CSC 458/2209 – Computer Networking Systems

Handout # 9: The Internet Protocol, Routing and Forwarding

Professor Yashar Ganjali
Department of Computer Science
University of Toronto

ganjali7@cs.toronto.edu
http://www.cs.toronto.edu/~yganjali

Announcements

- Problem Set 1 out today (January 27th)
  - 5 Problems (15 parts)
  - Due: Friday, Feb. 7th at 5pm.
  - Submit electronically on MarkUS.
    - File name: ps1.pdf

- This week's tutorial:
  - Problem Set 1 review and sample problems

- Programming assignment 1
  - Due Friday February 14th at 5pm.
  - Don't leave to the last minute.

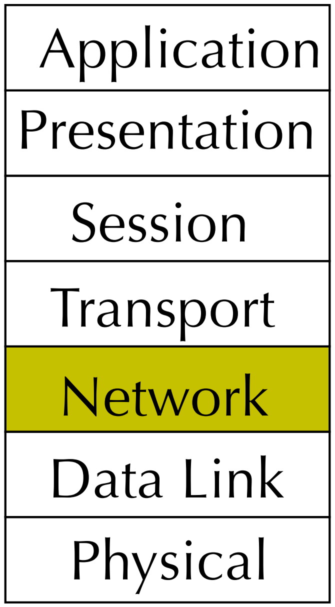
Announcements – Cont'd

- Reading for this week:
  - Chapter 3 of the textbook
  - Next week: Chapter 4

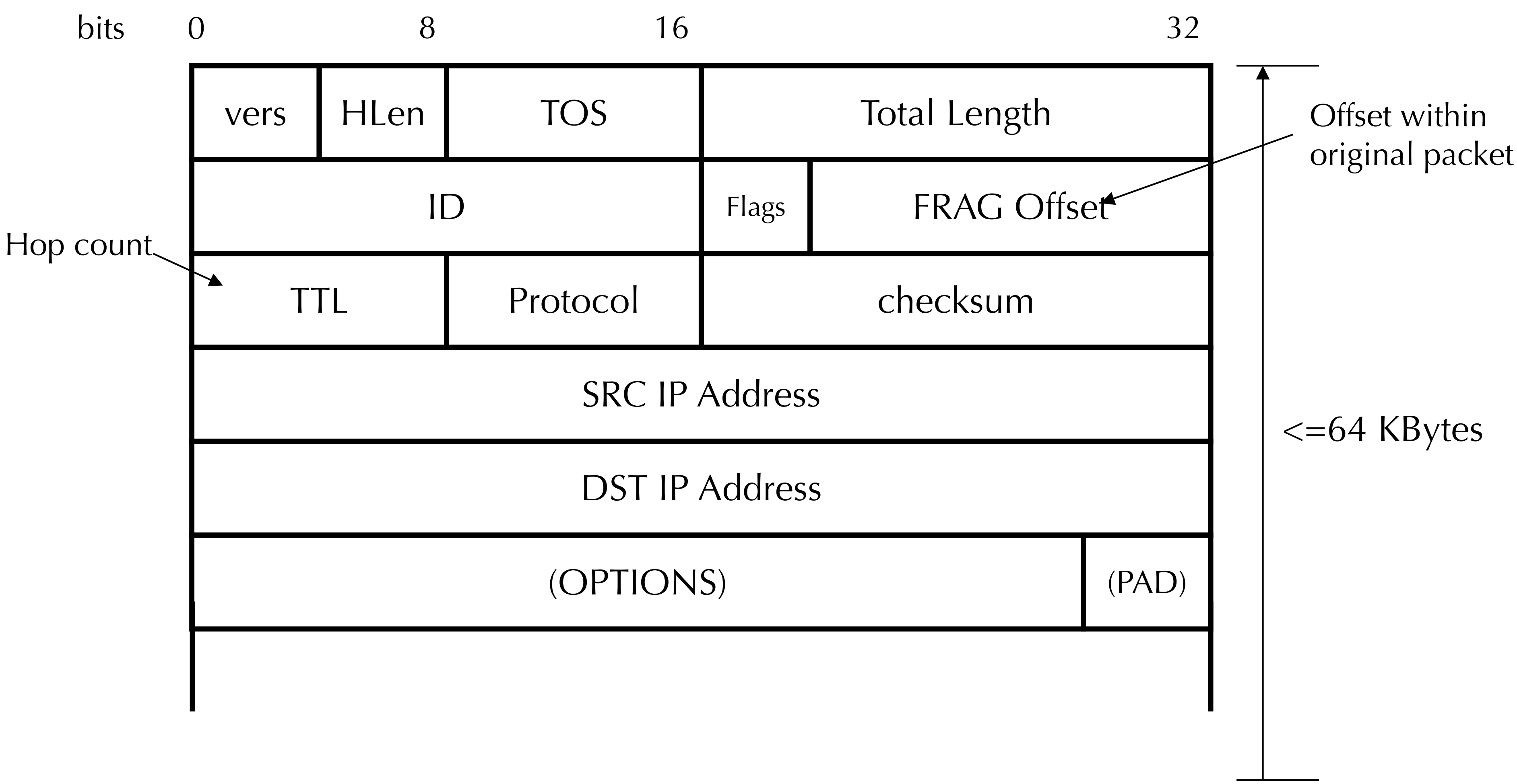
- Midterm exam
  - L0101: Monday February 24th
  - L0201: Tuesday February 25th
  - In class: same room and time as the lecture
  - For undergraduate and graduate students
  - Covers everything up to the end of Lecture 6 (Transport Protocol)

The Story

- So far …
  - Layers, and protocols
  - Link layer
  - Interconnecting LANs
    - Hubs, switches, and bridges
  - The Internet Protocol
    - IP datagram, fragmentation
    - Naming and addressing
    - CIDR, DNS
- This time
  - Routing and forwarding

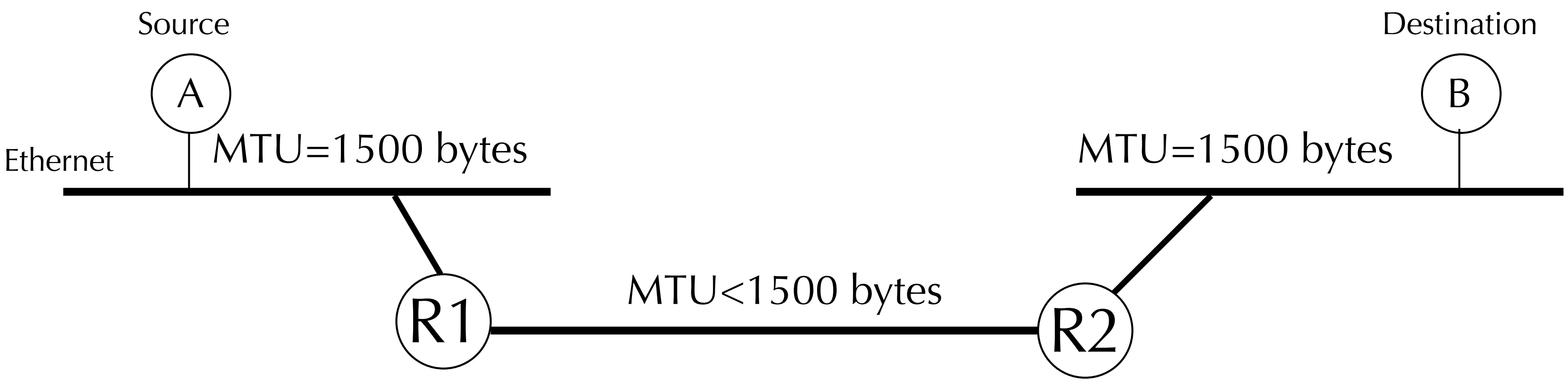


The IP Datagram -- Recap

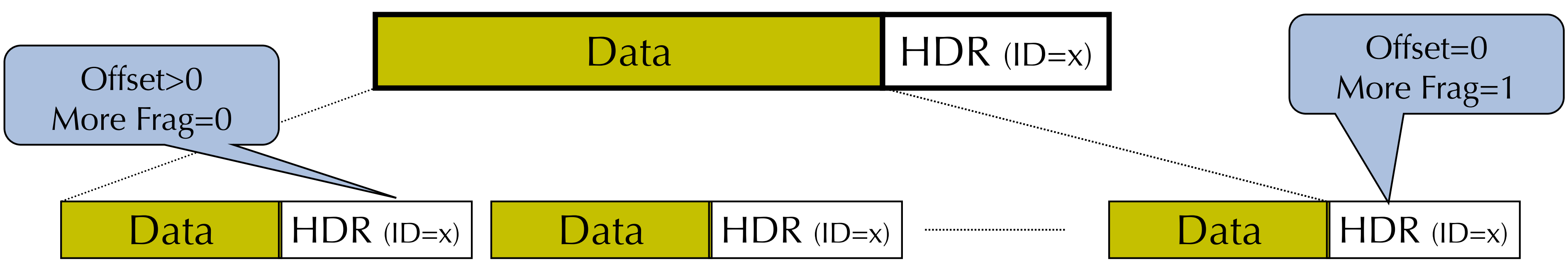


Fragmentation

Problem: A router may receive a packet larger than the maximum transmission unit (MTU) of the outgoing link.



Solution: R1 fragments the IP datagram into multiple, self-contained datagrams.



Fragmentation

- Fragments are re-assembled by the destination host; not by intermediate routers.
- To avoid fragmentation, hosts commonly use path MTU discovery to find the smallest MTU along the path.
- Path MTU discovery involves sending various size datagrams until they do not require fragmentation along the path.
- Most links use MTU>=1500bytes today.
- Try:
  `traceroute -F www.uwaterloo.ca 1500 and`
  `traceroute -F www.uwaterloo.ca 1501`
- (DF=1 set in IP header; routers send "ICMP" error message, which is shown as "!F").
- Bonus: Can you find a destination for which the path MTU < 1500 bytes?

Switches vs. Routers

- We talked about switches (Link Layer).
  - In network layer, we use "routers" to forward packets.

- Advantages of switches over routers:
  - Plug-and-play
  - Fast filtering and forwarding of frames
  - No pronunciation ambiguity (e.g., "rooter" vs. "rowter")! ☺

- Disadvantages of switches over routers
  - Topology is restricted to a spanning tree
  - Large networks require large ARP tables
  - Broadcast storms can cause the network to collapse

Packet Routing and Forwarding

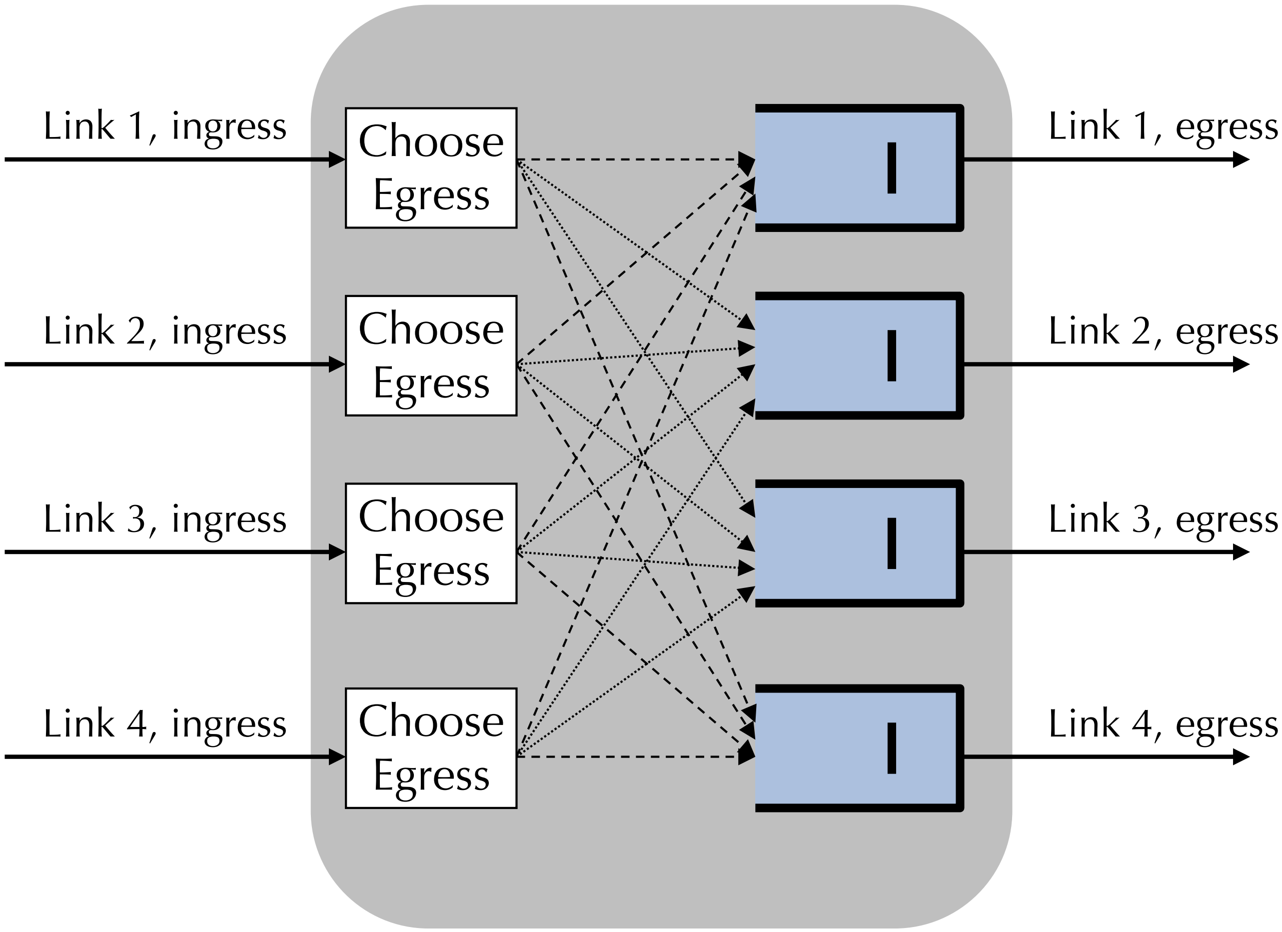
- Forwarding IP datagrams
  - Class-based vs. CIDR

- Routing Techniques
  - Naïve: Flooding
  - Distance vector: Distributed Bellman Ford Algorithm
  - Link state: Dijkstra's Shortest Path First-based Algorithm

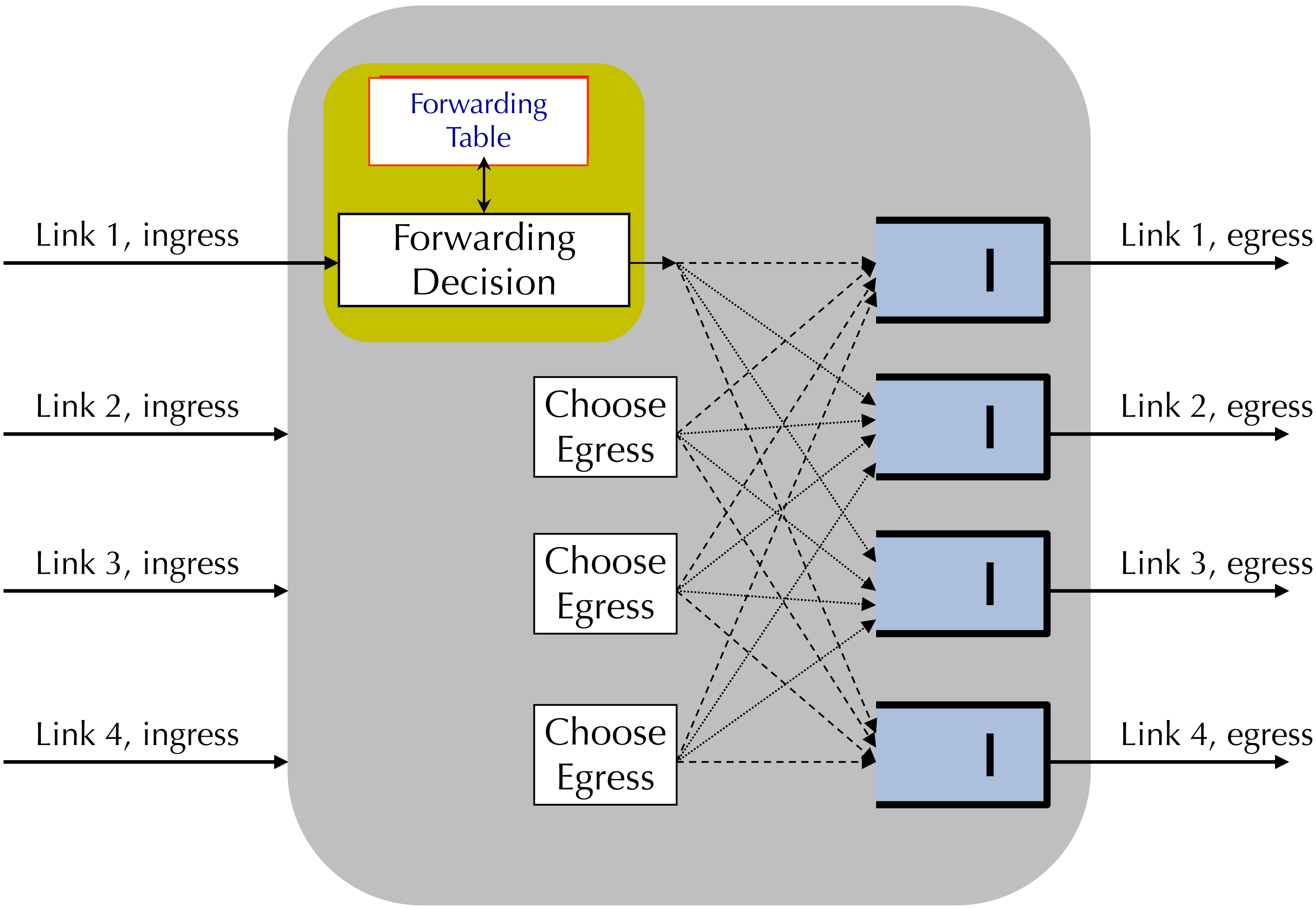
Hop-by-Hop Packet Forwarding

- Each router has a forwarding table
  - Maps destination addresses…
  - … to outgoing interfaces
- Upon receiving a packet
  - Inspect the destination IP address in the header
  - Index into the table
  - Determine the outgoing interface
  - Forward the packet out that interface
- Then, the next router in the path repeats
  - And the packet travels along the path to the destination

Inside a Router



Inside a Router



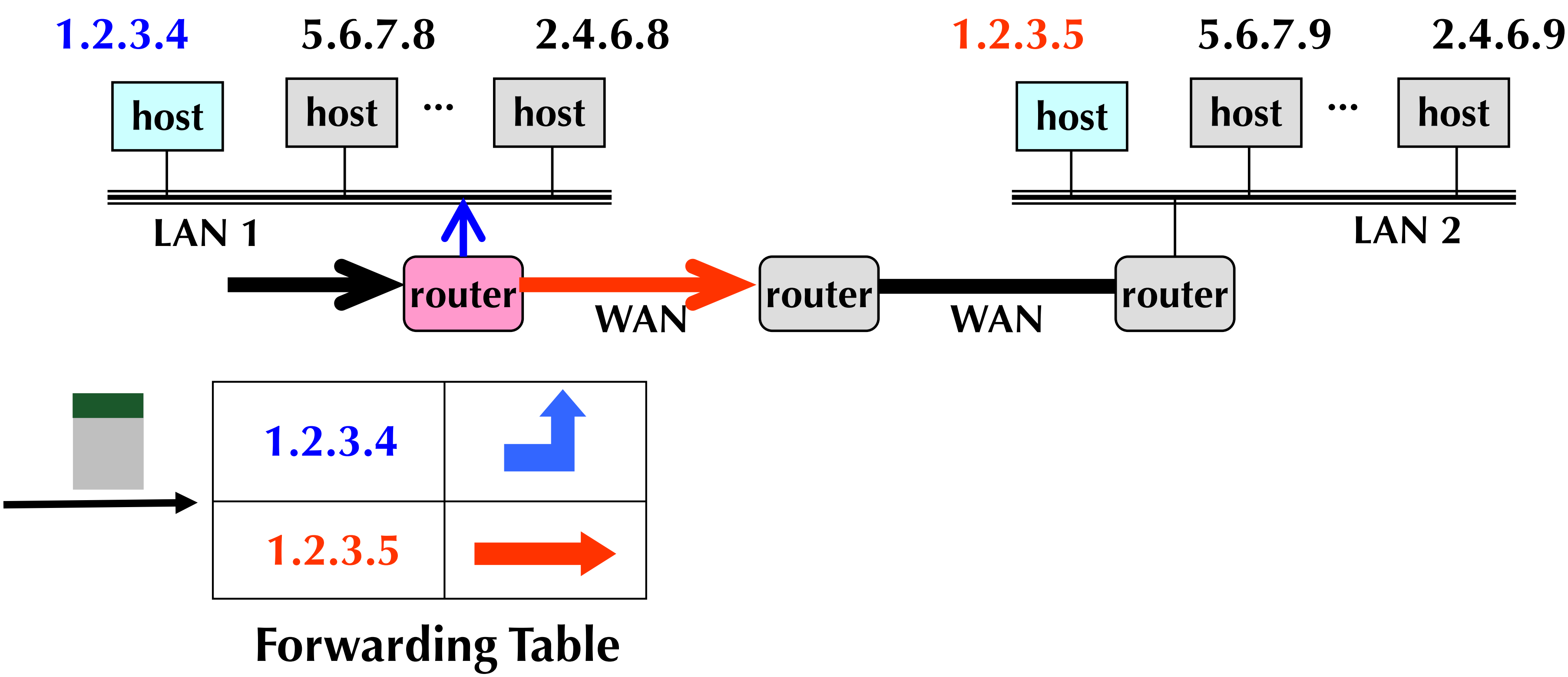
Forwarding in an IP Router

- Lookup packet DA in forwarding table.
  - If known, forward to correct port.
  - If unknown, drop packet.
- Decrement TTL, update header Checksum.
- Forward packet to outgoing interface.
- Transmit packet onto link.

Question:
How is the address looked up in a real router?

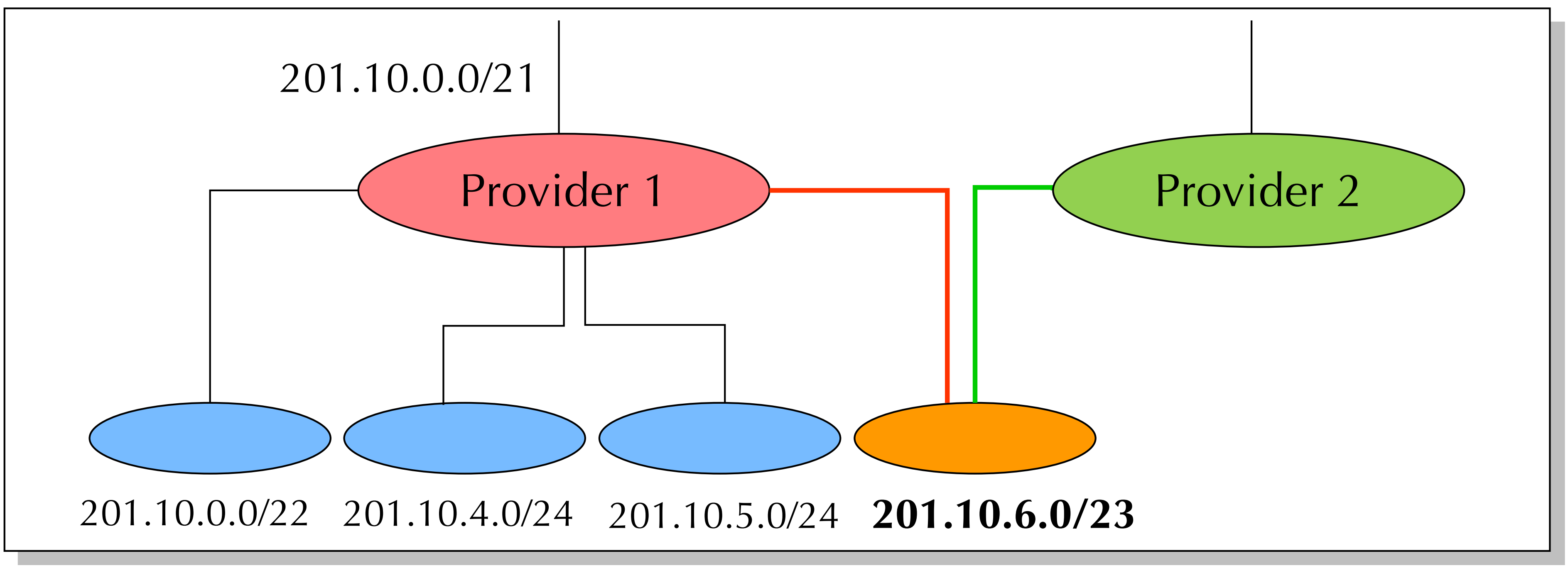
Separate Table Entries Per Address

- If a router had a forwarding entry per IP address
  - Match destination address of incoming packet
  - … to the forwarding-table entry
  - … to determine the outgoing interface



CIDR Makes Packet Forwarding Harder

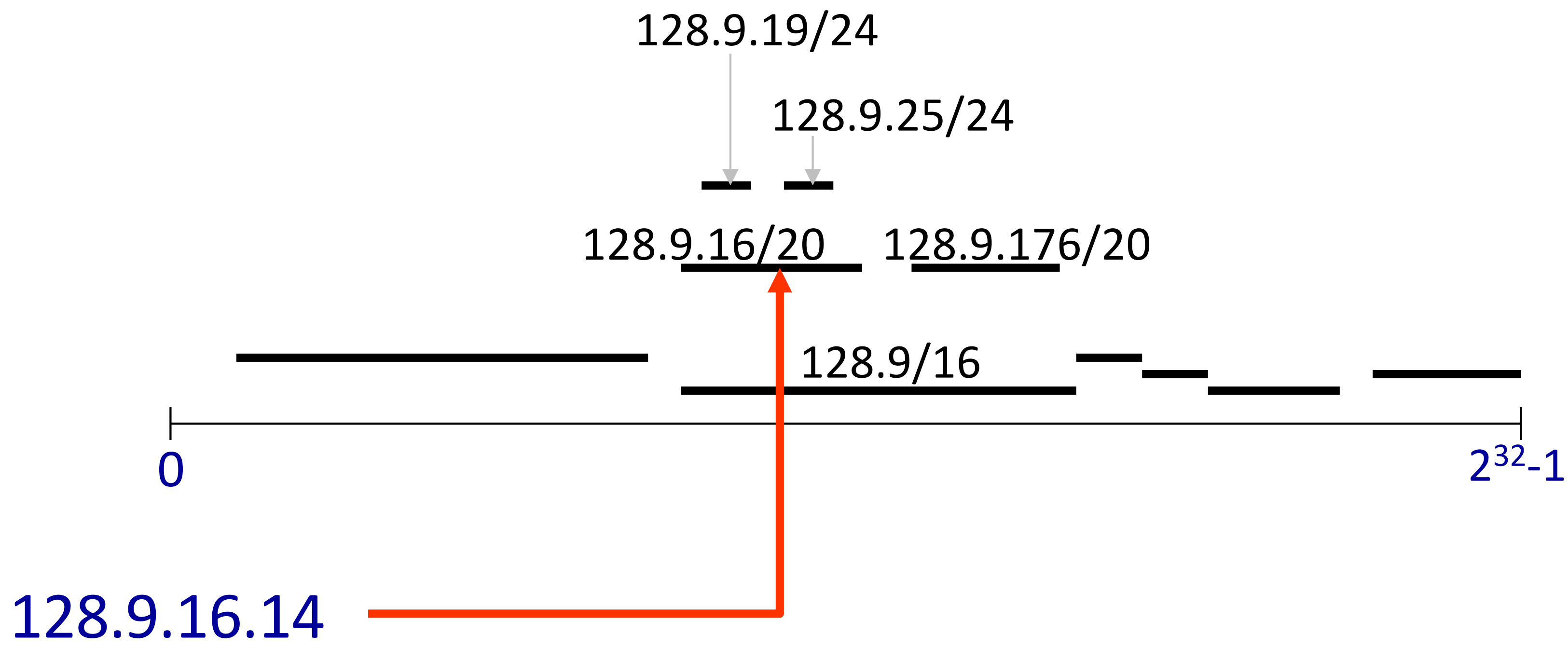
- There's no such thing as a free lunch
  - CIDR allows efficient use of the limited address space
  - But, CIDR makes packet forwarding much harder
- Forwarding table may have many matches
  - E.g., table entries for 201.10.0.0/21 and



Longest Prefix Match Forwarding

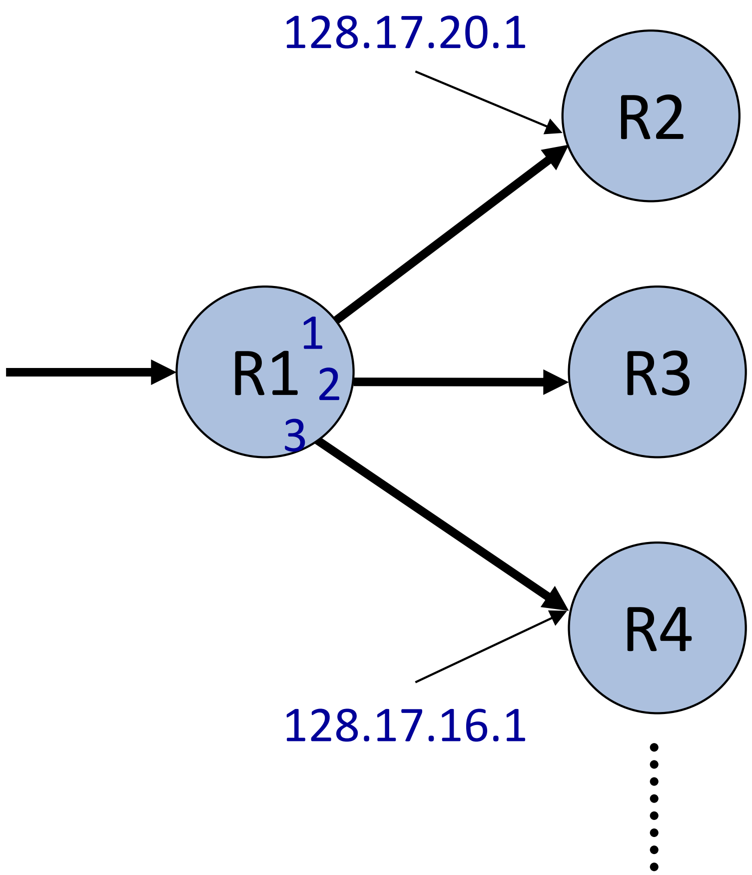
- Forwarding tables in IP routers
  - Maps each IP *prefix* to next-hop link(s)
- Destination-based forwarding
  - Packet has a destination address
  - Router identifies longest-matching prefix
  - Cute algorithmic problem: very fast lookups

Classless Inter-Domain Routing (CIDR) – Addressing



Most specific route = "longest matching prefix"

How a Router Forwards Datagrams



e.g. 128.9.16.14 => Port 2

Prefix	Next-hop	Port
65/8	128.17.16.1	3
128.9/16	128.17.14.1	2
128.9.16/20	128.17.14.1	2
128.9.19/24	128.17.10.1	7
128.9.25/24	128.17.14.1	2
128.9.176/20	128.17.20.1	1
142.12/19	128.17.16.1	3

Forwarding Table

Simplest Algorithm is Too Slow

- Scan the forwarding table one entry at a time
  - See if the destination matches the entry
  - If so, check the size of the mask for the prefix
  - Keep track of the entry with longest-matching prefix
- Overhead is linear in size of the forwarding table
  - Today, that means 400,000-500,000 entries!
  - And, the router may have just a few nanoseconds
  - … before the next packet is arriving
- Need greater efficiency to keep up with line rate
  - Better algorithms
  - Hardware implementations

Lookup Performance Required

Line Rate	PktSize = 40B	PktSize = 240B
155 Mb/s	480 Kp/s	80 Kp/s
2.5 Gb/s	7.81 Mp/s	1.3 Mp/s
10 Gb/s	31.25 Mp/s	5.21 Mp/s
100 Gb/s	312.5 Mp/s	52.1 Mp/s

b/s: bits per second p/s: packets per second

Fast Lookups

- The are algorithms that are faster than linear scan
  - Proportional to number of bits in the address
- We can use special hardware
  - Content Addressable Memories (CAMs)
  - Allows look-ups on a key rather than flat address
- Huge innovations in the mid-to-late 1990s
  - After CIDR was introduced (in 1994)
  - … and longest-prefix match was a major bottleneck

Where do Forwarding Tables Come From?

- Routers have forwarding tables
  - Map prefix to outgoing link(s)
- Entries can be statically configured
  - E.g., "map 12.34.158.0/24 to Port 1"
- But, this doesn't adapt
  - To failures
  - To new equipment
  - To the need to balance load
  - …
- That is where other technologies come in…
  - Routing protocols, DHCP, and ARP

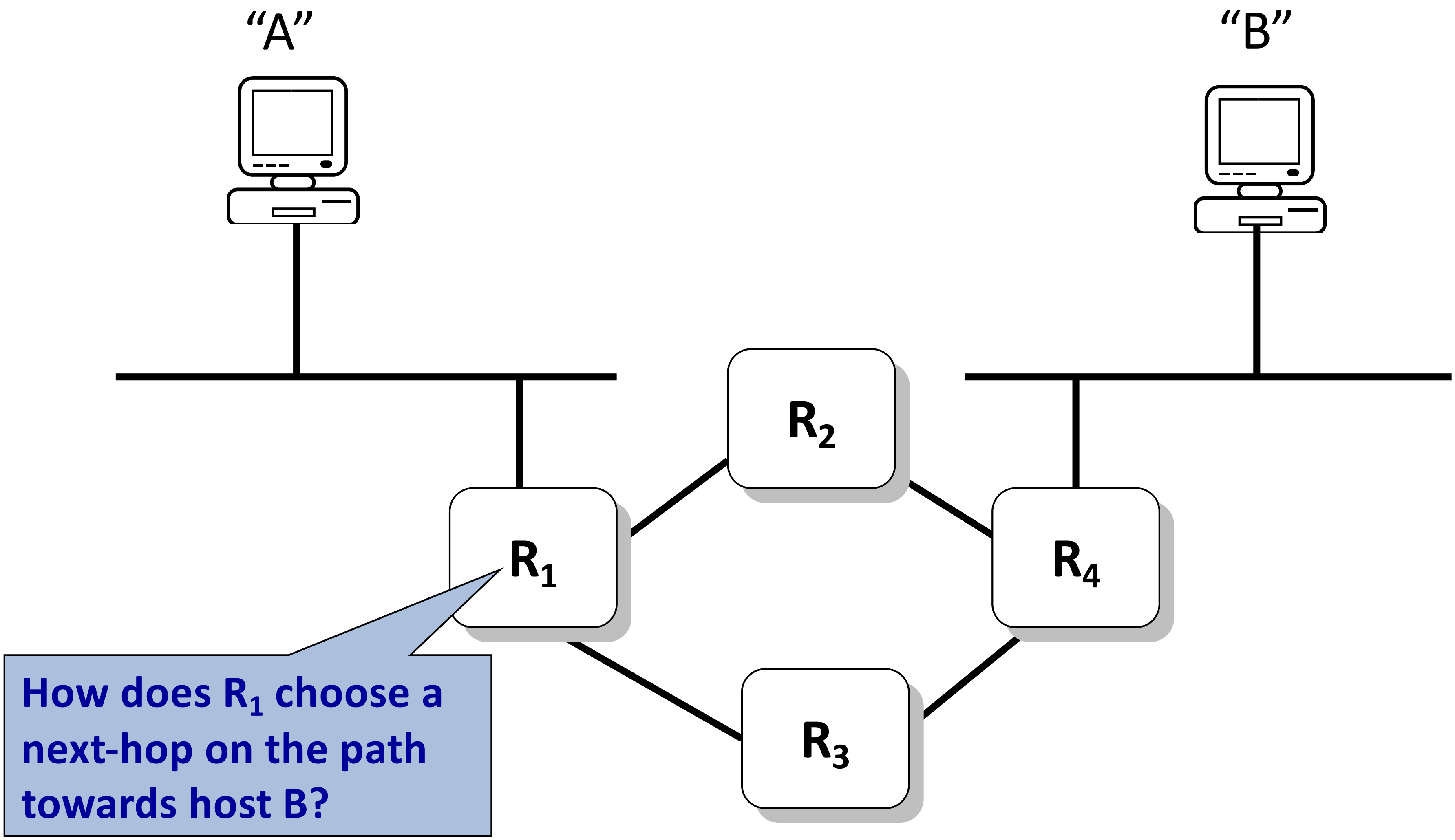
Packet Routing and Forwarding

- Forwarding IP datagrams
  - Class-based vs. CIDR

- Routing Techniques
  - Naïve: Flooding
  - Distance vector: Distributed Bellman Ford Algorithm
  - Link state: Dijkstra's Shortest Path First-based Algorithm

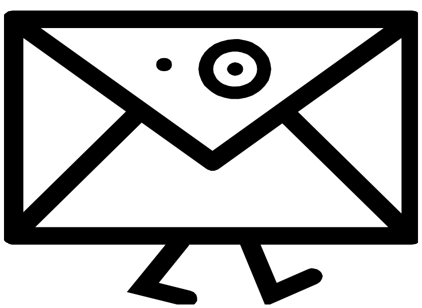
Routing is a very complex subject and has many aspects. Here, we will concentrate on the basics.

The Problem


"A"
"B"
R_2
R_1
R_4
R_3
How does R_1 choose a next-hop on the path towards host B?

What is Routing?

- A famous quotation from RFC 791
  - "A name indicates what we seek.
    An address indicates where it is.
    A route indicates how we get there."
    -- Jon Postel



Forwarding vs. Routing

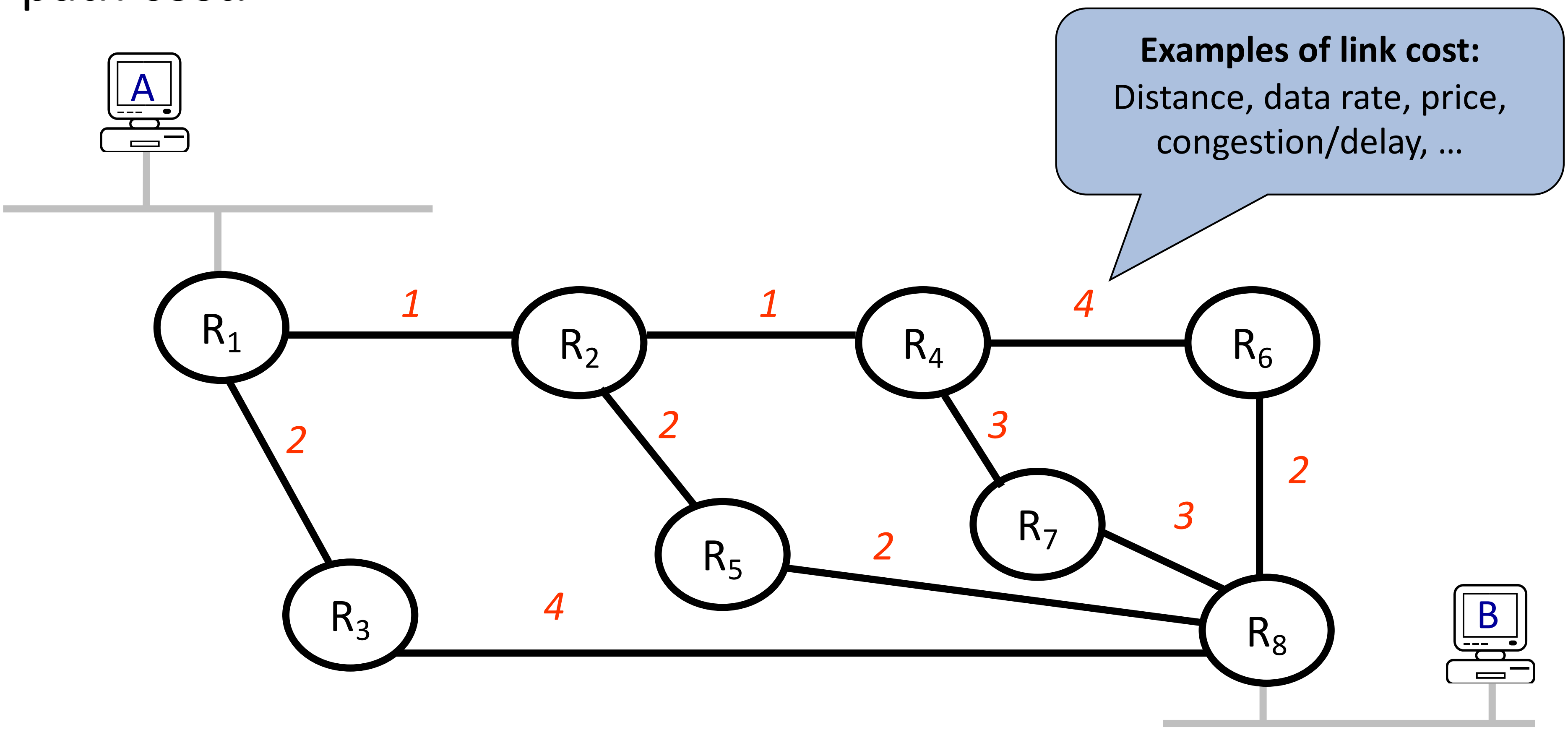
- Forwarding: *data plane*
  - Directing a data packet to an outgoing link
  - Individual router using a forwarding table
- Routing: *control plane*
  - Computing paths the packets will follow
  - Routers talking amongst themselves
  - Individual router creating a forwarding table

Why Does Routing Matter?

- End-to-end performance
  - Quality of the path affects user performance
  - Propagation delay, throughput, and packet loss
- Use of network resources
  - Balance of the traffic over the routers and links
  - Avoiding congestion by directing traffic to lightly-loaded links
- Transient disruptions during changes
  - Failures, maintenance, and load balancing
  - Limiting packet loss and delay during changes

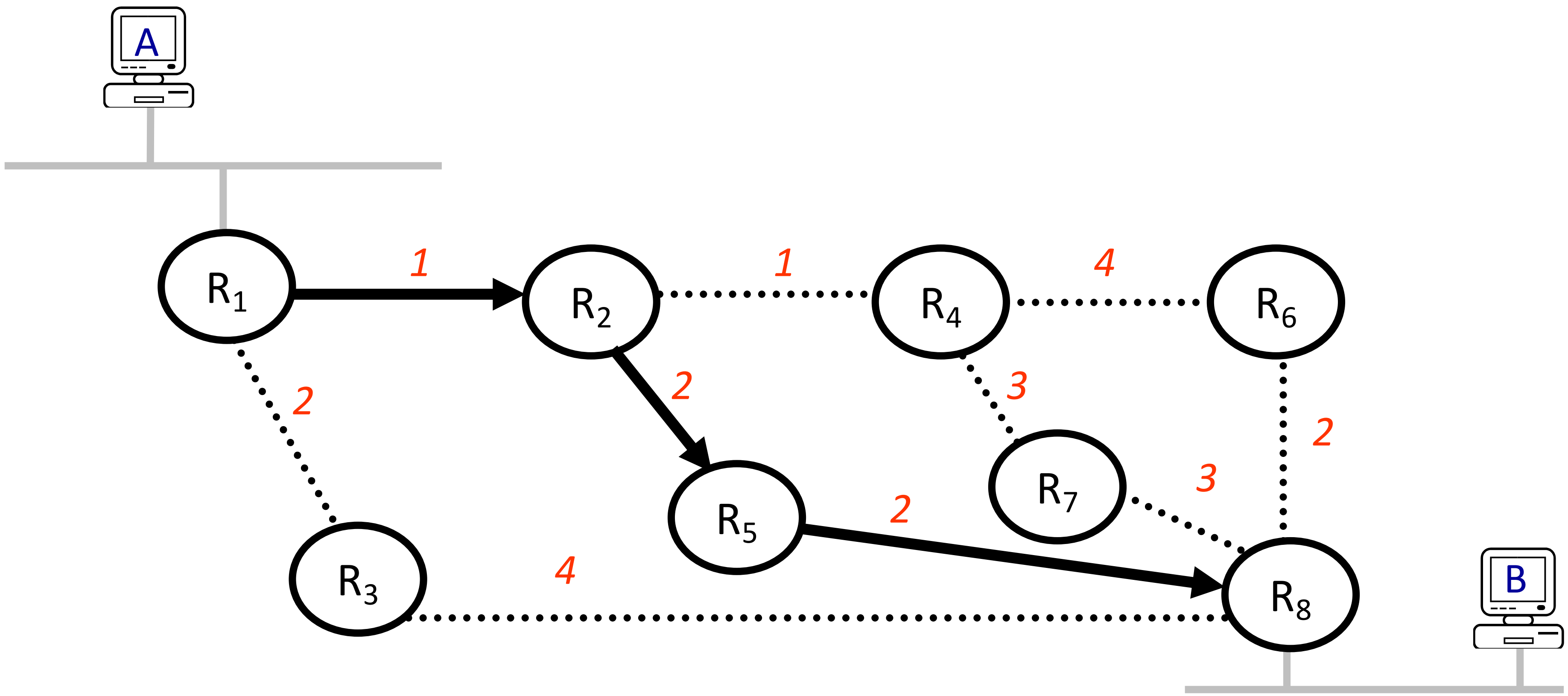
Example Network

Objective: Determine the route from A to B that minimizes the path cost.

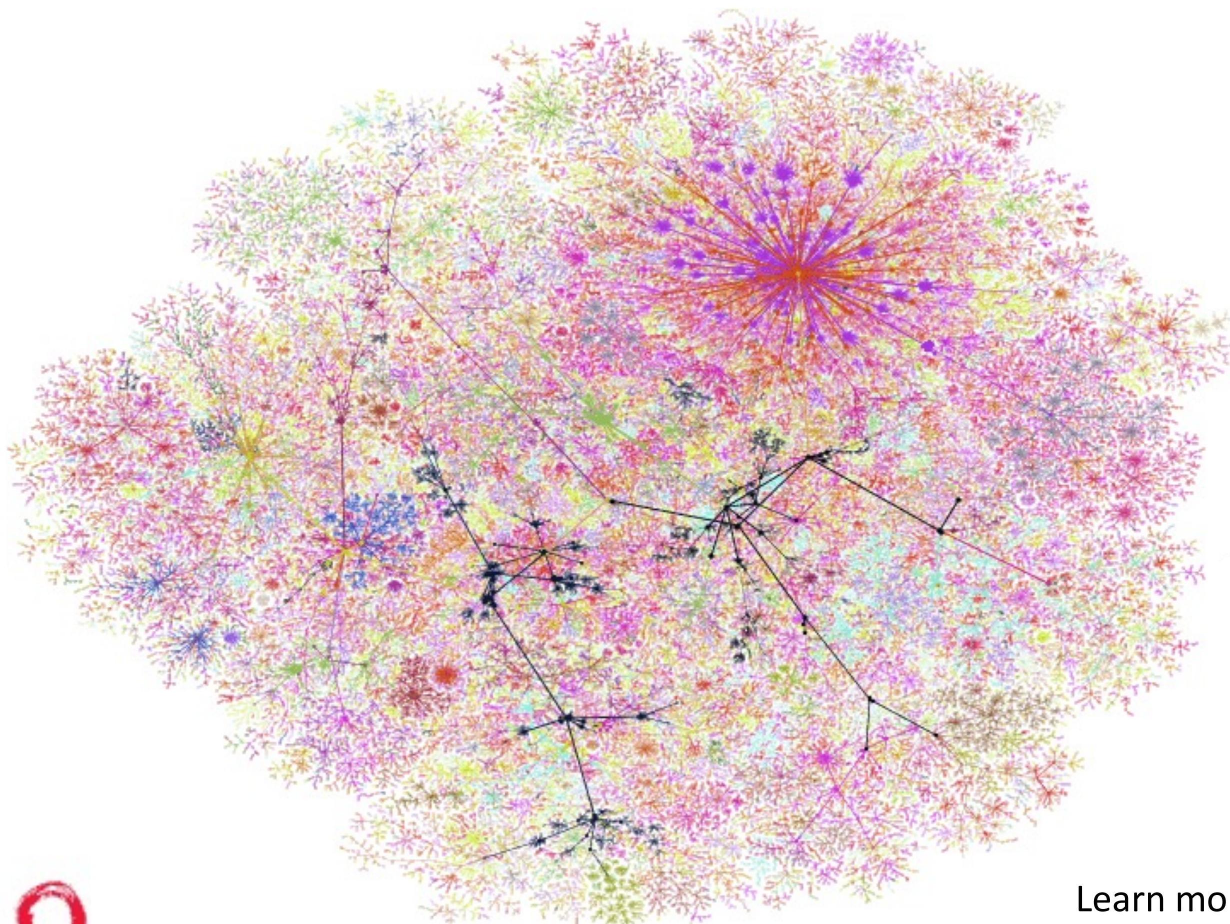


Example Network

In this simple case, solution is clear from inspection



What about this Network...!?



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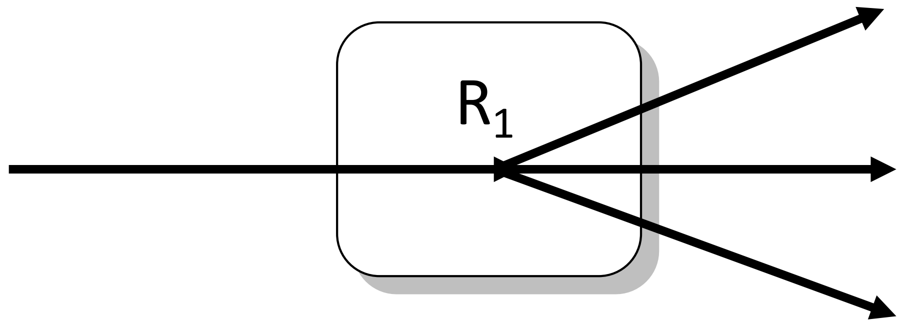
Technique 1: Naïve Approach

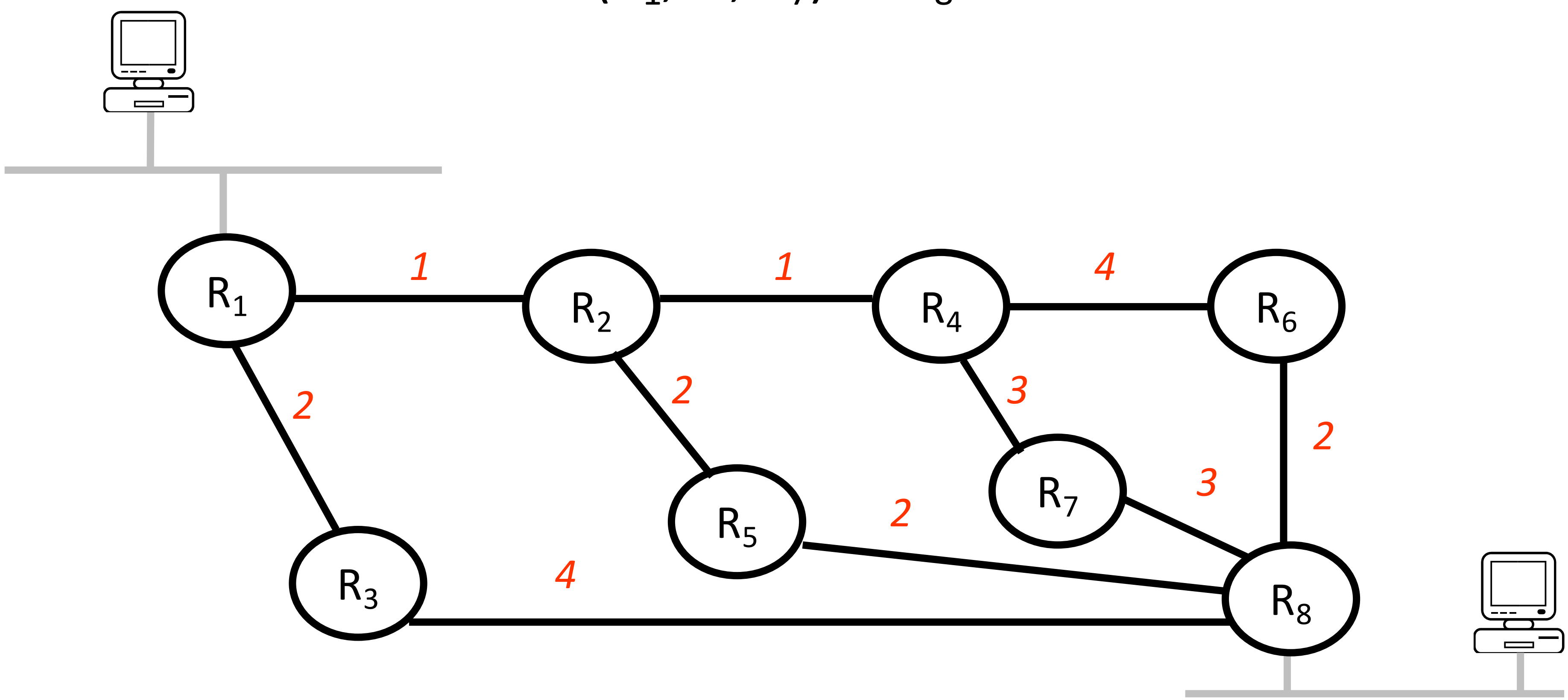
Flood! -- Routers forward packets to all ports except the ingress port.



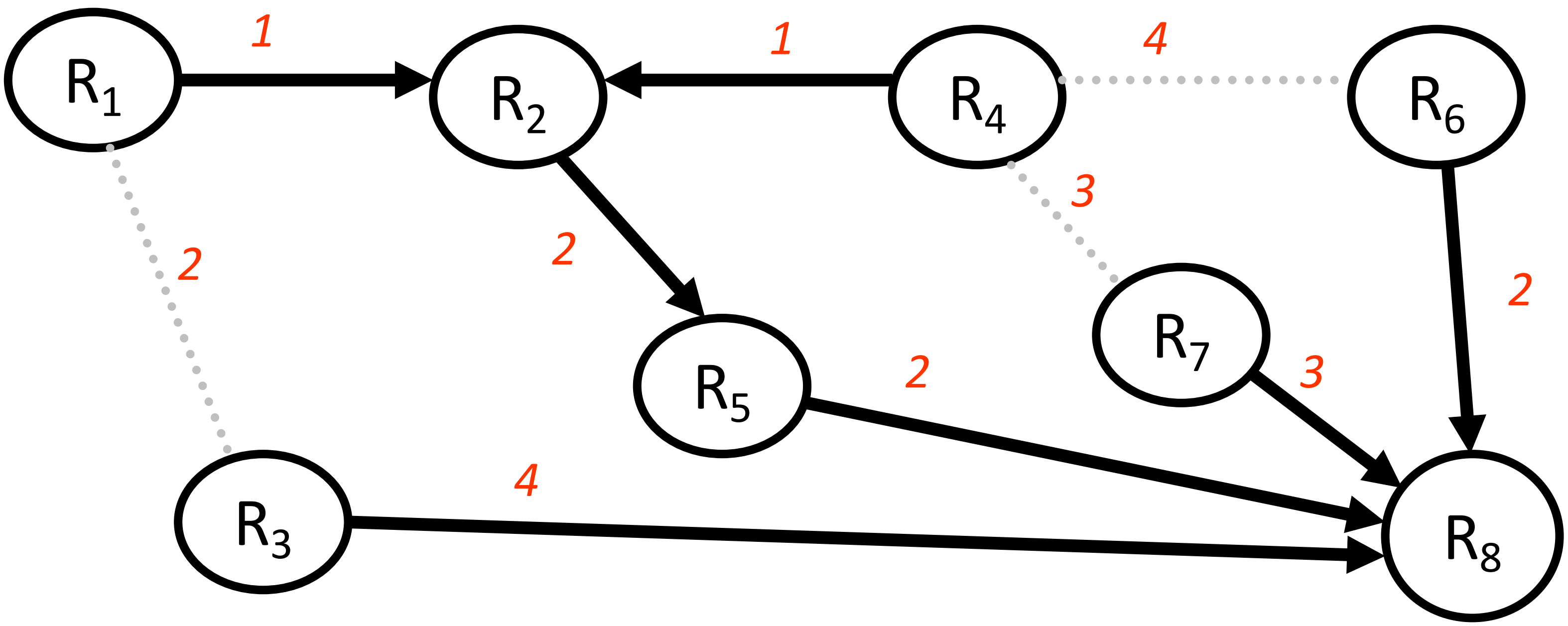
- Advantages:
  - Simple
  - Every destination in the network is reachable.
- Disadvantages:
  - Some routers receive a packet multiple times.
  - Packets can go round in loops forever.
  - Inefficient.

Lowest Cost Routes

Objective: Find the lowest cost route from each of (R_1, …, R_7) to R_8.



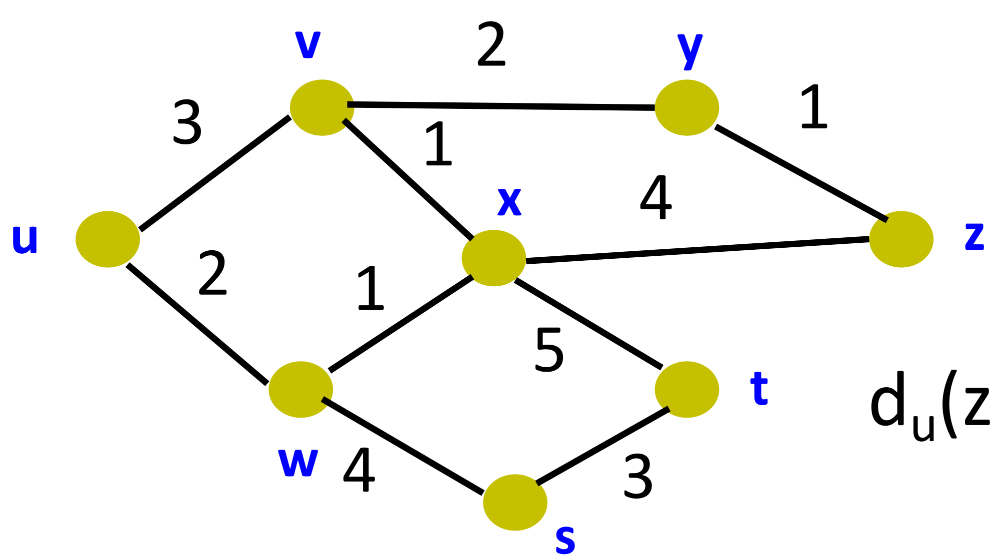
A Spanning Tree



- The solution is a spanning tree with R8 as the root of the tree.
- Tree: There are no loops.
- Spanning: All nodes included.
- We'll see two algorithms that build spanning trees automatically:
  - The distributed Bellman-Ford algorithm
  - Dijkstra's shortest path first algorithm

Technique 2: Distance Vector Distributed 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



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

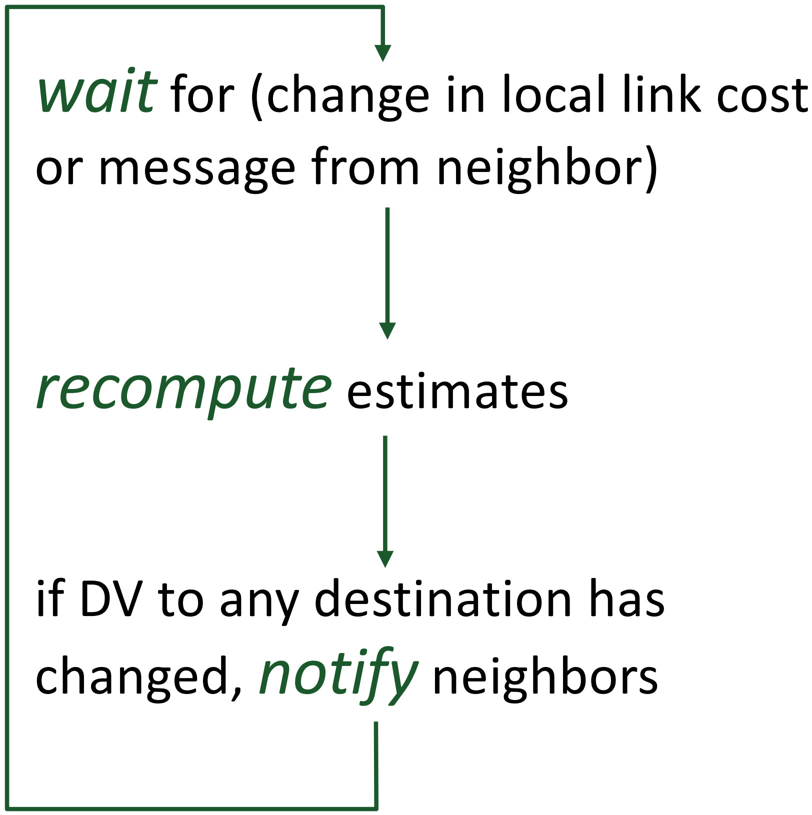
Distance Vector Algorithm

- $c(x,v)$ = cost for direct link from x to v
  - Node x maintains costs of direct links $c(x,v)$
- $D_x(y)$ = estimate of least cost from x to y
  - Node x maintains distance vector $\mathbf{D}_x = [D_x(y): y \in N]$
- Node x maintains its neighbors' distance vectors
  - For each neighbor v, x maintains $\mathbf{D}_v = [D_v(y): y \in N]$
- Each node v periodically sends D_v to its neighbors
  - And neighbors update their own distance vectors
  - $D_x(y) \leftarrow \min_v\{c(x,v) + D_v(y)\}$ for each node $y \in N$
- Over time, the distance vector D_x converges

Distance Vector Algorithm

- Iterative, asynchronous: each local iteration caused by:
  - Local link cost change
  - Distance vector update message from neighbor
- Distributed:
  - Each node notifies neighbors only when its DV changes
  - Neighbors then notify their neighbors if necessary

Each node:



Distance Vector Example: Step 1

Optimum 1-hop paths

Table for A		
Dst	Cst	Hop
A	0	A
B	4	B
C	∞	–
D	∞	–
E	2	E
F	6	F

Table for B		
Dst	Cst	Hop
A	4	A
B	0	B
C	∞	–
D	3	D
E	∞	–
F	1	F

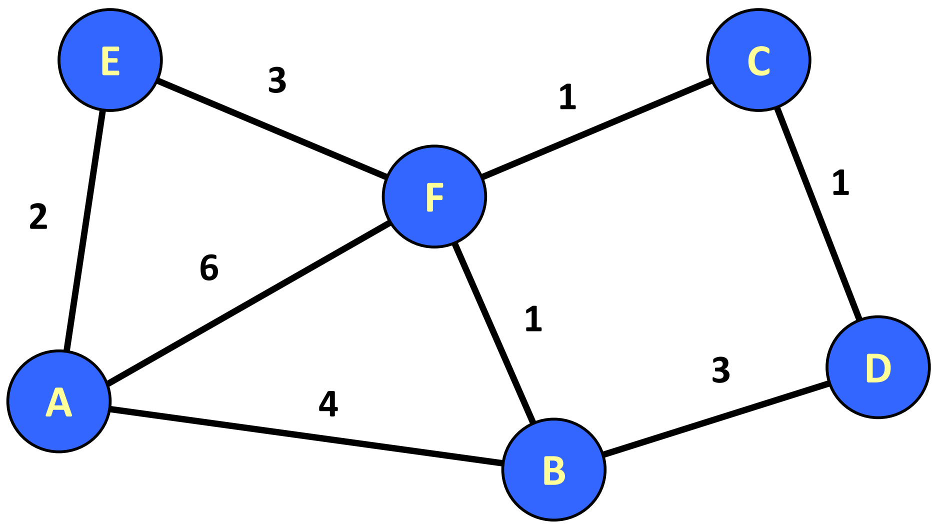


Table for C		
Dst	Cst	Hop
A	∞	–
B	∞	–
C	0	C
D	1	D
E	∞	–
F	1	F

Table for D		
Dst	Cst	Hop
A	∞	–
B	3	B
C	1	C
D	0	D
E	∞	–
F	∞	–

Table for E		
Dst	Cst	Hop
A	2	A
B	∞	–
C	∞	–
D	∞	–
E	0	E
F	3	F

Table for F		
Dst	Cst	Hop
A	6	A
B	1	B
C	1	C
D	∞	–
E	3	E
F	0	F

Distance Vector Example: Step 2

Optimum 2-hop paths

Table for A			Table for B		
Dst	Cst	Hop	Dst	Cst	Hop
A	0	A	A	4	A
B	4	B	B	0	B
C	7	F	C	2	F
D	7	B	D	3	D
E	2	E	E	4	F
F	5	E	F	1	F

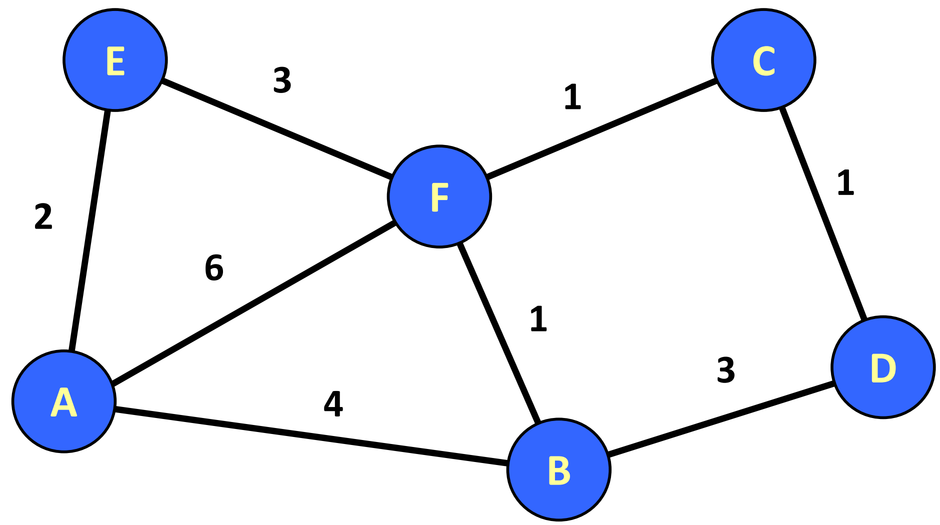


Table for C			Table for D			Table for E			Table for F		
Dst	Cst	Hop	Dst	Cst	Hop	Dst	Cst	Hop	Dst	Cst	Hop
A	7	F	A	7	B	A	2	A	A	5	B
B	2	F	B	3	B	B	4	F	B	1	B
C	0	C	C	1	C	C	4	F	C	1	C
D	1	D	D	0	D	D	∞	–	D	2	C
E	4	F	E	∞	–	E	0	E	E	3	E
F	1	F	F	2	C	F	3	F	F	0	F

Distance Vector Example: Step 3

Optimum 3-hop paths

Table for A			Table for B		
Dst	Cst	Hop	Dst	Cst	Hop
A	0	A	A	4	A
B	4	B	B	0	B
C	6	E	C	2	F
D	7	B	D	3	D
E	2	E	E	4	F
F	5	E	F	1	F

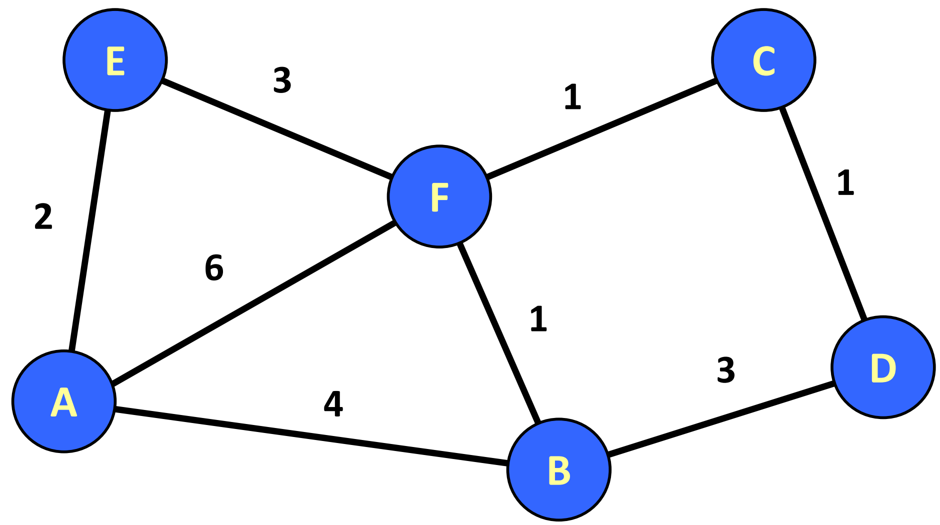


Table for C			Table for D			Table for E			Table for F		
Dst	Cst	Hop	Dst	Cst	Hop	Dst	Cst	Hop	Dst	Cst	Hop
A	6	F	A	7	B	A	2	A	A	5	B
B	2	F	B	3	B	B	4	F	B	1	B
C	0	C	C	1	C	C	4	F	C	1	C
D	1	D	D	0	D	D	5	F	D	2	C
E	4	F	E	5	C	E	0	E	E	3	E
F	1	F	F	2	C	F	3	F	F	0	F

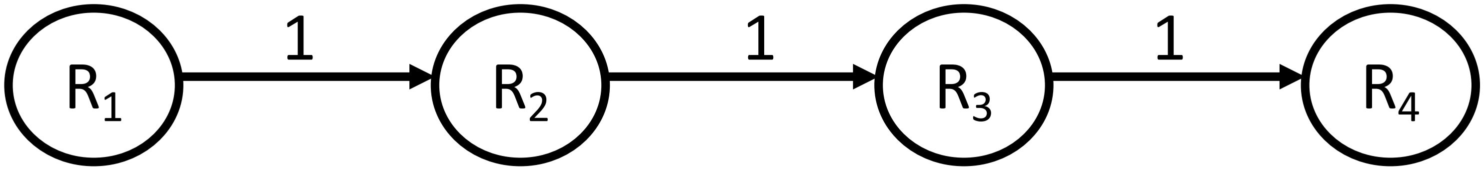
Bellman-Ford Algorithm

- Questions:
  - How long can the algorithm take to run?
  - How do we know that the algorithm always converges?
  - What happens when link costs change, or when routers/links fail?

- Topology changes make life hard for the Bellman-Ford algorithm…

A Problem with Bellman-Ford

Bad news travels slowly



Consider the calculation of distances to R_4:

Time	R_1	R_2	R_3
0	3,R_2	2,R_3	1, R_4
1	3,R_2	2,R_3	3,R_2
2	3,R_2	4,R_3	3,R_2
3	5,R_2	4,R_3	5,R_2
…	"Counting to infinity"		…

$R_3 \rightarrow R_4$ fails

Counting to Infinity Problem – Solutions

- Set infinity = "some small integer" (e.g. 16). Stop when count = 16.
- Split Horizon: Because R_2 received lowest cost path from R_3, it does not advertise cost to R_3
- Split-horizon with poison reverse: R_2 advertises infinity to R_3
- There are many problems with (and fixes for) the Bellman-Ford algorithm.

Technique 3: Link State

Dijkstra's Shortest Path First Algorithm

- Routers send out update messages whenever the state of an incident link changes.
  - Called "Link State Updates"

- Based on all link state updates received each router calculates lowest cost path to all others, starting from itself.
  - Use Dijkstra's single-source shortest path algorithm
  - Assume all updates are consistent

- At each step of the algorithm, router adds the next shortest (i.e. lowest-cost) path to the tree.

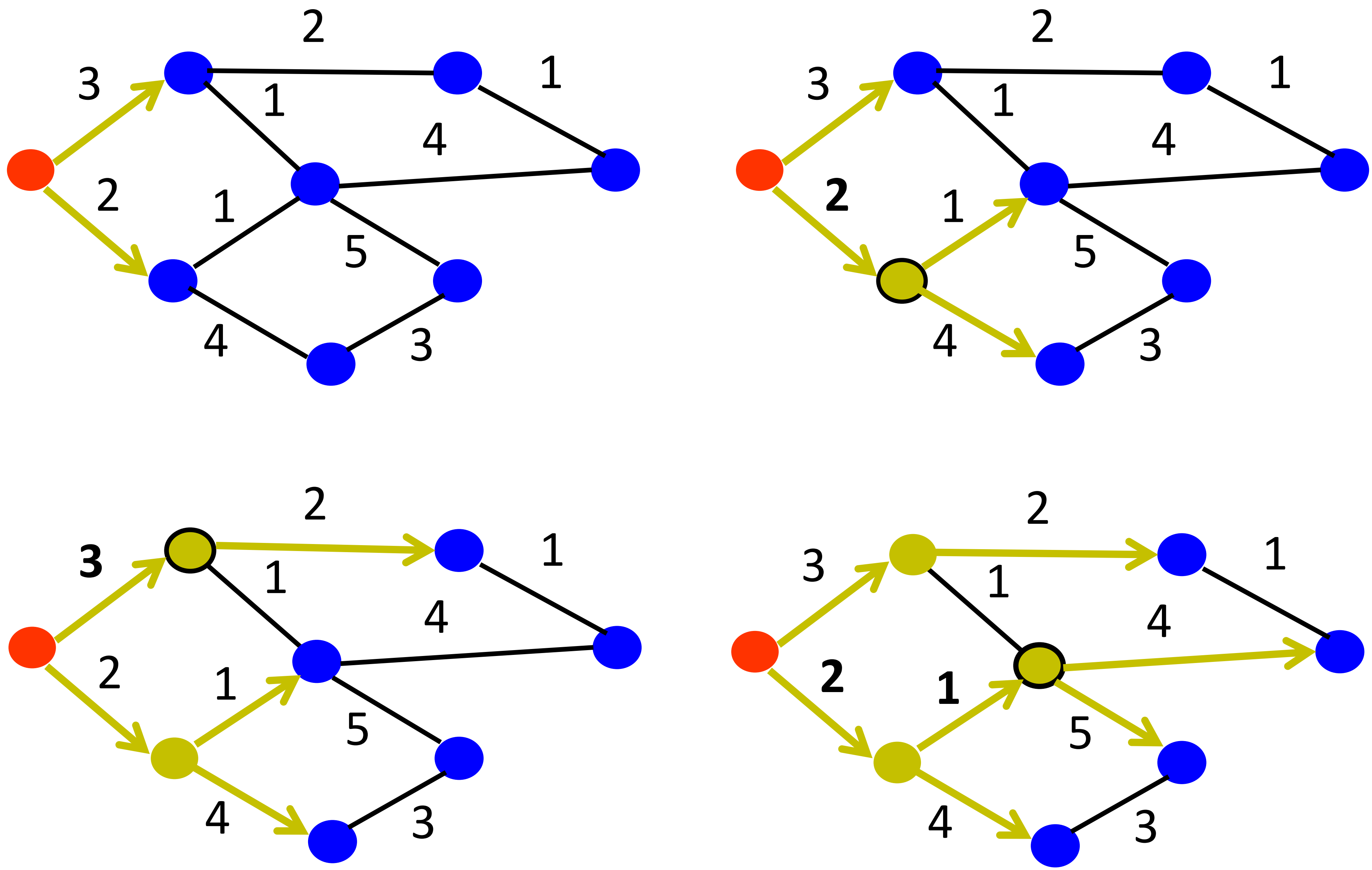
- Finds spanning tree rooted at the router.

Dijsktra's Algorithm

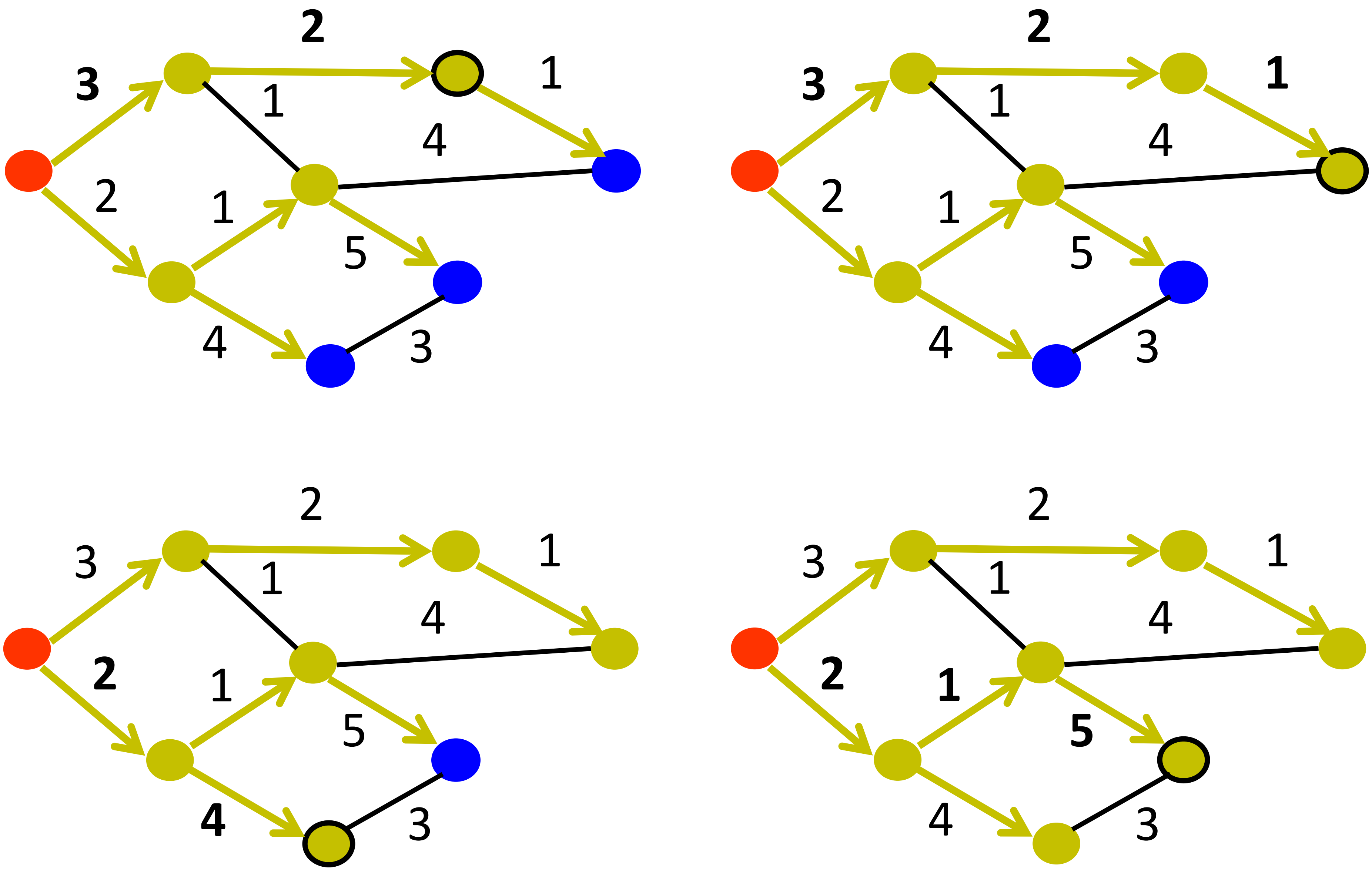
```
Initialization:
  S = {u}
  for all nodes v
    if v adjacent to u {
        D(v) = c(u,v)
    else D(v) = ∞

Loop
  find w not in S with the smallest D(w)
  add w to S
  update D(v) for all v adjacent to w and not in S:
      D(v) = min{D(v), D(w) + c(w,v)}
until all nodes in S
```

Dijkstra's Algorithm Example

Find Routes for the Red (Leftmost) Node

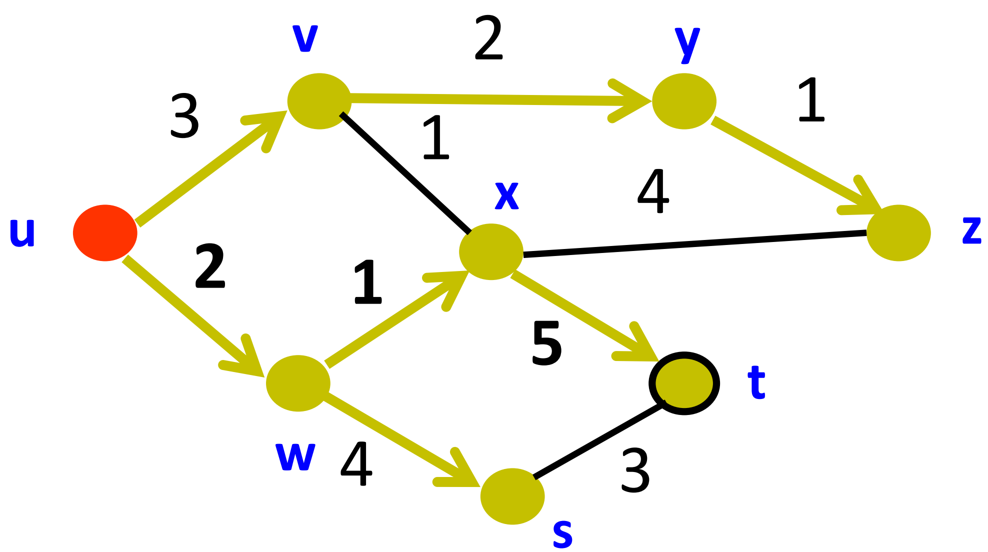


Dijkstra's Algorithm Example



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)

Reliable Flooding of LSP

- The Link State Packet:
  - The ID of the router that created the LSP
  - List of directly connected neighbors, and cost
  - Sequence number
  - TTL

- Reliable Flooding
  - Resend LSP over all links other than incident link, if the sequence number is newer. Otherwise drop it.

- Link State Detection:
  - Link layer failure
  - Loss of "hello" packets

Comparison of LS and DV algorithms

Message complexity

LS: with n nodes, E links, O(nE) messages sent

DV: exchange between neighbors only

- Convergence time varies

Speed of Convergence

LS: $O(n^2)$ algorithm requires O(nE) messages

DV: convergence time varies

- May be routing loops
- Count-to-infinity problem

Robustness: what happens if router malfunctions?

LS:

- Node can advertise incorrect *link* cost
- Each node computes only its *own* table

DV:

- DV node can advertise incorrect *path* cost
- Each node's table used by others (error propagates)