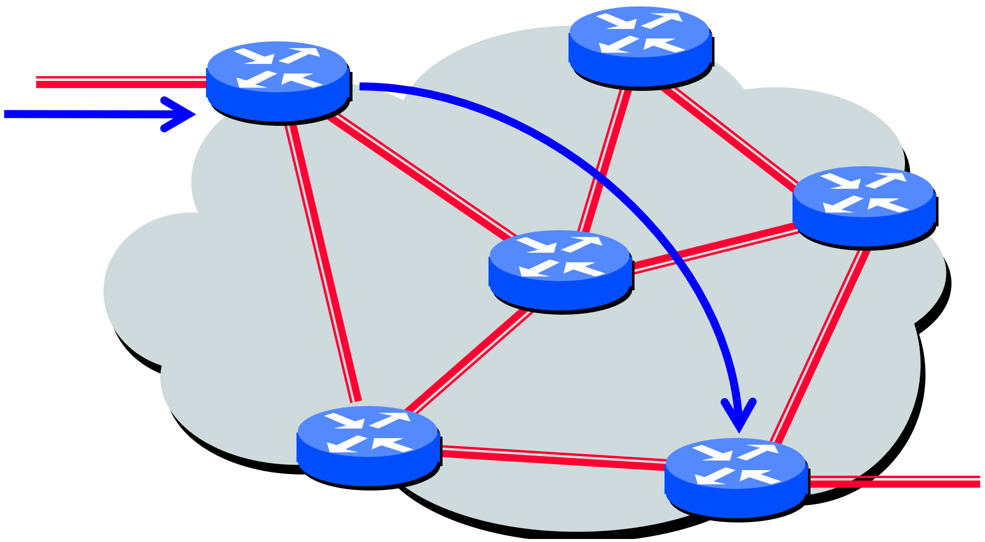


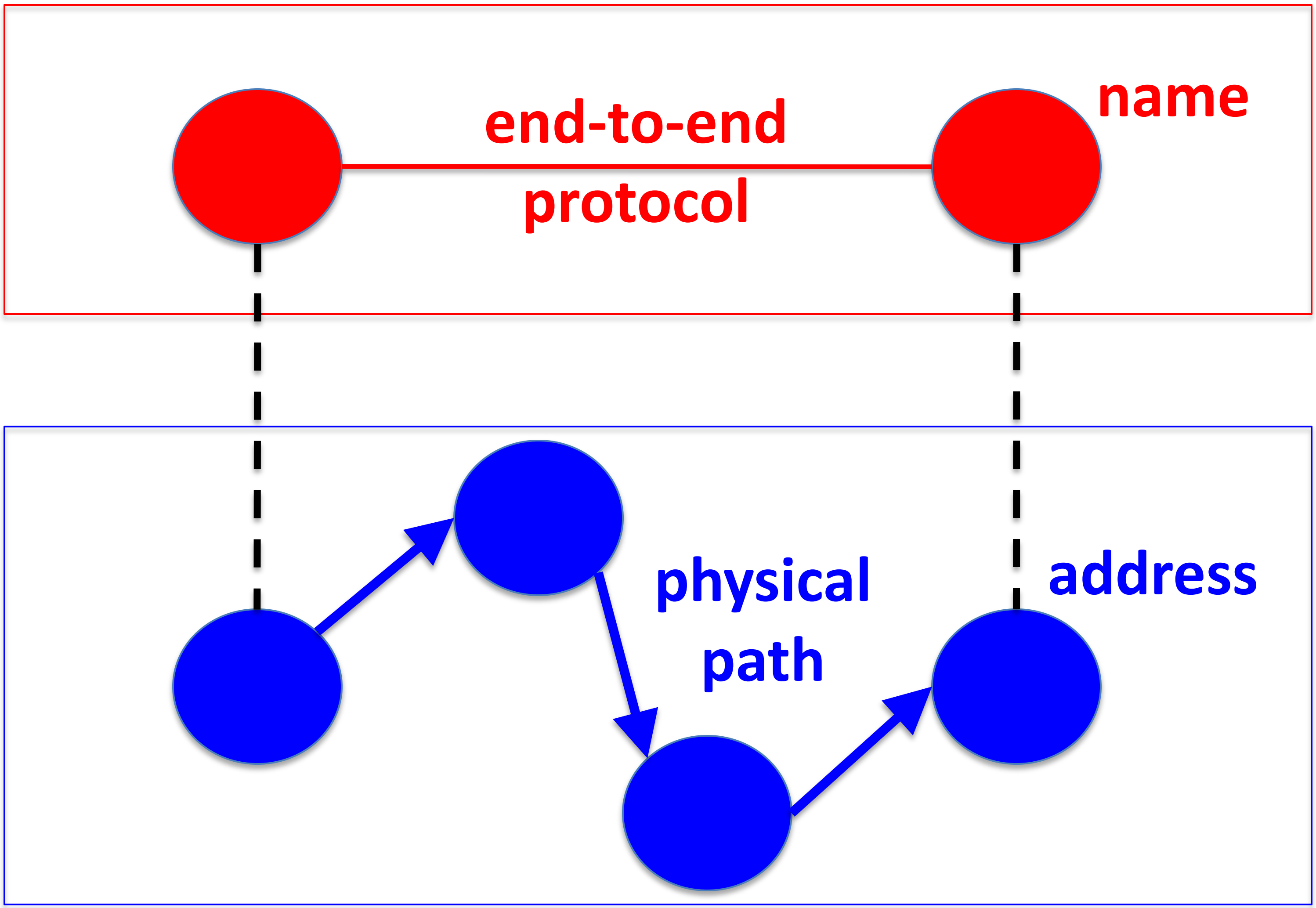
Routing

Kyle Jamieson

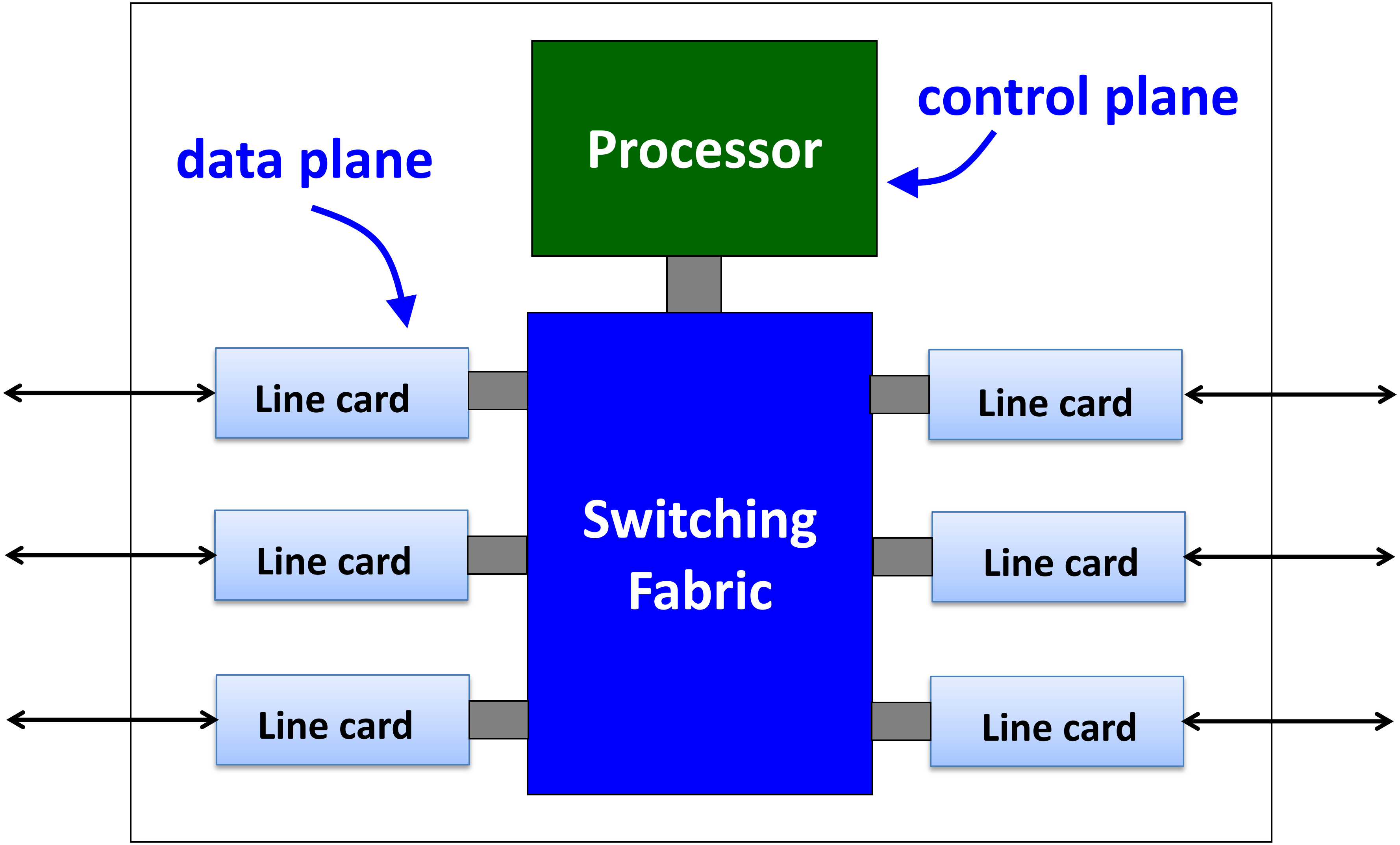
Lecture 9

COS 461: Computer Networks

Routing: Mapping End-to-End Communication to Path



Data and Control Planes



Routing vs. Forwarding

- **Routing:** control plane
  - Computing paths the packets will follow
  - Routers talk among themselves
    - → **Create the forwarding tables**
- **Forwarding:** data plane
  - Directing a data packet to an outgoing link
  - Using the forwarding tables

Three Issues to Address

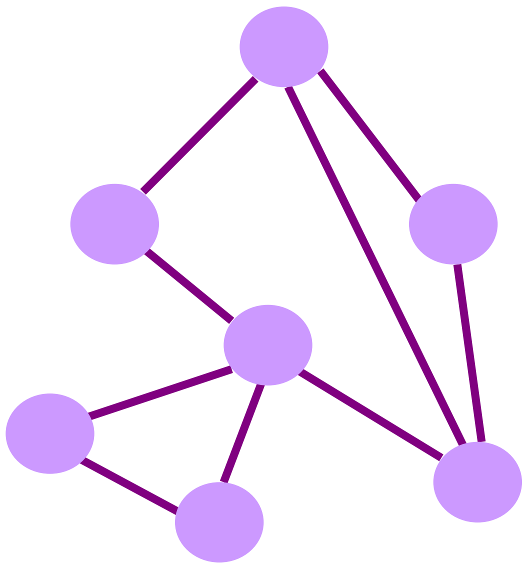
- What does the protocol compute?
  - E.g., shortest paths
- What algorithm does the protocol run?
  - E.g., link-state routing
- How do routers learn end-host locations?
  - E.g., injecting into the routing protocol

What Does the Protocol Compute?

Different Types of Paths

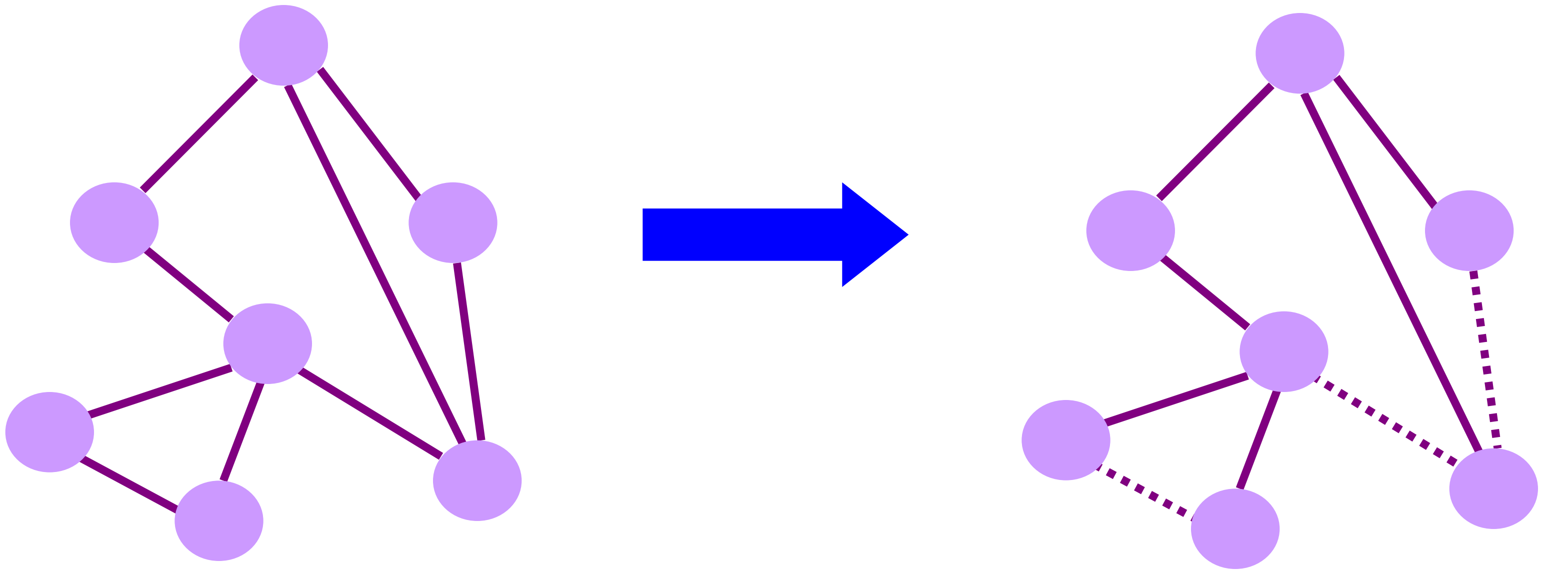
- Static model: ***What* is computed** (not *how* computation performed)

- Trade-offs
  - State to represent the paths
  - Efficiency of the paths
  - Ability to support multiple paths
  - Complexity of path computation



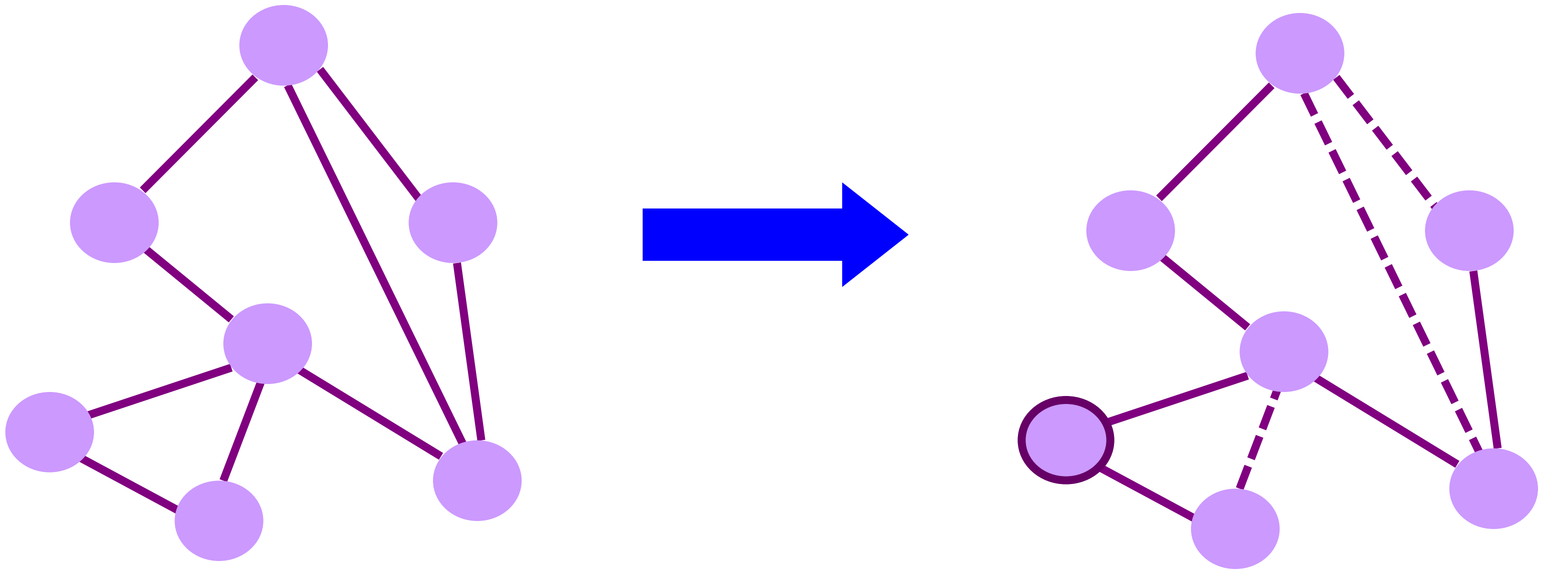
Spanning Tree

- 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



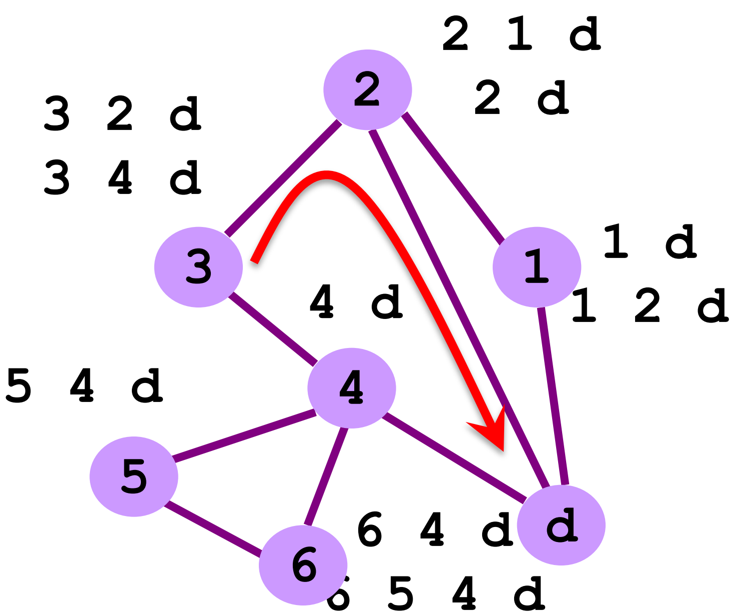
Shortest Paths

- 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



Local Policy at Each Hop

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



Local Policy at Each Hop

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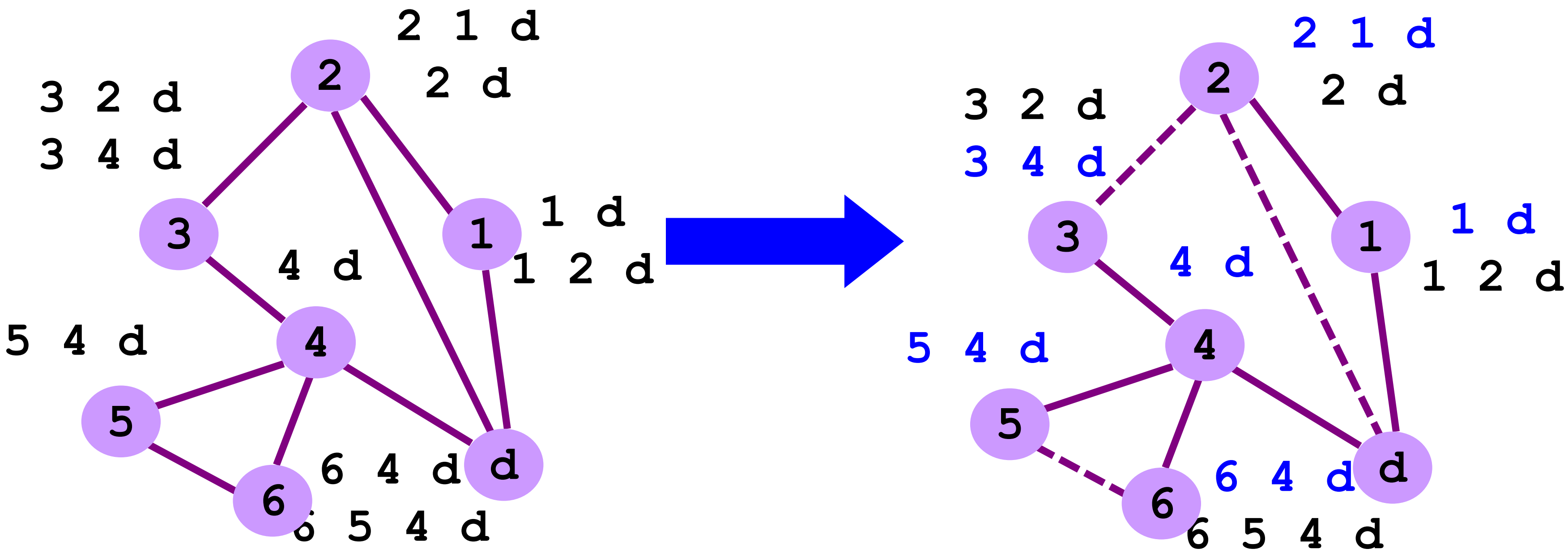
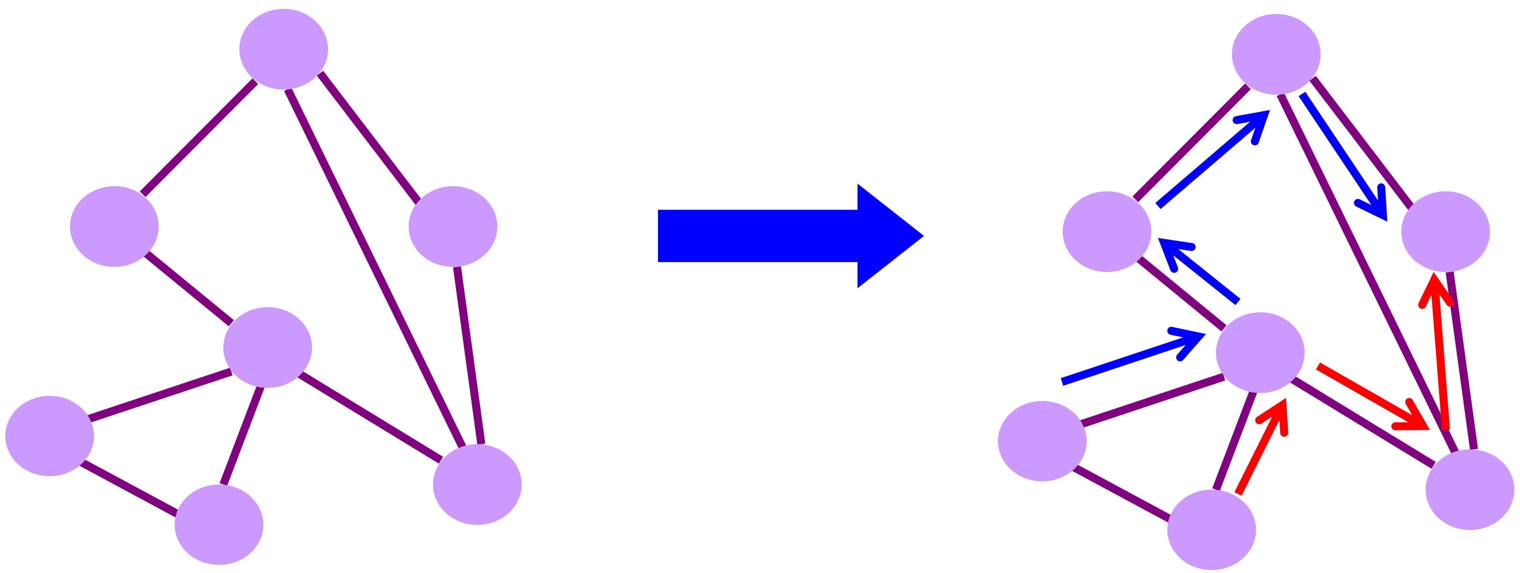


End-to-End Path Selection

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



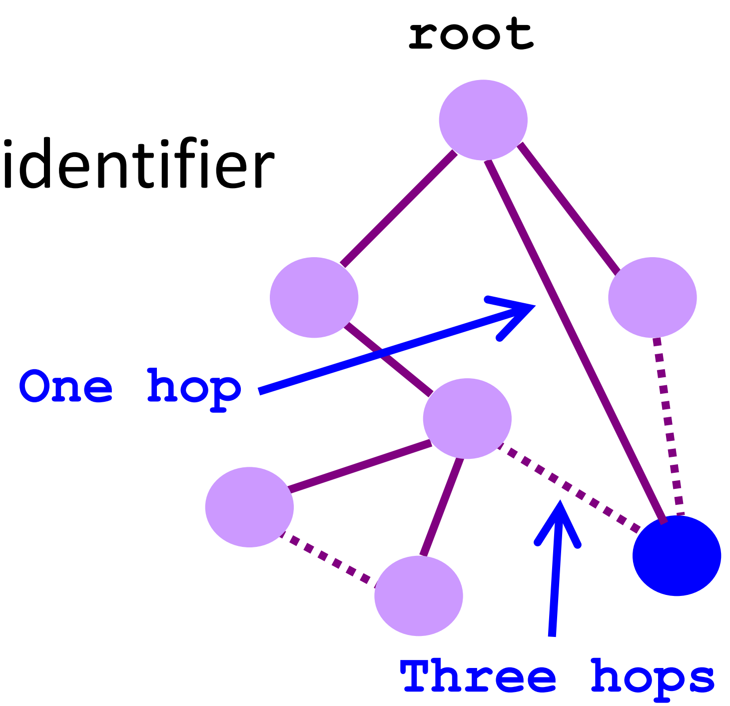
How to Compute Paths?

Spanning Tree

Shortest Paths

Spanning Tree Algorithm

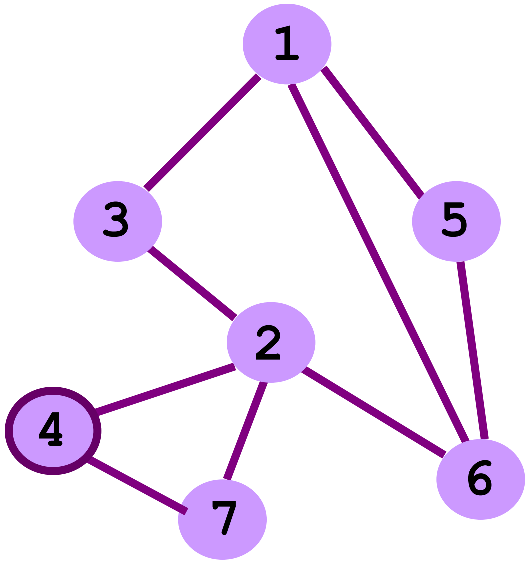
- Elect a root
  - The switch with the smallest identifier
  - And form a tree from there
- Algorithm
  - Repeatedly talk to neighbors
    - "I think node Y is the root"
    - "My distance from Y is d"
  - Update based on neighbors
    - **First priority:** Prefer smaller id as the root
    - **Second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



Used in Ethernet LANs

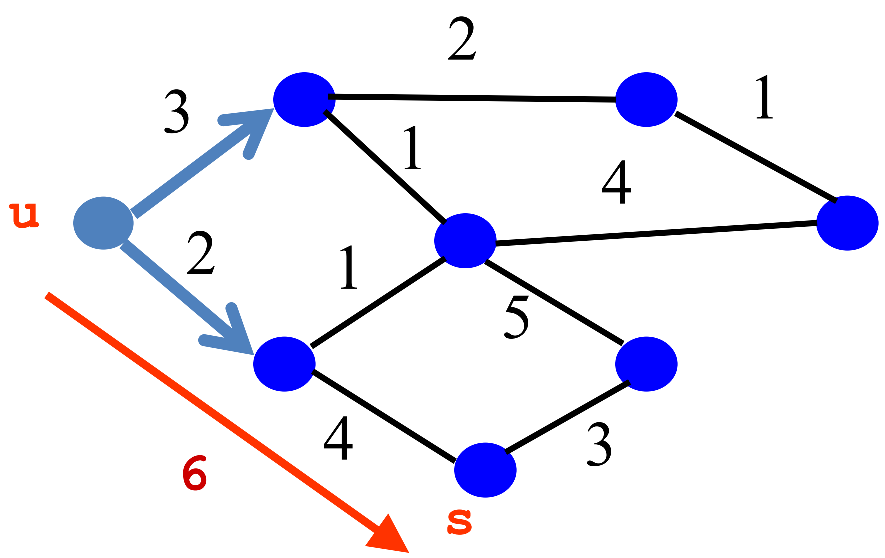
Spanning Tree Example: Switch #4

- Switch #4 thinks it is the root
  - Sends **(4, 0, 4)** message to 2 and 7
  - Notation: (my root, my distance, my ID)
- Switch #4 hears from #2
  - Receives **(2, 0, 2)** message from 2
  - Thinks #2 is root and it's 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
  - Edges: ***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

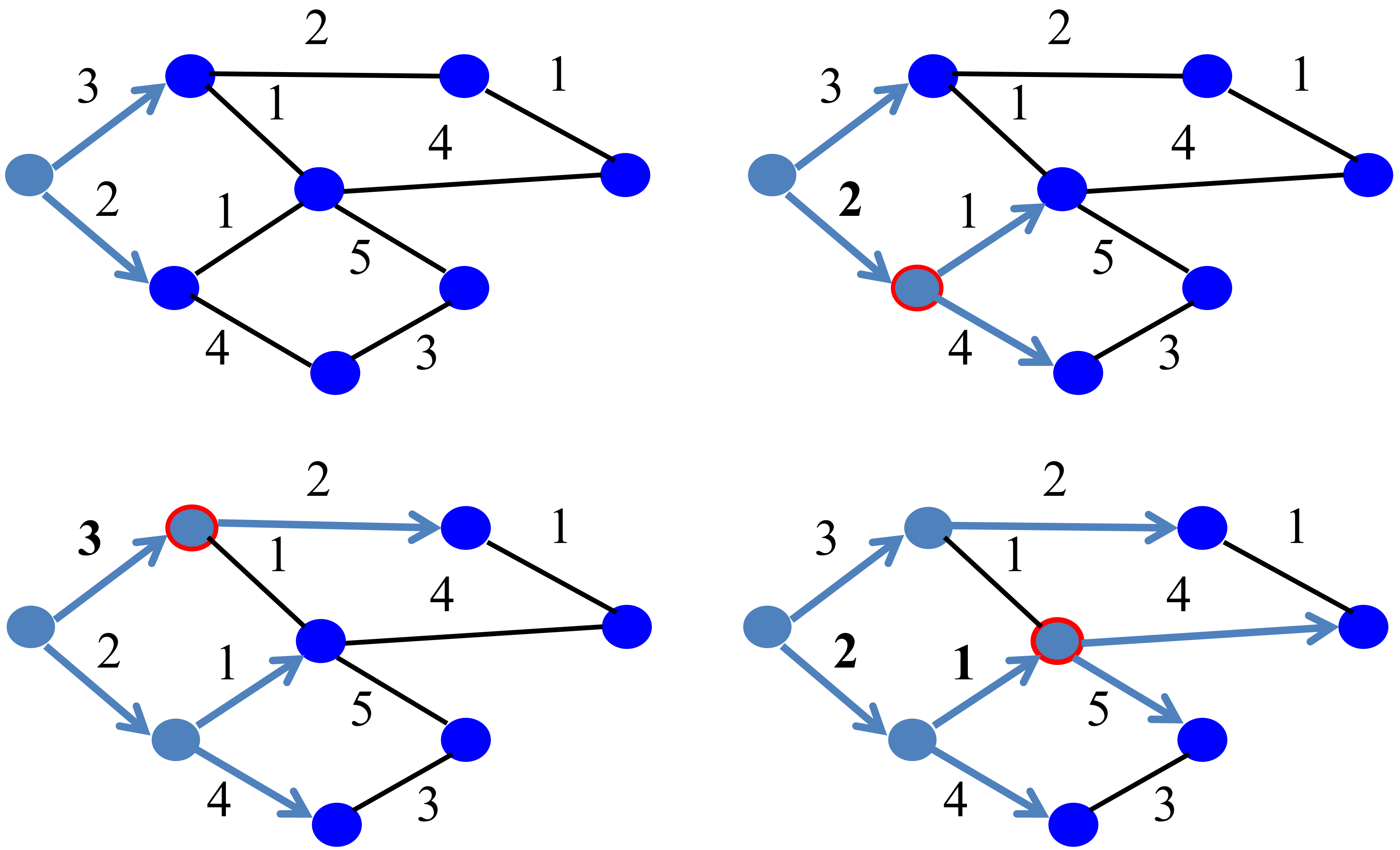
S = {u}
for all nodes v
  if (v is adjacent to u)
    D(v) = c(u,v)
  else D(v) = ∞

Loop

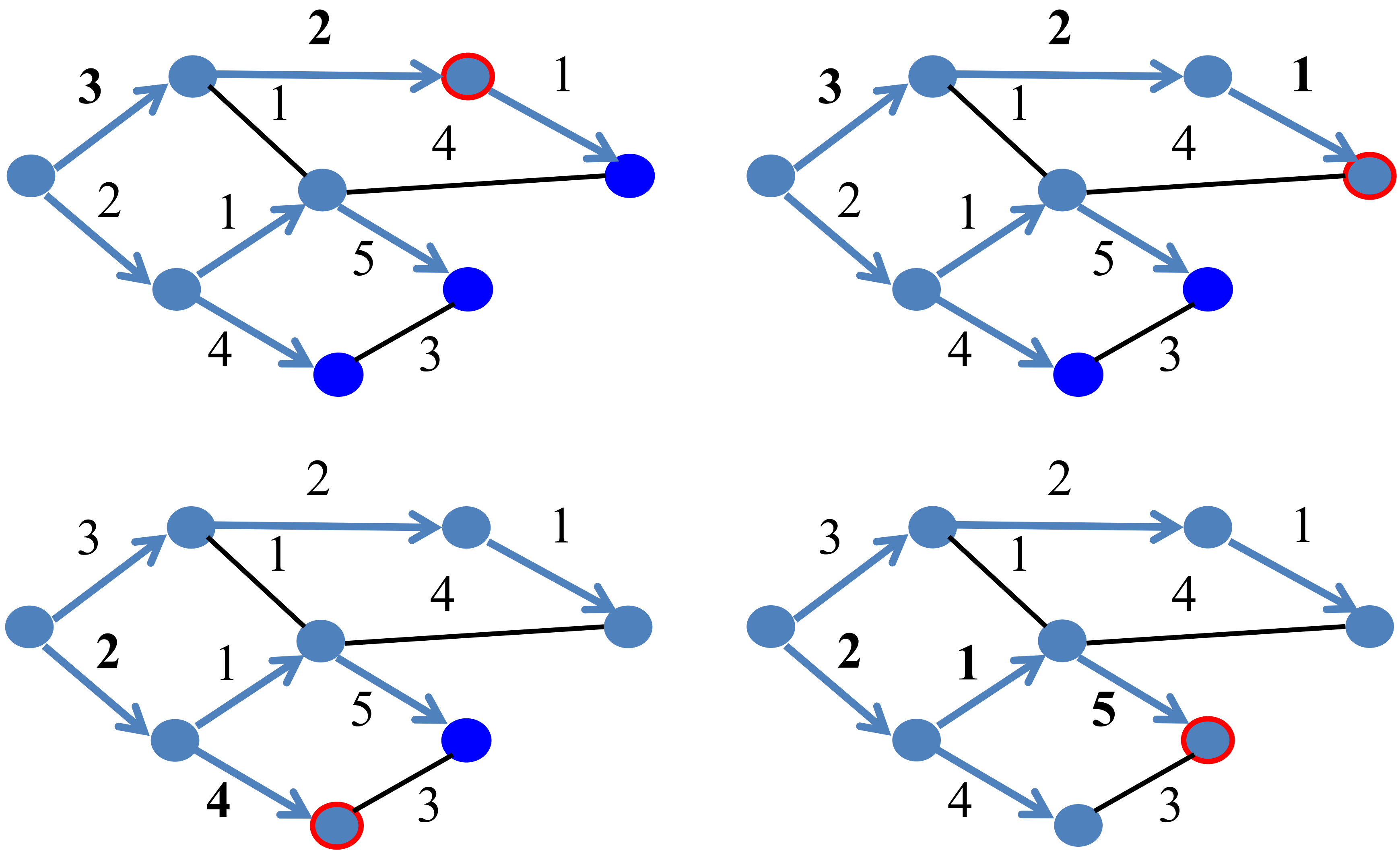
add w with smallest D(w) to S
update D(v) for all adjacent (to w) v:
  D(v) = min{D(v), D(w) + c(w,v)}
until all nodes are in S

Used in OSPF and IS-IS

Link-State Routing Example

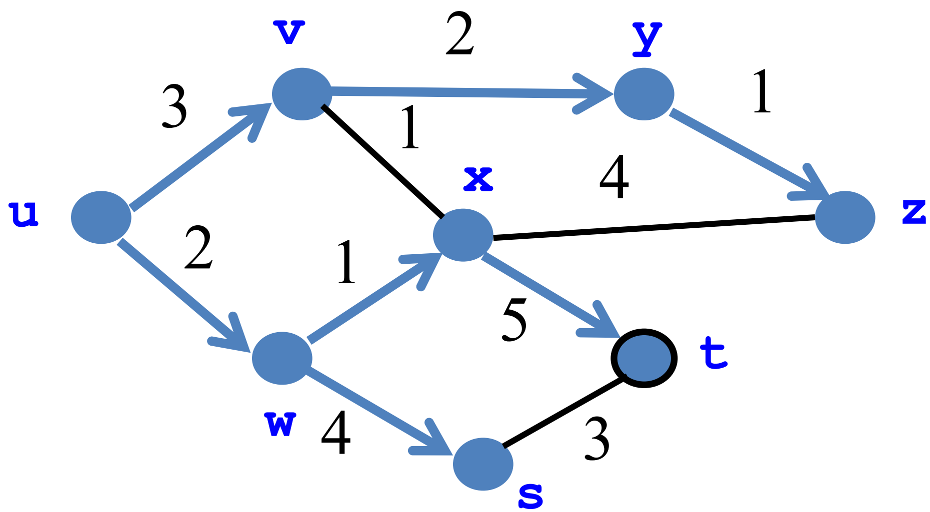


Link-State Routing Example (cont.)



Link State: Shortest-Path Tree

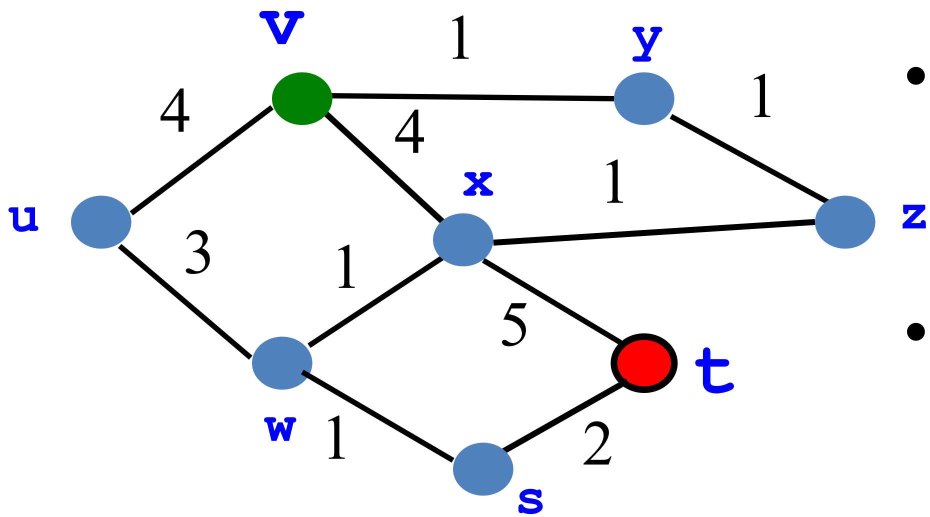
- Shortest-path tree from u



- Forwarding table at u

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

Link State: Shortest-Path Tree



Find shortest path **from** *t* **to** *v*

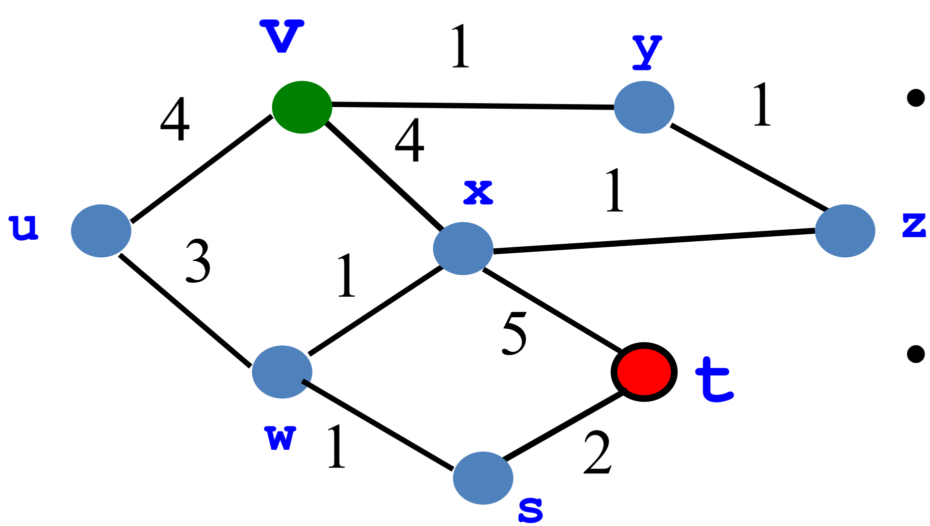
- Forwarding table entry at *t*?

  (Y) (t,x) (M) (t, s)

- Distance from *t* to *v*?

  (Y) 6 (M) 7 (C) 8 (A) 9

Link State: Shortest-Path Tree



Find shortest path *t* to *v*

- Forwarding table entry at *t*

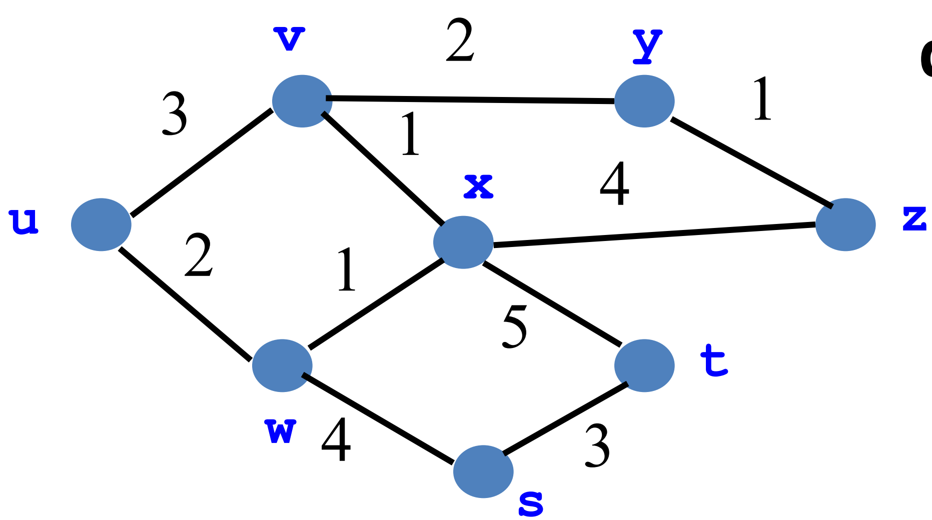
  (Y) (t,x) (M) (t, s)

- Distance from *t* to *v*

  (Y) 6 (M) 7 (C) 8 (A) 9

Distance Vector: Bellman-Ford Algo

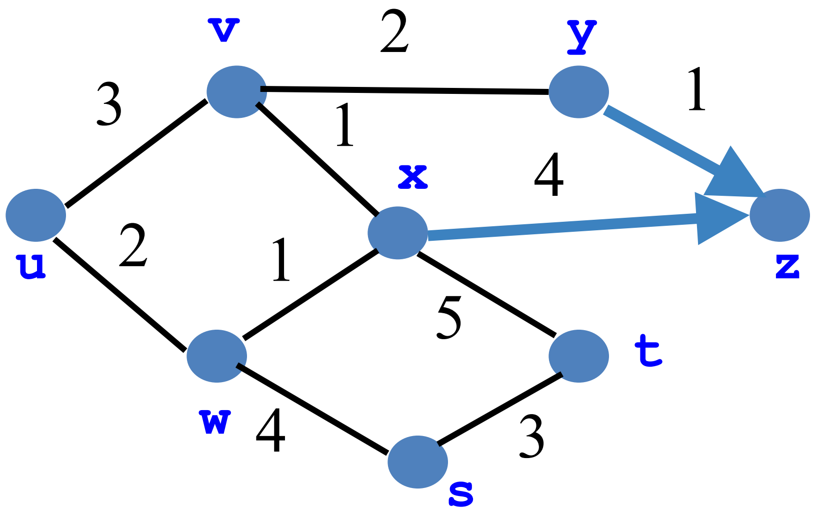
- Define distances at each node x
  - $d_x(y)$ = cost of least-cost path from x to y
- Update distances based on neighbors
  - $d_x(y) = \min \{c(x,v) + d_v(y)\}$ over all neighbors v

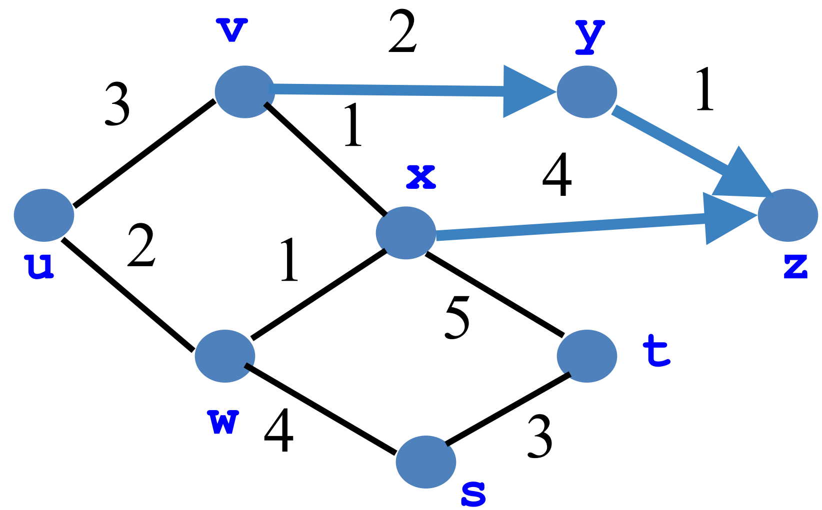


$$d_u(z) = \min\{\ c(u,v) + d_v(z),\ c(u,w) + d_w(z)\}$$

Used in RIP and EIGRP

Distance Vector Example





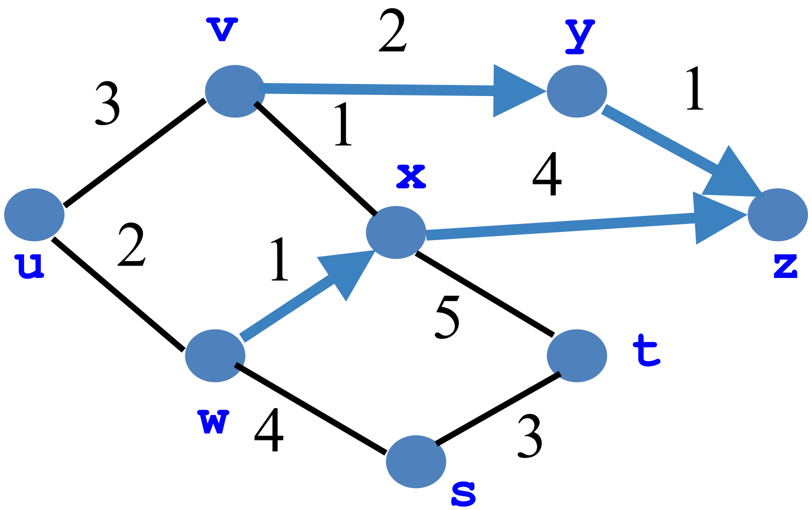
$d_y(z) = 1$

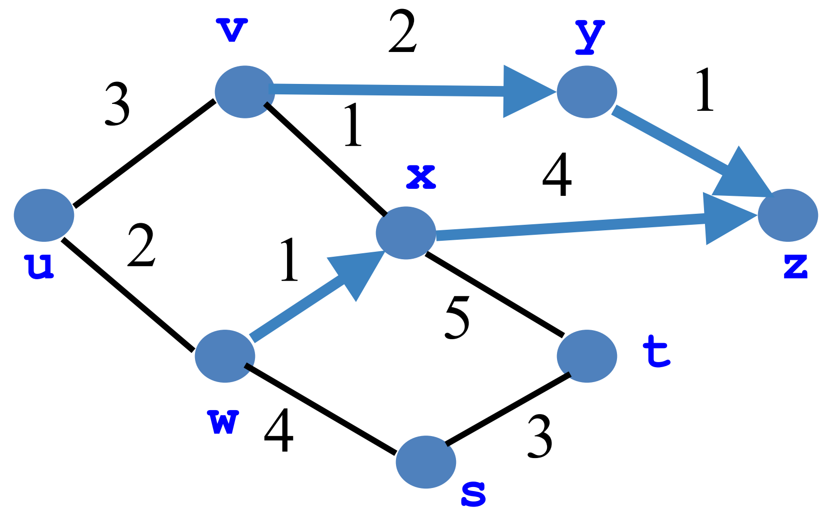
$d_x(z) = 4$

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

$= 3$

Distance Vector Example (Cont.)



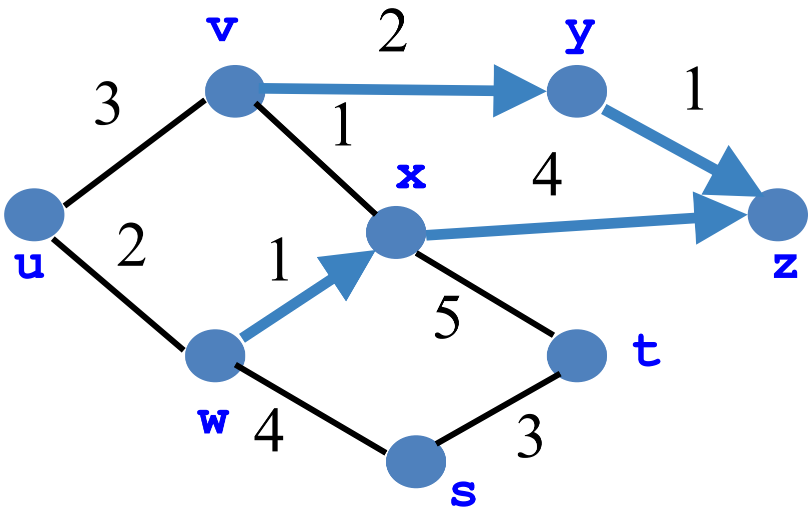


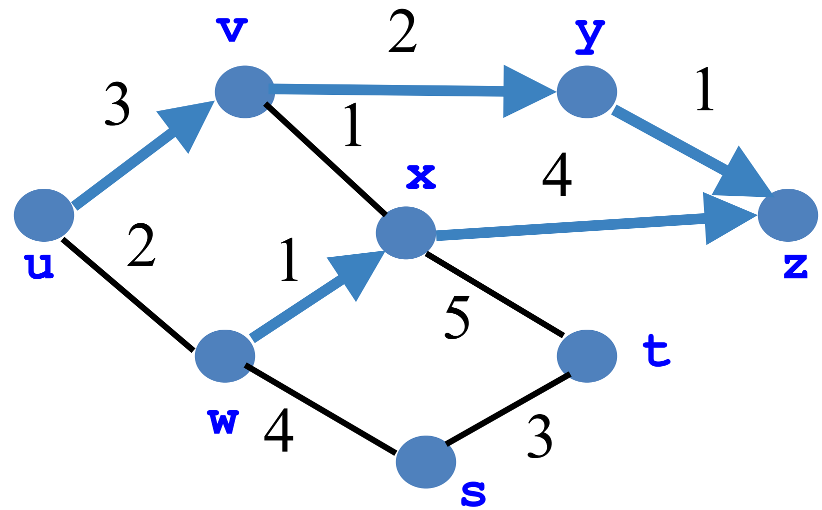
$d_w(z) = \min\{\ 1+d_x(z),$
$4+d_s(z),$
$2+d_u(z)\ \}$
$= 5$

$d_u(z) =$

(Y) 5 (M) 6 (C) 7

Distance Vector Example (Cont.)



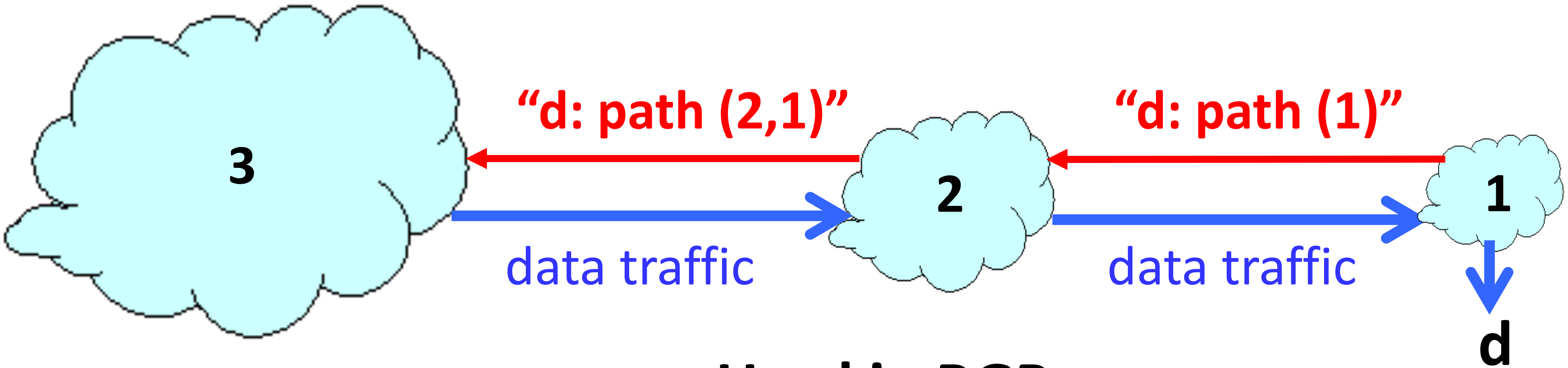


$$d_w(z) = \min\{\ 1+d_x(z),\ 4+d_s(z),\ 2+d_u(z)\ \} = 5$$

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

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



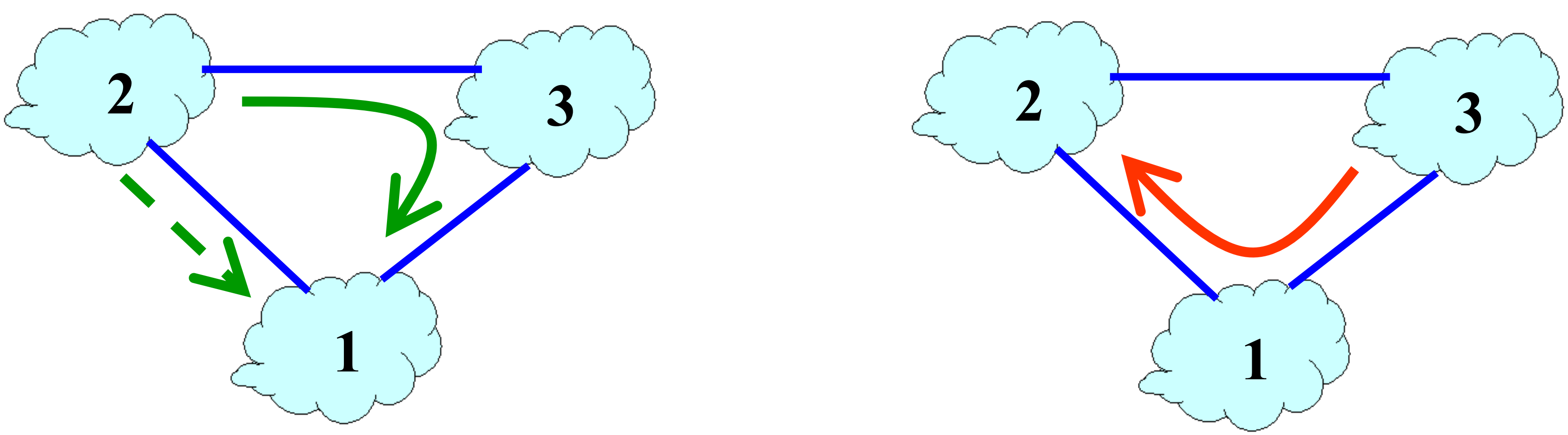
Used in BGP

Path-Vector: Flexible Policies

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

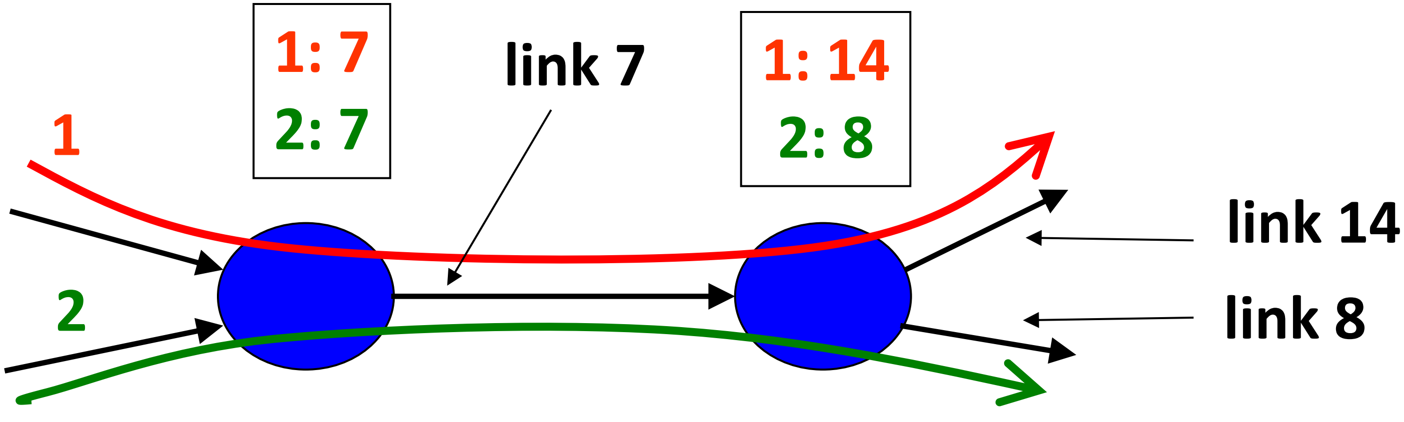
Node 2 prefers "2, 3, 1" over "2, 1"

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

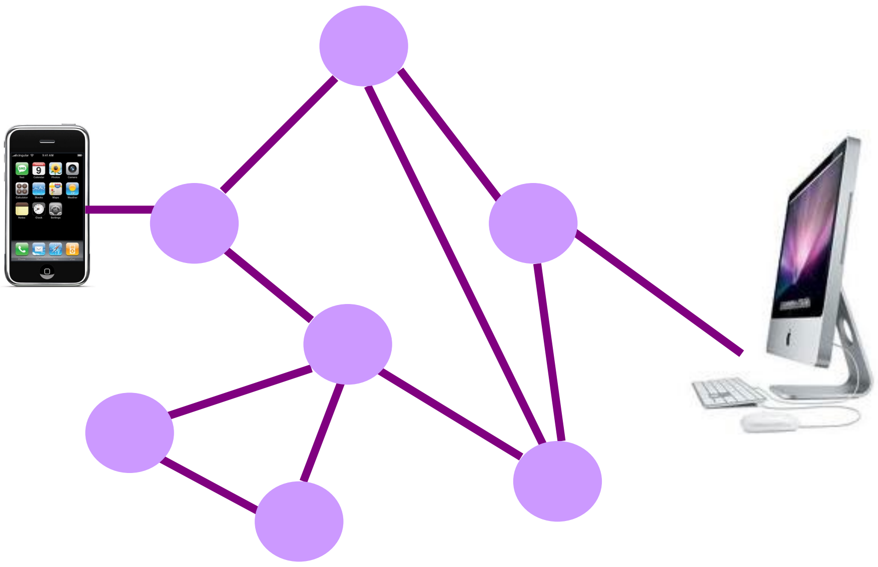
Source Routing

- 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)

Learning Where the Hosts Are

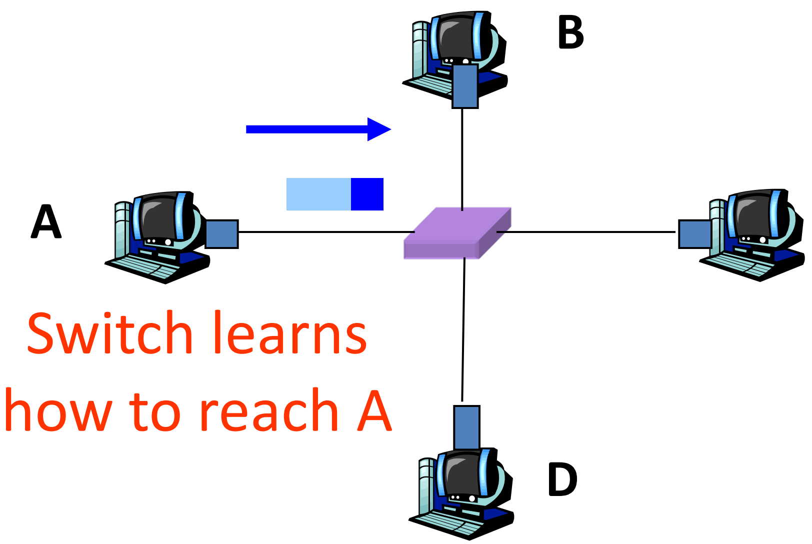
Finding the Hosts

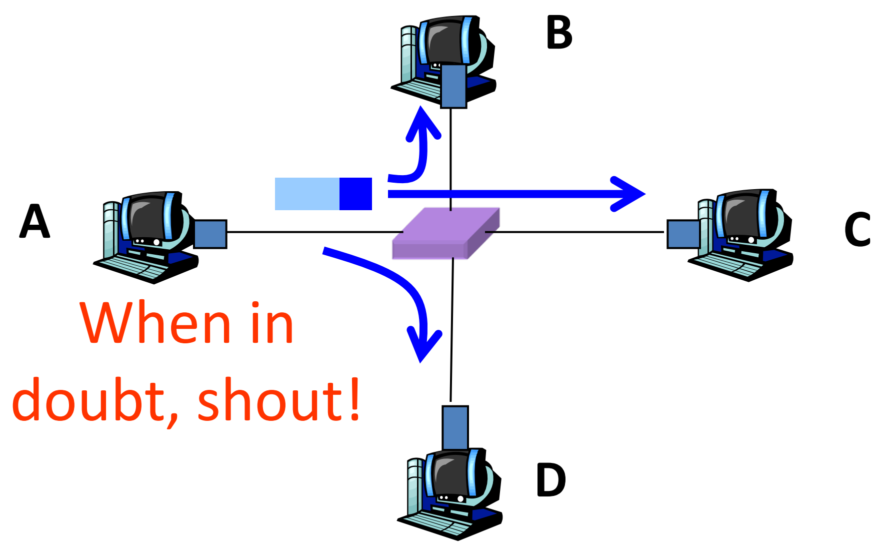
- Building a forwarding table
  - Computing paths between network elements
  - … and figuring out where the end-hosts are
- How to find the hosts?
  1. Learning/flooding
  2. Injecting into the routing protocol
  3. Dissemination using a different protocol
  4. Directory service



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

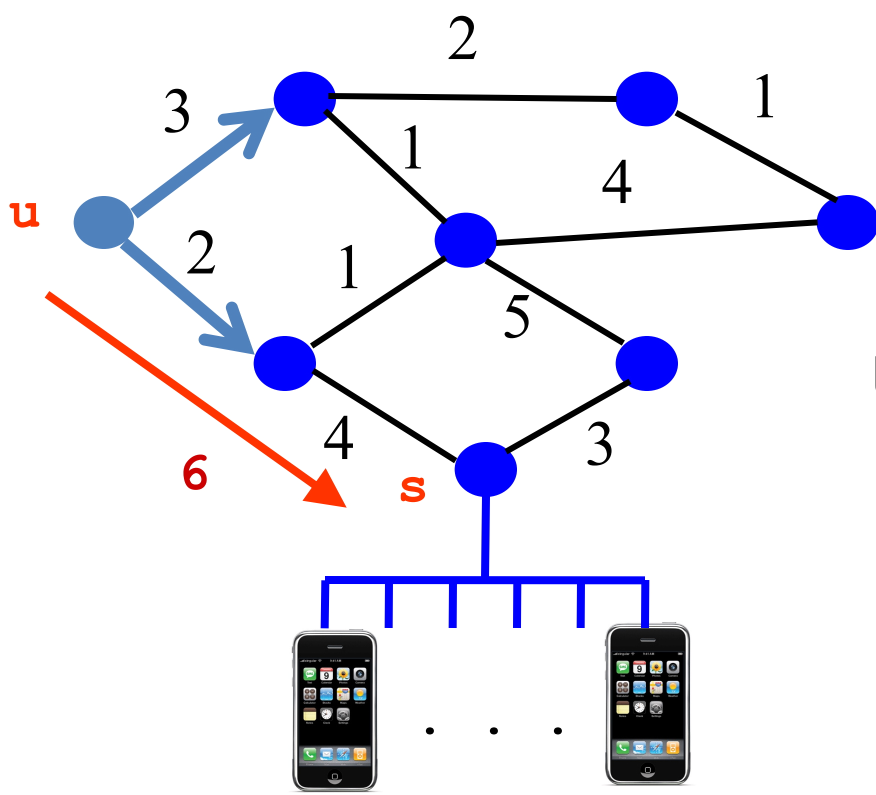




Used in Ethernet LANs

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



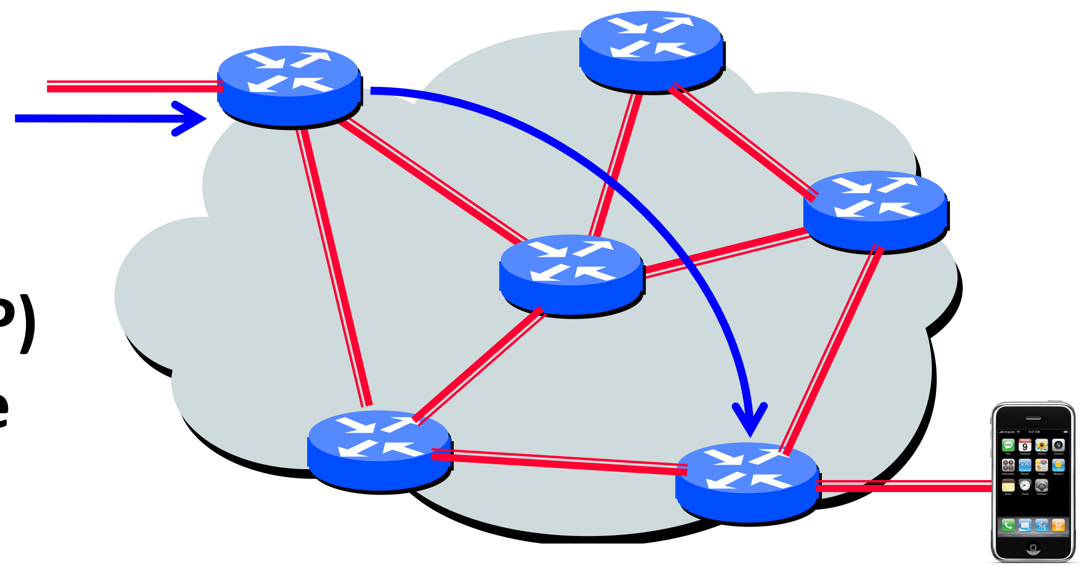
Used in OSPF and IS-IS, especially in enterprise networks

Disseminate With Another Protocol

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

disseminate route to other routers

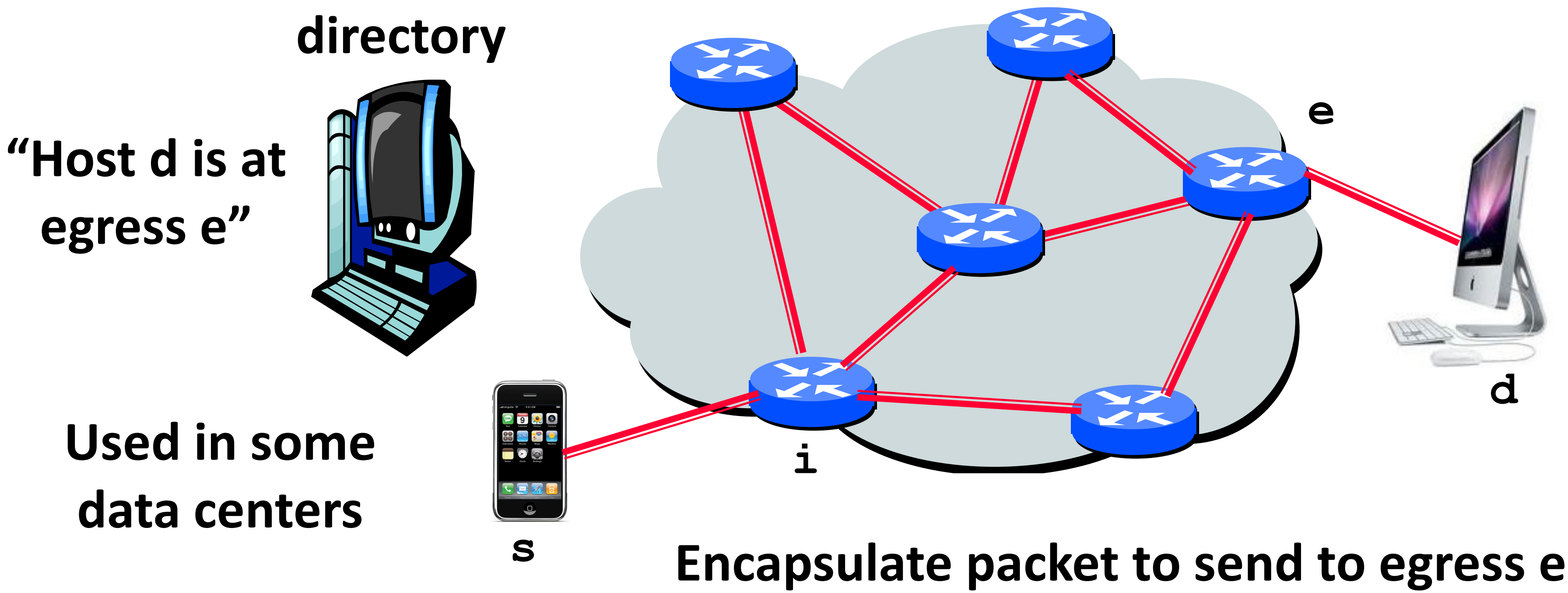
learn a route to d (e.g., via BGP)



Internal BGP (iBGP) used in backbone networks

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



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