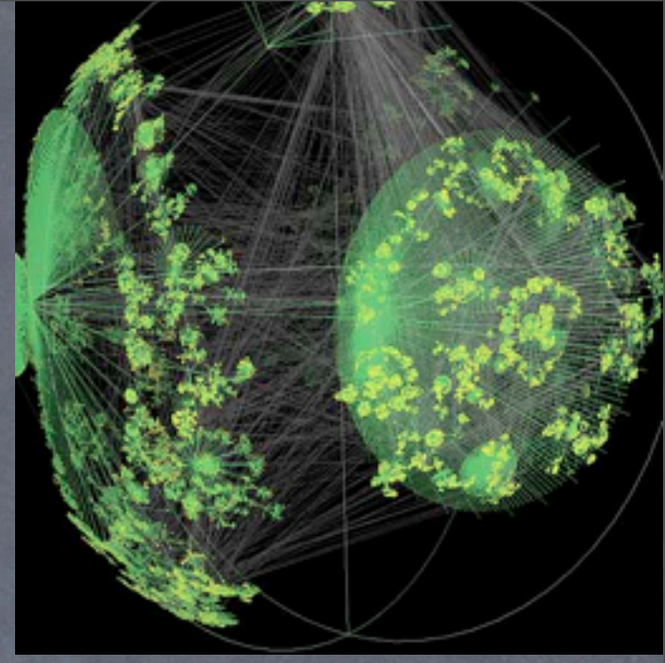
UNIVERSITY OF CAMBRIDGE

RVC Royal Veterinary College University of London



Structural Evolution of the Internet Topology

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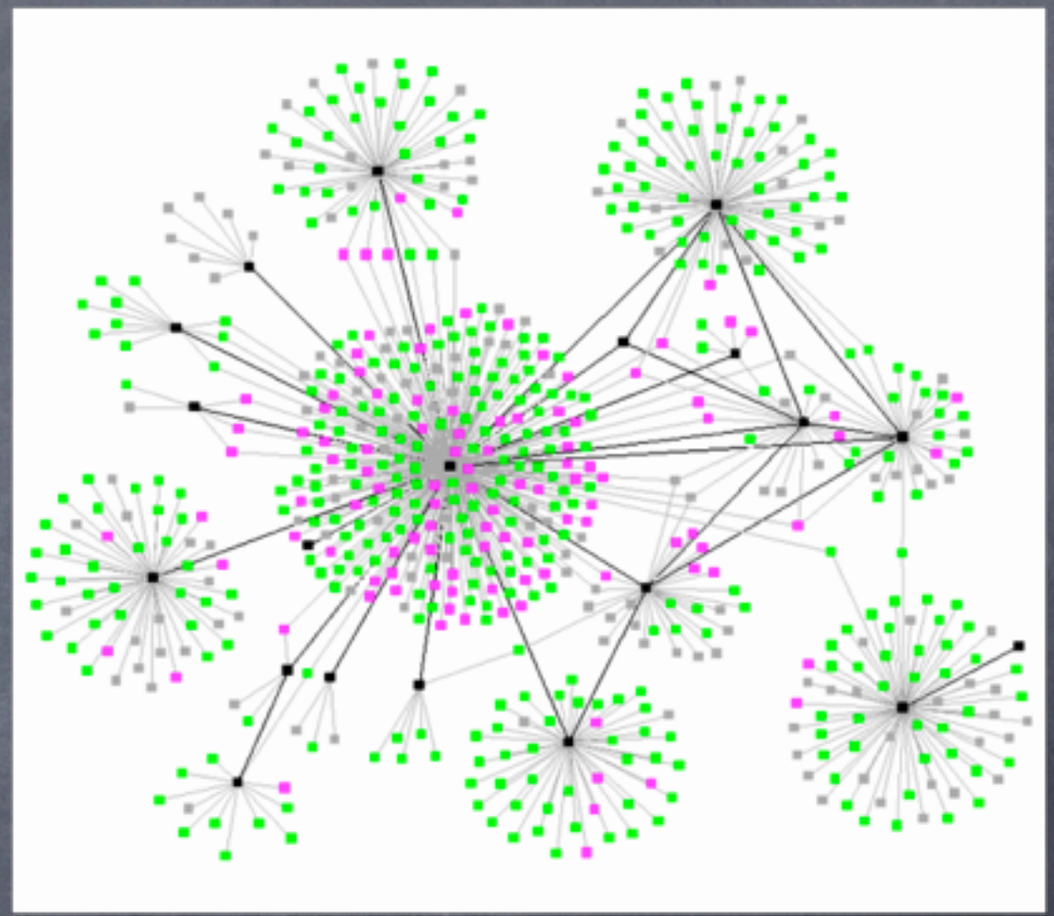
9th November 2010
Mphil ACS Network Architecture

Internet Topology

- Inference
- Characterisation
- Generation
- Evolution



Inference

- Router Level topology
- Administrative System (AS) Level Topology

Donnet et al, Internet Topology Discovery: a Survey, (IEEE Communications Survey and Tutorials 2007)

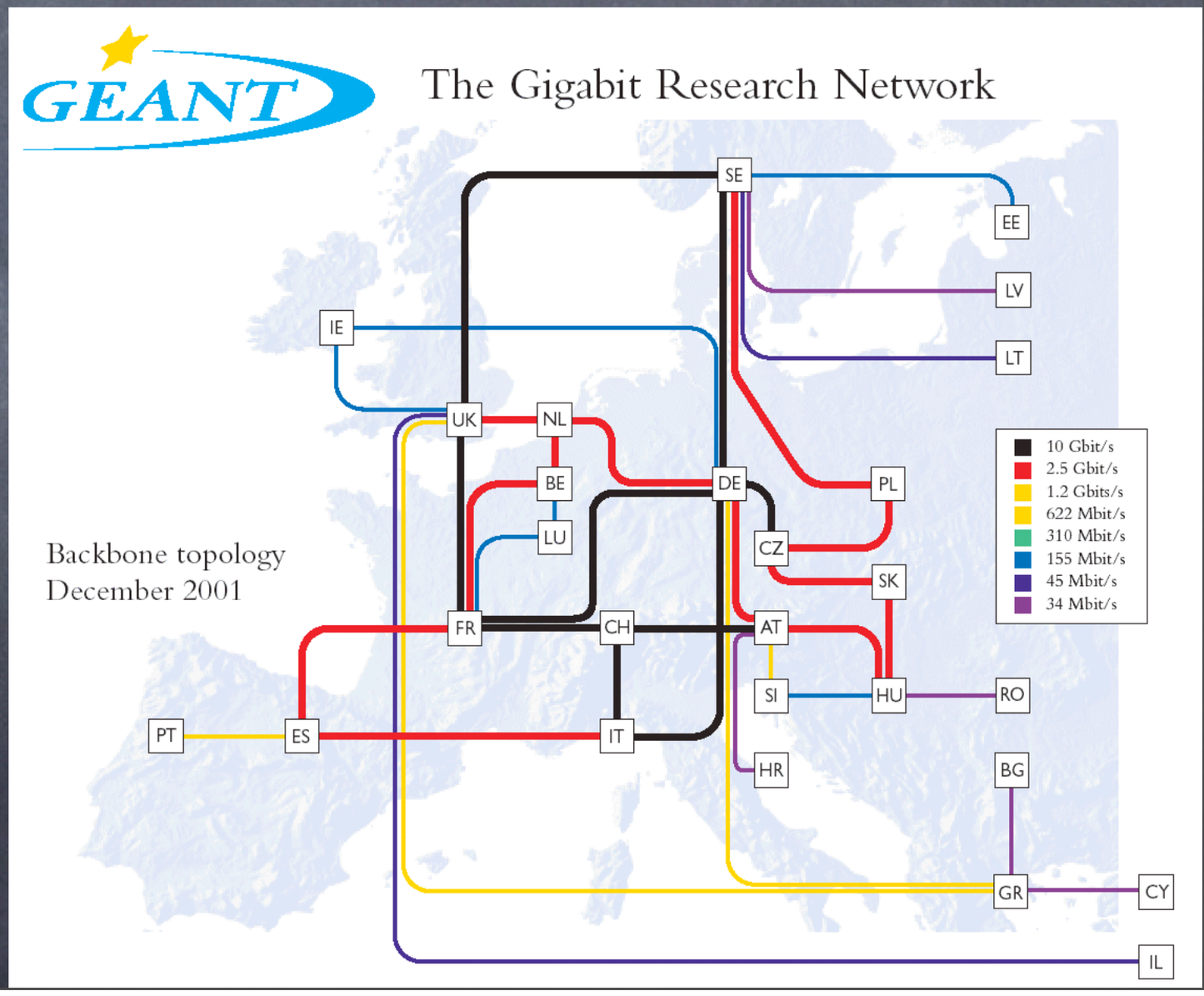
Haddadi et al, Network Topologies: Inference, Modelling and Generation, (IEEE Communications Survey and Tutorials 2008)

Router level topology

- Inferred by sending out traceroutes globally
- Core Routers (CAIDA Archipelago: www.caida.org/projects/ark/)
- End-host (Dimes www.netdimes.org)
- Single ISP domain (Rocketfuel www.cs.washington.edu/research/networking/rocketfuel/)
- Accurate route that PACKETS take
- Issues: Router Alias Resolution, ECMP, Firewalls,

AS Level topology

- Is formed of Autonumous Systems (ASes)
- Determined by relationships (Physical, connectivity, political) between ASes

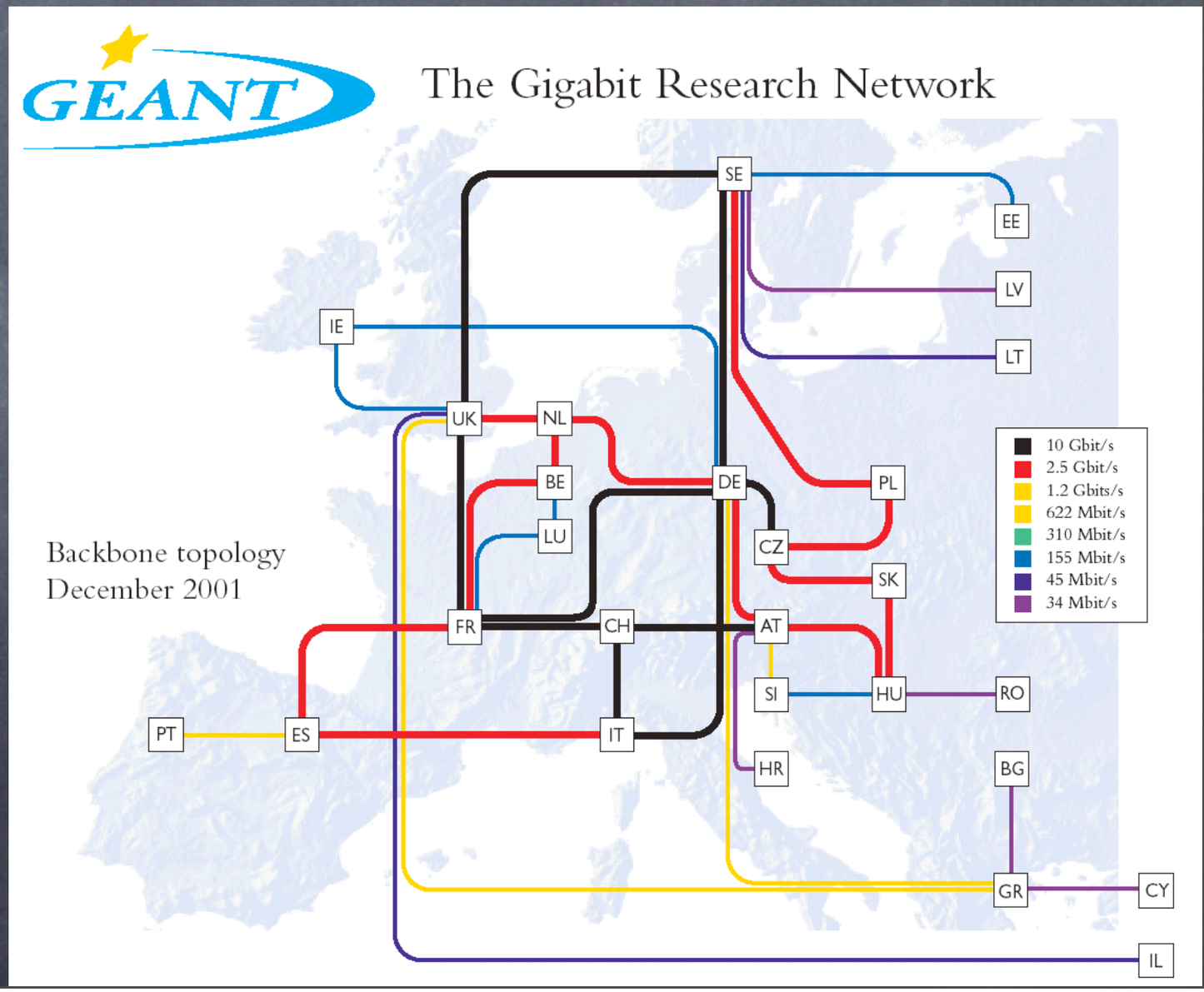


AS Level topology

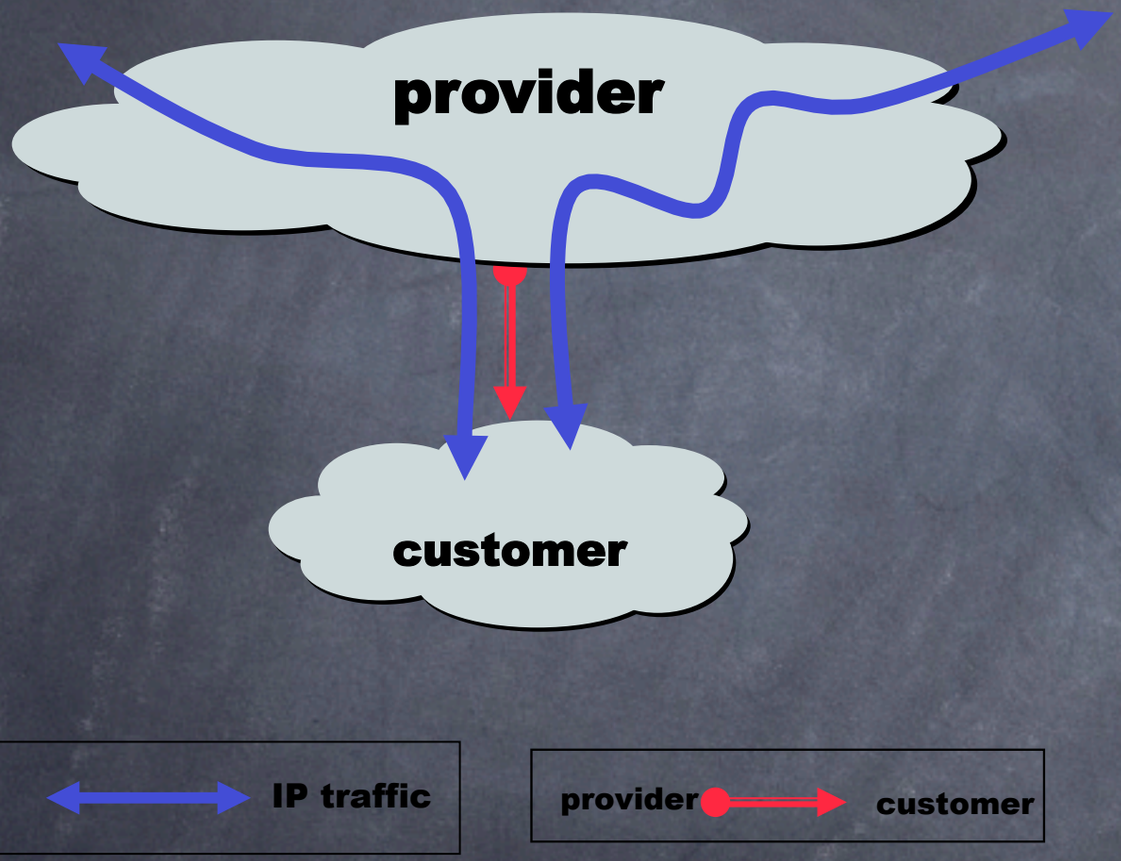
- Is formed of Autonumous Systems (ASes)
- Determined by relationships (Physical, connectivity, political) between ASes

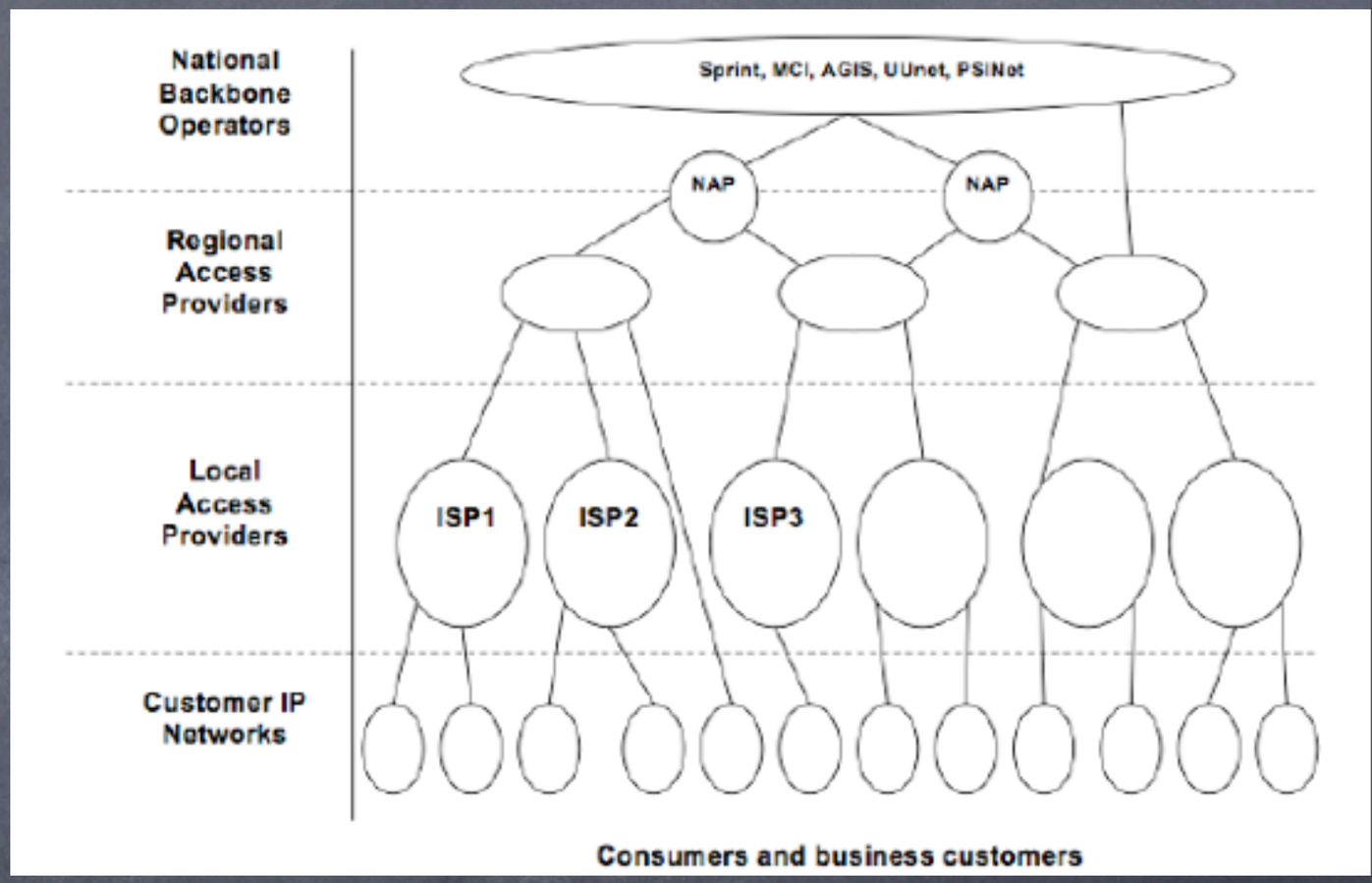
As Topology does not accurately represent the routes taken by packets, nor it represents the physical topology, e.g., GEANT

e.g.: http://networktools.nl/asinfo/
www.google.com



BGP types of relationship
Customer-Provider

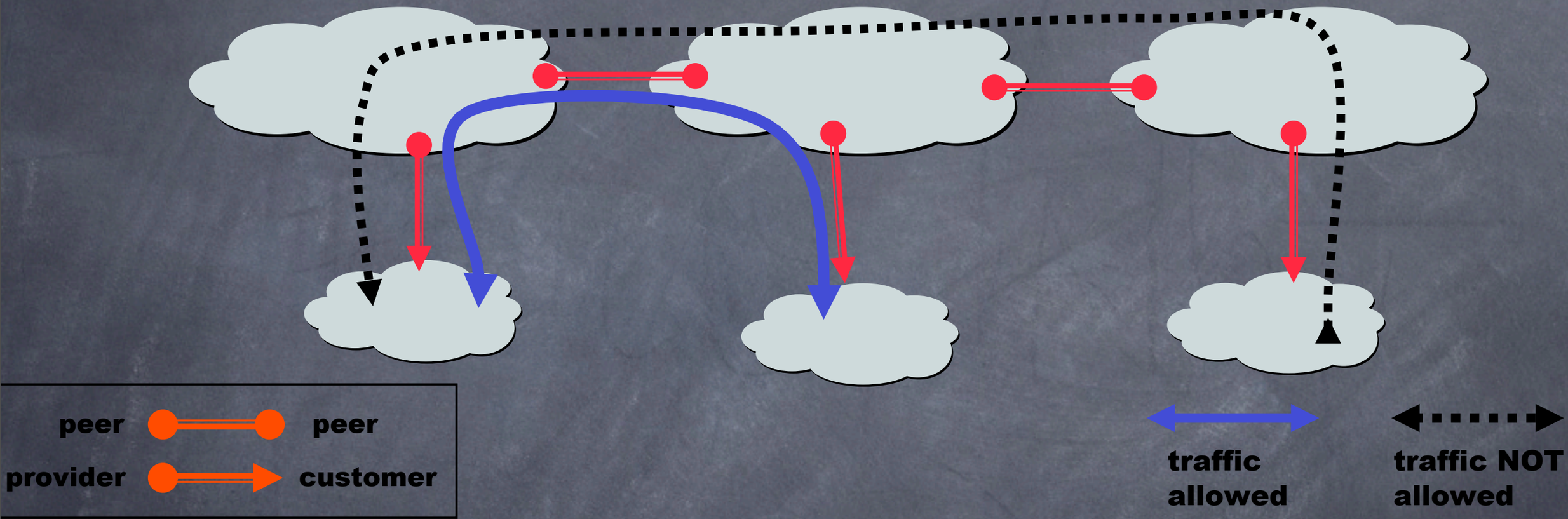




Customer pays the provider for connectivity

Slide source: Tim Griffin, BGP Tutorial, ICNP 2002

BGP types of relationship
Peering Relationship



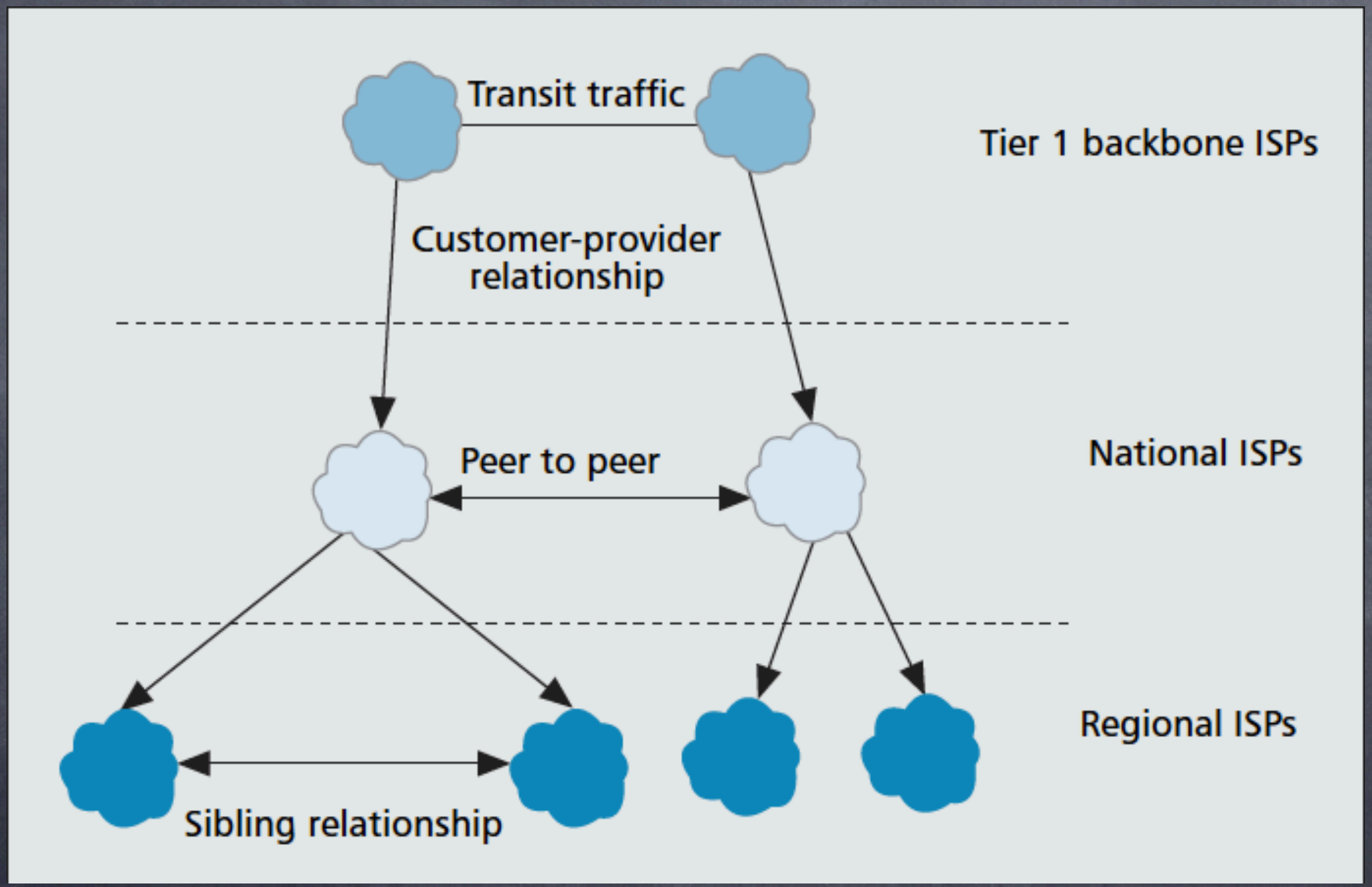
Peers provide transit between their respective customers

Peers do not provide transit between peers

Peers (often) do not exchange $$$

Slide source: Tim Griffin, BGP Tutorial, ICNP 2002

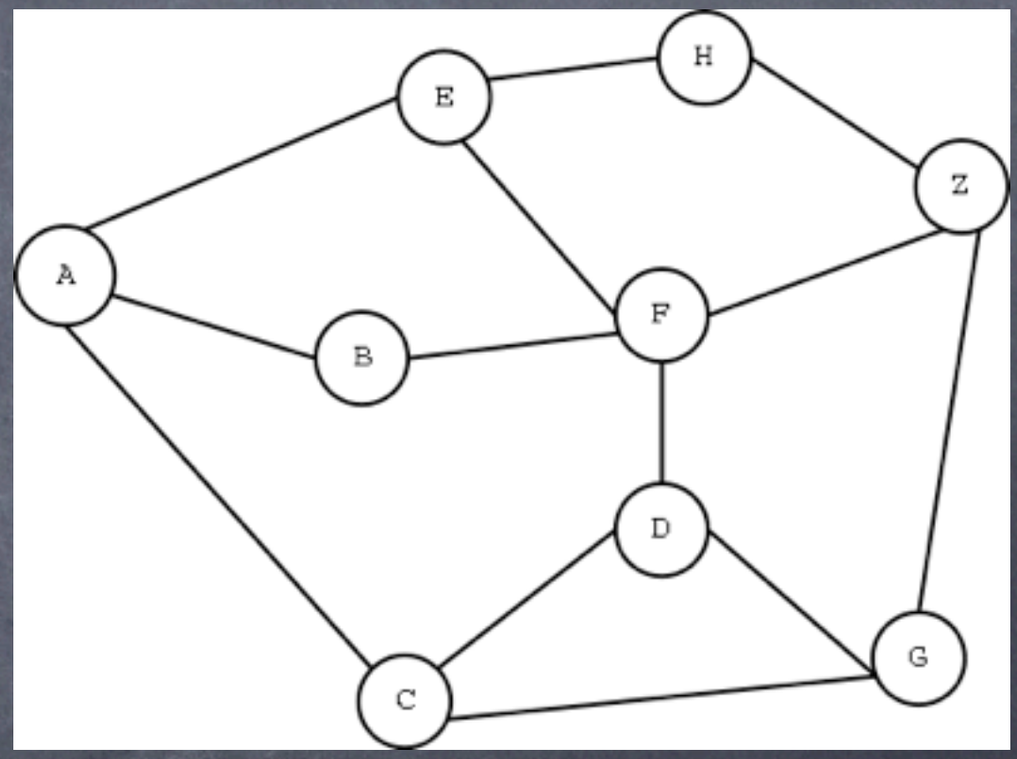
BGP Overview



Commercial relationships between ISPs

Quantifying Measures

- Node Degree Distribution
- Average Neighbour Connectivity
- Clustering Coefficients
- Assortativity
- K-core
- Shortest Path Distribution



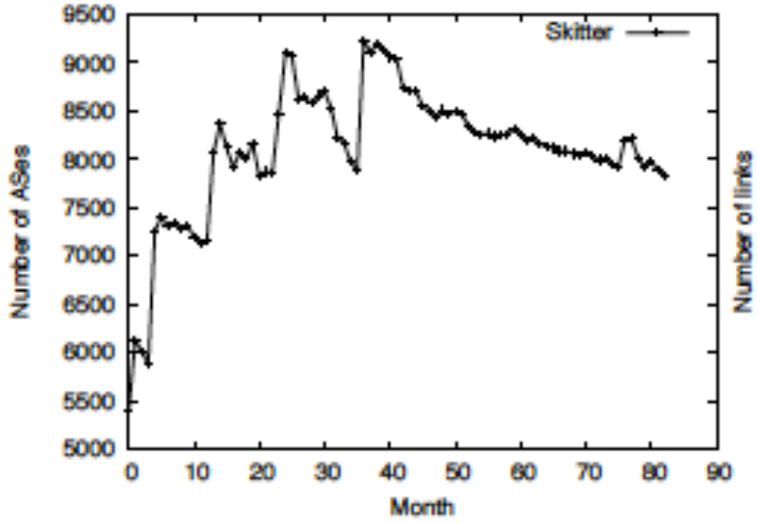
Hamed Haddadi, Damien Fay, Almerima Jamakovic, Olaf Maennel, Andrew W. Moore, Richard Mortier, Miguel Rio, Steve Uhlig, "Beyond Node Degree: Evaluating AS Topology Models", Technical Report UCAM-CL-TR-725, University of Cambridge, Computer Laboratory, July 2008

Data sources

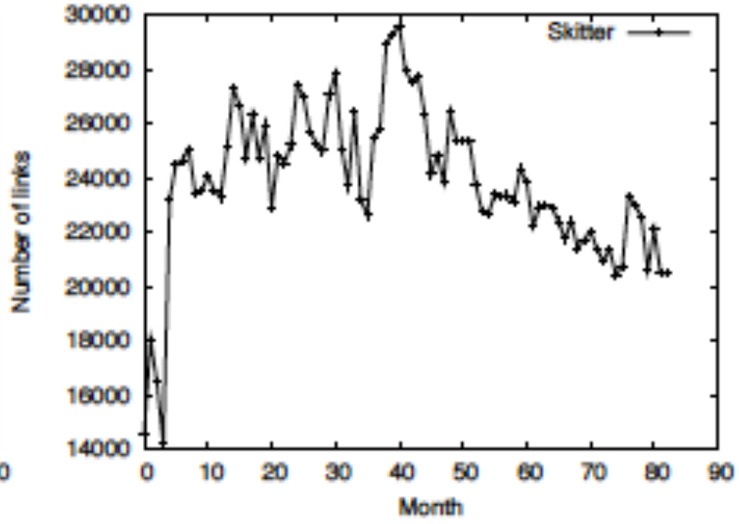
- **CAIDA AS Topology:** 7 years of traceroute measurements, starting in January 2001, IP addresses reported in the traceroutes are mapped to AS numbers using RouteViews BGP data

- **UCLA Topology data:** 52 snapshots, one per month, from January 2004 to April 2008. using data sources such as BGP routing tables and updates from RouteViews, RIPE Abilene and LookingGlass servers.

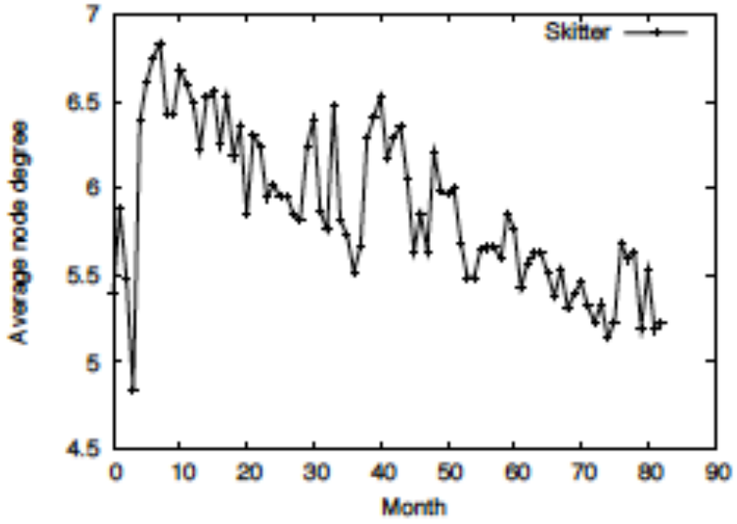
Skitter View



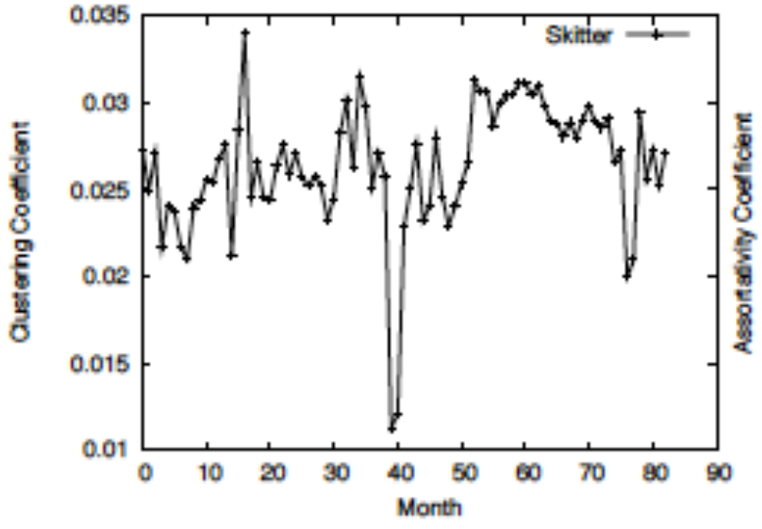
(a) Number of nodes



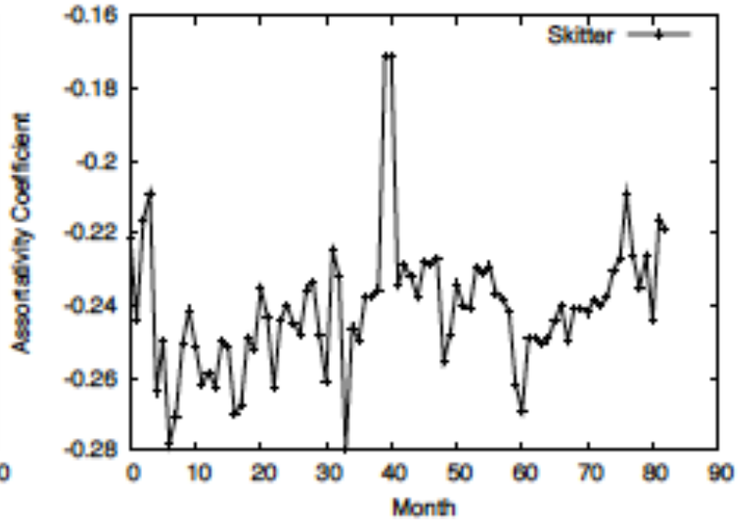
(b) Number of links



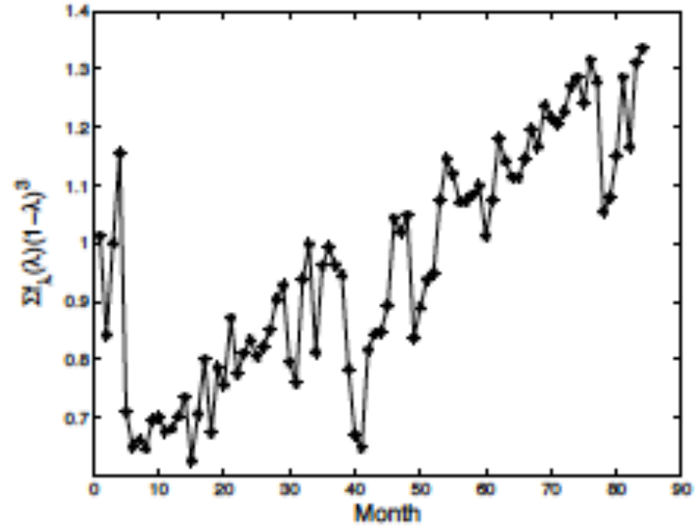
(c) Average degree



(d) Clustering coefficient

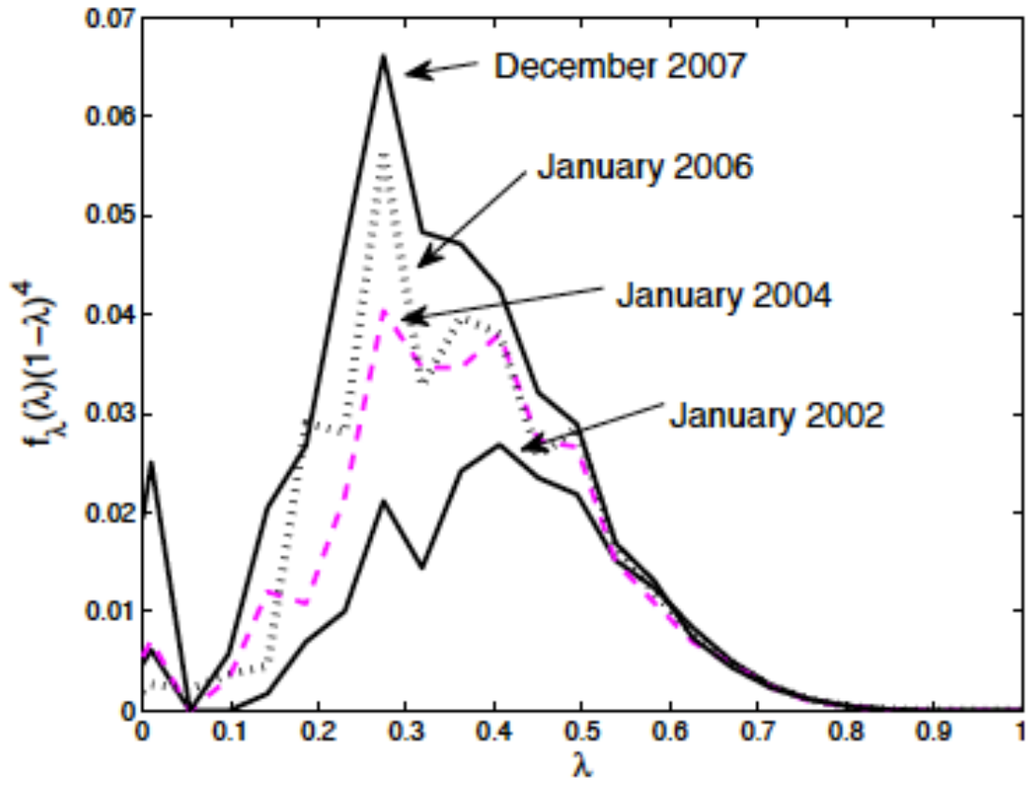


(e) Assortativity coefficient

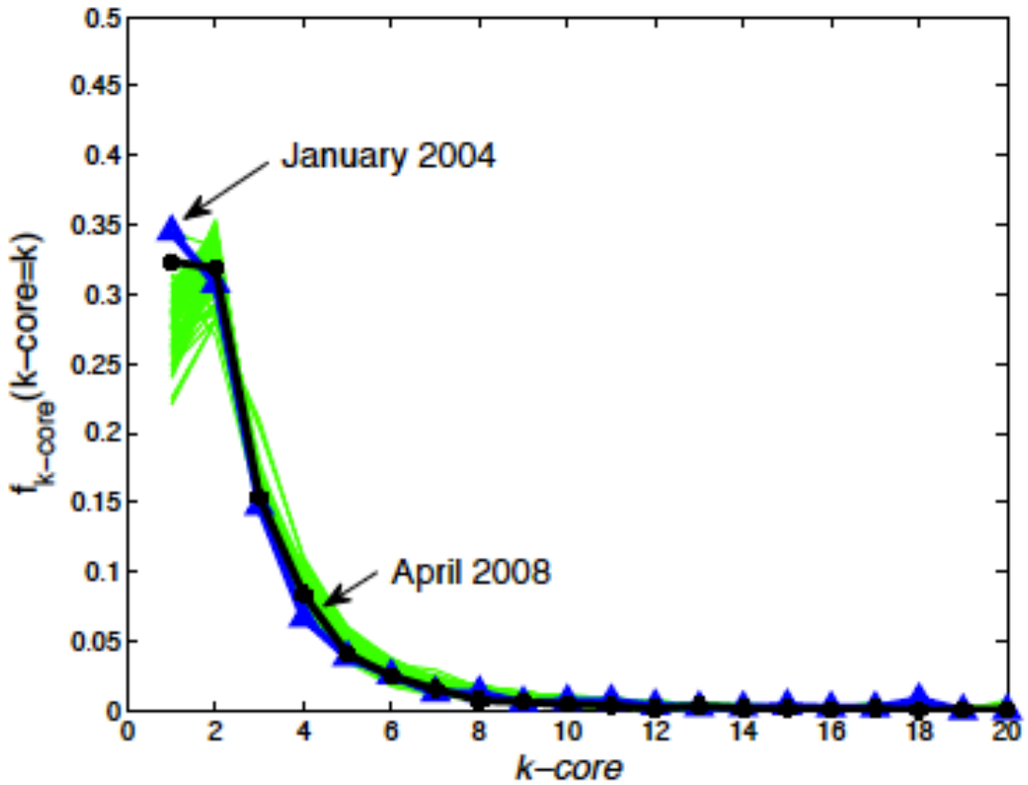


(f) $\omega(G, 3)$

Skitter View



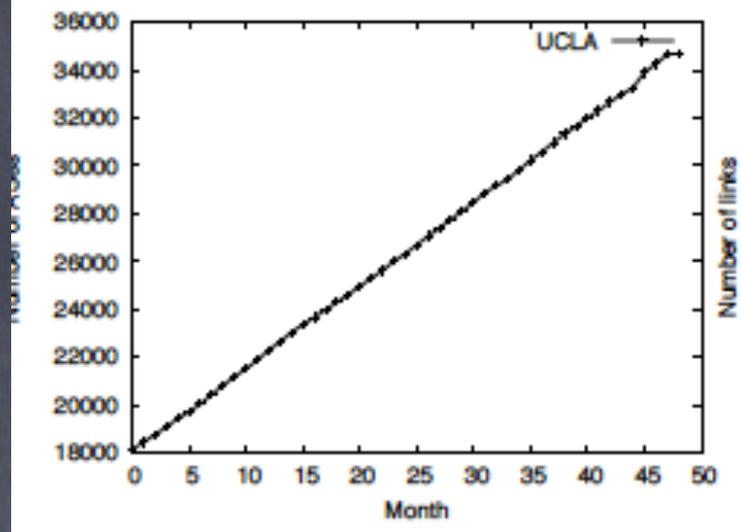
(a) WSD, Skitter topology.



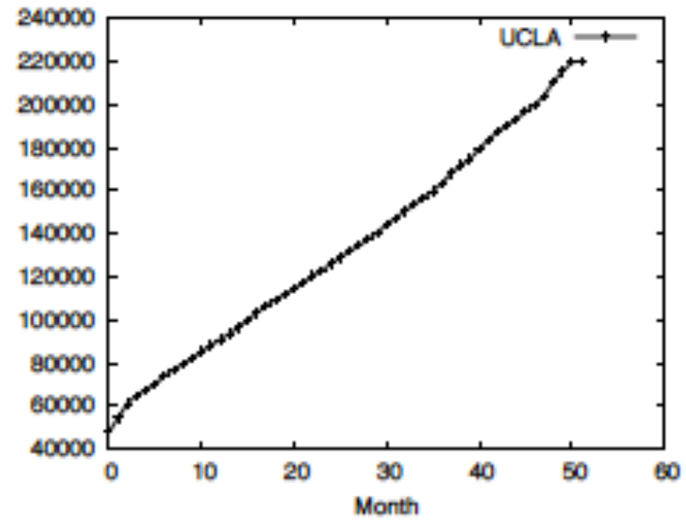
(b) k-core proportions, Skitter topology.

Skitter data suggests an Internet moving from a less hierarchical to more hierarchical topology, as if the core was becoming more dominant.

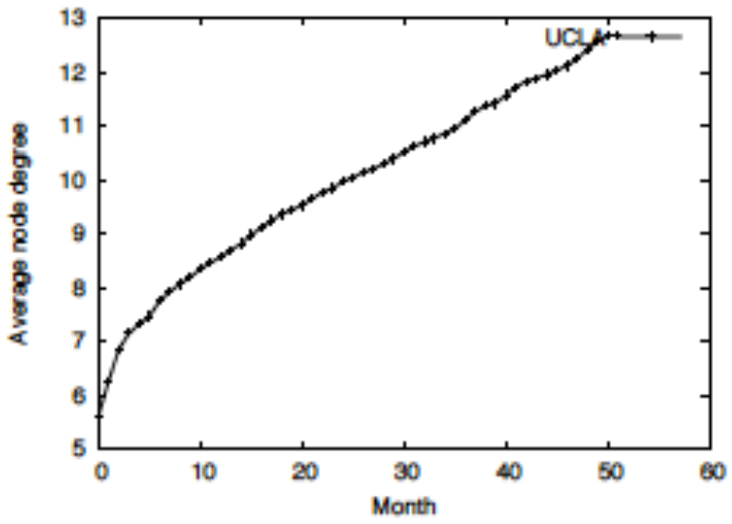
UCLA View



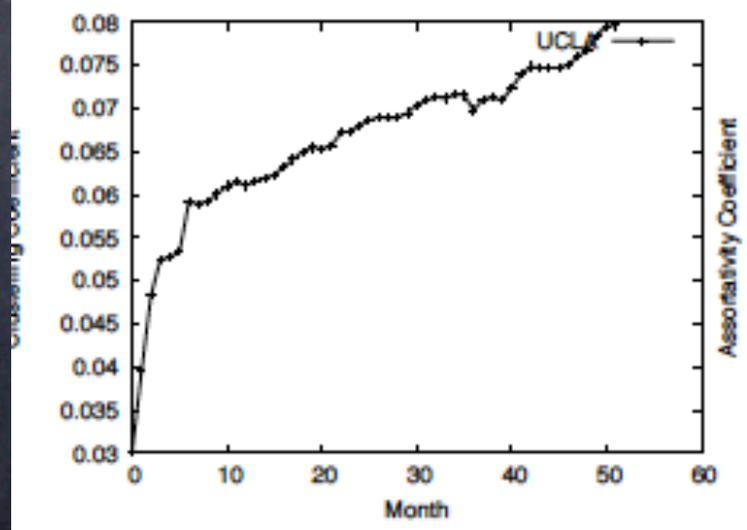
(a) Number of nodes

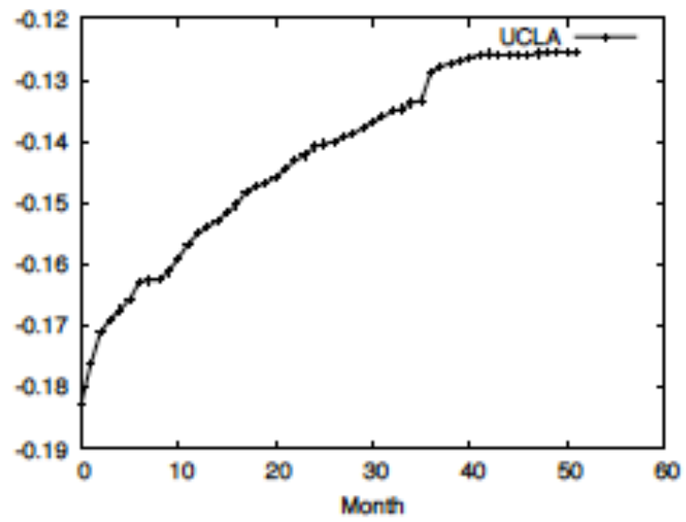


(b) Number of links

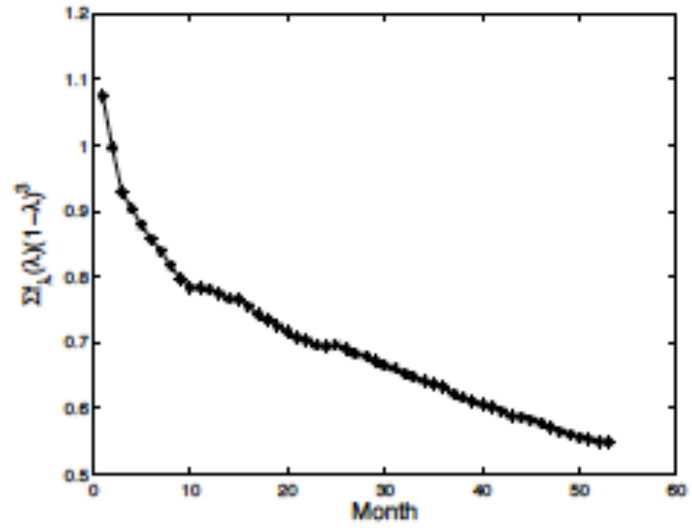


(c) Average node degree



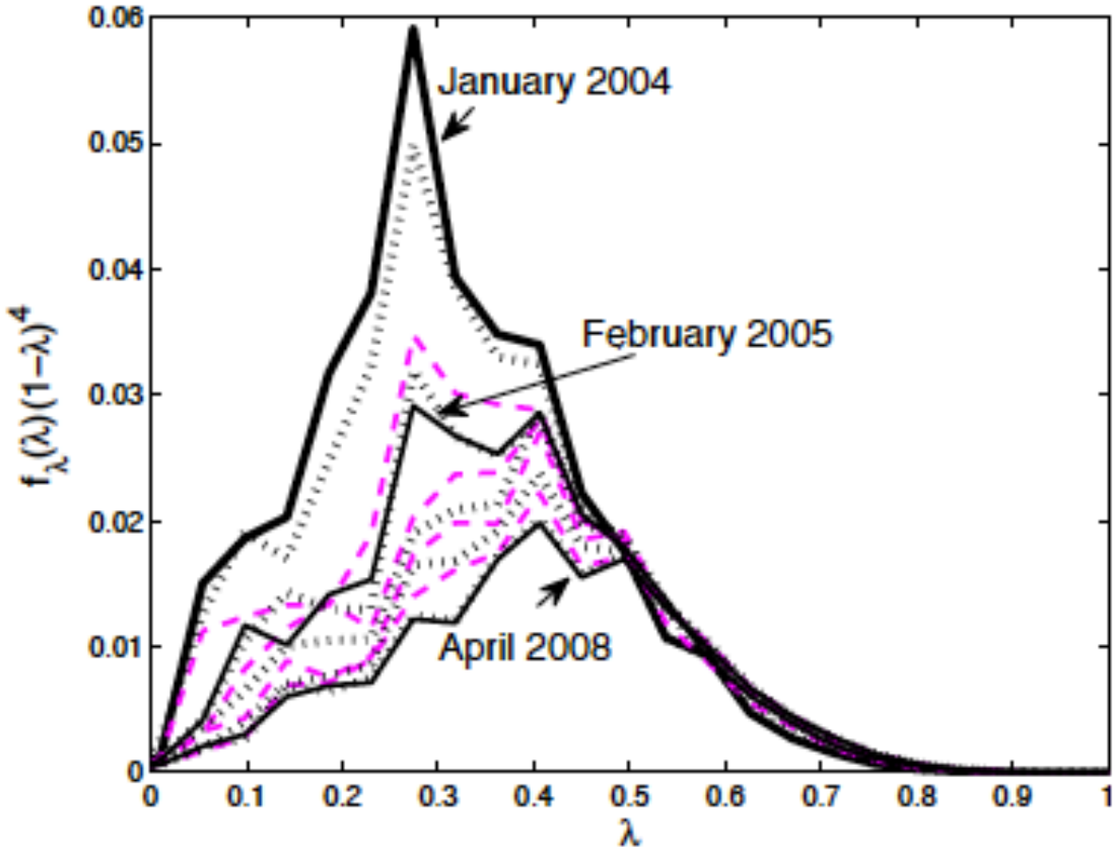


(d) Clustering coefficient (e) Assortativity coefficient

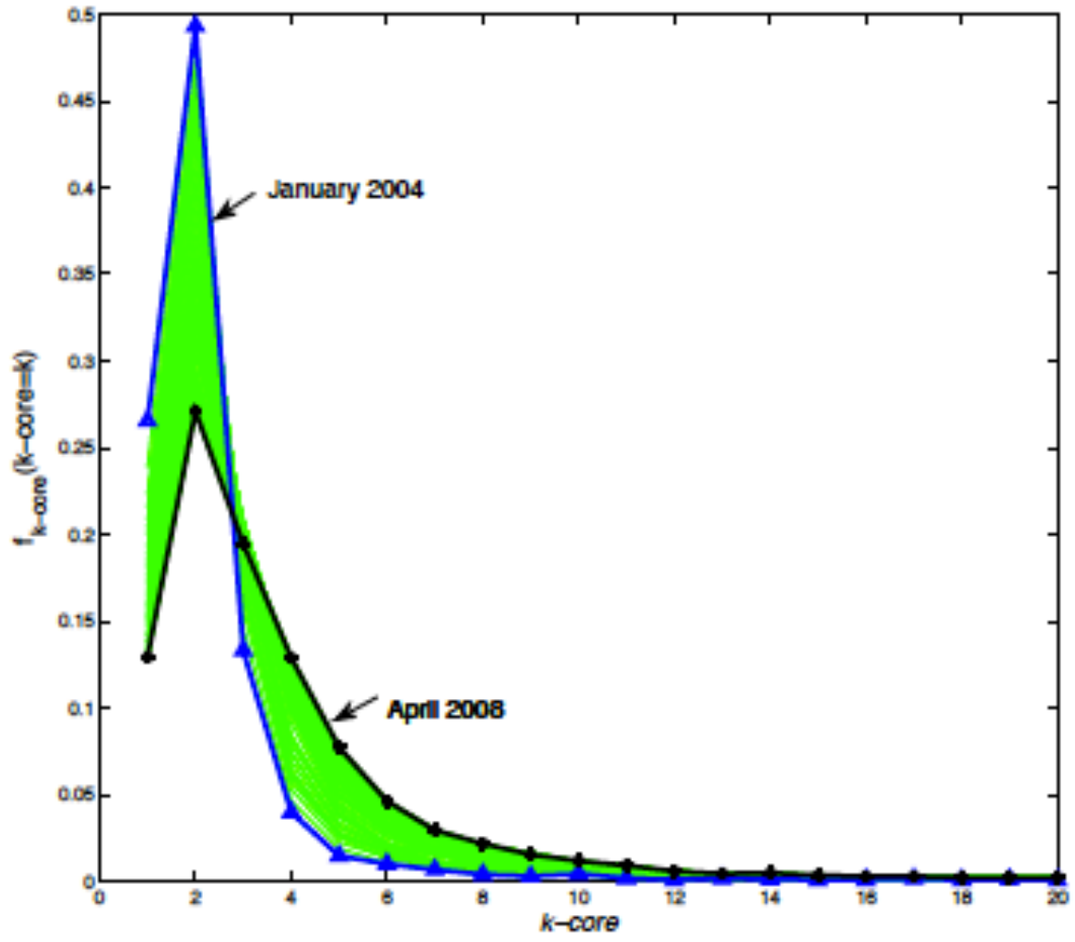


(f) $\omega(G, 3)$

UCLA View



(a) WSD, UCLA topology.



(b) k-core proportions, UCLA topology.

UCLA dataset shows a weakening hierarchy in the Internet, with more peering connections between nodes on average.

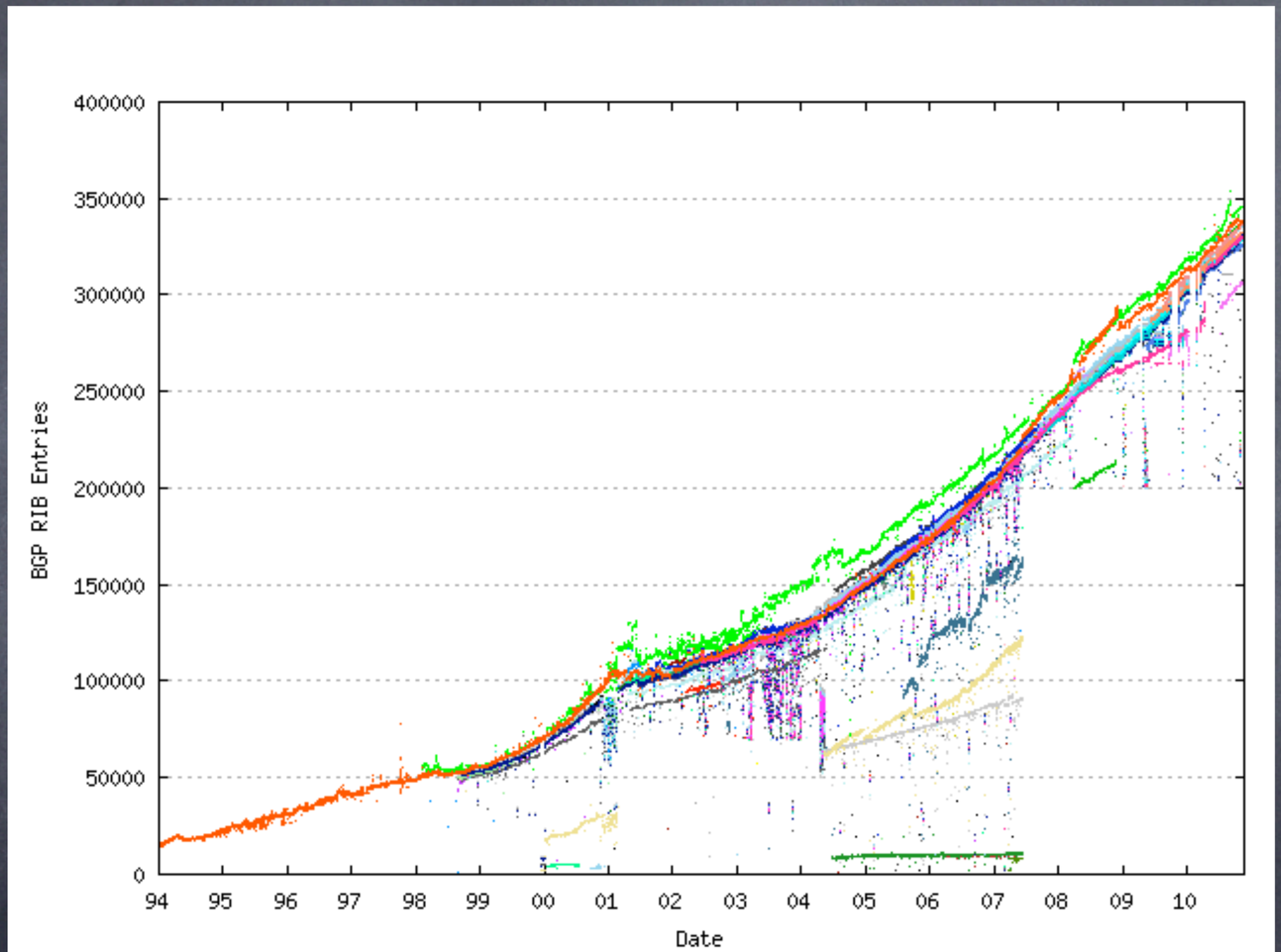
Reconciling datasets

Time	Autonomous Systems				AS Edges			
	Total	Intersect.	Skit-only	UCLA-only	Total	Intersect.	Skit-only	UCLA-only
Jan. 2006	25,301	32.6%	0%	67.4%	114,847	15.4%	5.3%	79.3%
Mar. 2006	26,007	31.6%	0%	68.4%	118,786	14.9%	4.4%	80.7%
May. 2006	26,694	30.5%	0%	69.5%	124,052	13.8%	4.6%	81.5%
Jul. 2006	27,396	29.5%	0%	70.5%	128,624	13.2%	3.7%	83.1%
Sep. 2006	28,108	28.7%	0%	71.3%	133,813	12.6%	3.4%	84.0%
Nov. 2006	28,885	27.9%	0%	72.1%	139,447	12.4%	3.4%	84.2%
Jan. 2007	29,444	27.2%	0%	72.8%	144,721	11.6%	3.1%	85.3%
Mar. 2007	30,236	26.5%	0%	73.5%	151,380	11.2%	3.0%	85.8%
May. 2007	30,978	25.6%	0%	74.4%	157,392	10.5%	2.7%	86.8%
Jul. 2007	31,668	25.9%	0%	86.1%	166,057	10.0%	3.8%	86.2%
Sep. 2007	32,326	24.5%	0%	75.5%	168,876	9 .7%	2.5%	87.8%
Nov. 2007	33,001	23.9%	0%	76.1%	174,318	9 .5%	2.2%	88.3%

Table 1. Statistics on AS and AS edge counts in the intersection of both Skitter and UCLA datasets, and for each dataset alone.

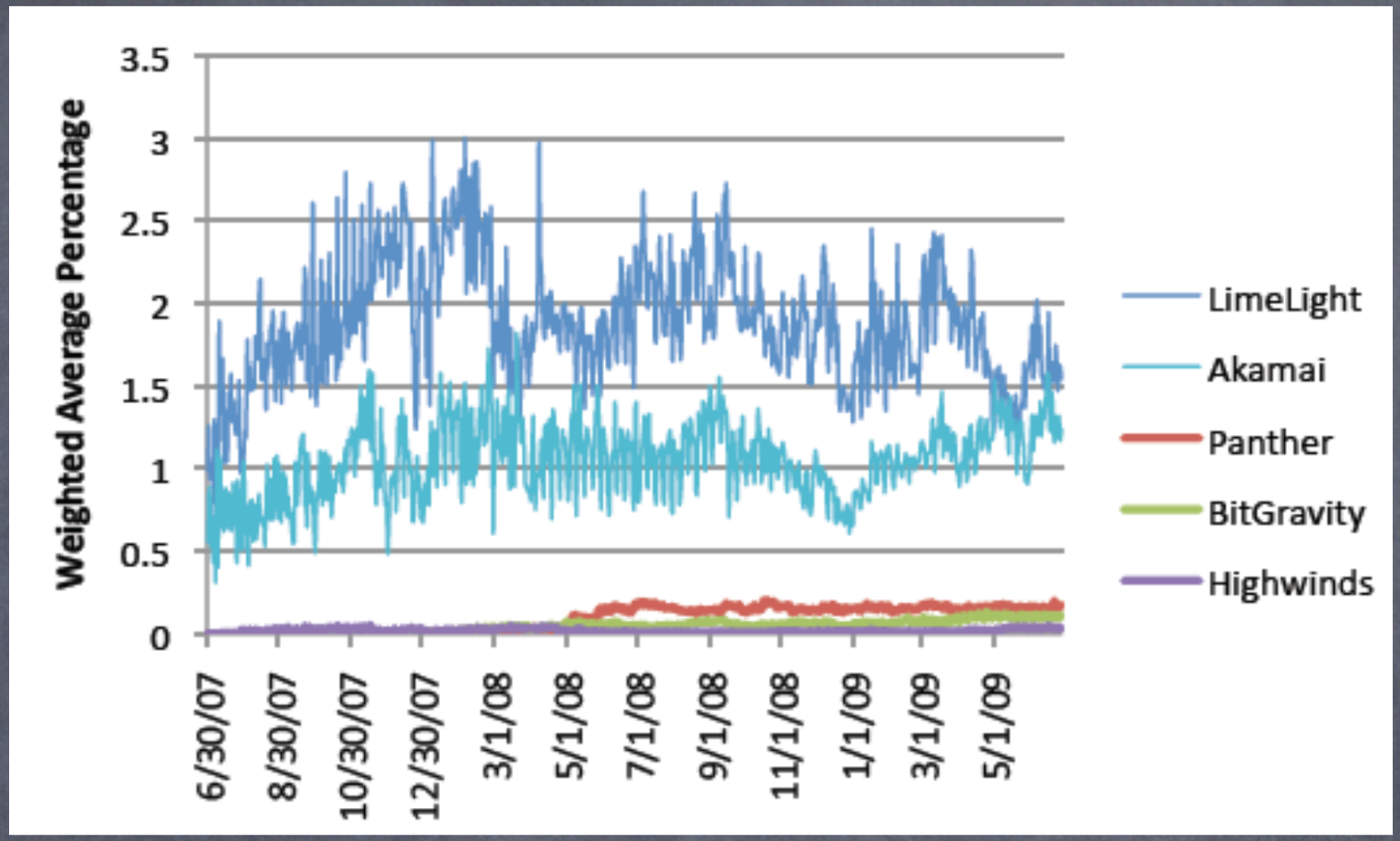
The Internet, once seen as a tree-like, disassortative network with strict power-law properties, is moving towards an assortative and highly inter-connected network.

Growth of BGP Routing Table



Slide source: Geoff Huston, APNIC

what Next: CDNs



10% of Internet traffic and growing largely

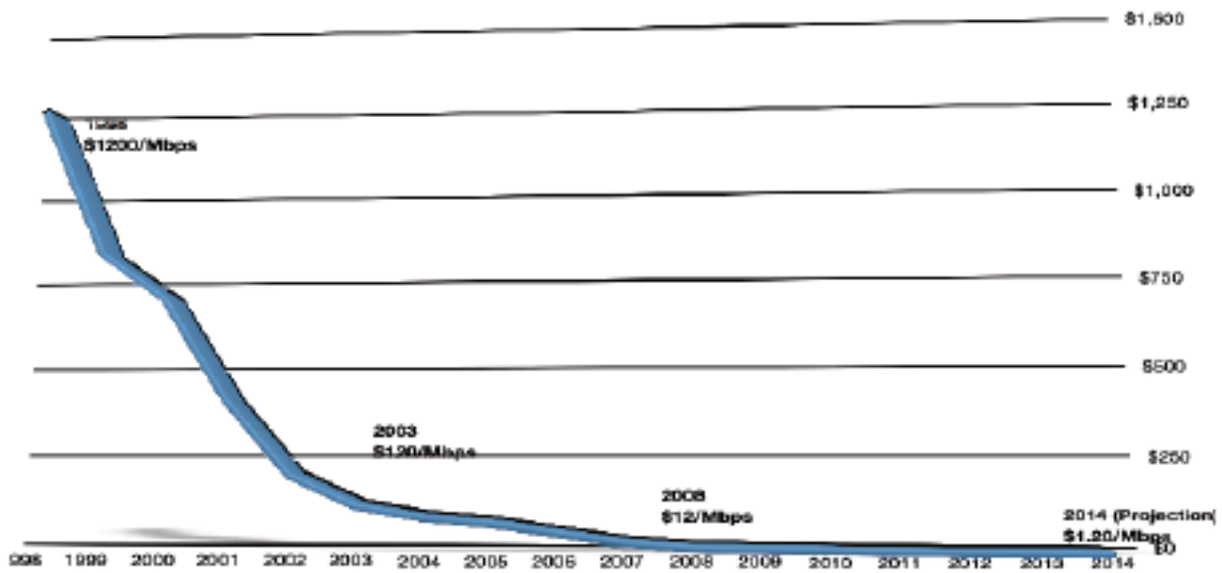
Decline of P2P traffic

Increased streaming, direct downloads & CDN

Graph source: Craig Labovitz, Arbor Networks

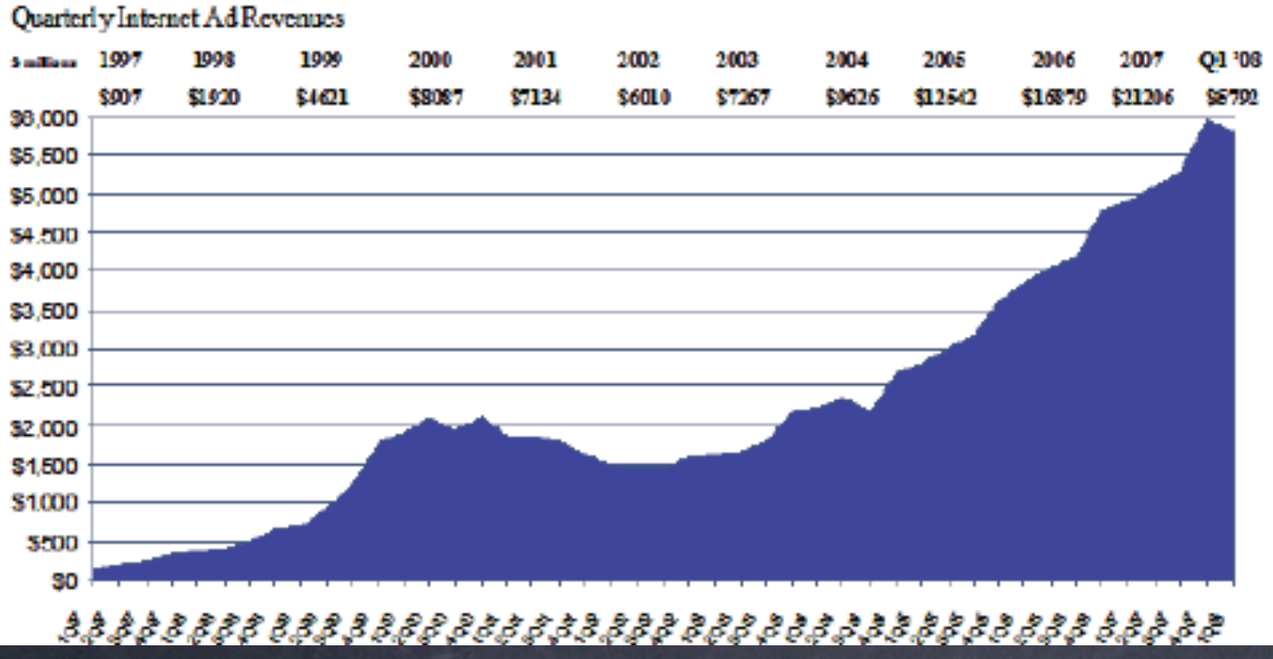
What next: Money

Market Forces in New Internet



Revenue from Internet Transit

Source: Dr. Peering, Bill Norton



Revenue from Internet Advertisement

Source: Interactive Advertising Bureau

Graph source: Craig Labovitz, Arbor Networks

Reading and references

- 2009 Internet Observatory Report, Labovitz et. al., Arbor Networks, NANOG 47
- H. Haddadi et. al., Mixing Biases: Structural Changes in the AS Topology Evolution, (COST-TMA 2010), Zürich, Switzerland, April 2010
- Fay et. al., Weighted Spectral Distribution for Internet Topology Analysis: Theory and Applications, IEEE/ACM Transactions on Networking (ToN), Volume 18, Issue 1, February 2010
- Amogh Dhamdhere and Constantine Dovrolis. 2008. Ten years in the evolution of the internet ecosystem. In Proceedings of the 8th ACM SIGCOMM conference on Internet measurement (IMC '08)
- H. Haddadi et. al., Modeling internet topology dynamics. SIGCOMM Computer Communications Review 38, 2 (March 2008)

Next Session

Online Social Networks

Animal Association Networks

Human Contact Networks

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