Routing

- Algorithm to establish routing table to make widely distributed endpoints appear to be directly connected.
- Key questions:
  - How to choose a best path?
  - How to scale to millions of users?
  - How to adapt to failures or changes?

Global and Local Knowledge

- Forwarding is a local decision, requiring only next-hop information.
- Computation of “best route” requires global knowledge.
- But global knowledge is challenging:
  - Hard to collect, often out of date, and big.
  - How to summarize in a locally-relevant way?

General Needs for Routing

- Compute optimal paths for each destination (need notion of ‘optimal’).
- Be robust in the case of failures/changes.
- Minimize control message exchanges.
- Minimize routing table space.

Routing Pitfalls

- **Loops**: Should local forwarding information be inconsistent with global topology, can form loops (black holes).
- **Oscillations**: Dynamically adapting to load can shift load, lead to congestion, and repeat.
- Unusual under normal operation, often due to user mis-configuration.

Fundamental Choices

- Centralized or Distributed Routing.
- Source-based versus Hop-by-hop.
- Stochastic versus Deterministic paths.
- Single or Multi-path.
- Dynamic versus Static route selection.
Routing for Packet Networks

- Internet doesn’t have very predictable traffic flow, may have unreliable links, and not terribly much redundancy (compare vs phone network)
- Routers are assumed to know:
  - address of each neighbor
  - cost of reaching each neighbor

Choices in Internet Routing

- Centralized or Distributed Routing
- Source-based versus Hop-by-hop
- Stochastic versus deterministic paths
- Single or multi-path
- Dynamic versus static route selection

Distance Vector & Link-State Routing

- Distance-Vector
  - tell neighbors about distances to all destinations
  - node’s computation depends on neighbors
- Link-State
  - tell all routers distance to each neighbor
  - each router computes its best paths
- Both are distributed algorithms

Distance Vector Operation

- Each router maintains a distance vector:
  - (dest, cost) tuple, one per destination
  - initialize with lowest costs to attached neighbors, and highest cost (infinity) to all non-neighbors
- Periodically send copy of distance vector to all neighbors

DV Route Computation

- Upon receiving a distance vector, compare current cost to destination with calculated cost using the sending router to reach the destination
- If neighbor path results in lower cost, switch
- Assuming no changes, eventually converges to proper shortest paths
Problems with DV Approaches

- If links or routers fail, DV approach may fail to converge.
- Problem is related to route computation in one router being "hidden" from neighbors (choice is internal).
- Downstream routers do not have enough information to avoid bad next-hop choices (which may lead to looping).

The Count to Infinity Problem

- Assume we use hop count as metric.
- A uses B and B uses C to reach Internet with costs 3, 2, 1, respectively.

- C's Internet link breaks.
- C erroneously switches to B, increases its cost to B's +1 = 3.
- B's path cost is now C's plus 1 = 4.
- A hasn't realized what has happened yet.
The Count to Infinity Problem

- B’s path cost is still 4
- A’s & C’s cost are now B’s + 1 = 5

Count to Infinity Problem

- Classic DV protocols (and some with modifications) can suffer this C2I problem
- Example indicates the trivial C2I problem, but even with extensions, DV schemes can be subject to C2I under more complicated topologies
- Many enhancements have been suggested...

Path Vector

- One approach to solve C2I problem
- Extend distance vectors to be path vectors:
  - annotate each entry in the DV by the path used to compute the cost advertised
- Expands routing table size and control message size
- Used by BGP (later)

Triggered Updates

- Classical (Bellman/Ford) DV suggests re-advertising DV on any change
- Could be quite frequent, especially given highly dynamic costs (delay, utilization)
- So, slow down advertising rate (adversely affects C2I problem) but send immediate updates on link failures

Split Horizon

- Router never advertises the cost of a destination to neighbor N if N is the current next-hop for the destination
- Solves trivial C2I problem
- Poison reverse: same idea, but instead of no advertisement, use infinity cost instead [used by RIP]
Source Tracing

- Augment DV to include penultimate router on path to destination
- Sufficient information for a source to construct entire path to destination
- Like path vector, but less table space

Link-State Routing

- In DV, the path or cost to destination is partially determined by its neighbors
- With LS, every router gets complete topology information. Using same algorithms, will compute same paths (avoiding loops)
- Two components: topology dissemination and shortest-path algorithm

LS Components

- Purpose of topology dissemination is to establish a consistent link state database in each router
- Once established, each router individually computes shortest paths from it to all destinations

LS Topology Dissemination

- Each router sends link-state advertisements (LSAs) using controlled flooding [max 1 hop away like RPB]:
  - (router ID, neighbor's ID, cost to neighbor)
- Flooding is fast and can easily be made reliable using acknowledgements
- LSAs never traverse same link >1 time in the same direction

LSA Sequence Numbers

- When links fail, adjacent routers detect failure and send infinity LSA
- Need a way for this LSA to “override” older, stored LSAs
- If the network is to continue running for a long time, could over-run the field allocated for sequence numbers

Wrapped Sequence Numbers

- If adding to a high sequence number results in a small value, it has wrapped
- Use very large numbers, and if the difference between two possibly adjacent number is huge, assume a wrap
- So, a is older than b across space N if:
  - a < b and |b - a| < N/2, or
  - a > b and |b - a| > N/2
Bootstrapping Seq. Numbers

- What sequence number should a booting router use for its LSAs?
- Might risk flooding messages which are always ignored
- Clever Solution: Lollipop Sequence Space [Perlman83]

Lollipop Sequence Space

- Better solution for newly-booted routers
- Scheme where new seq number is unique from all others it could have used
- Partition space of size N into three parts:
  - \([-N/2..0]\), 0, \([N/2..N/2-1]\]
  - Start with \(-N/2\), then \(-N/2+1\), etc...
  - Once 0 reached, stay in circular part of space

Why Called Lollipop?

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- Scheme where new seq number is unique from all others it could have used
- Partition space of size N into three parts:
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Lollipop Sequence Space: Comparisons

- \(a\) is older than \(b\) on span \(N\) if:
  - \(a < 0\) and \(a < b\), or
  - \(a > 0\), \(a < b\), and \((b - a) < N/4\), or
  - \(a > 0\), \(b > 0\), and \((a - b) > N/4\)
- \([-N/2\) the oldest seq number]
- When receiving an old number, must inform sender of latest seq number

Partitioning

- A network partition (division) causes LS databases on the sides of the partition to diverge
- If the partition is repaired, simple exchange of updates are not sufficient; need to resynchronize entire LS database
- Version numbers used to identify which entries need to be exchanged

Database Description Records

- Contain \((\text{link ID}, \text{version})\) pairs
- Like LSAs but with less info, so cheaper to exchange
- Allows routers to determine the set of records they lack or are out-of-date
- Routers then request the records they need using request/response protocol
Link vs Router Failure

- Link failures detected by routers which can flood this info directly
- Most LS protocols use HELLO messages to detect router failure
- Failure to respond to some number of the HELLO queries indicates failed router and causes flooding of corresponding info

Computing Shortest Paths

- Once LSAs are reliably flooded, need to execute shortest path for all destinations
- Dijkstra's shortest path algorithm
  - Computes shortest paths from root (local router) to all possible destinations
  - Greedy algorithm which adds the least cost path to next candidate node to current shortest path set of nodes

Dijkstra's Shortest Path

- Two sets P (permanent) & T (temporary)
- P: in current SP set, T: not yet in set
  - P: initially current node, T: initially NULL
- Every node in T must be reachable by a path from a node in P
- Find every way to reach the T node from a P node; add min cost one to P, repeat

Dijkstra's Shortest Path

- More precisely:
  - For the node p just added to P, add each of its neighbors n to T such that:
    - If n is not in T, add it, annotating it with p's ID and the cost to reach it through p
    - If n is already in T and path through p has lower cost, remove earlier instance of n and add new instance annotated with p's ID and cost to reach it through p
  - Pick the node n that has the smallest cost in T and, if not already in P, add it to P. Use its annotation to determine the router p to use to reach n. If T is empty, done.

Shortest Path

- Algorithm performs $O((E + N) \log N)$ [E: link, N: router]; if E remains relatively constant with increased N, just $O(N \log N)$
- At completion of algorithm, each router knows the router on the shortest path to reach it
- Can use technique like source-tracing to compute next hops for every destination

DV versus LS Routing

- Conventional wisdom is that LS is more stable and avoids loops better, but loops may form during topology changes
- Modifications to basic DV scheme takes care of loops
- LSAs might carry data using multiple metrics [also recall easy multicast]
DV versus LS Routing [2]

- LS schemes tend to converge faster than classical DV, but not clear with triggered updates and other modifications
- DV comparably simple due to complexity in avoiding corruption of LS database
- DV usually requires less memory and CPU time (no Dijkstra computation)