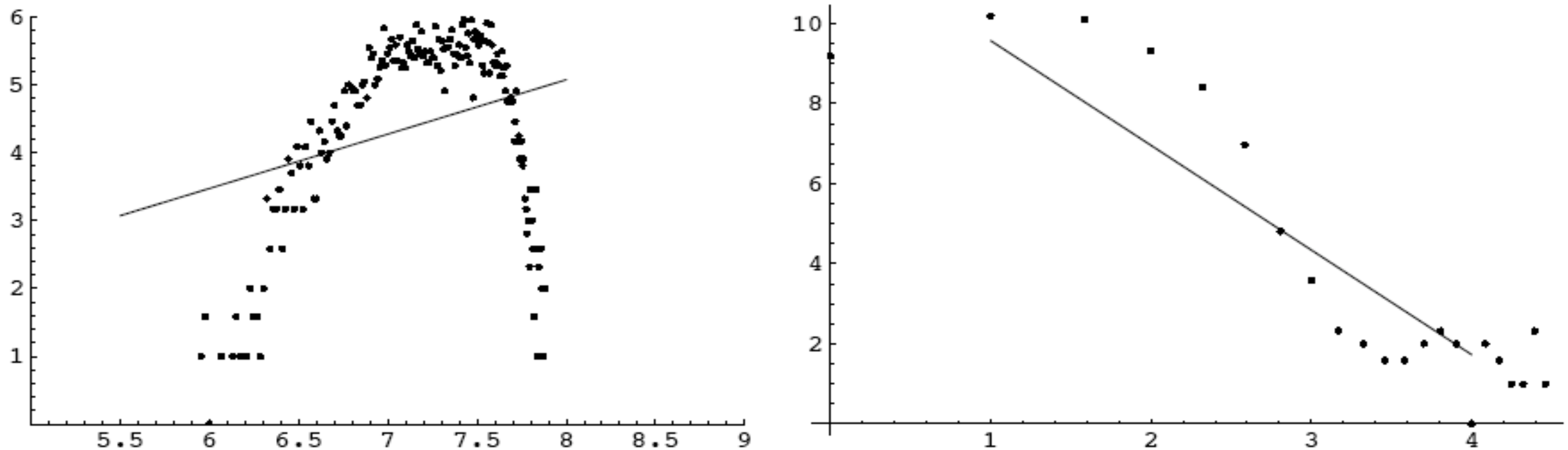


Figure 1: Log-log plot of frequency f_d vs. outdegree d for a 5000-node Waxman topology (left) and a 6660-node Transit-Stub topology (right). The correlation coefficient is 0.4 for the Waxman topology, and 0.9 for the Transit-Stub topology.

How to generate topology that follows power laws?

Where does power law comes from?

Internet

Diameter of the World-Wide Web

Despite its increasing role in communication, the World-Wide Web remains uncontrolled: any individual or institution can create a website with any number of documents and links. This unregulated growth leads to a huge and complex web, which becomes a large directed graph whose vertices are documents and whose edges are links (URLs) that point from one document to another. The topology of this graph determines the web's connectivity and consequently how effectively we can locate information on it. But its enormous size (estimated to be at least 8×10^8 documents[1]) and the continual changing of documents and links make it impossible to catalogue all the vertices and edges.

The extent of the challenge in obtaining a complete topological map of the web is

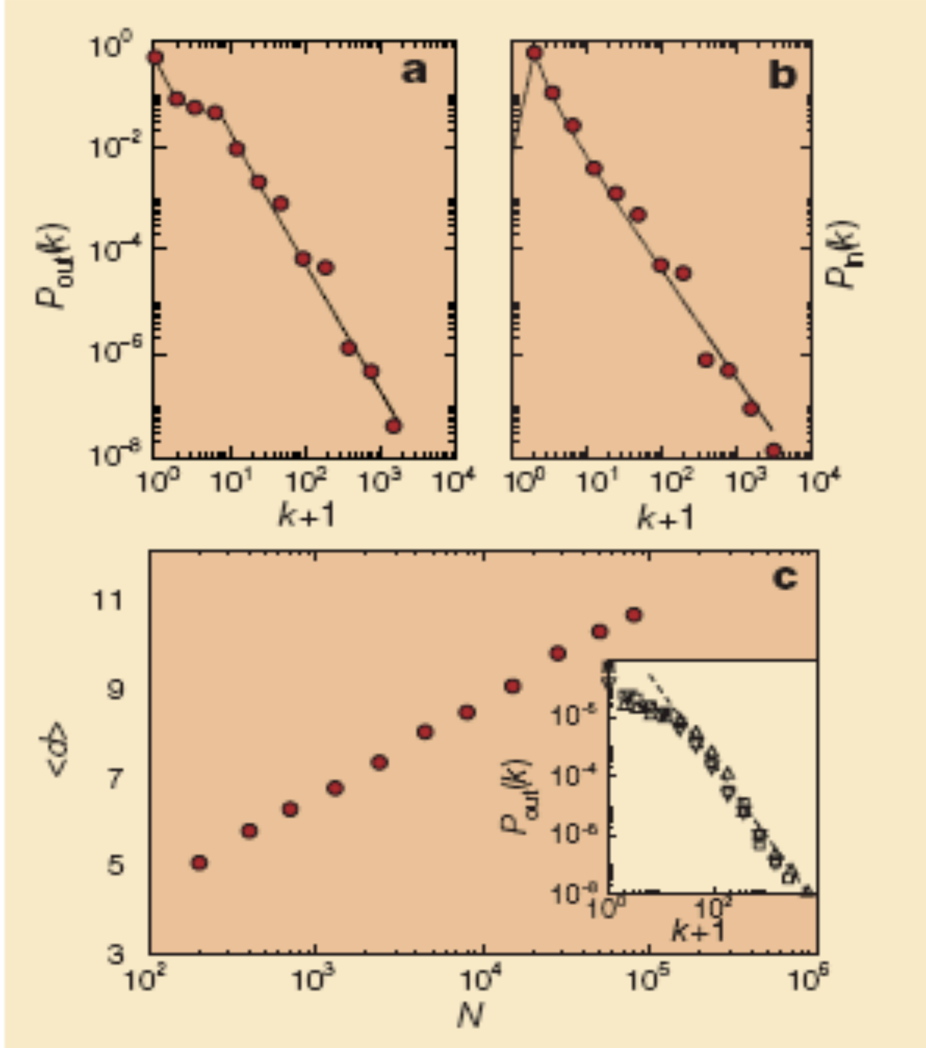
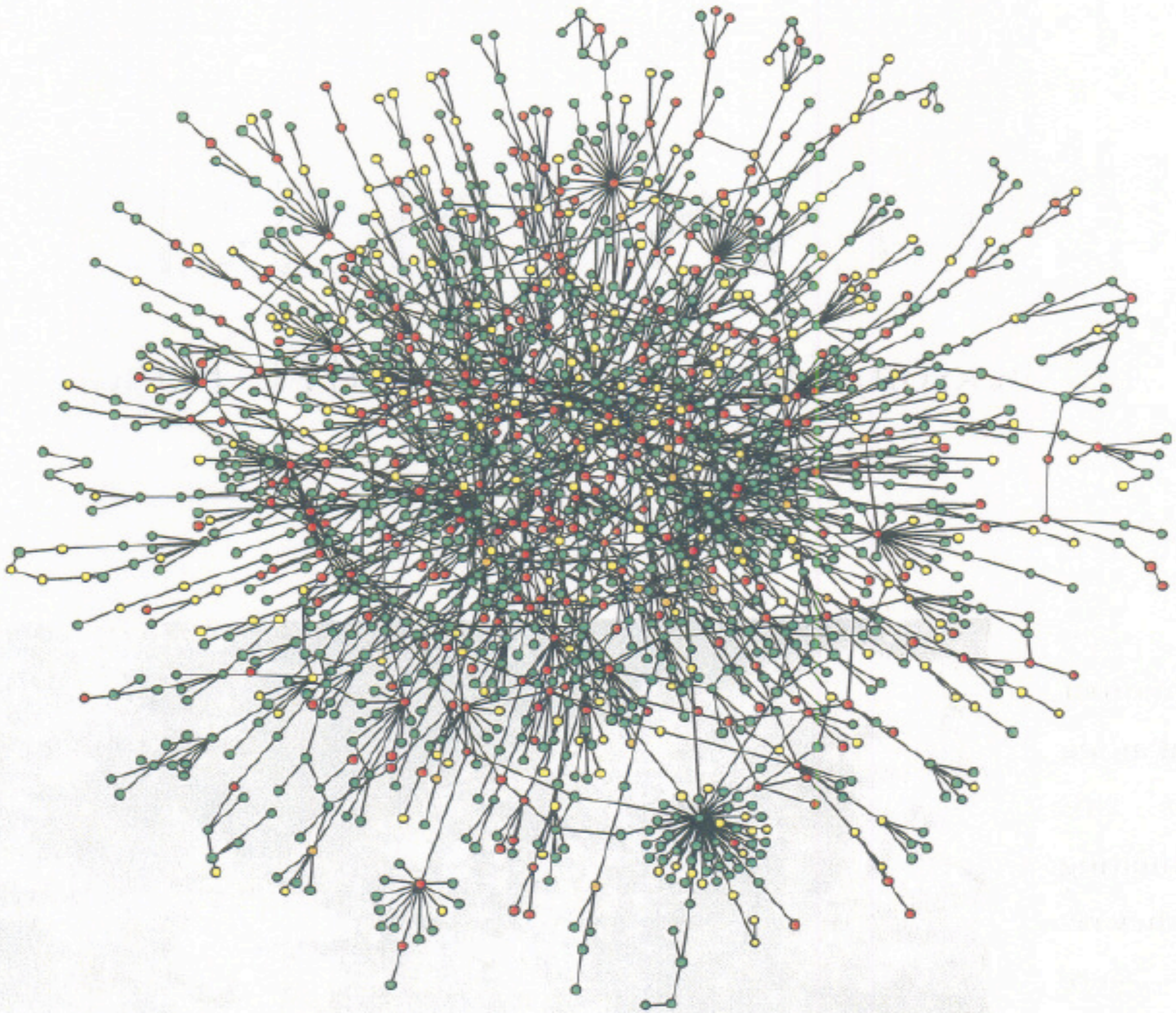


Figure 1 Distribution of links on the World-Wide Web. **a,** Outgoing links (URLs found on an HTML document); **b,** incoming links (URLs pointing to a certain HTML document). Data were obtained from the complete map of the nd.edu domain, which contains 325,729 documents and 1,469,680 links. Dotted lines represent analytical

Scientific American, “Scale-Free Networks”, May 2003



MAP OF INTERACTING PROTEINS in yeast highlights the discovery that highly linked, or hub, proteins tend to be crucial for a cell's survival. Red denotes essential proteins (their removal will cause the cell to die). Orange represents proteins of some importance (their removal will slow cell growth). Green and yellow represent proteins of lesser or unknown significance, respectively.

Even the network of actors in Hollywood—popularized by the game Six Degrees of Kevin Bacon, in which players try to connect actors to Bacon via the movies in which they have appeared together—is scale-free. A quantitative analy-

each other. When we investigated Baker's yeast, one of the simplest eukaryotic (nucleus-containing) cells, with thousands of proteins, we discovered a scale-free topology: although most proteins interact with only one or two others, a few are able to

Now it has more than three
networks have expanded si
lywood had only a handfu
1890, but as new people joi
the network grew to incluc
half a million, with the roo
ing to veteran actors. The
only a few routers about t
ago, but it gradually grew
lions, with the new routers a
to those that were already p
work. Thanks to the grow
real networks, older node:
opportunities to acquire lin

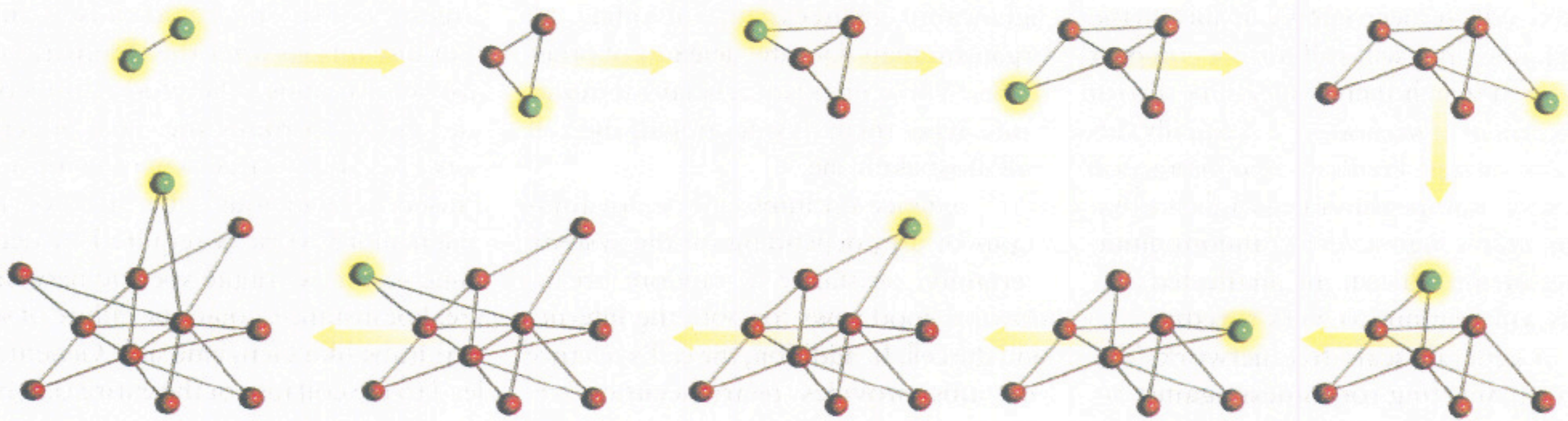
Furthermore, all nodes a
When deciding where to li
page, people can choose fron
locations. Yet most of us are
only a tiny fraction of the f
that subset tends to include t
nected sites because they are
By simply linking to those r
exercise and reinforce a bias
This process of "preferentia
occurs elsewhere. In Hollyw

Examples of Scale-Free Networks

NETWORK	NODES	LINKS
Cellular metabolism	Molecules involved in burning food for energy	Participation in the same biochemical reaction
Hollywood	Actors	Appearance in the same movie
Internet	Routers	Optical and other physical connections
Protein regulatory network	Proteins that help to regulate a cell's activities	Interactions among proteins
Research collaborations	Scientists	Co-authorship of papers
Sexual relationships	People	Sexual contact
World Wide Web	Web pages	URLs

BIRTH OF A SCALE-FREE NETWORK

A SCALE-FREE NETWORK grows incrementally from two to 11 nodes in this example. When deciding where to establish a link, a new node (*green*) prefers to attach to an existing node (*red*) that already has many other connections. These two basic mechanisms—growth and preferential attachment—will eventually lead to the system's being dominated by hubs, nodes having an enormous number of links.



Generating Power Law Topology (simplified)

“On the Original of Power Laws in Internet Topologies”

A Medina, I Matta, J Byers, ACM SIGCOMM, ‘00 http://www.cs.bu.edu/b... | http://www.nd.edu/~ne... | BRITE: Boston university...

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Boston University Representative Internet Topology Generator

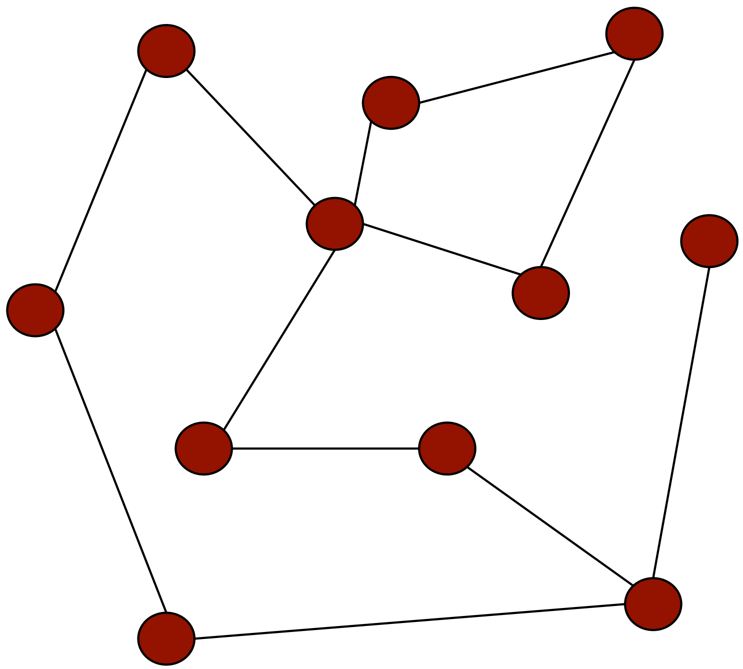
Overview

BRITE is no longer supported by its developers, but questions can be asked on the brite-users mailing list.

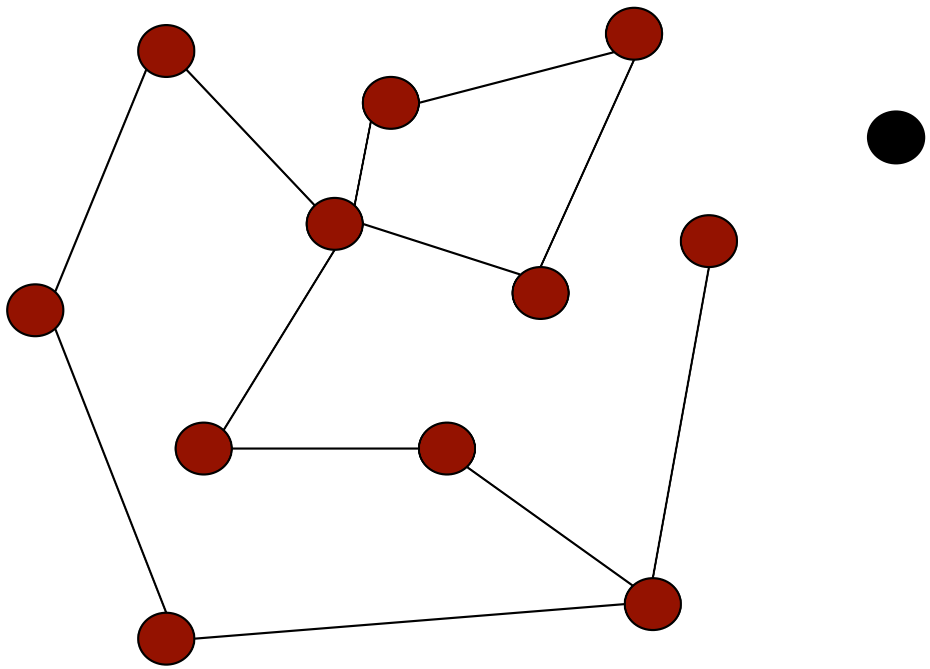
Effective engineering of the Internet is predicated upon a detailed understanding of issues such as the large-scale structure of its underlying physical topology, the manner in which it evolves over time, and the way in which its constituent components contribute to its overall function. Unfortunately, developing a deep understanding of these issues has proven to be a challenging task, since it in turn involves solving difficult problems such as mapping the actual topology, characterizing it, and developing models that capture its emergent behavior. Consequently, even though there are a number of topology models, it is an open question as to how representative the topologies they generate are of the actual Internet. Our goal is to produce a topology generation framework which improves the state of the art and is based on design principles which include representativeness, inclusiveness, and interoperability. **Representativeness** leads to synthetic topologies that accurately reflect many aspects of the actual Internet topology (e.g. hierarchical structure, degree distribution, etc.). **Inclusiveness** combines the strengths of as many generation models as possible in a single generation tool. **Interoperability** provides interfaces to widely-used simulation applications such as ns, SSF and OmNet++ as well as visualization applications. We call such a tool a **universal topology generator**.

BRITE is an approach towards universal topology generation. We designed BRITE to be:

Randomly generate a small graph

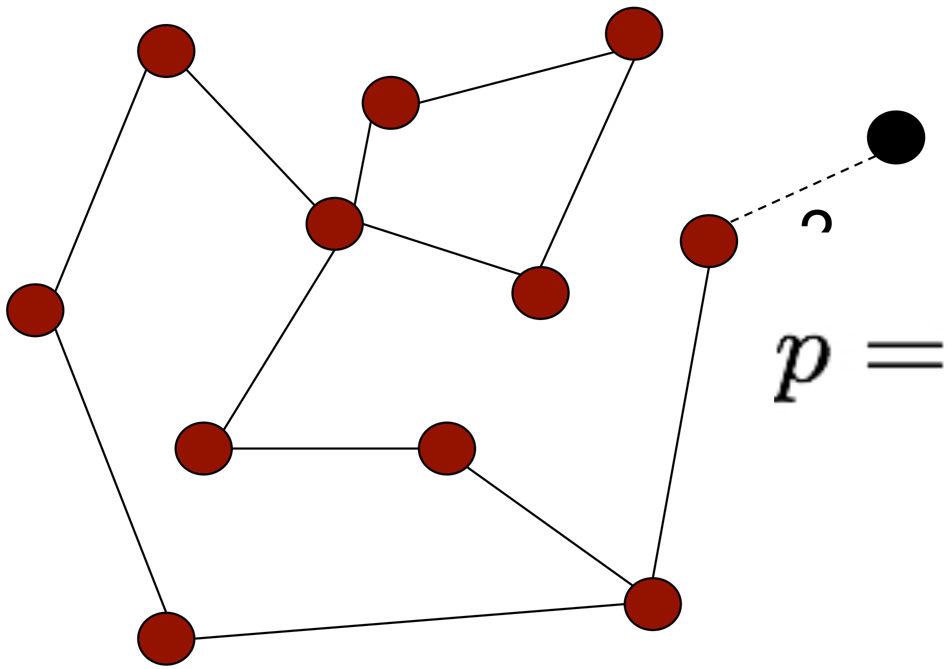


Incremental Growth:
Add one node at a time



Preferential Attachment:

Connects to a neighbor i with a probability



$$p = \frac{d_i}{\sum_{j \in C} d_j}$$

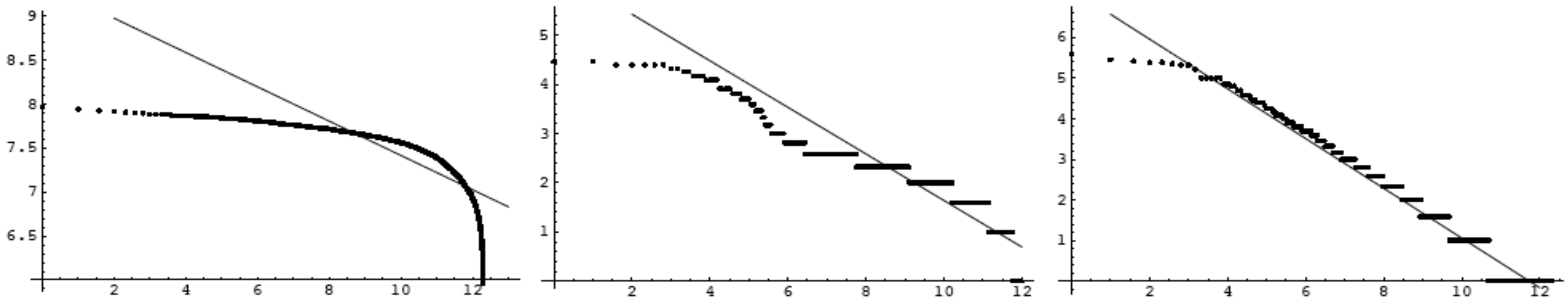
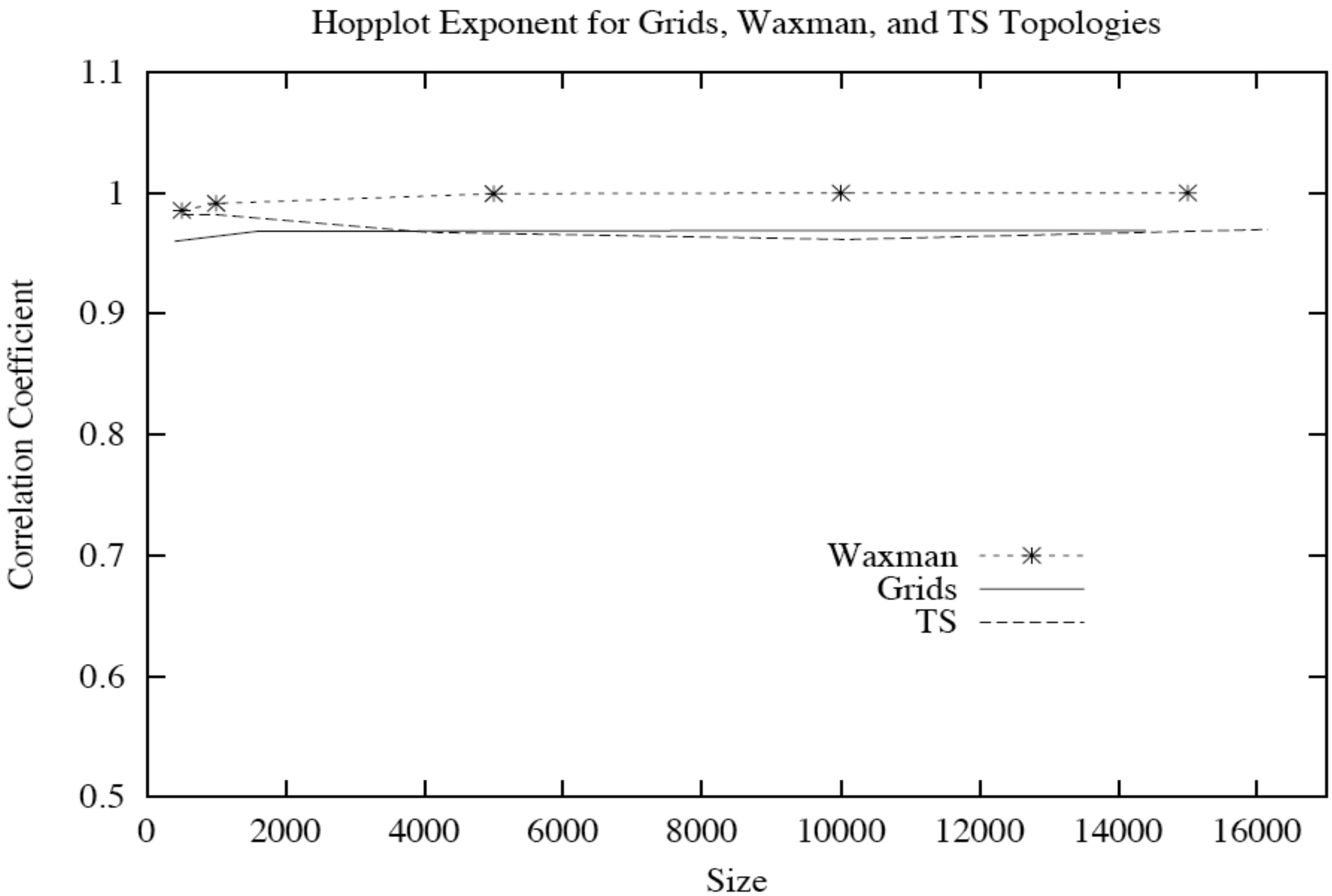


Figure 6: Log-log plot of outdegree d_v vs. rank for a 5000-node Waxman topology (left), a 4040-node Transit-Stub topology (middle) and a 5000-node BRITE topology with preferential connectivity and incremental growth (right). The correlation coefficient is 0.81 for the Waxman topology, 0.87 for the Transit-Stub topology, and 0.96 for the BRITE topology.


Hopplot Exponent for Grids, Waxman, and TS Topologies
Correlation Coefficient
1.1
1
0.9
0.8
0.7
0.6
0.5
0
2000
4000
6000
8000
10000
12000
14000
16000
Size
Waxman
Grids
TS