COMP 3331/9331: Computer Networks and Applications

Week 8

Network Layer: Control Plane (Routing)

Chapter 5: Section 5.1 – 5.2, 5.6

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

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

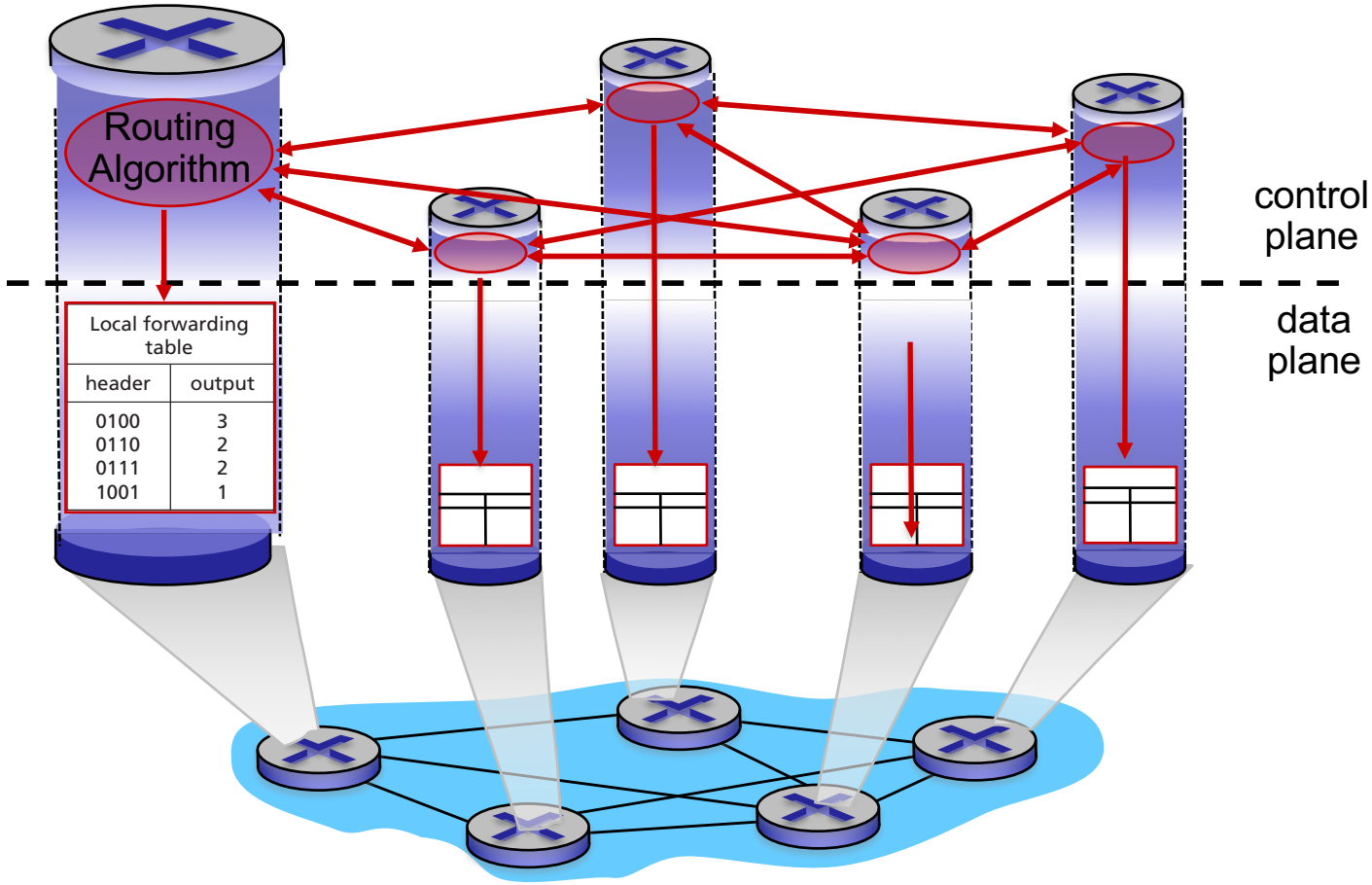
control plane

Two approaches to structuring network control plane:

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

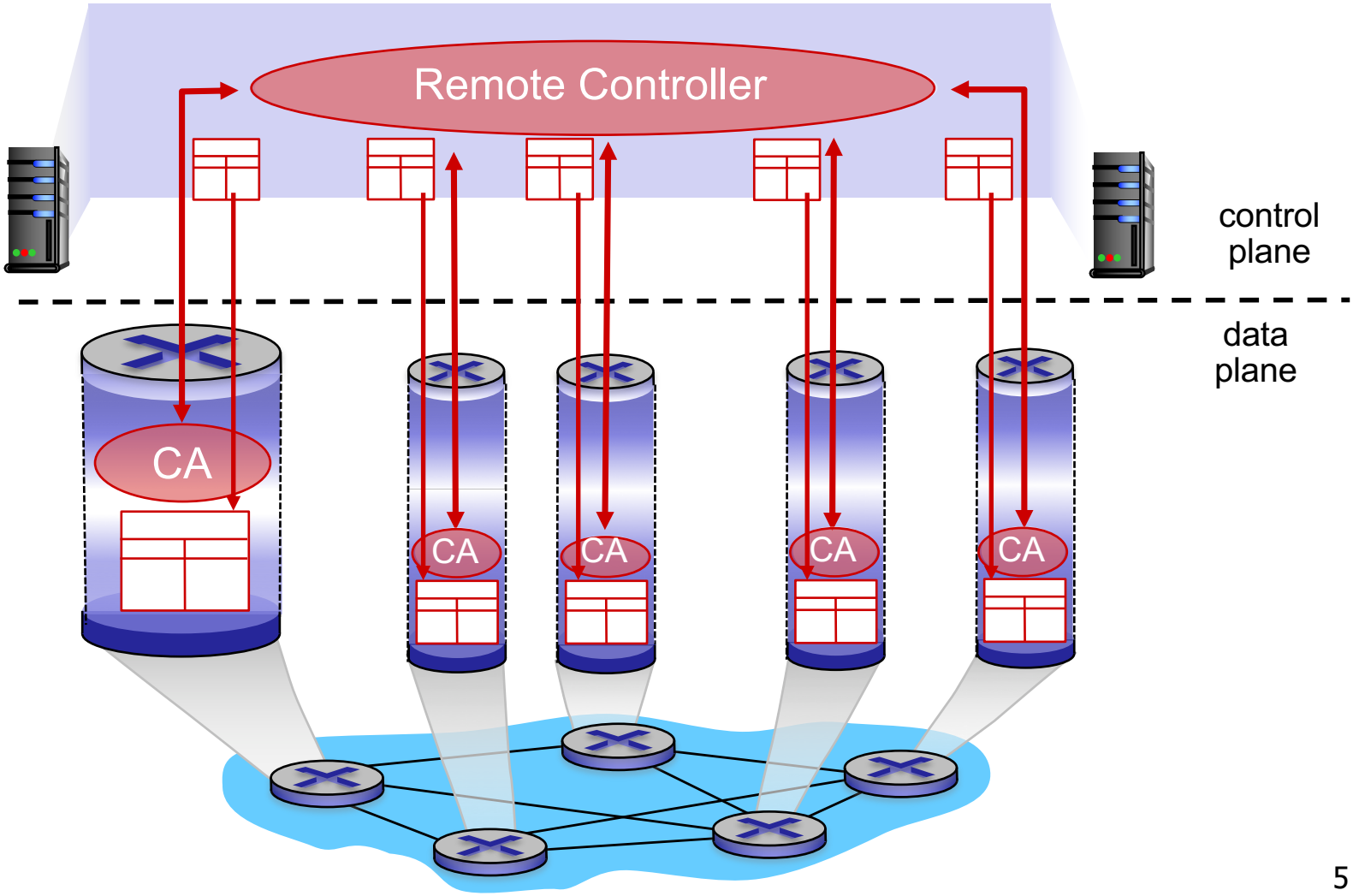
Per-router control plane

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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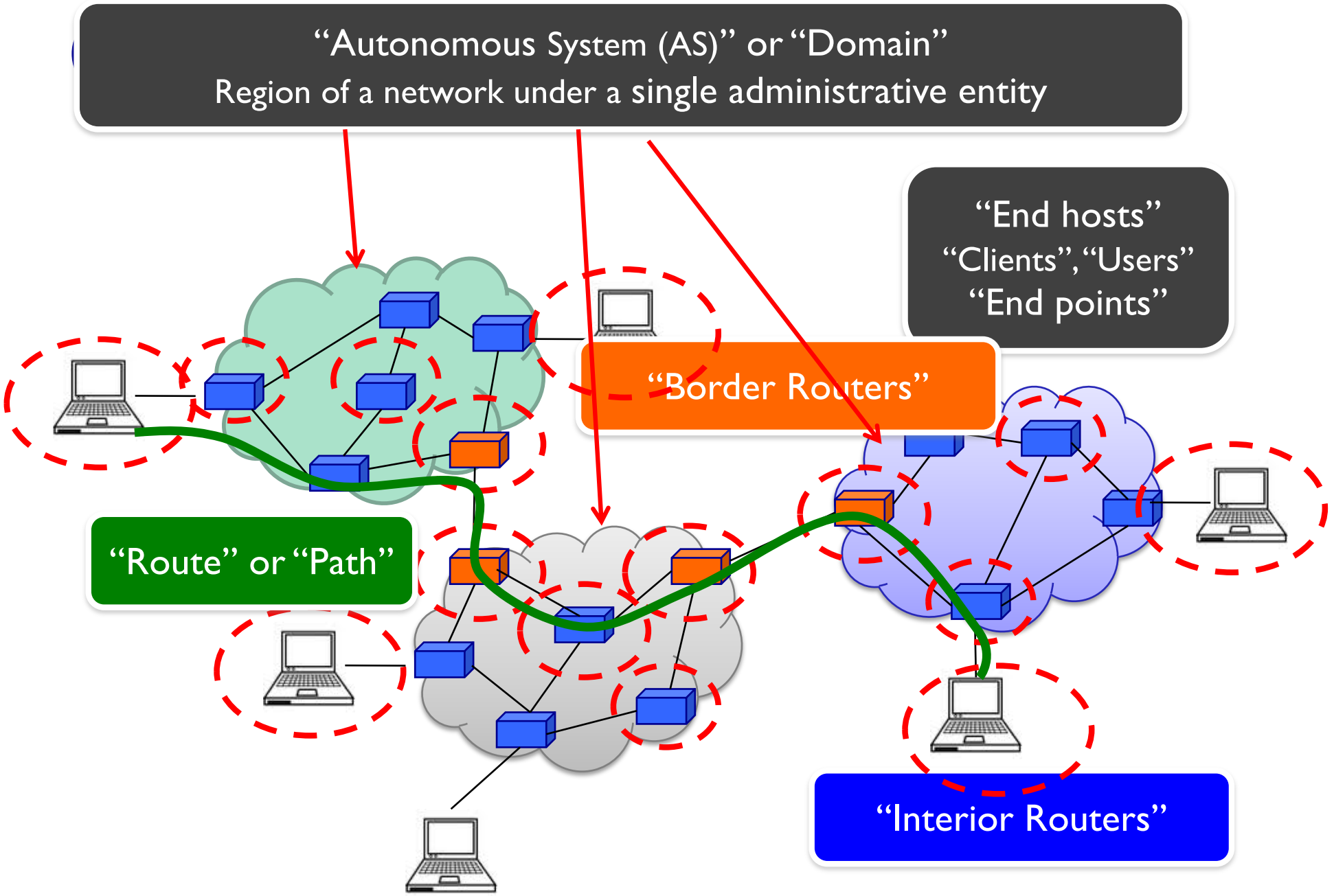
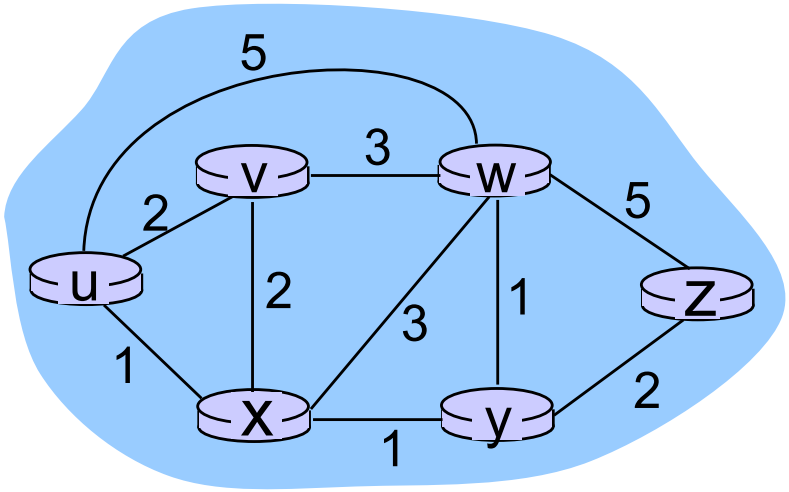

"Autonomous System (AS)" or "Domain"
Region of a network under a single administrative entity
"End hosts"
"Clients", "Users"
"End points"
"Border Routers"
"Route" or "Path"
"Interior Routers"

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

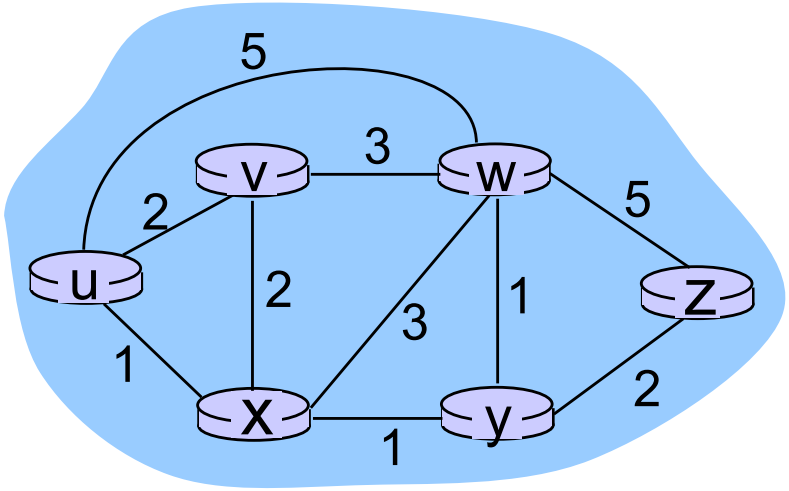


graph: G = (N,E)

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)

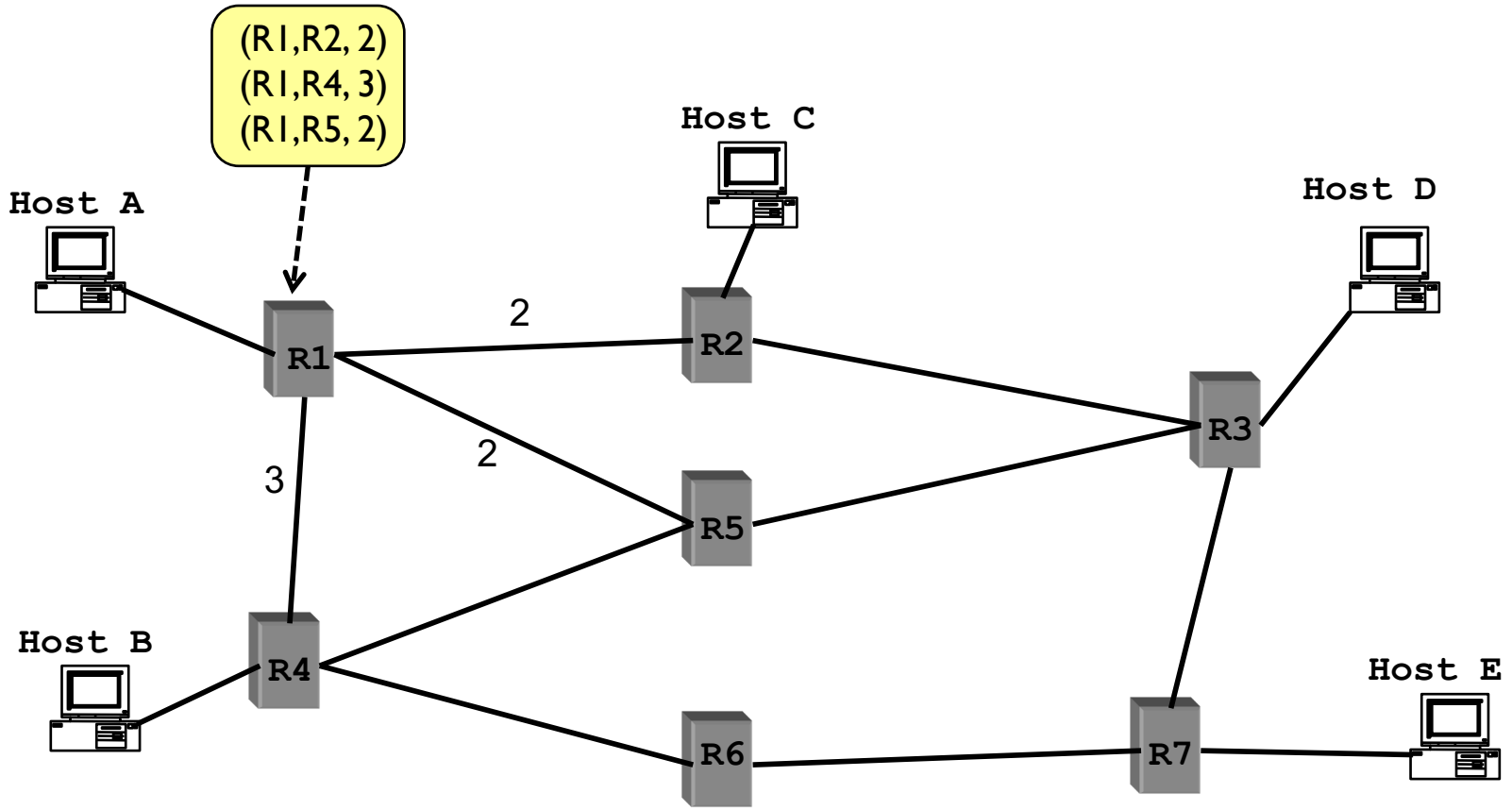
- Routers maintain cost of each link in the network
- Connectivity/cost changes flooded to all routers
- Converges quickly (less inconsistency, looping, etc.)
- Limited network sizes

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

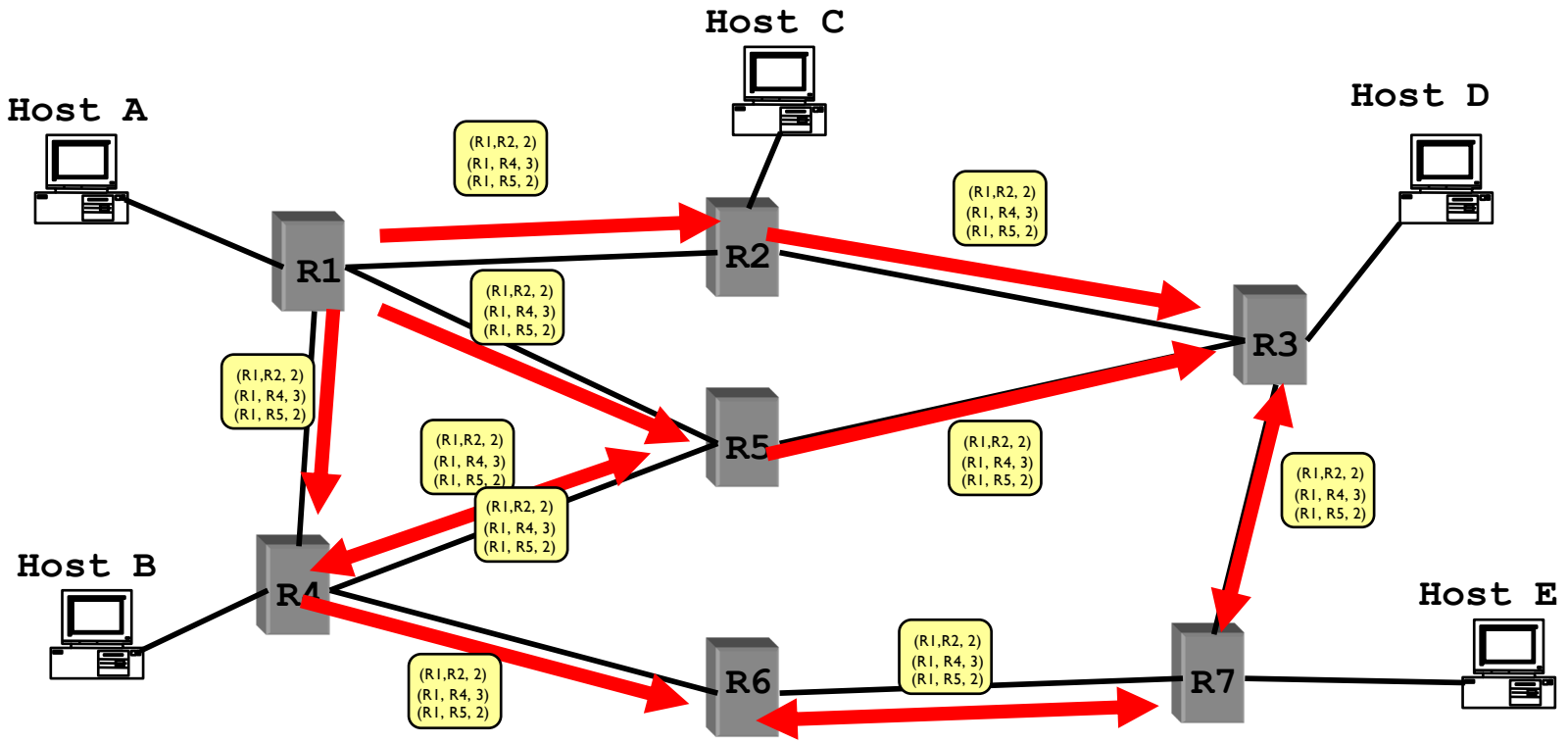
Link State Routing

- 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

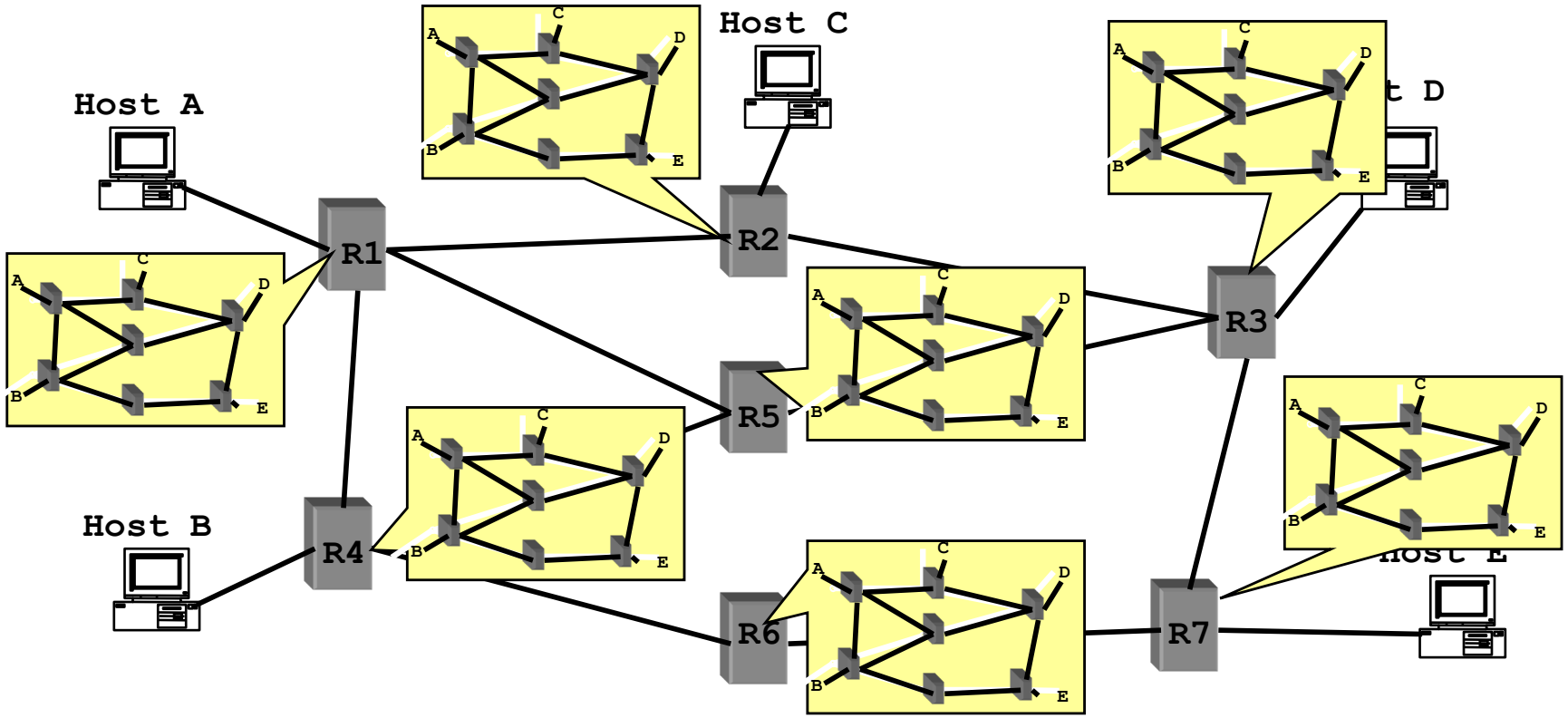


Flooding LSAs

- 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:

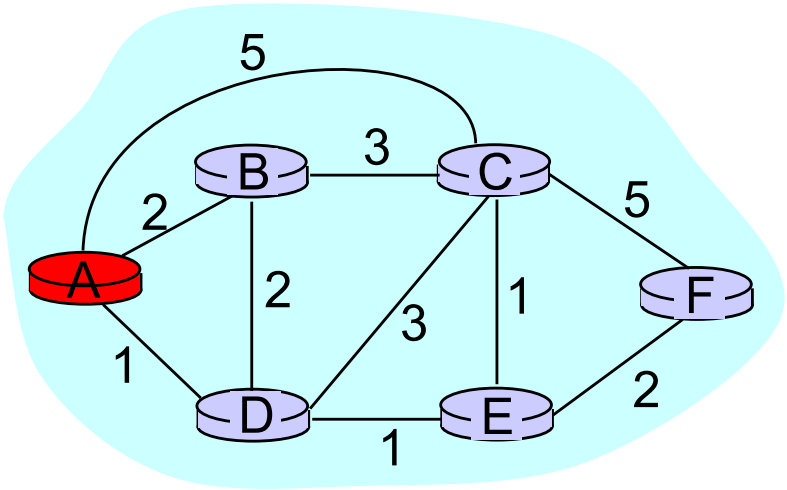
- c(x,y): link cost from node x to y; = ∞ if not direct neighbors
- D(v): current value of cost of path from source to dest. v
- p(v): predecessor node along path from source to v
- N': set of nodes whose least cost path definitively known

Dijsktra's Algorithm

```
1  Initialization:
2    N' = {u}
3    for all nodes v
4      if v adjacent to u
5          then D(v) = c(u,v)
6      else D(v) = ∞
7
8   Loop
9     find w not in N' such that D(w) is a minimum
10    add w to N'
11    update D(v) for all v adjacent to w and not in N' :
12       D(v) = min( D(v), D(w) + c(w,v) )
13    /* new cost to v is either old cost to v or known
14     shortest path cost to w plus cost from w to v */
15  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

Step	Set N'	D(B),p(B)	D(C),p(C)	D(D),p(D)	D(E),p(E)	D(F),p(F)
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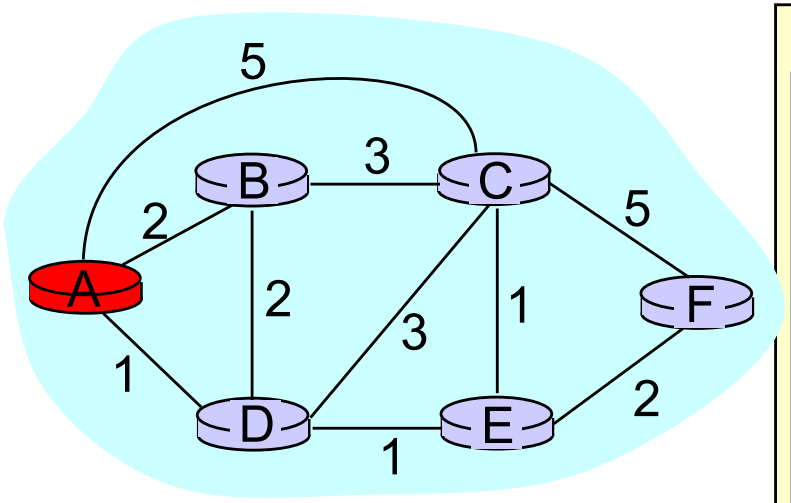


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14    until all nodes in N';
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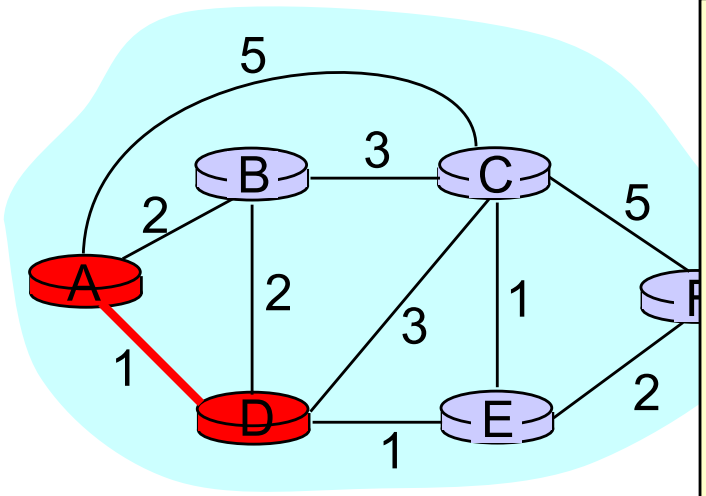
1	AD					
2						
3						
4						
5						

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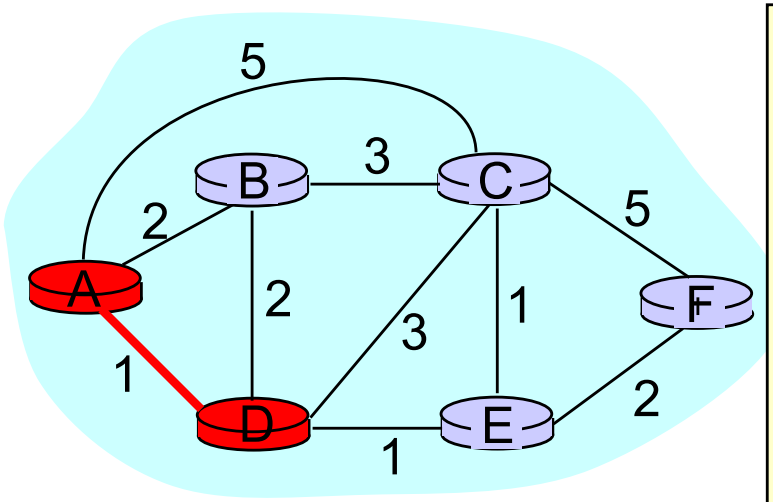
1	AD	2, A	4,D		2,D	
2						
3						
4						
5						

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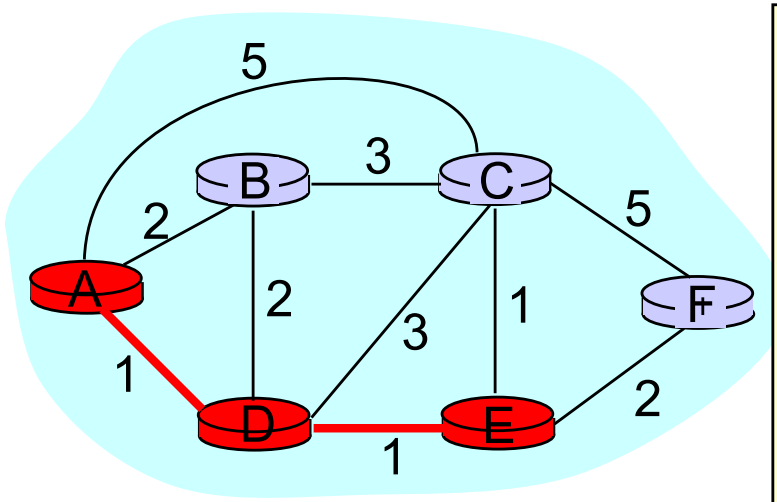


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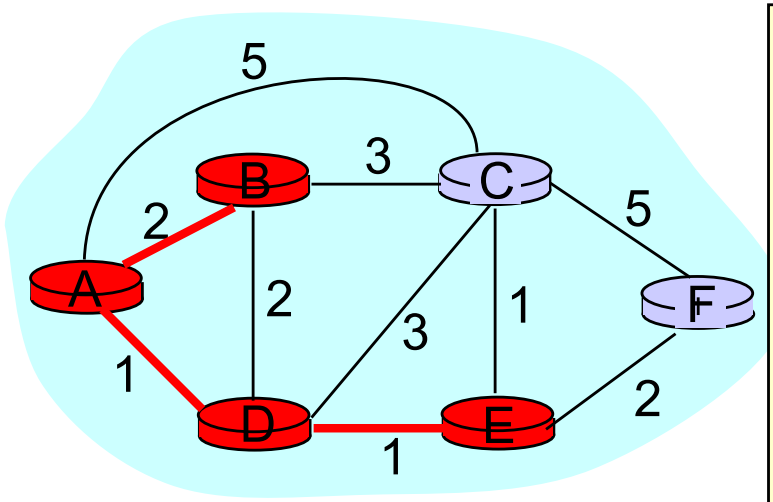
3	ADEB		3,E			4,E
4						
5						

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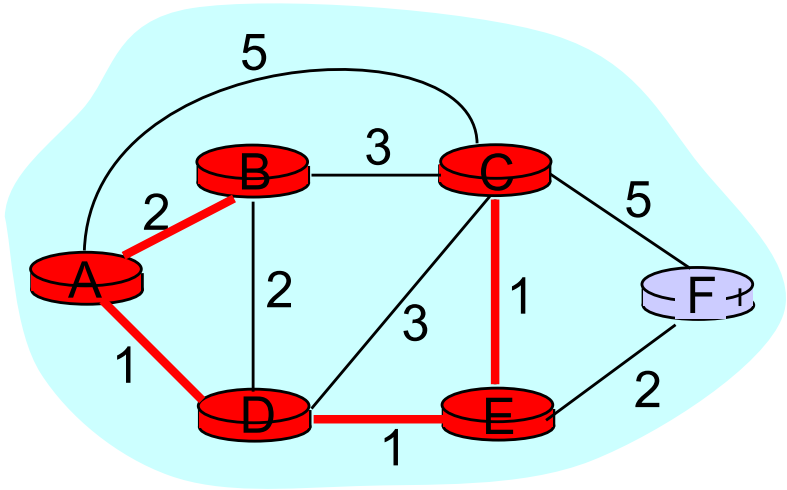
1	AD	2,A	4,D		2,D	
2	ADE	2,A	3,E			4,E
3	ADEB		3,E			4,E
4	ADEBC					4,E
5						

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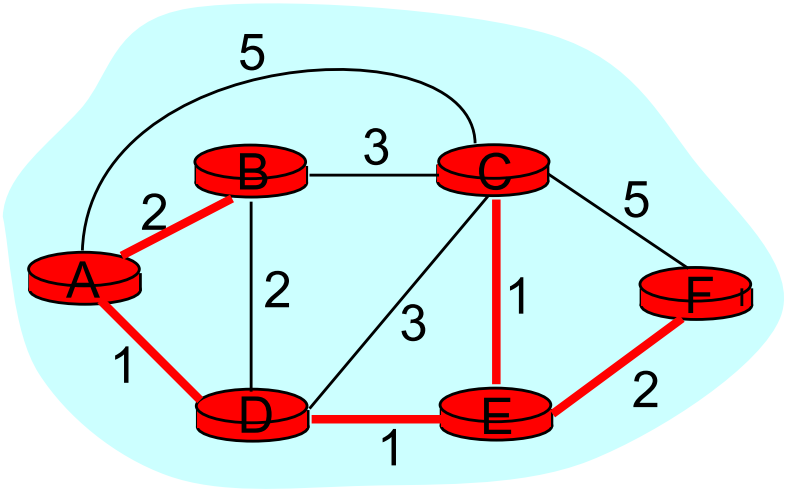
2	ADE	2,A	3,E			4,E
3	ADEB		3,E			4,E
4	ADEBC					4,E
→ 5	ADEBCF					

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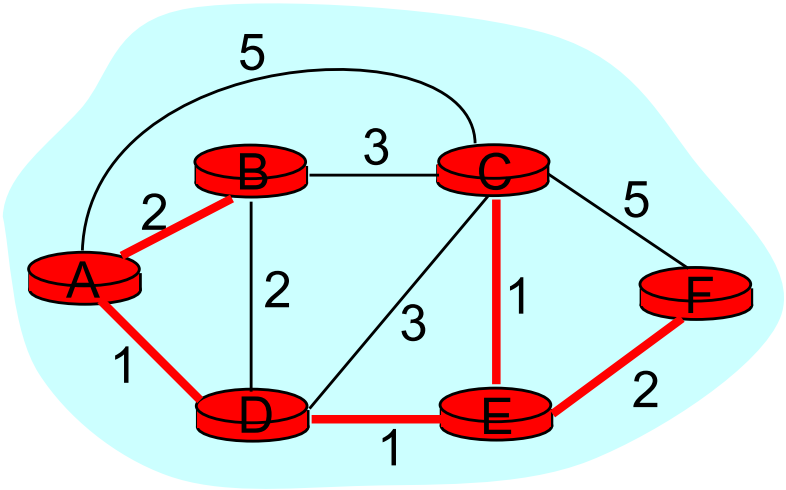
3	ADEB					
4	ADEBC					
5	ADEBCF					

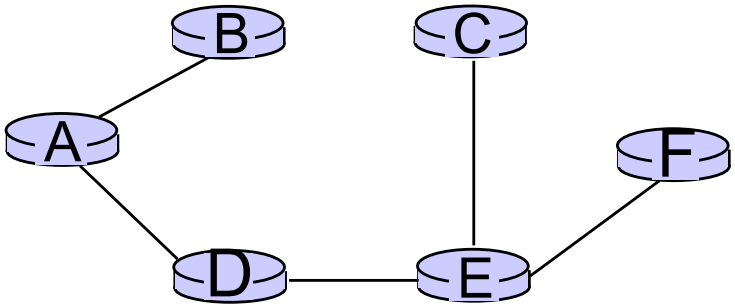


To determine path A → C (say), work backward from C via p(v)

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:



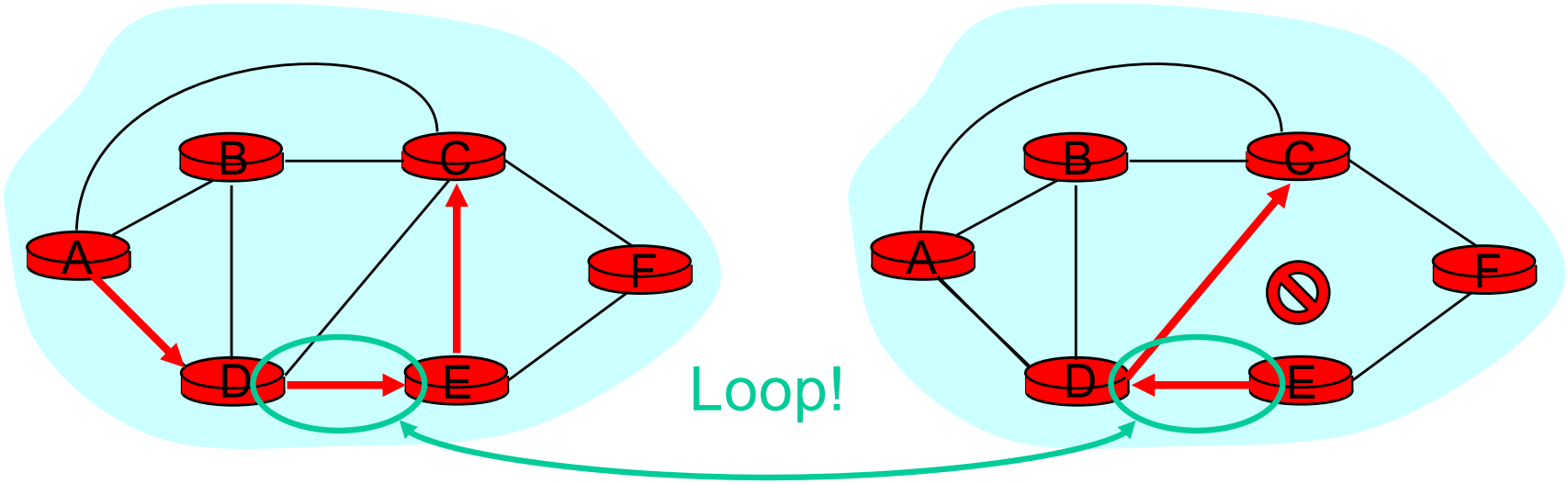
Destination	Link
B	(A,B)
C	(A,D)
D	(A,D)
E	(A,D)
F	(A,D)

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



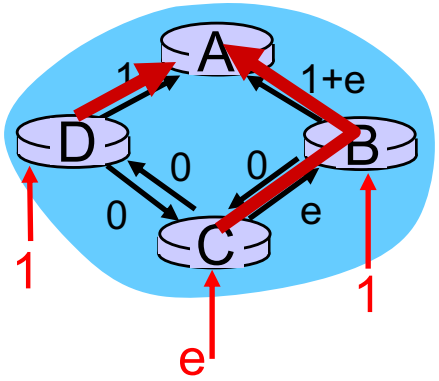
A and D think that this is the path to C

E thinks that this is the path to C

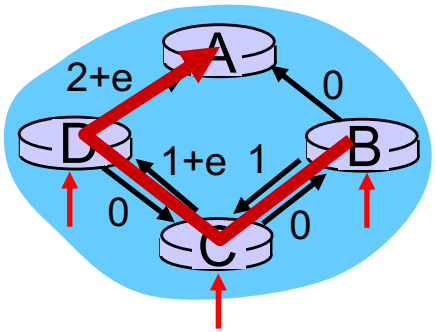
Oscillations

oscillations possible:

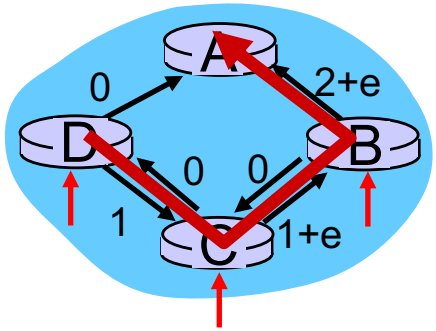
- e.g., suppose link cost equals amount of carried traffic:



initially



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



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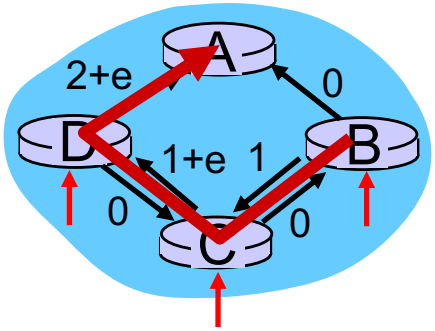

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Network layer, control plane: outline

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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

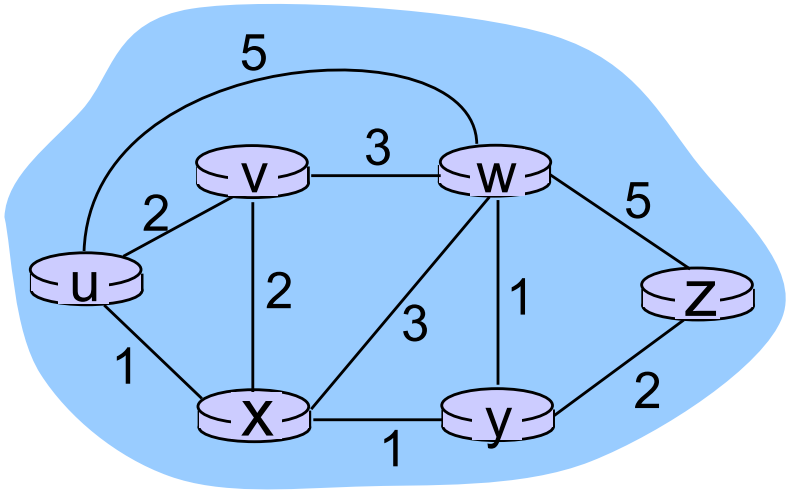
$$d_x(y) = \min_v \{c(x,v) + d_v(y)\}$$

$d_v(y)$: cost from neighbor v to destination y

$c(x,v)$: cost to neighbor v

$\min_v$: *min* taken over all neighbors v of x

Bellman-Ford example



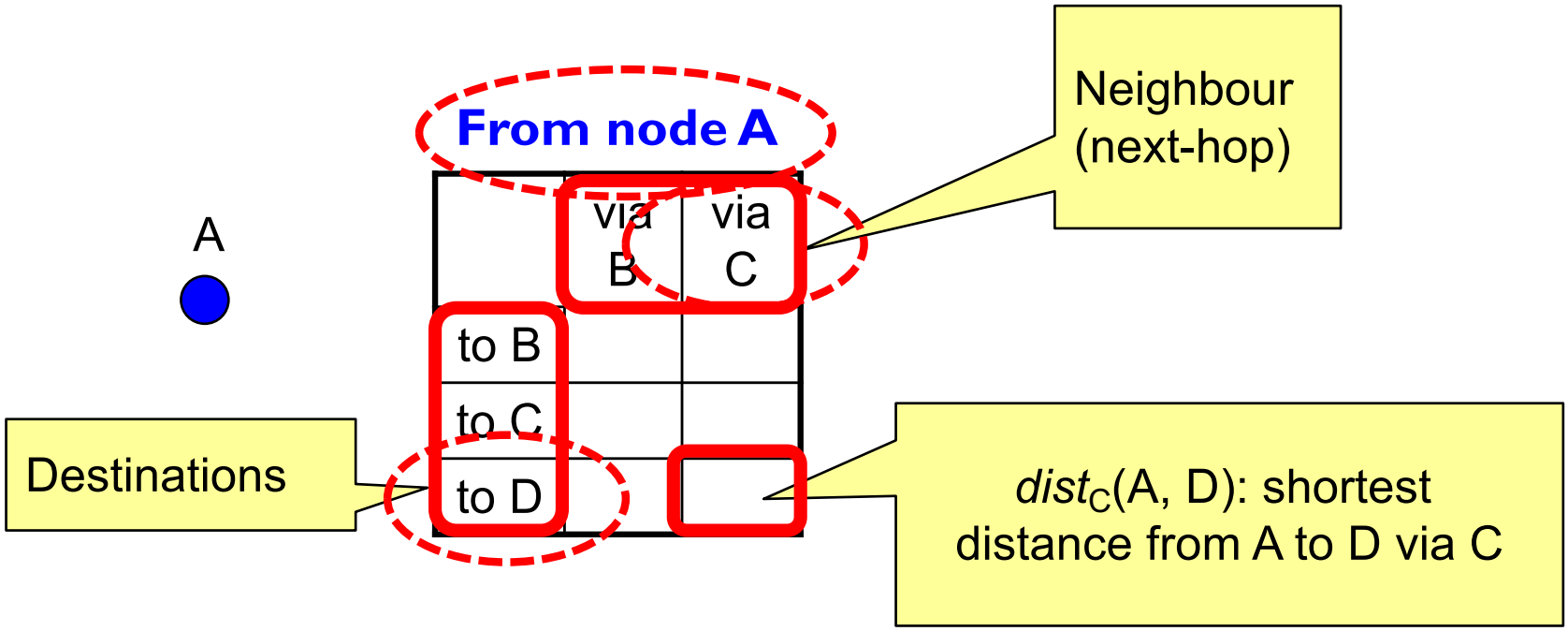
clearly, $d_v(z) = 5$, $d_x(z) = 3$, $d_w(z) = 3$

B-F equation says:

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

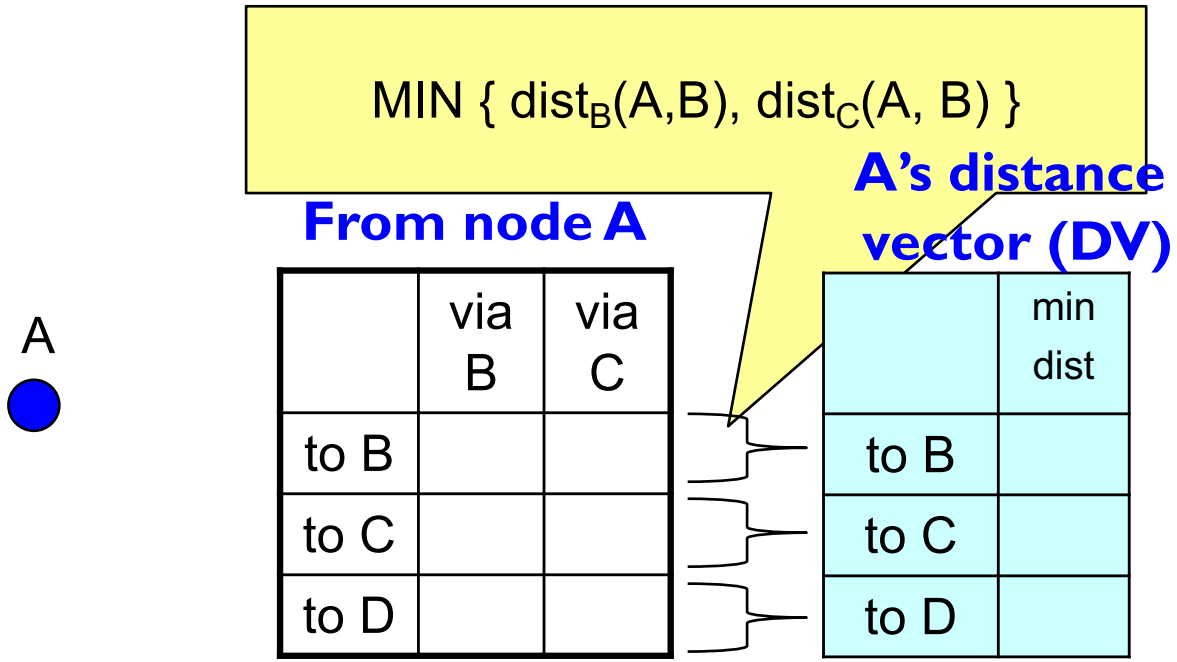
node achieving minimum is next
hop in shortest path, used in forwarding table

How Distance-Vector (DV) works



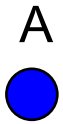
Each router maintains its shortest distance to every destination via each of its neighbours

How Distance-Vector (DV) works



Each router computes its shortest distance to every destination via any of its neighbors

How Distance-Vector (DV) works



From node A

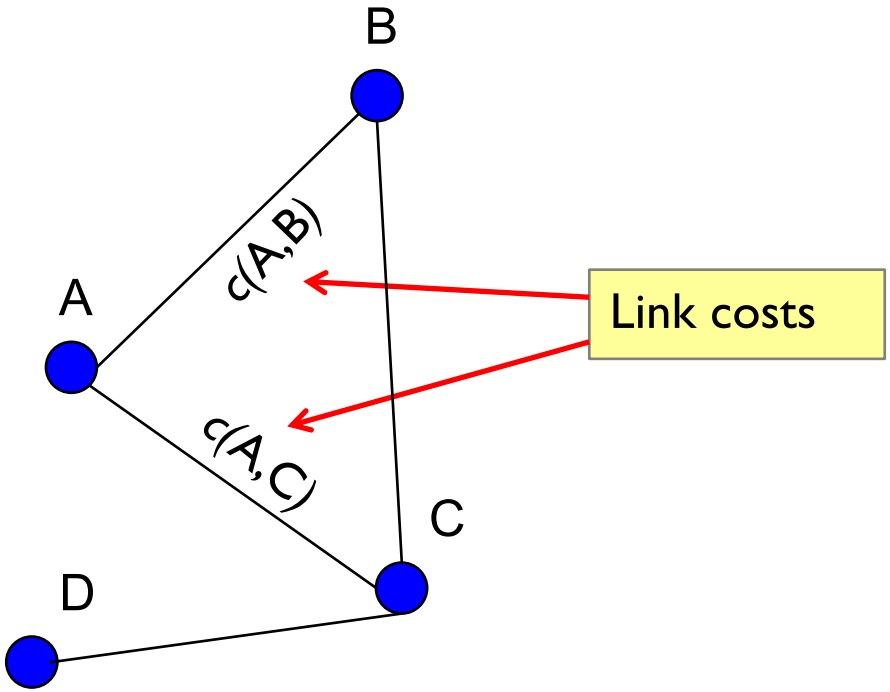
	via B	via C
to B	?	?
to C	?	?
to D	?	?

A's DV

	min dist
to B	?
to C	?
to D	?

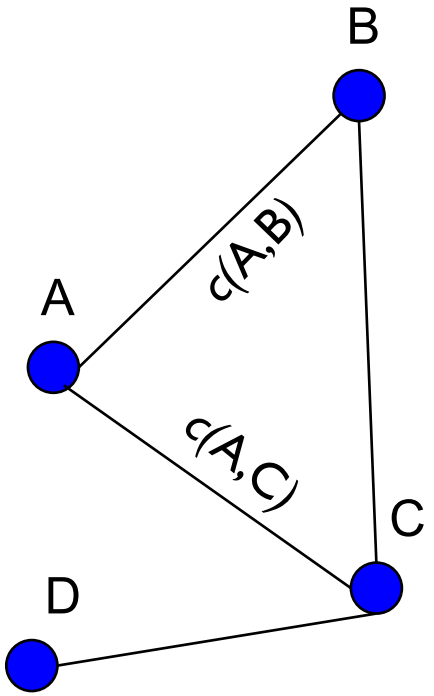
How does A initialize its dist() table and DV?

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)

A's DV

	mindist
to B	c(A,B)
to C	c(A,C)

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

$D_x(y) = \min\{c(x,y) + D_y(y), c(x,z) + D_z(y)\}$
$= \min\{2+0 , 7+1\} = 2$

$D_x(z) = \min\{c(x,y) + D_y(z), c(x,z) + D_z(z)\}$
$= \min\{2+1 , 7+0\} = 3$

node x table

to	via y	via z	
y	2	∞	2
z	∞	7	7

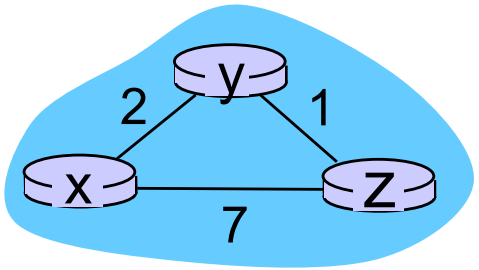
to	via y	via z	
y	2	8	2
z	3	7	3

node y table

to	via x	via z	
x	2	∞	2
z	∞	1	1

node z table

to	via x	via y	
x	7	∞	7
y	∞	1	1



time

$D_x(y) = \min\{c(x,y) + D_y(y), c(x,z) + D_z(y)\}$
$= \min\{2+0 , 7+1\} = 2$

$D_x(z) = \min\{c(x,y) + D_y(z), c(x,z) + D_z(z)\}$
$= \min\{2+1 , 7+0\} = 3$

node x table

to \ via	y	z
y	2	∞
z	∞	7

to \ via	y	z
y	2	8
z	3	7

to \ via	y	z
y	2	8
z	3	7

node y table

to \ via	x	z
x	2	∞
z	∞	1

to \ via	x	z
x	2	8
z	9	1

to \ via	x	z
x	2	4
z	5	1

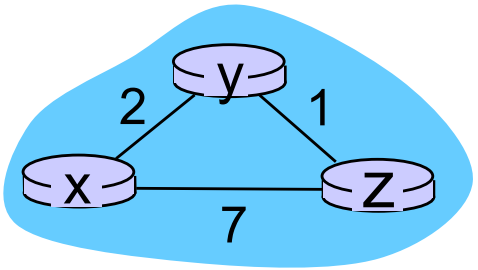
node z table

to \ via	x	y
x	7	∞
y	∞	1

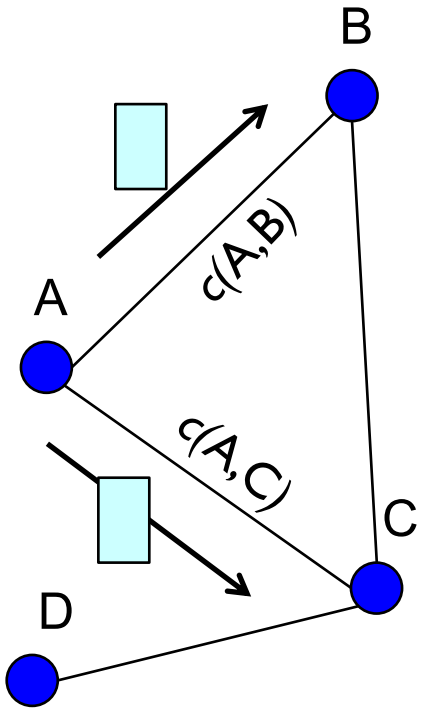
to \ via	x	y
x	7	3
y	9	1

to \ via	x	y
x	7	3
y	9	1

time



How Distance-Vector (DV) works



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

From node A

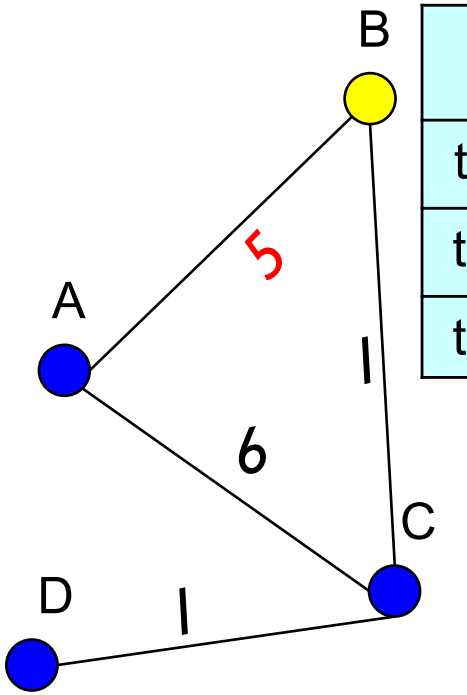
	via B	via C
to B	*c*(A,B)	∞
to C	∞	*c*(A,C)

A's DV

	mindist
to B	5
to C	6
to D	7

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	7

From node B

	via A	via C
to A	5	7
to C	11	1
to D	12	2

B's DV

	mindist
to A	5
to C	1
to D	2

Routers process received DVs

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:

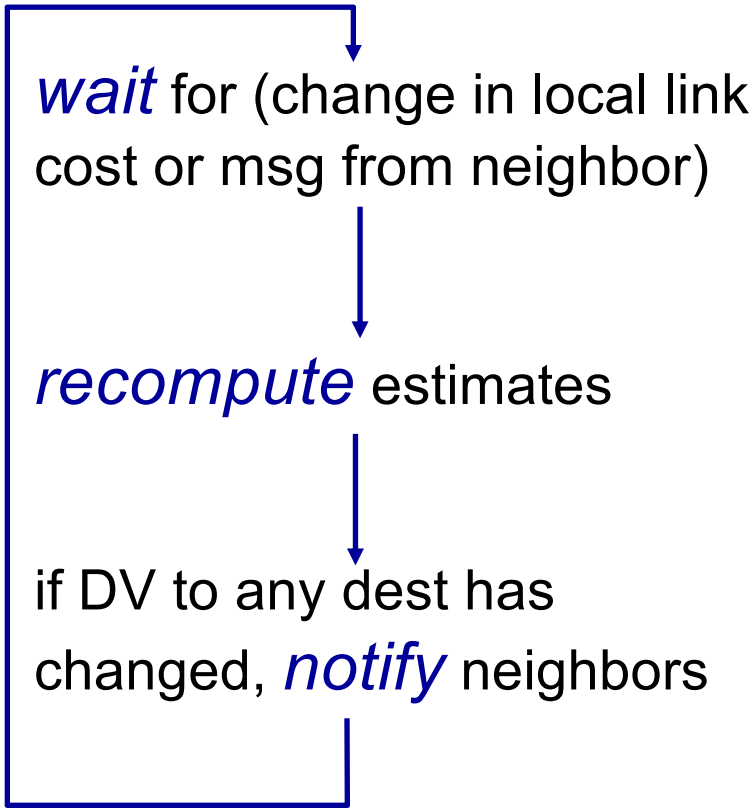
each local iteration caused by:

- 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:



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

```
0 At node A
1 Initialization:
2    for all destinations V  do
3         if V is neighbor of A
4              dist_V(A, V) = mindist(A,V) = c(A,V);
5         else
6              dist_V(A, V) = mindist(A,V) = ∞;
7      send mindist(A, *) to all neighbors
 loop:
8    wait (until A sees a link cost change to neighbor V  /* case 1 */
9           or until A receives mindist(V,*) from neighbor V)    /* case 2 */
10    if (c(A,V) changes by ±d)  /* ⇐ case 1 */
11       for all destinations Y do
12                dist_V(A,Y) =  dist_V(A,Y) ± d
13    else /* ⇐ case 2: */
14       for all destinations Y do
15                dist_V(A,Y) = c(A,V) + mindist(V, Y);
16    update mindist(A,*)
15   if (there is a change in mindist(A, *))
16         send mindist(A, *) to all neighbors
17  forever
```

Distance Vector: How Does it Work

- Periodically, each router sends its DV (destination, distance columns) to *directly connected* routers
- When router *K* receives DV from router *J*, *K* updates its table if:
  - J knows a shorter route for a given destination
  - J knows a destination K didn't know about
  - K currently routes to a destination through J and J's distance to that destination has changed

Router Message Exchange

Routing Table for Router K

To	Distance	Route
Net1	0	Direct
Net2	0	Direct
Net4	8	L
Net17	5	M
Net24	6	J
Net30	2	Q
Net42	2	J

Update from Router J

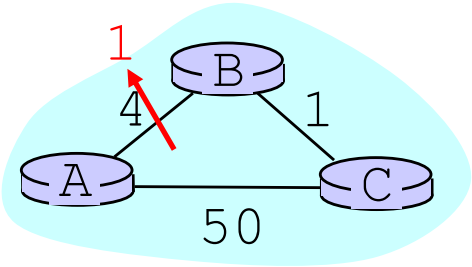
To	Distance
Net1	1
Net4	3
Net17	6
Net21	4
Net24	5
Net30	10
Net42	3

- If distance is *N* for *J*, it is *N+Cj* for *K*
  - packet has to go through router J
- If *K* updates or adds an entry in response to *J*'s message, it assigns Route=*J*

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



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

Node A

to	B	C
B	4	51
C	5	50

	B	C
B	1	51
C	2	50

	B	C
B	1	51
C	3	1

	B	C
B	1	51
C	3	1

	B	C
B	1	51
		50

Node B

	A	C
A	4	6
C	9	1

	A	C
A	1	6
C	6	1

	A	C
		3
C	3	1

Node C

	A	B
A	50	5
B	54	1

	A	B
A	50	5
B	54	1

	A	B
A	50	5
B	51	1

	A	B
A	50	2
B	51	1

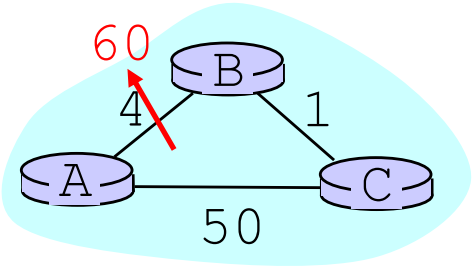
	A	B
A	50	2
B	51	1

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

A-B changed

Via

Node A

to	via B	via C
B	4	51
C	5	50

to	via B	via C
B	60	51
C	61	50

Node B

to	via A	via C
A	4	6
C	9	1

to	via A	via C
A	60	6
C	65	1

Node C

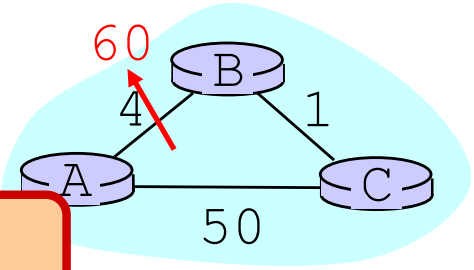
to	via A	via B
A	50	5
B	54	1

to	via A	via 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

	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
Node A (via / to)	B: 4, 51 C: 5, 50	B: 60, 51 C: 61, 50	B: 60, 51 C: 61, 50	B: 60, 51 C: 61, 50	B: 60, 51 C: 61, 50
Node B (via / to)	A: 4, 6 C: 9, 1	A: 60, 6 C: 65, 1	A: 60, 6 C: 110, 1	A: 60, 6 C: 110, 1	A: 60, 8 C: 110, 1
Node C (via / to)	A: 50, 5 B: 54, 1	A: 50, 5 B: 54, 1	A: 50, 5 B: 101, 1	A: 50, 7 B: 101, 1	A: 50, 7 B: 101, 1

Link cost changes here

"bad news travels slowly"
(not yet converged)

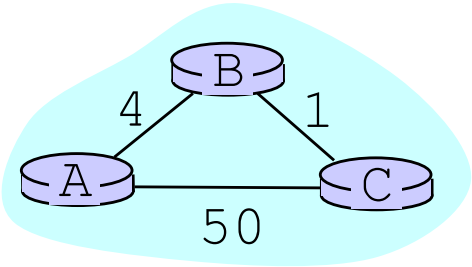
The "Poisoned Reverse" Rule

- 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

Via

Node A

to	B	C
B	4	51
C	5	50

Mindist: 4, 5

Mindist: 4, ∞

Node B

	A	C
A	4	∞
C	∞	1

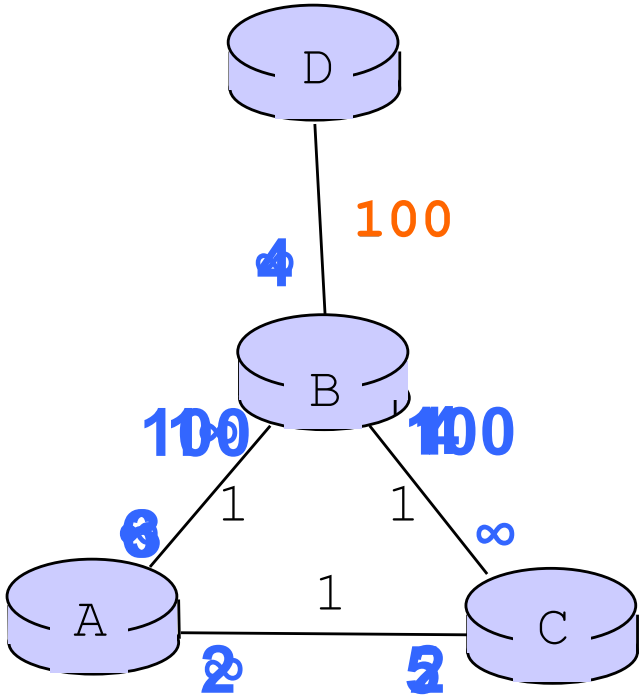
Node C

	A	B
A	50	5
B	54	1

Mindist: 5, 1

Mindist: ∞, 1

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



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

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

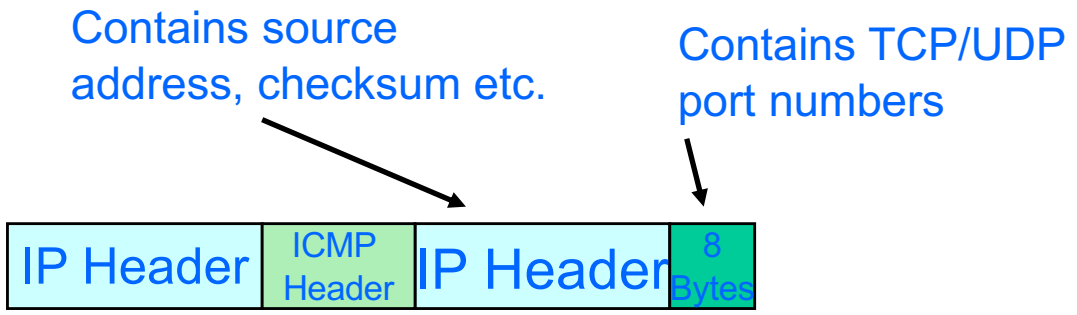
- link state
- distance vector
- hierarchical routing

5.6 ICMP: The Internet Control Message Protocol

Self study

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