Measurement:
Techniques, Strategies, and Pitfalls

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Internet Measurement

- Process of collecting data that measure certain phenomena about the network
  - Should be a science
  - *Today:* closer to an art form

- **Key goal:** Reproducibility

- "Bread and butter" of networking research
  - Deceptively complex
  - Probably one of the most difficult things to do correctly

Types of Data

Active

- traceroute
- ping
- UDP probes
- TCP probes
- Application-level “probes”
  - Web downloads
  - DNS queries

Passive

- Packet traces
  - Complete
  - Headers only
  - Specific protocols
- Flow records
- Specific data
  - Syslogs …
  - HTTP server traces
  - DHCP logs
  - Wireless association logs
  - DNSBL lookups
  - …
- Routing data
  - BGP updates / tables, ISIS, etc.

Outline: Tools and Pitfalls

- Aspects of Data Collection
  - **Precision:** At what granularity are measurements taken?
  - **Accuracy:** Does the data capture phenomenon of interest?
  - **Context:** How was the data collected?

- Tools
  - Active
    - Ping, traceroute, etc.
    - **Accuracy pitfall example:** traceroute
  - Passive
    - Packet captures (*e.g.*, tcpdump, DAG)
    - Flow records (*e.g.,* netflow)
    - Routing data (*e.g.,* BGP, IS-IS, etc.)
    - **Context pitfall example:** eBGP multihop data collection

Outline (continued)

- Strategies
  - Cross validate
    - consistency checks
    - multiple “overlapping” measurements
  - Examine Zeroth-Order

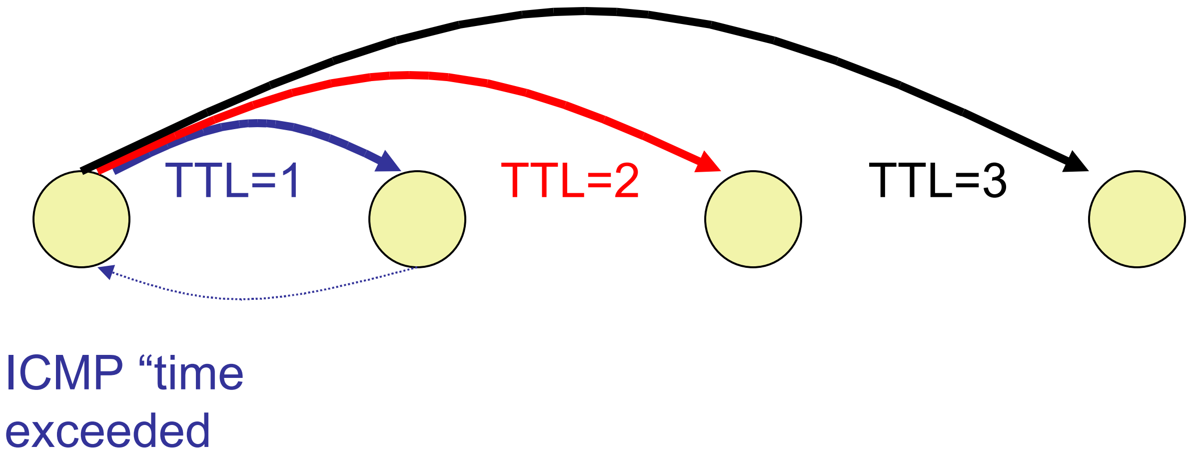
- Database as secret weapon

- Other considerations
  - Anonymization and privacy
  - Maintaining longitudinal data

Active Measurement

How Traceroute Works

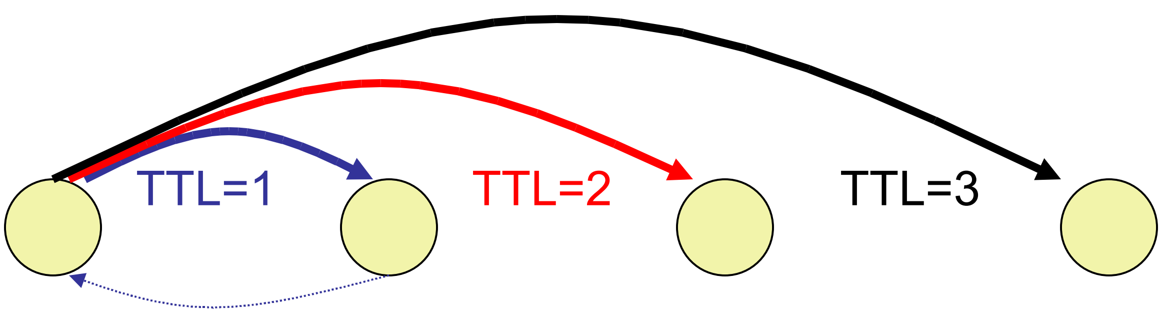
- Send packets with increasing TTL values



- Nodes along IP layer path decrement TTL
- When TTL=0, nodes return “time exceeded” message

Problems with Traceroute

- Can't unambiguously identify one-way outages
  - Failure to reach host : failure of *reverse* path?
- ICMP messages may be filtered or rate-limited
- IP address of "time exceeded" packet may be the *outgoing* interface of the *return* packet



Famous Traceroute Pitfall

- **Question: What ASes does traffic traverse?**
- **Strawman approach**
  - Run traceroute to destination
  - Collect IP addresses
  - Use "`whois`" to map IP addresses to AS numbers

- Thought Questions
  - What IP address is used to send "time exceeded" messages from routers?
  - How are interfaces numbered?
  - How accurate is whois data?

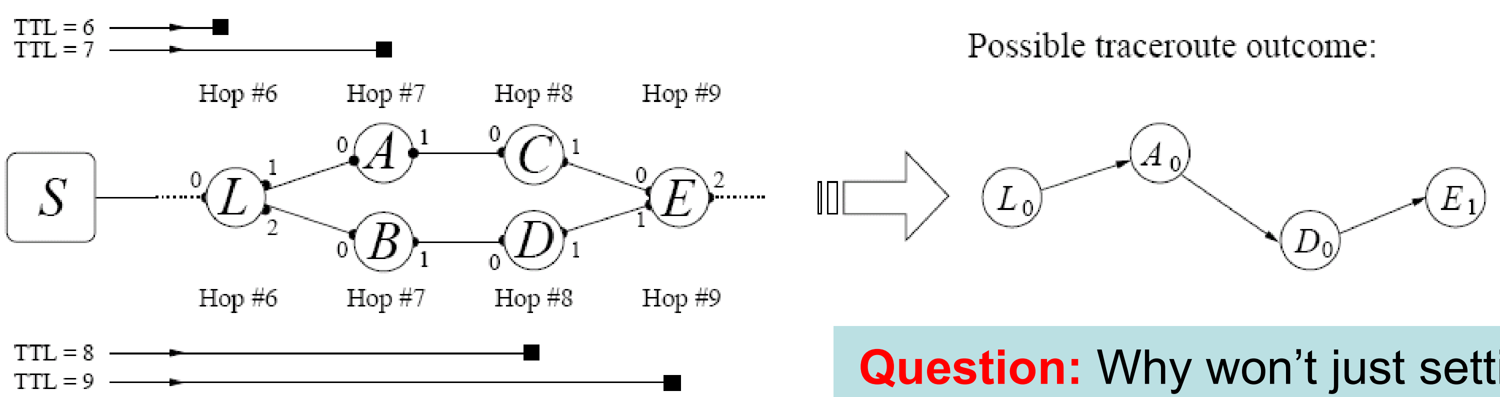
More Caveats: Topology Measurement

- Routers have multiple interfaces
- Measured topology is a function of vantage points

- **Example:** Node degree
  - Must “alias” all interfaces to a single node (PS 2)
  - Is topology a function of vantage point?
    - Each vantage point forms a tree
    - See Lakhina *et al.*

Less Famous Traceroute Pitfall

- Host sends out a sequence of packets
  - Each has a different destination port
  - Load balancers send probes along different paths
    - Equal cost multi-path
    - Per flow load balancing



Question: Why won't just setting same port number work?

Soule *et al.*, "Avoiding Traceroute Anomalies with Paris Traceroute", *IMC 2006*

Designing for Measurement

- What mechanisms should routers incorporate to make traceroutes more useful?
  - Source IP address to “loopback” interface
  - AS number in time-exceeded message
  - ??

Passive Measurement

Packet Capture: tcpdump/bpf

- Put interface card in promiscuous mode
- Use bpf to extract packets of interest

Accuracy Issues

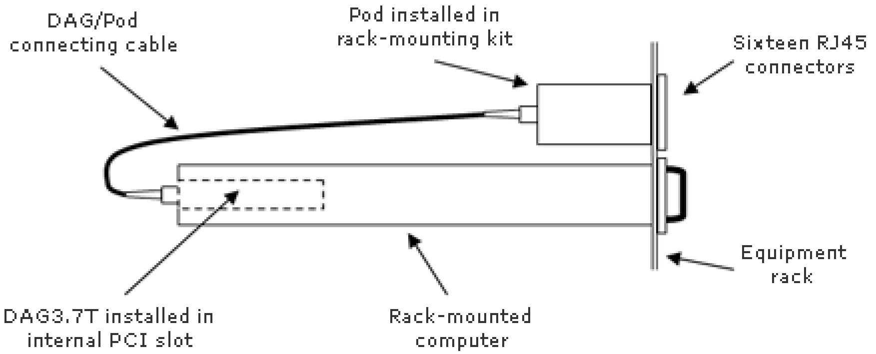
- Packets may be dropped by filter
  - Failure of tcpdump to keep up with filter
  - Failure of filter to keep up with dump speeds

Question: How to recover lost information from packet drops?

Packet Capture on High-Speed Links

Example: Georgia Tech OC3Mon

- Rack-mounted PC
- Optical splitter
- Data Acquisition and Generation (DAG) card



Source: endace.com

Traffic Flow Statistics

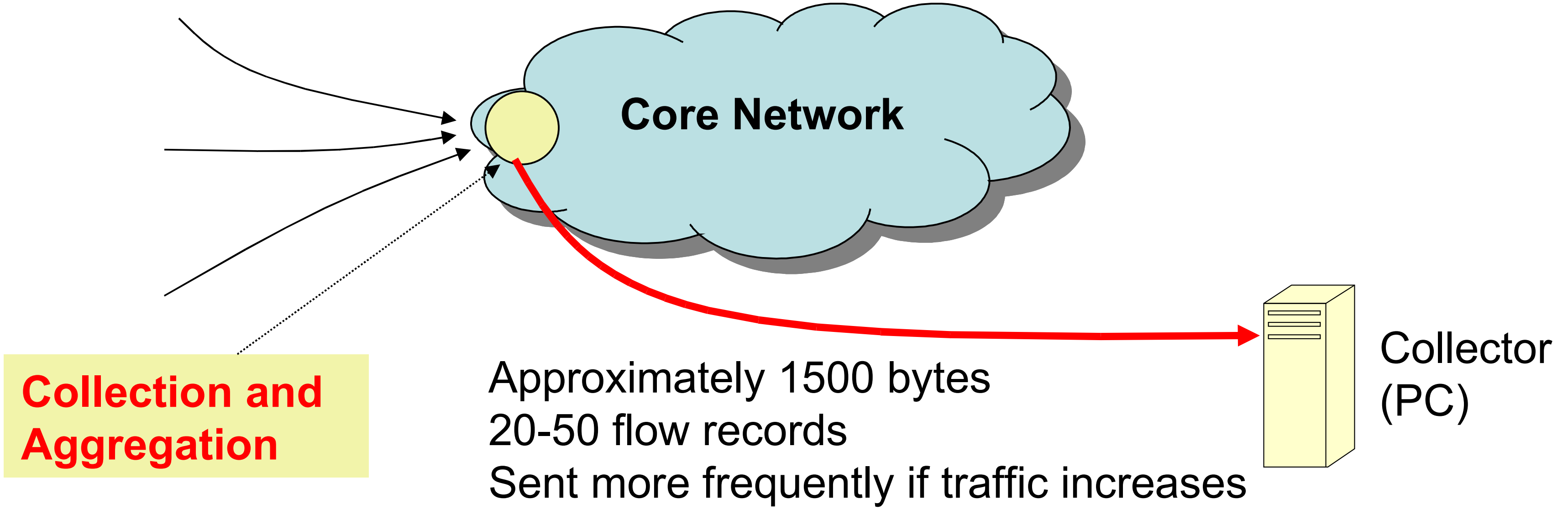
- *Flow monitoring* (*e.g*., Cisco Netflow)
  - Statistics about groups of related packets (*e.g.,* same IP/TCP headers and close in time)
  - Recording header information, counts, and time
- More detail than SNMP, less overhead than packet capture
  - Typically implemented directly on line card

What is a flow?

- **Source IP address**
- **Destination IP address**
- **Source port**
- **Destination port**
- **Layer 3 protocol type**
- TOS byte (DSCP)
- Input logical interface (ifIndex)

Cisco Netflow

- Basic output: "Flow record"
  - Most common version is v5
  - Latest version is v10 (RFC 3917)
- Current version (10) is being standardized in the IETF (*template-based*)
  - More flexible record format
  - Much easier to add new flow record types



Flow Record Contents

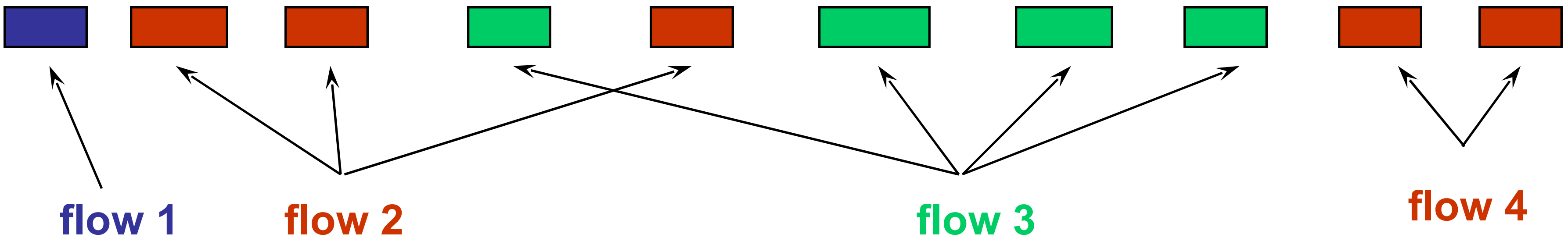
Basic information about the flow…

- Source and Destination, IP address and port
- Packet and byte counts
- Start and end times
- ToS, TCP flags

…plus, information related to routing

- Next-hop IP address
- Source and destination AS
- Source and destination prefix

Aggregating Packets into Flows



- **Criteria 1:** Set of packets that “belong together”
  - Source/destination IP addresses and port numbers
  - Same protocol, ToS bits, …
  - Same input/output interfaces at a router (if known)

- **Criteria 2:** Packets that are “close” together in time
  - Maximum inter-packet spacing (e.g., 15 sec, 30 sec)
  - **Example:** flows 2 and 4 are different flows due to time

Netflow Processing

1. **Create and update flows in NetFlow Cache**

SrcIf	SrcIPadd	DstIf	DstIPadd	Protocol	TOS	Flgs	Pkts	SrcPort	SrcMsk	SrcAS	DstPort	DstMsk	DstAS	NextHop	Bytes/Pkt	Active	Idle
Fa1/0	173.100.21.2	Fa0/0	10.0.227.12	11	80	10	11000	00A2	/24	5	00A2	/24	15	10.0.23.2	1528	1745	4
Fa1/0	173.100.3.2	Fa0/0	10.0.227.12	6	40	0	2491	15	/26	196	15	/24	15	10.0.23.2	740	41.5	1
Fa1/0	173.100.20.2	Fa0/0	10.0.227.12	11	80	10	10000	00A1	/24	180	00A1	/24	15	10.0.23.2	1428	1145.5	3
Fa1/0	173.100.6.2	Fa0/0	10.0.227.12	6	40	0	2210	19	/30	180	19	/24	15	10.0.23.2	1040	24.5	14

1. **Expiration**

- **Inactive timer expired (15 sec is default)**
- **Active timer expired (30 min (1800 sec) is default)**
- **NetFlow cache is full (oldest flows are expired)**
- **RST or FIN TCP Flag**

SrcIf	SrcIPadd	DstIf	DstIPadd	Protocol	TOS	Flgs	Pkts	SrcPort	SrcMsk	SrcAS	DstPort	DstMsk	DstAS	NextHop	Bytes/Pkt	Active	Idle
Fa1/0	173.100.21.2	Fa0/0	10.0.227.12	11	80	10	11000	00A2	/24	5	00A2	/24	15	10.0.23.2	1528	1800	4

1. **Aggregation?**

No / **Yes**

e.g. Protocol-Port Aggregation Scheme becomes

Protocol	Pkts	SrcPort	DstPort	Bytes/Pkt
11	11000	00A2	00A2	1528

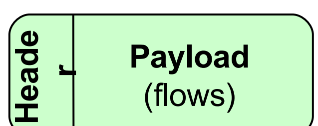
1. **Export Version**

Non-Aggregated Flows – export **Version 5 or 9**

Aggregated Flows – export **Version 8 or 9**

1. **Transport Protocol**

Export Packet

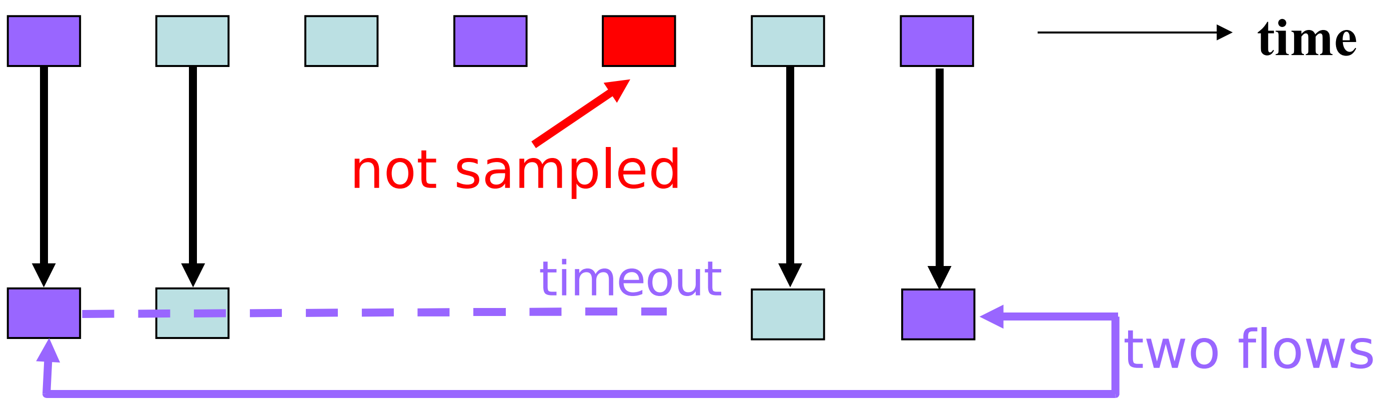


Reducing Measurement Overhead

- **Filtering:** on interface
  - destination prefix for a customer
  - port number for an application (e.g., 80 for Web)
- **Sampling:** before insertion into flow cache
  - Random, deterministic, or hash-based sampling
  - 1-out-of-n or stratified based on packet/flow size
  - *Two types:* packet-level and flow-level
- **Aggregation:** after cache eviction
  - packets/flows with same next-hop AS
  - packets/flows destined to a particular service

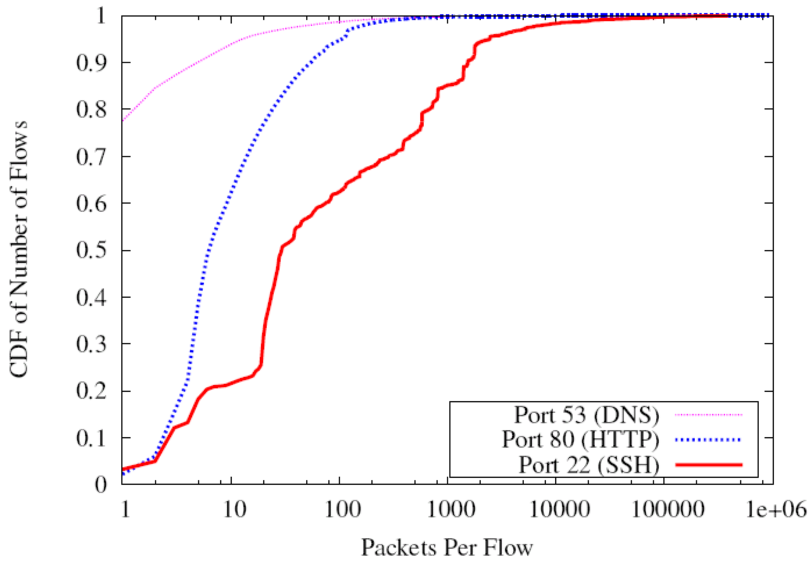
Packet Sampling

- Packet sampling before flow creation (Sampled Netflow)
  - 1-out-of-m sampling of individual packets (*e.g.*, m=100)
  - Create of flow records over the sampled packets
- Reducing overhead
  - Avoid per-packet overhead on (m-1)/m packets
  - Avoid creating records for a large number of small flows
- Increasing overhead (in some cases)
  - May split some long transfers into multiple flow records
  - … due to larger time gaps between successive packets



Problems with Packet Sampling

- Determining size of original flows is tricky
  - For a flow originally of size *n*, the size of the *sampled* flow follows a binomial distribution
  - Extrapoliation can result in big errors
  - Much research in reducing such errors
    (upcoming lectures)
- Flow records can be lost
- Small flows may be eradicated entirely



Accuracy Depends on Phenomenon

- Even naïve random sampling probably decent for capturing the *existence* of large flows

- Accurately measuring other features may require different approaches
  - Sizes of large flows
  - Distribution of flow sizes
  - Existence of small flows (coupon collection)
  - Size of small flows
  - Traffic "matrix"

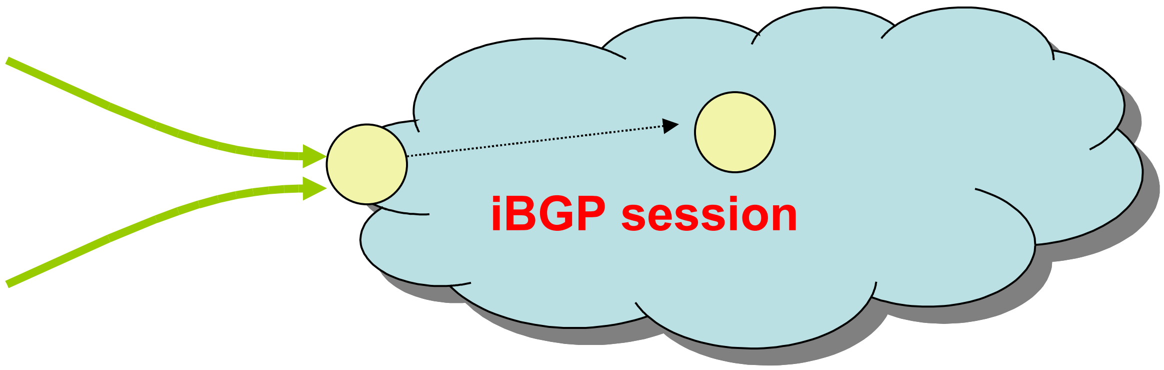
- More in upcoming lectures

Sampling: Flow-Level Sampling

- Sampling of flow records evicted from flow cache
  - When evicting flows from table or when analyzing flows
- Stratified sampling to put weight on “heavy” flows
  - Select all long flows and sample the short flows
- Reduces the number of flow records
  - Still measures the vast majority of the traffic

Flow 1, 40 bytes ← sample with 0.1% probability
Flow 2, 15580 bytes
Flow 3, 8196 bytes
Flow 4, 5350789 bytes ← sample with 100% probability
Flow 5, 532 bytes
Flow 6, 7432 bytes ← sample with 10% probability

Routing Data



- IGP
- BGP
  - Collection methods
    - eBGP (typically “multihop”)
    - iBGP
  - Table dumps: Periodic, complete routing table state (direct dump from router)
  - Routing updates: Continuous, incremental, best route only

BGP Routing Updates: Example

TIME: 07/06/06 19:49:52
TYPE: BGP4MP/STATE_CHANGE
PEER: 18.31.0.51 AS65533
STATE: Active/Connect

TIME: 07/06/06 19:49:52
TYPE: BGP4MP/STATE_CHANGE
PEER: 18.31.0.51 AS65533
STATE: Connect/Opensent

TIME: 07/06/06 19:49:52
TYPE: BGP4MP/STATE_CHANGE
PEER: 18.31.0.51 AS65533
STATE: Opensent/Active

TIME: 07/06/06 19:49:55
TYPE: BGP4MP/MESSAGE/Update
FROM: 18.168.0.27 AS3
TO: 18.7.14.168 AS3
WITHDRAW
  12.105.89.0/24
  64.17.224.0/21
  64.17.232.0/21
  66.63.0.0/19
  89.224.0.0/14
  198.92.192.0/21
  204.201.21.0/24

Accuracy issue: Old versions of Zebra would not process updates during a table dump…buggy timestamps.

The Importance of Context: Case Studies with Routing Data

Context Pitfall: AS-Level Topologies

- **Question:** What is the Internet's AS-level topology?
- **Strawman approach**
  - Routeviews routing table dumps
  - Adjacency for each pair of ASes in the AS path

- Problems with the approach?
  - Completeness: Many edges could be missing. Why?
    - Single-path routing
    - Policy: ranking and filtering
    - Limited vantage points
  - Accuracy
  - Coarseness

Context Pitfall: Routing Instability

- **Question:** Does worm propagation cause routing instability?
- **Strawman approach:**
  - Observe routing data collected at RIPE RIRs
  - Correlate routing update traffic in logs with time of worm spread
  - Finding: Lots of routing updates at the time of the worm sprreading!
  - **(Bogus) conclusion:** Worm spreading causes route instability

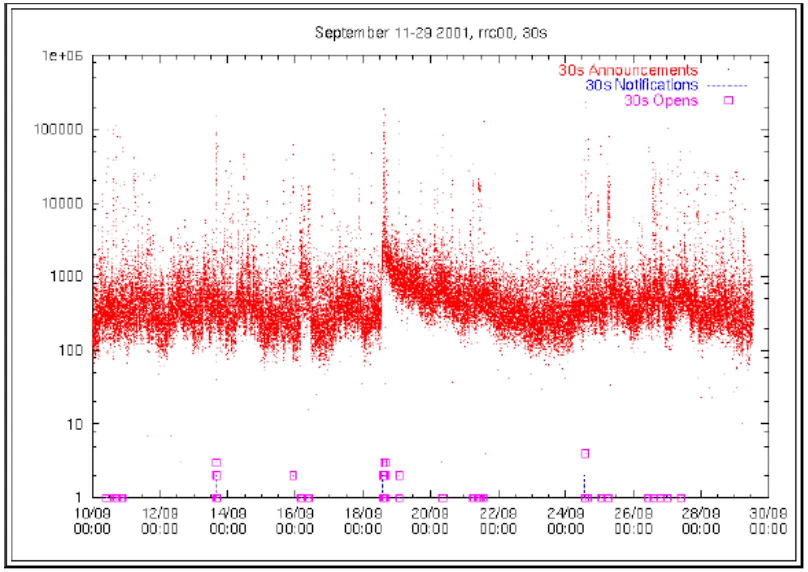


Figure 5: A zoom-in on the BGP message storm of 18–22 September.

Cowie *et al.*, "Global Routing Instabilities Triggered by Code Red II and Nimda Worm Attacks"

Missing/Ignored Context: Instability + eBGP multihop …

Strategy: Examine the Zeroth-Order

- Paxson calls this "looking at spikes and outliers"
- **More general:** Look at the data, not just aggregate statistics
  - Tempting/dangerous to blindly compute aggregates
  - Timeseries plots are telling (gaps, spikes, etc.)
  - Basics
    - Are the raw trace files empty?
      - Need not be 0-byte files (*e.g.*, BGP update logs have state messages but no updates)
    - Metadata/context: Did weird things happen during collection (machine crash, disk full, etc.)

Strategy: Cross-Validation

- Paxson breaks cross validation into two aspects
  - Self-consistency checks (and sanity checks)
  - Independent observations
    - Looking at same phenomenon in multiple ways

Example Sanity Checks

- Is time moving backwards?
  - PS1's IGP packet trace
  - Paxson's probing example
  - **Typical cause:** Clock synchronization issues

- Has the the speed of light increased?
  - *E.g.*, 10ms cross-country latencies

- Do values make sense?
  - IP addresses that look like 0.0.1.2 indicate bug

Cross-Validation Example

- Traceroutes captured in parallel with BGP routing updates
- **Puzzle**
  - Route monitor sees route withdrawal for prefix
  - Routing table has no route to the prefix
  - IP addresses within prefix still reachable from within the IP address space (*i.e.,* traceroute goes through)
- Why?
  - Collection bugs … or
  - Broken mental model of routing setup

Databases: Secret Weapon

- Easy way to get lots of summary statistics
  - Regular first-order stats (*cf.* Paxson's recommendation)
    - Latest timestamp, number of updates, etc.
  - **Cross-validation** becomes easier (quick and dirty SQL)
  - **Joint analysis** of diverse datasets is a common need

- **Caveats!**
  - Insertion must be done properly
    - Always, always save raw data
  - Beware the table join

Horror Story #1: Buggy Postprocessing

- Logs maintained at each host
- Files collected

Example RON Monitoring Logs

```
1103659228.224614 S 14b13270 0 8 18.7.14.168 66.26.83.103
1103659228.252509 R 14b13270 1 8 18.7.14.168 66.26.83.103
1103659229.388441 S 55a4b9a1 0 8 18.7.14.168 192.249.24.10
1103659229.611096 R 55a4b9a1 1 8 18.7.14.168 192.249.24.10
1103659231.200177 S bf1207a0 0 8 18.7.14.168 12.46.129.20
1103659231.270053 R bf1207a0 1 8 18.7.14.168 12.46.129.20
1103659233.109900 S 55e244c0 0 8 18.7.14.168 112.12.8.0
1103659234.308722 S 8ba24c76 0 8 18.7.14.168 18.97.168.219
```

Horror Story #1: Buggy Insertion

- Raw files pulled to archive
  - Archive stores directories month-by-month
  - Files named by unixtime (start,end)
  - Files pulled into directory by month
- Insertion into DB: one archive directory at a time

Horror Story #2: Join Queries

Anonymization

Longitudinal Studies

- Extremely valuable
- Extremely hard to maintain
  - Requires constant babysitting (disks fill up, programs/OSes upgraded, IP addresses change, etc.)
- A few pointers
  - Store all mappings that are not invariant
  - Regular regression, backup, first-order stats
  - Paxson's "master script" idea can help with regression