Control Plane

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Fall 2010 (TTh 1:30-2:50 in COS 302)

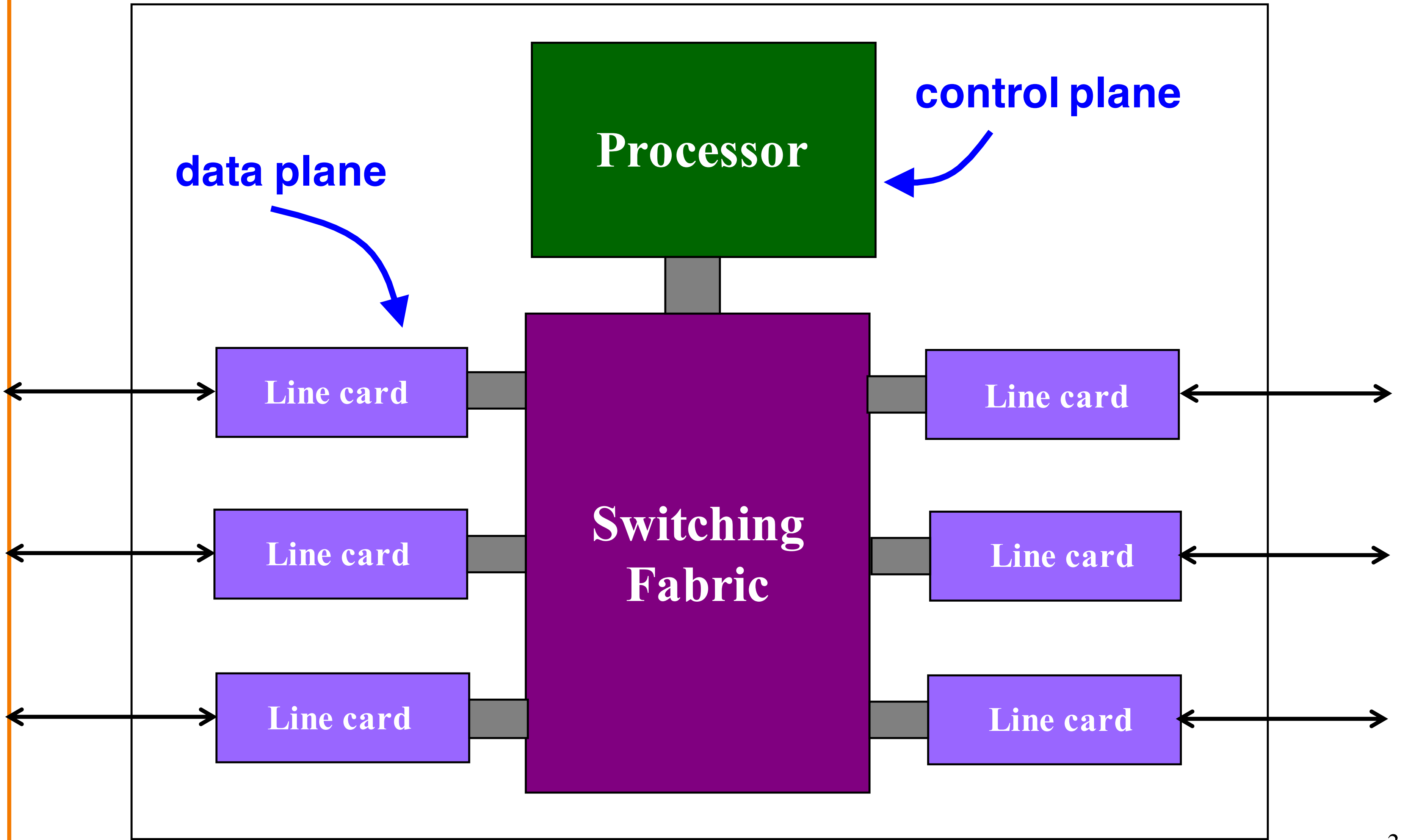
COS 561: Advanced Computer Networks

http://www.cs.princeton.edu/courses/archive/fall10/cos561/

Data, Control, and Management Planes

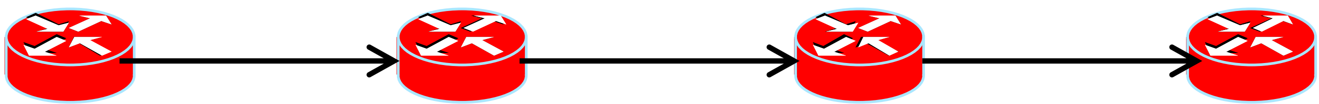
	Data	Control	Management
Time-scale	Packet (nsec)	Event (10 msec to sec)	Human (min to hours)
Tasks	Forwarding, buffering, filtering, scheduling	Routing, signaling	Analysis, configuration
Location	Line-card hardware	Router software	Humans or scripts

Data and Control Planes



Routing vs. Forwarding

- Routing: control plane
  - –Computing paths the packets will follow
  - –Routers talking amongst themselves
  - –Individual router *creating* a forwarding table
- Forwarding: data plane
  - –Directing a data packet to an outgoing link
  - –Individual router *using* a forwarding table



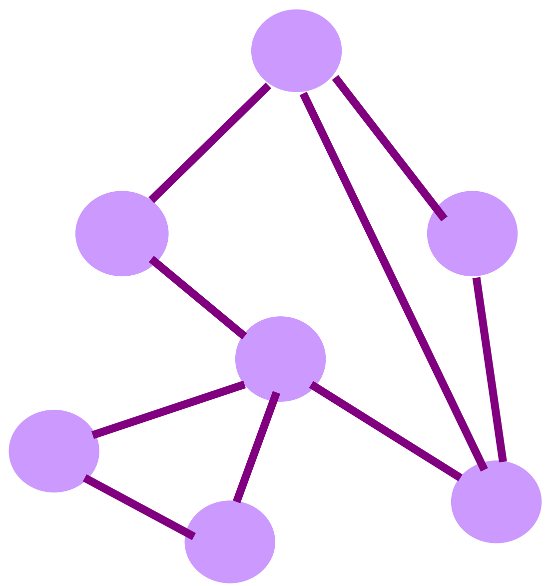
Routing Protocols

- What does the protocol compute?
  - Spanning tree, shortest path, local policy, arbitrary end-to-end paths
- What algorithm does the protocol run?
  - Spanning-tree construction, distance vector, link-state routing, path-vector routing, source routing, end-to-end signaling
- How do routers learn end-host locations?
  - Learning/flooding, injecting into the routing protocol, dissemination using a different protocol, and directory server

What Does the Protocol Compute?

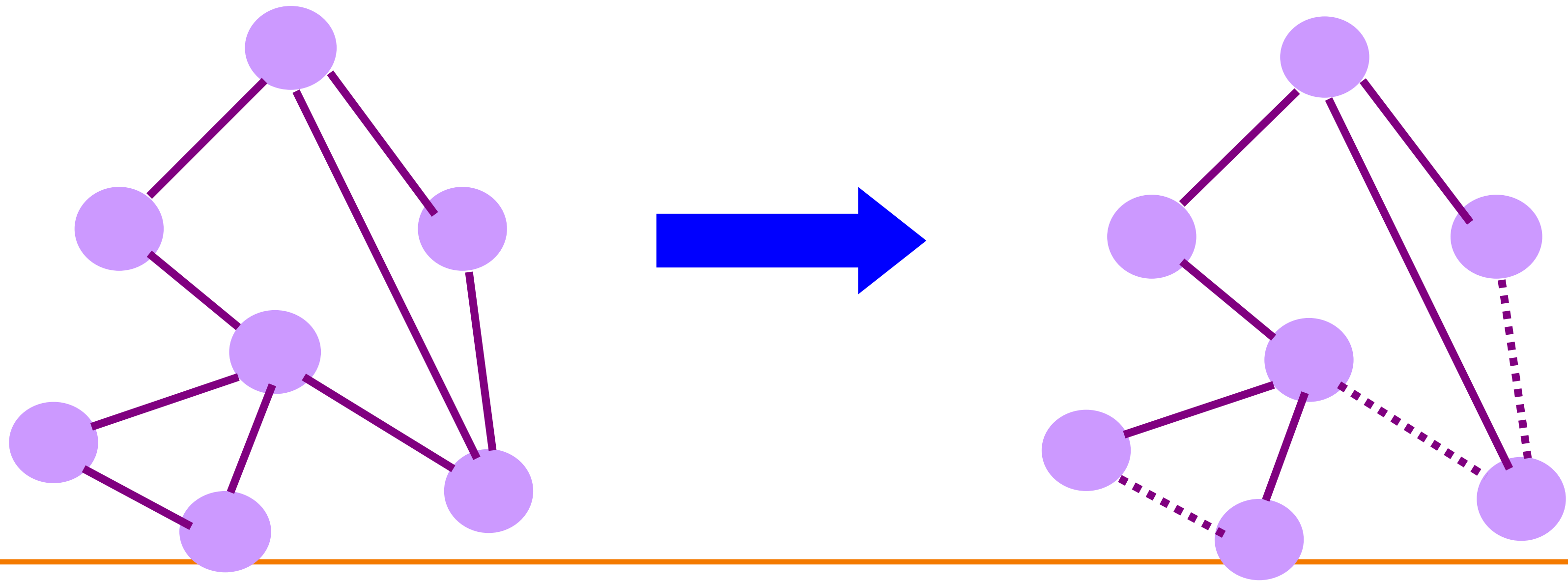
Different Ways to Represent Paths

- Static model
  - What is computed, i.e., what is the outcome
  - Not how the (distributed) computation is performed
- Trade-offs
  - State required to represent the paths
  - Efficiency of the resulting paths
  - Ability to support multiple paths
  - Complexity of computing the paths
  - Which nodes are in charge
- Applied in different settings
  - LAN, intradomain, interdomain



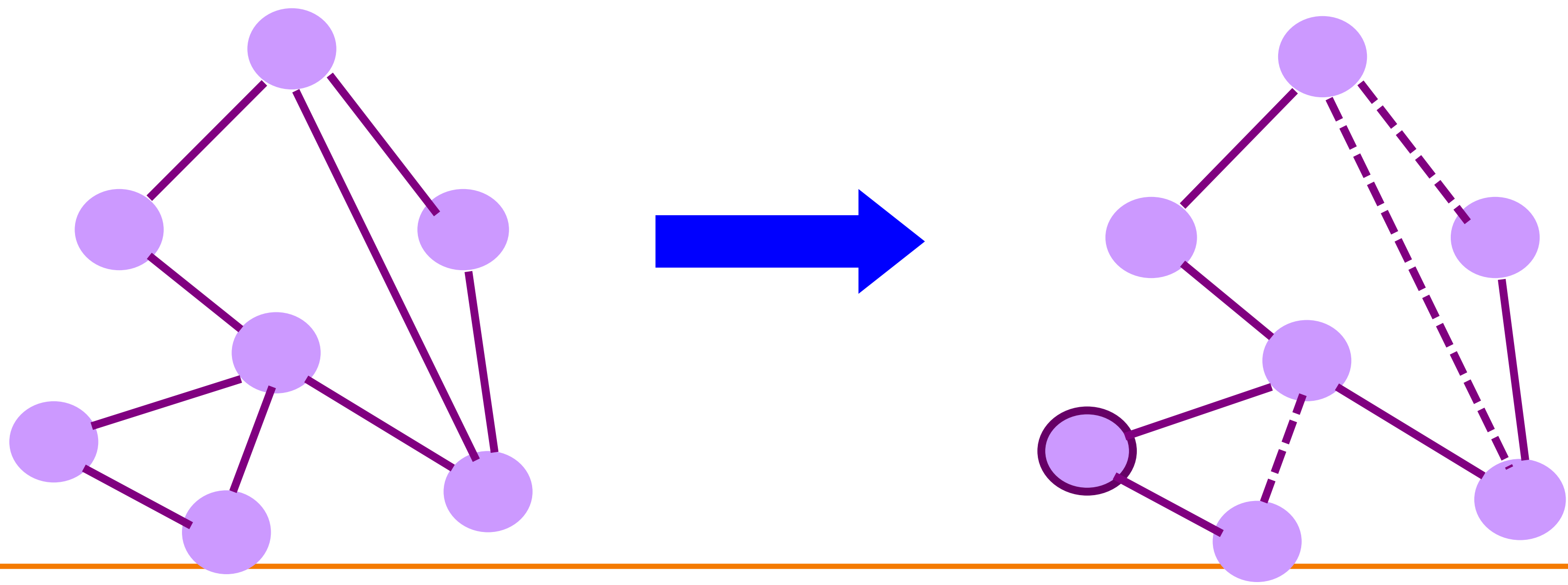
Spanning Tree

- One tree that reaches every node
  - Single path between each pair of nodes
  - No loops, so can support broadcast easily
- Disadvantages
  - Paths are sometimes long
  - Some links are not used at all



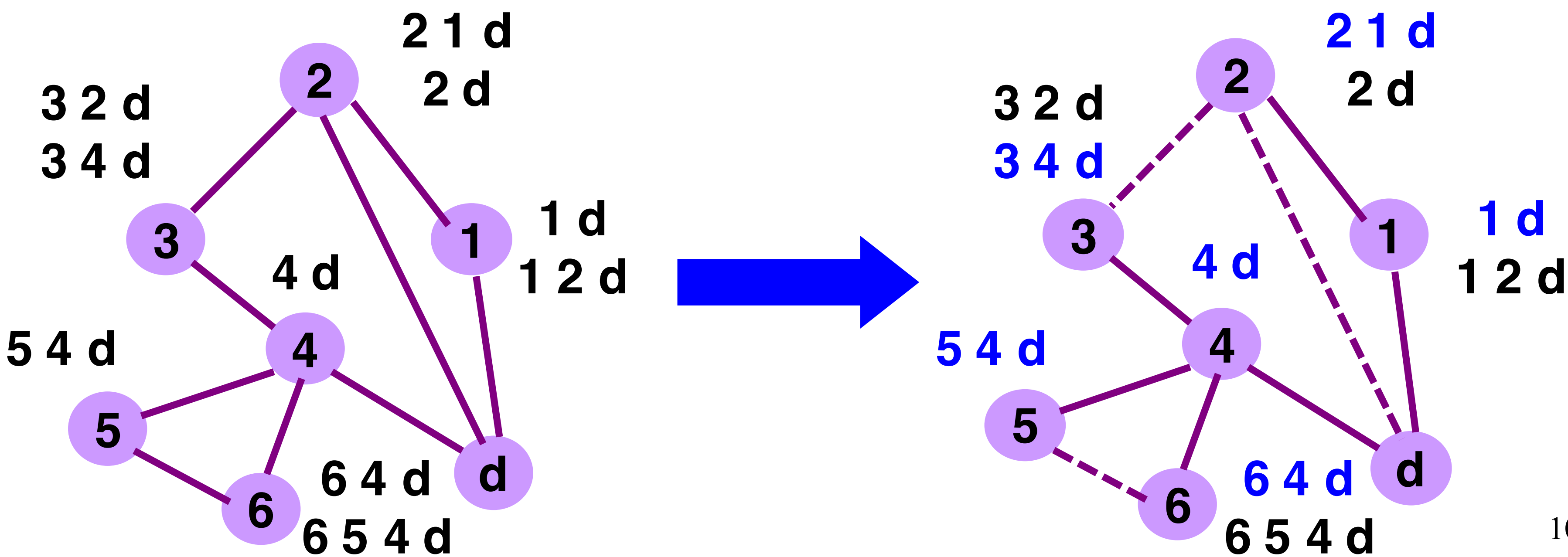
Shortest Paths

- Shortest path(s) between each pair of nodes
  - Separate shortest-path tree rooted at each node
  - Minimum hop count or minimum sum of edge weights
- Disadvantages
  - All nodes need to agree on the link metrics
  - Multipath routing is limited to Equal Cost MultiPath



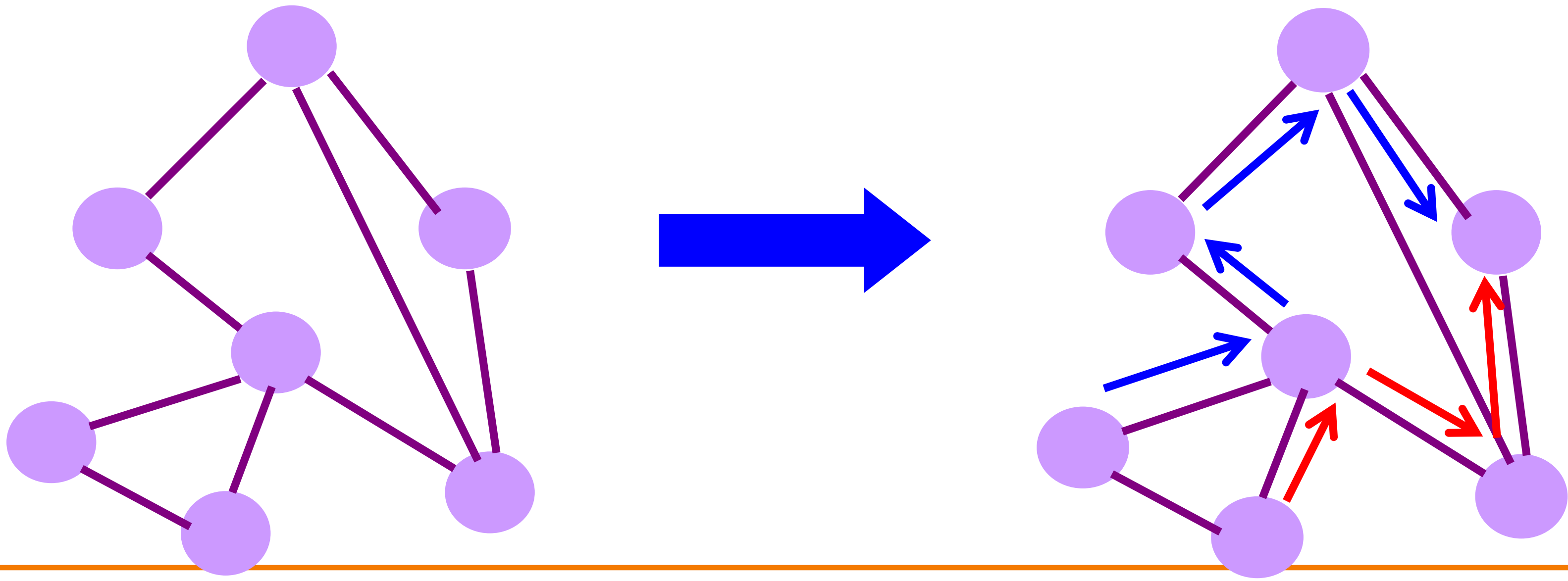
Locally Policy at Each Hop

- Locally best path
  - Local policy: each node picks the path it likes best
  - … among the paths chosen by its neighbors
- Disadvantages
  - More complicated to configure and model



End-to-End Path Selection

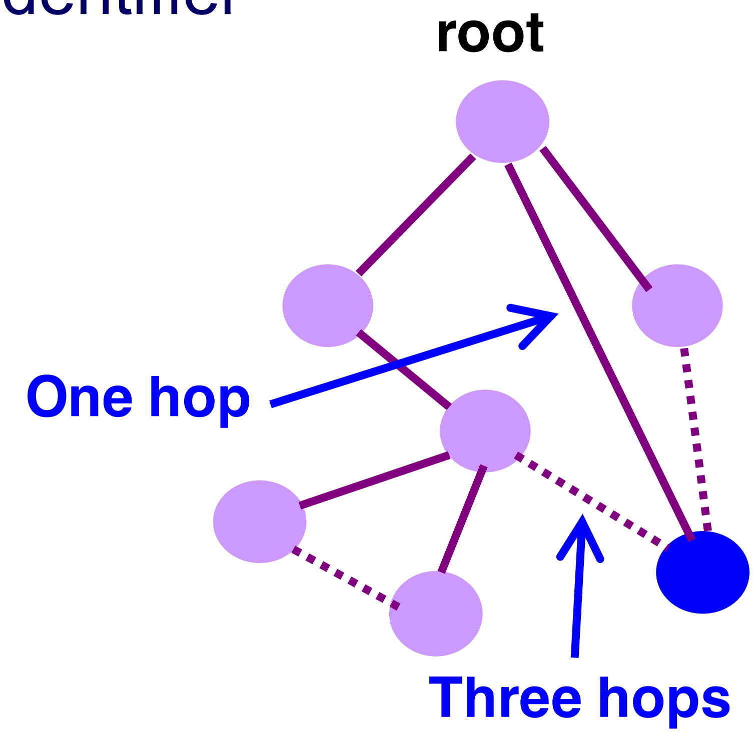
- End-to-end path selection
  - Each node picks its own end to end paths
  - … independent of what other paths other nodes use
- Disadvantages
  - More state and complexity in the nodes
  - Hop-by-hop destination-based forwarding is not enough



How to Compute Paths?

Spanning Tree Algorithm

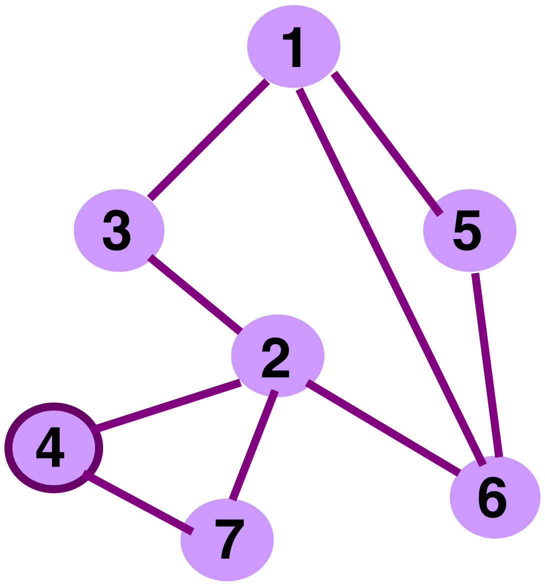
- Elect a root
  - The switch with the smallest identifier
  - And form a tree from there
- Algorithm
  - Repeatedly talk to neighbors
    - “I think node Y is the root”
    - “My distance from Y is d”
  - Update your information based on neighbors
    - Smaller id as the root
    - Smaller distance d+1
  - Don’t use interfaces not in the path



Used in Ethernet-based LANs

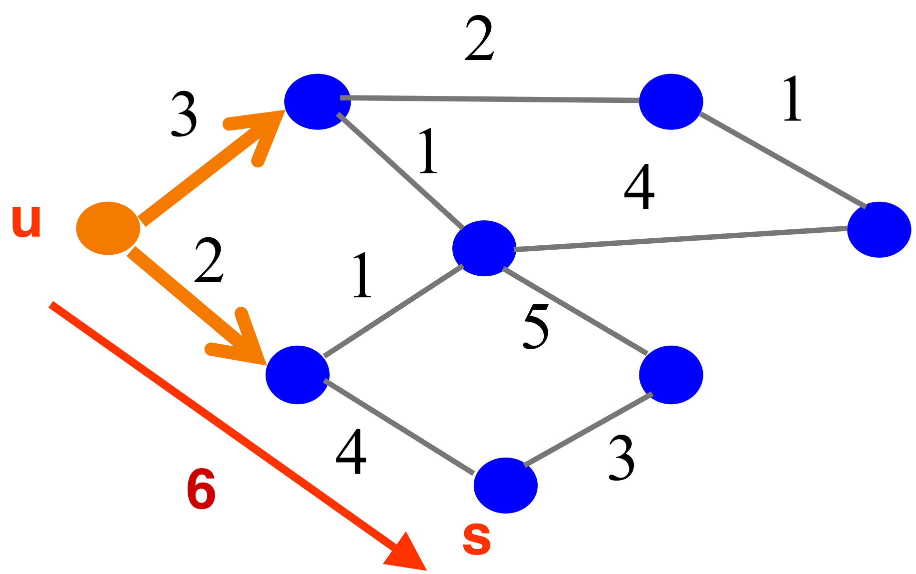
Spanning Tree Example: Switch #4

- 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
  - And realizes this is a longer path
  - So, prefers its own one-hop path
  - 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

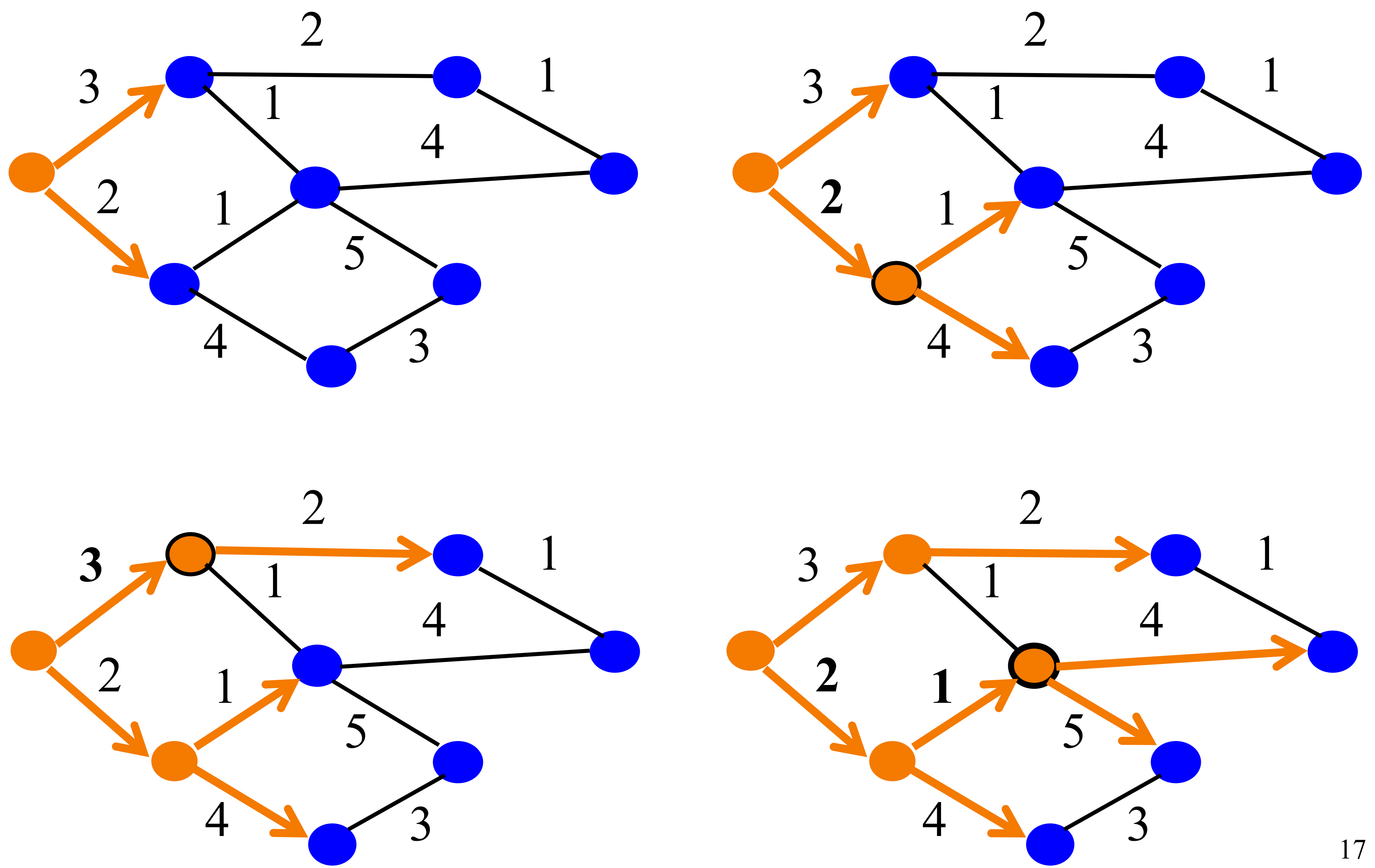
update D(v) for all adjacent v:

  D(v) = min{D(v), D(w) + c(w,v)}

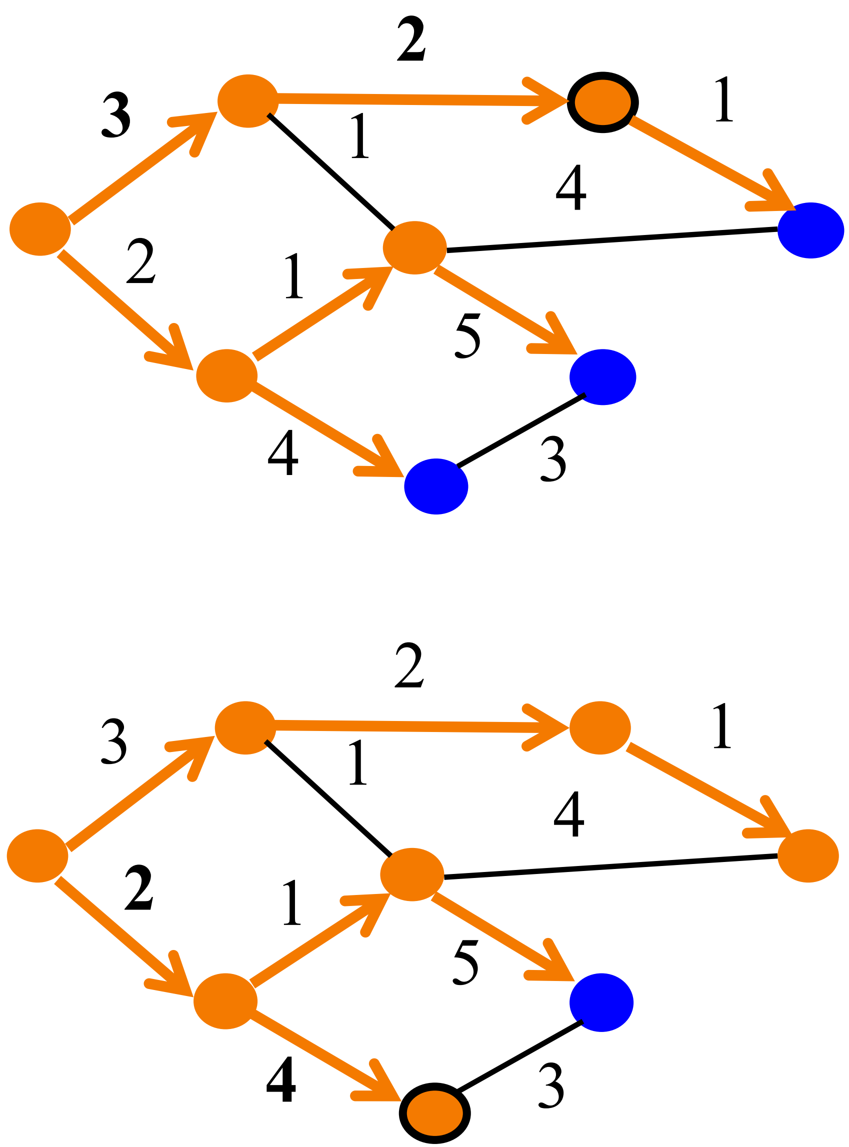
until all nodes are in S

Used in OSPF and IS-IS

Link-State Routing Example

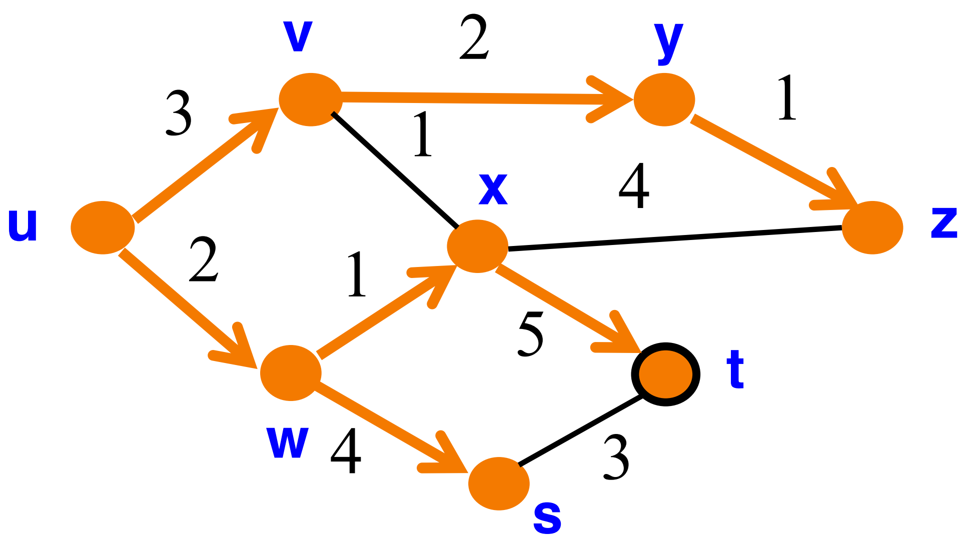


Link-State Routing Example (cont.)



Link State: Shortest-Path Tree

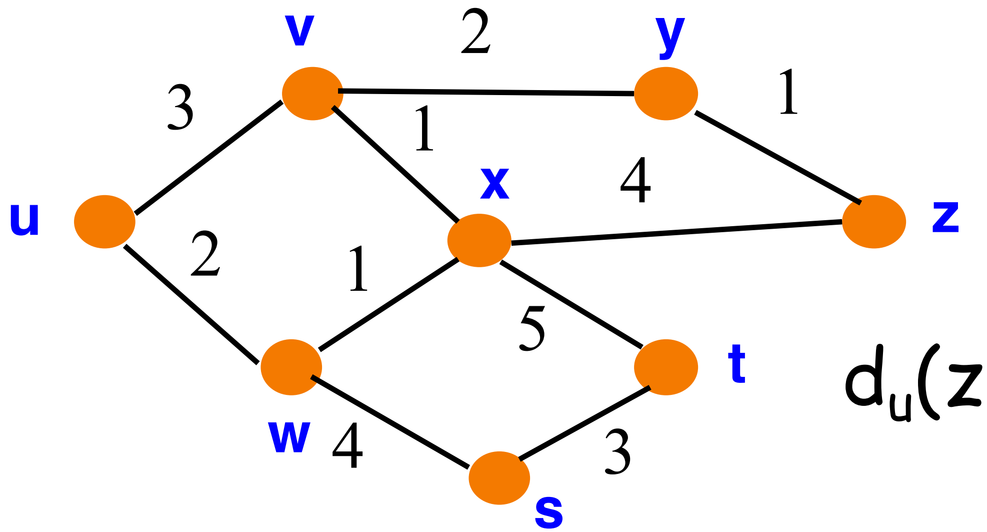
- Shortest-path tree from u
- Forwarding table at u



	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



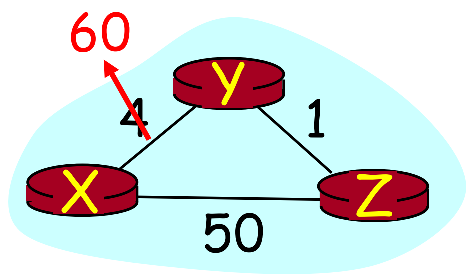
$$d_u(z) = \min\{c(u,v) + d_v(z),\ c(u,w) + d_w(z)\}$$

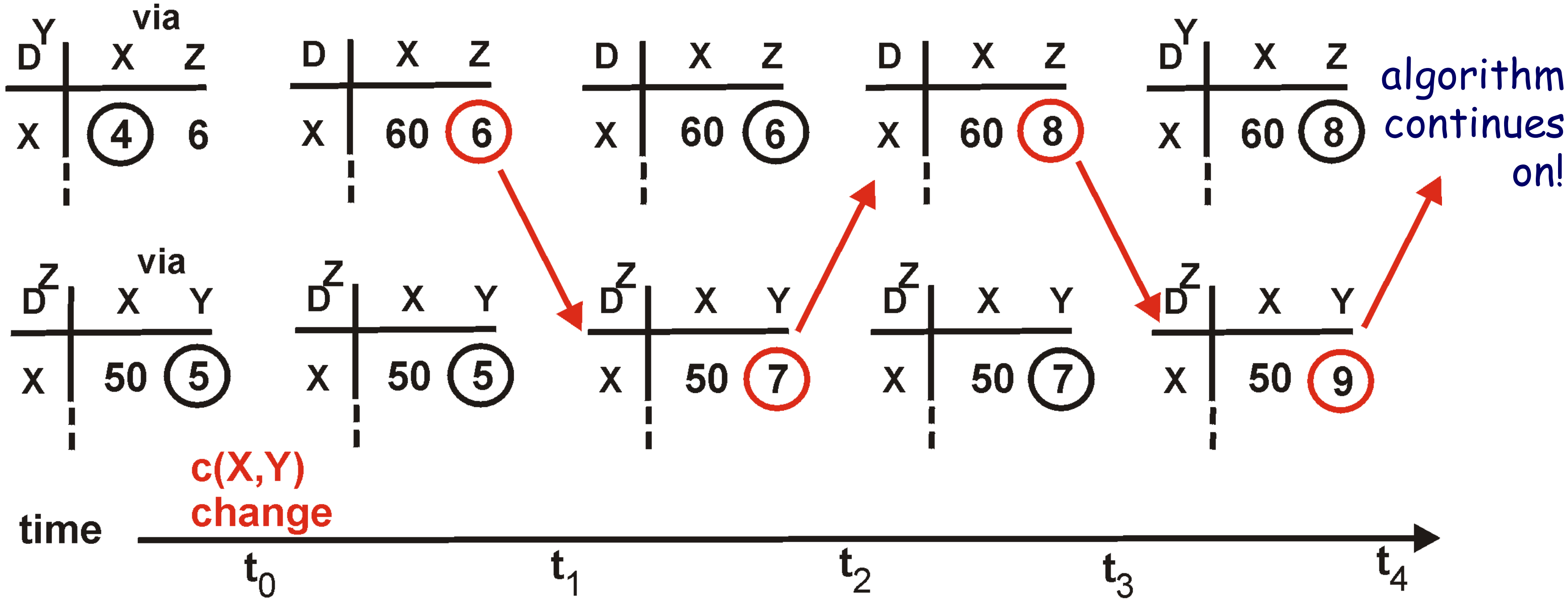
Used in RIP and EIGRP

Distance Vector: Count to Infinity

Link cost changes:

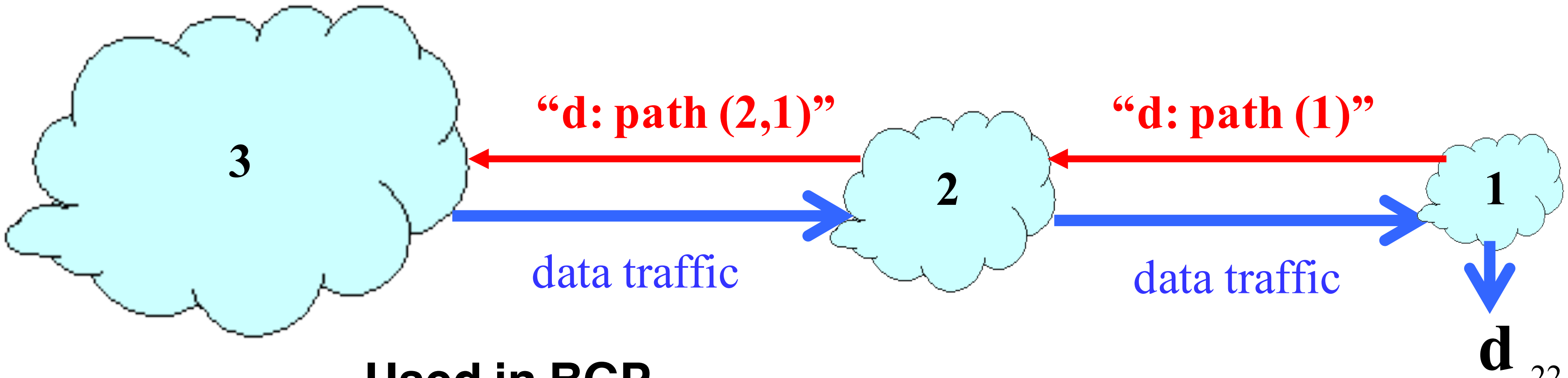
- Good news travels fast
- Bad news travels slow - “count to infinity” problem!





Path-Vector Routing

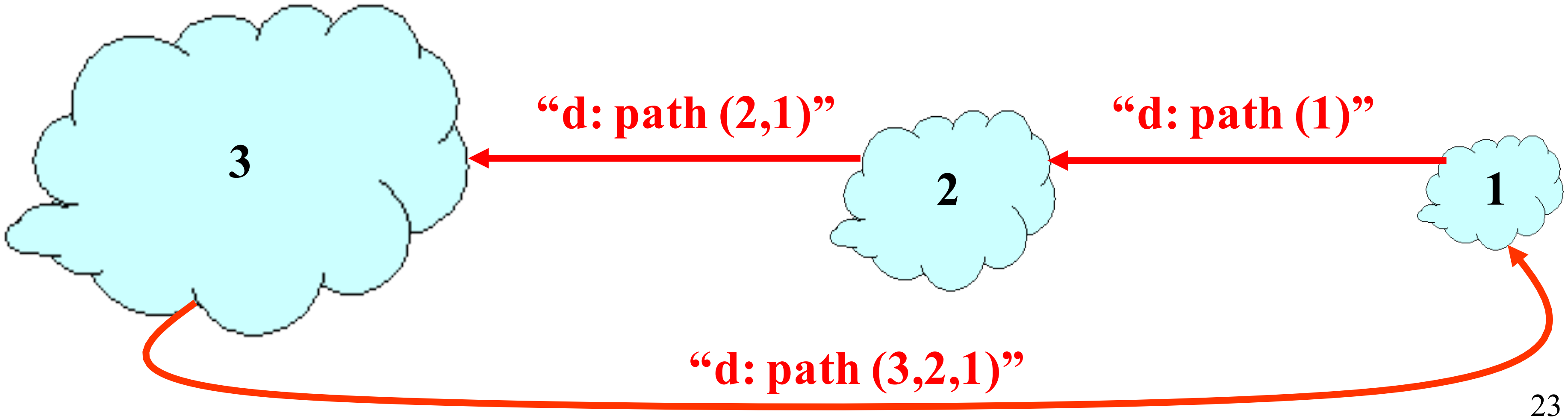
- Extension of distance-vector routing
  - –Support flexible routing policies
  - –Avoid count-to-infinity problem
- Key idea: advertise the entire path
  - –Distance vector: send *distance metric* per dest d
  - –Path vector: send the *entire path* for each dest d



Used in BGP

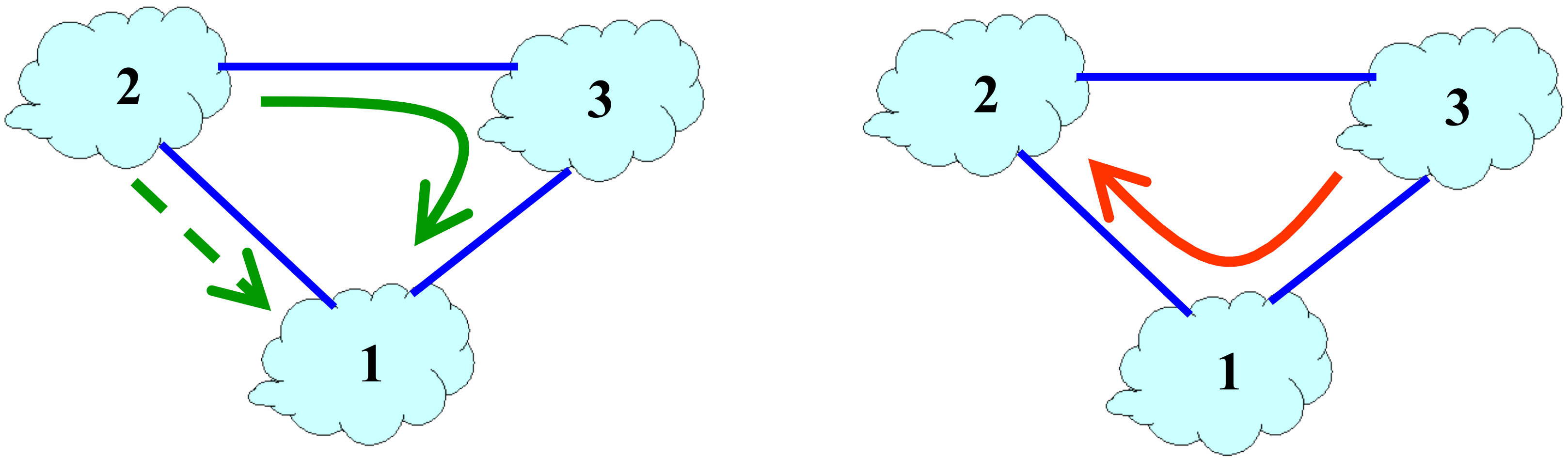
Path-Vector: Faster Loop Detection

- Node can easily detect a loop
  - –Look for its own node identifier in the path
  - –E.g., node 1 sees itself in the path “3, 2, 1”
- Node can simply discard paths with loops
  - –E.g., node 1 simply discards the advertisement



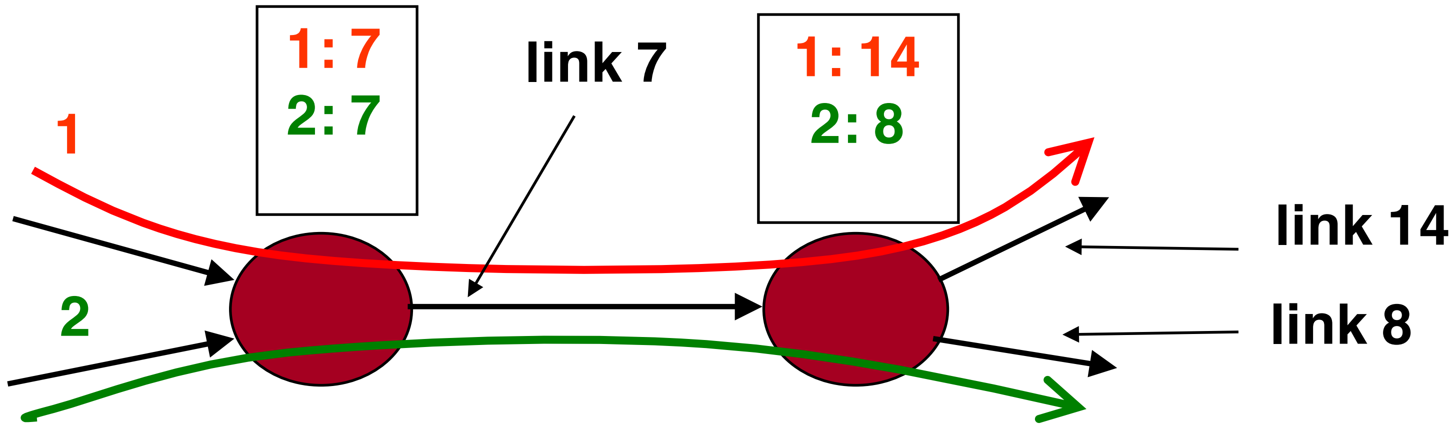
Path-Vector: Flexible Policies

- Each node can apply local policies
  - –Path selection: Which path to use?
  - –Path export: Which paths to advertise?
- Examples
  - –Node 2 may prefer the path "2, 3, 1" over "2, 1"
  - –Node 1 may not let node 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
- Routers supports virtual circuits
  - 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

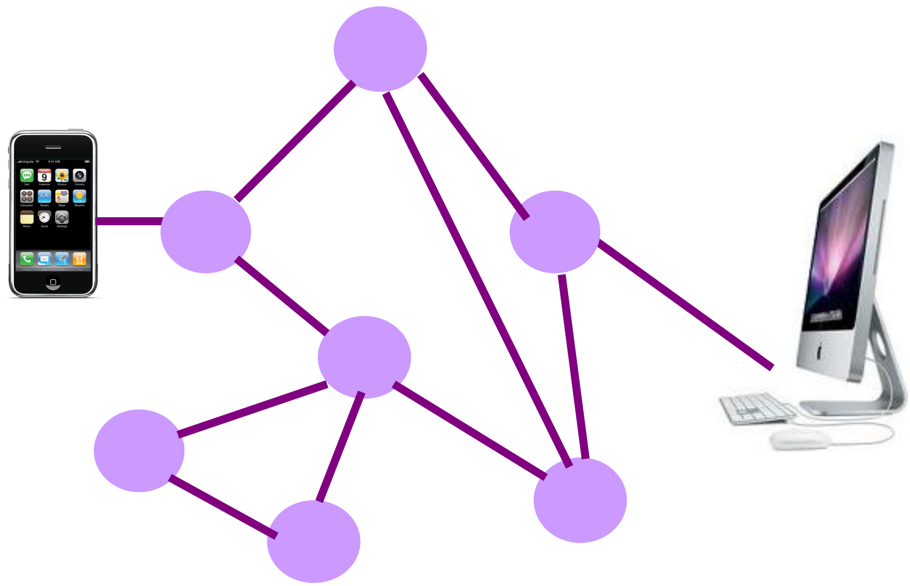
- Similar to end-to-end signaling
  - –But the data packet carries the hops in the path
  - –… rather than the routers storing big tables
- End-host control
  - –Tell the end host the topology
  - –Let the end host select the end-to-end path
- Variations of source routing
  - –Strict: specify every hop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

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

Learning Where the Hosts Are

Finding the Hosts

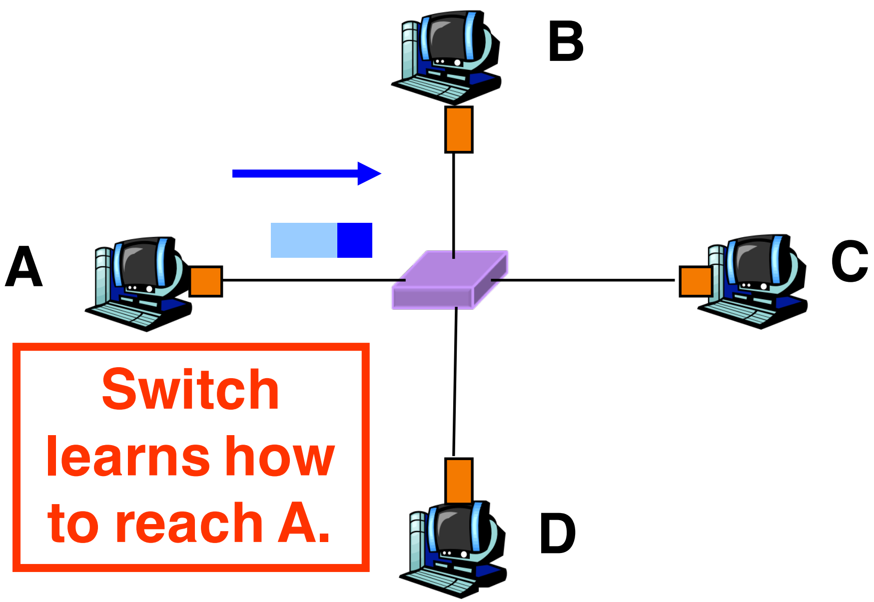
- Building a forwarding table
  - Computing paths between network elements
  - … and figuring out where the end-hosts are
  - … to map a destination address to an outgoing link
- How to find the hosts?
  - Learning/flooding
  - Injecting into the routing protocol
  - Dissemination using a different protocol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

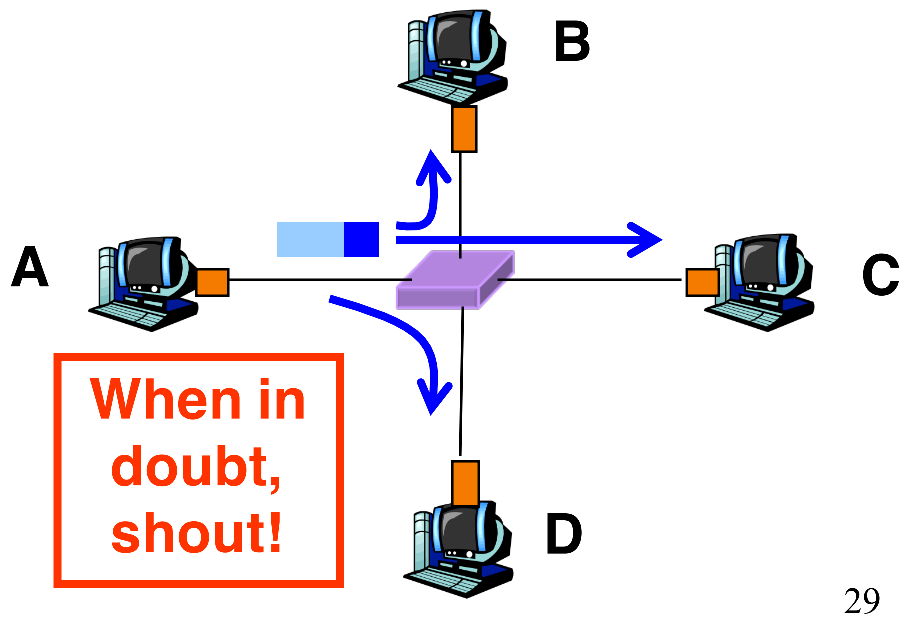


Learning and Flooding

- 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 for the one where the frame arrived

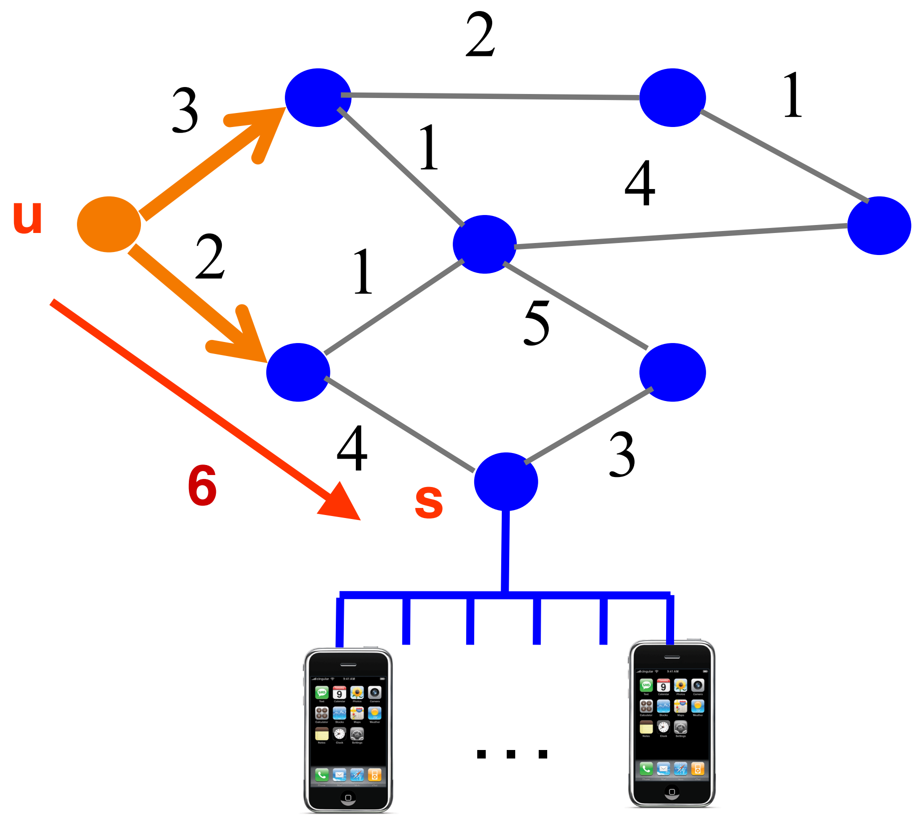




Used in Ethernet LANs

Inject into Routing Protocol

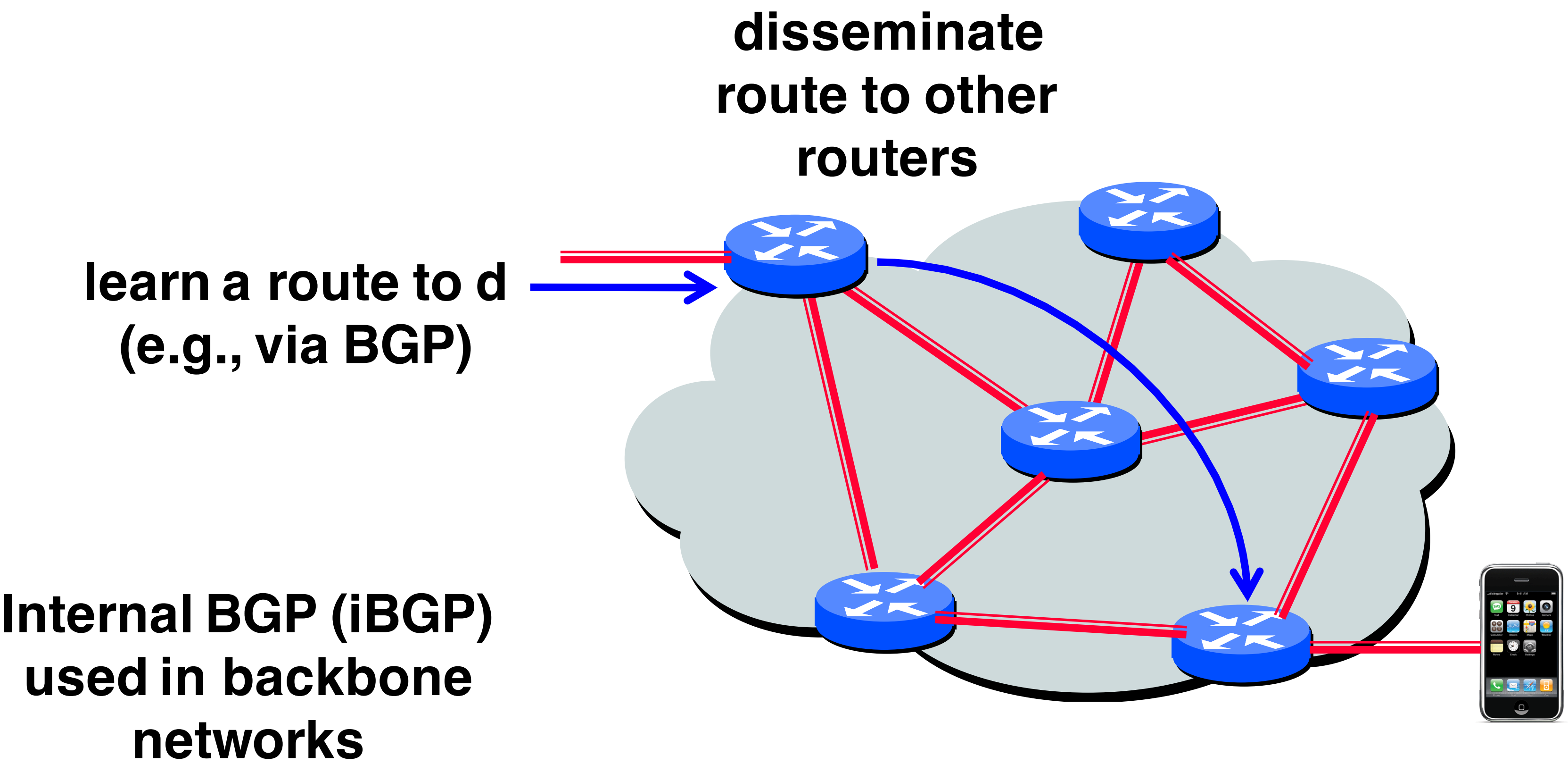
- Treat the end host (or subnet) as a node
  - And disseminate in the routing protocol
  - E.g., flood information about where addresses attach



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

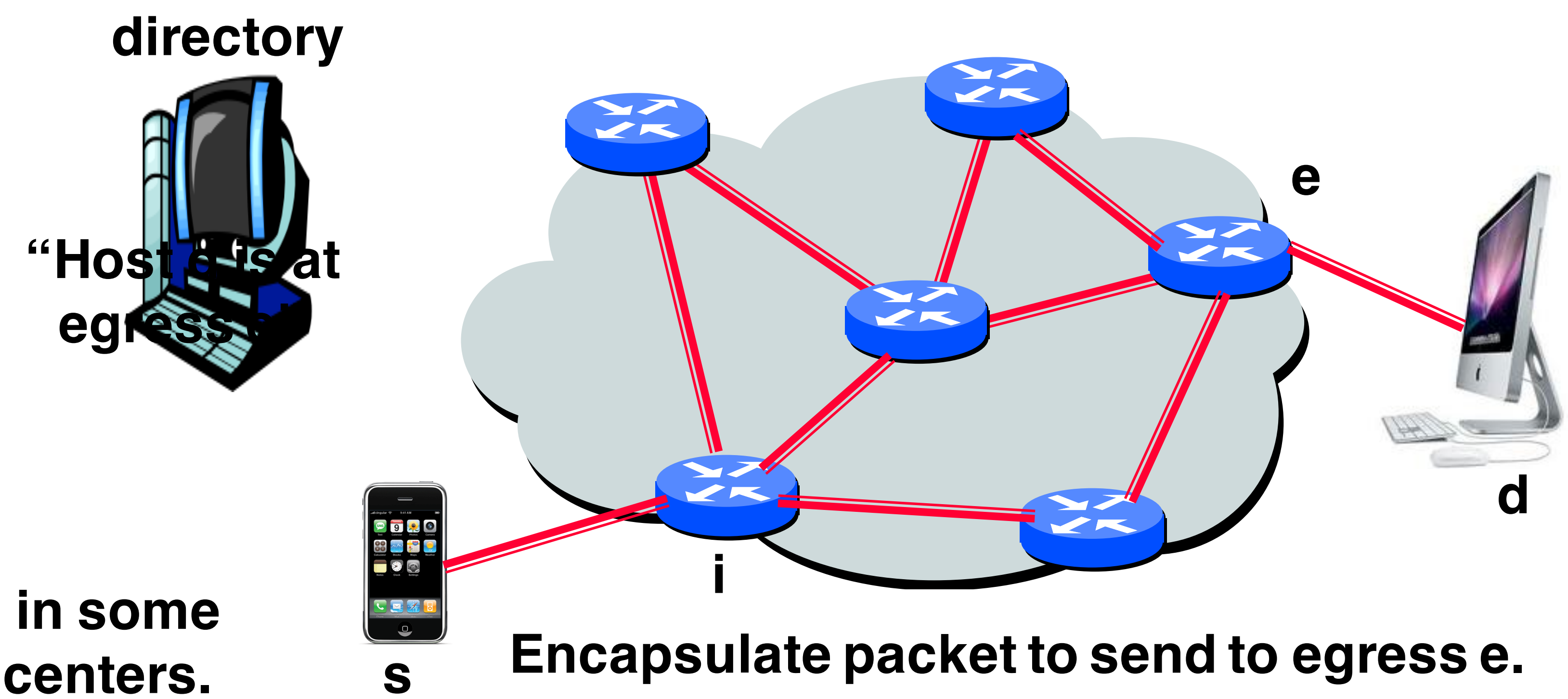
Disseminate With Another Protocol

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



Directory Service

- Contact a service to learn the location
  - Lookup the end-host or subnet address
  - … and learn the label to put on the packet
  - … to get the traffic to the right egress point



Used in some data centers.

Encapsulate packet to send to egress e.

Conclusion

- Routing is challenging
  - Distributed computation
  - Challenges with scalability and dynamics
- Many different solutions for different environments
  - Ethernet LAN: 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
    - E.g., link-state routing or multiple spanning trees
    - E.g., directory service or injection of subnets into routing protocol
- An active research area…

“Design Philosophy of the DARPA Internet Protocols”

(*ACM SIGCOMM*, 1988)

David Clark

Design Goals

- Primary goal
  - Effective technique for multiplexed utilization of existing interconnected networks (e.g., ARPAnet, packet radio)
- Important goals
  - Survivability in the face of failure
  - Multiple types of communication service
  - Wide variety of network technologies
- Less important goals
  - Distributed management of resources
  - Cost effectiveness
  - Host attachment with low level of effort
  - Accountability of resources

Consequences of the Goals

- Effective multiplexed utilization of existing networks
  - Packet switching, not circuit switching
- Continued communication despite network failures
  - Routers don't store state about ongoing transfers
  - End hosts provide key communication services
- Support for multiple types of communication service
  - Multiple transport protocols (e.g., TCP and UDP)
- Accommodation of a variety of different networks
  - Simple, best-effort packet delivery service
  - Packets may be lost, corrupted, or delivered out of order
- Distributed management of network resources
  - Multiple institutions managing the network
  - Intradomain and interdomain routing protocols

Questions

- What if we started with different goals?
  - Network management
  - Less concern about backwards compatibility
  - More concern about security
- Can we address new challenges
  - Management, security, privacy, sensor nets, …
  - Without sacrificing the other goals?
  - Without a major change to the architecture?

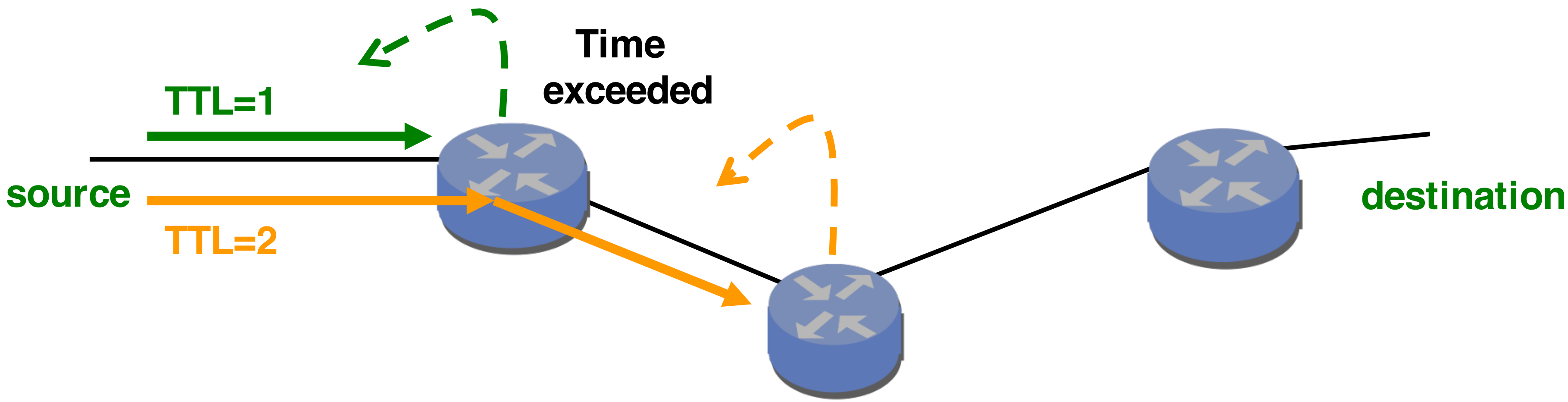
"End-to-End Routing Behavior in the Internet"

(*ACM SIGCOMM*, 1996; *ToN*, 1997)

Vern Paxson

Measurement With Traceroute

- Traceroute tool to measure the forwarding path
  - Send packets with TTL=1, 2, 3…
  - Record the source of the “time exceeded” message



- Useful, but introduces many challenges
  - Path changes
  - Non-participating nodes
  - Inaccurate, two-way measurements

Questions

- Why can't we measure the Internet more directly?
  - What can we do about it?
- Right division of labor between host and network?
  - For path selection
  - For network monitoring
- How do we fix these routing problems?
  - In a decentralized, federated network
  - How to incentivize better network management

Backup Slides on Paxson Paper

Paxson Study: Forwarding Loops

- Forwarding loop
  - Packet returns to same router multiple times
- May cause traceroute to show a loop
  - If loop lasted long enough
  - So many packets traverse the loopy path
- Traceroute may reveal false loops
  - Path change that leads to a longer path
  - Causing later probe packets to hit same nodes
- Heuristic solution
  - Require traceroute to return same path 3 times

Paxson Study: Causes of Loops

- Transient vs. persistent
  - Transient: routing-protocol convergence
  - Persistent: likely configuration problem
- Challenges
  - Appropriate time boundary between the two?
  - What about flaky equipment going up and down?
  - Determining the cause of persistent loops?
- Anecdote on recent study of persistent loops
  - Provider has static route for customer prefix
  - Customer has default route to the provider

Paxson Study: Path Fluttering

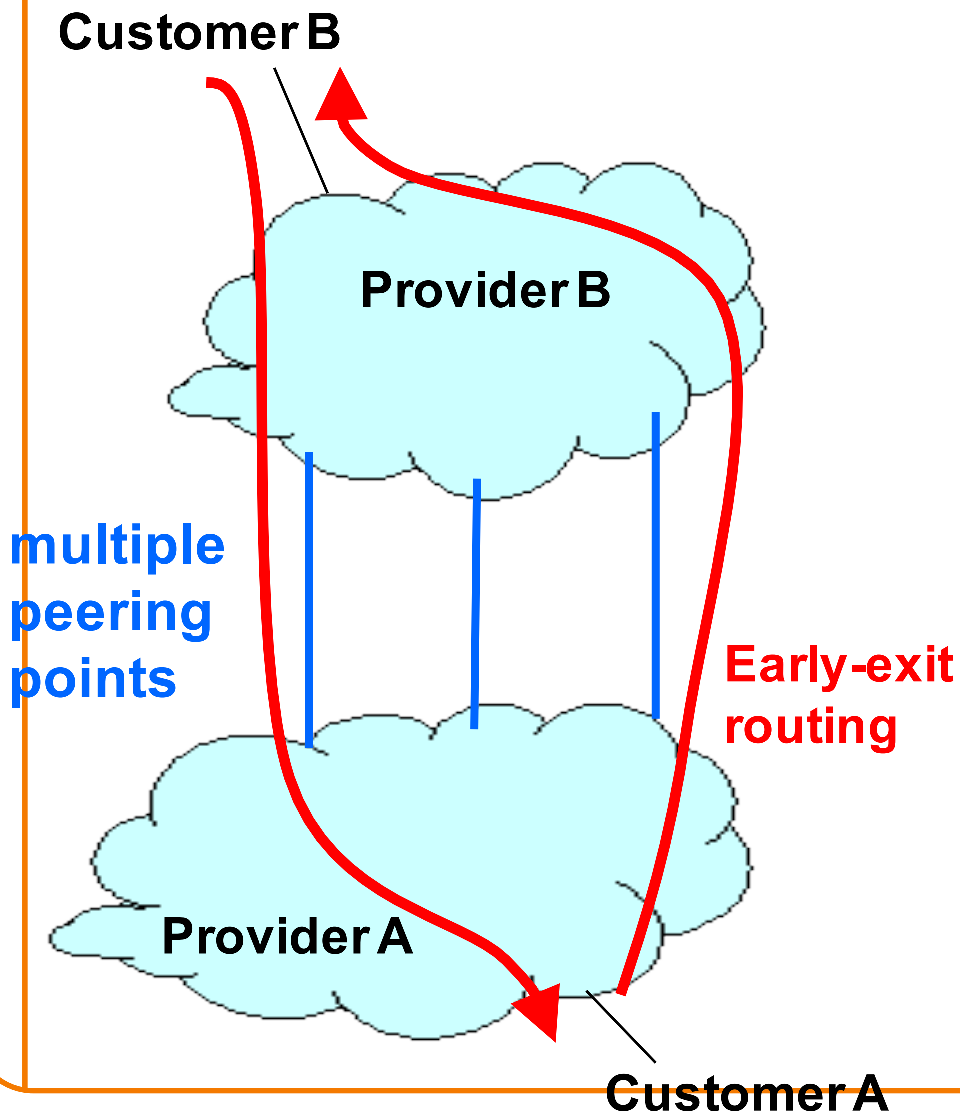
- Rapid changes between paths
  - Multiple paths between a pair of hosts
  - Load balancing policies inside the network
- Packet-based load balancing
  - Round-robin or random
  - Multiple paths for packets in a single flow
- Flow-based load balancing
  - Hash of some fields in the packet header
  - E.g., IP addresses, port numbers, etc.
  - To keep packets in a flow on one path

Paxson Study: Routing Stability

- Route prevalence
  - Likelihood of observing a particular route
  - Relatively easy to measure with sound sampling
  - Poisson arrivals see time averages (PASTA)
  - Most host pairs have a dominant route
- Route persistence
  - How long a route endures before a change
  - Much harder to measure through active probes
  - Look for cases of multiple observations
  - Typical host pair has path persistence of a week

Paxson Study: Route Asymmetry

- Hot-potato routing



- Other causes
  - Asymmetric link weights in intradomain routing
  - Cold-potato routing, where AS requests traffic enter at particular place
- Consequences
  - Lots of asymmetry
  - One-way delay is not necessarily half of the round-trip time