Routing

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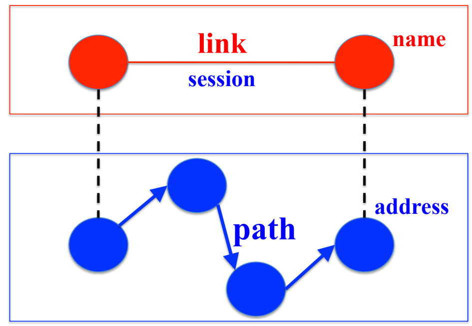
COS 461: Computer Networks
Lectures: MW 10-10:50am in Architecture N101

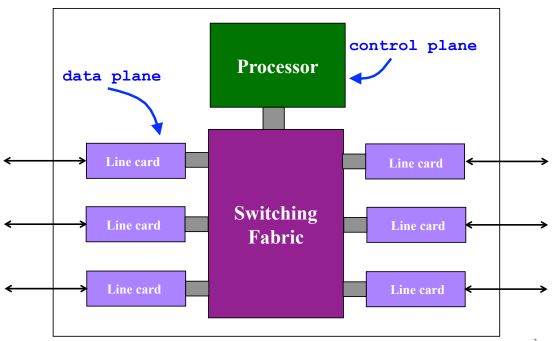
http://www.cs.princeton.edu/courses/archive/spr12/cos461/

Routing: Mapping Link to Path



2

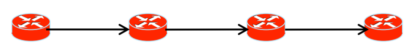
Data and Control Planes



3

Routing vs. Forwarding

- **Routing:** control plane
  - Computing paths the packets will follow
  - Routers talking amongst themselves
  - Creating the forwarding tables
- **Forwarding:** data plane
  - Directing a data packet to an outgoing link
  - Using the forwarding tables



4

Routing Protocols

- What does the protocol compute?
  - E.g., shortest paths
- What algorithm does the protocol run?
  - E.g., link-state routing
- How do routers learn end-host locations?
  - E.g., injecting into the routing protocol

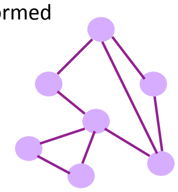
5

What Does the Protocol Compute?

6

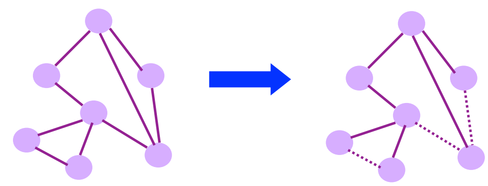
Different Ways to Represent Paths

- Static model
  - *What* is computed, i.e., what is the outcome
  - Not *how* the computation is performed
- Trade-offs
  - State to represent the paths
  - Efficiency of the paths
  - Ability to support multiple paths
  - Complexity of path computation



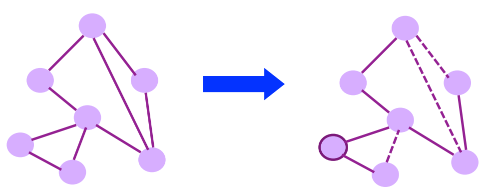
Spanning Tree

- One tree that reaches every node
  - Single path between each pair of nodes
  - No loops, so can support broadcast easily
  - But, paths are long, and some links not used



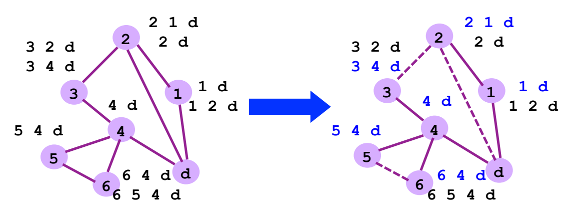
Shortest Paths

- Shortest path(s) between pairs of nodes
  - A shortest-path tree rooted at each node
  - Min hop count or min sum of edge weights
  - Multipath routing is limited to Equal Cost MultiPath



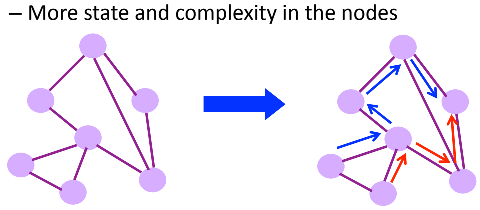
Locally Policy at Each Hop

- Locally best path
  - Local policy: each node picks the path it likes best
  - … among the paths chosen by its neighbors



End-to-End Path Selection

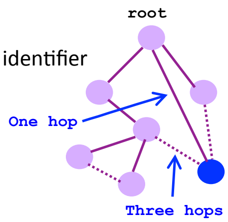
- End-to-end path selection
  - Each node picks its own end to end paths
  - … independent of what other paths other nodes use
  - More state and complexity in the nodes



How to Compute Paths?

Spanning Tree Algorithm

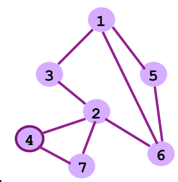
- Elect a root
  - The switch with the smallest identifier
  - And form a tree from there
- Algorithm
  - Repeatedly talk to neighbors
    - "I think node Y is the root"
    - "My distance from Y is d"
  - Update based on neighbors
    - Smaller id as the root
    - Smaller distance d+1



Used in Ethernet LANs

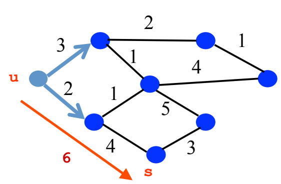
Spanning Tree Example: Switch #4

- Switch #4 thinks it is the root
  - Sends (4, 0, 4) message to 2 and 7
- Switch #4 hears from #2
  - Receives (2, 0, 2) message from 2
  - … and thinks that #2 is the root
  - And realizes it is just one hop away
- Switch #4 hears from #7
  - Receives (2, 1, 7) from 7
  - But, this is a longer path, so 4 prefers 4-2 over 4-7-2
  - And removes 4-7 link from the tree



Shortest-Path Problem

- Compute: *path costs* to all nodes
  - From a given source u to all other nodes
  - Cost of the path through each outgoing link
  - Next hop along the least-cost path to s



Link State: Dijkstra's Algorithm

- Flood the topology information to all nodes
- Each node computes shortest paths to other nodes

Initialization

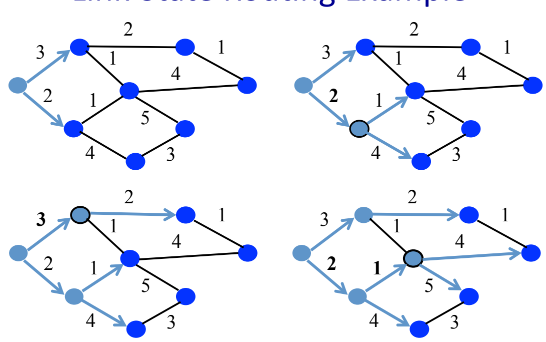
```
S = {u}
for all nodes v
  if (v is adjacent to u)
    D(v) = c(u,v)
  else D(v) = ∞
```

Loop

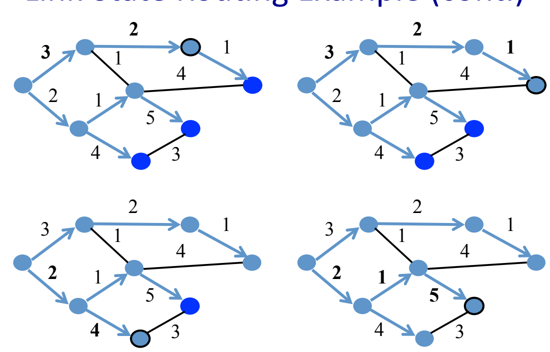
```
add w with smallest D(w) to S
update D(v) for all adjacent v:
   D(v) = min{D(v), D(w) + c(w,v)}
until all nodes are in S
```

Used in OSPF and IS-IS

Link-State Routing Example

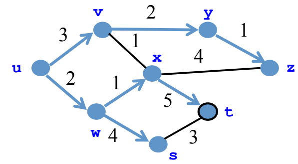


Link-State Routing Example (cont.)



Link State: Shortest-Path Tree

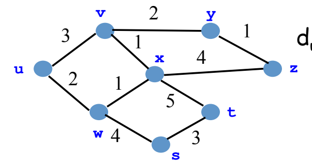
- Shortest-path tree from u
- Forwarding table at u



	link
v	(u,v)
w	(u,w)
x	(u,w)
y	(u,v)
z	(u,v)
s	(u,w)
t	(u,w)

Distance Vector: Bellman-Ford Algo

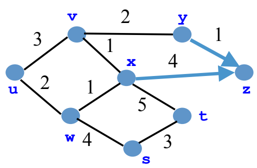
- Define distances at each node x
  - $d_x(y)$ = cost of least-cost path from x to y
- Update distances based on neighbors
  - $d_x(y) = \min \{c(x,v) + d_v(y)\}$ over all neighbors v



$d_u(z) = \min\{c(u,v) + d_v(z),$
$c(u,w) + d_w(z)\}$

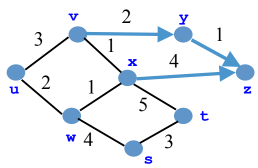
Used in RIP and EIGRP

Distance Vector Example



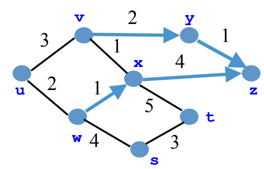
$d_y(z)=1$

$d_x(z)=4$

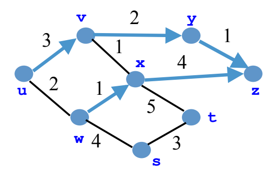


$d_v(z)= \min\{2+d_y(z),$
$1+d_x(z)\}$
$= 3$

Distance Vector Example (Cont.)



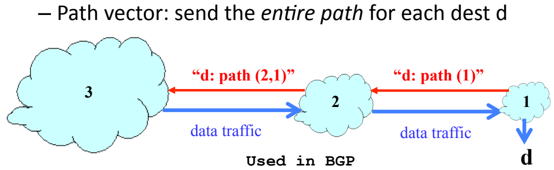
$d_w(z)= \min\{1+d_x(z),$
$4+d_s(z),$
$2+d_u(z)\}$
$= 5$



$d_u(z)= \min\{3+d_v(z),$
$2+d_w(z)\}$
$= 6$

Path-Vector Routing

- Extension of distance-vector routing
  - Support flexible routing policies
- Key idea: advertise the entire path
  - Distance vector: send *distance metric* per dest d
  - Path vector: send the *entire path* for each dest d

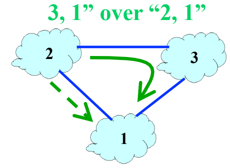


Used in BGP

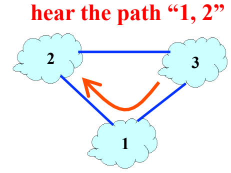
Path-Vector: Flexible Policies

- Each node can apply local policies
  - Path selection: Which path to use?
  - Path export: Which paths to advertise?

Node 2 prefers "2, 3, 1" over "2, 1"

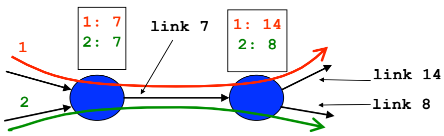


Node 1 doesn't let 3 hear the path "1, 2"



End-to-End Signaling

- Establish end-to-end path in advance
  - Learn the topology (as in link-state routing)
  - End host or router computes and signals a path
    - Signaling: install entry for each circuit at each hop
    - Forwarding: look up the circuit id in the table



Used in MPLS with RSVP

25

Source Routing

- Similar to end-to-end signaling
  - But the data packet carries the hops in the path
- End-host control
  - Tell the end host the topology
  - Let the end host select the end-to-end path
- Variations of source routing
  - Strict: specify every hop
  - Loose: specify intermediate points

Used in IP source routing (but almost *always* disabled)

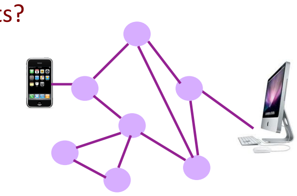
26

Learning Where the Hosts Are

27

Finding the Hosts

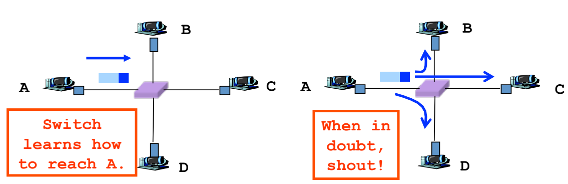
- Building a forwarding table
  - Computing paths between network elements
  - … and figuring out where the end-hosts are
- How to find the hosts?
  - Learning/flooding
  - Injecting into the routing protocol
  - Dissemination using a different protocol
  - Directory service



28

Learning and Flooding

- When a frame arrives
  - Inspect the *source* address
  - Associate address with the incoming interface
- When the frame has an unfamiliar *destination*
  - Forward out all interfaces
  - … except incoming interface

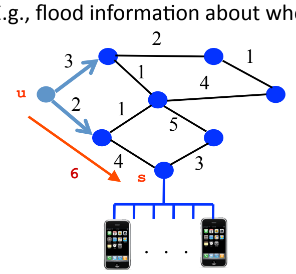


Used in Ethernet LANs

29

Inject into Routing Protocol

- Treat the end host (or subnet) as a node
  - And disseminate in the routing protocol
  - E.g., flood information about where addresses attach

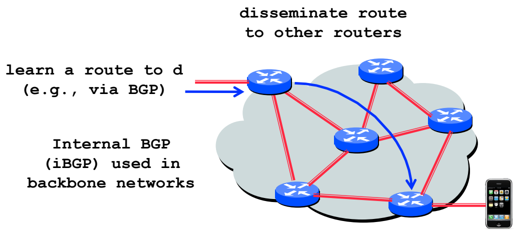


Used in OSPF and IS-IS, especially in enterprise networks

30

Disseminate With Another Protocol

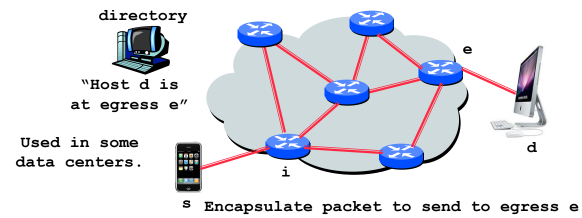
- Distribute using another protocol
  - One router learns the route
  - … and shares the information with other routers



31

Directory Service

- Contact a service to learn the location
  - Look up the end-host or subnet address
  - … to determine the label to put on the packet



32

Conclusions: Many Different Solutions

- Ethernet LAN and home networks
  - Spanning tree, MAC learning, flooding
- Enterprise
  - Link-state routing, injecting subnet addresses
- Backbone
  - Link-state routing inside, path-vector routing with neighboring domains, and iBGP dissemination
- Data centers
  - Many different solutions, still in flux

33

Coming Next…

- Friday precept
  - Host configuration
- Monday lecture
  - Guest lecture on congestion control
  - Professor Michael Freedman
- Wednesday lecture
  - Quality of service

34