CS 268: Routing Behavior in the Internet

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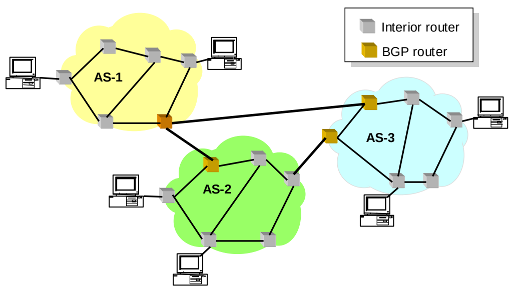
Internet Routing

- Internet organized as a two level hierarchy
- First level – autonomous systems (AS's)
  - AS – region of network under a single administrative domain
- AS's run an intra-domain routing protocols
  - Distance Vector, e.g., RIP
  - Link State, e.g., OSPF
- Between AS's runs inter-domain routing protocols, e.g., Border Gateway Routing (BGP)
  - De facto standard today, BGP-4

Example



Intra-domain Routing Protocols

- Based on unreliable datagram delivery
- Distance vector
  - Routing Information Protocol (RIP), based on Bellman-Ford
  - Each router periodically exchange reachability information to its neighbors
  - Minimal communication overhead, but it takes long to converge, i.e., in proportion to the maximum path length
- Link state
  - Open Shortest Path First Protocol (OSPF), based on Dijkstra
  - Each router periodically floods immediate reachability information to other routers
  - Fast convergence, but high communication and computation overhead

Inter-domain Routing

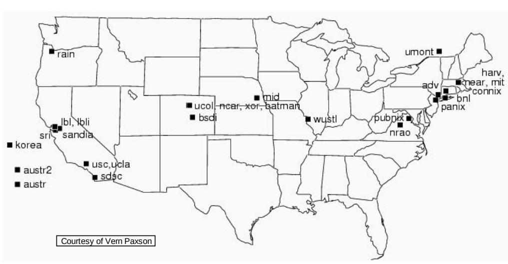
- Use TCP
- Border Gateway Protocol (BGP), based on Bellman-Ford path vector
- AS's exchange reachability information through their BGP routers, only when routes change
- BGP routing information – a sequence of AS's indicating the path traversed by a route; next hop
- General operations of a BGP router:
  - Learns multiple paths
  - Picks best path according to its AS policies
  - Install best pick in IP forwarding tables

End-to-End Routing Behavior in the Internet [Paxson '95]

- Idea: use end-to-end measurements to determine
  - Route pathologies
  - Route stability
  - Route symmetry

Methodology

- Run Network Probes Daemon (NPD) on a large number of Internet sites



Methodology

- Each NPD site periodically measure the route to another NPD site, by using traceroute
- Two sets of experiments
- D_1 – measure each virtual path between two NPD's with a mean interval of 1-2 days, Nov-Dec 1994
- D_2 – measure each virtual path using a bimodal distribution inter-measurement interval, Nov-Dec 1995
  - 60% with mean of 2 hours
  - 40% with mean of 2.75 days
- Measurements in D_2 were paired
  - Measure A→B and then B→A

Traceroute Example

sky.cs.berkeley.edu → whistler.cmcl.cs.cmu.edu

```
traceroute to whistler.cmcl.cs.cmu.edu (128.2.181.87), 30 hops max, 38 byte packets
 1  snr45 (128.32.45.1)  0.570 ms  0.434 ms  0.415 ms
 2  gig10-cnr1.EECS.Berkeley.EDU (169.229.3.65)  0.506 ms  0.513 ms  0.434 ms
 3  gigE5-0-0.inr-210-cory.Berkeley.EDU (169.229.1.45)  0.726 ms  0.570 ms  0.553 ms
 4  fast1-0-0.inr-001-eva.Berkeley.EDU (128.32.0.1)  1.357 ms  0.998 ms  1.020 ms
 5  pos0-0.inr-000-eva.Berkeley.EDU (128.32.0.65)  1.459 ms  2.371 ms  1.600 ms
 6  pos3-0.c2-berk-gsr.Berkeley.EDU (128.32.0.90)  3.103 ms  1.406 ms  1.575 ms
 7  SUNV--BERK.POS.calren2.net (198.32.249.14)  3.005 ms  3.085 ms  2.407 ms
 8  abilene--QSV.POS.calren2.net (198.32.249.62)  6.112 ms  6.834 ms  6.218 ms
 9  dnvr-scrm.abilene.ucaid.edu (198.32.8.2)  34.213 ms  27.145 ms  27.368 ms
10  kscy-dnvr.abilene.ucaid.edu (198.32.8.14)  38.403 ms  38.121 ms  38.514 ms
11  ipls-kscy.abilene.ucaid.edu (198.32.8.6)  47.855 ms  47.558 ms  47.649 ms
12  clev-ipls.abilene.ucaid.edu (198.32.8.26)  54.037 ms  53.849 ms  53.492 ms
13  abilene.psc.net (192.88.115.122)  57.109 ms  56.706 ms  57.343 ms
14  cmu.psc.net (198.32.224.36)  58.794 ms  58.237 ms  58.491 ms
15  CS-VLAN255.GW.CMU.NET (128.2.255.209)  58.072 ms  58.496 ms  57.747 ms
16  WHISTLER.CMCL.CS.CMU.EDU (128.2.181.87)  57.715 ms  57.932 ms  57.557 ms
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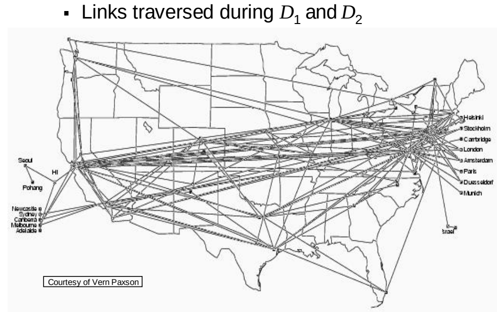
Methodology

- Links traversed during D_1 and D_2



Courtesy of Vern Paxson

Methodology

- Exponential sampling
  - Unbiased sampling – measures instantaneous signal with equal probability
  - PASTA principle – Poisson Arrivals See Time Averages
- Is data representative?
  - Argue that sampled AS's are on half of the Internet routes
- Confidence intervals for probability that an event occurs

Limitations

- Just a small subset of Internet paths
- Just two points at a time
- Difficult to say why something happened
- 5%-8% of time couldn't connect to NPD's → Introduces bias toward underestimation of the prevalence of network problems

Routing Pathologies

- Persistent routing loops
- Temporary routing loops
- Erroneous routing
- Connectivity altered mead-stream
- Temporary outages (> 30 sec)

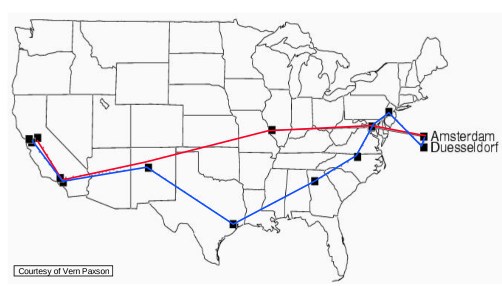
Routing Loops & Erroneous Routing

- Persistent routing loops (10 in D_1 and 50 in D_2)
  - Several hours long (e.g., > 10 hours)
  - Largest: 5 routers
  - All loops intra-domain
- Transient routing loops (2 in D_1 and 24 in D_2)
  - Several seconds
  - Usually occur after outages
- Erroneous routing (one in D_1)
  - A route UK→USA goes through Israel

Route Changes

- Connectivity change in mid-stream (10 in D_1 and 155 in D_2)
  - Route changes during measurements
  - Recovering bimodal: (1) 100's msec to seconds; (2) order of minutes
- Route fluttering
  - Rapid route oscillation

Example of Route Fluttering



Problems with Fluttering

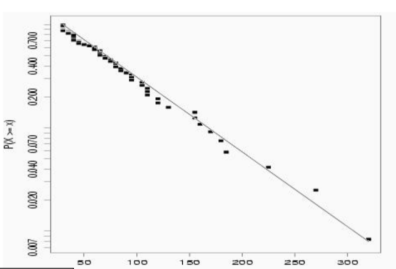
- Path properties difficult to predict
  - This confuses RTT estimation in TCP, may trigger false retransmission timeouts
- Packet reordering
  - TCP receiver generates DUPACK's, may trigger spurious fast retransmits
- These problems are bad only for a large scale flutter; for localized flutter is usually ok

Infrastructure Failures

- NPD's unreachable due to many hops (6 in D_2)
  - Unreachable → more than 30 hops
  - Path length not necessary correlated with distance
    - 1500 km end-to-end route of 3 hops
    - 3 km (MIT – Harvard) end-to-end route of 11 hops
- Temporary outages
  - Multiple probes lost. Most likely due to:
    - Heavy congestions lasting 10's of seconds
    - Temporary lost of connectivity

Distribution of Long Outages (> 30 sec)

- Geometric distribution



Courtesy of Vern Paxson

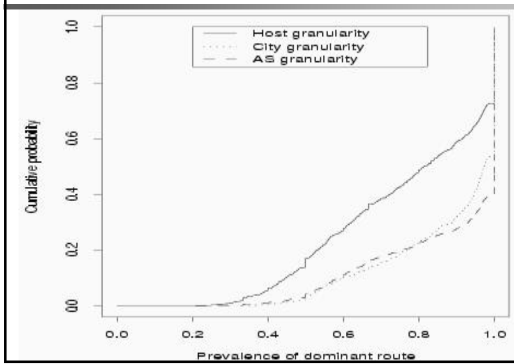
Pathology Summary

Pathology	Probability	Trend
Persistent routing loops	0.13–0.16%	
Temporary routing loops	0.055–0.078%	
Erroneous routing	0.004–0.004%	
Connectivity altered mid-stream	0.16% // 0.44%	worse
Infrastructure failure	0.21% // 0.48%	worse
Temporary outage $\geq$ 30 secs	0.96% // 2.2%	worse
Total user-visible pathologies	1.5% // 3.4%	worse

Routing Stability

- Prevalence: likelihood to observe a particular route
  - Steady state probability that a virtual path at an arbitrary point in time uses a particular route
  - Conclusion: In general Internet paths are strongly dominated by a single route
- Persistence: how long a route remains unchanged
  - Affects utility of storing state in routers
  - Conclusion: routing changes occur over a wide range of time scales, i.e., from minutes to days

Route Prevalence



Route Persistence

Time scale	% Paths	Notes
seconds	N/A	Load-balancing “flutter.”
minutes	N/A	“Tightly-coupled” routers.
10’s of minutes	9%	Some involved different cities, AS’s.
hours	4%	Usually intra-network changes.
6+ hours	19%	Also intra-network changes.
days	68%	or even weeks.

Route Symmetry

- 30% of the paths in D_1 and 50% in D_2 visited different cities
- 30% of the paths in D_2 visited different AS’s
- Problems:
  - Break assumption that one-way latency is RTT/2

Summary of Paxson's Findings

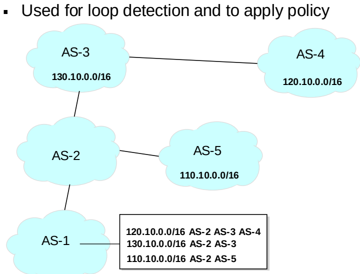
- Pathologies doubled during 1995
- Asymmetries nearly doubled during 1995
- Paths heavily dominated by a single route
- Over 2/3 of Internet paths are reasonable stable (> days). The other 1/3 varies over many time scales

Internet Routing Instability [Labovitz et al '96]

- Methodology
  - Collect routing messages from five public exchange points over nine months
- Problems caused by routing instability
  - Increased delays, packet loss and reordering, time for routes to converge (small-scale route changes)
- Relevant BGP information
  - AS-Path (see next slide)
  - Next hop: Next hop to reach a network
- Two routes are the same if they have the same AS-Path and Next hop

AS-Path

- Sequence of AS's a route traverses
- Used for loop detection and to apply policy



BGP Information Exchange

- Announcements: a router has either
  - Learned of a new route, or
  - Made a policy decision that it prefers a new route
- Withdrawals: a router concludes that a network is no longer reachable
  - Explicit: associated to the withdrawal message
  - Implicit: when a route is replaced as a result of an announcement message
- In steady state BGP updates should be only the result of infrequent policy changes
  - Update rate → measure of network stability

Types of Inter-domain Routing Updates

- Forwarding instability: may reflect topology changes
- Policy fluctuations (Routing instability): may reflect changes in routing policy information
- Pathological updates: redundant updates that are neither routing nor forwarding instability
- Instability: forwarding instability and policy fluctuation → change forwarding path

Routing Successive Events (Instability)

- WADiff: a route is explicitly withdrawn as it becomes unreachable, and is later replaced with an alternative route (forwarding instability)
- AADiff: a route is implicitly withdrawn and replaced by an alternative route as the original route becomes unavailable or a new preferred route becomes available (forwarding instability)
- WADup: a route is explicitly withdrawn, and reannounced later (forwarding instability or pathological behavior)

Routing Successive Events (Pathological Instability)

- AADup: A route is implicitly withdrawn and replaced with a duplicate of the original route (pathological behavior or policy fluctuation)
- WWDup: The repeated transmission of BGP withdrawals for a prefix that is currently unreachable (pathological behavior)

Findings

- BGP updates more than one order of magnitude larger than expected
- Routing information dominated by pathological updates
  - Implementation problems:
    - Routers do not maintain the history of the announcements sent to neighbors
    - When a router gets topological changes they just sent these announcements to all neighbors, irrespective of whether the router sent previous announcements about that route to a neighbor or not
  - Self-synchronization – BGP routers exchange information simultaneously → may lead to periodic link/router failures
  - Unconstrained routing policies may lead to persistent route oscillations

Findings

- Instability and redundant updates exhibits strong correlation with load (30 seconds, 24 hours and seven days periods)
  - Overloaded routers fail to respond an their neighbors withdrawn them
- Instability usually exhibits high frequency
- Pathological updates exhibits both high and low frequencies
- No single AS dominates instability statistics
- No correlation between size of AS and its impact on instability statistics
- There is no small set of paths that dominate instability statistics

Conclusions

- Routing in the Internet exhibits many undesirable behaviors
  - Instability over a wide range of time scales
  - Asymmetric routes
  - Network outages
  - Problem seems to worsen
- Many problems are due to software bugs or inefficient router architectures

Lessons

- Even after decades of experience routing in the Internet is not a solved problem
- This attests the difficulty and complexity of building distributed algorithm in the Internet, i.e., in a heterogeneous environment with products from various vendors
- Simple protocols may increase the chance to be
  - Understood
  - Implemented right