# COMP 3331/9331: Computer Networks and Applications

Week 8

Network Layer: Data Plane + Control Plane (Routing)

**Chapter 4: Section 4.3**

**Chapter 5: Section 5.1 – 5.2, 5.6**

# Network Layer, data plane: outline

4.1 Overview of Network layer
- data plane
- control plane

4.2 What's inside a router

4.3 IP: Internet Protocol
- datagram format
- fragmentation
- IPv4 addressing
- network address translation
- IPv6

# IPv6: motivation

- *initial motivation:* 32-bit address space soon to be completely allocated.
- additional motivation:
  - header format helps speed processing/forwarding
  - header changes to facilitate QoS

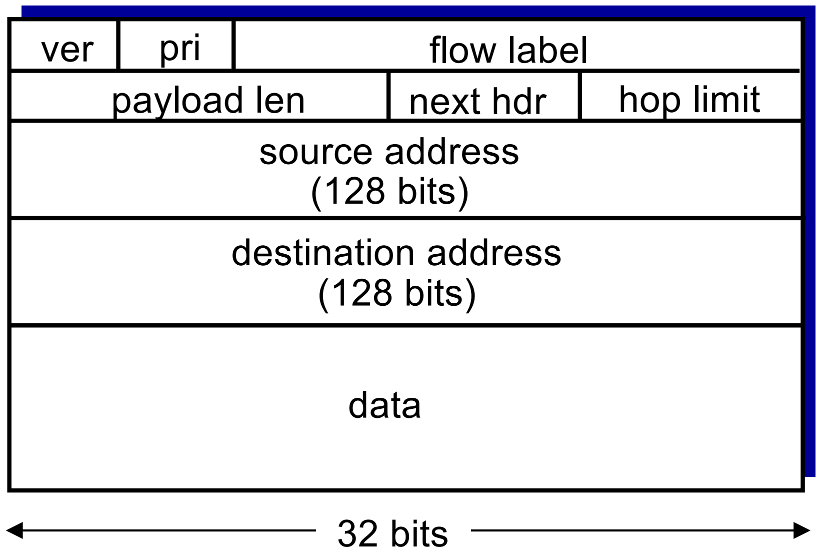
*IPv6 datagram format:*

  - fixed-length 40 byte header
  - no fragmentation allowed

https://www.google.com/intl/en/ipv6/statistics.html

# IPv6 datagram format

*priority:* identify priority among datagrams in flow (traffic class)
*flow Label:* identify datagrams in same "flow."
(concept of "flow" not well defined).
*next header:* identify upper layer protocol for data

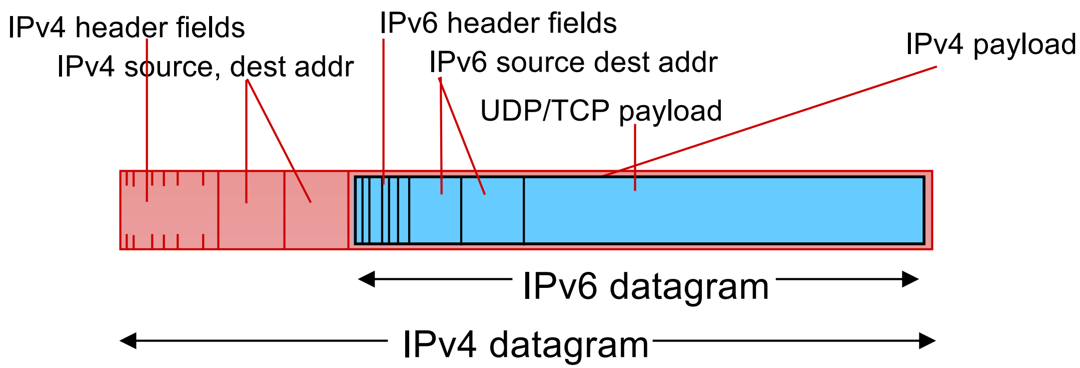


# Other changes from IPv4

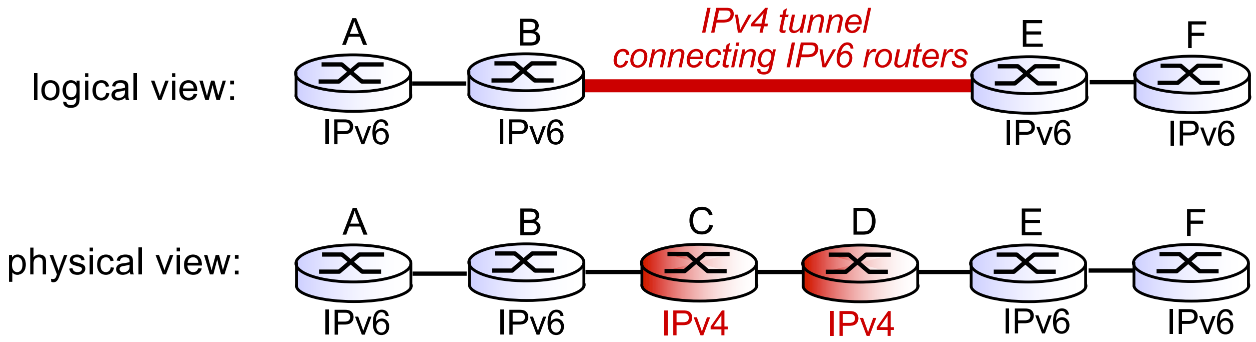
- *checksum:* removed entirely to reduce processing time at each hop
- *options:* allowed, but outside of header, indicated by "Next Header" field
- *ICMPv6:* new version of ICMP
  - additional message types, e.g. "Packet Too Big"
  - multicast group management functions

# Transition from IPv4 to IPv6

- not all routers can be upgraded simultaneously
  - no "flag days"
  - how will network operate with mixed IPv4 and IPv6 routers?
- *tunneling:* IPv6 datagram carried as *payload* in IPv4 datagram among IPv4 routers



# Tunneling (IPv6 over IPv4)



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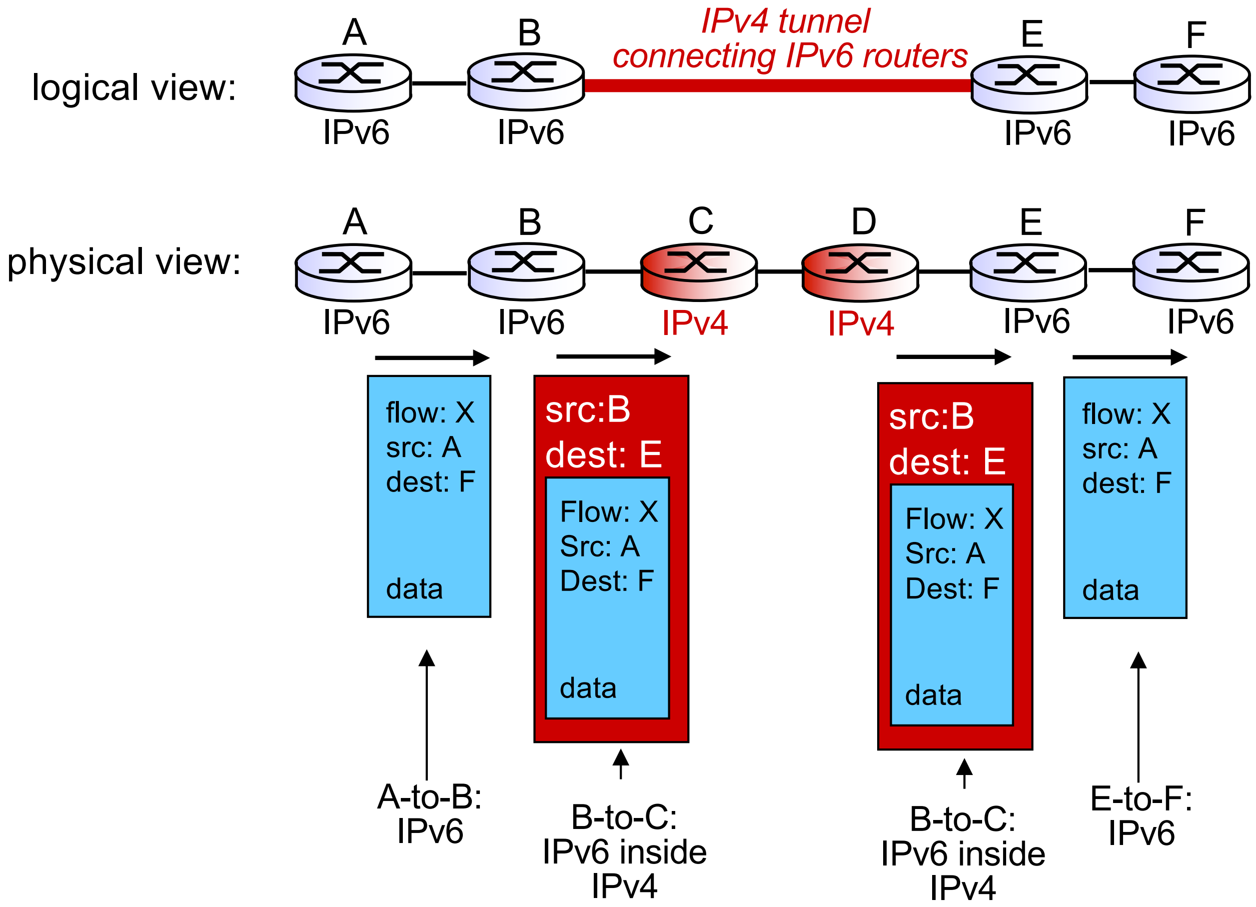
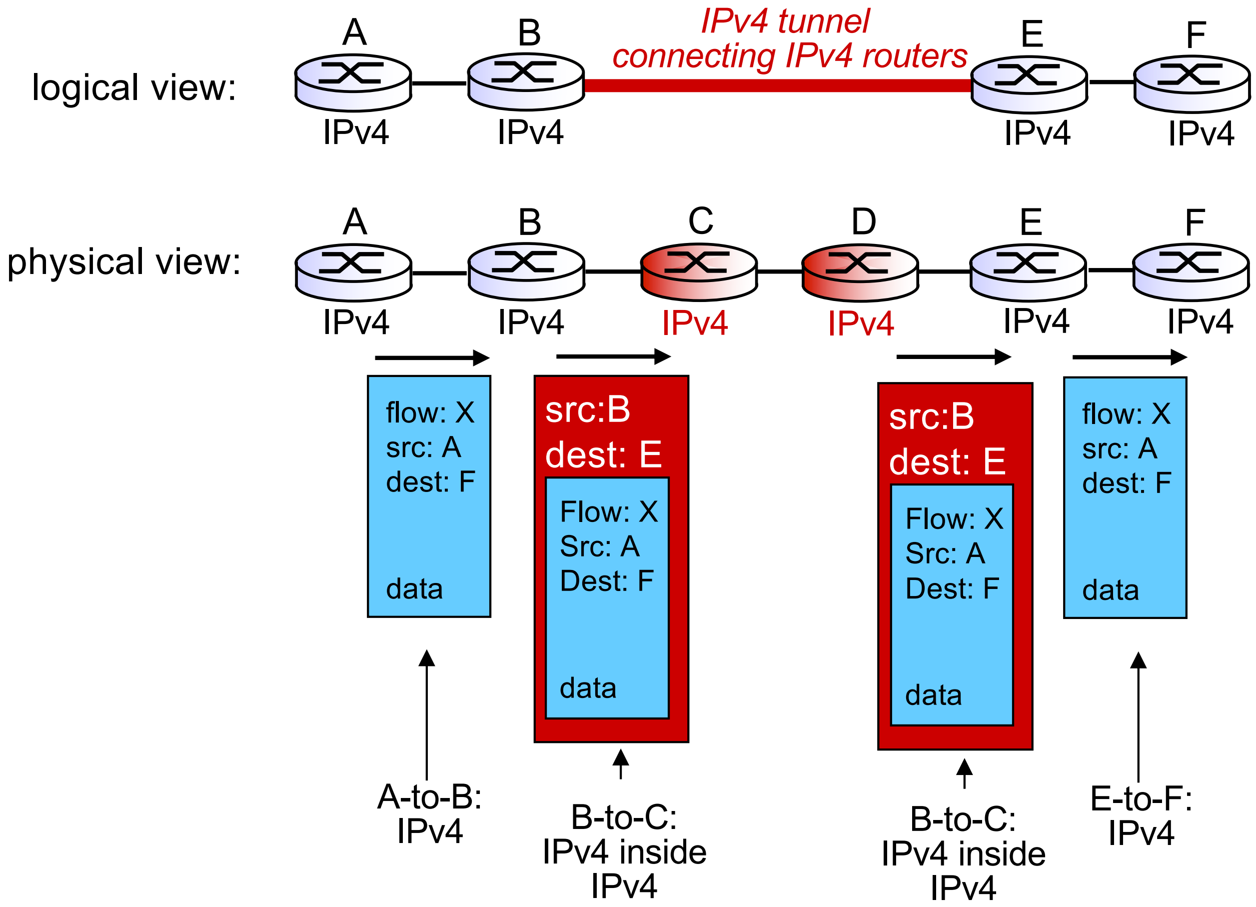


# Tunneling (IPv4 over IPv4)

**Used in VPNs**



# Network layer, control plane: outline

5.1 introduction

5.2 routing protocols

- link state
- distance vector
- hierarchical routing

5.6 ICMP: The Internet Control Message Protocol

Self study (not on exam)

# Network-layer functions

*Recall: two network-layer functions:*

- *forwarding:* move packets from router's input to appropriate router output

*data plane*

- *routing:* determine route taken by packets from source to destination

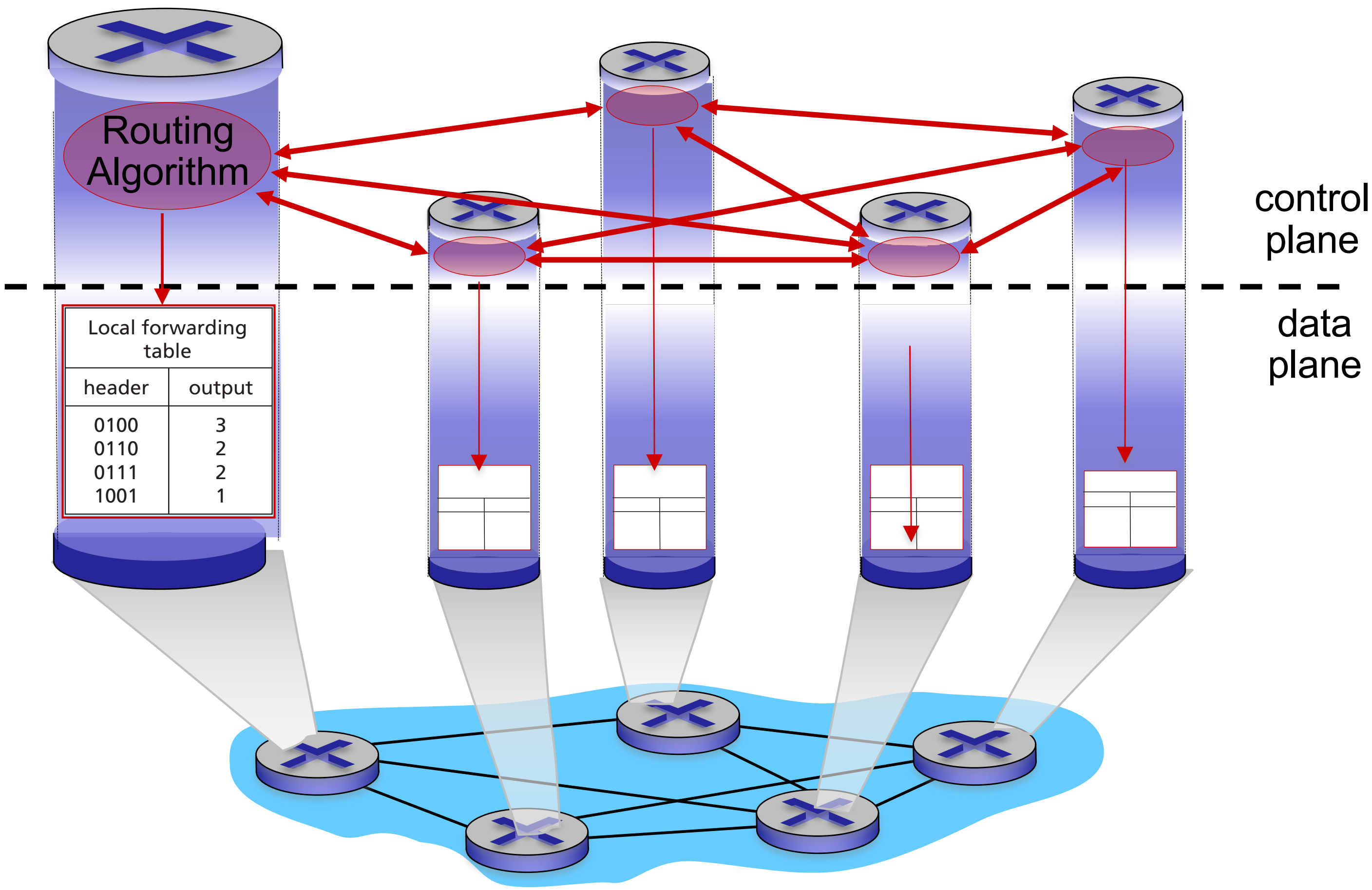
*control plane*

*Two approaches to structuring network control plane:*

- per-router control (traditional)
- logically centralized control (software defined networking)

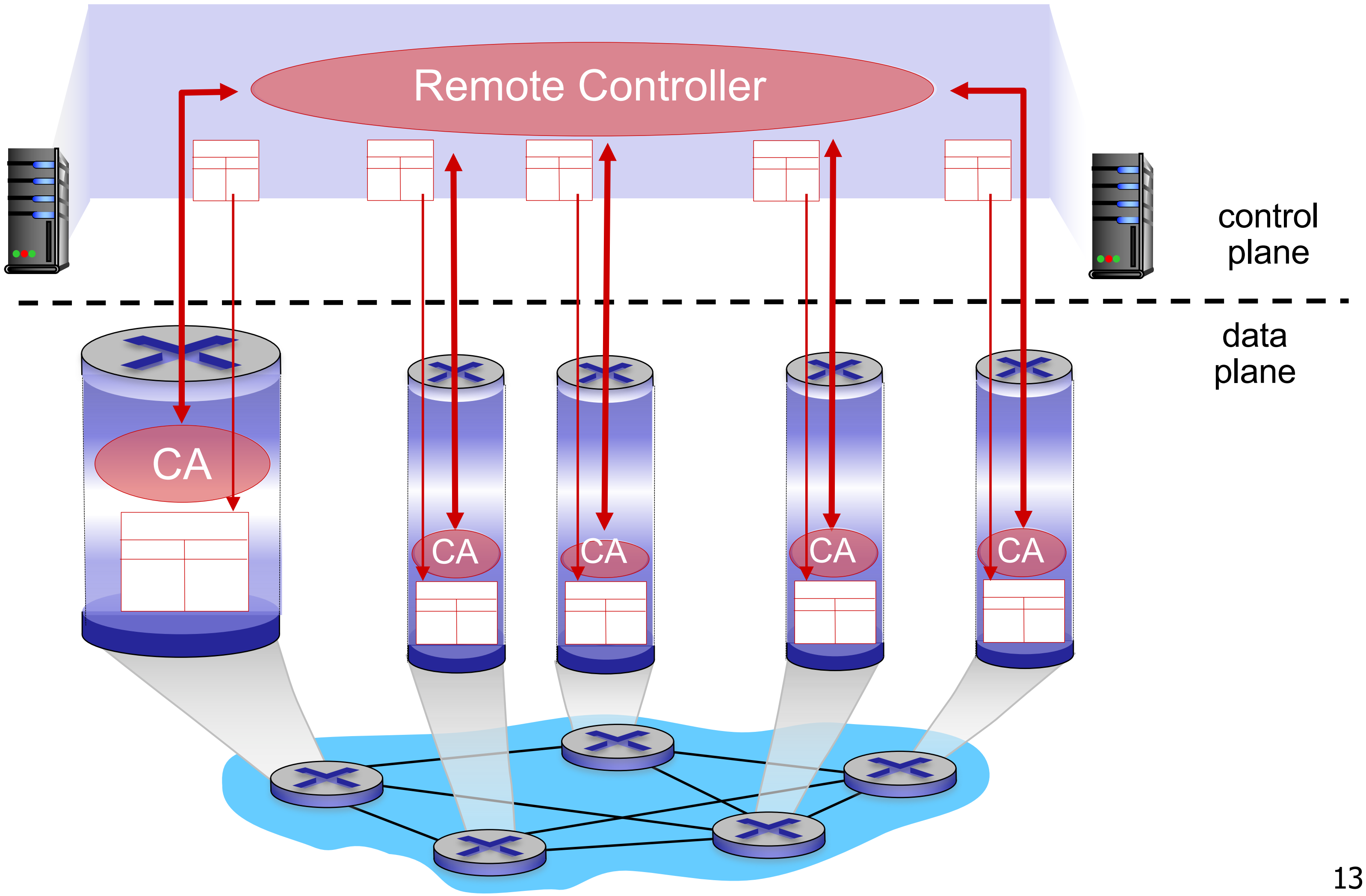
# Per-router control plane

Individual routing algorithm components *in each and every router* interact with each other in control plane to compute forwarding tables



# Logically centralized control plane

A distinct (typically remote) controller interacts with local control agents (CAs) in routers to compute forwarding tables



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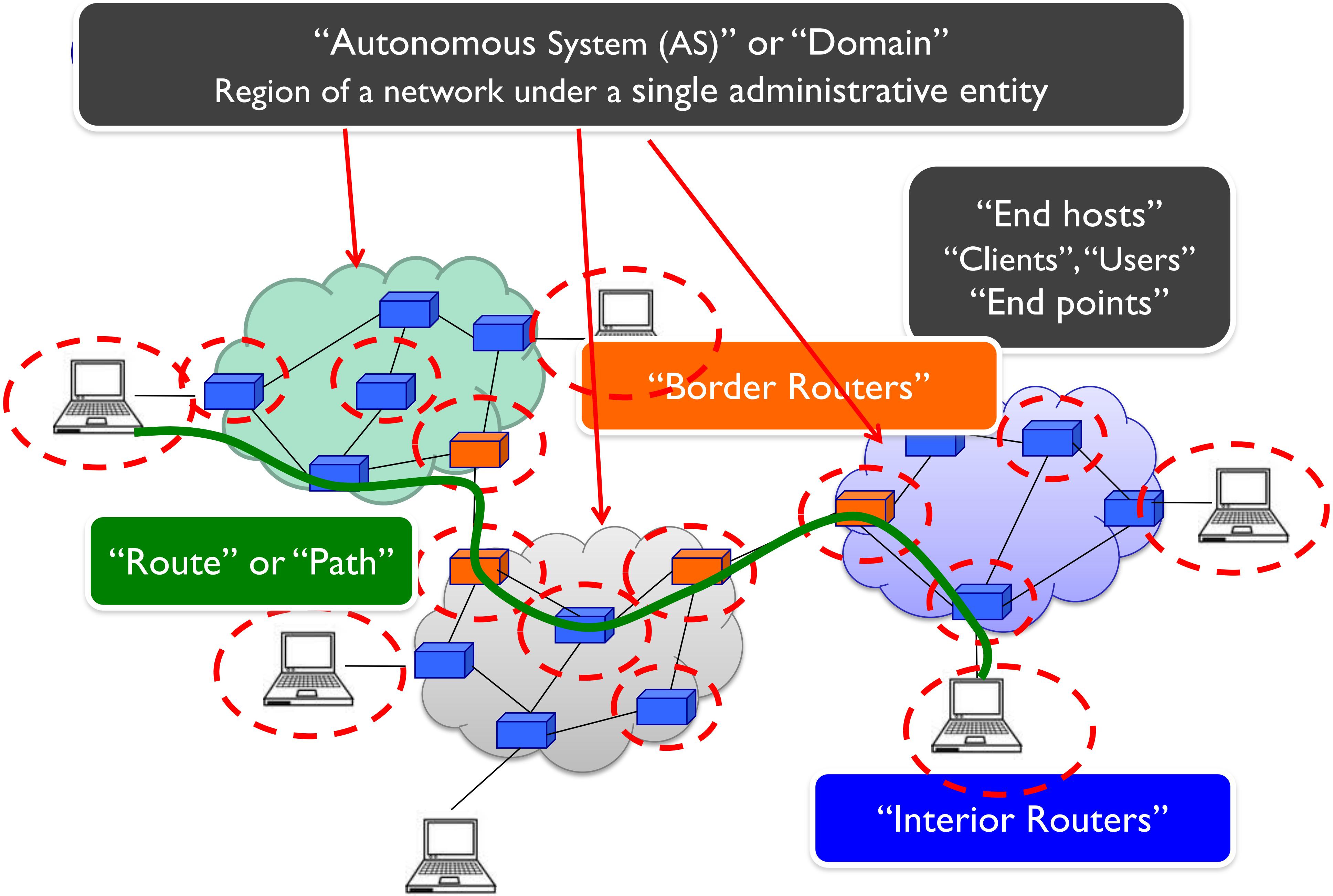

"Autonomous System (AS)" or "Domain"
Region of a network under a single administrative entity
"End hosts"
"Clients", "Users"
"End points"
"Border Routers"
"Route" or "Path"
"Interior Routers"

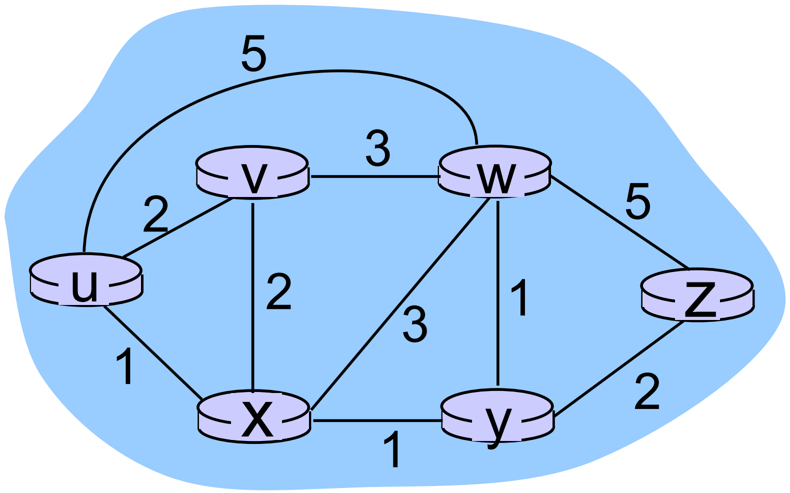
# Internet Routing

- Internet Routing works at two levels

- Each AS runs an intra-domain routing protocol that establishes routes within its domain
  - AS -- region of network under a single administrative entity
  - Link State, e.g., Open Shortest Path First (OSPF)
  - Distance Vector, e.g., Routing Information Protocol (RIP)

- ASes participate in an inter-domain routing protocol that establishes routes between domains
  - Path Vector, e.g., Border Gateway Protocol (BGP)

# Graph abstraction

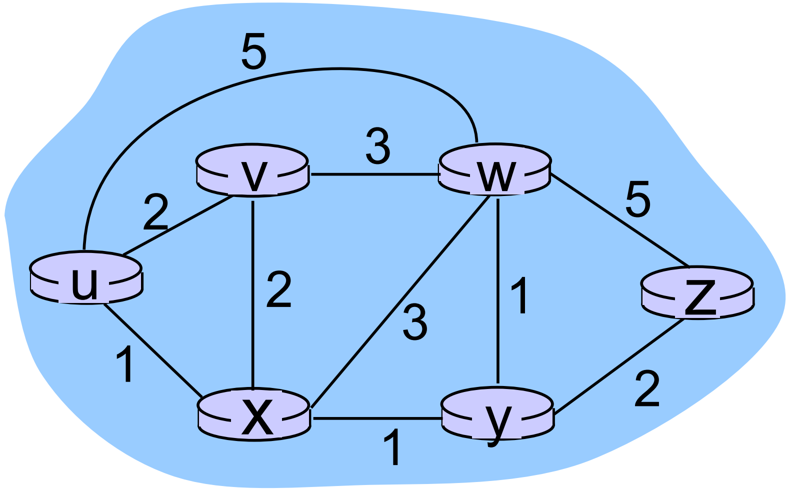



graph: G = (N,E)

N = set of routers = { u, v, w, x, y, z }

E = set of links ={ (u,v), (u,x), (u,w), (v,x), (v,w), (x,w), (x,y), (w,y), (w,z), (y,z) }

# Graph abstraction: costs




c(x,x' ) = cost of link (x,x' )
e.g., c(w,z) = 5

cost of path $(x_1, x_2, x_3, \ldots, x_p) = c(x_1,x_2) + c(x_2,x_3) + \ldots + c(x_{p-1},x_p)$

*key question:* what is the least-cost path between u and z ?
*routing algorithm:* algorithm that finds that least cost path

# Link Cost

- Typically simple: all links are equal
- Least-cost paths => shortest paths (hop count)
- Network operators add policy exceptions
  - Lower operational costs
  - Peering agreements
  - Security concerns

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# Routing algorithm classes

*Link State (Global)*

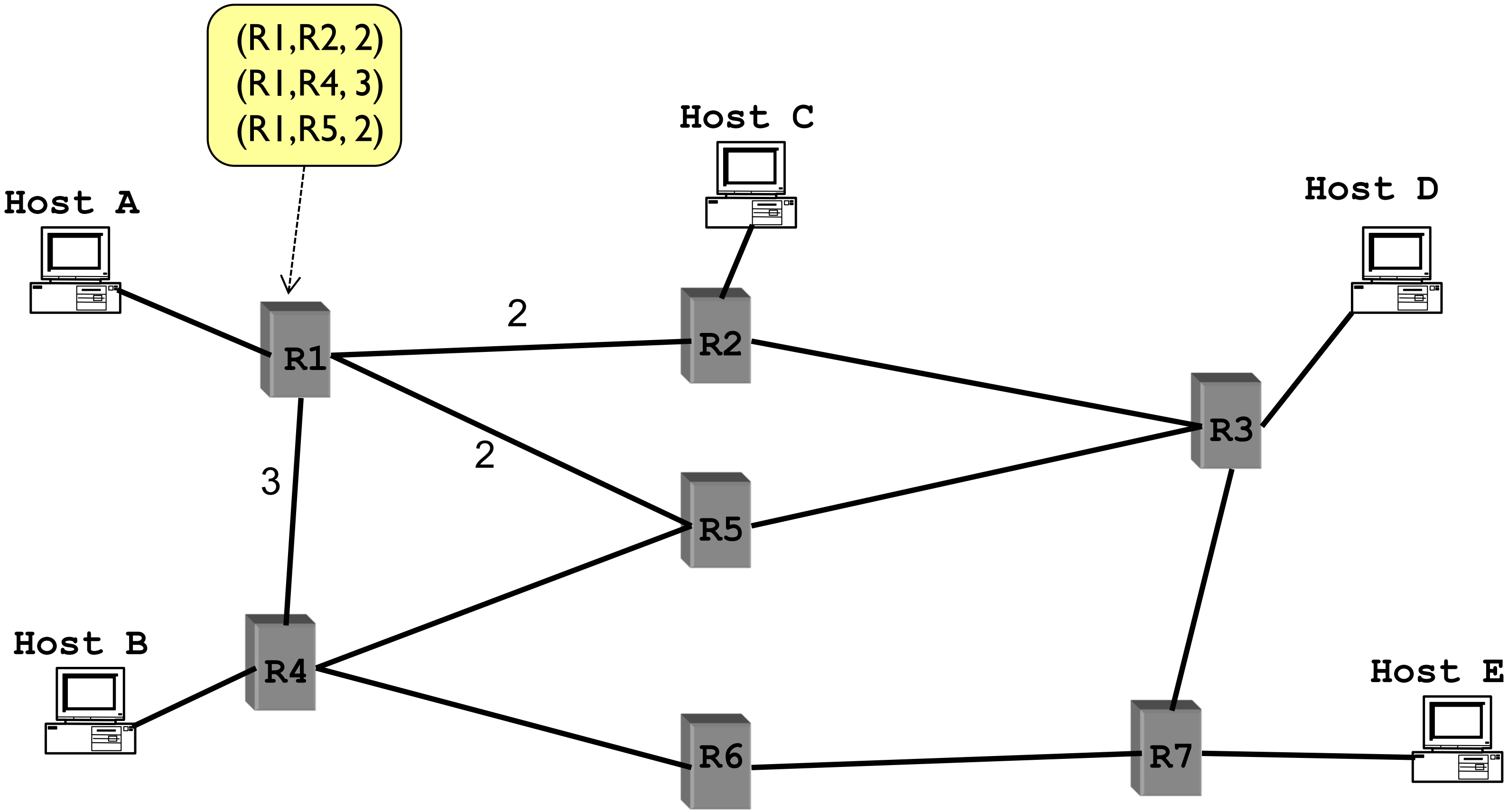
- Routers maintain cost of each link in the network
- Connectivity/cost changes flooded to all routers
- Converges quickly (less inconsistency, looping, etc.)
- Limited network sizes

*Distance Vector (Decentralised)*

- Routers maintain next hop & cost of each destination.
- Connectivity/cost changes iteratively propagate form neighbour to neighbour
- Requires multiple rounds to converge
- Scales to large networks

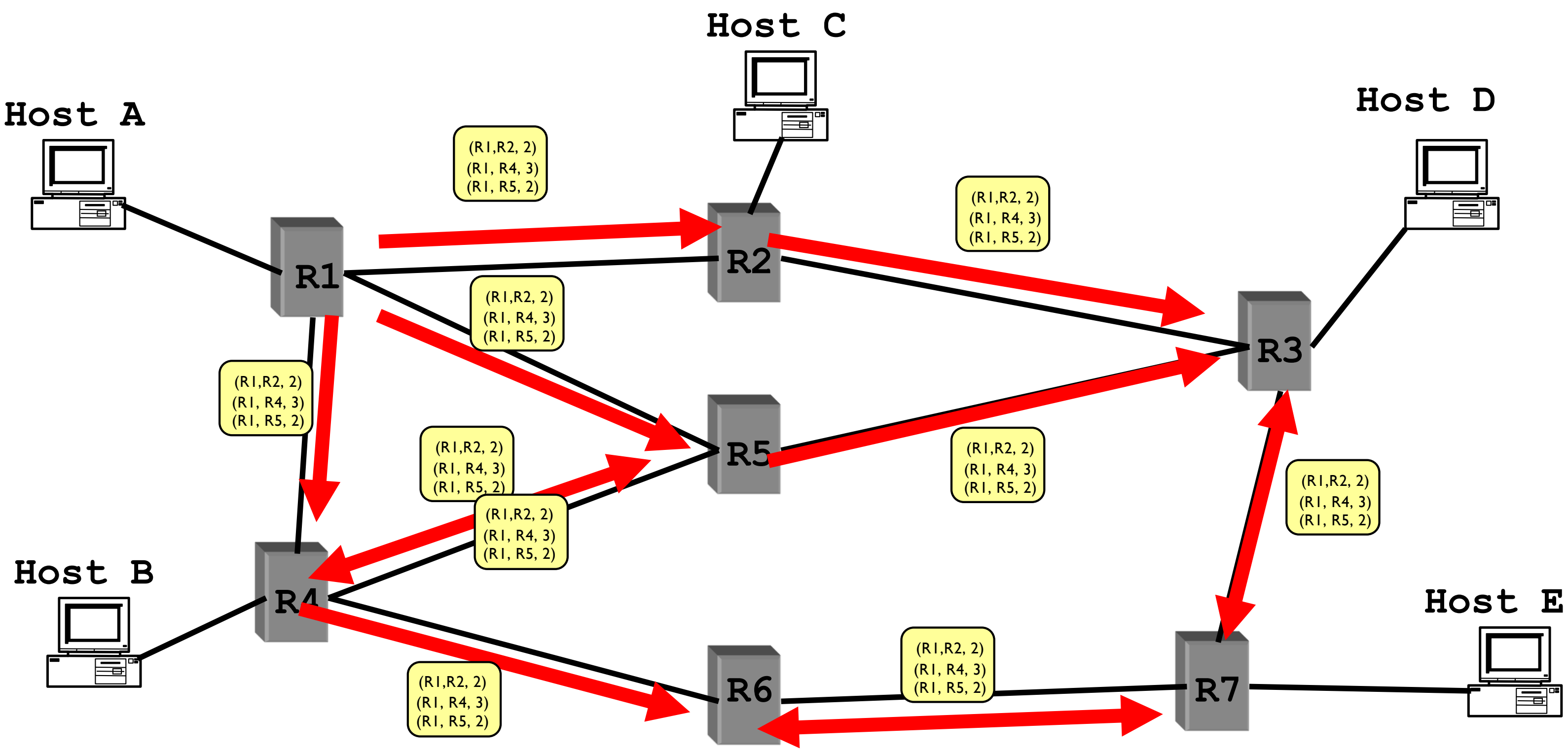
# Link State Routing

- Each node maintains its local "link state" (LS)
  - i.e., a list of its directly attached links and their costs



# Link State Routing

- Each node maintains its local "link state" (LS)
- Each node floods its local link state
  - on receiving a new LS message, a router forwards the message to all its neighbors other than the one it received the message from

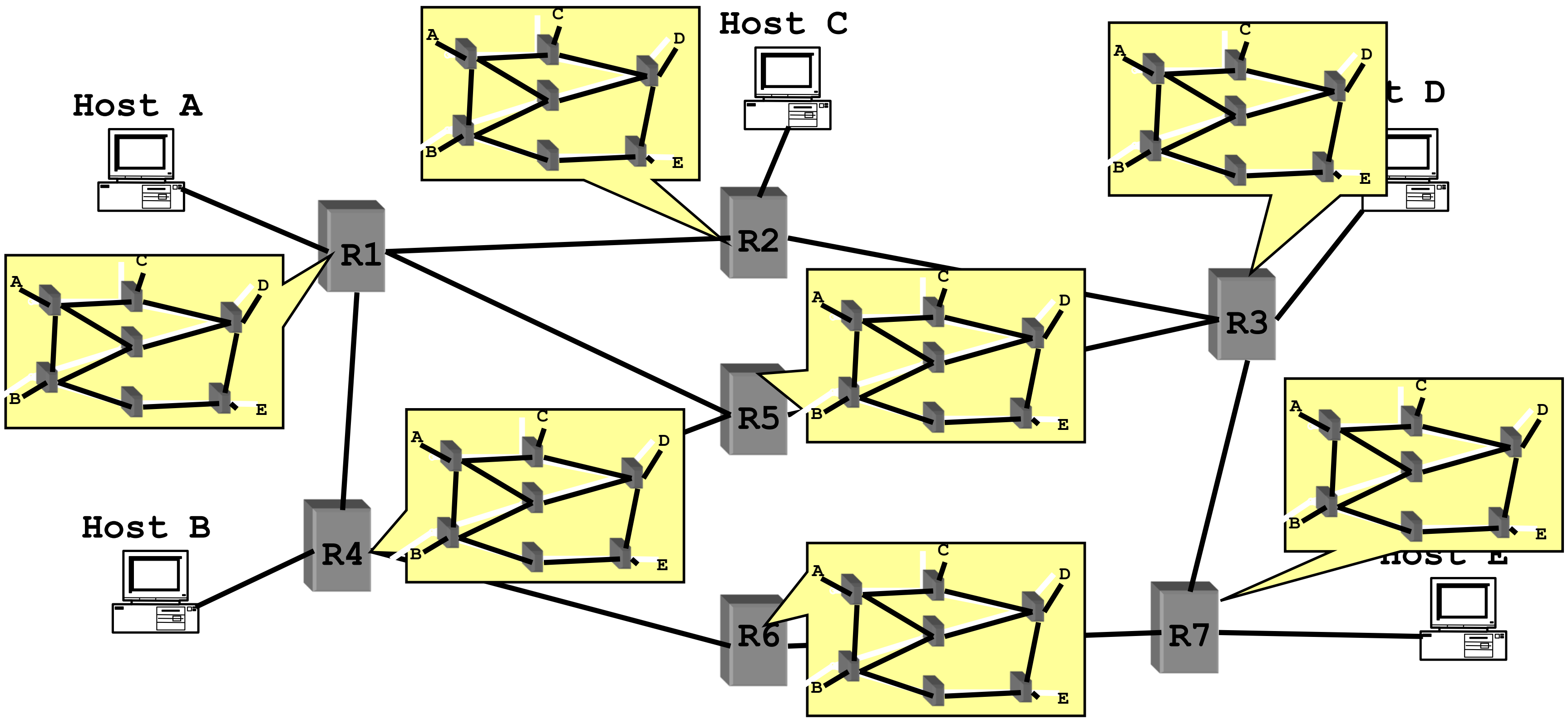


# Flooding LSAs

- Routers transmit Link State Advertisement (LSA) on links
  - A neighbouring router forwards out on all links except incoming
  - Keep a copy locally; don't forward previously-seen LSAs
- Challenges
  - Packet loss
  - Out of order arrival
- Solutions
  - Acknowledgements and retransmissions
  - Sequence numbers
  - Time-to-live for each packet

# Link State Routing

- Each node maintains its local "link state" (LS)
- Each node floods its local link state
- Eventually, each node learns the entire network topology
  - Can use Dijkstra's to compute the shortest paths between nodes



# A Link-State Routing Algorithm

*Dijkstra's algorithm*

- net topology, link costs known to all nodes
  - accomplished via "link state broadcast"
  - all nodes have same info
- computes least cost paths from one node ('source") to all other nodes
  - gives *forwarding table* for that node
- iterative: after k iterations, know least cost path to k dest.'s

*notation:*

- c(x,y): link cost from node x to y; = ∞ if not direct neighbors
- D(v): current value of cost of path from source to dest. v
- p(v): predecessor node along path from source to v
- N': set of nodes whose least cost path definitively known

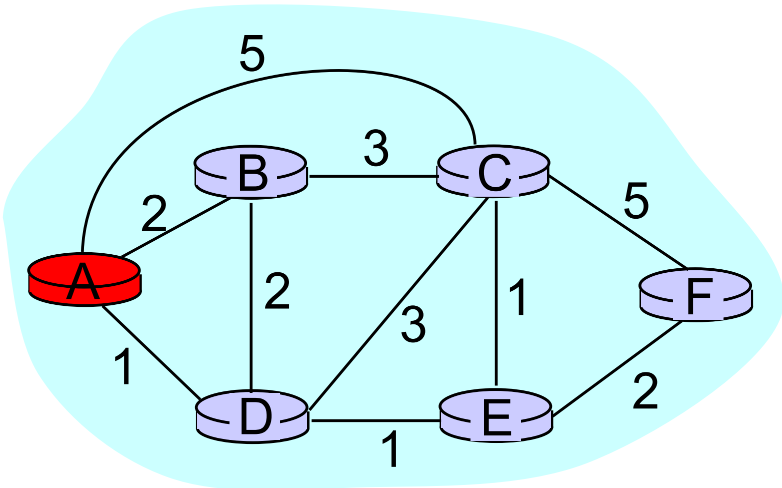
# Dijsktra's Algorithm

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

Loop
  find w not in N' such that D(w) is a minimum
  add w to N'
  update D(v) for all v adjacent to w and not in N' :
      D(v) = min( D(v), D(w) + c(w,v) )
  /* new cost to v is either old cost to v or known
   shortest path cost to w plus cost from w to v */
until all nodes in N'
```

# Example: Dijkstra's Algorithm

| Step | Set N' | D(B),p(B) | D(C),p(C) | D(D),p(D) | D(E),p(E) | D(F),p(F) |
|---|---|---|---|---|---|---|
| 0 | A | 2,A | 5,A | 1,A | ∞ | ∞ |
| 1 | | | | | | |
| 2 | | | | | | |
| 3 | | | | | | |
| 4 | | | | | | |
| 5 | | | | | | |




1 ***Initialization:***
2   **N'** = {A};
3   for all nodes ***v***
4     if ***v*** adjacent to ***A***
5       then D(v) = c(A,v);
6       else D(v) = ∞;
…

# Example: Dijkstra’s Algorithm

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| 3 | | | | | | |
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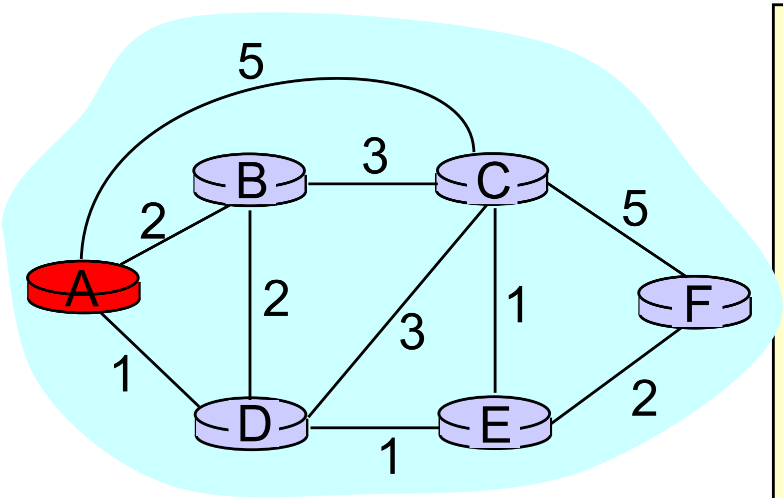


```
…
Loop
    find w not in N’ s.t. D(w) is a minimum;
    add w to N’;
   update D(v) for all v adjacent
      to w and not in N’:
   If D(w) + c(w,v) < D(v) then
      D(v) = D(w) + c(w,v); p(v) = w;
 until all nodes in N’;
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| 2 | | | | | | |
| 3 | | | | | | |
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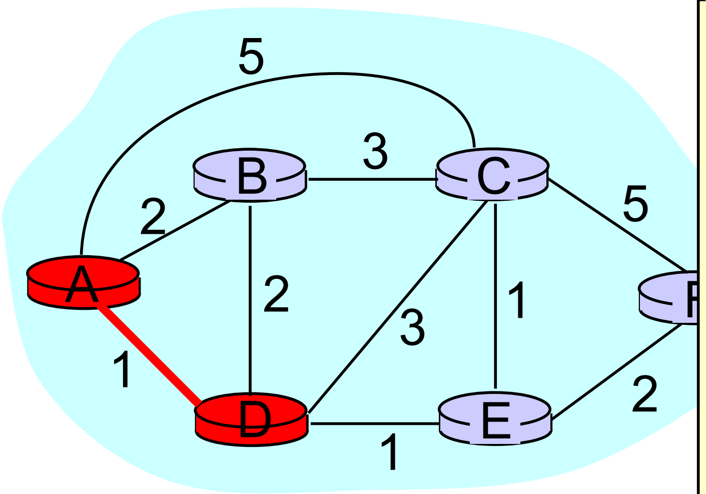
| 5 | | | | | | |

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| 2 | | | | | | |
| 3 | | | | | | |
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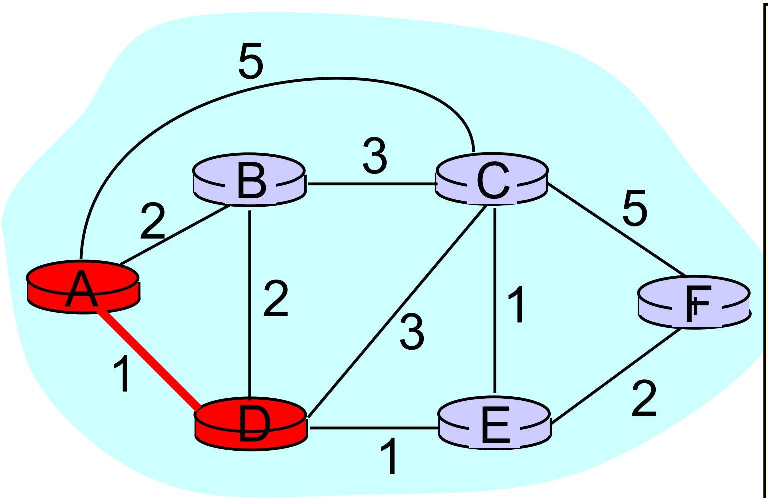
| 5 | | | | | | |

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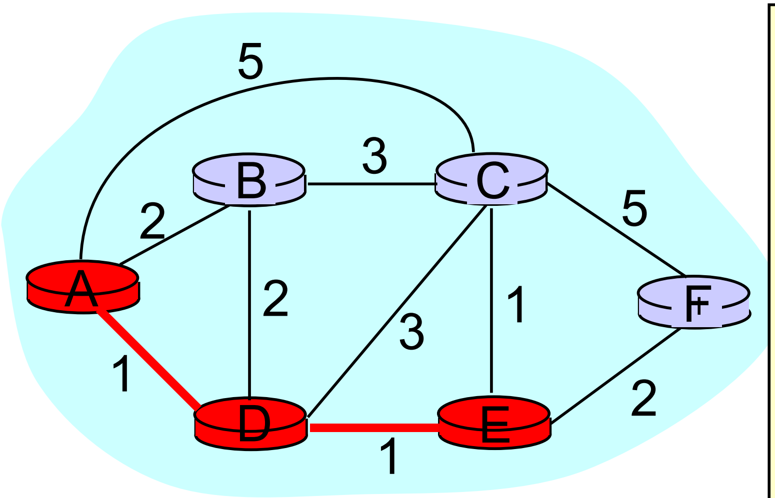
| 1 | AD | 2, A | 4,D | | 2,D | |
| 2 | ADE | 2, A | 3,E | | | 4,E |
| 3 | | | | | | |
| 4 | | | | | | |
| 5 | | | | | | |

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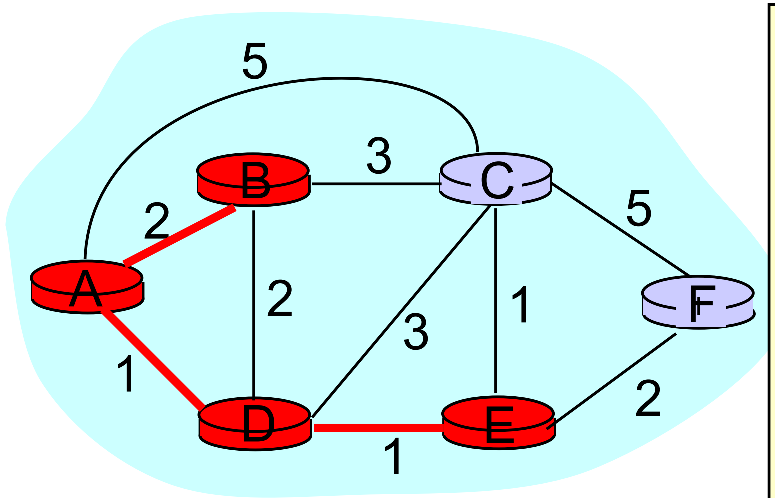
| 3 | ADEB | | 3,E | | | 4,E |
| 4 | | | | | | |
| 5 | | | | | | |

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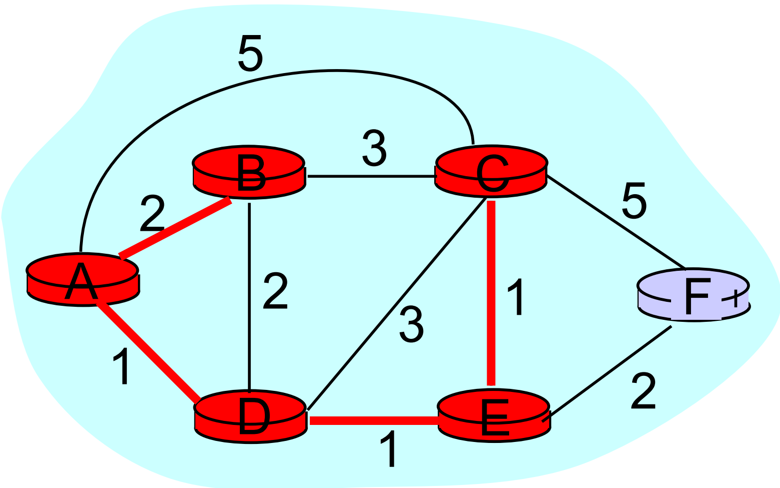
| 1 | AD | 2,A | 4,D | | 2,D | |
| 2 | ADE | 2,A | 3,E | | | 4,E |
| 3 | ADEB | | 3,E | | | 4,E |
| 4 | ADEBC | | | | | 4,E |
| 5 | | | | | | |

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***Loop***
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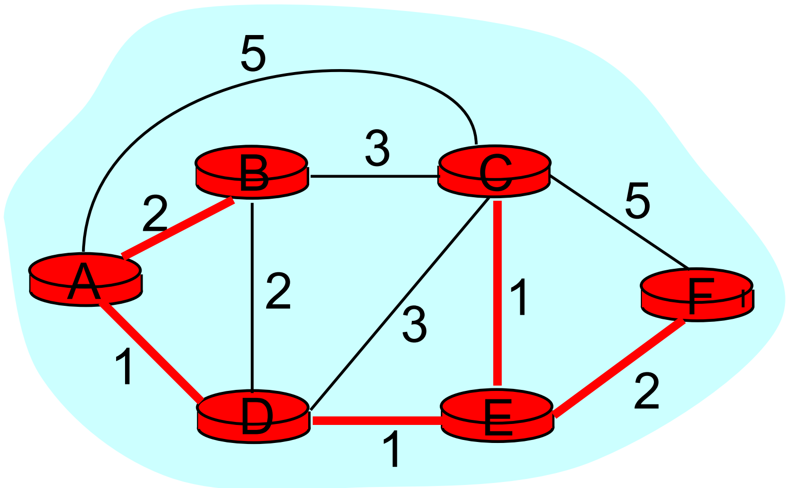
| 1 | AD | 2,A | 4,D | | 2,D | |
| 2 | ADE | 2,A | 3,E | | | 4,E |
| 3 | ADEB | | 3,E | | | 4,E |
| 4 | ADEBC | | | | | 4,E |
| 5 | ADEBCF | | | | | |

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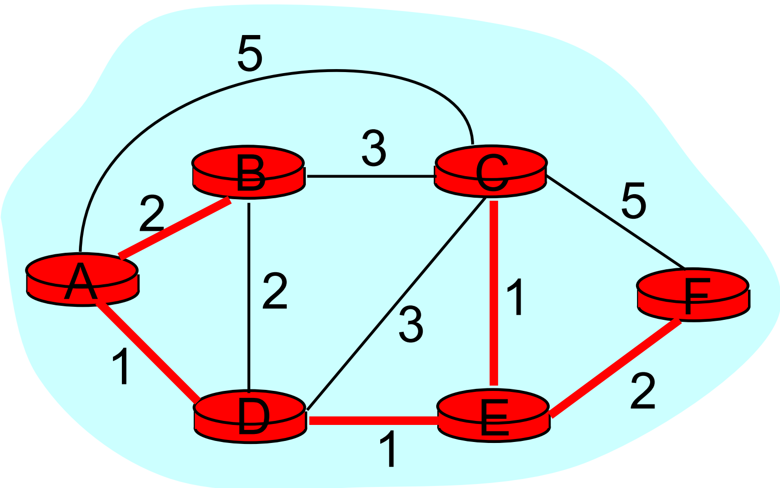
| 5 | ADEBCF | | | | | |

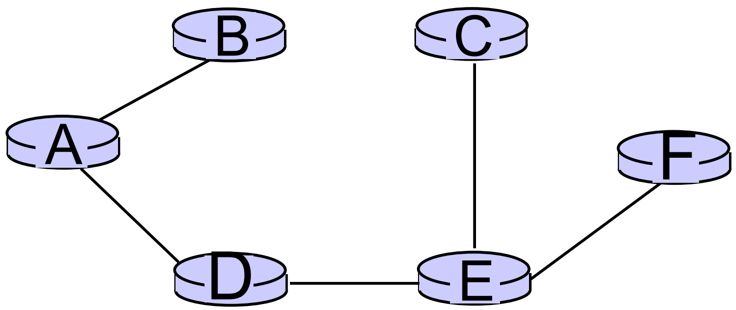



To determine path A → C (say), work backward from C via p(v)

# The Forwarding Table

- Running Dijkstra at node A gives the shortest path from A to all destinations
- We then construct the *forwarding table*

resulting shortest-path tree from A:



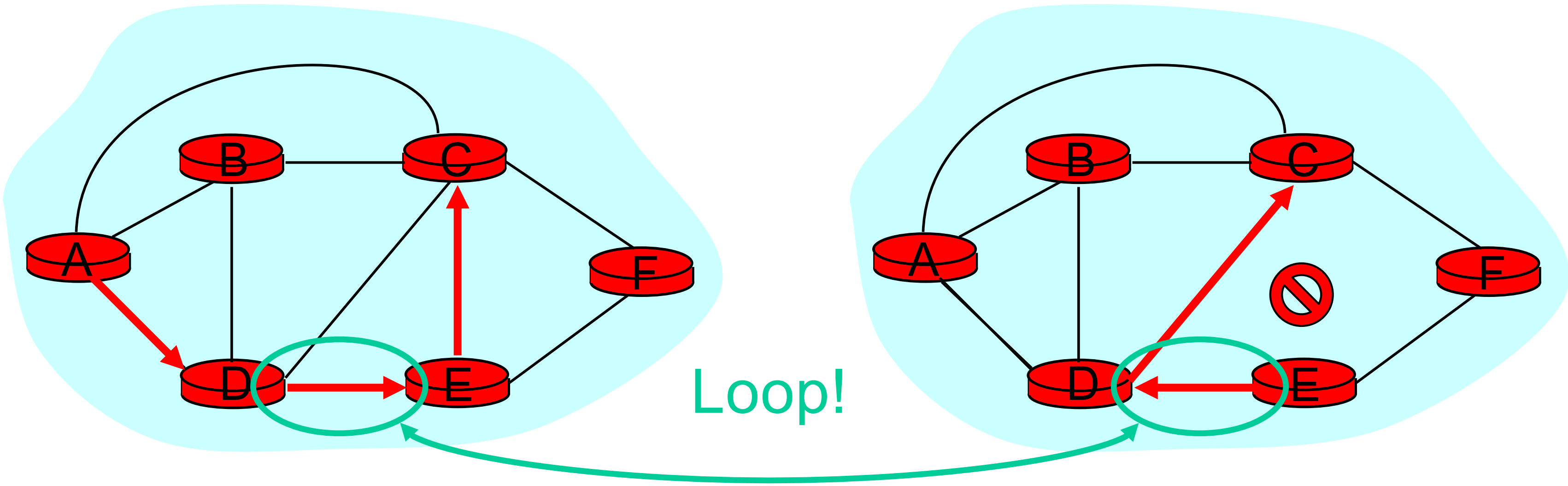

| Destination | Link |
|---|---|
| B | (A,B) |
| C | (A,D) |
| D | (A,D) |
| E | (A,D) |
| F | (A,D) |

# Issue #1: Scalability

- How many messages needed to flood link state messages?
  - O(N x E), where N is #nodes; E is #edges in graph
- Processing complexity for Dijkstra's algorithm?
  - $O(N^2)$, because we check all nodes w not in N' at each iteration and we have O(N) iterations
- How many entries in the LS topology database? O(E)
- How many entries in the forwarding table? O(N)

# Issue#2: Transient Disruptions

- Inconsistent link-state database
  - Some routers know about failure before others
  - The shortest paths are no longer consistent
  - Can cause **transient** forwarding loops



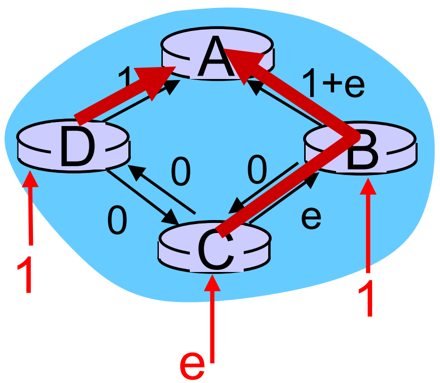

**A and D think that this is the path to C**

**E thinks that this is the path to C**

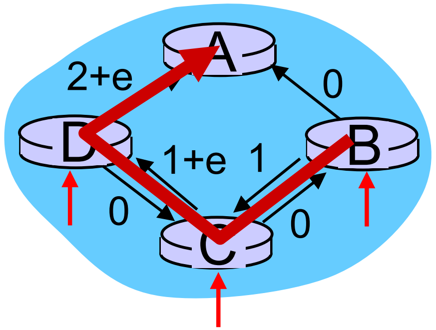
# Oscillations

*oscillations possible:*

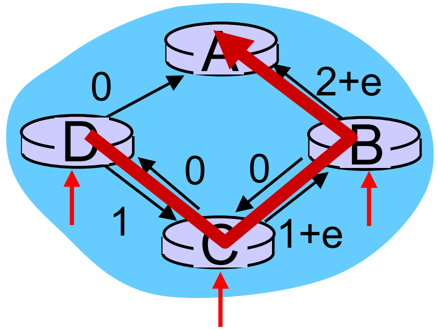
- e.g., suppose link cost equals amount of carried traffic:




initially




given these costs, find new routing…. resulting in new costs

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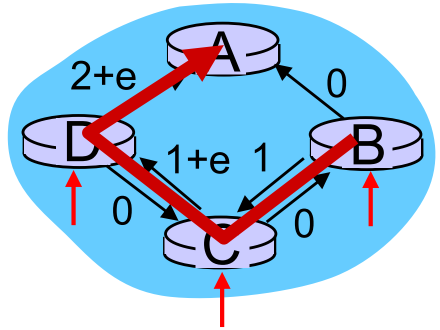


given these costs, find new routing…. resulting in new costs

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- link state
- distance vector
- hierarchical routing

5.6 ICMP: The Internet Control Message Protocol

# Distance vector algorithm

*Bellman-Ford equation*

let

$d_x(y)$ := cost of least-cost path from x to y

then

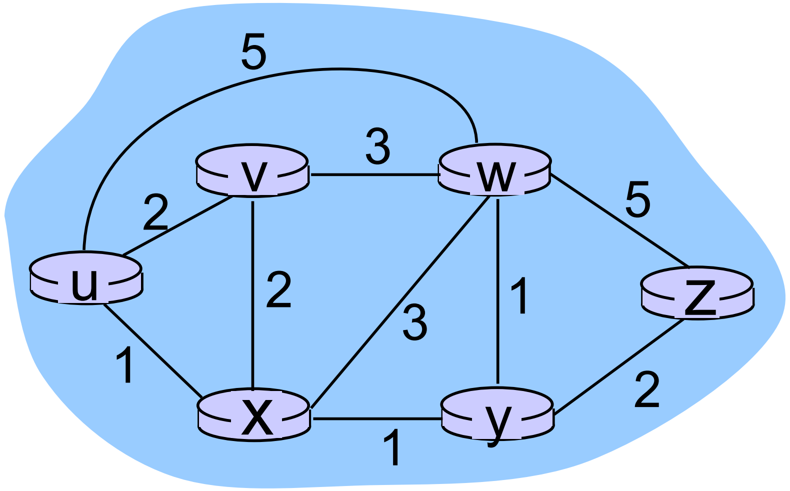
$$d_x(y) = \min_v \{c(x,v) + d_v(y)\}$$

cost from neighbor v to destination y

cost to neighbor v

*min* taken over all neighbors v of x

# Bellman-Ford example



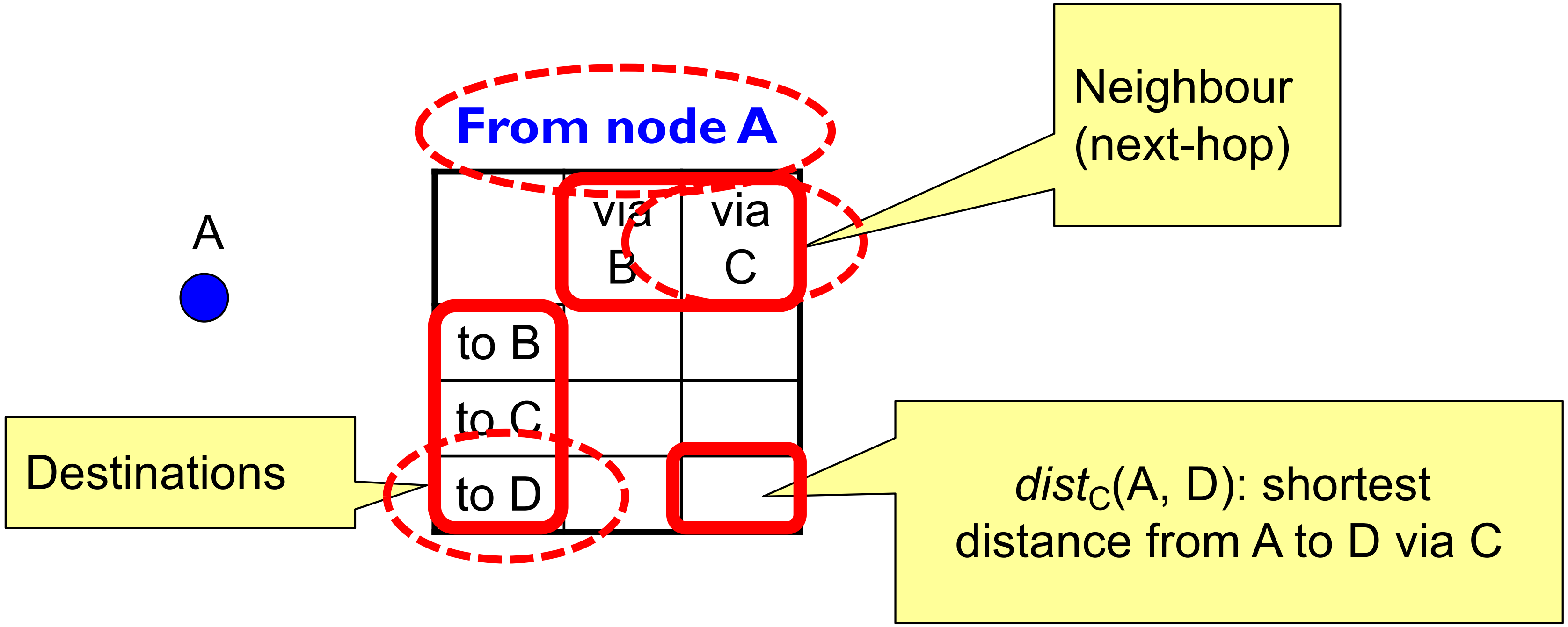

clearly, $d_v(z) = 5$, $d_x(z) = 3$, $d_w(z) = 3$

B-F equation says:

$$\begin{aligned} d_u(z) &= \min \{ c(u,v) + d_v(z), \\ &\qquad c(u,x) + d_x(z), \\ &\qquad c(u,w) + d_w(z) \} \\ &= \min \{2 + 5, \\ &\qquad 1 + 3, \\ &\qquad 5 + 3\} = 4 \end{aligned}$$

node achieving minimum is next
hop in shortest path, used in forwarding table

# How Distance-Vector (DV) works




Each router maintains its shortest distance to every destination via each of its neighbours

# How Distance-Vector (DV) works

MIN { $dist_B(A,B)$, $dist_C(A, B)$ }

A

**From node A**

| | via B | via C |
|---|---|---|
| to B | | |
| to C | | |
| to D | | |

**A's distance vector (DV)**

| | min dist |
|---|---|
| to B | |
| to C | |
| to D | |

Each router computes its shortest distance to every destination via <u>any</u> of its neighbors

# How Distance-Vector (DV) works

A

**From node A**

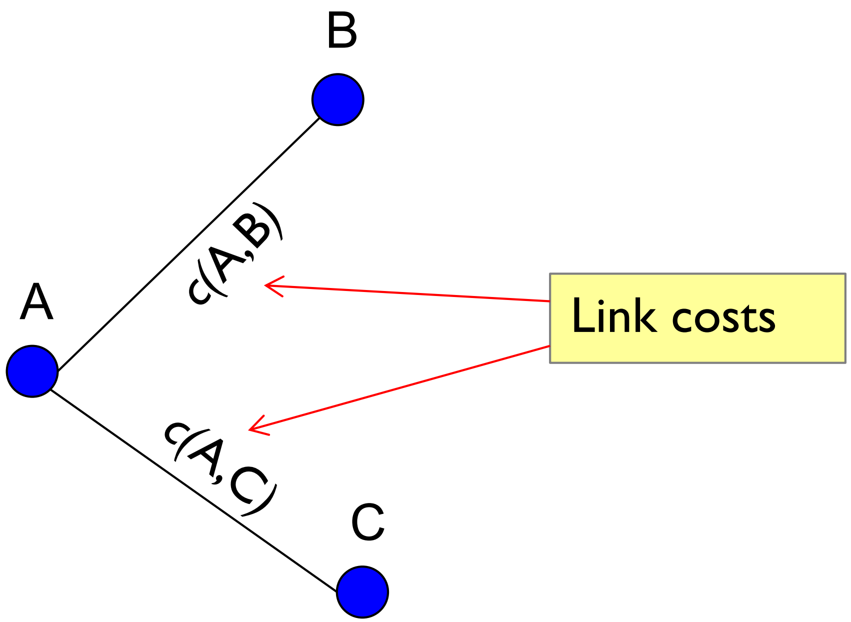
| | via B | via C |
|---|---|---|
| to B | ? | ? |
| to C | ? | ? |
| to D | ? | ? |

**A's DV**

| | min dist |
|---|---|
| to B | ? |
| to C | ? |
| to D | ? |

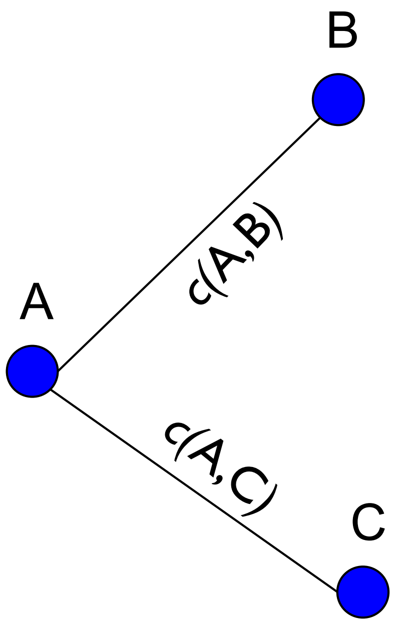
How does A initialize its dist() table and DV?

# How Distance-Vector (DV) works




How does A initialize its dist() table and DV?

# How Distance-Vector (DV) works




**From node A**

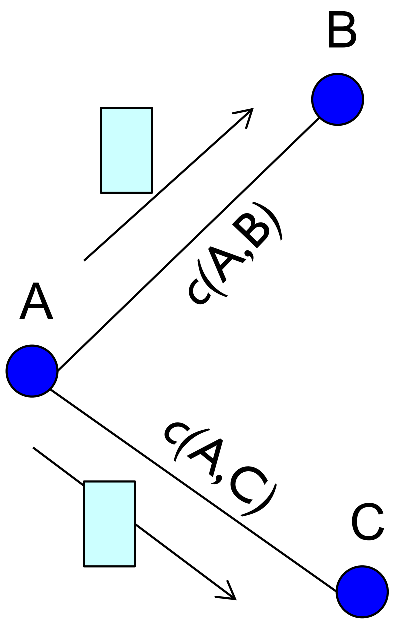
| | via B | via C |
|---|---|---|
| to B | *c*(A,B) | ∞ |
| to C | ∞ | *c*(A,C) |
| to D | ∞ | ∞ |

**A's DV**

| | mindist |
|---|---|
| to B | c(A,B) |
| to C | c(A,C) |
| to D | ∞ |

Each router initializes its *dist*() table based on its immediate neighbors and link costs

# How Distance-Vector (DV) works




Assume that A's DV is as follows at some later time

**From node A**

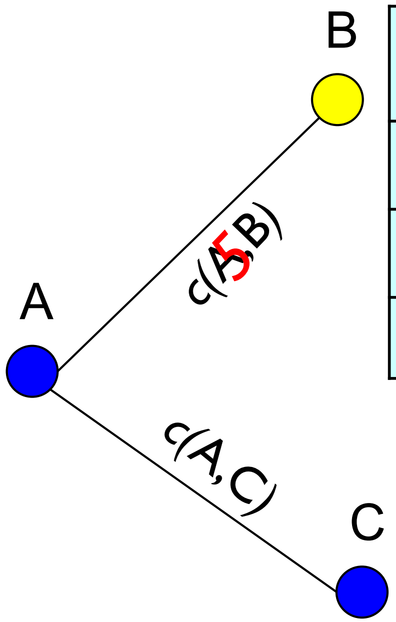
| | via B | via C |
|---|---|---|
| to B | *c*(A,B) | ∞ |
| to C | ∞ | *c*(A,C) |
| to D | ∞ | ∞ |

**A's DV**

| | mindist |
|---|---|
| to B | 5 |
| to C | 6 |
| to D | 2 |

Each router sends its DV to its immediate neighbors

# How Distance-Vector (DV) works




**A's DV**

| | min |
|---|---|
| to B | 5 |
| to C | 6 |
| to D | 2 |

**From node B**

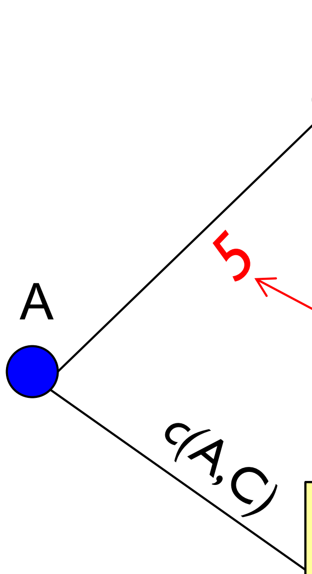
| | via A | via C |
|---|---|---|
| to A | 5 | ∞ |
| to C | 15 | 1 |
| to D | ∞ | ∞ |

**B's DV**

| | mindist |
|---|---|
| to A | 5 |
| to C | 1 |
| to D | ∞ |

Routers process received DVs

# How Distance-Vector (DV) works




**A's DV**

| | min |
|---|---|
| to B | 5 |
| to C | 6 |
| to D | 2 |

**From node B**

| | via A | via C |
|---|---|---|
| to A | 5 | ∞ |
| to C | 11 | 1 |
| to D | 7 | ∞ |

**B's DV**

| | mindist |
|---|---|
| to A | 5 |
| to C | 1 |
| to D | 7 |

new = c(B,A) + *mindist*(A, D)

Routers process received DVs

And repeat…

# Distance Vector Routing

- Each router knows the links to its neighbors
- Each router has provisional "shortest path" to every other router -- its distance vector (DV)
- Routers exchange this DV with their neighbors
- Routers look over the set of options offered by their neighbors and select the best one
- Iterative process converges to set of shortest paths

# Distance vector routing

*iterative, asynchronous:*
each local iteration caused by:

- local link cost change
- DV update message from neighbor

*distributed:*

- each node notifies neighbors *only* when its DV changes
  - neighbors then notify their neighbors if necessary

*each node:*

*wait* for (change in local link cost or msg from neighbor)

↓

*recompute* estimates

↓

if DV to any dest has changed, *notify* neighbors

# Distance Vector

- c(i,j): link cost from node *i* to *j*
- $dist_Z(A,V)$: shortest dist. from A to V via Z
- mindist(A,V): shortest dist. from A to V

```
At node A
Initialization:
  for all destinations V  do
      if V is neighbor of A
          dist_V(A, V) = mindist(A,V) = c(A,V);
      else
          dist_V(A, V) = mindist(A,V) = ∞;
   send mindist(A, *) to all neighbors
loop:
  wait (until A sees a link cost change to neighbor V  /* case 1 */
        or until A receives mindist(V,*) from neighbor V)   /* case 2 */
   if (c(A,V) changes by ±d)  /* ⇐ case 1 */
      for all destinations Y do
              dist_V(A,Y) =  dist_V(A,Y) ± d
   else /* ⇐ case 2: */
      for all destinations Y do
              dist_V(A,Y) = c(A,V) + mindist(V, Y);
   update mindist(A,*)
  if (there is a change in mindist(A, *))
        send mindist(A,  *) to all neighbors
  forever
```

# Distance Vector

- c(i,j): link cost from node *i* to *j*
- $dist_Z(A,V)$: shortest dist. from A to V via Z
- mindist(A,V): shortest dist. from A to V

**At node A**

***Initialization:***

**for all** destinations *V* **do**
    **if** *V* is neighbor of *A*
        $dist_V(A, V)$ = mindist(A,V) = c(*A*,*V*);
    **else**
        $dist_V(A, V)$ = mindist(A,V) = $\infty$;
**send** mindist(*A*, *) to all neighbors

***loop:***

**wait** (until *A* sees a link cost change to neighbor *V* /* **case 1** */
    or until *A* receives mindist(V,*) from neighbor *V*) /* **case 2** */
**if** (c(*A*,*V*) changes by $\pm d$) /* $\Leftarrow$ **case 1** */
    **for all** destinations Y **do**
        $dist_V(A,Y) = dist_V(A,Y) \pm d$
**else** /* $\Leftarrow$ **case 2:** */
    **for all** destinations Y **do**
        $dist_V(A,Y)$ = c(*A*,*V*) + mindist(*V*, *Y*);
update mindist(*A*,*)
**if** (there is a change in mindist(A, *))
    **send** mindist(*A*, *) to all neighbors
**forever**

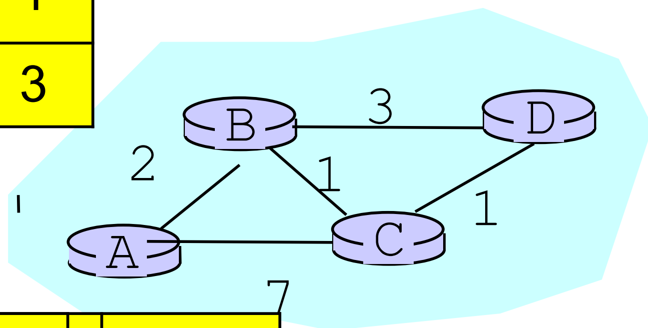
# Example: Initialization

**from Node B**

| | via A | via C | via D | min dist |
|---|---|---|---|---|
| to A | 2 | ∞ | ∞ | 2 |
| to B | - | - | - | 0 |
| to C | ∞ | 1 | ∞ | 1 |
| to D | ∞ | ∞ | 3 | 3 |

**from Node D**

| | via B | via C | min dist |
|---|---|---|---|
| to A | ∞ | ∞ | ∞ |
| to B | 3 | ∞ | 3 |
| to C | ∞ | 1 | 1 |
| to D | - | - | 0 |




**from Node A**

| | via B | via C | min dist | min dist |
|---|---|---|---|---|
| to A | - | - | 0 | 0 |
| to B | 2 | ∞ | 2 | 2 |
| to C | ∞ | 7 | 7 | 7 |
| to D | ∞ | ∞ | ∞ | ∞ |

**from Node C**

| | via A | via B | via D | min dist |
|---|---|---|---|---|
| to A | 7 | ∞ | ∞ | 7 |
| to B | ∞ | 1 | ∞ | 1 |
| to C | - | - | - | 0 |
| to D | ∞ | ∞ | 1 | 1 |

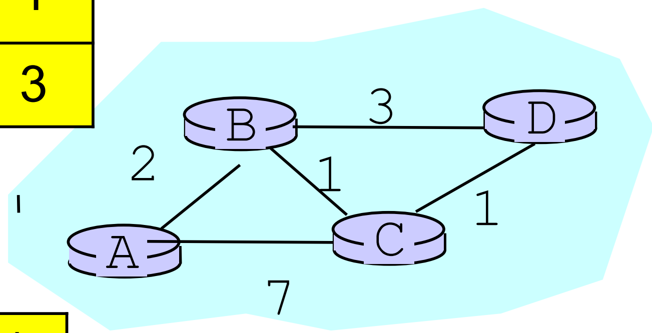
# Example: C sends update to A

**from Node B**

| | via A | via C | via D | min dist |
|---|---|---|---|---|
| to A | 2 | ∞ | ∞ | 2 |
| to B | - | - | - | 0 |
| to C | ∞ | 1 | ∞ | 1 |
| to D | ∞ | ∞ | 3 | 3 |

**from Node D**

| | via B | via C | min dist |
|---|---|---|---|
| to A | ∞ | ∞ | ∞ |
| to B | 3 | ∞ | 3 |
| to C | ∞ | 1 | 1 |
| to D | - | - | 0 |



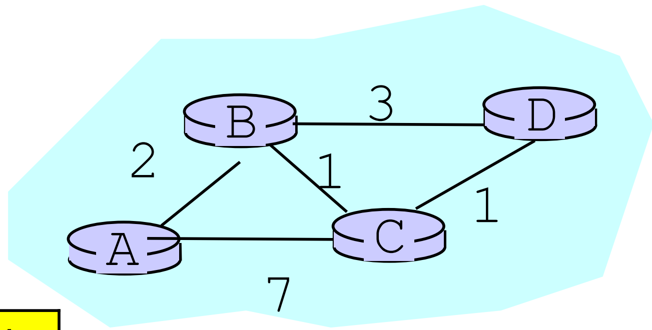

**from Node A**

| | via B | via C | min dist |
|---|---|---|---|
| to A | - | - | 0 |
| to B | 2 | ∞ | 2 |
| to C | ∞ | 7 | 7 |
| to D | ∞ | ∞ | ∞ |

**from Node C**

| | via A | via B | via D | min dist |
|---|---|---|---|---|
| to A | 7 | ∞ | ∞ | 7 |
| to B | ∞ | 1 | ∞ | 1 |
| to C | - | - | - | 0 |
| to D | ∞ | ∞ | 1 | 1 |

# Example: C sends update to A



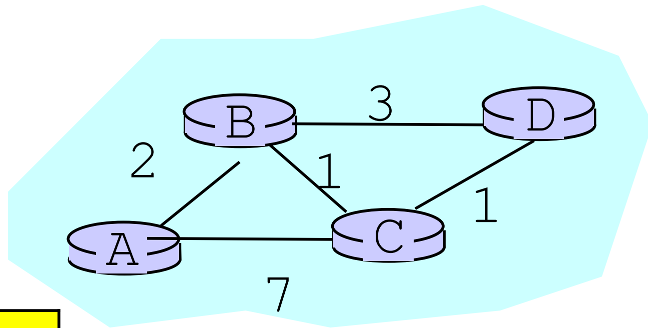

**from Node A**

| | via B | via C |
|---|---|---|
| to A | - | - |
| to B | 2 | ∞ |
| to C | ∞ | 7 |
| to D | ∞ | ∞ |

| min dist |
|---|
| 0 |
| 2 |
| 7 |
| ∞ |

| min dist |
|---|
| 7 |
| 1 |
| 0 |
| 1 |

# Example: C sends update to A



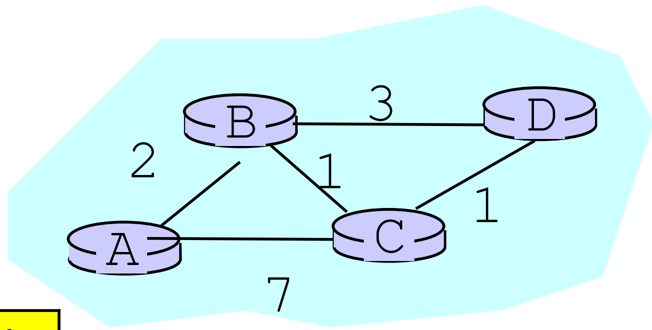

**from Node A**

| | via B | via C |
|---|---|---|
| to A | - | - |
| to B | 2 | **8** |
| to C | ∞ | 7 |
| to D | ∞ | **8** |

| min dist |
|---|
| 0 |
| 2 |
| 7 |
| ∞ |

| min dist |
|---|
| 7 |
| 1 |
| 0 |
| 1 |

# Example: C sends update to A




**from Node A**

| | via B | via C |
|---|---|---|
| to A | - | - |
| to B | 2 | **8** |
| to C | ∞ | 7 |
| to D | ∞ | **8** |

| min dist |
|---|
| 0 |
| 2 |
| 7 |
| **8** |

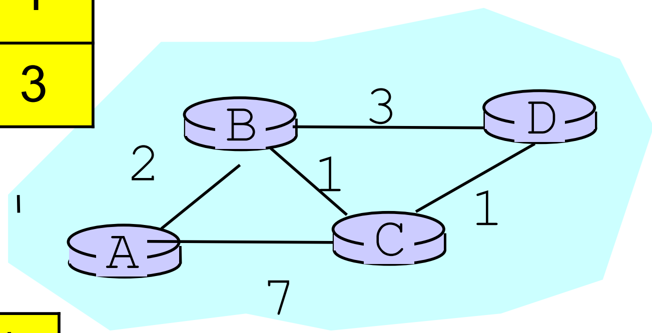
# Example: now B sends update to A

**from Node B**

| | via A | via C | via D | min dist |
|---|---|---|---|---|
| to A | 2 | ∞ | ∞ | 2 |
| to B | - | - | - | 0 |
| to C | ∞ | 1 | ∞ | 1 |
| to D | ∞ | ∞ | 3 | 3 |

**from Node D**

| | via B | via C | min dist |
|---|---|---|---|
| to A | ∞ | ∞ | ∞ |
| to B | 3 | ∞ | 3 |
| to C | ∞ | 1 | 1 |
| to D | - | - | 0 |




**from Node A**

| | via B | via C | min dist |
|---|---|---|---|
| to A | - | - | 0 |
| to B | 2 | 8 | 2 |
| to C | ∞ | 7 | 7 |
| to D | ∞ | 8 | 8 |

**from Node C**

| | via A | via B | via D | min dist |
|---|---|---|---|---|
| to A | 7 | ∞ | ∞ | 7 |
| to B | ∞ | 1 | ∞ | 1 |
| to C | - | - | - | 0 |
| to D | ∞ | ∞ | 1 | 1 |

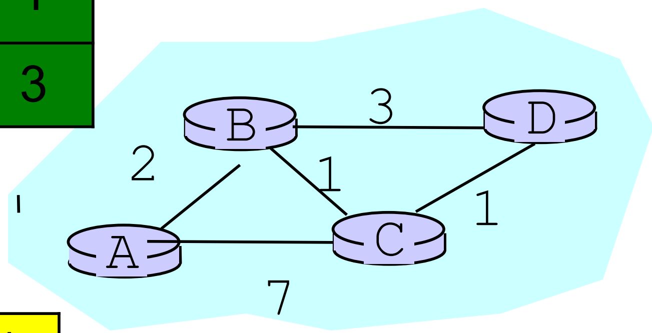
# Example: now B sends update to A

from Node B

| | via A | via C | via D | min dist |
|---|---|---|---|---|
| to A | 2 | ∞ | ∞ | 2 |
| to B | - | - | - | 0 |
| to C | ∞ | 1 | ∞ | 1 |
| to D | ∞ | ∞ | 3 | 3 |

from Node D

| | via B | via C | min dist |
|---|---|---|---|
| to A | ∞ | ∞ | ∞ |
| to B | 3 | ∞ | 3 |
| to C | ∞ | 1 | 1 |
| to D | - | - | 0 |




from Node A

| | via B | via C | min dist |
|---|---|---|---|
| to A | - | - | 0 |
| to B | 2 | 8 | 2 |
| to C | ∞ | 7 | 7 |
| to D | ∞ | 8 | 8 |

from Node C

| | via A | via B | via D | min dist |
|---|---|---|---|---|
| to A | 7 | ∞ | ∞ | 7 |
| to B | ∞ | 1 | ∞ | 1 |
| to C | - | - | - | 0 |
| to D | ∞ | ∞ | 1 | 1 |

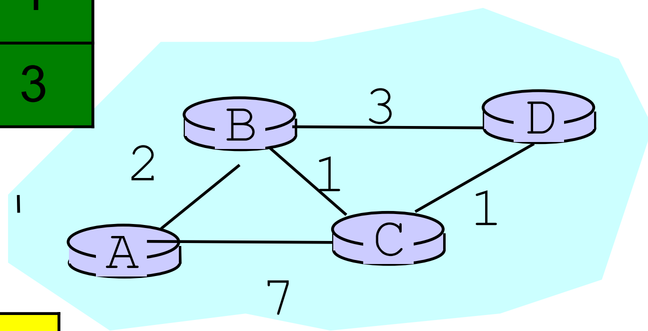
# Example: now B sends update to A

**from Node B**

| | via A | via C | via D | min dist |
|---|---|---|---|---|
| to A | 2 | ∞ | ∞ | 2 |
| to B | - | - | - | 0 |
| to C | ∞ | 1 | ∞ | 1 |
| to D | ∞ | ∞ | 3 | 3 |

**from Node D**

| | via B | via C | min dist |
|---|---|---|---|
| to A | ∞ | ∞ | ∞ |
| to B | 3 | ∞ | 3 |
| to C | ∞ | 1 | 1 |
| to D | - | - | 0 |




**from Node A**

| | via B | via C | min dist |
|---|---|---|---|
| to A | - | - | 0 |
| to B | 2 | 8 | 2 |
| to C | **3** | 7 | 7 |
| to D | **5** | 8 | 8 |

**from Node C**

| | via [illegible] | via [illegible] | via [illegible] | min dist |
|---|---|---|---|---|
| [illegible] | [illegible] | [illegible] | [illegible] | 7 |
| [illegible] | [illegible] | [illegible] | [illegible] | 1 |
| to C | - | - | - | 0 |
| to D | ∞ | ∞ | 1 | 1 |

Make sure you know why this is 5, not 4!

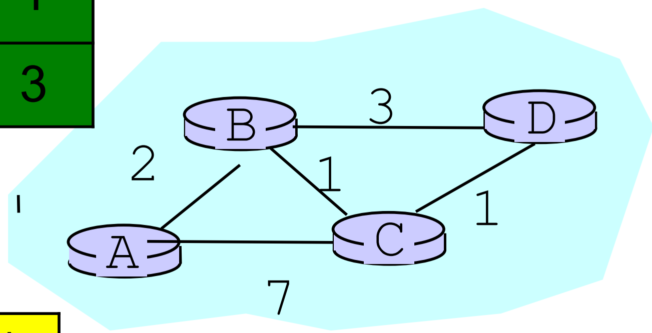
# Example: now B sends update to A

**from Node B**

| | via A | via C | via D | min dist |
|---|---|---|---|---|
| to A | 2 | ∞ | ∞ | 2 |
| to B | - | - | - | 0 |
| to C | ∞ | 1 | ∞ | 1 |
| to D | ∞ | ∞ | 3 | 3 |

**from Node D**

| | via B | via C | min dist |
|---|---|---|---|
| to A | ∞ | ∞ | ∞ |
| to B | 3 | ∞ | 3 |
| to C | ∞ | 1 | 1 |
| to D | - | - | 0 |




**from Node A**

| | via B | via C | min dist |
|---|---|---|---|
| to A | - | - | 0 |
| to B | 2 | 8 | 2 |
| to C | **3** | 7 | **3** |
| to D | **5** | 8 | **5** |

**from Node C**

| | via A | via B | via D | min dist |
|---|---|---|---|---|
| to A | 7 | ∞ | ∞ | 7 |
| to B | ∞ | 1 | ∞ | 1 |
| to C | - | - | - | 0 |
| to D | ∞ | ∞ | 1 | 1 |

*All nodes know the best two-hop paths.*

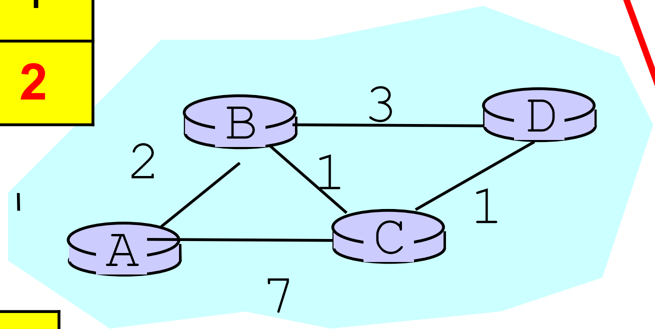
Make sure you believe this

from Node B

| | via A | via C | via D | min dist |
|---|---|---|---|---|
| to A | 2 | 8 | ∞ | 2 |
| to B | - | - | - | 0 |
| to C | 9 | 1 | 4 | 1 |
| to D | ∞ | 2 | 3 | 2 |

from Node D

| | via B | via C | min dist |
|---|---|---|---|
| to A | 5 | 8 | 5 |
| to B | 3 | 2 | 2 |
| to C | 4 | 1 | 1 |
| to D | - | - | 0 |




from Node A

| | via B | via C | min dist |
|---|---|---|---|
| to A | - | - | 0 |
| to B | 2 | 8 | 2 |
| to C | 3 | 7 | 3 |
| to D | 5 | 8 | 5 |

from Node C

| | via A | via B | via D | min dist |
|---|---|---|---|---|
| to A | 7 | 3 | ∞ | 3 |
| to B | 9 | 1 | 4 | 1 |
| to C | - | - | - | 0 |
| to D | ∞ | 4 | 1 | 1 |

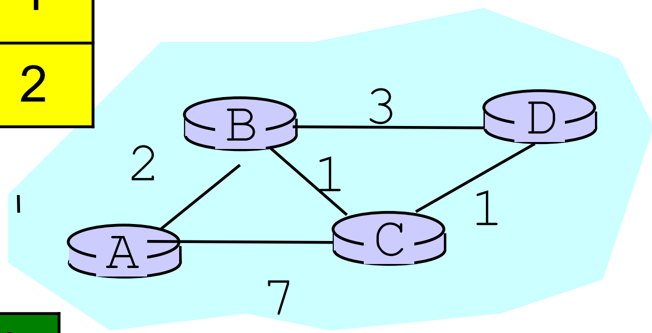
# Example: Now A sends update to B

**from Node B**

| | via A | via C | via D | min dist |
|---|---|---|---|---|
| to A | 2 | 8 | ∞ | 2 |
| to B | - | - | - | 0 |
| to C | 9 | 1 | 4 | 1 |
| to D | ∞ | 2 | 3 | 2 |

**from Node D**

| | via B | via C | min dist |
|---|---|---|---|
| to A | 5 | 8 | 5 |
| to B | 3 | 2 | 2 |
| to C | 4 | 1 | 1 |
| to D | - | - | 0 |




**from Node A**

| | via B | via C | min dist |
|---|---|---|---|
| to A | - | - | 0 |
| to B | 2 | 8 | 2 |
| to C | 3 | 7 | 3 |
| to D | 5 | 8 | 5 |

**from Node C**

| | via A | via B | via D | min dist |
|---|---|---|---|---|
| to A | 7 | 3 | ∞ | 3 |
| to B | 9 | 1 | 4 | 1 |
| to C | - | - | - | 0 |
| to D | ∞ | 4 | 1 | 1 |

# Example: Now

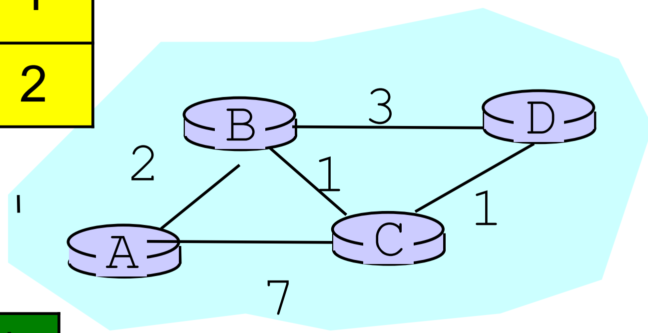
Updated

**from Node B**

| | via A | via C | via D | min dist |
|---|---|---|---|---|
| to A | 2 | 8 | ∞ | [illegible] |
| to B | - | - | [illegible] | 0 |
| to C | 5 | 1 | 4 | 1 |
| to D | 7 | 2 | 3 | 2 |

**from Node D**

| | via B | via C | min dist |
|---|---|---|---|
| to A | 5 | 8 | 5 |
| to B | 3 | 2 | 2 |
| to C | 4 | 1 | 1 |
| to D | - | - | 0 |




**from Node A**

| | via B | via C | min dist |
|---|---|---|---|
| to A | - | - | 0 |
| to B | 2 | 8 | 2 |
| to C | 3 | 7 | 3 |
| to D | 5 | 8 | 5 |

**from Node C**

| | via A | via B | via D | min dist |
|---|---|---|---|---|
| to A | 7 | 3 | ∞ | 3 |
| to B | 9 | 1 | 4 | 1 |
| to C | - | - | - | 0 |
| to D | ∞ | 4 | 1 | 1 |

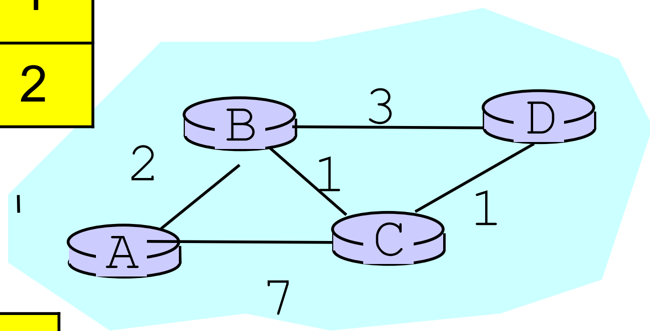
# Check: *All nodes know the best three-hop paths.*

**from Node B**

| | via A | via C | via D | min dist |
|---|---|---|---|---|
| to A | 2 | 4 | 8 | 2 |
| to B | - | - | - | 0 |
| to C | 5 | 1 | 4 | 1 |
| to D | 7 | 2 | 3 | 2 |

**from Node D**

| | via B | via C | min dist |
|---|---|---|---|
| to A | 5 | 4 | 4 |
| to B | 3 | 2 | 2 |
| to C | 4 | 1 | 1 |
| to D | - | - | 0 |




**from Node A**

| | via B | via C | min dist |
|---|---|---|---|
| to A | - | - | 0 |
| to B | 2 | 8 | 2 |
| to C | 3 | 7 | 3 |
| to D | 4 | 8 | 4 |

Check

**from Node C**

| | via A | via B | via D | min dist |
|---|---|---|---|---|
| to A | 7 | 3 | 6 | 3 |
| to B | 9 | 1 | 3 | 1 |
| to C | - | - | - | 0 |
| to D | 12 | 3 | 1 | 1 |

# Example: End of 3rd Full Exchange

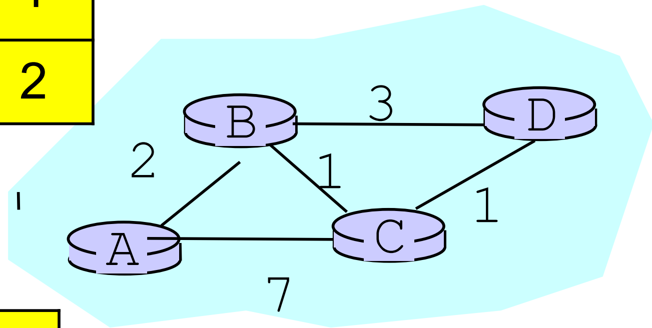
No further change in DVs → Convergence!

**from Node B**

| | via A | via C | via D | min dist |
|---|---|---|---|---|
| to A | 2 | 4 | 7 | 2 |
| to B | - | - | - | 0 |
| to C | 5 | 1 | 4 | 1 |
| to D | 6 | 2 | 3 | 2 |

**from Node D**

| | via B | via C | min dist |
|---|---|---|---|
| to A | 5 | 4 | 4 |
| to B | 3 | 2 | 2 |
| to C | 4 | 1 | 1 |
| to D | - | - | 0 |




**from Node A**

| | via B | via C | min dist |
|---|---|---|---|
| to A | - | - | 0 |
| to B | 2 | 8 | 2 |
| to C | 3 | 7 | 3 |
| to D | 4 | 8 | 4 |

**from Node C**

| | via A | via B | via D | min dist |
|---|---|---|---|---|
| to A | 7 | 3 | 5 | 3 |
| to B | 9 | 1 | 3 | 1 |
| to C | - | - | - | 0 |
| to D | 11 | 3 | 1 | 1 |

# Intuition

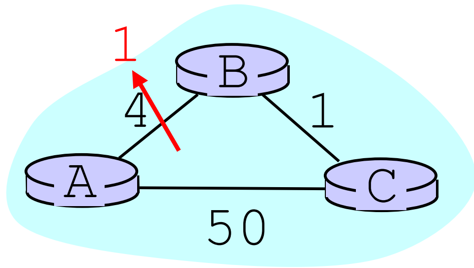
- Initial state: best one-hop paths
- One simultaneous round: best two-hop paths
- Two simultaneous rounds: best three-hop paths
- …
- Kth simultaneous round: best (k+1) hop paths

- Must eventually converge
  - as soon as it reaches longest best path
- …..but how does it respond to changes in cost?

# Problems with Distance Vector

- A number of problems can occur in a network using distance vector algorithm
- Most of these problems are caused by slow convergence or routers converging on incorrect information
- *Convergence* is the time during which all routers come to an agreement about the best paths through the internetwork
  - whenever topology changes there is a period of instability in the network as the routers converge
- Reacts rapidly to good news, but leisurely to bad news

# DV: Link Cost Changes




Columns: Stable state; A-B changed; A sends its DV to B, C; B sends its DV to A, C; C sends its DV to A, B

via

to

**Node A**

Stable state:

| | B | C |
|---|---|---|
| B | 4 | 51 |
| C | 5 | 50 |

A-B changed:

| | B | C |
|---|---|---|
| B | 1 | 51 |
| C | 2 | [illegible] |

A sends its DV to B, C:

| | B | C |
|---|---|---|
| B | 1 | 51 |
| C | [illegible] | [illegible] |

B sends its DV to A, C:

| | B | C |
|---|---|---|
| B | 1 | 51 |
| C | [illegible] | [illegible] |

C sends its DV to A, B:

| | B | C |
|---|---|---|
| B | 1 | 51 |
| C | [illegible] | 50 |

**Node B**

Stable state:

| | A | C |
|---|---|---|
| A | 4 | 6 |
| C | 6 | 1 |

A-B changed:

| | A | C |
|---|---|---|
| A | 1 | 6 |
| C | 6 | 1 |

A sends its DV to B, C:

| | [illegible] | [illegible] |
|---|---|---|
| [illegible] | [illegible] | [illegible] |
| C | 3 | 1 |

B sends its DV to A, C:

| | [illegible] | [illegible] |
|---|---|---|
| [illegible] | [illegible] | [illegible] |
| C | 3 | 1 |

C sends its DV to A, B:

| | [illegible] | C |
|---|---|---|
| [illegible] | [illegible] | 3 |
| C | 3 | 1 |

**Node C**

Stable state:

| | A | B |
|---|---|---|
| A | 50 | 5 |
| B | 54 | 1 |

A-B changed:

| | A | B |
|---|---|---|
| A | 50 | 5 |
| B | 54 | 1 |

A sends its DV to B, C:

| | A | B |
|---|---|---|
| A | 50 | 5 |
| B | 51 | 1 |

B sends its DV to A, C:

| | A | B |
|---|---|---|
| A | 50 | 2 |
| B | 51 | 1 |

C sends its DV to A, B:

| | A | B |
|---|---|---|
| A | 50 | 2 |
| B | 51 | 1 |

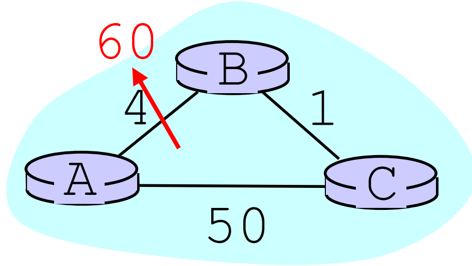
N
pa

deduct 3 from distances $dist_B(A,*)$ and $dist_A(B,*)$

Link cost changes here

**"good news travels fast"**

# DV: Link Cost Changes




Stable state (via / to)

A-B changed

**Node A**

Stable state:

| | B | C |
|---|---|---|
| B | 4 | 51 |
| C | 5 | 50 |

A-B changed:

| | B | C |
|---|---|---|
| B | 60 | 51 |
| C | 61 | 50 |

**Node B**

Stable state:

| | A | C |
|---|---|---|
| A | 4 | 6 |
| C | 6 | 1 |

A-B changed:

| | A | C |
|---|---|---|
| A | 60 | 6 |
| C | 65 | 1 |

**Node C**

Stable state:

| | A | B |
|---|---|---|
| A | 50 | 5 |
| B | 54 | 1 |

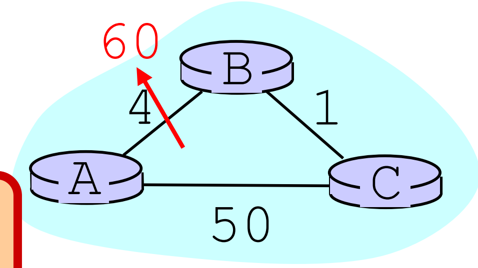
A-B changed:

| | A | B |
|---|---|---|
| A | 50 | 5 |
| B | 54 | 1 |

add 56 to distances $dist_B(A,*)$ and $dist_A(B,*)$

**Link cost changes here**

# DV: Link Cost Changes




**This is the "Counting to Infinity" Problem**

Stages: Stable state | A-B changed | A sends its DV to B, C | B sends its DV to A, C | C sends its DV to A, B

(rows: to; columns: via)

**Node A**

Stable state:

| | B | C |
|---|---|---|
| B | 4 | 51 |
| C | 5 | 50 |

A-B changed:

| | B | C |
|---|---|---|
| B | 60 | 51 |
| C | 61 | 50 |

A sends its DV to B, C:

| | B | C |
|---|---|---|
| B | 60 | 51 |
| C | 61 | 50 |

B sends its DV to A, C:

| | B | C |
|---|---|---|
| B | 60 | 51 |
| C | 61 | 50 |

C sends its DV to A, B:

| | B | C |
|---|---|---|
| B | 60 | 51 |
| C | 61 | 50 |

**Node B**

Stable state:

| | A | C |
|---|---|---|
| A | 4 | 6 |
| C | 9 | 1 |

A-B changed:

| | A | C |
|---|---|---|
| A | 60 | 6 |
| C | 65 | 1 |

A sends its DV to B, C:

| | A | C |
|---|---|---|
| A | 60 | 6 |
| C | 110 | 1 |

B sends its DV to A, C:

| | A | C |
|---|---|---|
| A | 60 | 6 |
| C | 110 | 1 |

C sends its DV to A, B:

| | A | C |
|---|---|---|
| A | 60 | 8 |
| C | 110 | 1 |

**Node C**

Stable state:

| | A | B |
|---|---|---|
| A | 50 | 5 |
| B | 54 | 1 |

A-B changed:

| | A | B |
|---|---|---|
| A | 50 | 5 |
| B | 54 | 1 |

A sends its DV to B, C:

| | A | B |
|---|---|---|
| A | 50 | 5 |
| B | 101 | 1 |

B sends its DV to A, C:

| | A | B |
|---|---|---|
| A | 50 | 7 |
| B | 101 | 1 |

C sends its DV to A, B:

| | A | B |
|---|---|---|
| A | 50 | 7 |
| B | 101 | 1 |

**Link cost changes here**

**"bad news travels slowly"**
**(not yet converged)**

# The “Poisoned Reverse” Rule

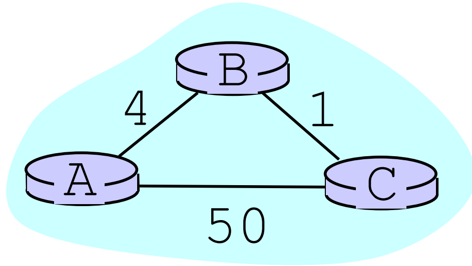
- Heuristic to avoid count-to-infinity

- If B routes via C to get to A:
  - B tells C its (B’s) distance to A is infinite
    (so C won’t route to A via B)

# DV: Poisoned Reverse

*If B routes through C to get to A:*

*B tells C its (B's) distance to A is infinite*




Stable state

**Node A** (via: B, C; to: B, C)

| | B | C |
|---|---|---|
| B | 4 | 51 |
| C | 5 | 50 |

**Node B**

| | A | C |
|---|---|---|
| A | 4 | ∞ |
| C | ∞ | 1 |

**Node C**

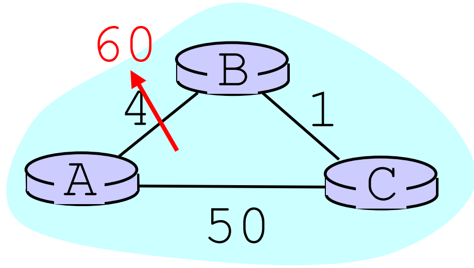
| | A | B |
|---|---|---|
| A | 50 | 5 |
| B | 54 | 1 |

| Mindist | Mindist |
|---|---|
| 4 | 4 |
| 5 | ∞ |

| Mindist | Mindist |
|---|---|
| 5 | ∞ |
| 1 | 1 |

# DV: Poisoned Reverse

*If B routes through C to get to A:*
*B tells C its (B's) distance to A is infinite*




Stable state (via / to) | A-B changed

**Node A**

| | B | C |
|---|---|---|
| B | 4 | 51 |
| C | 5 | 50 |

| | B | C |
|---|---|---|
| B | 60 | 51 |
| C | 61 | 50 |

**Node B**

| | A | C |
|---|---|---|
| A | 4 | ∞ |
| C | ∞ | 1 |

| | A | C |
|---|---|---|
| A | 60 | 6 |
| C | 65 | 1 |

**Node C**

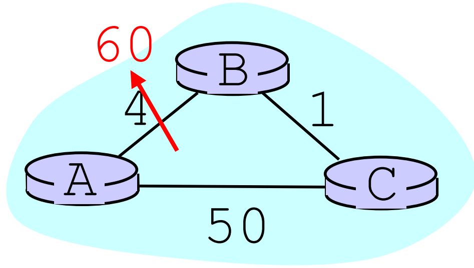
| | A | B |
|---|---|---|
| A | 50 | 5 |
| B | 54 | 1 |

| | A | B |
|---|---|---|
| A | 50 | 5 |
| B | 54 | 1 |

**Link cost changes here**

# DV: Poisoned Reverse

*If B routes through C to get to A:*
*B tells C its (B's) distance to A is infinite*




(columns = via, rows = to)

**Node A**

Stable state

| | B | C |
|---|---|---|
| B | 4 | 51 |
| C | 5 | 50 |

A-B changed

| | B | C |
|---|---|---|
| B | 60 | 51 |
| C | 61 | 50 |

A sends its DV to B, C

| | B | C |
|---|---|---|
| B | 60 | 51 |
| C | 61 | 50 |

B sends its DV to A, C

| | B | C |
|---|---|---|
| B | 60 | 51 |
| C | 61 | 50 |

**Node B**

Stable state

| | A | C |
|---|---|---|
| A | 4 | ∞ |
| C | ∞ | 1 |

A-B changed

| | A | C |
|---|---|---|
| A | 60 | ∞ |
| C | ∞ | 1 |

A sends its DV to B, C

| | A | C |
|---|---|---|
| A | 60 | ∞ |
| C | 110 | 1 |

B sends its DV to A, C

| | A | C |
|---|---|---|
| A | 60 | ∞ |
| C | 110 | 1 |

**Node C**

Stable state

| | A | B |
|---|---|---|
| A | 50 | 5 |
| B | 54 | 1 |

A-B changed

| | A | B |
|---|---|---|
| A | 50 | 5 |
| B | 54 | 1 |

A sends its DV to B, C

| | A | B |
|---|---|---|
| A | 50 | 5 |
| B | ∞ | 1 |

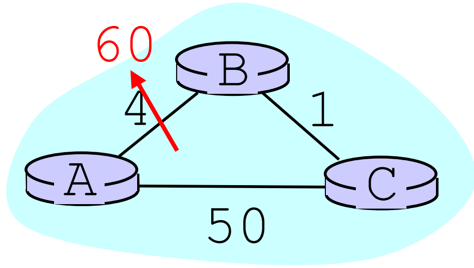
B sends its DV to A, C

| | A | B |
|---|---|---|
| A | 50 | 7 |
| B | ∞ | 1 |

**Link cost changes here**

# DV: Poisoned Reverse

*If B routes through C to get to A:*
*B tells C its (B's) distance to A is infinite*




### Stable state

via

Node A (to)

| | B | C |
|---|---|---|
| B | 4 | 51 |
| C | 5 | 50 |

Node B

| | A | C |
|---|---|---|
| A | 4 | ∞ |
| C | ∞ | 1 |

Node C

| | A | B |
|---|---|---|
| A | 50 | 5 |
| B | 54 | 1 |

### A-B changed

Node A

| | B | C |
|---|---|---|
| B | 60 | 51 |
| C | 61 | 50 |

Node B

| | A | C |
|---|---|---|
| A | 60 | ∞ |
| C | ∞ | 1 |

Node C

| | A | B |
|---|---|---|
| A | 50 | 5 |
| B | 54 | 1 |

### A sends its DV to B, C

Node A

| | B | C |
|---|---|---|
| B | 60 | 51 |
| C | 61 | 50 |

Node B

| | A | C |
|---|---|---|
| A | 60 | ∞ |
| C | 110 | 1 |

Node C

| | A | B |
|---|---|---|
| A | 50 | 5 |
| B | ∞ | 1 |

### B sends its DV to A, C

Node A

| | B | C |
|---|---|---|
| B | 60 | 51 |
| C | 61 | 50 |

Node B

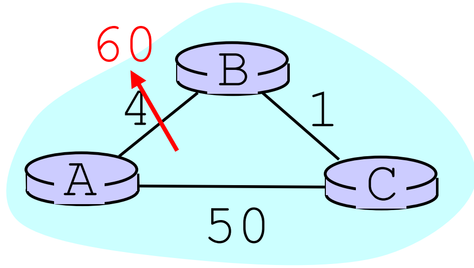
| | A | C |
|---|---|---|
| A | 60 | ∞ |
| C | 110 | 1 |

Node C

| | A | B |
|---|---|---|
| A | 50 | 61 |
| B | ∞ | 1 |

**Link cost changes here**

# DV: Poisoned Reverse




*If B routes through C to get to A:*
*B tells C its (B's) distance to A is infinite*

### Stable state

via

**Node A** (to)

| | B | C |
|---|---|---|
| B | 4 | 51 |
| C | 5 | 50 |

**Node B**

| | A | C |
|---|---|---|
| A | 4 | ∞ |
| C | ∞ | 1 |

**Node C**

| | A | B |
|---|---|---|
| A | 50 | 5 |
| B | 54 | 1 |

### A-B changed

**Node A**

| | B | C |
|---|---|---|
| B | 60 | 51 |
| C | 61 | 50 |

**Node B**

| | A | C |
|---|---|---|
| A | 60 | ∞ |
| C | ∞ | 1 |

**Node C**

| | A | B |
|---|---|---|
| A | 50 | 5 |
| B | 54 | 1 |

### A sends its DV to B, C

**Node A**

| | B | C |
|---|---|---|
| B | 60 | 51 |
| C | 61 | 50 |

**Node B**

| | A | C |
|---|---|---|
| A | 60 | ∞ |
| C | 110 | 1 |

**Node C**

| | A | B |
|---|---|---|
| A | 50 | 5 |
| B | ∞ | 1 |

### B sends its DV to A, C

**Node A**

| | B | C |
|---|---|---|
| B | 60 | 51 |
| C | 61 | 50 |

**Node B**

| | A | C |
|---|---|---|
| A | 60 | ∞ |
| C | 110 | 1 |

**Node C**

| | A | B |
|---|---|---|
| A | 50 | 61 |
| B | ∞ | 1 |

### C sends its DV to A, B

**Node A**

| | B | C |
|---|---|---|
| B | 60 | 51 |
| C | 61 | 50 |

**Node B**

| | A | C |
|---|---|---|
| A | 60 | 51 |
| C | 110 | 1 |

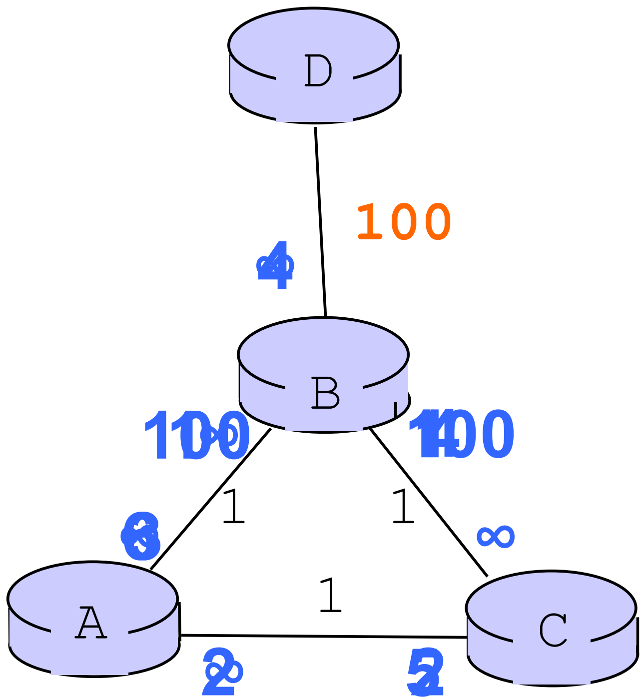
**Node C**

| | A | B |
|---|---|---|
| A | 50 | ∞ |
| B | ∞ | 1 |

**Link cost changes here**

Converges after C receives another update from B

# Will Poison-Reverse Completely Solve the Count-to-Infinity Problem?




Numbers in blue denote the best cost
to destination D advertised along the link

# Quiz: Link-state routing

- In link state routing, each node sends information of its direct links (i.e., link state) to __________?

A. Immediate neighbours
B. All nodes in the network
C. Any one neighbor
D. No one

**www.zeetings.com/salil**

# Quiz: Distance-vector routing

- In distance vector routing, each node shares its distance table with __________?

A. Immediate neighbours
B. All nodes in the network
C. Any one neighbor
D. No one

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# Quiz: Distance-vector routing

- Which of the following is true of distance vector routing?

A. Convergence delay depends on the topology (nodes and links) and link weights
B. Convergence delay depends on the number of nodes and links
C. Each node knows the entire topology
D. A and C
E. B and C

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# Comparison of LS and DV algorithms

*message complexity*

- ***LS:*** with n nodes, E links, O(nE) msgs sent
- ***DV:*** exchange between neighbors only
  - convergence time varies

*speed of convergence*

- ***LS:*** $O(n^2)$ algorithm requires O(nE) msgs
  - may have oscillations
- ***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 propagate thru network

# Real Protocols

*Link State*

Open Shortest Path First (OSPF)

Intermediate system to intermediate system (IS-IS)

*Distance Vector*

Routing Information Protocol (RIP)

Interior Gateway Routing Protocol (IGRP-Cisco)

Border Gateway Protocol (BGP)

# Network layer, control plane: outline

5.1 introduction

5.2 routing protocols

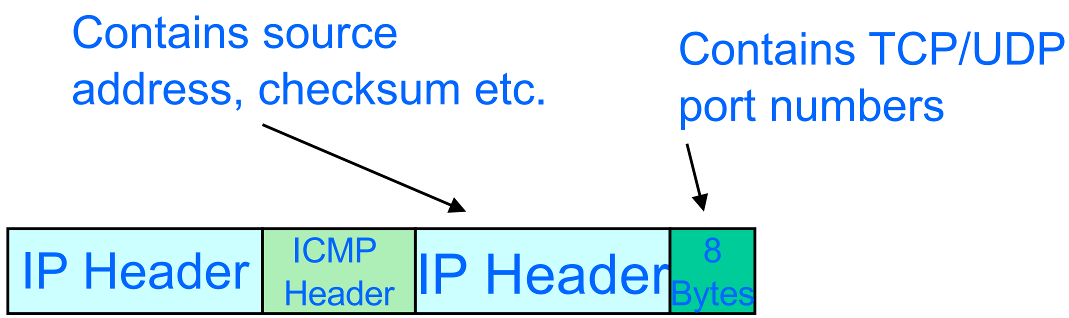
- link state
- distance vector
- hierarchical routing

5.6 ICMP: The Internet Control Message Protocol

Self study (not on exam)

# ICMP: Internet Control Message Protocol

- Used by hosts & routers to communicate network level infromation
  - Error reporting: unreachable host, network, port
  - Echo request/reply (used by ping)
- Works above IP layer
  - ICMP messages carried in IP datagrams
- ICMP message: type, code plus IP header and first 8 bytes of IP datagram payload causing error



# ICMP: Internet Control Message Protocol

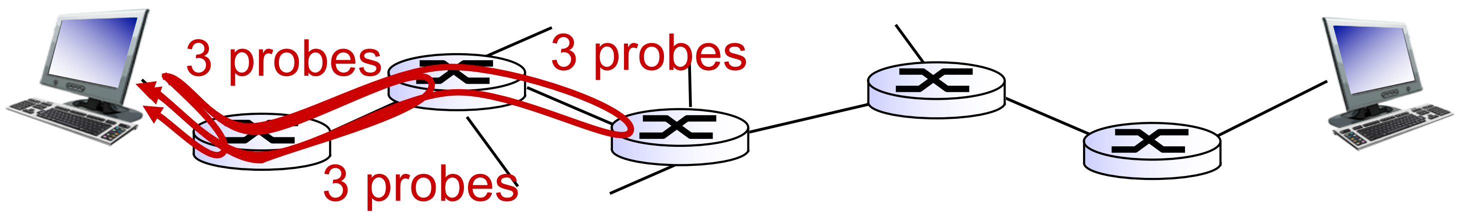
| Type | Code | Description |
|---|---|---|
| 0 | 0 | echo reply(ping) |
| 3 | 0 | dest. network unreachable |
| 3 | 1 | dest host unreachable |
| 3 | 3 | dest port unreachable |
| 3 | 4 | frag needed; DF set |
| 8 | 0 | echo request(ping) |
| 11 | 0 | TTL expired |
| 11 | 1 | frag reassembly time exceeded |
| 12 | 0 | bad IP header |

# Traceroute and ICMP

- Source sends series of UDP segments to dest
  - first set has TTL =1
  - second set has TTL=2, etc.
  - unlikely port number
- When *n*th set of datagrams arrives to nth router:
  - router discards datagrams
  - and sends source ICMP messages (type 11, code 0)
  - ICMP messages includes IP address of router
- when ICMP messages arrives, source records RTTs

*stopping criteria:*

- UDP segment eventually arrives at destination host
- destination returns ICMP "port unreachable" message (type 3, code 3)
- source stops



# Summary

- Network Layer: Data Plane
  - Overview
  - IP
- Network Layer: Control Plane
  - Routing Protocols
    - Link–state
    - Distance Vector
  - ICMP