

Inferring Internet AS Relationships Based on BGP Routing Policies

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Abstract—The type of business relationships between the Internet autonomous systems (AS) determines the BGP inter-domain routing. Previous works on inferring AS relationships relied on the connectivity information between ASes. In this paper we infer AS relationships by analysing the routing policies of ASes encoded in the BGP attributes `Communities` and the `Locpref`. We accumulate BGP data from RouteViews, RIPE RIS and the public Route Servers in August 2010 and February 2011. Based on the routing policies extracted from data of the two BGP attributes, we obtain AS relationships for 39% links in our data, which include all links among the Tier-1 ASes and most links between Tier-1 and Tier-2 ASes. We also reveal a number of special AS relationships, namely the hybrid relationship, the partial-transit relationship, the indirect peering relationship and the backup links. These special relationships are relevant to a better understanding of the Internet routing. Our work provides a profound methodological progress for inferring the AS relationships.

Index Terms—Internet, Autonomous Systems, BGP, measurement, inter-domain routing, business relationships, inference algorithms.

I. INTRODUCTION

In the last two decades there has been a great effort in studying the Internet topology at the autonomous systems (AS) level. A number of topology datasets were collected, various topological properties were discovered and a number of network models were proposed [1], [2], [3], [4], [5].

The AS topology graph alone, however, is not enough for studying the Internet inter-domain routing. This is because the business relationships between ASes play a crucial role in the decision process of BGP routing [6], [7]. Without the knowledge on AS relationships, we cannot determine whether a path on the topology graph is valid for BGP routing in practice. It is analogue to the situation where we cannot be sure whether there is a direct train service between London and Frankfurt by just looking at the railway map of Europe.

Internet research and engineering demand data and knowledge on both the AS topology and the AS relationships. For business reasons, ASes do not want to disclose their relationships. In the last decade a number of algorithms have been proposed to infer AS relationships based on the AS topology data [8], [9], [10], [11]. Since the topology data only contain the connectivity information between ASes, these algorithms had to use various heuristics. The quality of their results have been questioned.

In this paper we propose to infer AS relationships using extra sources of information, namely the BGP `Communities` and `LocPrf` (Local Preference) attributes [12]. These BGP attributes encode the routing policies of ASes and therefore closely reflect the business relationships between ASes. Our approach allow us to infer AS relationships in a more direct way with increased certainty.

II. BACKGROUND

Internet inter-domain routing is a collaborative effort between ASes, which interconnect and exchange routing information using the BGP protocol. ASes negotiate contractual agreements to define their business relations and impose technical restrictions on traffic exchange. On the Internet, connectivity does not imply traffic reachability, which is fundamentally determined by the business relationships between ASes. The AS business relationships are coarsely divided into three categories.

- 1) Transit relationship, including customer-to-provider (c2p) and provider-to-customer (p2c). It is established when an AS (customer) pays a better-connected AS (provider) to transit traffic with the Internet.
- 2) Peering relationship, or peer-to-peer (p2p), which allows two ASes to freely exchange traffic between themselves and their customers to avoid the cost of sending traffic through a provider.
- 3) Sibling relationship, which allows two ASes (usually under the same administration) to freely exchange traffic without any cost or routing limitations.

BGP routes are usually exported following the so-called *valley-free* rule [8], i.e. a customer route can be exported to any neighbour, but a route from a peer or a provider can only be exported to customers. Hence, a path (of a series of adjacent AS links) is valley-free if it follows such patterns: (1) $n \times c2p + m \times p2c$; or (2) $n \times c2p + p2p + m \times p2c$; where n and $m \geq 0$. The sibling links can be inserted freely without changing the valley-free property of a path.

The valley-free rule describes a typical routing path that is valid for inter-domain routing. Most valid routing paths are valley-free because they comply with the business interest of ASes, i.e. to minimize operation cost and maximize revenue. It should be noted that the valley-free rule is not an enforcement

rule. It is observed that a small number of routing paths do not follow this rule.

Most ASes try to hide their business relations. In the last decade researchers have introduced a number of algorithms to infer the AS relationships [8], [13], [9], [14], [15], [10], [11], [16]. These algorithms have produced conflicting results. BGP simulations using such data have produced poor results [17], [18]. The existing inference algorithms are limited by the fact that they relied on the AS connectivity information (obtained from the BGP `ASPATH` attribute or traceroute data) and therefore they had to predict AS relationships by using various heuristics based on a number of assumptions.

In the following we propose to infer the AS relationships based on the AS routing policies encoded in the BGP `Communities` and `LocPrf` attributes.

III. INFERRING FROM THE COMMUNITIES ATTRIBUTE

A. The Communities Attribute

The `Communities` attribute is an entry in BGP update messages. It contains a series of 32-bit numbers, called the `Communities` values. An AS can define many `Communities` values with various meanings, and then use them to tag AS links with additional information. For example some values directly state the AS relationship of the links, and some are instructions for other ASes to take an action on traffic engineering. Although the `Communities` attribute is optional, it has become intensively used by ASes to facilitate BGP advertisement and to implement flexible routing policies [12]. The `Communities` attribute data can be extracted from BGP table dumps and update messages and they are also available from public route servers.

Values of the `Communities` attribute are not standardised. Many ASes explain the meaning of their `Communities` values in their Internet Routing Registry (IRR) records [19] or in the resources of their Network Operation Centers (NOC). A database of NOC websites can be found in the PeeringDB records [20].

Figure 1 shows an entry from a BGP table dump. From the `ASPATH` contains three AS links, namely AS4589–AS15412, AS15412–AS18101 and AS18101–AS45528. The `Communities` values ‘4589:***’ are determined by AS 4589 to describe the link with AS 15412. For example from IRR and NOC we learn that the `Communities` value 4589:612 encodes the meaning ‘Route received from a LINX peer’, we can identify the relationship between AS4589 and AS15412 is p2p. Similarly, the `Communities` value 15412:705 corresponds to ‘Route received from customer’, we know the relationship of link AS15412–AS18101 is p2c.

B. The Communities Attribute Data

The RouteViews [21] and the RIPE RIS [22] projects deploy hundreds of BGP monitors around the globe to collect BGP data. We accumulated daily dumps of BGP tables and update messages from all monitors deployed by RouteViews and RIPE RIS from 1 – 31 August 2010 and from 1 – 28 February 2011, respectively.

```

TYPE: TABLE_DUMP_V2/IPV4_UNICAST
PREFIX: 1.22.73.0/24
FROM: 206.223.115.10 AS4589
ORIGIN: IGP
ASPATH: 4589 15412 18101 45528
NEXT_HOP: 206.223.115.10
COMMUNITY: 4589:2 4589:410 4589:612
4589:14413 15412:604 15412:614 15412:621
15412:705 15412:1431 18101:1344
18101:50120 18101:50420

```

Fig. 1. Example of an entry from the BGP table dump data.

TABLE I
AS RELATIONSHIPS INFERRED FROM ROUTING POLICIES

	Aug 2010	Feb 2011
Number of paths	18,570,393	24,549,355
Number of AS links	111,511	116,719
Number of ASes	33,559	38,603
Number of inferred links	43,155	43,821
Number of ASes	16,877	16,918
Transit relationship	25,892	26,075
Peering relationship	17,996	18,603
Sibling relationship	176	177
Hybrid relationship	909	1,034
Indirect peering	708	811
Partial-transit relationship	1,526	1,828
Backup links	1,087	1,205
Inferred from <code>Communities</code>	36,340	38,130
Inferred from <code>LocPrf</code>	12,441	12,602

We extract AS adjacency information from the `ASPATH` attribute. We filter out (1) the reserved and private AS numbers (i.e. 23456 and 56320–65535) that should not appear in normal BGP advertisements and (2) path cycles that result from misconfiguration. Table 1 shows the numbers of unique AS paths, AS links and AS numbers (ASN) obtained from the two monthly datasets.

The BGP data contains many BGP attributes. The `ASPATH` attribute has been used in the passive measurement of the Internet AS topology, where all other BGP attributes data were discarded. Subsequently the existing algorithms have relied on the AS topology information (the passive measurement or the active measurement based on traceroute data) to predict AS relationships. Here we utilise extra information sources provided by the `Communities` and `LocPrf` attributes which encode the AS routing policies and therefore can be used to extract AS relationships.

We extract the `Communities` attribute from our BGP update messages data. We obtain `Communities` attribute values for 3,189 ASes. By mining the IRR and the NOCs, we are able to extract the meaning of `Communities` values for 312 ASes, These are well-connected ASes with large numbers of links, including all Tier-1 ASes and the majority of Tier-2 ASes.

By analysing the routing policies encoded in the meaning of `Communities` values, we directly identify the AS relationships for tens of thousands of links. The routing policy

information also enable us to reveal the following four special types of AS relationships that would not be discovered by existing inference algorithms.

C. The Hybrid Relationship

The traditional model of AS relationships assumes that two ASes have the same type of relationship for all the underlying physical connections. Hence, it is a 1-to-1 model that assigns one relationship type per AS pair. In reality AS interconnections can be more complex, resulting in a cases where two ASes agree different relationship types for different connections.

A hybrid relationship arises when two ASes agree to have both a peering relationship and a transit relationship. We identify two categories of hybrid links.

- IP version-dependent. Routing policies and paths for IPv4 traffic can differ significantly from those of IPv6. ASes often negotiate separate relationships for prefixes of different IP versions. Therefore two ASes may have a hybrid relationship if they are connected on both IPv4 and IPv6 planes.
- Location-dependent. The location of the Points-of-Presence (PoP) can affect AS relationships. Two ASes can have a hybrid relationship when they collocate at more than one private Network Access Points (NAP) or Internet eXchange Points (IXP). Figure 2 shows an example of a location-dependent hybrid relationship.
- Some hybrid links are dependent on both IP versions and PoP locations. For instance, two ASes may have an IPv6 transit relationship at a private NAP and an IPv4 peering relationship at an IXP.

A hybrid relationship is identified when a same AS link is tagged with different sets of `Communities` values in *different* BGP Update messages. For example, consider the AS link AS3549 – AS3292. We observe that in a record from a RIPE monitor this link is tagged with the `Communities` 3549:2771 (route received from peer) and 3549:31208 (route received in Denmark), meaning that it is a peering relationship at a connection point in Denmark. Whereas in another record from a RouteViews monitor the same link is tagged with the `Communities` 3549:4354 (route received from customer) and 3549:30840 (route received in the USA), meaning that it is a transit relationship at a connection point in the USA.

It should be noted that if a link is tagged with different sets of `Communities` values in the *same* BGP Update message, we can not conclude it is a hybrid link. This mainly happens when an AS specifies dual meanings to `Communities` values. For example, AS1273 uses the values 1273:1*** to tag customers (where 1*** means all numbers starting with 1) and it uses the values 1273:3*** to tag both providers and route prepending. When we observe a link tagged with both 1273:1*** and 1273:3*** in the same BGP record, we can only identify that it is not a hybrid link but a prepended p2c link after we learn (from the IRR and NOC data) that prepending `Communities` values are only settable by customers. Setting dual meanings for a `Communities`

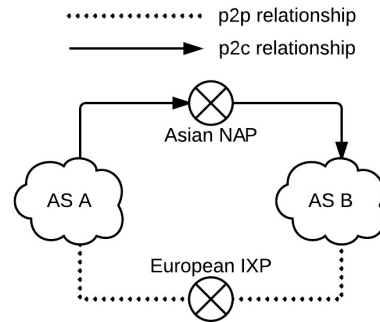


Fig. 2. Example of hybrid relationships between AS A and AS B. The relationship for the AS link through the IXP is p2p, while the relationship for the link through the private NAP is p2c.

value is not a good practice but we observe thousands of such cases in our BGP data. When this happens, we only infer an AS relationship if sufficient extra information is available from other data.

As shown in Table I, we discovered that 909 AS links have the transit/peering hybrid relationships in the August 2010 data. Although a small number, hybrid links are often between well-connected ASes. We observe that as high as 13% of AS links that carry both IPv4 and IPv6 traffic are hybrid links and more than 10% of all AS routing paths in our BGP data contain at least one hybrid link.

D. The Indirect Peering Relationship

The indirect peering relationship consists of two peering links, which together function as one ‘virtual’ peering link. It typically occurs when two ASes are peering with the same route server at an IXP such that they gain access to each other’s network as if they have a peering link (without actually having a physical connection). We can detect this indirect peering relationship by the fact that both of the ASes tag the route server as a peering IXP.

Using our `Communities` data collected from BGP update messages, we discover that of the peering links, there are 708 peering links that can form 354 pair of indirect peering relationship. Each of the peering link can appear alone in their own routing paths. When two adjacent peering links form an indirect peering relationship, they do not violate the valley-free principle. From the prospect of Internet routing, these two peering links can be replaced by one peering link.

E. The Partial-Transit Relationship

A customer AS can multihomed to more than one providers. The partial-transit relationship is a special case of the transit relationship where providers of a multihomed customer agree to offer transit within a limited geographical scope. A multihomed customer may use `Communities` values to instruct a national provider to serve traffic destined in the same country and an international provider to serve international traffic (Figure 3).

For example we observe AS3300 (as a provider) provides the customer-settable `Communities` value 3300:2100 which

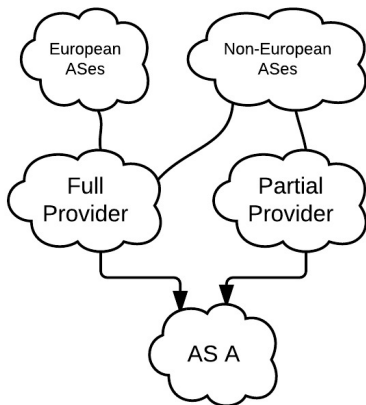


Fig. 3. Example of the partial-transit relationship. AS A has a partial-transit relationship with the partial provider, which only transit its traffic to non-European ASes.

prevents a customer's route to be announced in Europe. A partial-transit link is only visible and used locally. Occasionally it can be fully activated (by the customer) if a provider of the customer fails (by setting relevant `Communities` values).

F. The Backup Links

Backup links are usually invisible and they do not carry any traffic. When there is a disruption in the network, they are activated and become visible globally. But they will disappear once the network recovers. The backup links are not a new type of AS relationship. Rather they are *transit* links that have the backup function. Backup links are relevant to the Internet routing robustness and reliability. Backup links can be set in the following two ways. In our inference we identify both types of backup links.

When an AS has more than one available routes to a destination, it can set a preferred route and make other routes artificially less favorable. This is usually achieved by the traffic engineering technique of path prepending. The same technique can be used to create the backup links. The advantage is that such backup links can be automatically activated when the preferred route is disrupted. We identify a prepended backup link if the followings are satisfied: (a) it is a transit link; (b) the customer prepends the `AS_PATH` attribute such that the link is in an artificially longer path; and (c) we only observe the link for a short lifespan, e.g. less than 5 consecutive days in our monthly data.

Another technique to achieve backup links is the use of the `Communities` values of `NO-EXPORT` and `NO-ADVERTISE` that instruct a provider not to advertise the customer routes to anyone.

IV. INFERRING FROM THE `LOCPrf` ATTRIBUTE

A. The `LocPrf` Attribute

An AS with more than one neighbours may receive multiple route advertisements for the same IP prefix. In this case the AS can give each route a preference value, i.e. the `LocPrf`

attribute, usually based on the relationship type with the next-hop AS. (When the `LocPrf` attribute cannot determine the best route, other metrics such as the path length are used.)

For a given prefix, the route with the highest `LocPrf` value is used as the preferred route. A usual policy configuration - confirmed by [23] - requires that routes received from customers have the highest `LocPrf` value, while routes learned from providers have the lowest value. Therefore it is possible to use the `LocPrf` values to reverse-engineer AS relationships. In our inference the `LocPrf` attribute is used as a complementary information source to the `Communities` attribute. `Communities` are used for the interpretation of the `LocPrf` values, allowing us to detect exceptions to the above `LocPrf` ordering (e.g. when a peer is given higher preference than a customer).

B. The `LocPrf` Attribute Data

`LocPrf` is a local attribute and is not included in the BGP announcements received by RouteViews and RIPE monitors. The `LocPrf` values can be obtained by having a direct interface to a BGP router. Telnet access to such interfaces is provided through public Route Servers that allow remote execution of non-privileged BGP commands.

We collect weekly table dumps from 28 public Route Servers (that belong to 26 large ISPs) in the same periods of time as above (August 2010 and February 2011 respectively). We accumulate 12,441 links which contain 5,839 ASes.

C. Analysing `LocPrf` Attribute Values

In the simplest case, an AS uses only three `LocPrf` attribute values; the largest value (most preferable) is for the c2p relationship, the smallest value (least preferable) is for the p2c relationship and the middle is for the peering relationship.

However we observe that most ASes use many `LocPrf` values. An extreme example is illustrated in Figure 4. For example customers can use `Communities` values to request for upscaling or downscaling their `LocPrf` value for traffic engineering purposes. For each of such ASes, we try to identify the default `LocPrf` values that are most frequently used:

- 1) For each `LocPrf` value, we find out the number of links that the AS has assigned the value to. We also search for the number of AS paths in our BGP data that contain these links. We then calculate the distribution of links and paths, respectively, as a function of `LocPrf` values (see Figure 4).
- 2) The `LocPrf` values with the highest frequencies are chosen as the default values. We may choose more than three default values if their frequencies are significantly larger than the rest. This happens when two similar `LocPrf` values are widely used for the same type of relationship with slightly different routing preference. In our work, we have chosen at most 5 default values.
- 3) We use the meaning of `Communities` attribute values obtained in the above to create a mapping between decide the relationship type of the default `LocPrf` values.

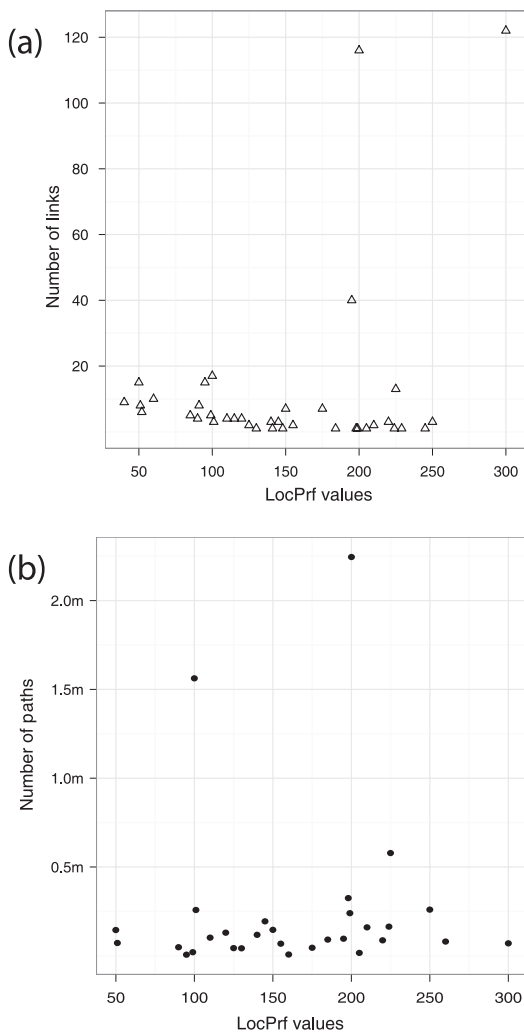


Fig. 4. The appearance frequency of the LocPrf values of AS 4436 in (a) AS links and (b) AS paths, respectively, in our BGP data.

Usually the largest default value is for the c2p relationship and the smallest default value is for the p2c relationship.

In certain cases we can infer the meaning of more LocPrf values based on the default values obtained from the above. For example if the majority of prefixes received from a peer AS are tagged with the default peer LocPrf value and a few prefixes from the same AS are tagged with a slightly smaller LocPrf value, and if this smaller value does not coincide the default transit value, we conclude that it is also a peer value with a reduced preference. We verify such conclusions against the Communities information and we discard any discrepancy. Note that the LocPrf attribute values can only be used to infer transit and peering relationships.

V. OUR INFERENCE RESULTS

We combined the inference results obtained from the Communities and LocPrf attributes. As shown in Table 1, we are able to infer AS relationship for 43,155 links in total, which account for 39% of the links that are present in our BGP

data. These links include all links among the Tier-1 ASes and most links between Tier-1 and Tier-2 ASes. A hybrid link is counted as both a transit link and a peering link. The partial-transit links and the backup links are included in the total number of transit links. When the relationship of a links is inferred from both BGP attributes, we only accept it if the two reach the same conclusion.

We did not attempt to extract as many AS relationships as possible. Rather, our focus is to increase the certainty of the inferred AS relationships.

- The Communities and LocPrf attributes are configured by ASes themselves and are used by them in the BGP routing process. It is expected that ASes should use them to accurately reflect their business relationships.
- We collect our BGP data from the available sources that have been well studied and widely used. Some of the sources, e.g. the public Route Servers, are playing a crucial role in facilitating the Internet BGP routing.
- We cross-examine results obtained from different attributes or data sources. We discard any inconsistency or ambiguity from our results. This sometimes involves large amount of manual checks.
- We try to use as few heuristics as possible. When we have to use a heuristic, for example, to identify the default LocPrf values, we make sure that the heuristic complies with engineering practice and supported by previous studies, and we impose safety checks.

We will publish the complete datasets on our webpage at <http://web4.cs.ucl.ac.uk/staff/S.Zhou/BAB/>, which will include all raw data and inference results.

VI. DISCUSSION

Here we discuss some questions regarding our inference and provide our responses to them.

A. The meaning of Communities values

We extract the meaning of Communities values mainly from the IRR databases, which may contain inaccurate or stale information [24]. To mitigate this problem, we take out two sanity checks. (1) If an AS has a looking glass or a route server, we cross-check the Communities values with LocPrf values. (2) If we have the Communities values for a link from both sides of the link, we check whether they have the same Communities meaning. Note that there is no incentive for an AS to provide inaccurate Communities information, because other ASes use the information to interpret the Communities values received from the AS. In our work we found only one AS provided inaccurate Communities meanings, which was removed from our study.

We utilize Communities values that not only encode relationship data, but also other policy information such as path prepending or limited route advertisement. This extra policy information provides a valuable resource to understand special relationship types.

B. The meaning of *LocPrf* values

It is rare, but does happen that an AS may use the highest *LocPrf* value for a peering relationship. We infer the meaning of a *LocPrf* value not only by comparing the value and its appearance frequency with other values, but more importantly, by using the meaning of *Communities* values tagged on relevant links. We discard any *LocPrf* value which is not frequently used or has any uncertainty. Therefore this type of anomalies are excluded from our inference.

C. AS relationship vs BGP routing

It is rare, but is possible that some ASes implement BGP routing policies that do not exactly reflect their business relationships. It is not a problem, however, if the obtained AS relationship data is used for studying and engineering Internet BGP routing.

D. Completeness

We only infer 39% of links that are visible in our BGP data. The Internet definitely contains more links than our BGP data. Indeed it is known that many links are missing from the BGP table-based topology measurements [25], [26], [27].

Nevertheless, our inferred AS relationships cover the majority of links in the core of Internet, i.e. links among the Tier-1 ASes and between Tier-1 and Tier-2 ASes. It is essential to infer these AS relationships correctly as these links are important for the global routing.

The peripheral, small ASes often have only one or two links, which are primarily either a c2p or a s2s links.

Our future work will try to infer more AS links.

VII. RELATED WORKS ON AS RELATIONSHIP INFERENCE

In the past decade researchers have introduced a number of algorithms to infer AS relationships using AS topology data.

Based on the valley-free property, Gao [8] proposed a relationship inference heuristic that classifies the AS links according to their connectivity degree. Gao's algorithm was refined by a follow-up work [13] (PTE) which introduced the use of Partial relationship Information (PI) as a starting point for the inference process.

Subramanian et al [9] formulated the ToR as an optimization problem. Two independent studies [14], [15] proved that the ToR problem is NP-hard and proposed approximate solutions by reducing the ToR to a 2SAT problem which can be solved in linear time. Dimitropoulos et al. [10] observed that the ToR formulation can result in multiple solutions without being possible to determine the best. As a response they proposed an enhanced ToR algorithm that incorporates the degree difference as an additional criterion for the maximization of peering links.

In [28] the Acyclic Type of Relationship (AToR) problem is defined. According to AToR when p2c relationships are assigned a directed edge, the resulting AS graph should be acyclic. In [29] the authors validate the acyclicity of the AS graph and propose a heuristic to solve the maximal AToR problem.

Oliveira et al. [11] proposed a more deterministic algorithm exploiting the known fact that the Tier-1 ASes are interconnected with peering relationships. Links that are part of paths that traverse the Tier-1 network are classified as c2p while all the rest are regarded as p2p. Essentially this algorithm is similar to PTE in the sense that the PI is the peering relationships between the Tier-1 ASes, but the extension of the partial information depends solely on the valley-free heuristic. A similar approach is followed in [16] where more general definitions of the Internet core are explored.

These works are common in that they mainly relied on a single data source, i.e. the AS connectivity data. Although sophisticated heuristics have been used, the connectivity data itself is inherently limited in providing useful information for inferring AS relationships. Some heuristics can even introduce errors. Inference results produced by different existing algorithms are often inconsistent and sometimes conflict to each other. Two recent works [17], [18] showed that BGP simulations based on these data lead to poor results. In addition, existing algorithms are not capable of discovering any unconventional AS relationships.

VIII. CONCLUSION

In comparison to previous algorithms, our approach is simple and straightforward. We collect the same BGP data in the same way as previous works. The difference is that previous works fundamentally depend on the *ASPATH* attribute, which only contains AS connectivity information. Whereas we look into two other BGP attributes which have been under-utilized by previous works.

ASes use the BGP attributes *Communities* and the *Locpref* to communicate and implement their routing policies. The attributes data provide valuable information for us to infer AS relationships in a more direct and reliable way.

We do not claim our results are 100% correct and we intend to make improvements to our method. What is important is that our work provides a profound methodological progress for inferring the AS relationships.

We only infer 39% of links visible in our dataset. We did not attempt to infer as many AS relationships as possible. Rather we make efforts to ensure that the inferred relationships are as accurate and reliable as possible. These links include most of the important links that form the backbone of the Internet. Our future work will aim to infer more AS relationships.

The rich information on the routing policies revealed by the two BGP attributes allow us to discover a number of special relationship types. The existing algorithms are incapable of discovering them. These special relationships are relevant to a better understanding of the Internet routing

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