ECE 578
FUNDAMENTALS OF COMPUTER NETWORKS

Project – 2
The Internet Topology

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INTRODUCTION

An autonomous system (AS) is a group of interconnected Internet Protocol (IP) routing prefixes that are managed by one or more network operators on behalf of a single administrative entity or domain and that presents a common and clearly defined routing policy to the Internet. Each AS is assigned an autonomous system number (ASN), for use in Border Gateway Protocol (BGP) routing.

Autonomous Systems are classified into three broad types:

- Stub AS—an AS that has only a single connection to one other AS; such an AS will only carry local traffic (within an AS)
- Multihomed AS—an AS that has connections to more than one other AS but that refuses to carry transit traffic
- Transit AS—an AS that has connections to more than one other AS and that is designed to carry both transit and local traffic.

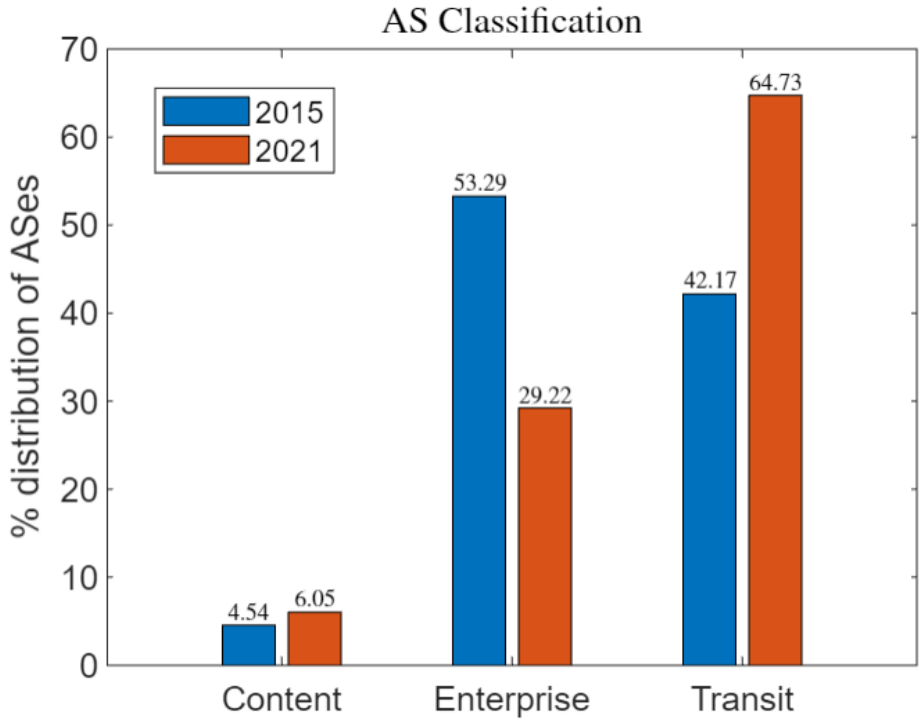
AS relationships are identified by studying the Internet topology through AS links inferred from BGP path advertisements. Each AS has:

1. The global node degree: the number of distinct links (all types) incident to the AS.
2. The customer degree: the number of direct customers of AS.
3. The peer degree: the number of peers of AS.
4. The provider degree: the number of providers for AS.

This project aims to study the Internet topology at the Autonomous System (AS) level using real topological data, classify them and infer relationships between ASes. The coding platform used for this project is MATLAB and data used for the generation of graphs and tables were obtained from CAIDA archives *(http://www.caida.org/).*

2.1 AS CLASSIFICATION

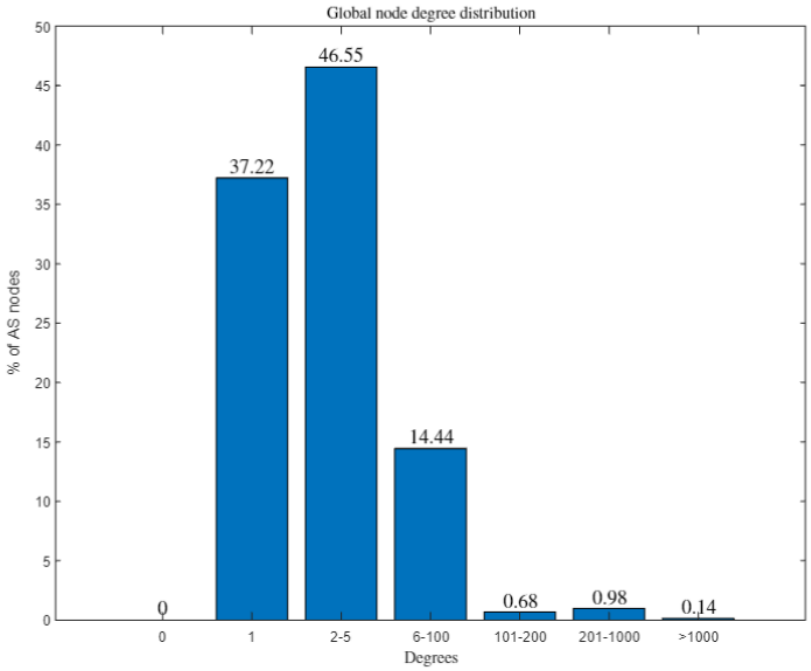
RESULTS



Graph 1:Comparison of AS Classification for 2015 and 2021

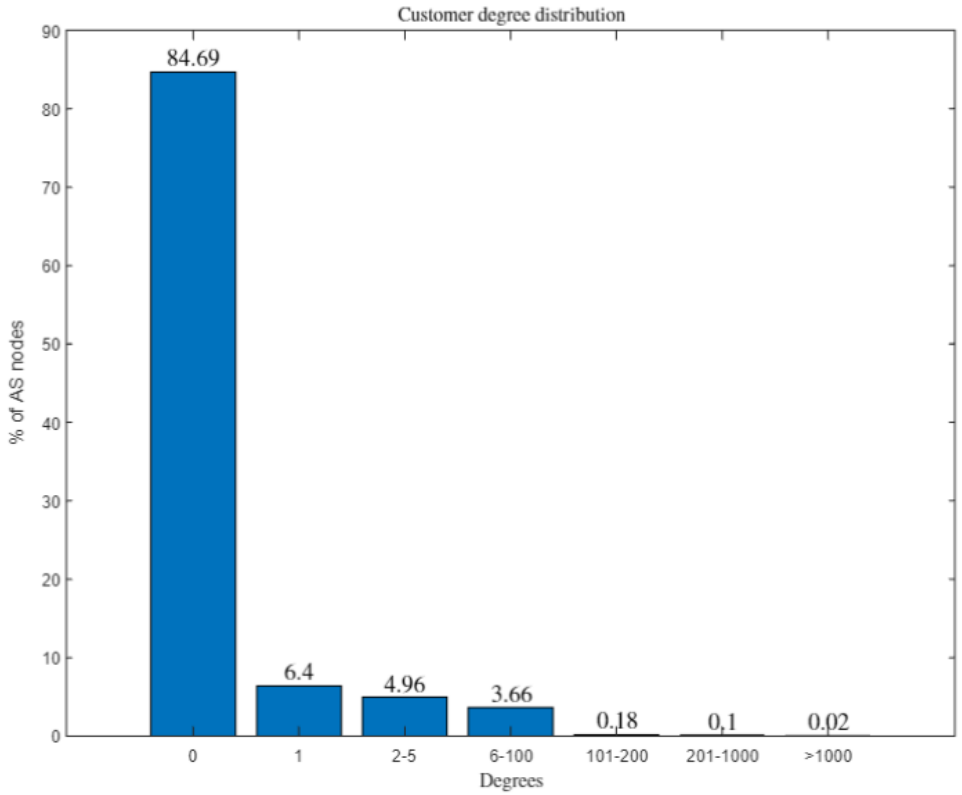
We can see from the distribution that in 2015, Enterprise ASes were the majority and comprised more than half of the total ASes, followed by Transit ASes. Content ASes formed a very small portion of the entire system in 2015. However, in 2021, the Transit ASes form the vast majority of ASes on the Internet topology. The percentage of Enterprise ASes decreased to almost half of what it was back in 2015. This does not necessarily mean that the total number of Enterprise ASes decreased over the years. Although significant changes were observed for the distributions of the Enterprise and Transit ASes, the percentage of Content ASes increased only slightly over the years. To summarize, as time progressed, there was a rise in the proportion of network providers i.e., transit traffic carriers and a fall in the overall proportion of consumers. This trend may have resulted due to two reasons: i) network administrators felt the need to increase the number of providers to transmit data more efficiently or ii) there was a greater financial benefit in operating network providing businesses. For instance, when peers agree to carry traffic without or at reduced costs, Transit ASes incur lower costs in providing services to customers.

2.2 TOPOLOGY INFERENCE THROUGH AS LINKS



Graph 2a: Global node degree distribution

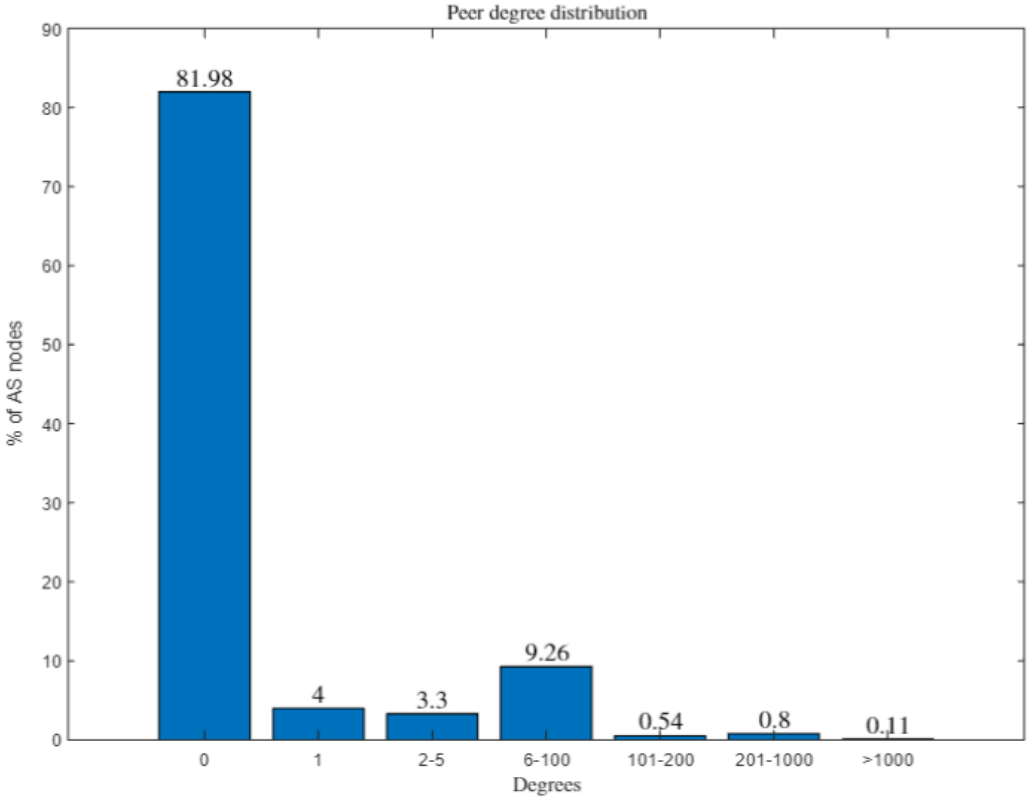
In Graph 2a, we can see the distribution of ASes with respect to global node degrees. The dataset that we worked with contains ASes with either p2c or p2p links and hence, no AS node has a zero global node degree as shown by the histogram above. Stubs account for a global node degree of 1 since they have no peers or customers. The global node degree distribution is concentrated between 1-5 indicating very higher proportions of stubs and ASes with few interconnections. In addition, it can be observed from the above graph that the percentage of AS nodes connected to more than 100 other AS nodes is negligible. Hence, we can conclude that the distribution of network providers is much lower than the distribution of consumers. This fact is also supported by Graph 4 which was prepared using the same dataset as Graph 2a.



Graph 2b: Customer degree distribution

Stubs and multi-homed ASes have no customers and hence, account for the bar at bin 0. From Graph 2b, we observe that almost 85% of the AS nodes have a customer degree of 0. This result is strongly supported by Graph 4 which was computed using the same dataset as Graph 2b.

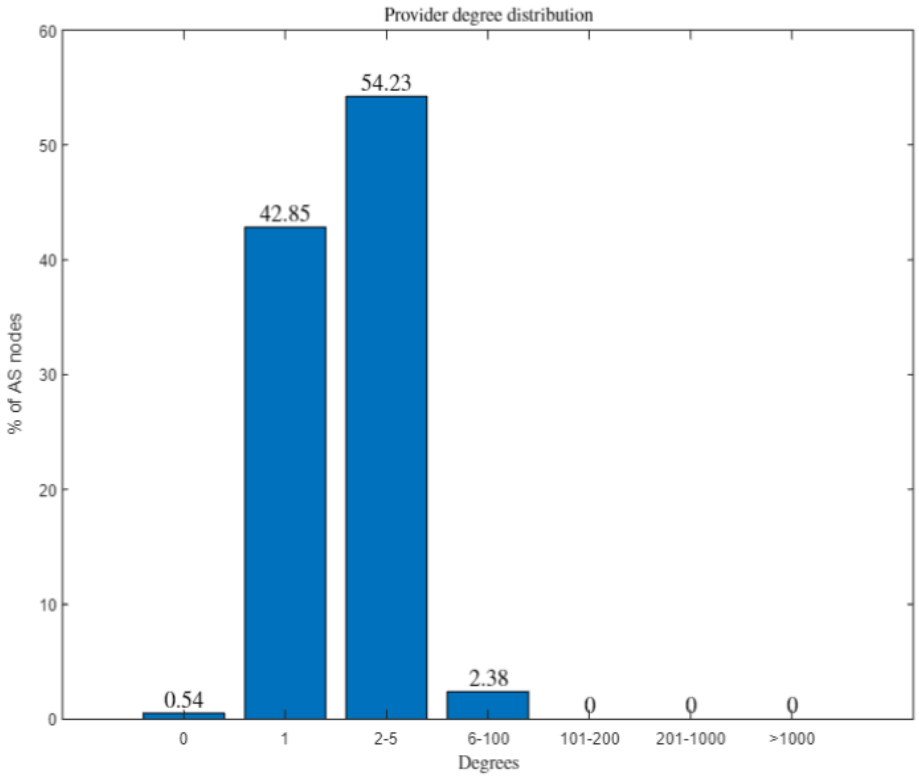
Nodes having consumer degrees greater than 0 correspond to network providers (essentially Transit ASes) and comprise a minor portion of the distribution as shown in Graph 2b. These results are also consistent with Graph 4 which comprise of only 15.31% Transit ASes. From Graph 2b, we can also infer that Transit ASes possessing over 100 direct customers are far less common than ones with 1-100 direct customers.



Graph 2c: Peer degree distribution

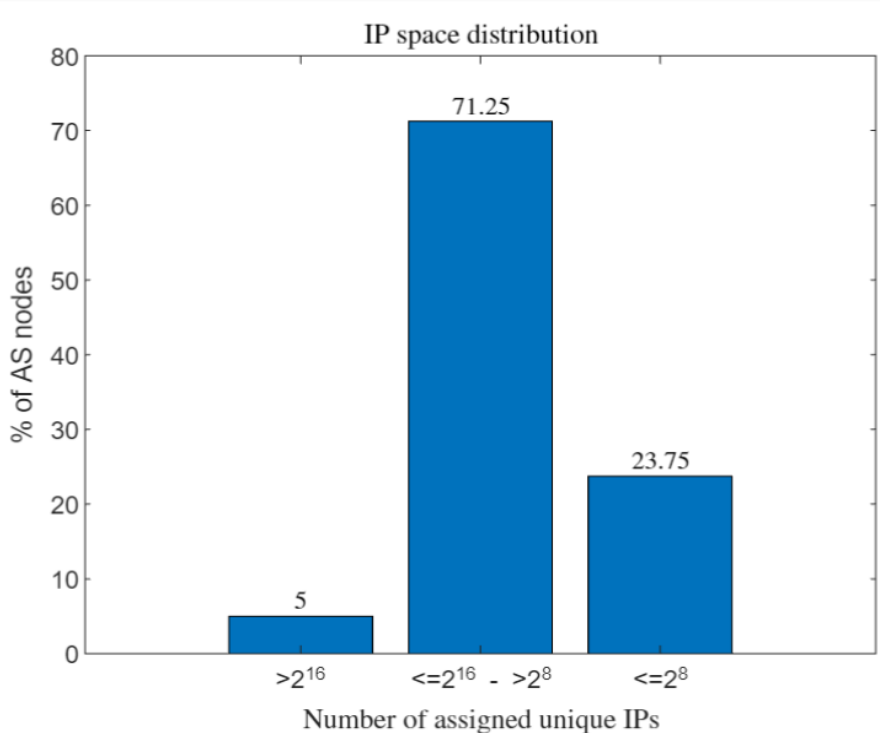
Graph 2c has a similar distribution as Graph 2b. Stubs do not possess any peers and hence, they account for the bar at bin 0. From Graph 2c, it can be observed that over 80% of the AS nodes have a peer degree of 0. Again, this fact is again strongly supported by Graph 4 which uses the same dataset as Graph 2c.

The multi-homed and Transit ASes are responsible for the bars at bins greater than 0. These ASes comprise a small portion of the distribution as shown in Graph 2c. These results are also consistent with Graph 4 where the Transit and Content ASes make up only 25.12% the entire distribution. From Graph 2c, we can also infer that when ASes do possess peers, they are more likely to possess 6-100 peers.



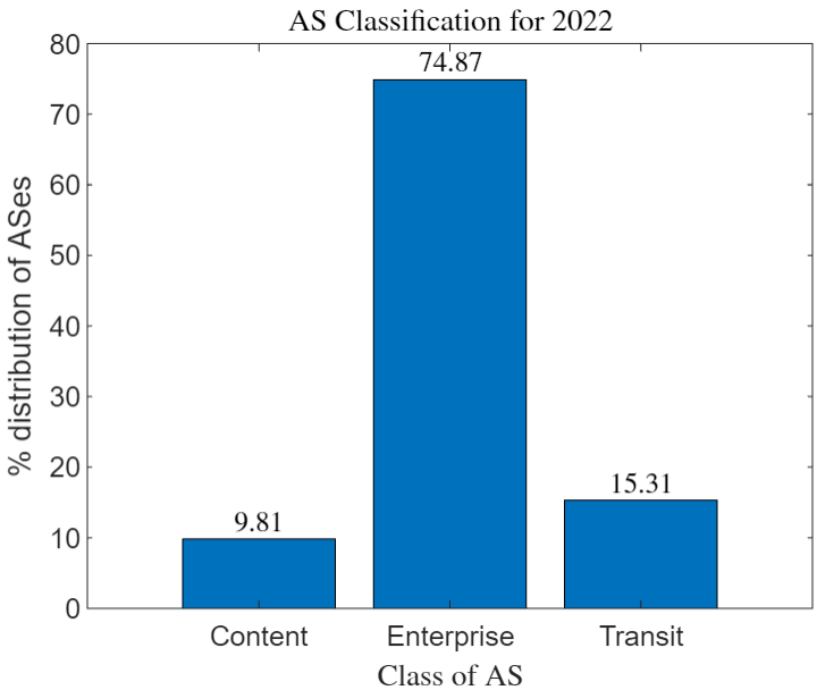
Graph 2d: Provider degree distribution

Graph 2d is somewhat similar in shape to Graph 2a. The highest tier providers do not have any providers for themselves and hence account for 0.54% of all ASes as represented by the bar at bin 0. Stubs and Transit ASes with exactly one provider (if present) are responsible for the bar at bin 1. However, since multi-homed ASes possess atleast two providers, they do not play a role in generating the bar at bin 1. Similarly, stubs do not play a role in the bars at bins greater than 1. Since the distribution is mostly concentrated between provider degrees 1-5, it can be concluded that the number of providers for the majority of ASes is limited to 5. From Graph 2d, it can also be deduced that none of the nodes have more than 100 providers.



Graph 3: IP Space Distribution

The bins of Graph 3 were selected based on the number of unique host IPs represented by a particular class of network. The leftmost bar corresponds to a Class A network, the middle bar represents a Class B network, and the rightmost bar represents a Class C network. The prefixes advertised by an AS node inform us about the size of the IP space. A shorter prefix length corresponds to a larger IP space since a higher number of bits are assigned for hosts and vice versa. From Graph 3, it can be deduced that the majority of the AS nodes possess medium IP spaces, and they are followed by nodes possessing small IP spaces. Only 5% of the nodes possess large IP spaces. These minority nodes can reach a large number of hosts and hence are expected to reside in the highest tiers of the Internet topology. The distribution of ASes on the basis of IP space size thus gives an idea about how dense each tier of the hierarchy is. From the results of Graph 3, it can be concluded that the higher tiers are the least dense, the middle tiers are most dense, and the lower tiers have moderate densities.



Graph 4: AS Classification for 2022

In contrast to Graph 1, we observe that the Enterprise ASes dominate the AS distribution in Graph 4. Besides, the difference in the distributions of Enterprise and Transit ASes is much larger for Graph 4. The proportion of the Content ASes is highest for 2022 when compared with years 2015 and 2021. However, the Content ASes form the minor class in the overall AS distributions for each of three years i.e., 2015, 2021 and 2022.

The huge reduction in the distribution of Transit ASes (from 64.73% in 2021 to 15.31% in 2022) may have occurred as a result of either improved network providing infrastructures (which reduced the number of Transit ASes required to meet consumer demands) or reduced financial benefits in providing transit facilities (probably due to inflation or peers wanting to form monopolies).

2.3 INFERENCE OF TIER-1 ASES

Rank	AS Number	AS Organization	No. of Incident Links
1	6939	HURRICANE	9766
2	3356	LEVEL3	6423
3	14840	LACNIC	4600
4	24482	APNIC	4550
5	51185	ONECOM	4517
6	35280	F5-ORG-ANS21	4314
7	1828	UNITAS	4197
8	61568	LACNIC	4001
9	58511	ANYCAST-GLOBAL-BACKBONE	3330
10	199524	GCORE	3257

Table 1: First 10 ASes added to the clique

The size of the T1 list obtained is 14745 and the first 10 ASes added are shown in Table 1.

The list of Tier 1 ASes was computed by finding the largest clique (complete graph) in the AS topology graph using the following algorithm.

- Rank all the ASes according to their global degree and organize them to a descending order set: R = {AS1, AS2, ...}, where degree(ASi) > degree (ASi+1).
- Initialize the clique S = {AS1}.
- If AS2 is connected to AS1, via any type of link add it to S. That is S = {AS1, AS2},
- If AS3 is connected to AS1 and AS2, add it to S. That is S = {AS1, AS2, AS3}.
- Terminate when you find the first AS that is not connected to all ASes in S.

The result shows that the Hurricane AS Organization is at the top of the list, indicating that it has the greatest number of links to other ASes and is the most highly and densely connected AS system.

2.4 CUSTOMER CONES AND AS RANK

AS Rank	AS#	AS Name	AS Degree	Customer Cone					
				Number Of			Percentage Of		
				ASes	IP	IP Prefix	ASes	IP	IP Prefix
1	3356	Level 3 Parent, LLC	6423	48814	750940	2103691203	43.39%	71.03%	68.79%
2	1299	Arelion	2335	37885	669870	1511957957	33.68%	63.36%	49.44%
3	174	Cogent Communications	6633	34795	622431	1273197642	30.93%	58.87%	41.63%
4	2914	NTT America, Inc.	1590	20598	457432	1058148113	18.31%	43.27%	34.6%
5	6762	Telecom Italia Sparkle S.P.A.	626	20412	374802	569332197	18.15%	35.45%	18.62%
6	3257	GTT Communications Inc	2014	19645	447096	974917701	17.46%	42.29%	31.88%
7	6939	Hurricane Electric LLC	9766	18899	331900	491155056	16.8%	31.39%	16.06%
8	6461	Zayo Bandwidth	2322	17169	311801	492764395	15.26%	29.49%	16.11%
9	6453	Tata Communications (America) Inc	649	16772	398228	814459392	14.91%	37.67%	26.63%
10	3491	PCCW Global, Inc.	756	12371	291353	485260237	11%	27.56%	15.87%
11	5511	Orange S.A.	302	11451	186981	341831994	10.18%	17.69%	11.18%
12	1273	Vodafone Group PLC	301	7930	150682	286625679	7.05%	14.25%	9.37%
13	9002	RETN Limited	1477	7928	106301	91800184	7.05%	10.05%	3%
14	4637	Telstra International Limited	697	6872	181112	378514005	6.11%	17.13%	12.38%
15	12956	Telefonica Global Solutions SL	253	4673	108554	172792190	4.15%	10.27%	5.65%

Table 2: Top 15 ASes ranked by the customer cone in the number of reachable ASes