Scalable Routing

Outline

- Routing Algorithms
- Scalability

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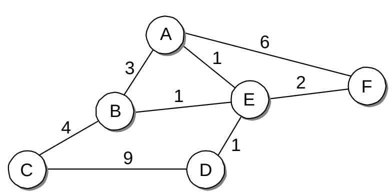
Overview

- Forwarding vs Routing
  - forwarding: to select an output port based on destination address and routing table
  - routing: process by which routing table is built
- Network as a Graph



- Problem: Find lowest cost path between two nodes
- Factors
  - static: topology
  - dynamic: traffic load and link failure

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Distance Vector Algorithm

- Each node maintains a set of triples
  - **`(Destination, Cost, NextHop)`**
- Directly connected neighbors exchange updates
  - periodically (on the order of several seconds)
  - whenever table changes (called *triggered* update)
- Each update is a list of pairs:
  - (**`Destination, Cost)`**
- Update local table if receive a “better” route
  - smaller cost
  - higher cost from the current NextHop (e.g. link failures)
- Refresh existing routes; delete if they time out

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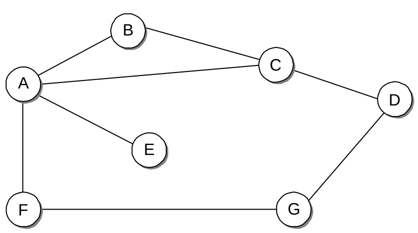
Example



Destination	Cost	NextHop
A	1	A
C	1	C
D	2	C
E	2	A
F	2	A
G	3	A

pp. 275 ~ 277, Tables 4.5 – 4.8

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Routing Loops

- Example 1: Fast Convergence
  - F detects that link to G has failed
  - F sets distance to G to infinity and sends update t o A
  - A sets distance to G to infinity since it uses F to reach G
  - A receives periodic update from C with 2-hop path to G
  - A sets distance to G to 3 and sends update to F
  - F decides it can reach G in 4 hops via A
- Example 2: "Count to Infinity" due to the loop A-B-C
  - link from A to E fails
  - A advertises distance of infinity to E
  - B and C still advertise a distance of 2 to E *periodically*
    - NextHop is not in updates
    - Timing: sent before B, C receive (E, ∞) from A, received after (E, ∞).
  - B decides it can reach E in 3 hops; advertises this to A
  - A decides it can read E in 4 hops; advertises this to C
  - C decides that it can reach E in 5 hops…

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Loop-Breaking Heuristics

- Set infinity to 16
  - Nodes can be reached beyond 16 links.
  - RIP (Routing Information Protocol)
- Split horizon
  - For the triple (dest, cost, X), don't include (dest, cost) in the update sent to X.
  - with poison reverse: for the triple (dest, cost, X), include (dest, ∞) in the update sent to X.
  - Solve loops involving two nodes (e.g. G x A ↔ B)
  - Cannot but solve loops of three or more nodes

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Link State

- Strategy
  - send to all nodes (not just neighbors) information about directly connected links (not entire routing table)
- Link State Packet (LSP)
  - id of the node that created the LSP
  - cost of link to each directly connected neighbor
  - sequence number (SEQNO)
  - time-to-live (TTL) for this packet

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Link State (cont)

- Reliable flooding
  - store most recent (see seqno) LSP from each node
  - forward LSP to all nodes but one that sent it
  - generate new LSP periodically
    - increment SEQNO
  - start SEQNO at 0 when reboot
  - decrement TTL of each stored LSP
    - discard when TTL=0

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Route Calculation

- Dijkstra's shortest path algorithm
  - See example on pp. 286 - 287
- Let
  - *N* denotes set of nodes in the graph
  - *l* (*i*, *j*) denotes non-negative cost (weight) for edge (*i*, *j*)
  - *s* denotes this node
  - *C*(*n*) denotes cost of the path from *s* to node *n*
  - *M* denotes the set of nodes incorporated so far

```
M = {s}
for each n in N - {s}
   C(n) = l(s, n)
while (N != M)
   M = M union {w} such that C(w) is the minimum for
       all w in (N - M)
   for each n in (N - M)
      C(n) = MIN(C(n), C (w) + l(w, n ))
```

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Metrics

- Assigning "1" to each link is inefficient
  - Satellite links have higher propagation delays.
  - Links have different capacities
    - OSPF uses *100Mbps / C*
  - Links have dynamic traffic loads
- New ARPANET metric
  - for each packet, record its arrival time (**AT**) and record departure time (**DT**)
  - when link-level ACK arrives, compute

    Delay = (DT - AT) + Transmit + Latency
  - link cost = average *delay* over some time period
  - if timeout (link-level ACK used), reset **DT** to departure time for retransmission
    - **DT- AT** captures not only queuing delay, but also the link reliability

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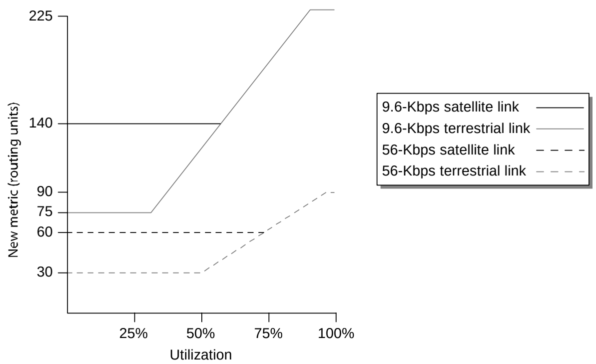
Metrics (cont)

- Problems:
  - under heavy load, DT – AT dominates the delay. Traffic moves back and forth between links
  - A 56 kbps looks <u>too</u> costly than a 9.6 kbps terrestrial link (due to the long delay), making its bandwidth underutilized.
- Revised Metrics (p.293)

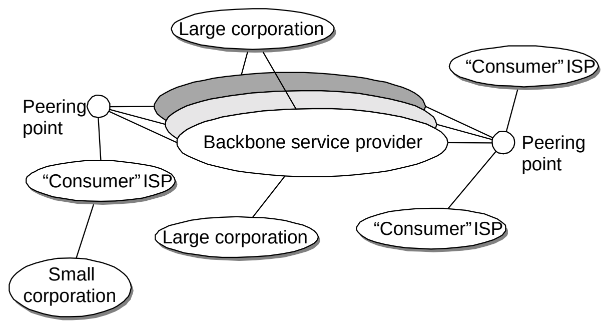


DV vs. LS

- LS is more stable and robust
  - With DV, incorrect computation can spread to entire network.
- LS avoids loops better
- LS converges faster than DV
- LS reveals the complete topology.
- DV requires less memory and CPU time
  - maintains neighbor states only
  - no Dijkstra's algorithm
  - Since LS floods LSP to entire network, *seqno* and hence *checksum* are introduced to guarantee consistency

Internet Structure Today

- Large corporation networks can be connected to Backbone.
- Consumers can be connected to ISPs
- Many providers arrange to interconnect to each other at a single “peering” point.



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How to Make Routing Scale

- Flat versus Hierarchical Addresses
- Inefficient use of Hierarchical Address Space
  - class C with 2 hosts (2/255 = 0.78% efficient)
  - class B with 256 hosts (256/65535 = 0.39% efficient)
- Still Too Many Networks
  - routing tables and route propagation protocols do not scale
- Subnetting
  - divide a “large” network number (e.g. class B) into smaller network spaces for physical networks with small numbers (< 65535) of hosts.
- Supernetting
  - aggregate “small” network numbers (e.g. class C) into a “larger” network number for a physical network with more than 255 hosts

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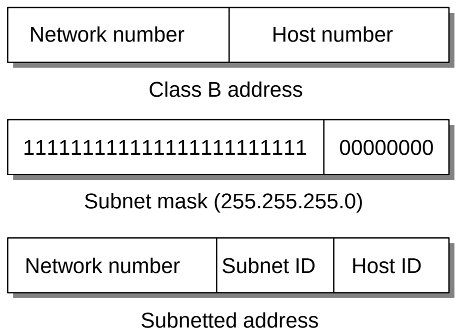
Subnetting

- Add another level to address/routing hierarchy: *subnet*
- *Subnet masks* define variable partition of host part
  - For networks with small number of hosts.
  - Do not have to align with byte boundary
- Subnets visible only within site
  - routing scalability



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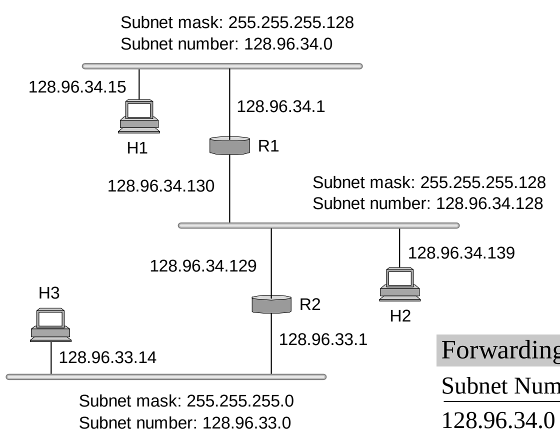
Subnet Example



Forwarding table at router R1

Subnet Number	Subnet Mask	Next Hop
128.96.34.0	255.255.255.128	interface 0
128.96.34.128	255.255.255.128	interface 1
128.96.33.0	255.255.255.0	R2

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Forwarding Algorithm

- External routers only see class B network number: 128.96
  - One entry is kept for all hosts under 128.96
- Internal routers and hosts use subnet masks:
  - **`(SubnetNum, SubnetMask, NextHop)`**
  - Routers search for a match:
    `dest IP & SubnetMask == SubnetNum ?`
    `(SubnetNum & SubnetMask == SubnetNum)`
  - Sending hosts use the above to see whether the dest IP is in the local subnet (e.g H1 → H2).
  - Use a default router if nothing matches

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Supernetting

- Assign block of contiguous network numbers to nearby networks
  - Called CIDR: Classless Inter-Domain Routing
- Use a bit mask (CIDR mask) to identify block size
- All routers must understand CIDR addressing
- Efficient address allocation and Scalable Routing
- Used by BGP
- Forwarding: longest prefix match based on PATRICIA tree

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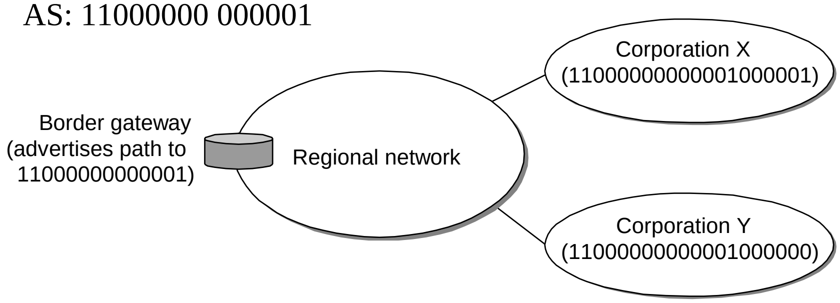
Example: 2 levels of Supernetting

- Corporation Y: 11000000 00000100 0000
- Corporation X:
  - Class C numbers: 192.4.16, …… 192.4.32 → 11000000 00000100 0001
- ……
- AS: 11000000 000001



Route Propagation

- Know a smarter router
  - hosts know local default router
  - local routers know site routers
  - site routers know core router
  - core routers know everything
- Autonomous System (AS)
  - corresponds to an administrative domain
  - examples: University, company, backbone network
  - assign each AS a 16-bit number
- Two-level route propagation hierarchy
  - interior gateway protocol (each AS selects its own)
  - exterior gateway protocol (Internet-wide standard)

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Popular Interior Gateway Protocols

- RIP: Route Information Protocol
  - distance-vector algorithm
  - based on hop-count
- OSPF: Open Shortest Path First
  - recent Internet standard
  - uses link-state algorithm
  - supports authentication
  - supports load balancing
    - Install routes with same costs. Attempt to send approximately the same amount of traffic along each of the routes. (e.g. destination-based)

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BGP-4: Border Gateway Protocol

- AS Types
  - stub AS: has a single connection to one other AS
    - carries local traffic only
  - multihomed AS: has connections to more than one AS but refuses to carry transit traffic
  - transit AS: has connections to more than one AS
    - carries both transit and local traffic
- Each AS has:
  - one or more border routers
  - BGP *speakers* that advertise:
    - local networks
    - other reachable networks (transit AS only)
    - gives *path* information

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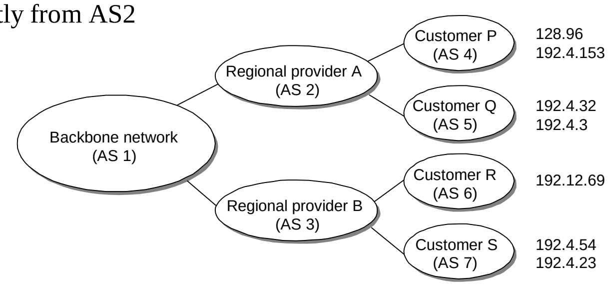
BGP Example

- Speaker for AS2 advertises reachability to P and Q
  - network 128.96, 192.4.153, 192.4.32, and 192.4.3, can be reached directly from AS2



- Speaker for backbone advertises
  - networks 128.96, 192.4.153, 192.4.32, and 192.4.3 can be reached along the path (AS1, AS2).
- Speaker can cancel previously advertised paths

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IP Version 6

- Classless 128-bit addresses
  - Every atom in the universe can have an IP address.
- IPv4-compatible IPV6 address: zero-extend IPv4 address to 128 bits
- 010… Provider-based Unicast Address
  - Similar to CIDR in IPv4
  - A provider with few customers could have a longer prefix (less address space)
  - All addresses in Europe, for example, can have a common Registry ID, for routing scalability.

3	m	n	o	p	125- m- n- o- p
010	RegistryID	ProviderID	SubscriberID	SubnetID	InterfaceID

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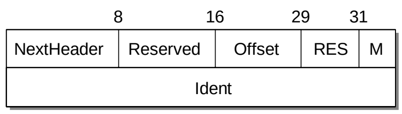
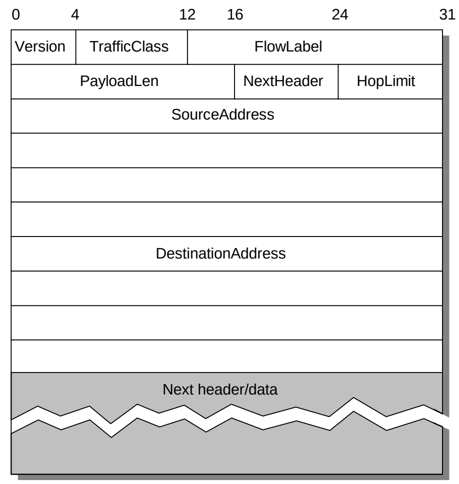
IPv6 Header

- Version = 6
- QoS with Priority and Flow Label
- NextHeader: Protocol or Options
  - E.g. extension header for IPv6 fragmentations





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