Today’s Agenda

- AS relationship inference
  - Why is it important ?
  - Why is it difficult ?
  - Some algorithms proposed in the literature
  - Evaluating inference algorithms
  - Some open problems.

Applications of Accurate Global AS Graphs

- Internet service management
  - Placement of proxy servers, web-hosting servers
- Help administrators in
  - Traffic engineering
  - Network management, debugging, fixing problems
- Aid ISPs in signing contracts
- Aid inter-domain routing algorithms (avoid route divergence, e.g.)
- Verify consistency of IRR database
- Help optimize various network protocols and services (P2P, CDN, …)

Challenges of Inferring AS Relationships (1)

1. AS relationships come from contracts between ISPs, which they don't want to reveal
   - Hard to evaluate inference algorithms!
2. Multiple sources of information, which could be contradicting
   - Internet registries like ARIN
   - BGP routing table entries from different Ass
3. Information is incomplete and erroneous (configuration errors, e.g.)
   - Only have access to a subset of BGP tables
   - Some edges are impossible to see without direct BGP table access (e.g. peer-peer edge between small ASes)

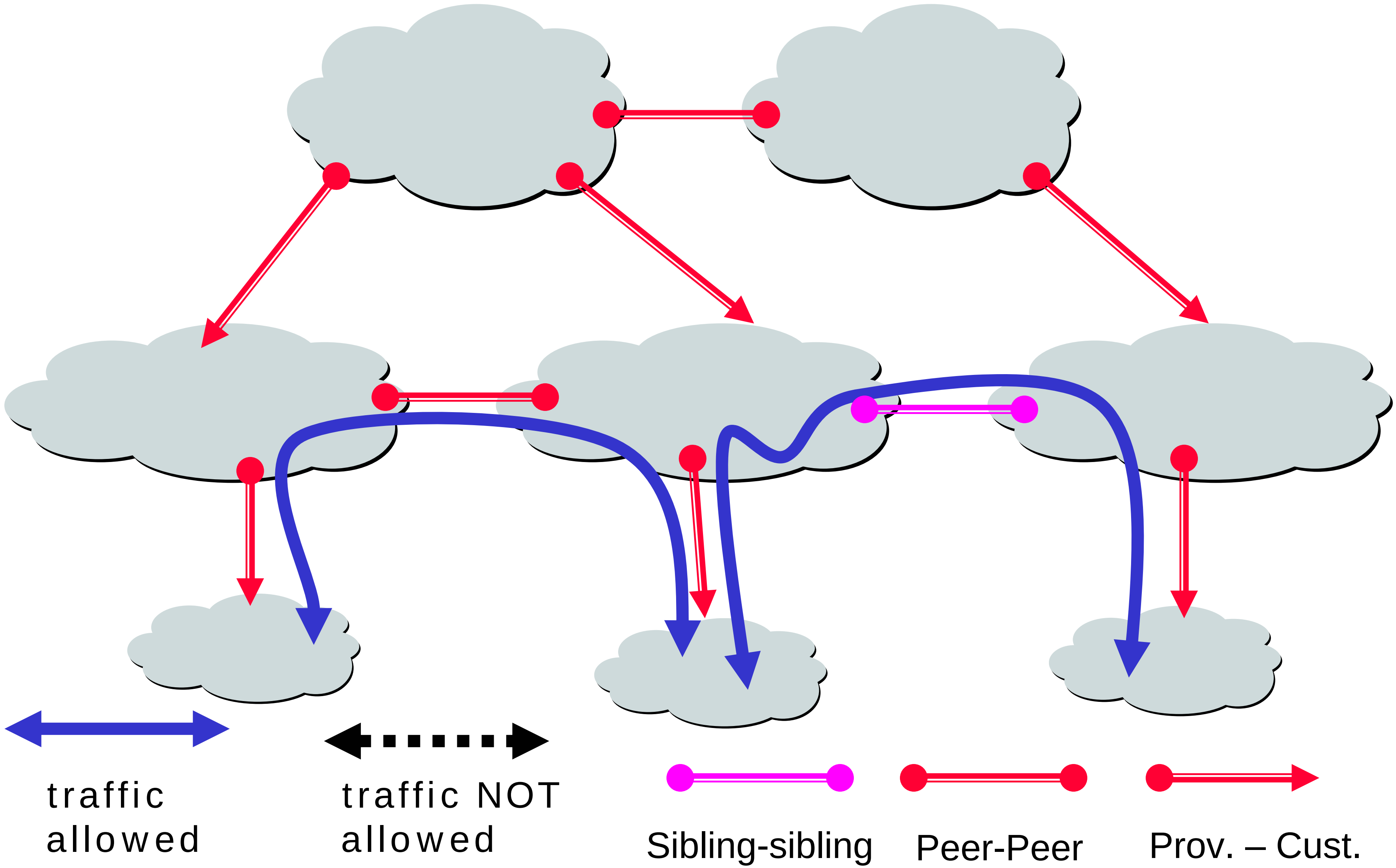
Challenges of Inferring AS Relationships (2)

4. Geography might play a role
   - E.g., contract between X & Y in the U.S. may be different from that in Europe
5. AS pairs may have *back-up* relationships
6. AS pairs may peer indirectly

Some Basic Assumptions (1)

- Four types of AS-AS relationships
  - Provider-Customer, Customer-Provider: $$$
  - Peer-Peer: exchange traffic between customers
  - Sibling-Sibling: two AS's belong to the same administrative domains, or have a mutual transit agreement
- Rules for exporting routes:
  - To a provider or a sibling: its own, customers', siblings', **not** peers' nor other providers'
  - To a customer or a peer: everything

Some Basic Assumptions (2)



Input Data

- Looking Glass Servers: BGP routing table snapshots
  - Route Viewer Server (Oregon)
  - NANOG's looking glass links
- Routing Arbiter Database (RADB)
  - Archives of routing policies
- Internet Routing Registries
  - > 50 routing policy databases conforming to RPSL
- WHOIS Services
  - Name/addresses of routing domain owners
- Traceroute
  - Gives much more specific data

How to Evaluate Inference Algorithms

- Small number of invalid paths
- Compare outputs of different algorithms
- Compare outputs with data from IRR, RADB and other sources
- Compare outputs with proprietary data

Some Current Solutions

- Lixin Gao, ToN 2000
- Subramanian et al., SIGCOMM 2002
- Battista et al., INFOCOM 2003;
  Erlebach et al., CCN 2002
- Xia & Gao, GLOBECOM 2005
- Some others

[Lixin Gao, ToN 2000]

- Uphill path: sequence of C-P and S-S edges
- Downhill path: sequence of P-C and S-S edges
- AS Paths are "valley free"
  - Uphill path
  - Downhill path
  - Uphill, then downhill
  - Uphill, then P-P edge
  - P-P edge, then downhill
  - Uphill, P-P edge, then downhill
- In general, AS paths have the form
  - [Uphill] ° [P-P edge] ° [Downhill]

Basic Algorithm

1. Compute degrees of ASes
2. For each path in routing tables
   - Highest degree AS assumed to be top provider
   - Pairs on the left are C-P
   - Pairs on the right are P-C
3. For each AS pairs (which are connected)
   - If labeled both C-P and P-C, then it’s S-S

Refined Algorithm

- Idea: allows 1 error in C-P or P-C classification

1. For every edge e
   - x = # of paths classifying e as C-P
   - y = # of paths classifying e as P-C
2. If (x > y = 0 or 1) then e is C-P
3. If (y > x = 0 or 1) then e is P-C
4. Otherwise, e is S-S

Final Algorithm

1. Coarsely classify edges into C-P, P-C, S-S using either basic or refined algorithms
2. Identify pairs that cannot be P-P
   - P-P can only involve top provider in a path
   - Plus another heristic (top provider is likelier to peer with higher degree neighbor)
3. For the rest of the edges, classify as P-P if the difference in degrees is at most R (=60)

Findings

- 90.5% AS pairs are C-P or P-C
- 1.5% AS pairs are S-S
- < 8% AS pairs are P-P

- 99.8% inferred relationships are confirmed by AT&T internal data
- 50% of S-S relationships are confirmed by WHOIS
  - Not confirmed doesn't mean they're wrong (yet)

- Can also identify erroneous routing table entries
  - Mis-configuration
  - Weird AS relationships

[Subramanian et al., SIGCOMM 2002]

- Only assume P-P, C-P, and P-C
- Exporting rules:
  - To a provider: its own, customers', **not** other providers and peers
  - To a peer: its own, customers', **not** providers and peers
  - To a customer: everything
- Data gathered from multiple *vantage* points
- Valid paths: +…+-…-, or +…+0-…-
- **ToR Problem**
  - Given a graph G=(V,E), and a set of paths P
  - Find an edge-labeling with +, -, 0 to minimize the number of invalid paths

Heuristic: Observation and Key Ideas

- Keys
  - Find breaking point between downhill & uphill
  - Reconcile differences viewed from vantage points
- Observations
  - Provider-Customer relationship is acyclic
  - Take view source into account: views from tier-1 ASes tend to be acyclic

Heuristic: AS Ranking

- Rank each AS for each vantage point
  - Leaves are ranked 1
  - Recursively remove leaves and increase ranks
  - For the final connected component, assign last rank
- Map AS_i to a vector $(r_{i1}, \ldots r_{in})$
  - r_{ij} = rank of AS_i viewed from vantage point $_j$
  - $l_{ij} = |\{k : r_{ik} > r_{jk}\}|$
    number of vantage points that rank i higher than j
  - $e_{ij} = |\{k : r_{ik} = r_{jk}\}|$
    number of vantage points that rank i = j

Heuristic: Inferring Peer-Peer Relationship

- Equivalence
  - AS_i and AS_j are *equivalent* if $e_{ij} > n/2$
  - If they are connected, then they are peers
  - This deals with peers visible from lots of vantage points
- Probabilistic equivalence
  - AS_i and AS_j are prob. equiv. If $1/\delta_1 \leq l_{ij}/l_{ji} \leq \delta_1$ (δ_1 is close to 1, chosen to be 2 in the paper)
  - If they are connected, then they are peers
  - This deals with peers partially visible

Heuristic: Inferring Provider-Customer Relationship

- Dominance
  - AS_i dominates AS_j if $l_{ij} \geq n/2$ and $l_{ji} = 0$
  - If they share an edge, AS_i is a provider of AS_j
- Probabilistic dominance
  - If $l_{ij}/l_{ji} > \delta_0$ for large $\delta_0 > \delta_1$ ($\delta_0 = 3$ in the paper)
- In applying the rules
  - Deterministic dominance and equivalence applied first
  - Probabilistic ones after

Findings

- Validation based on # of path anomalies
- Percentage of anomalies between 0.6% and 3.0%
  - Many anomalies due to sibling relationship between ASes of the same administration
  - Merging, splitting of ISPs
- Result helps classify Internet ASes into 5 hierarchical levels
  - Dense core
  - Transit core
  - Outer core
  - Small regional ISPs
  - Customers

Works on the ToR Problem

- Determining if there is a good labeling
[Battista et al., INFOCOM 2003], [Erlebach et al., CCN 2002]
  - Can be done in linear time with a reduction to 2SAT
  - If there is a good labeling, it's linear-time computable
  - Solve 2SAT by computing strongly connected components and topological ordering (standard technique!)
- Max-ToR Problem [Erlebach et al., CCN 2002]
  - NP-Hard
  - Cannot be approximated to within $n^{1-\varepsilon}$ for any $\varepsilon > 0$ unless NP=coRP (Reduction from Independent Set)
- Max-ToR with bounded path lengths [Erlebach et al., CCN 2002]
  - APX-complete in general
  - Approximable to within $2^k/(k+1)$ where k is path-length upper bound

[Xiao et al. GLOBECOM 2005]

- Obtained partially real AS relationships
  - Usages of BGP community attributes
  - Instances of AS-SET objects in IRR databases
  - Routing policies in IRR databases
  - Partial AS relationships from RADB and IRR databases
- Evaluated algorithms by [Gao, 2000], [Subramanian et al., 2002]
  - Did not touch algorithms by [Battista et al 2003]
  - The other two don't predict peer-peer edges well (<50%)
- Proposed a new heuristic
  - Out-perform the other two on peer-peer, now obtain about 90% accuracy