# Project: Inter-AS Routing and Path Inflation

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## I. Introduction

The Internet is an interconnected collection of about $60,000$ networks, called Autonomous Systems (ASes). Every pair of neighbor ASes is associated with a commercial relationship, which, ultimately, shape how traffic flows throughout the Internet. With some oversimplification, the commercial relationship between two neighbor ASes belongs to one of two types. In a *provider-customer* relationship the customer pays the provider to transit its traffic to and from the rest of the Internet, whereas in a *peer-peer* relationship the two peers exchange traffic between themselves and their customers without monetary compensations. The customer-provider relationships create an hierarchy in the Internet. At the bottom of the hierarchy are ASes without customers, called stubs. All other ASes transit traffic; they are called Internet Service Providers (ISP). At the top of the hierarchy are ASes without providers, called Tier-1s. The majority of ASes are stubs, which include content provider and content distribution networks, such as those of Google, Facebook, Amazon, and Akamai, access networks, and many enterprise networks. There only a dozen or so Tier-1s, including AT&T, CenturyLink, Verizon Enterprise Solutions, Deutsche Telekom Global Carrier, Telxius, and Tata Communications.

Figure 1 shows a small internet, where a provider is joined to a customer by a solid line, with the provider placed higher than the customer, and two peers are joined by a dashed line. For example, $u_6$ is a provider of both $u_2$ and $u_3$; $u_6$ and $u_7$ are peers. ASes $u_{10}$ and $u_{11}$ are Tier-1 and ASes $u_1$, $u_2$, $u_3$, and $u_4$ are stubs. The Center for Applied Internet Data Analysis (CAIDA) provides inferred topologies of the Internet annotated with the type of commercial relationships between neighbor ASes [2].

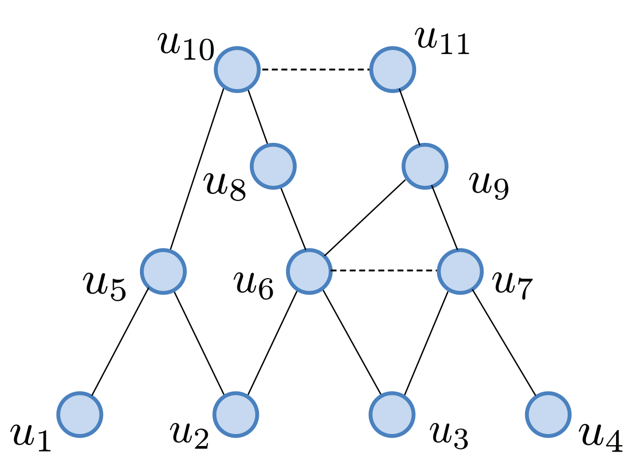


Fig. 1. An internet. Solid lines join providers to customers, with providers placed higher than customers. Dashed lines join peers.

## II. Routing according to commercial relationships

The Border Gateway Protocol (BGP) is the routing protocol running among the ASes of the Internet. BGP instantiates a separate computation per destination AS. Throughout the computation, each AS elects a unique route to the destination. BGP is configured so that every ISP makes profit from the business of transiting traffic, according to the commercial relationships it establishes with neighbor ASes. Specifically, we have the following routing policies [1]:

**Election:** An AS prefers a customer route (learned from a customer) to a peer route (learned from a peer), and prefers a peer route to a provider route (learned from a provider). The AS elects the most preferred of the routes learned from its neighbors.

**Extension:** An AS exports all elected routes to its customers and exports customers routes to all its neighbors, these being the only exportations allowed.

A *stable state* is a final state of BGP, characterized by the absence of BGP routing messages in transit in the network. A *customer cycle* is a cycle where every AS is a customer of the next around the cycle. If there are no customer cycles in a network, then BGP reaches a unique stable state. In that unique stable state, given a destination AS, every AS elects one of the following types of commercial route to reach the destination: (i) a customer route; (ii) a peer route; (iii) a provider route; or (iv) no route at all. The network is *commercially connected* if, for every destination AS, every AS elects a customer, a peer, or a provider route to reach that destination. Interestingly, there is a property involving only Tier-1 ASes that is equivalent to commercial connectedness (the reader is invited to discover it!).

The network of Figure 1 does not have customer cycles and is commercially connected. As examples of elected routes, we have that $u_{11}$, $u_9$, and $u_7$ elect customer routes to reach $u_4$; $u_{10}$ and $u_6$ elect peer routes to reach $u_4$; and $u_1$, $u2$, $u_3$, $u_5$, and $u_8$ elect provider routes to reach $u_4$. Node $u_{10}$ elects a peer route to reach $u_{11}$; all nodes other than $u_{10}$ elect a provider route to reach $u_{11}$.

## III. Path inflation

Subject to routing based on commercial relationships, ASes try to reach other ASes through the minimum number of hops. In order to accomplish this, the election and extension at each AS are refined as follows:

**Refinement to election:** Given a choice among customer routes, or among provider routes, or among peer routes, elect the shortest one.

**Refinement to extension:** When a route is exported by an AS to a neighbor AS, the length of the route is incremented.

Emphatically, the length of the commercial paths followed found by BGP is constrained by the commercial relationships between ASes. They are longer than (unconstrained) shortest paths, an effect called *path inflation*.

## IV. Your assignment

**What you have to do.** You will be given an internet in the format illustrated in the table below. Each line represents a link. The first value is the identifier of the AS at the tail of the link. The second value is the identifier

| | | |
|---|---|---|
| 4323 | 12122 | 1 |
| 12122 | 4323 | 3 |
| 7018 | 17228 | 1 |
| 17228 | 7018 | 3 |
| 29017 | 34309 | 2 |
| 34309 | 29017 | 2 |

of the AS at the head of the link. The third value is 1 if the tail of the link is a provider of the head of the link; it is 2 if the tail of the link is a peer of the head of the link; and it is 3 is the tail of the link is customer of the head of the link. For example, in the table above, the first two links imply that 4323 is a provider of 12122. The internet given does not have customer cycles and it is commercially connected, although you may want to devise an algorithm to check the validity of these properties. You are asked the following:

- Design and implement an algorithm that computes the type of commercial route elected at each AS to reach a common destination AS. Use this algorithm over all destination ASes to produce statistics, over all source-destination pairs, for the fraction of elected routes that are customer, peer, and provider routes.
- Design and implement an algorithm that computes the length of shortest commercial paths to reach a common destination AS. Present the complementary cumulative distribution function of the length of shortest commercial paths, over all source-destination pairs, and compare it with the complementary cumulative distribution function of the length of shortest paths.

**What you have to deliver, how, and when.**

- You have to deliver your code and a report with a cover page and no more than three other pages containing a clear explanation of your algorithms, the statistics asked for, and a short discussion.
- The code and the report should be sent in a .zip file to my email address with subject p2.<group number>.zip where <group number> is your group number.
- The deadline is November 29, 2019, 23:59.

**How I will evaluate your assignment.**

- Write your report clearly. Present your algorithms in a precise and concise manner.
- Be sure to test your code for correctness. I will take into consideration the efficiency of your algorithms.
- I will have a discussion with you about your report and will test your code at the end of the semestre, jointly with the other assignment.

## References

[1] L. Gao and J. Rexford, "Stable Internet routing without global coordination," *IEEE/ACM Transactions on Networking*, vol. 9, no. 6, pp. 681–692, December 2001.

[2] "The CAIDA AS relationships dataset," http://www.caida.org/data/active/as-relationship.