End-to-End Routing Behavior in the Internet

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Objective

• Understand the large-scale behavior of routing in the Internet
  – Routing behavior, not routing protocol
  – Analyze end-to-end measurements to determine:
    • Pathological conditions
    • Routing stability
    • Routing symmetry
Methodology

- Run Network Probe Daemon (NPD) on a number of Internet sites
  - Central control program: npd_control
  - Each NPD periodically measures the route to another NPD site using **traceroute**
  - How does **traceroute** work?
    - Start with a TTL (Time To Live) value of 1, get an ICMP reply from router that is 1 hop away
    - Next, use a TTL value of 2, get an ICMP message from router that is 2 hops away.
    - Continue until reach the destination
Methodology

• Two sets of measurements
  – D1: measure each virtual path between two sites with mean interval of 1-2 days
    • Each NPD traceroute once every two hours
    • Nov 8 to Dec 24 in 1994
  – D2: two different intervals combined
    • 60% with mean interval of 2 hours (bursts)
    • 40% with mean interval of 2.75 days
    • Paired measurements (A→B and immediately B→A)
    • Nov 3 to Dec 21 in 1995
Methodology

• Links traversed during D1 and D2
Routing Pathology

- Prevalence of routing loops
- Fluttering
- Temporary outages
- Connectivity altered mid-stream
- Infrastructure failure
- Erroneous routing
- Unreachable due to too many hops
Routing Pathology – Loops

- Persistent loops
  - Loop unsolved by end of the traceroute
  - 10 in D1 / 50 in D2
  - Two types of duration
    \((\geq 10 \text{ hrs} / \leq 3 \text{ hrs})\)
  - Clustered by location / time
  - Only one span multiple cities

Table 2: Persistent routing loops in \(D_2\)
Routing Pathology – Loops

• Temporary loops
  – Loop resolved during the traceroute
  – 2 in D1 / 23 in D2
  – In the order of seconds
  – Widespread connectivity property
    • 40 sec outage → loop in D.C. area → loss of connectivity all the way back to the source → connectivity regained
    • May reflect “ripple effects”
Routing Pathology – Fluttering

• Fluttering example (large-scale):

Route from St. Louis, Missouri to Mannheim, Germany

Solid: 17 hops
Dotted: 29 hops
Routing Pathology – Temporary outages

- **Sequence of Traceroute probes lost**
  - Temporary loss of connectivity
  - Heavy congestion lasting more than 10 sec

- In D1, 55% had no losses, 44% had 1 to 5 losses, and 0.96% had 6 or more losses (≥ 30 sec outage)

- In D2, 43% had no losses, 55% had 1 to 5 losses and 2.2% had 6 or more losses

- Outage more than 30 sec (6 or more losses)
  - Most prevalent pathology
  - Strong correlation with time-of-day patterns
In 1995, the likelihood of encountering serious end-to-end routing problem (pathology) more than doubled, and was 1 in 30

## Routing Pathology Summary

<table>
<thead>
<tr>
<th>Pathology</th>
<th>Probability</th>
<th>Trend</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Persistent loops</td>
<td>0.13–0.16%</td>
<td></td>
<td>Some lasted hours.</td>
</tr>
<tr>
<td>Erroneous routing</td>
<td>0.004–0.004%</td>
<td></td>
<td>No instances in $D_2$.</td>
</tr>
<tr>
<td>Mid-stream change</td>
<td>0.16% ─ 0.44%</td>
<td>worse</td>
<td>Suggests rapidly varying routes.</td>
</tr>
<tr>
<td>Infrastructure failure</td>
<td>0.21% ─ 0.48%</td>
<td>worse</td>
<td>No dominant link.</td>
</tr>
<tr>
<td>Outage ≥ 30 secs</td>
<td>0.96% ─ 2.2%</td>
<td>worse</td>
<td>Duration exponent. distributed.</td>
</tr>
<tr>
<td>Total pathologies</td>
<td>1.5% ─ 3.3%</td>
<td>worse</td>
<td></td>
</tr>
</tbody>
</table>
Routing Stability

• Definitions
  – Prevalence: overall likelihood to observe a particular route
  – Persistence: how long a route remains unchanged

• Three levels of granularity
  – Host, City, AS
Routing Stability – Prevalence

• $\pi_r$: Steady-state probability that a virtual path at an arbitrary point in time uses a particular route $r$

• Unbiased estimator of $\pi_r$ can be computed as

$$\hat{\pi}_r = \frac{k_r}{n}$$

• Prevalence of dominant route $p$

$$\hat{\pi}_{domp} = \frac{k_p}{n_p}$$
Routing Stability – Prevalence

Median value: 82% (host), 97% (city), 100% (AS)

In general, Internet paths are strongly dominated by a single route
Routing Stability – Persistence

- Persistence at different time scales

<table>
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<th>Time scale</th>
<th>%</th>
<th>Notes</th>
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</thead>
<tbody>
<tr>
<td>seconds</td>
<td>N/A</td>
<td>“Flutter” for purposes of load balancing. Treated separately, as a pathology, and not included in the analysis of persistence.</td>
</tr>
<tr>
<td>minutes</td>
<td>N/A</td>
<td>“Tightly-coupled routers.” We identified five instances, which we merged into single routers for the remainder of the analysis.</td>
</tr>
<tr>
<td>10’s of minutes</td>
<td>9%</td>
<td>Frequent route changes inside the network. In some cases involved routing through different cities or AS's.</td>
</tr>
<tr>
<td>hours</td>
<td>4%</td>
<td>Usually intra-network changes.</td>
</tr>
<tr>
<td>6+ hours</td>
<td>19%</td>
<td>Also intra-network changes.</td>
</tr>
<tr>
<td>days</td>
<td>68%</td>
<td>Bimodal. 50% of routes persist for under 7 days. The remaining 50% account for 90% of the total route lifetimes.</td>
</tr>
</tbody>
</table>

- 90% chance of observing a route with a duration of at least a week.
Routing Symmetry

• Analysis
  – Paired measurements to ensure asymmetry is actually being captured
  – Asymmetry is quite common (49% on a city granularity, 30% on AS granularity)
  – Large range of asymmetry involving different sites

• Size
  – Majority have single “hop” (one city / AS) asymmetry
Conclusion

- Likelihood of encountering routing pathology more than doubled between 1994 to 1995 (1.5% to 3.4%)
- Paths heavily dominated by single route
- Wide variation of persistence of route
- Asymmetry is common

- No typical Internet path
Discussion Points

• What are the consequences of fluttering?  
  – Good or Bad?

• Implications of this paper?

• Is there a better way to learn about routing behavior?
Thank you

Questions?
Methodology (backup)

• Exponential sampling
  – Time intervals: independent, exponentially distributed
    • Additive Random Sampling: unbiased
    • PASTA (Poisson Arrivals See Time Averages) principle

• Representativeness
  – Routes include non-negligible fraction of AS’s

• Devised a method to calculate and compare confidence intervals
Methodology (backup)

• Shortcomings
  – Not enough analysis provided on routing difficulties uncovered
  – Difficult to find out why and where in the path the problem occurred with end-to-end measurements
  – Centralized design issue
  – Only small subset of Internet routes
  – Only two points at a time
Routing Pathology – Route Change (backup)

• Mid Stream change
  – Route change during traceroute→outage
  – 10 in D1 / 155 in D2
  – Bimodal recovery times (seconds or minutes)

• Fluttering
  – Rapidly oscillating routing
  – Two cases (large-scale, localized)
Routing Pathology – Route Change (backup)

• Fluttering Problems
  – Difficulties from unstable network paths
  – Routing asymmetry problem
  – Unreliable path characteristic estimation
  – Out of order packets can lead to spurious “fast retransmissions” wasting bandwidth

• Localized fluttering is usually fine
Routing Pathology – Infra Failure (backup)

• Failure to reach destination
• Reasons other than loops and erroneous routing
• Estimated infrastructure availability
  – 99.7 ~ 99.9 % in D1
  – 99.4 ~ 99.6 % in D2
• Some correlation with time-of-day patterns
  – Peak: 1500~1600, 2nd Peak: 0600~0700, Min: 0900~1000
Routing Pathology – Too many hops (backup)

- **Traceroute** probe maximum of 30 hops
- None in D1 / 6 in D2
  - Internet has grown larger
- Hop count not necessarily correlated with distance
  - 1,500 km end-to-end route of 3 hops
  - 11 hops in 3 km distance