# CS 5114
# Network Programming Languages
# Control Plane

http://www.flickr.com/photos/rofi/2097239111/


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Based on lecture notes by Jennifer Rexford and Michael Freedman

# Announcements

Breakfast pickup and presentations posted to website

**Reviews:** start today!

- Only review one paper but please read them all
- Please submit by CMS in the future

**Homework #1**

- Will go out next Tuesday
- Due 2 weeks later
- Topic: OpenFlow programming

# Overview

## Host (last time)

- Network discovery and bootstrapping
- Resource allocation and interface to applications

## Data plane (next time)

- Streaming algorithms and switch fabric
- Forward, filter, buffer, schedule, mark, monitor, . . .

## Control plane (today)

- Distributed algorithms for computing paths
- Disseminating the addresses of end hosts

# Data, Control, and Management Planes

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

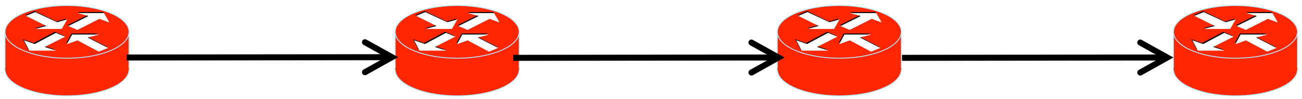
# Routing vs. Forwarding

**Routing:** control plane

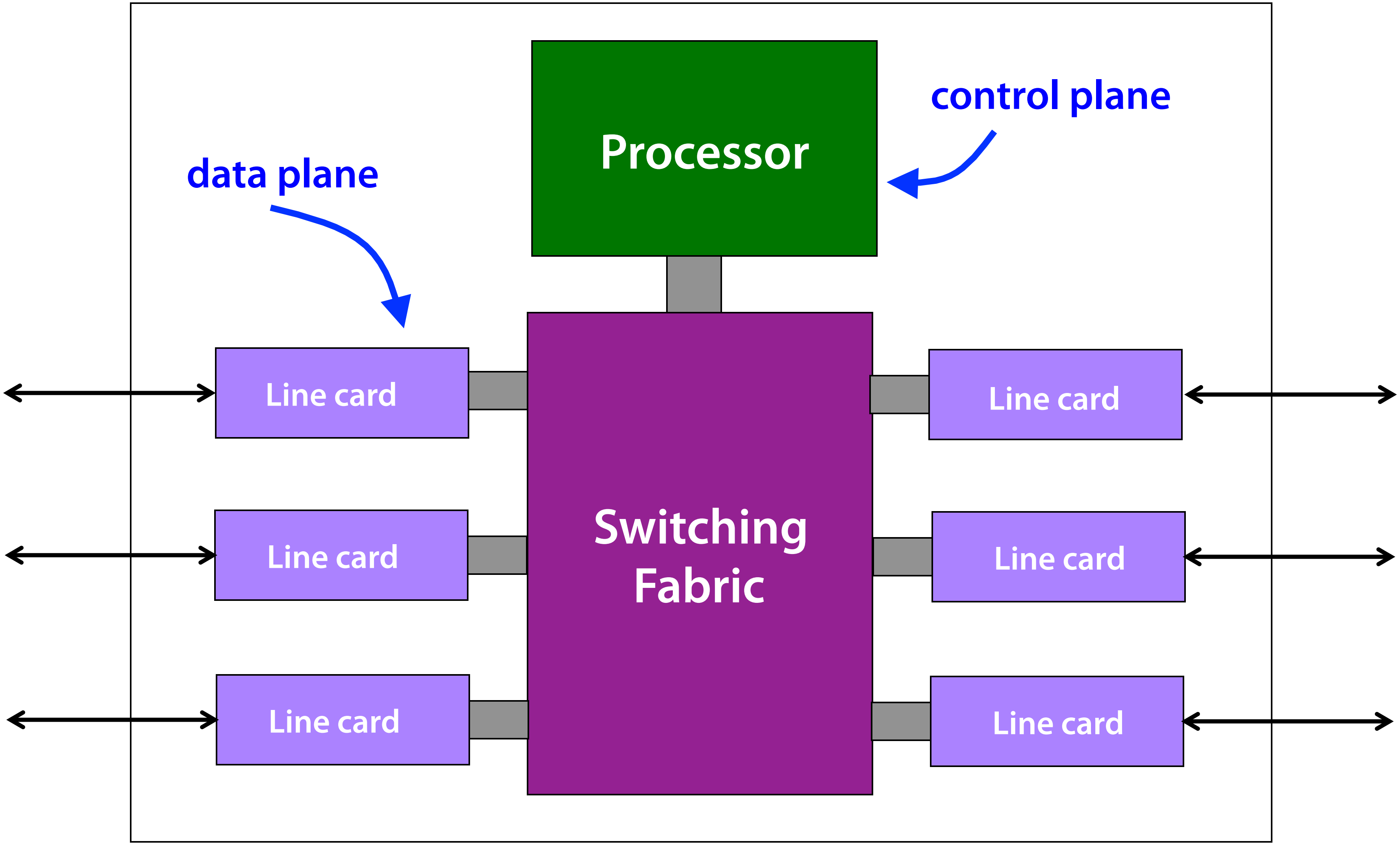
- Computing paths the packets will follow
- Routers talking amongst themselves
- Individual router *creating* a forwarding table

**Forwarding:** data plane

- Directing a data packet to an outgoing link
- Individual router *using* a forwarding table



# Data and Control Planes



# 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?

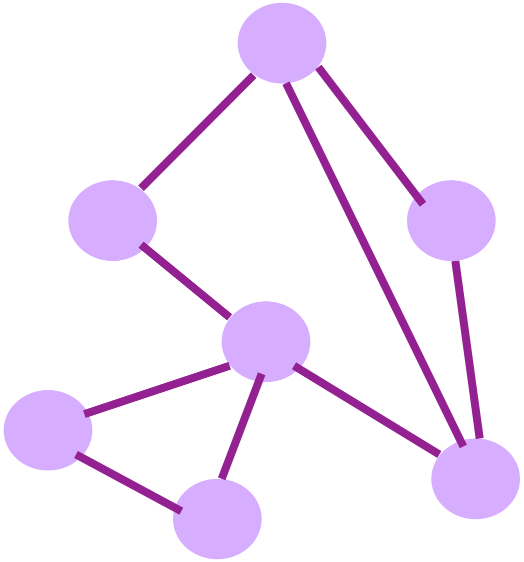
# Different Ways to Represent Paths

## Static Model

- The *outcome* of routing computations
- Not how the (distributed) computations are performed

## Trade-offs

- State required to represent the paths
- Efficiency of the resulting paths
- Ability to support multiple paths
- Complexity of computing paths
- Which nodes control the computation



## Different Settings

- LAN, intradomain, interdomain

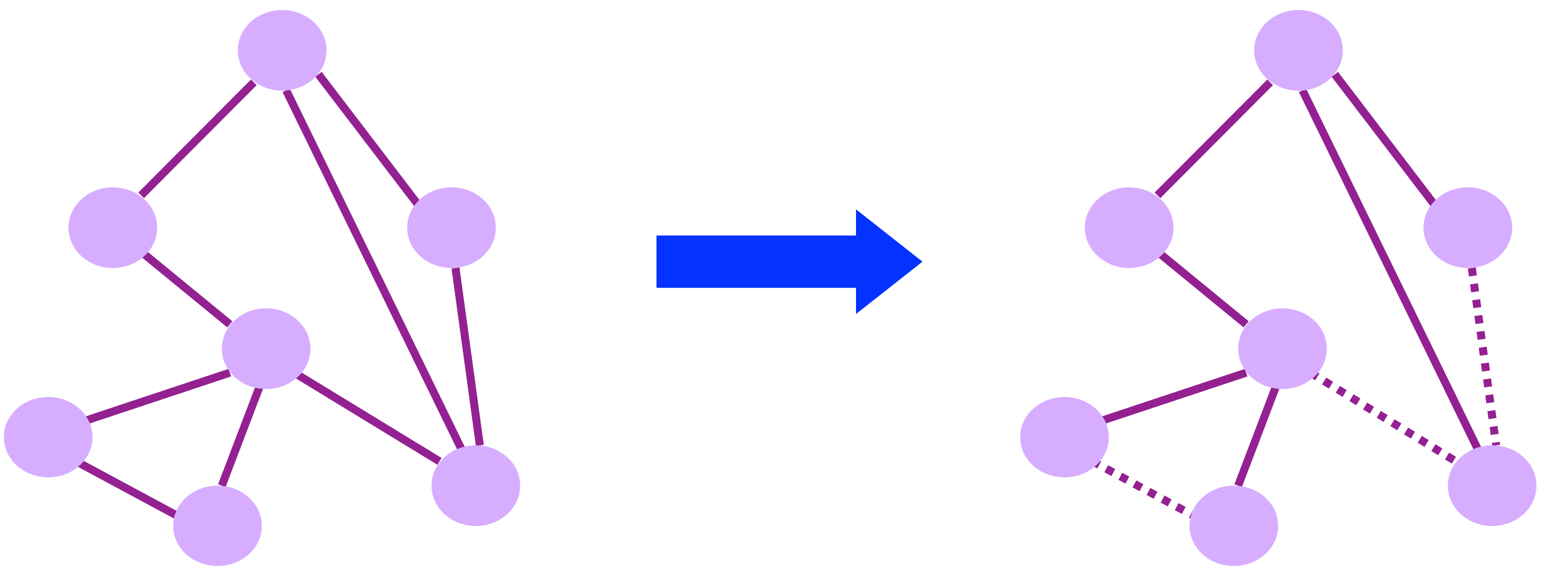
# Spanning Tree

A tree that connects every node

- Single path between each pair of nodes
- No loops, so supports broadcast easily

Disadvantages

- Paths can sometimes be long
- Some links unused!



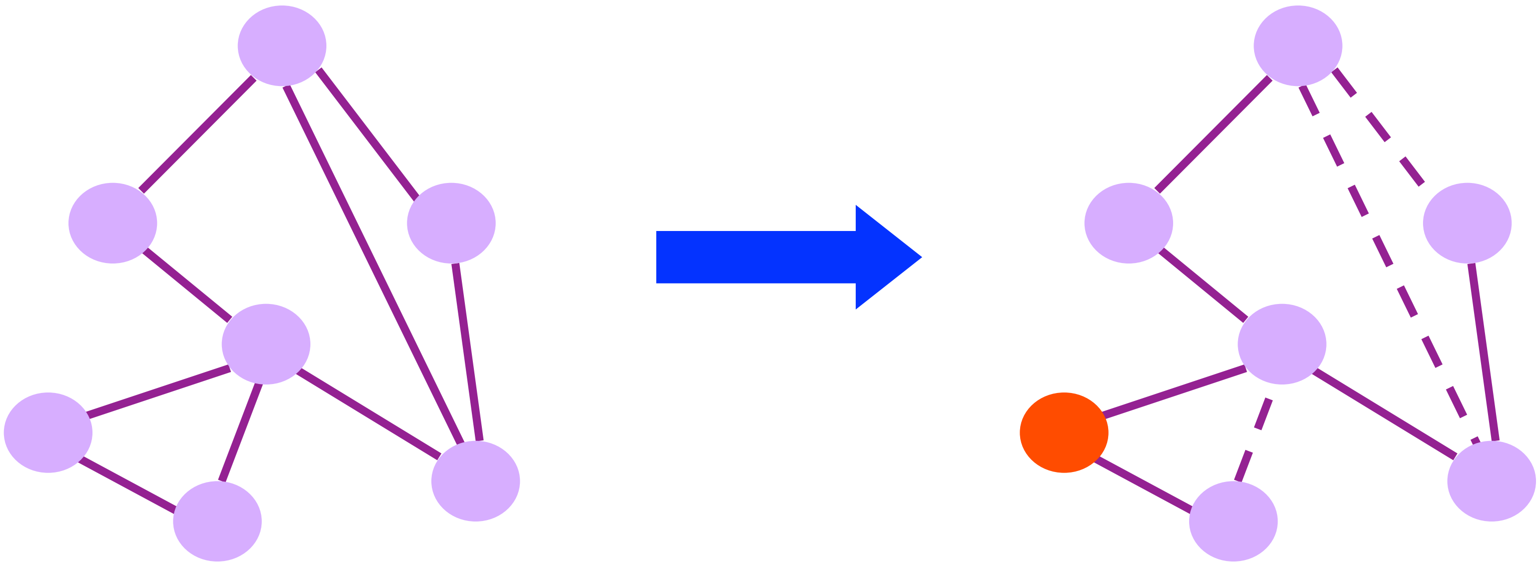
# Shortest Paths

## Shortest path(s) between each pair of nodes

- Separate shortest-path tree rooted at each node
- Minimum hop count (or minimum sum of weights)

## Disadvantages

- All nodes must agree on the link metrics
- Multipath routing is limited (e.g., Equal Cost Multipath)



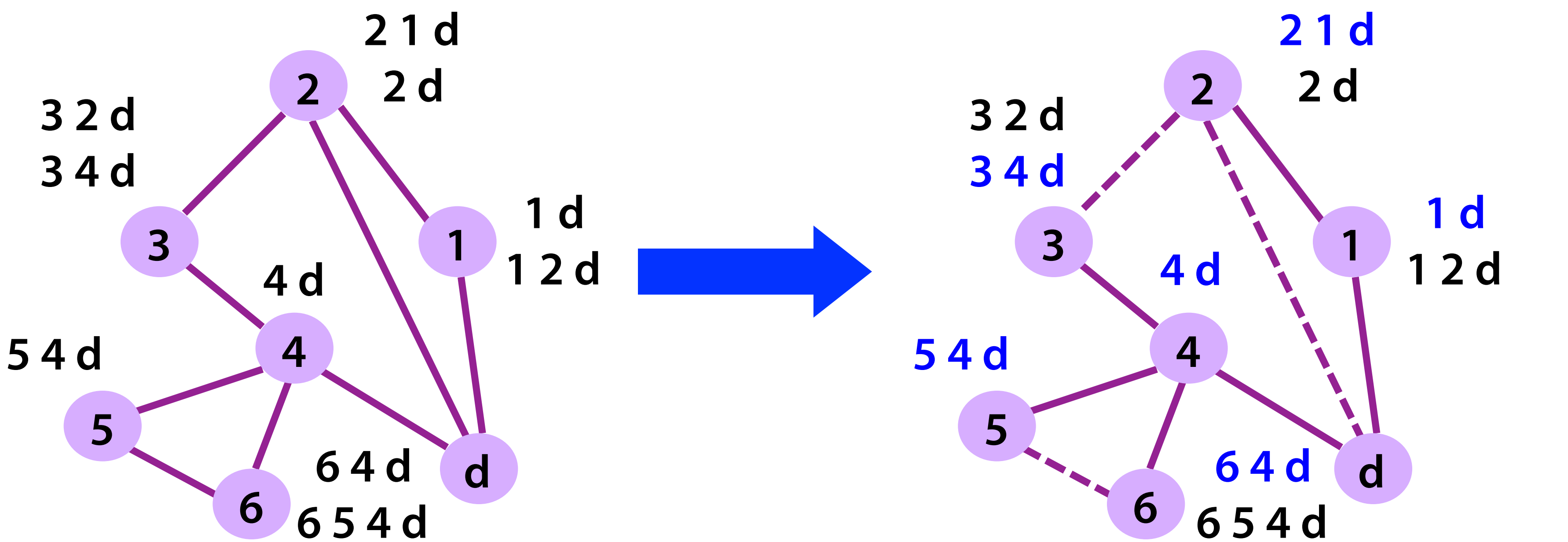
# Local Policy at Each Hop

## Locally best path

- Each node picks the path it likes best
- … from among the paths selected by its neighbors

## Disadvantages

- More complicated to configure and model



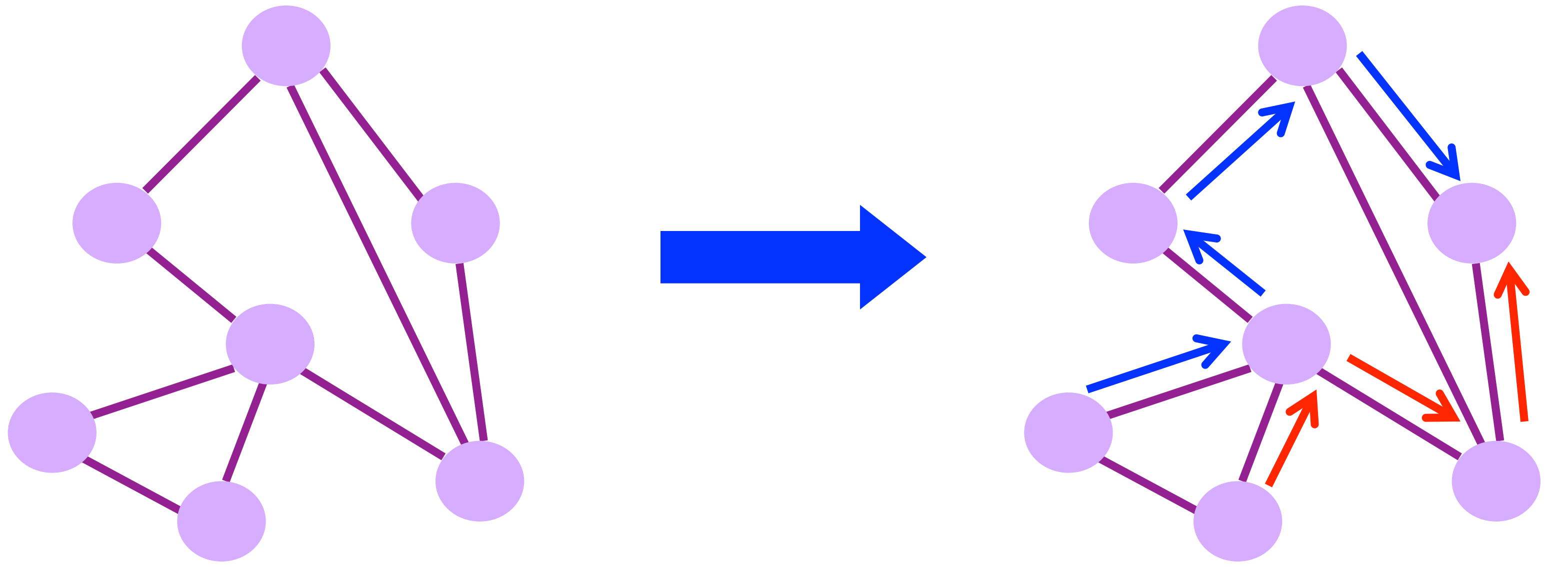
# End-to-End Path Selection

## 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?

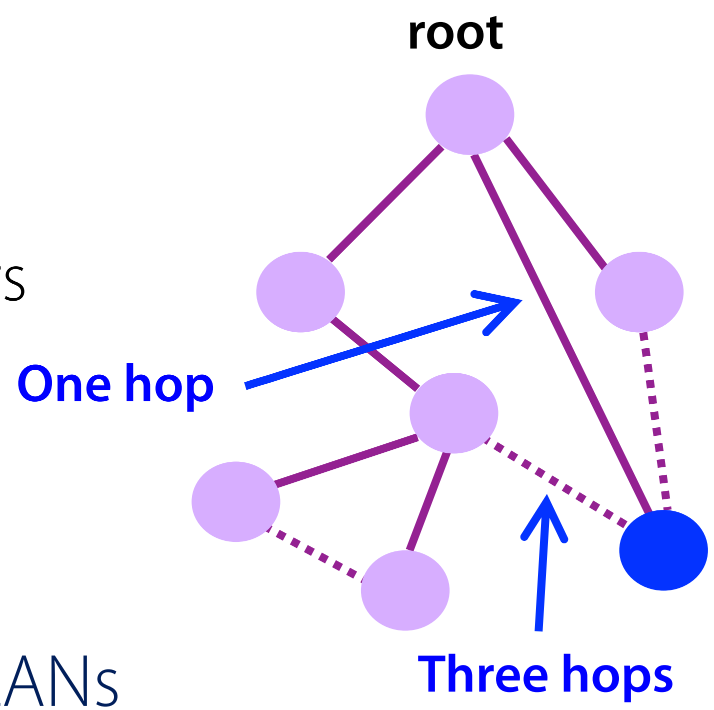
# Spanning Tree Algorithm

## Elect a root

- Select switch with the smallest identifier and form a tree

## Algorithm

- Repeatedly talk to neighbors
  - "I think node Y is the root"
  - "My distance from Y is d"
- Update state based on neighbors
  - Smaller id as the root
  - Smaller distance d+1
- Disable interfaces not on path




## Primarily used in Ethernet-based LANs

# Spanning Tree Example: Switch #4

## Switch #4 thinks it is the root

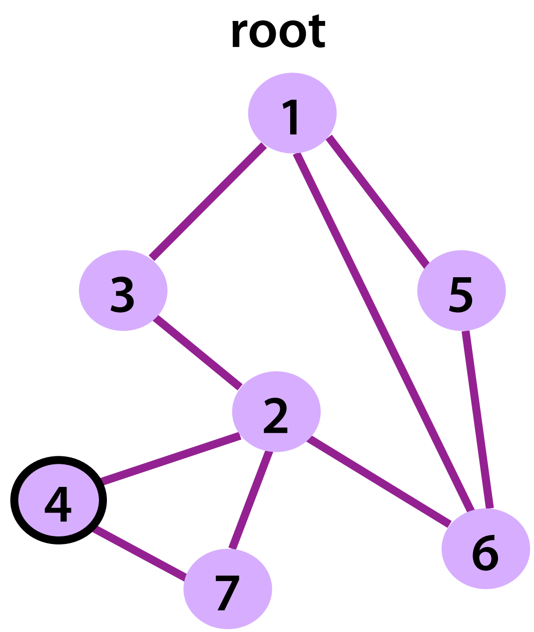
- Sends (4, 0, 4) message to 2 and 7

## 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

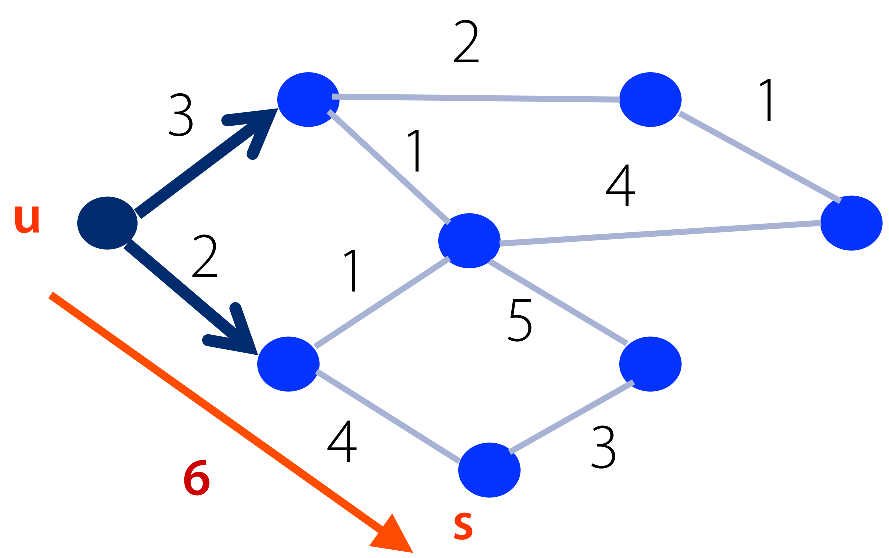
- Receives (2, 1, 7) from 7
- And realizes this is a longer path
- So, prefers its own one-hop path
- And removes 4-7 link from the tree



# 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**

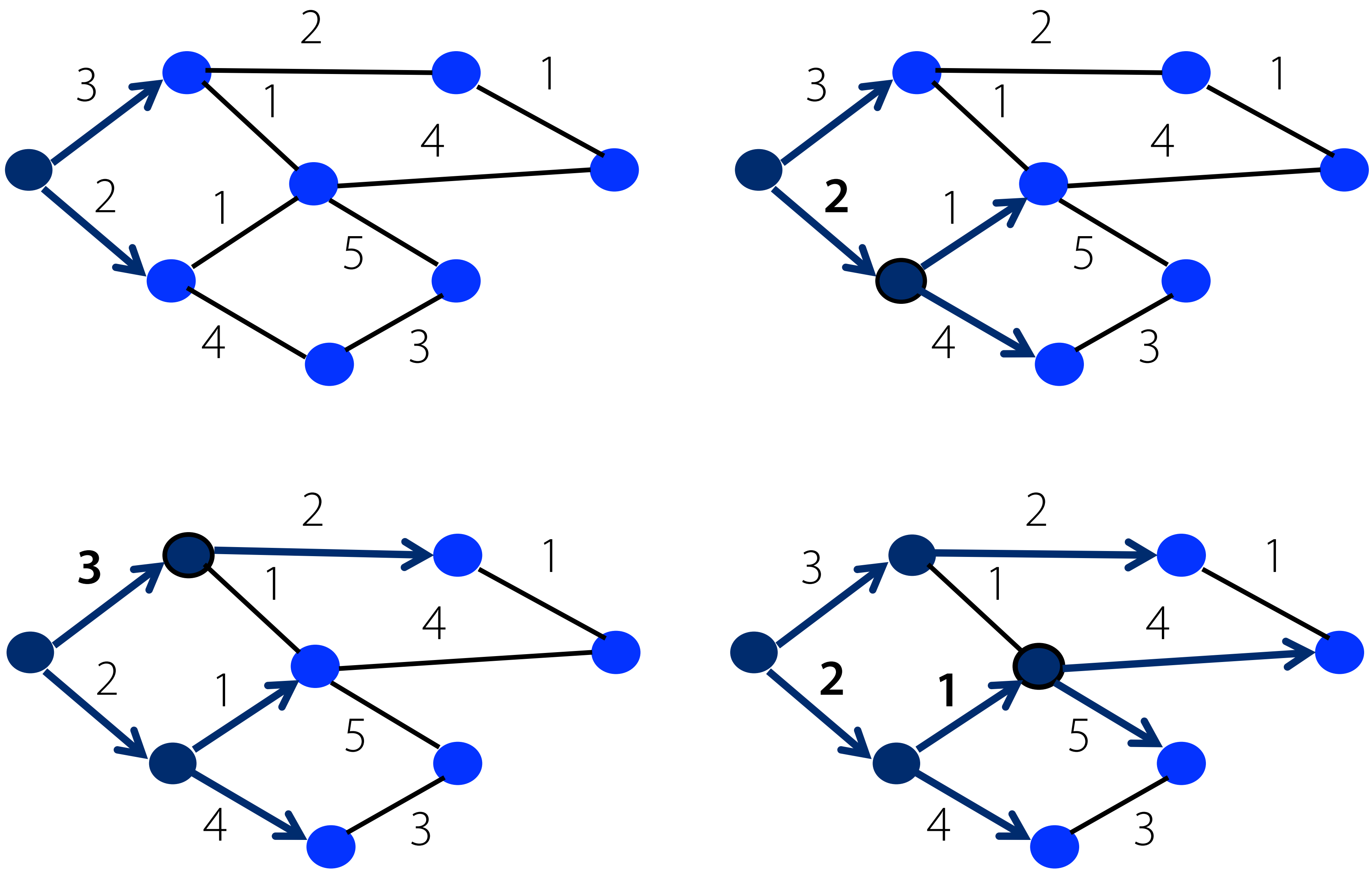
```
S = {u}
for all nodes v
   if (v is adjacent to u)
      D(v) = c(u,v)
   else D(v) = ∞
```

**Loop**

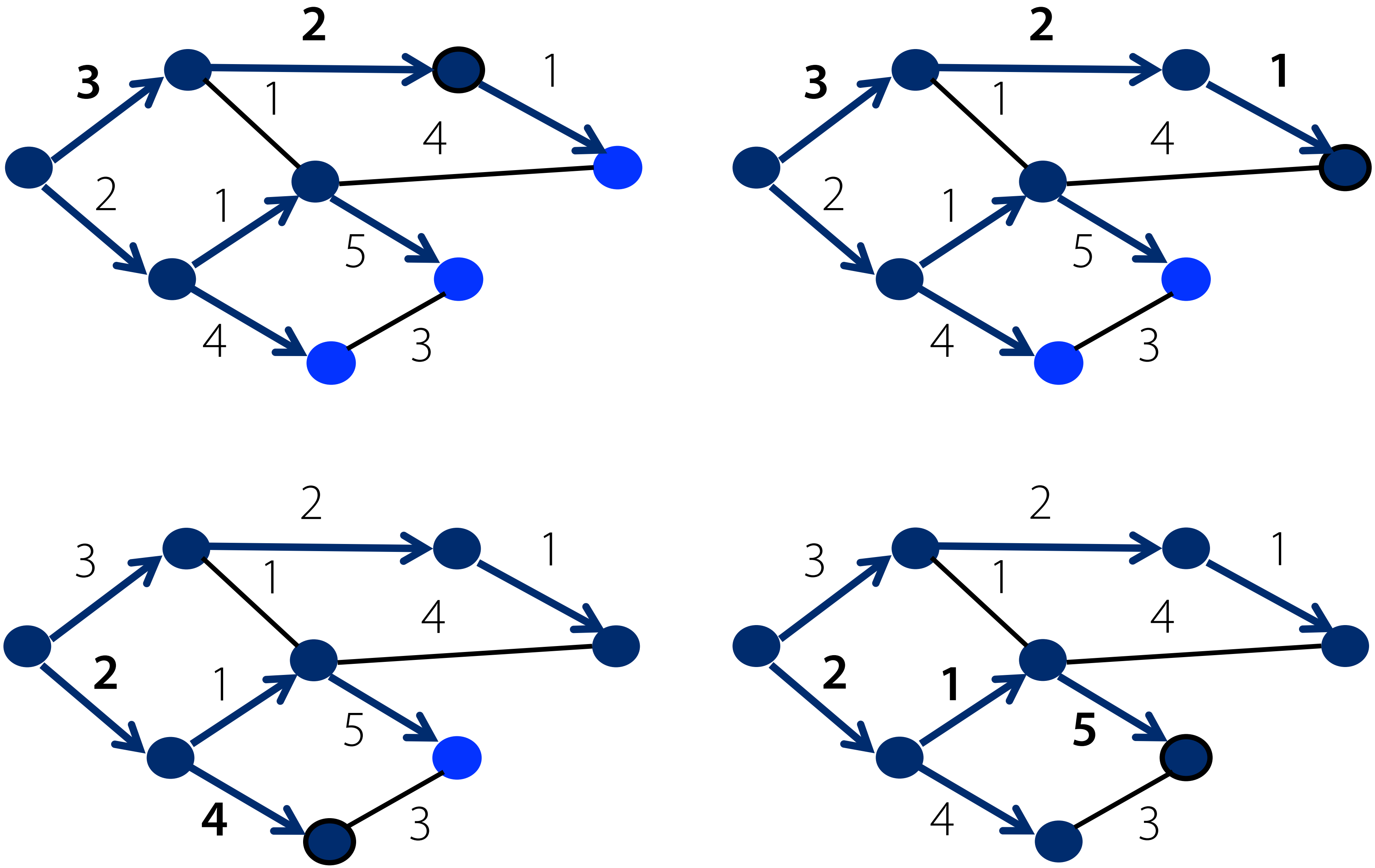
```
add w with smallest D(w) to S
update D(v) for all adjacent v:
   D(v) = min{D(v), D(w) + c(w,v)}
until all nodes are in S
```

**Used in OSPF and IS-IS**

# Link-State Routing Example

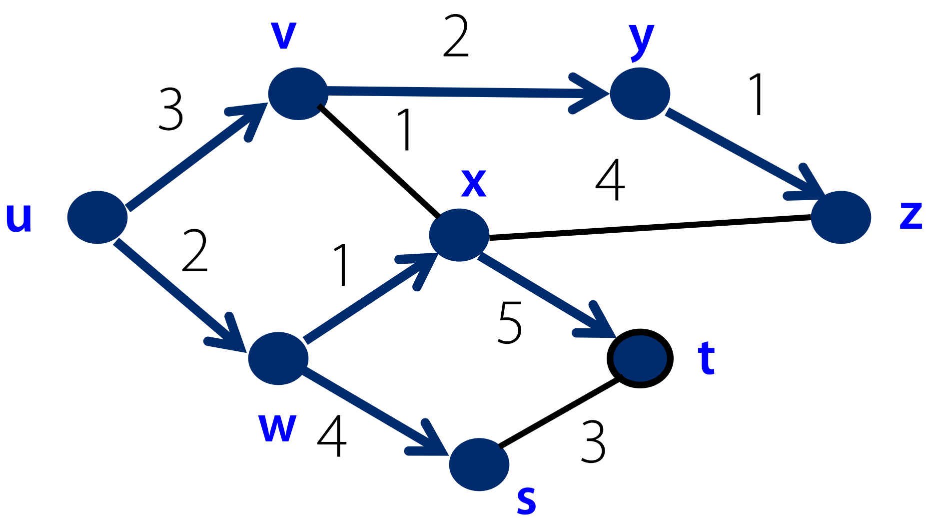


# Link-State Routing Example (continued)



# 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) |

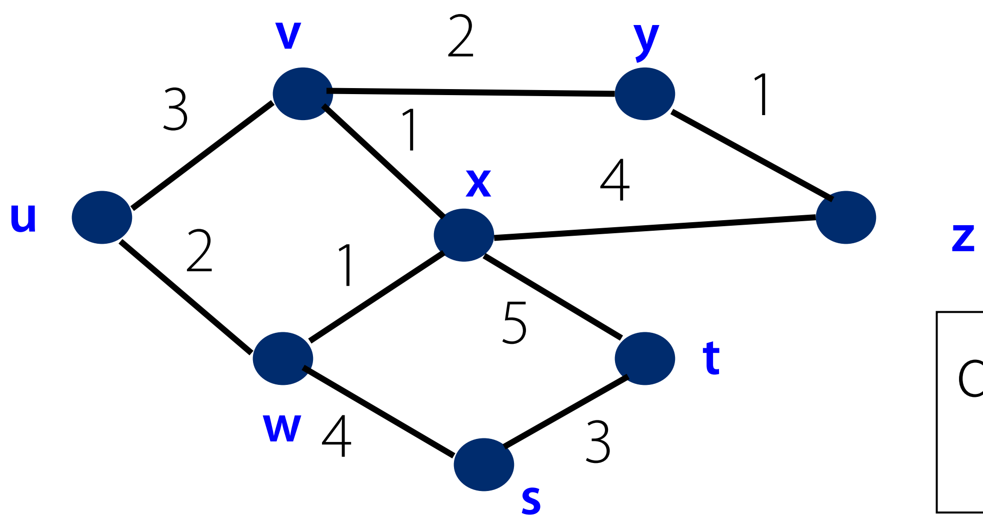
# Distance Vector: Bellman-Ford Algorithm

## 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



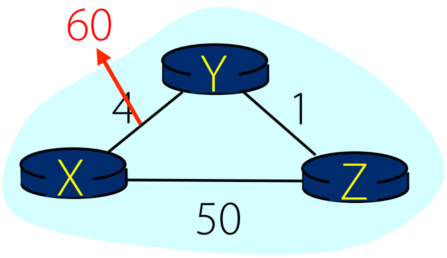

$$d_u(z) = \min\{c(u,v) + d_v(z),\ c(u,w) + d_w(z)\}$$

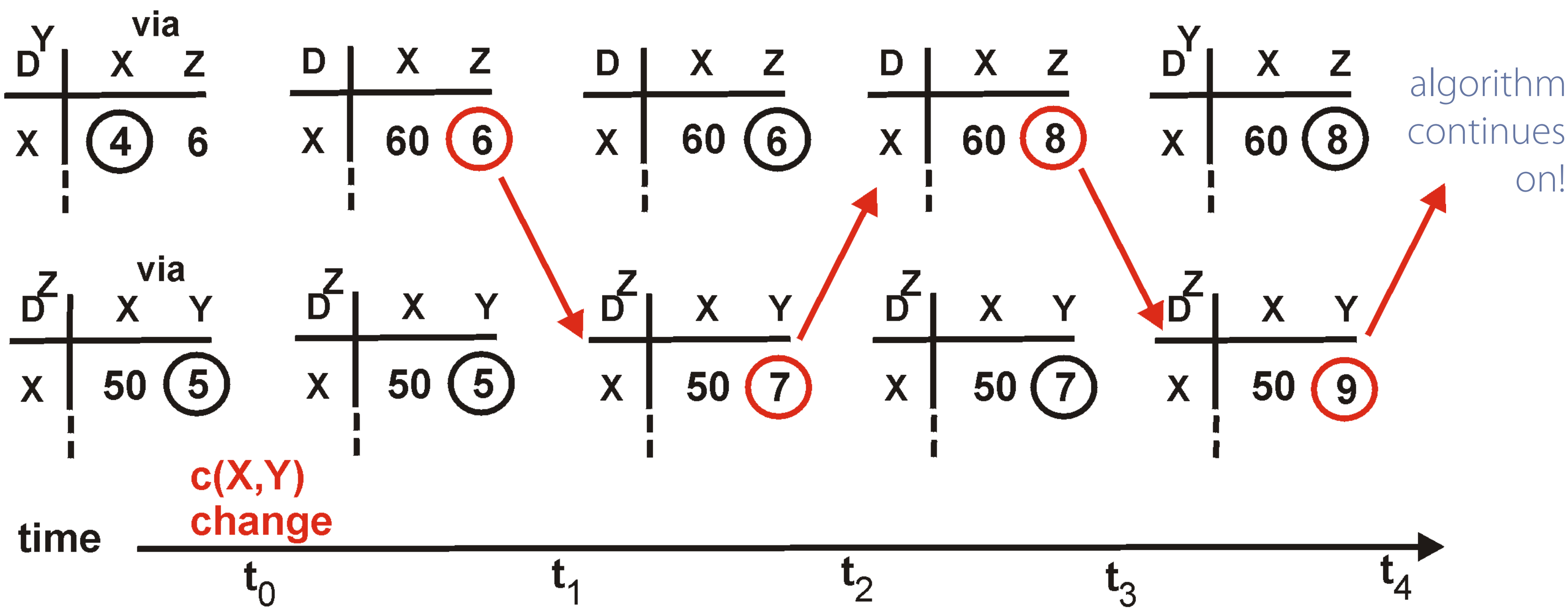
**Used in RIP and EIGRP**

# Distance Vector: Count to Infinity

## Link cost changes:

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



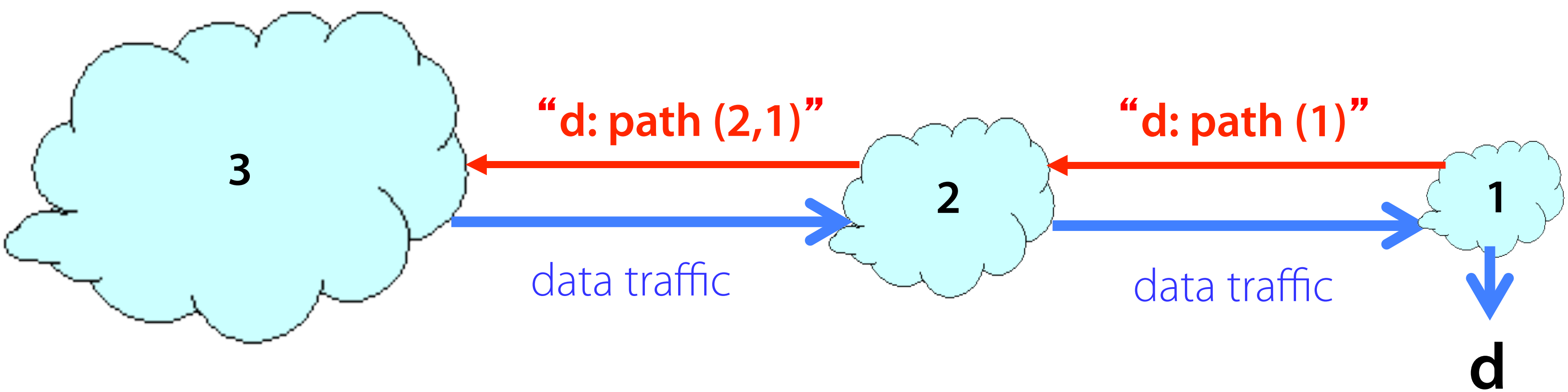
# Path-Vector Routing

Extension of distance-vector routing

- Support flexible routing policies
- Avoid count-to-infinity problem

Key idea: advertise the entire path

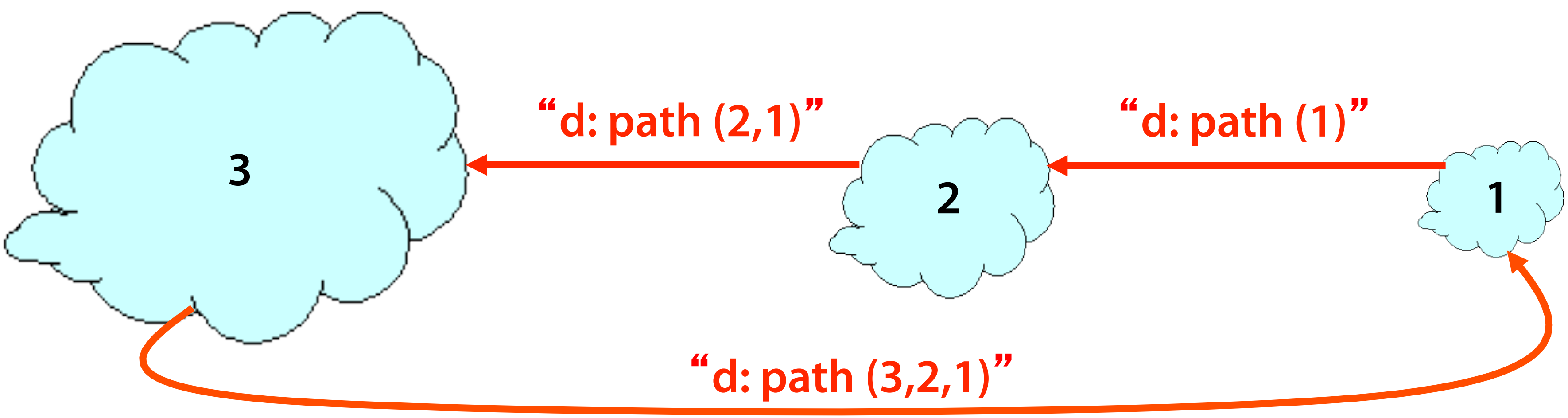
- Distance vector: send *distance metric* per dest d
- Path vector: send the *entire path* for each dest d




**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



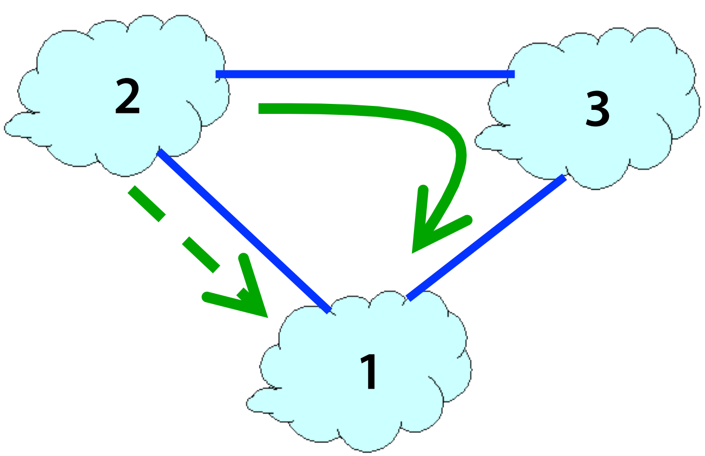
# Path-Vector: Flexible Policies

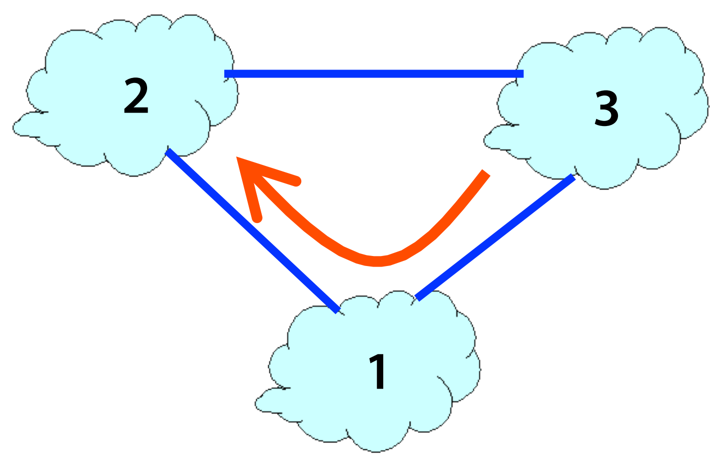
Each node can apply local policies

- 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”



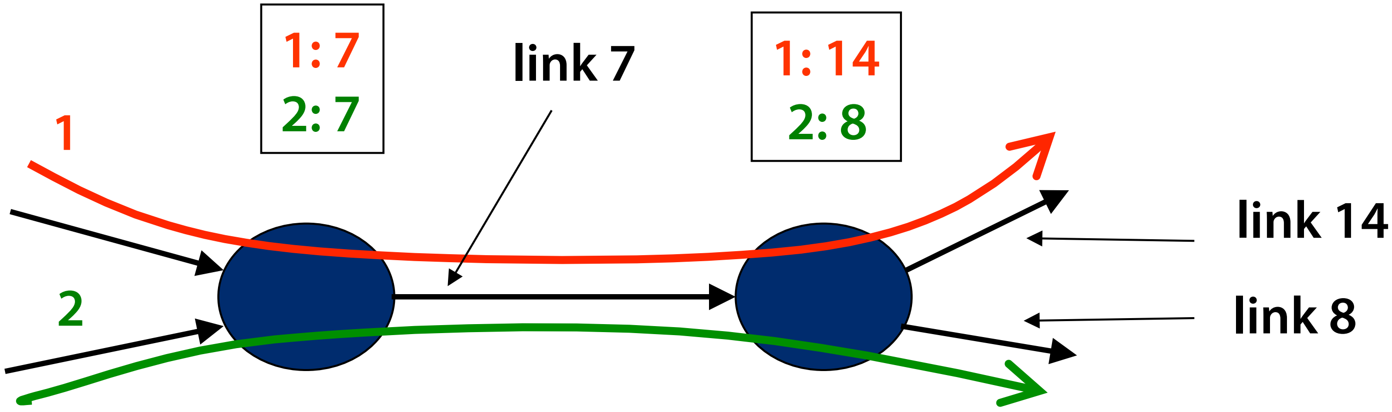
# End-to-End Signaling

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

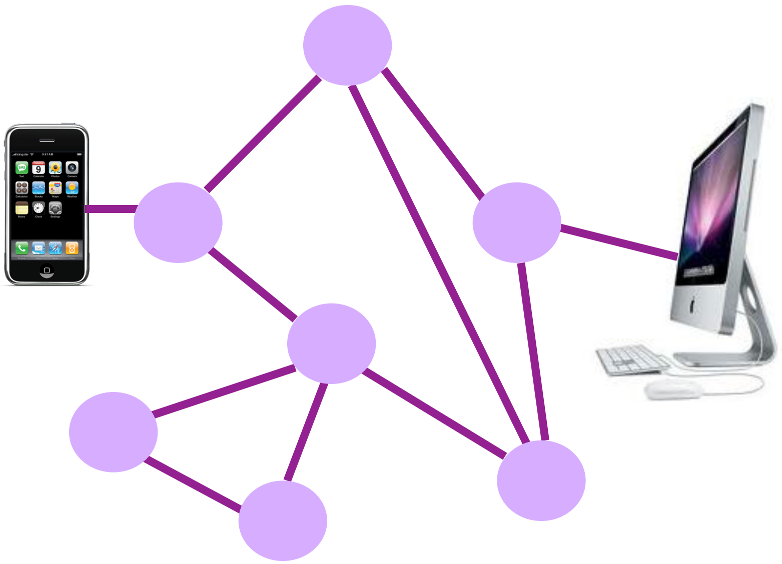
# Finding the Hosts

## 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 routing protocol
- Dissemination via different protocol
- Directory service



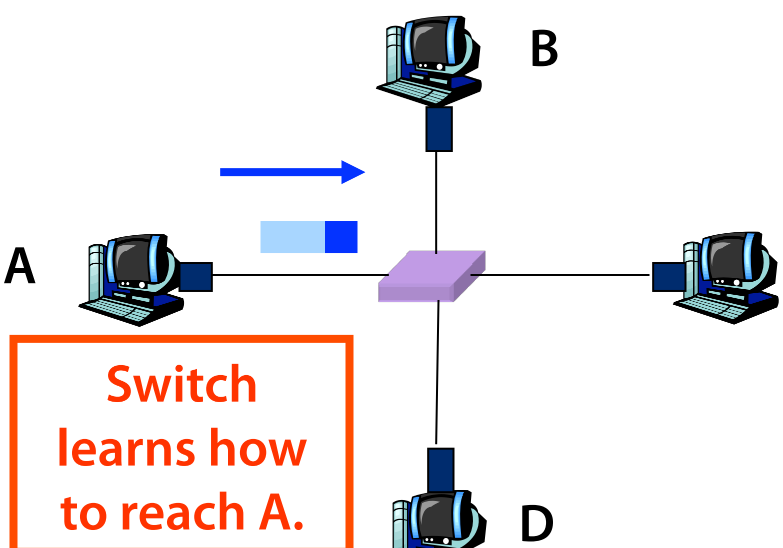
# Learning and Flooding

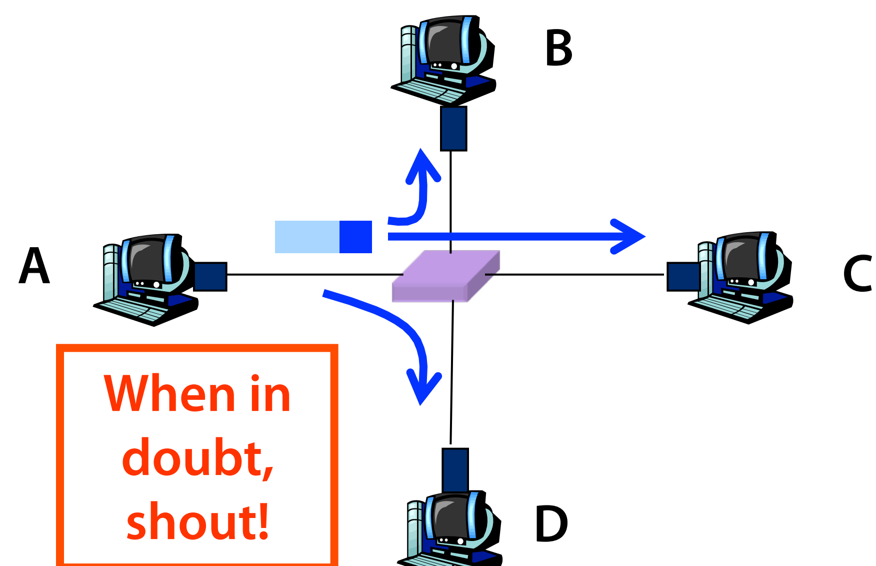
When a frame arrives

- 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



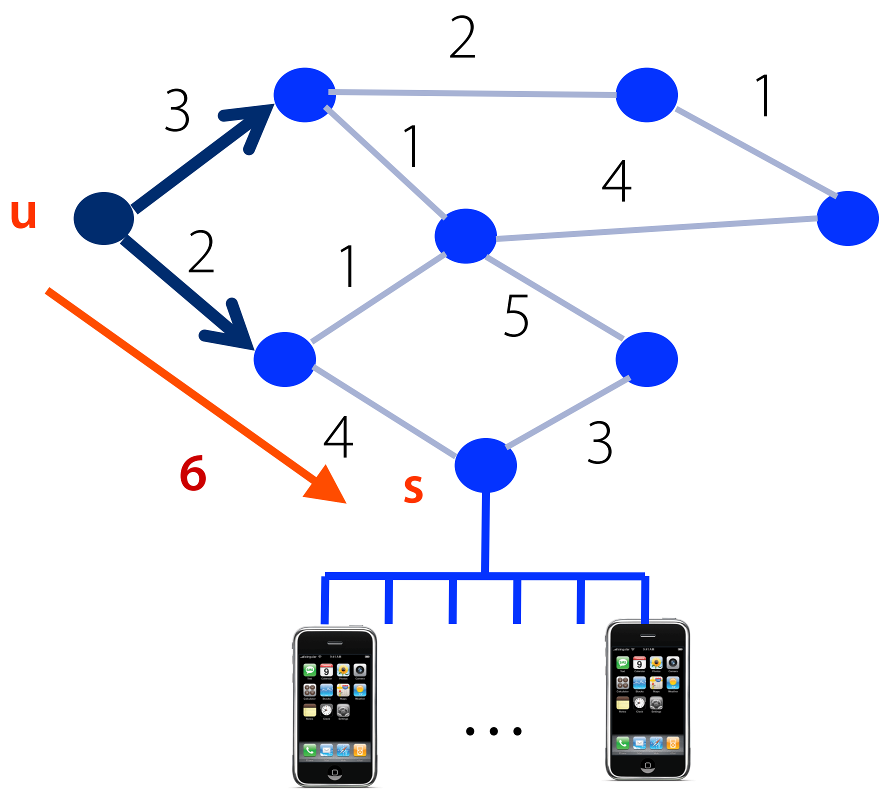




**Used in Ethernet LANs**

# 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**

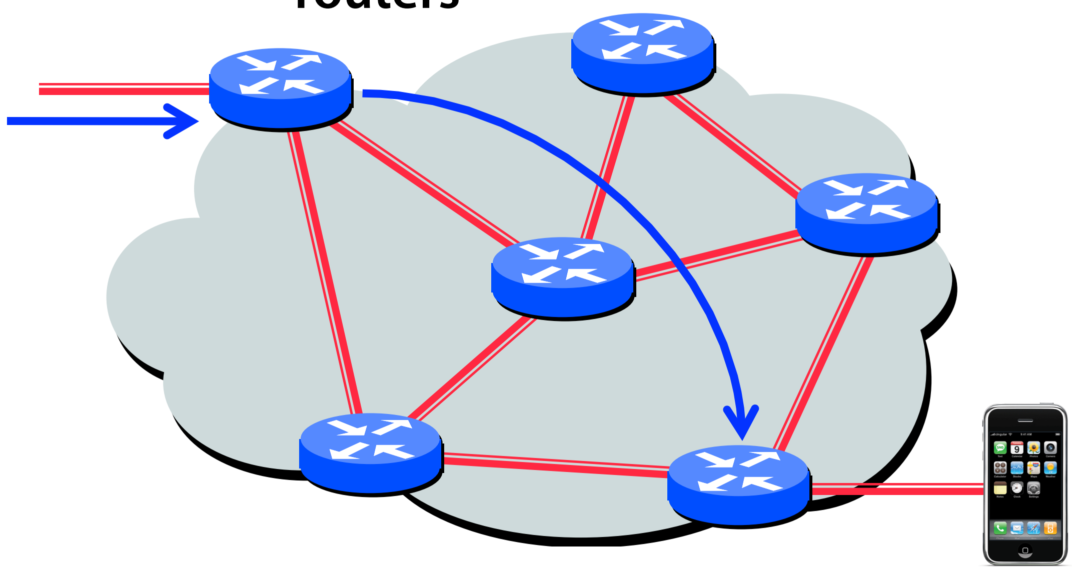
# Disseminate With Another Protocol

## Distribute using another protocol

- One router learns the route
- … and shares the information with other routers

**disseminate route to other routers**

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

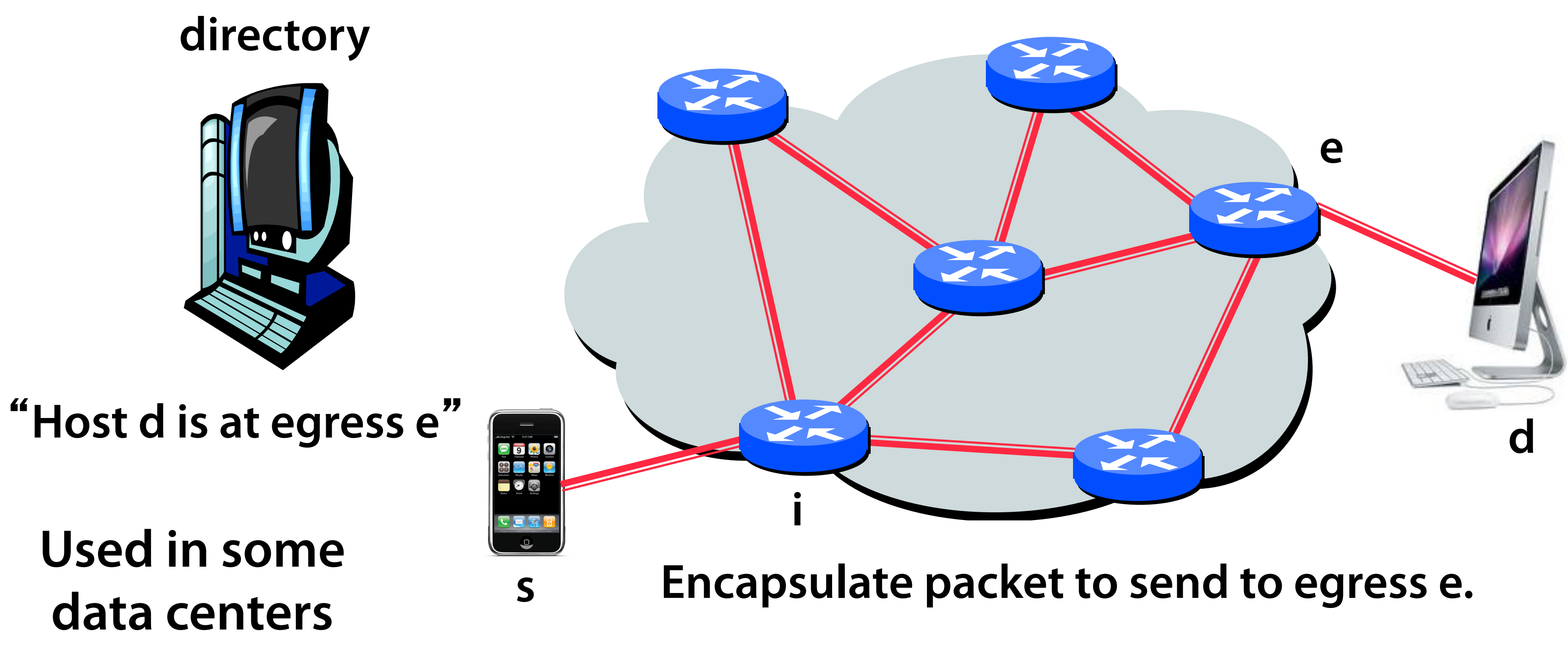


**Internal BGP (iBGP) used in backbone networks**

# Directory Service

## Contact a service to learn the location

- 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



# 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, inject subnet addresses
- **Backbone:** link-state 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, inject subnet

# “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”

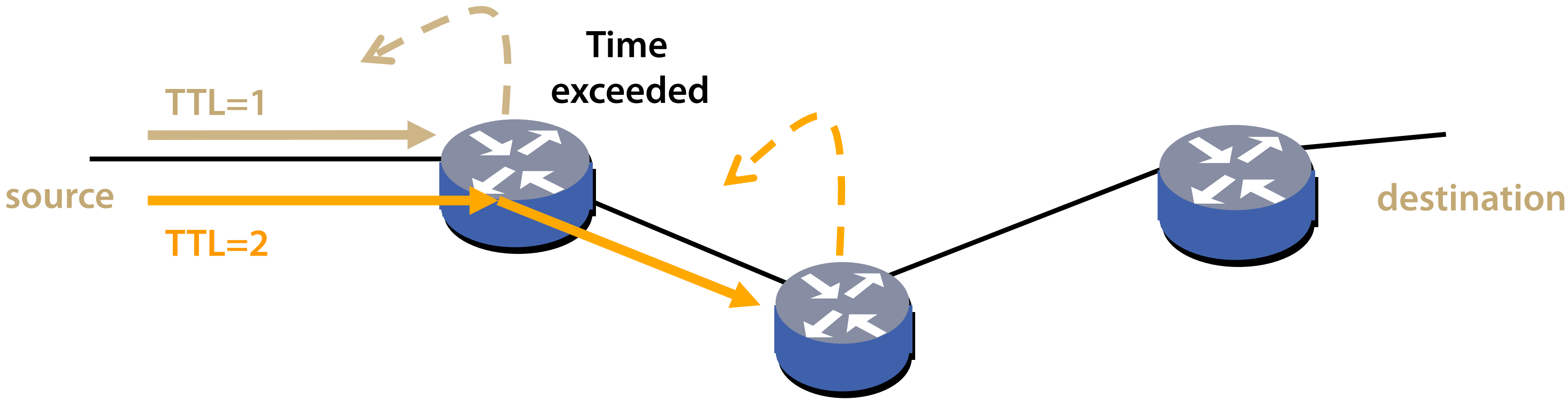
(*ACM SIGCOMM*, 1996; *ToN*, 1997)

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

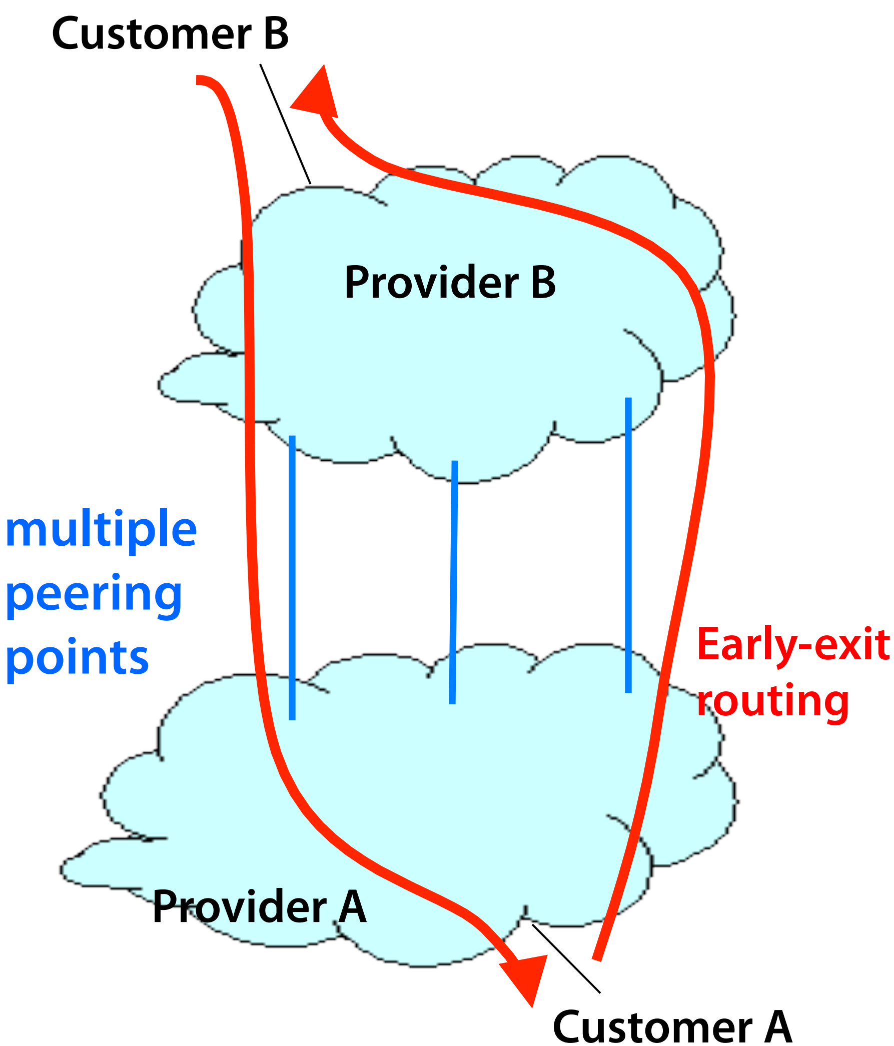
- Likelihood of observing a particular route
- Relatively easy to measure with sound sampling
- Poisson arrivals see time averages (PASTA)
- Most host pairs have a dominant route

## 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