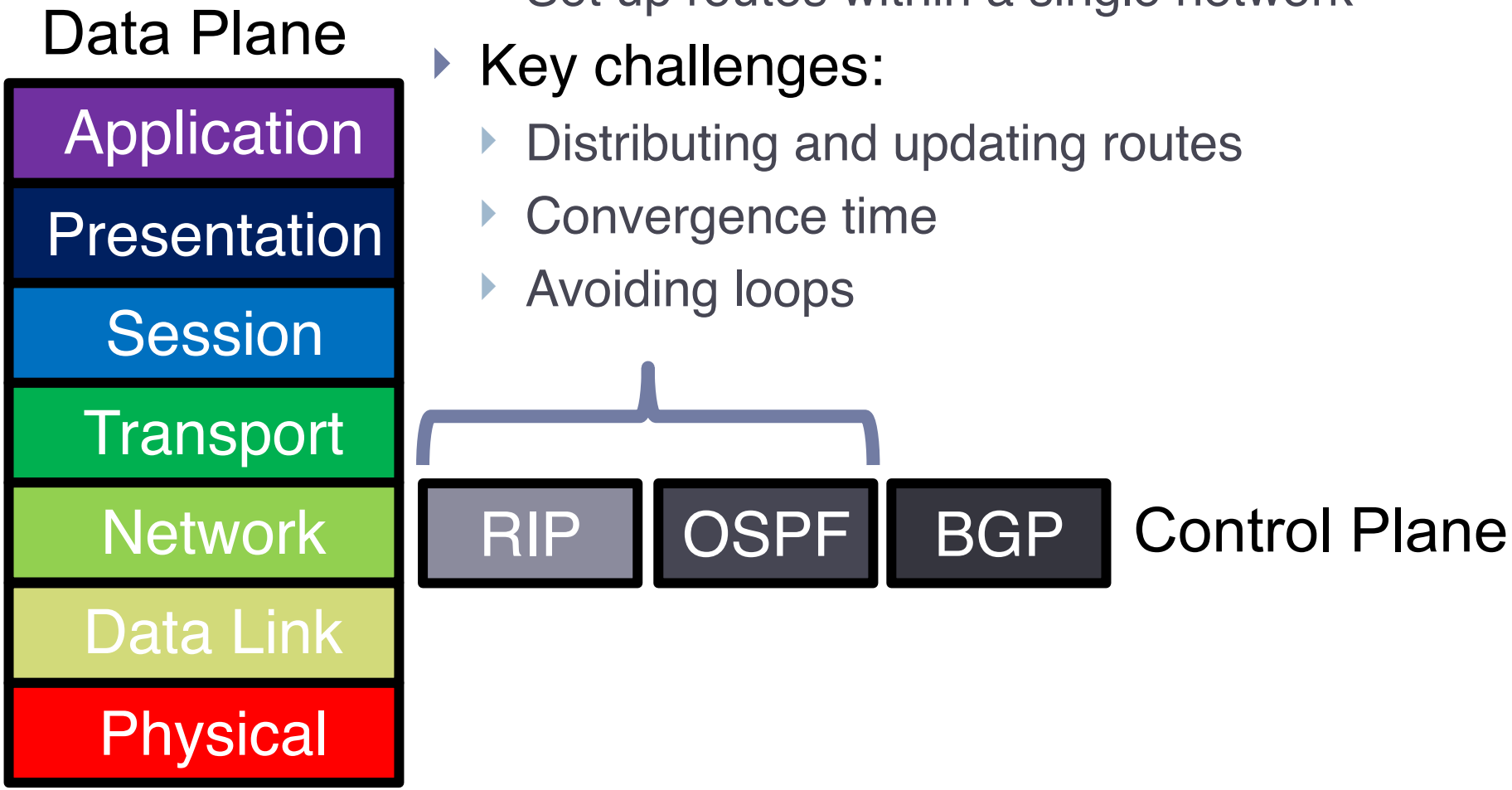
Cristina Nita-Rotaru

CS4700/5700: Network fundamentals

Intradomain routing.

Network Layer, Control Plane

- Function:
  - Set up routes within a single network
- Key challenges:
  - Distributing and updating routes
  - Convergence time
  - Avoiding loops



Internet Routing

- Internet organized as a two level hierarchy
- First level – autonomous systems (AS's)
  - AS – region of network under a single administrative domain
  - Examples: Comcast, AT&T, Verizon, Sprint, etc.

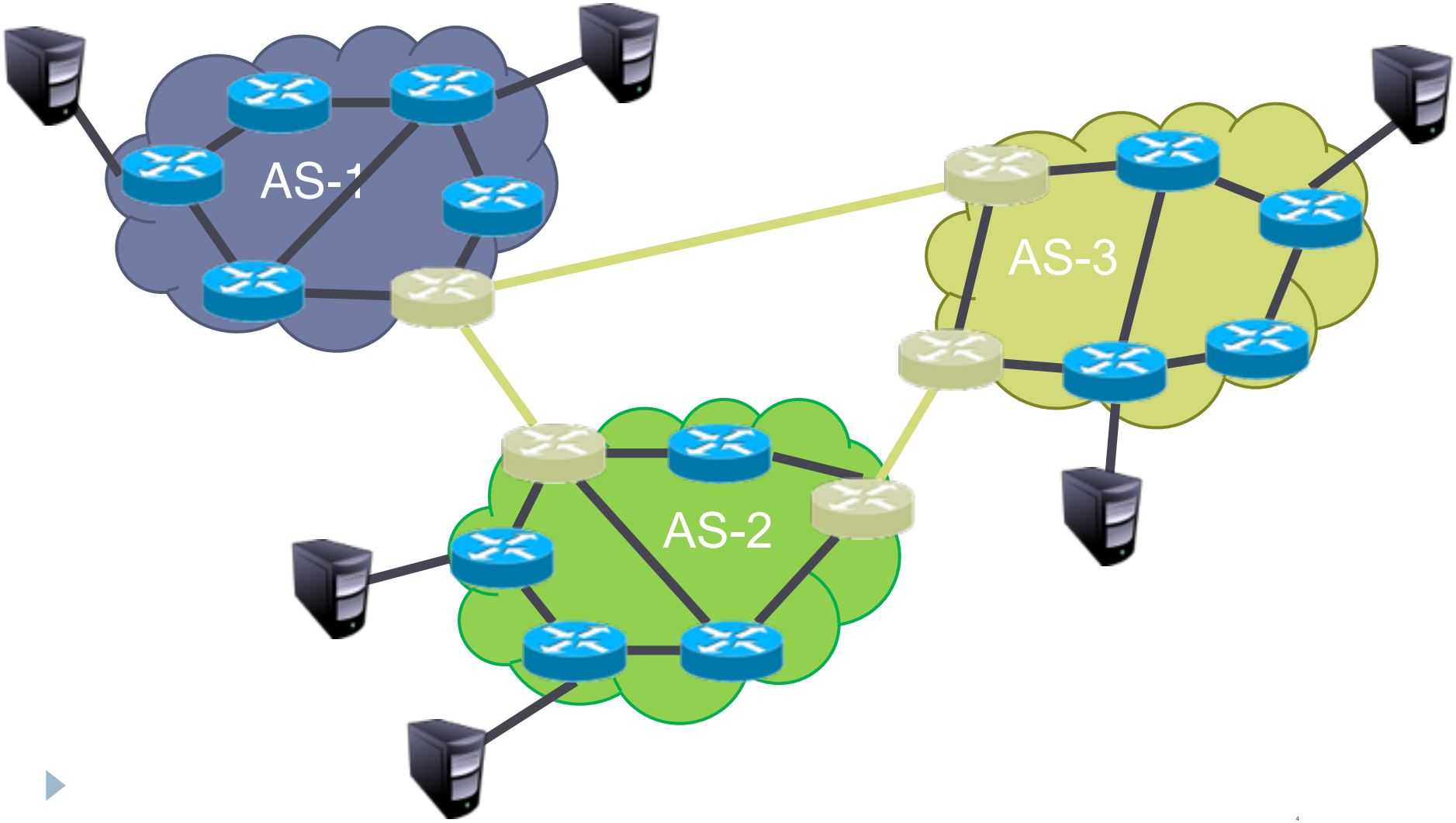
Internet Routing

- Internet organized as a two level hierarchy
- First level – autonomous systems (AS's)
  - AS – region of network under a single administrative domain
  - Examples: Comcast, AT&T, Verizon, Sprint, etc.
- AS's use intra-domain routing protocols internally
  - Distance Vector, e.g., Routing Information Protocol (RIP)
  - Link State, e.g., Open Shortest Path First (OSPF)

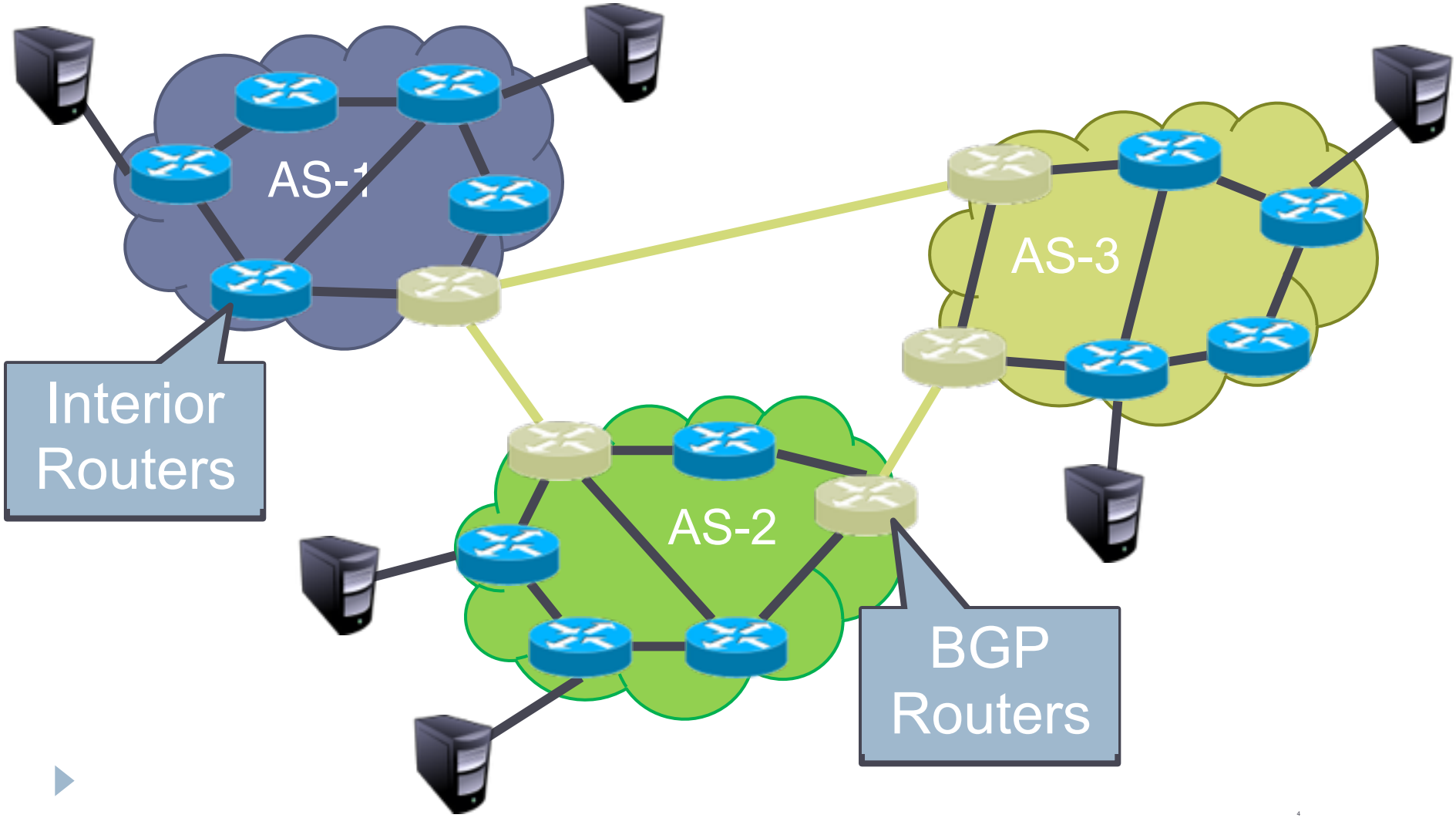
Internet Routing

- Internet organized as a two level hierarchy
- First level – autonomous systems (AS's)
  - AS – region of network under a single administrative domain
  - Examples: Comcast, AT&T, Verizon, Sprint, etc.
- AS's use intra-domain routing protocols internally
  - Distance Vector, e.g., Routing Information Protocol (RIP)
  - Link State, e.g., Open Shortest Path First (OSPF)
- Connections between AS's use inter-domain routing protocols
  - Border Gateway Routing (BGP)
  - De facto standard today, BGP-4

AS Example



AS Example



Why Do We Need ASes?

- Routing algorithms are not efficient enough to execute on the entire Internet topology

Why Do We Need ASes?

- Routing algorithms are not efficient enough to execute on the entire Internet topology
- Different organizations may use different routing policies

Why Do We Need ASes?

- Routing algorithms are not efficient enough to execute on the entire Internet topology
- Different organizations may use different routing policies
- Allows organizations to hide their internal network structure

Why Do We Need ASes?

- Routing algorithms are not efficient enough to execute on the entire Internet topology
- Different organizations may use different routing policies
- Allows organizations to hide their internal network structure
- Allows organizations to choose how to route across each other (BGP)

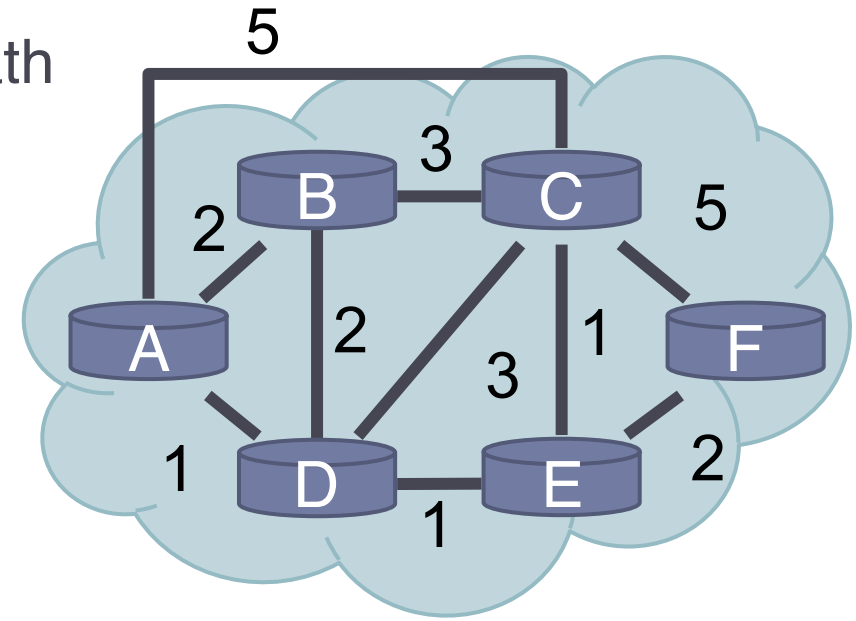
Why Do We Need ASes?

- Routing algorithms are not efficient enough to execute on the entire Internet topology
- Dif
  pol
- All
  str
- All
  ea

- Easier to compute routes
- Greater flexibility
- More autonomy/independence

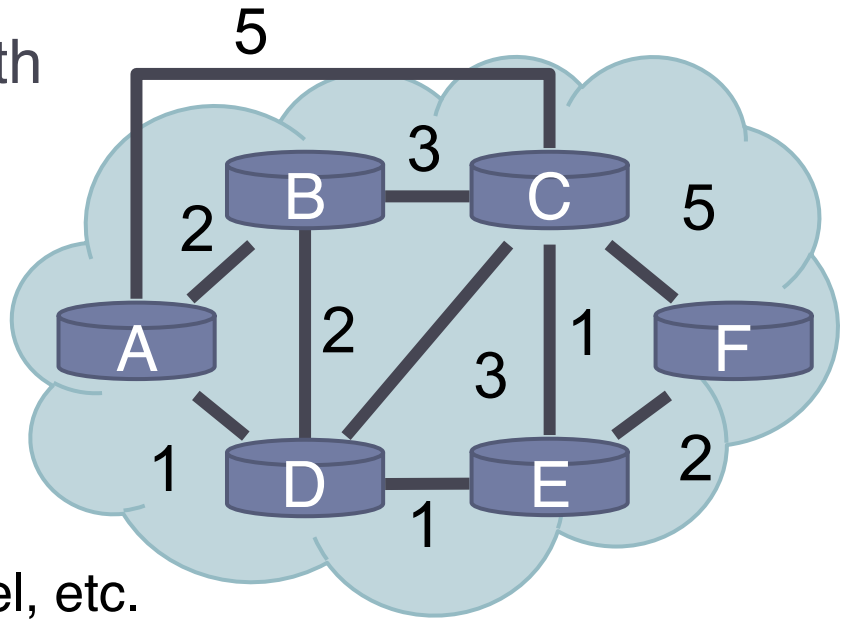
Routing on a Graph

- Goal: determine a “good” path through the network from source to destination
- What is a good path?
  - Usually means the shortest path
  - Load balanced
  - Lowest $$$ cost



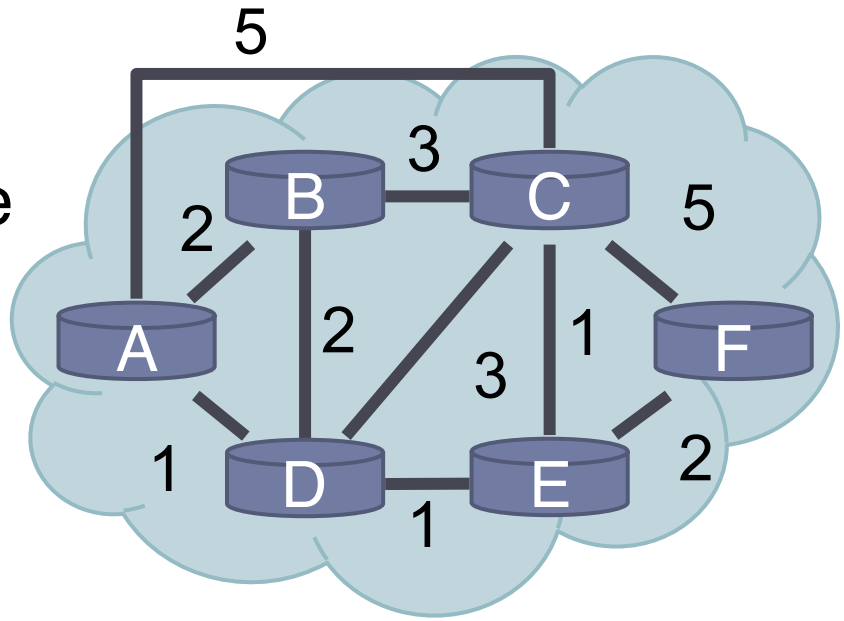
Routing on a Graph

- Goal: determine a “good” path through the network from source to destination
- What is a good path?
  - Usually means the shortest path
  - Load balanced
  - Lowest $$$ cost
- Network modeled as a graph
  - Routers → nodes
  - Link → edges
    - Edge cost: delay, congestion level, etc.



Routing Problems

- Assume
  - A network with N nodes
  - Each node only knows
    - Its immediate neighbors
    - The cost to reach each neighbor
- How does each node learn the shortest path to every other node?



Intra-domain Routing Protocols

Intra-domain Routing Protocols

- Distance vector
  - Routing Information Protocol (RIP), based on Bellman-Ford
  - Routers periodically exchange reachability information with neighbors

Intra-domain Routing Protocols

- Distance vector
  - Routing Information Protocol (RIP), based on Bellman-Ford
  - Routers periodically exchange reachability information with neighbors
- Link state
  - Open Shortest Path First (OSPF), based on Dijkstra
  - Each network periodically floods immediate reachability information to all other routers
  - Per router local computation to determine full routes

1: Distance Vector Routing

Distance Vector Routing

- What is a distance vector?
  - Current best known cost to reach a destination
- Idea: exchange vectors among neighbors to learn about lowest cost paths

Distance Vector Routing

- What is a distance vector?
  - Current best known cost to reach a destination
- Idea: exchange vectors among neighbors to learn about lowest cost paths

DV Table at Node C

Destination	Cost
A	7
B	1
D	2
E	5
F	1

- No entry for C
- Initially, only has info for immediate neighbors
  - Other destinations cost = ∞
- Eventually, vector is filled

Distance Vector Routing

- What is a distance vector?
  - Current best known cost to reach a destination
- Idea: exchange vectors among neighbors to learn about lowest cost paths

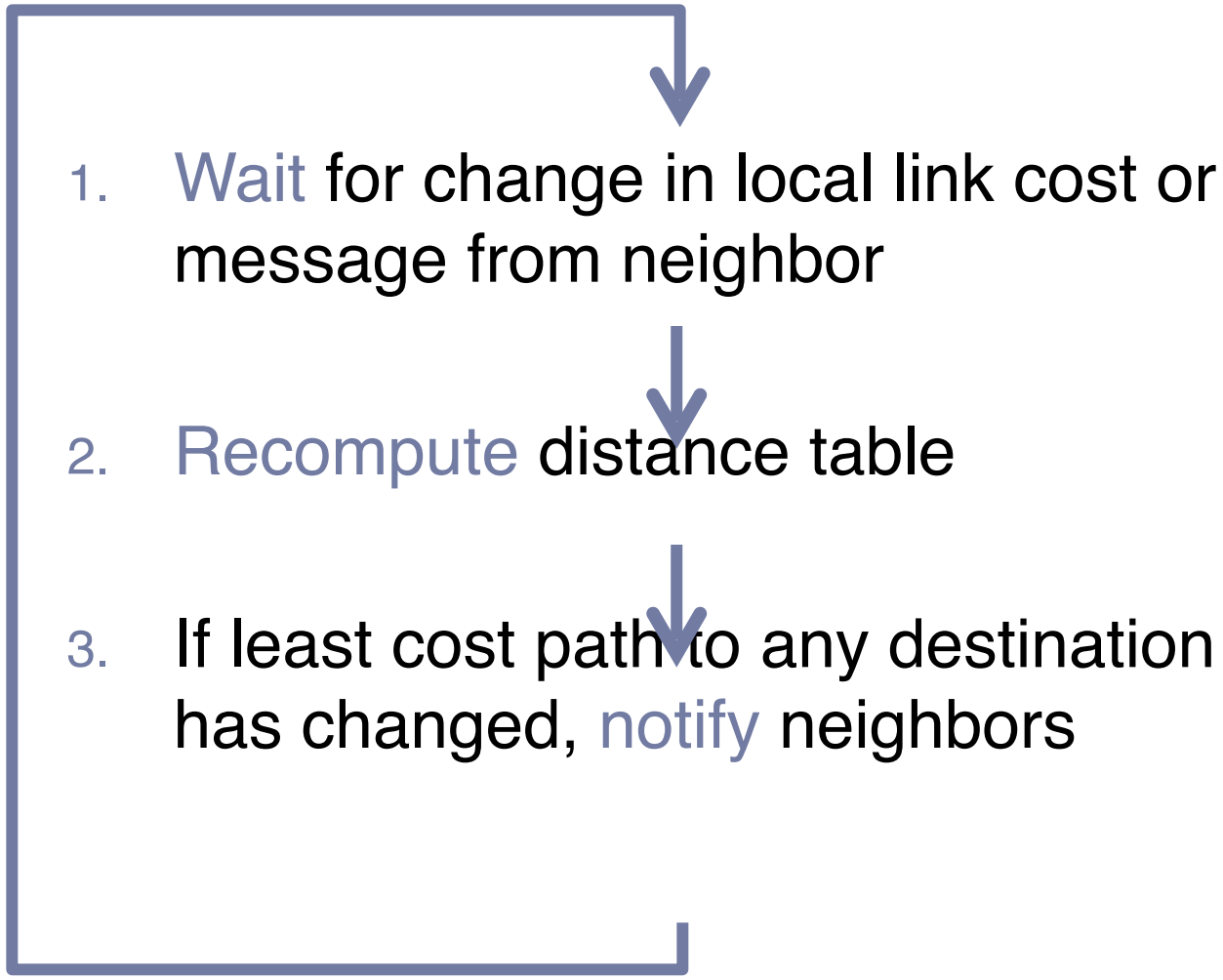
DV Table at Node C

Destination	Cost
A	7
B	1
D	2
E	5
F	1

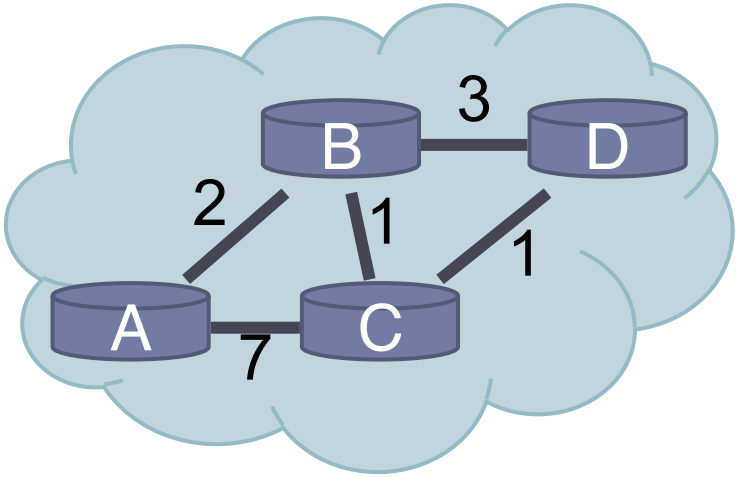
- No entry for C
- Initially, only has info for immediate neighbors
  - Other destinations cost = ∞
- Eventually, vector is filled

- Routing Information Protocol (RIP)

Distance Vector Routing Algorithm



Distance Vector Initialization



Node A

Dest.	Cost	Next
B	2	B
C	7	C
D	∞	

Node B

Dest.	Cost	Next
A	2	A
C	1	C
D	3	D

1. **Initialization:**
2. **for all** neighbors *V* **do**
3. **if** *V* adjacent to *A*
4. D(*A*, *V*) = c(*A*,*V*);
5. **else**
6. D(*A*, *V*) = ∞;

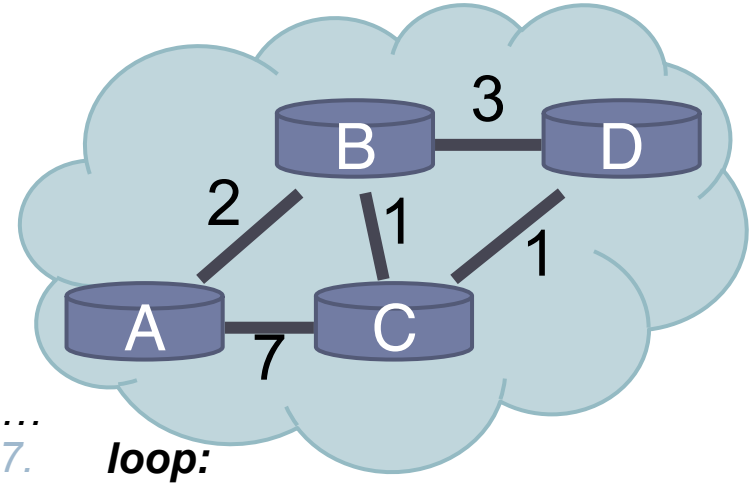
Node C

Dest.	Cost	Next
A	7	A
B	1	B
D	1	D

Node D

Dest.	Cost	Next
A	∞	
B	3	B
C	1	C

Distance Vector: 1st Iteration



Node A

Dest.	Cost	Next
B	2	B
C	7	C
D	∞	

Node B

Dest.	Cost	Next
A	2	A
C	1	C
D	3	D

```
…
7.  loop:
…
12. else if (update D(V, Y) received from V)
13.   for all destinations Y do
14.     if (destination Y through V)
15.       D(A,Y) = D(A,V) + D(V, Y);
16.     else
17.       D(A, Y) =
                  min(D(A, Y),
                  D(A, V) + D(V, Y));
18. if (there is a new min. for dest. Y)
19.   send D(A, Y) to all neighbors
20. forever
```

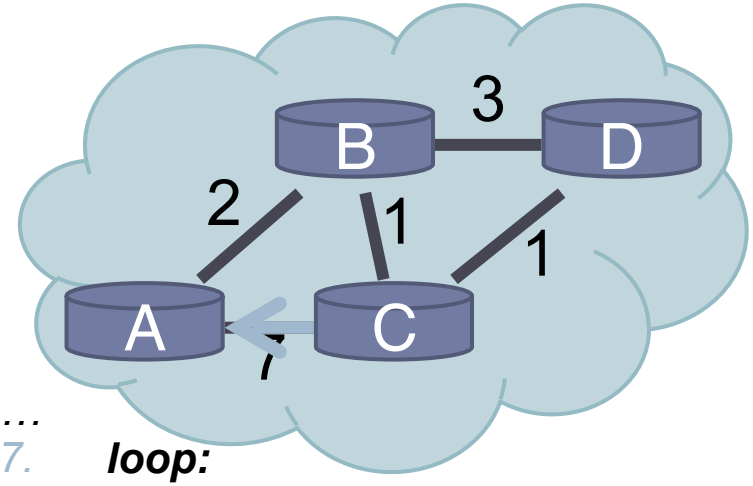
Node C

Dest.	Cost	Next
A	7	A
B	1	B
D	1	D

Node D

Dest.	Cost	Next
A	∞	
B	3	B
C	1	C

Distance Vector: 1st Iteration



Node A

Dest.	Cost	Next
B	2	B
C	7	C
D	∞	

Node B

Dest.	Cost	Next
A	2	A
C	1	C
D	3	D

```
…
7.  loop:
…
12. else if (update D(V, Y) received from V)
13.   for all destinations Y do
14.     if (destination Y through V)
15.       D(A,Y) = D(A,V) + D(V, Y);
16.     else
17.       D(A, Y) =
                  min(D(A, Y),
                  D(A, V) + D(V, Y));
18. if (there is a new min. for dest. Y)
19.   send D(A, Y) to all neighbors
20. forever
```

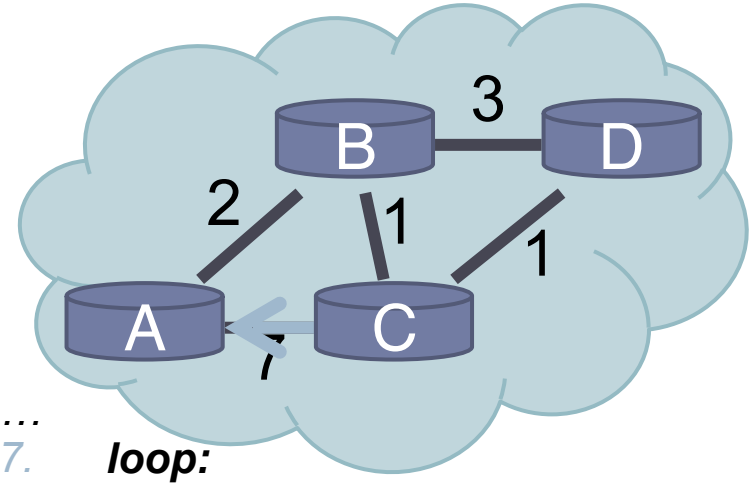
Node C

Dest.	Cost	Next
A	7	A
B	1	B
D	1	D

Node D

Dest.	Cost	Next
A	∞	
B	3	B
C	1	C

Distance Vector: 1st Iteration



Node A

Dest.	Cost	Next
B	2	B
C	7	C
D	∞	

Node B

Dest.	Cost	Next
A	2	A
C	1	C
D	3	D

```
…
7.  loop:
…
12. else if (update D(V, Y) received from V
13.   for all destinations Y do
14.     if (destination Y through V)
15.       D(A,Y) = D(A,V) + D(V,Y)
16.     else
17.       D(A, Y) = min(D(A,Y), D(A,V) + D(V,Y))
18. if (there is a new min. for dest. Y)
19.   send D(A, Y) to all neighbors
20. forever
```

$$D(A,D) = \min(D(A,D), D(A,C)+D(C,D)) = \min(\infty, 7 + 1) = 8$$

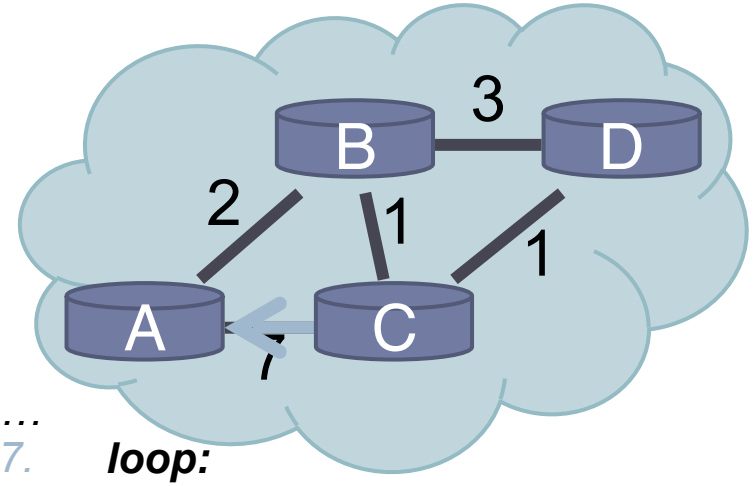
Node C

B	1	B
D	1	D

Node D

		Next
B	3	B
C	1	C

Distance Vector: 1st Iteration



Node A

Dest.	Cost	Next
B	2	B
C	7	C
D	∞ 8	C

Node B

Dest.	Cost	Next
A	2	A
C	1	C
D	3	D

```
…
7.  loop:
…
12. else if (update D(V, Y) received from V
13.   for all destinations Y do
14.     if (destination Y through V)
15.       D(A,Y) = D(A,V) + D(V,Y)
16.     else
17.       D(A, Y) = min(D(A,Y), D(A,V) + D(V,Y))
18. if (there is a new min. for dest. Y)
19.   send D(A, Y) to all neighbors
20. forever
```

D(A,D) = min(D(A,D), D(A,C)+D(C,D))
= min(∞, 7 + 1) = 8

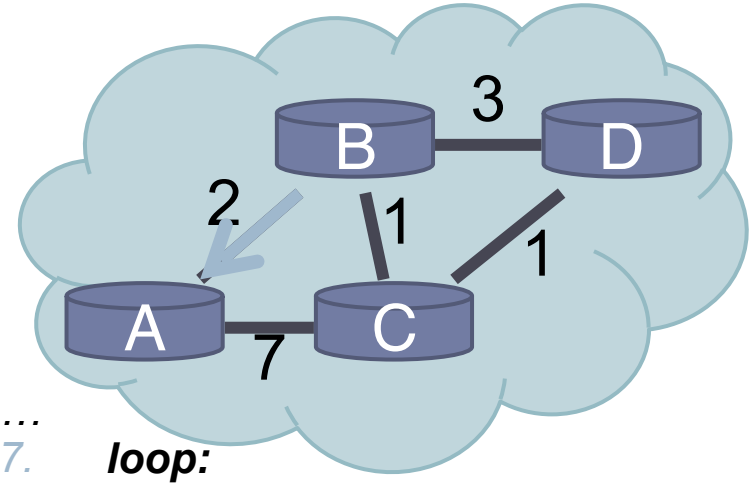
Node C

		Next
B	1	B
D	1	D

Node D

		Next
B	3	B
C	1	C

Distance Vector: 1st Iteration



Node A

Dest.	Cost	Next
B	2	B
C	7	C
D	∞ 8	C

Node B

Dest.	Cost	Next
A	2	A
C	1	C
D	3	D

```
…
7.  loop:
…
12. else if (update D(V, Y) received from V)
13.   for all destinations Y do
14.     if (destination Y through V)
15.       D(A,Y) = D(A,V) + D(V, Y);
16.     else
17.       D(A, Y) =
                  min(D(A, Y),
                  D(A, V) + D(V, Y));
18. if (there is a new min. for dest. Y)
19.   send D(A, Y) to all neighbors
20. forever
```

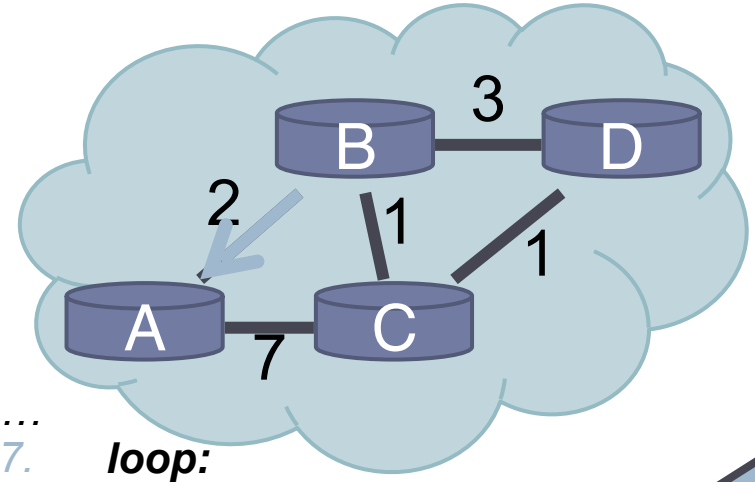
Node C

Dest.	Cost	Next
A	7	A
B	1	B
D	1	D

Node D

Dest.	Cost	Next
A	∞	
B	3	B
C	1	C

Distance Vector: 1st Iteration



Node A

Dest.	Cost	Next
B	2	B
C	7	C
D	∞ 8	C

Node B

Dest.	Cost	Next
A	2	A
C	1	C
D	3	D

```
…
7.  loop:
…
12. else if (update D(V, Y) rec
13.   for all dest
14.     if (destin
15.       D(A,Y) =
16.     else
17.       D(A, Y) =
                  min(D(A, Y),
                  D(A, V) + D(V, Y));
18. if (there is a new min. for dest. Y)
19.   send D(A, Y) to all neighbors
20. forever
```

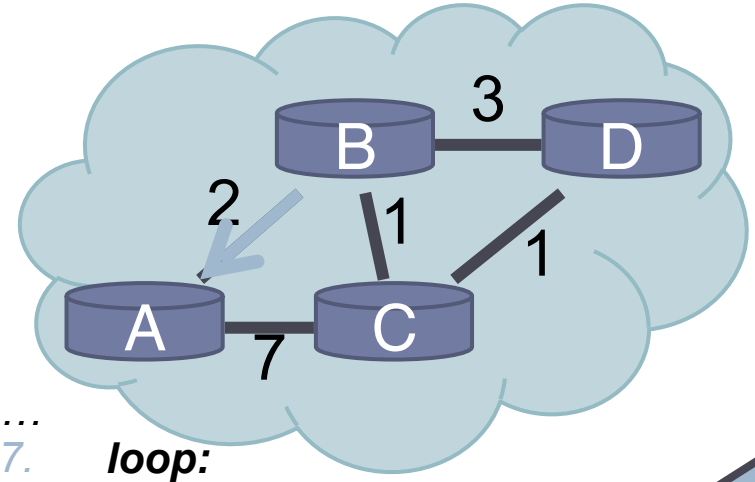
D(A,C) = min(D(A,C), D(A,B)+D(B,C))
= min(7, 2 + 1) = 3

e D

		t	Next
A	7	A	
B	1	B	
D	1	D	

A	∞	
B	3	B
C	1	C

Distance Vector: 1st Iteration



Node A

Dest.	Cost	Next
B	2	B
C	7 → 3	C → B
D	∞ → 8	→ C

Node B

Dest.	Cost	Next
A	2	A
C	1	C
D	3	D

```
…
7.  loop:
…
12. else if (update D(V, Y) rec
13.   for all dest
14.     if (destin
15.       D(A,Y) =
16.     else
17.       D(A, Y) =
                  min(D(A, Y),
                  D(A, V) + D(V, Y));
18. if (there is a new min. for dest. Y)
19.   send D(A, Y) to all neighbors
20. forever
```

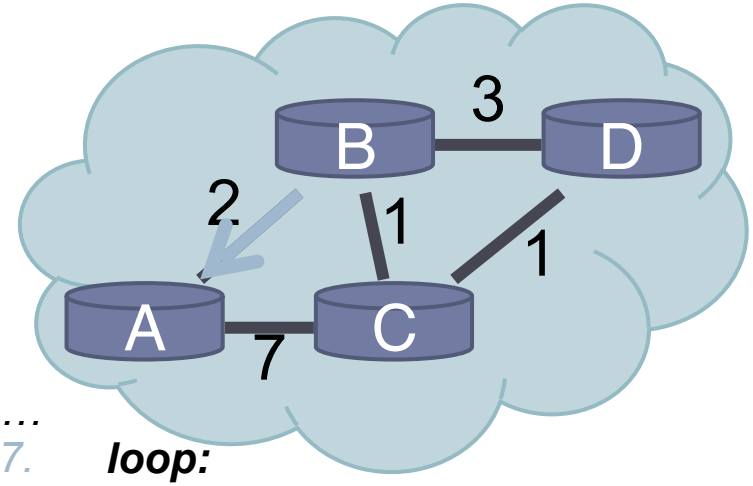
D(A,C) = min(D(A,C), D(A,B)+D(B,C))
= min(7, 2 + 1) = 3

e D

		t	Next
A	7	A	
B	1	B	
D	1	D	

A	∞	
B	3	B
C	1	C

Distance Vector: 1st Iteration



Node A

Dest.	Cost	Next
B	2	B
C	7 → 3	C → B
D	∞ → 8	→ C

Node B

Dest.	Cost	Next
A	2	A
C	1	C
D	3	D

```
…
7.  loop:
…
12. else if (update D(V, Y) received from V)
13.   for all destinations Y do
14.     if (destination Y through V)
15.       D(A,Y) = D(A,V) + D(V, Y);
16.     else
17.       D(A, Y) =
                  min(D(A, Y),
                  D(A, V) + D(V, Y));
18. if (there is a new min. for dest. Y)
19.   send D(A, Y) to all neighbors
20. forever
```

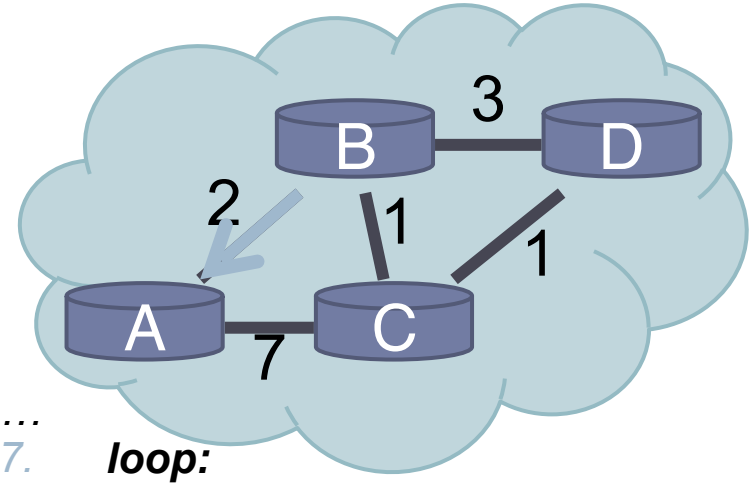
Node C

Dest.	Cost	Next
A	7	A
B	1	B
D	1	D

Node D

Dest.	Cost	Next
A	∞	
B	3	B
C	1	C

Distance Vector: 1st Iteration



Node A

Dest.	Cost	Next
B	2	B
C	7 3	C B
D	∞ 5	B

Node B

Dest.	Cost	Next
A	2	A
C	1	C
D	3	D

```
…
7.  loop:
…
12. else if (update D(V, Y) received from V)
13.   for all destinations Y do
14.     if (destination Y through V)
15.       D(A,Y) = D(A,V) + D(V, Y);
16.     else
17.       D(A, Y) =
                  min(D(A, Y),
                  D(A, V) + D(V, Y));
18. if (there is a new min. for dest. Y)
19.   send D(A, Y) to all neighbors
20. forever
```

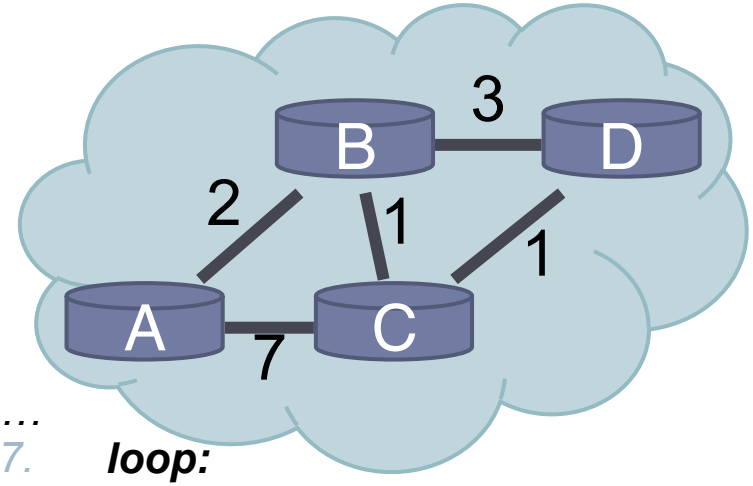
Node C

Dest.	Cost	Next
A	7	A
B	1	B
D	1	D

Node D

Dest.	Cost	Next
A	∞	
B	3	B
C	1	C

Distance Vector: 1st Iteration



…
7. ***loop:***

…
12. **else if** (update D(*V, Y*) received from *V*)
13. **for all** destinations Y **do**
14. **if** (destination *Y* through *V*)
15. D(*A,Y*) = D(*A,V*) + D(*V, Y*);
16. **else**
17. D(A, Y) =
min(D(*A, Y*),
D(*A, V*) + D(*V, Y*));
18. **if** (there is a new min. for dest. *Y*)
19. **send** D(*A, Y*) to all neighbors
20. **forever**

Node A

Dest.	Cost	Next
B	2	B
C	7 → 3	C → B
D	∞ → 5	B

Node B

Dest.	Cost	Next
A	2	A
C	1	C
D	2	C

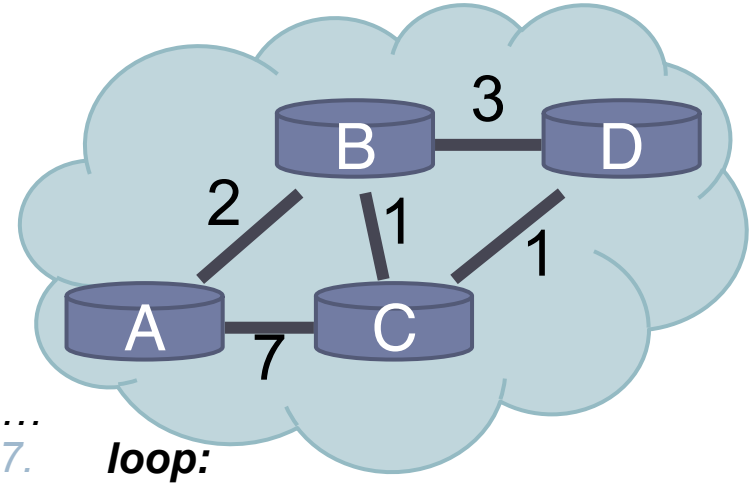
Node C

Dest.	Cost	Next
A	3	B
B	1	B
D	1	D

Node D

Dest.	Cost	Next
A	4	B
B	3	B
C	1	C

Distance Vector: End of 3rd Iteration




```
…
7.  loop:
…
12. else if (update D(V, Y) received from V)
13.   for all destinations Y do
14.     if (destination Y through V)
15.       D(A,Y) = D(A,V) + D(V, Y);
16.     else
17.       D(A, Y) =
                  min(D(A, Y),
                  D(A, V) + D(V, Y));
18. if (there is a new min. for dest. Y)
19.   send D(A, Y) to all neighbors
20. forever
```

Node A

Dest.	Cost	Next
B	2	B
C	3	B
D	4	B

Node B

Dest.	Cost	Next
A	2	A
C	1	C
D	2	C

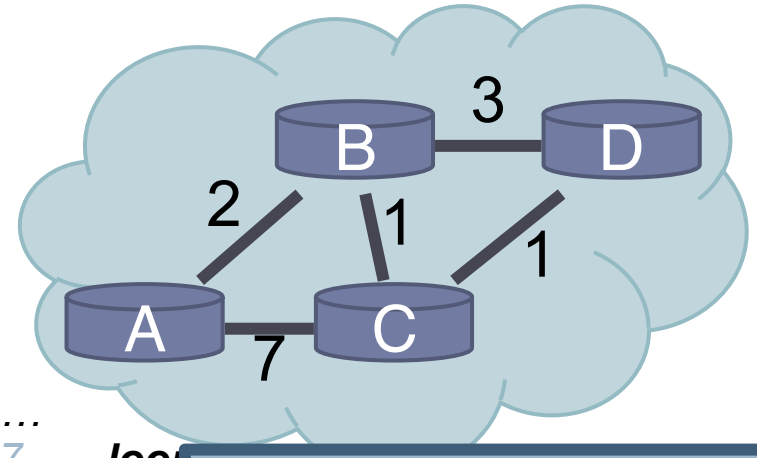
Node C

Dest.	Cost	Next
A	3	B
B	1	B
D	1	D

Node D

Dest.	Cost	Next
A	4	C
B	2	C
C	1	C

Distance Vector: End of 3rd Iteration



Node A

Dest.	Cost	Next
B	2	B
C	3	B
D	4	B

Node B

Dest.	Cost	Next
A	2	A
C	1	C
D	2	C

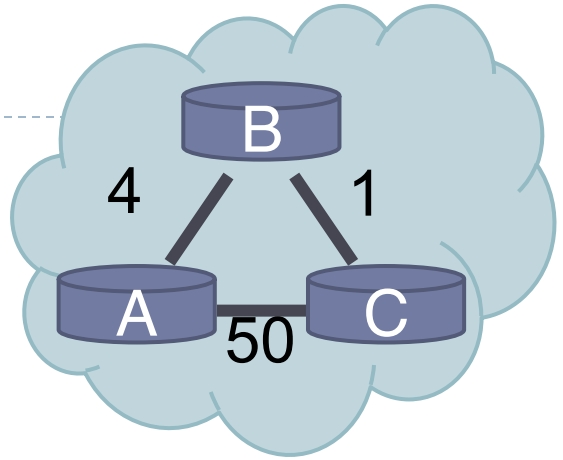
- Nothing changes, algorithm terminates
- Until something changes…

Dest.	Cost	Next
A	3	B
B	1	B
D	1	D

Dest.	Cost	Next
A	4	C
B	2	C
C	1	C

```
…
7.   loop
…
12.  else
13.    for
14.      if
15.
16.      e
17.        D(A, Y) =
                 min(D(A, Y),
                 D(A, V) + D(V, Y));
18.  if (there is a new min. for dest. Y)
19.    send D(A, Y) to all neighbors
20.  forever
```

```
7.   loop:
8.     wait (link cost update or update message)
9.     if (c(A,V) changes by d)
10.      for all destinations Y through V do
11.        D(A,Y) =  D(A,Y) + d
12.    else if (update D(V, Y) received from V)
13.      for all destinations Y do
14.        if (destination Y through V)
15.          D(A,Y) = D(A,V) + D(V, Y);
16.        else
17.          D(A, Y) = min(D(A, Y), D(A, V) + D(V, Y));
18.    if (there is a new minimum for destination Y)
19.      send D(A, Y) to all neighbors
20.  forever
```



Node B

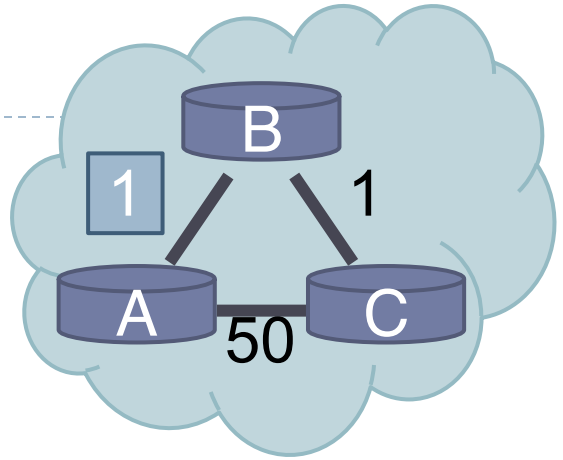
D	C	N
A	4	A
C	1	B

Node C

D	C	N
A	5	B
B	1	B

Time

```
7.   loop:
8.     wait (link cost update or update message)
9.     if (c(A,V) changes by d)
10.      for all destinations Y through V do
11.        D(A,Y) =  D(A,Y) + d
12.    else if (update D(V, Y) received from V)
13.      for all destinations Y do
14.        if (destination Y through V)
15.          D(A,Y) = D(A,V) + D(V, Y);
16.        else
17.          D(A, Y) = min(D(A, Y), D(A, V) + D(V, Y));
18.    if (there is a new minimum for destination Y)
19.      send D(A, Y) to all neighbors
20.  forever
```



Node B

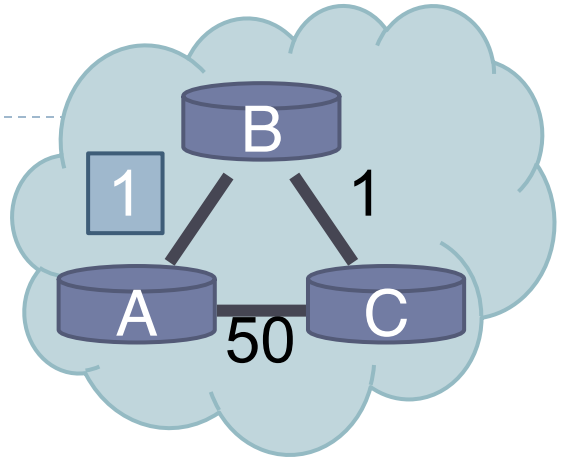
D	C	N
A	4	A
C	1	B

Node C

D	C	N
A	5	B
B	1	B

Time

```
7.    loop:
8.      wait (link cost update or update message)
9.      if (c(A,V) changes by d)
10.       for all destinations Y through V do
11.         D(A,Y) =  D(A,Y) + d
12.     else if (update D(V, Y) received from V)
13.       for all destinations Y do
14.         if (destination Y through V)
15.           D(A,Y) = D(A,V) + D(V, Y);
16.         else
17.           D(A, Y) = min(D(A, Y), D(A, V) + D(V, Y));
18.   if (                                tination Y)
19.
20.
```



Link Cost Changes, Algorithm Starts

Node B

D	C	N
A	4	A
C	1	B

D	C	N
A	1	A
C	1	B

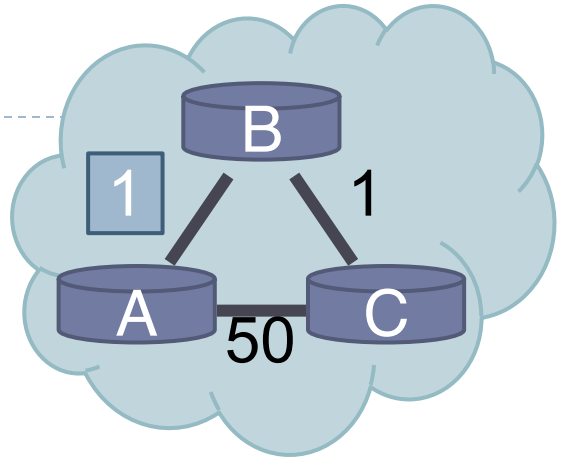
Node C

D	C	N
A	5	B
B	1	B

D	C	N
A	5	B
B	1	B

Time

```
7.    loop:
8.      wait (link cost update or update message)
9.      if (c(A,V) changes by d)
10.       for all destinations Y through V do
11.         D(A,Y) =  D(A,Y) + d
12.     else if (update D(V, Y) received from V)
13.       for all destinations Y do
14.         if (destination Y through V)
15.           D(A,Y) = D(A,V) + D(V, Y);
16.         else
17.           D(A, Y) = min(D(A, Y), D(A, V) + D(V, Y));
18.   if (
19.
20.
```



Link Cost Changes, Algorithm Starts

Node B

D	C	N
A	4	A
C	1	B

D	C	N
A	1	A
C	1	B

D	C	N
A	1	A
C	1	B

Node C

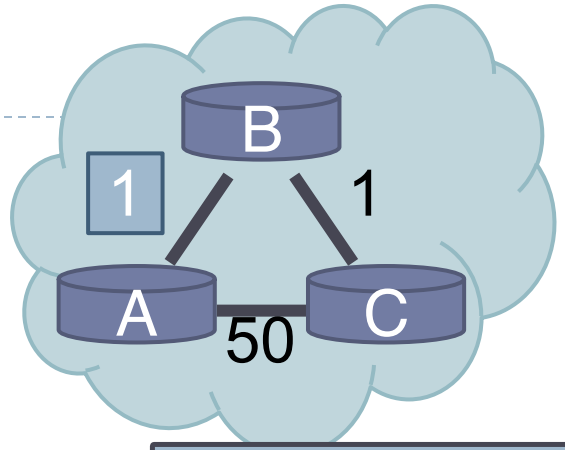
D	C	N
A	5	B
B	1	B

D	C	N
A	5	B
B	1	B

D	C	N
A	2	B
B	1	B

Time

```
7.    loop:
8.      wait (link cost update or update message)
9.      if (c(A,V) changes by d)
10.       for all destinations Y through V do
11.         D(A,Y) =  D(A,Y) + d
12.     else if (update D(V, Y) received from V)
13.       for all destinations Y do
14.         if (destination Y through V)
15.           D(A,Y) = D(A,V) + D(V, Y);
16.         else
17.           D(A, Y) = min(D(A, Y), D(A, V) + D(V, Y));
18.   if (                                  stination Y)
19.
20.
```



Link Cost Changes, Algorithm Starts

Algorithm Terminates

Node B

D	C	N
A	4	A
C	1	B

D	C	N
A	1	A
C	1	B

D	C	N
A	1	A
C	1	B

D	C	N
A	1	A
C	1	B

Node C

D	C	N
A	5	B
B	1	B

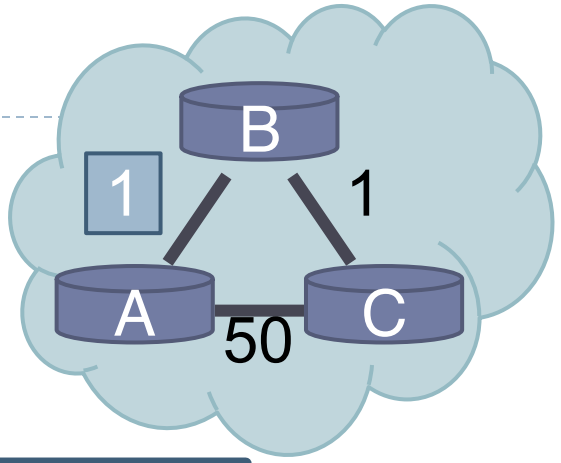
D	C	N
A	5	B
B	1	B

D	C	N
A	2	B
B	1	B

D	C	N
A	2	B
B	1	B

Time

```
7.   loop:
8.     wait (link cost update or update message)
9.     if (c(A,V) changes by d)
10.      for all destinations Y through V do
11.        D(A,Y) =  D(A,Y) + d
12.    else if (update D(V, Y) received from V)
13.      for all destinations Y do
14.        if (destination Y through V)
15.          D(A,Y) = D(A,V) + D(V, Y);
16.        else
17.          D(A, Y) = min(D(A, Y), D(A, V) + D(V, Y));
18.    if (there is a new minimum for destination Y)
19.      send D(A
20.  forever
```



Good news travels fast

Node B

D	C	N
A	4	A
C	1	B

D	C	N
A	1	A
C	1	B

D	C	N
A	1	A
C	1	B

D	C	N
A	1	A
C	1	B

Node C

D	C	N
A	5	B
B	1	B

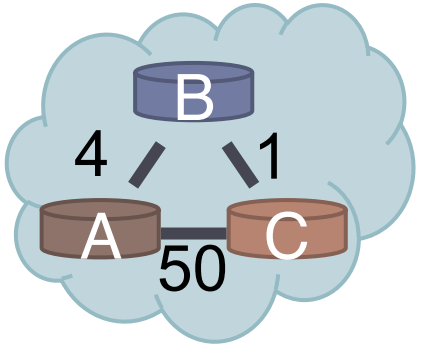
D	C	N
A	5	B
B	1	B

D	C	N
A	2	B
B	1	B

D	C	N
A	2	B
B	1	B

Time

Count to Infinity Problem



Node B

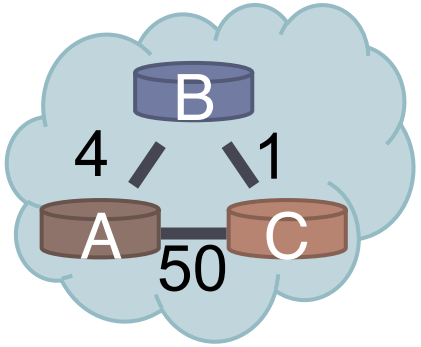
D	C	N
A	4	A
C	1	C

Node C

D	C	N
A	5	B
B	1	B

Time

Count to Infinity Problem



V Announcement Cache

Node A

D	C
B	4
C	5

Node C

D	C
A	5
B	1

Node B

D	C	N
A	4	A
C	1	C

Node C

D	C	N
A	5	B
B	1	B

Time

Count to Infinity Problem

V Announcement Cache

Node A

D	C
B	4
C	5

Node C

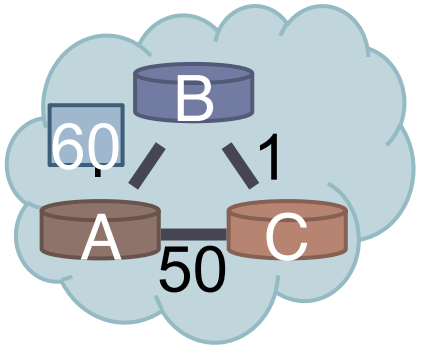
D	C
A	5
B	1

Node B

D	C	N
A	4	A
C	1	C

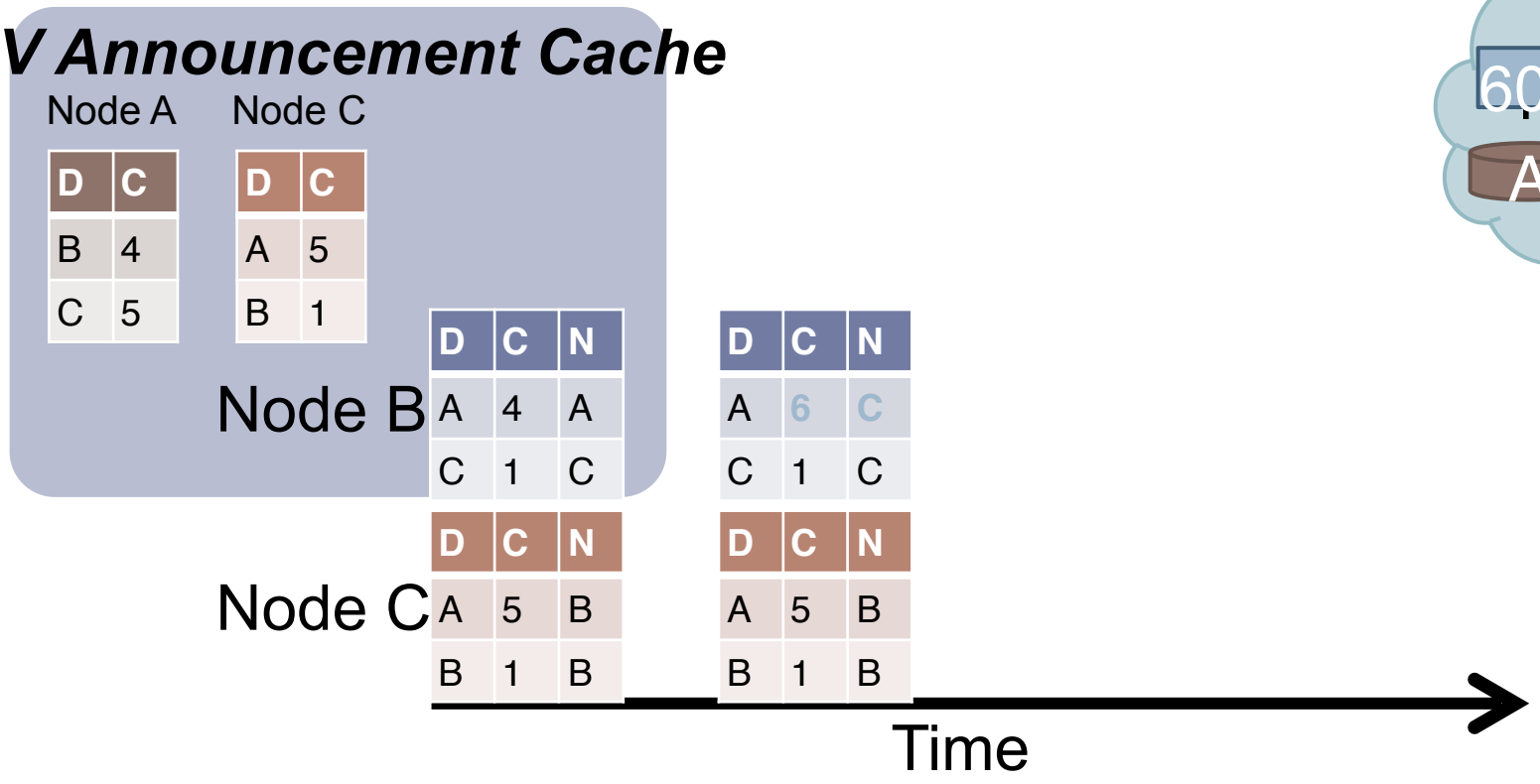
Node C

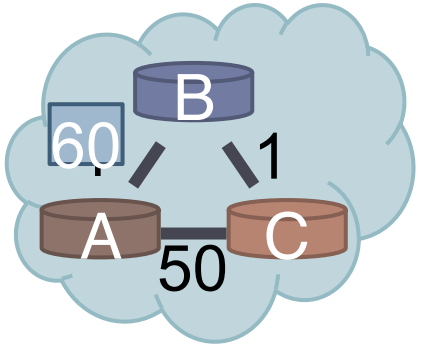
D	C	N
A	5	B
B	1	B



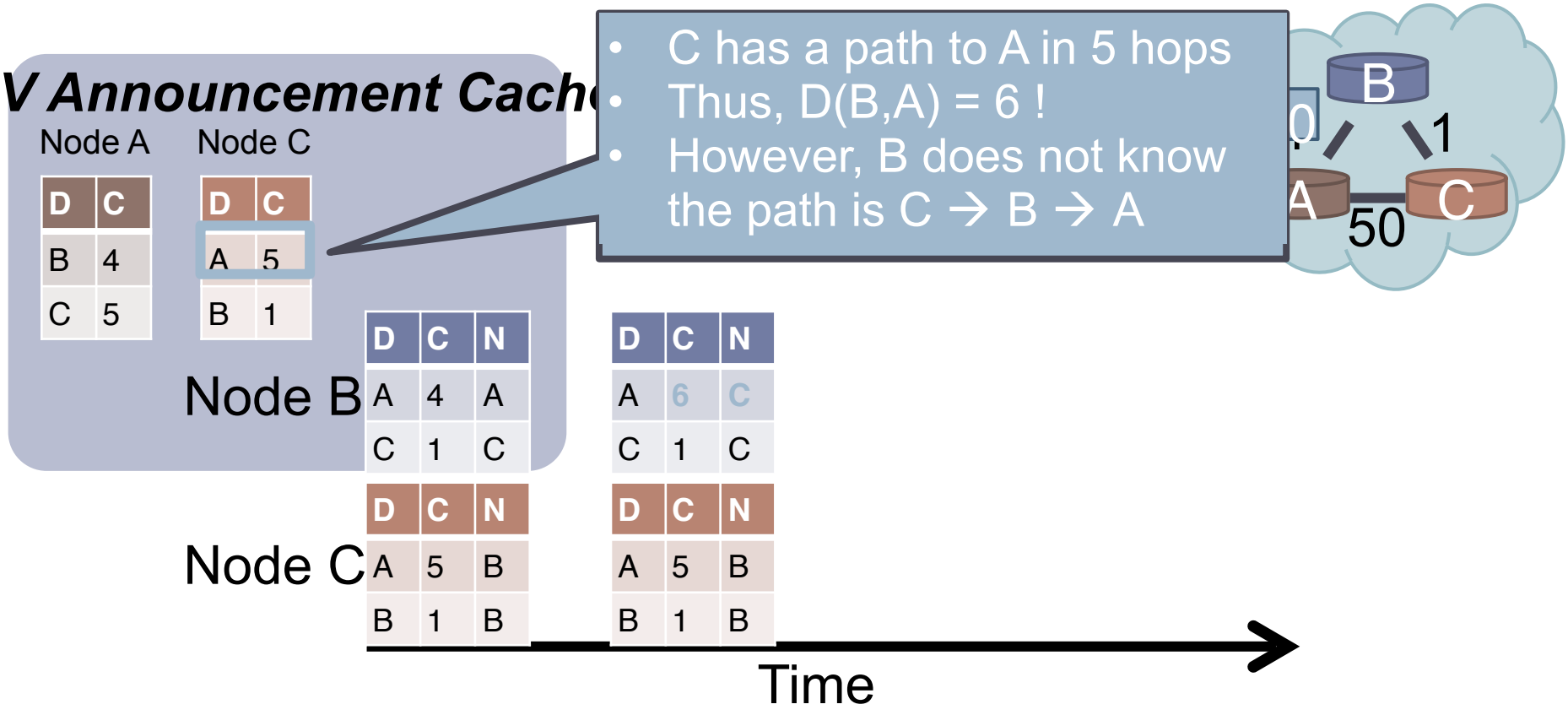
Time

Count to Infinity Problem

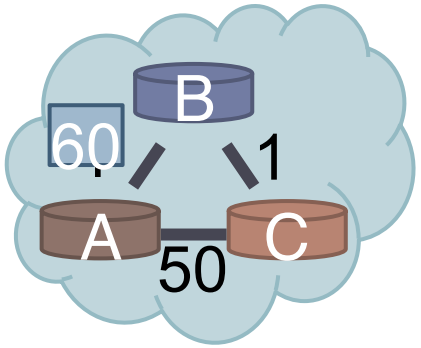




Count to Infinity Problem



Count to Infinity Problem



V Announcement Cache

Node A

D	C
B	4
C	5

Node C

D	C
A	5
B	1

Node B

D	C	N
A	4	A
C	1	C

D	C	N
A	6	C
C	1	C

D	C	N
A	6	C
C	1	C

Node C

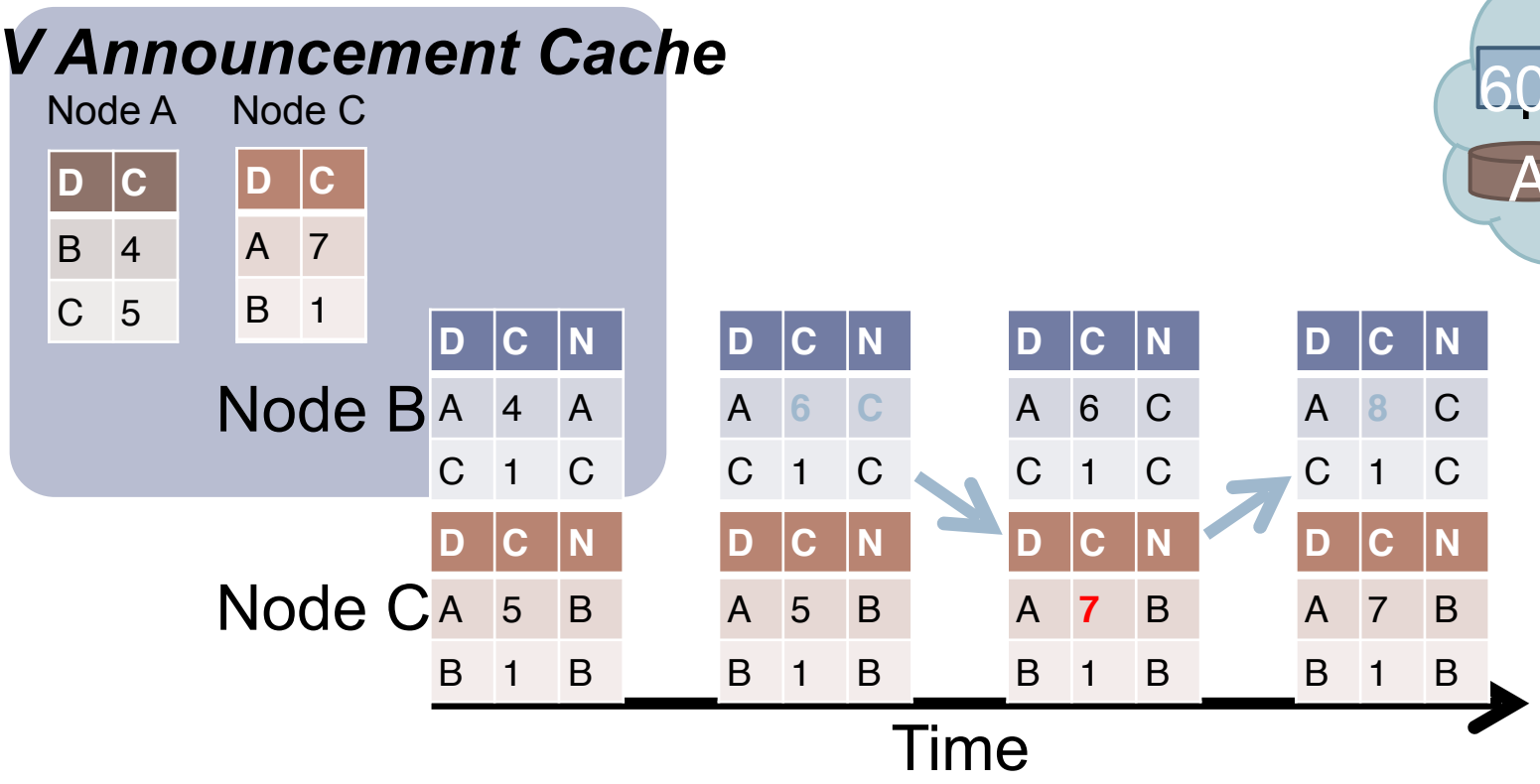
D	C	N
A	5	B
B	1	B

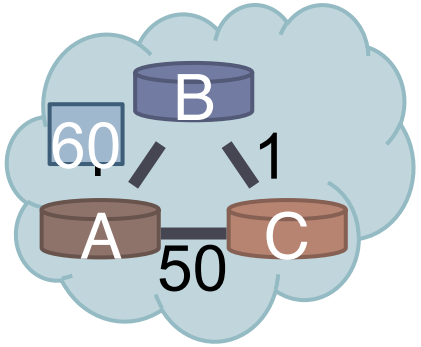
D	C	N
A	5	B
B	1	B

D	C	N
A	7	B
B	1	B

Time

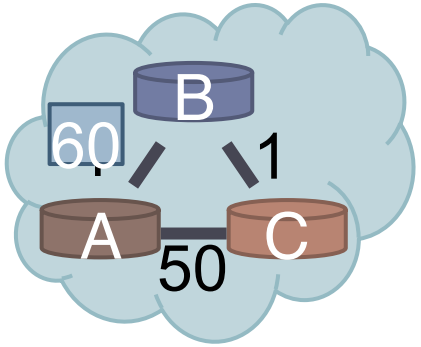
Count to Infinity Problem





Count to Infinity Problem

Bad news travels slowly



V Announcement Cache

Node A

D	C
B	4
C	5

Node C

D	C
A	7
B	1

Node B

D	C	N
A	4	A
C	1	C

D	C	N
A	6	C
C	1	C

D	C	N
A	6	C
C	1	C

D	C	N
A	8	C
C	1	C

Node C

D	C	N
A	5	B
B	1	B

D	C	N
A	5	B
B	1	B

D	C	N
A	7	B
B	1	B

D	C	N
A	7	B
B	1	B

Time

Poisoned Reverse

- If C routes through B to get to A
  - C tells B that D(C, A) = ∞

DV Announcement Cache

Node A

D	C
B	4
C	∞

Node C

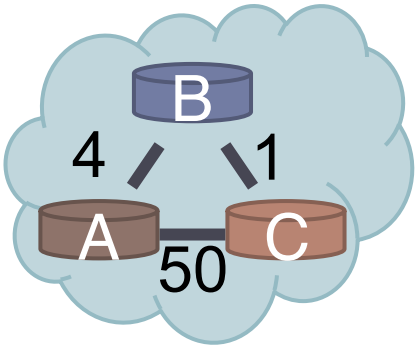
D	C
A	∞
B	1

Node B

D	C	N
A	4	A
C	1	B

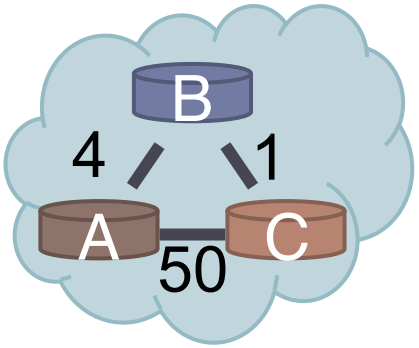
Node C

D	C	N
A	5	B
B	1	B



Poisoned Reverse

- If C routes through B to get to A
  - C tells B that D(C, A) = ∞



DV Announcement Cache

Node A

D	C
B	4
C	∞

Node C

D	C
A	∞
B	1

Node B

D	C	N
A	4	A
C	1	B

Node C

D	C	N
A	5	B
B	1	B

Time

Poisoned Reverse

- If C routes through B to get to A
  - C tells B that D(C, A) = ∞

DV Announcement Cache

Node A

D	C
B	4
C	∞

Node C

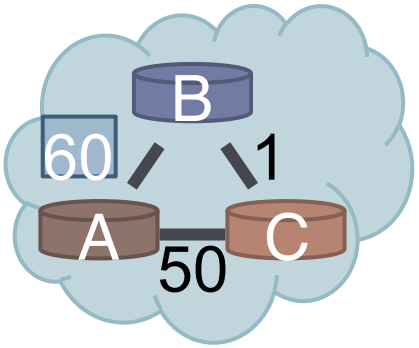
D	C
A	∞
B	1

Node B

D	C	N
A	4	A
C	1	B

Node C

D	C	N
A	5	B
B	1	B



Poisoned Reverse

- If C routes through B to get to A
  - C tells B that D(C, A) = ∞

DV Announcement Cache

Node A

D	C
B	4
C	∞

Node C

D	C
A	∞
B	1

Node B

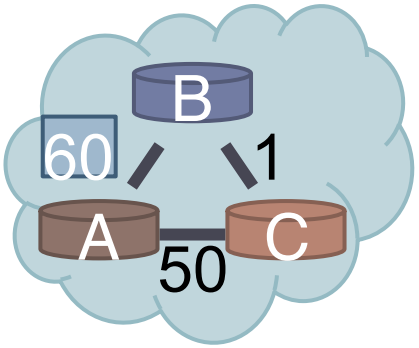
D	C	N
A	4	A
C	1	B

D	C	N
A	60	A
C	1	B

Node C

D	C	N
A	5	B
B	1	B

D	C	N
A	5	B
B	1	B



Time

Poisoned Reverse

- If C routes through B to get to A
  - C tells B that D(C, A) = ∞

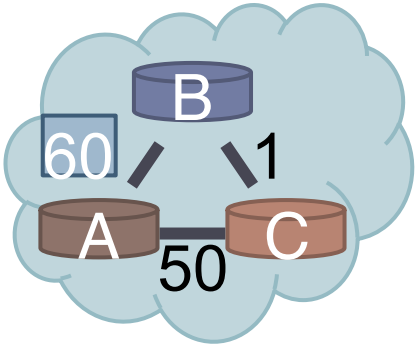
DV Announcement Cache

Node A

D	C
B	4
C	∞

Node C

D	C
A	∞
B	1



Node B

D	C	N
A	4	A
C	1	B

D	C	N
A	60	A
C	1	B

D	C	N
A	60	A
C	1	B

Node C

D	C	N
A	5	B
B	1	B

D	C	N
A	5	B
B	1	B

D	C	N
A	50	A
B	1	B

Time

Poisoned Reverse

- If C routes through B to get to A
  - C tells B that D(C, A) = ∞

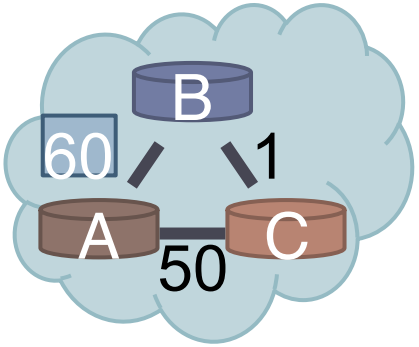
DV Announcement Cache

Node A

D	C
B	4
C	∞

Node C

D	C
A	50
B	1



Node B

D	C	N
A	4	A
C	1	B

D	C	N
A	60	A
C	1	B

D	C	N
A	60	A
C	1	B

D	C	N
A	51	C
C	1	B

Node C

D	C	N
A	5	B
B	1	B

D	C	N
A	5	B
B	1	B

D	C	N
A	**50**	**A**
B	1	B

D	C	N
A	50	A
B	1	B

Time

Poisoned Reverse

- If C routes through B to get to A
  - C tells B that D(C, A) = ∞

V Announcement Cache

Node A

D	C
B	4
C	∞

Node C

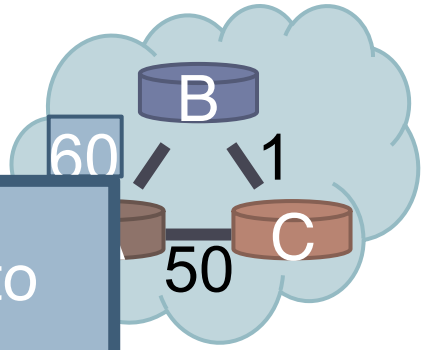
D
A
B

No

Does this completely solve this count to infinity problem?

NO

Multipath loops can still trigger the issue



Node C

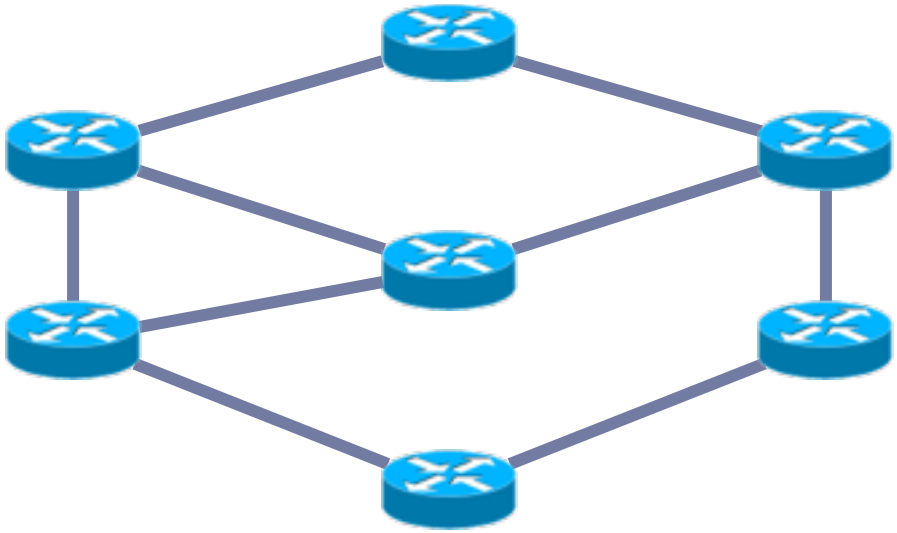
A	5	B		A	5	B		A	**50**	**A**		A	50	A
B	1	B		B	1	B		B	1	B		B	1	B

Time

2: Link State Routing

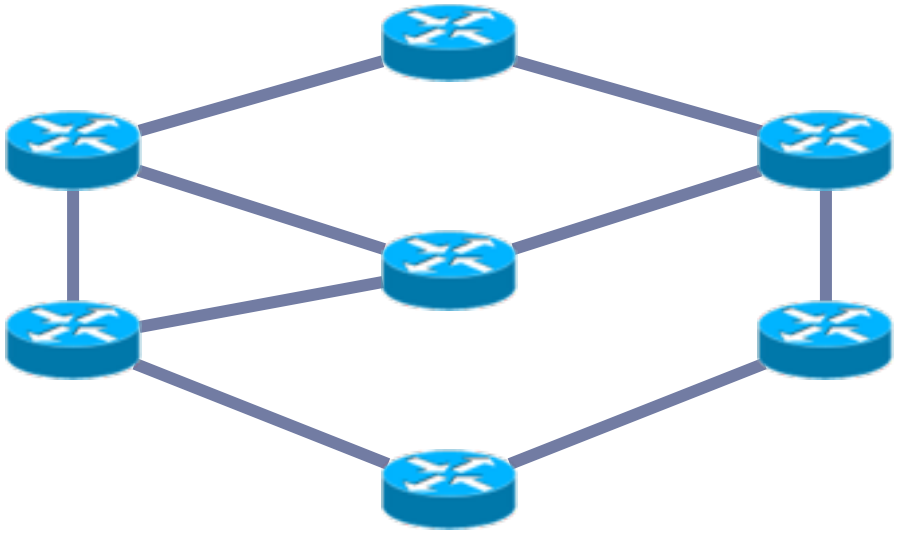
Link State Routing

- Each node knows its connectivity and cost to direct neighbors



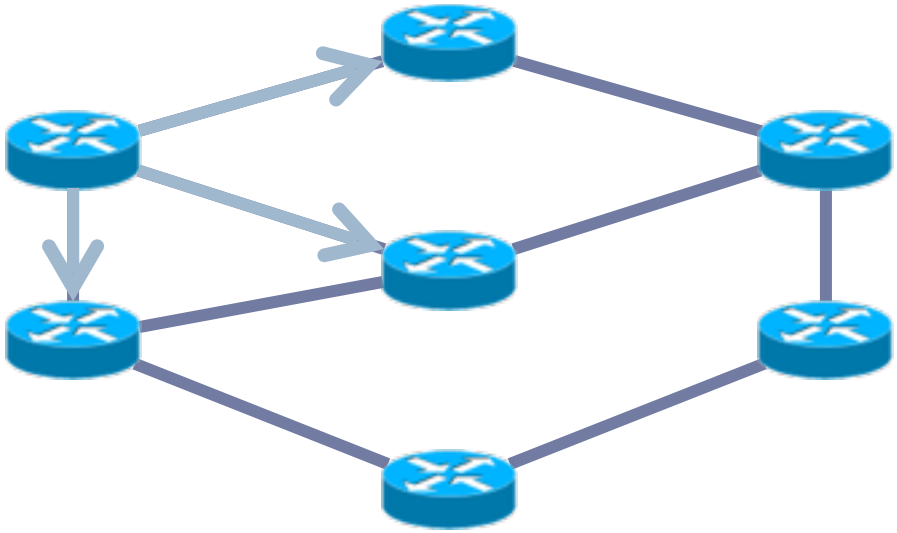
Link State Routing

- Each node knows its connectivity and cost to direct neighbors
- Each node tells every other node this information



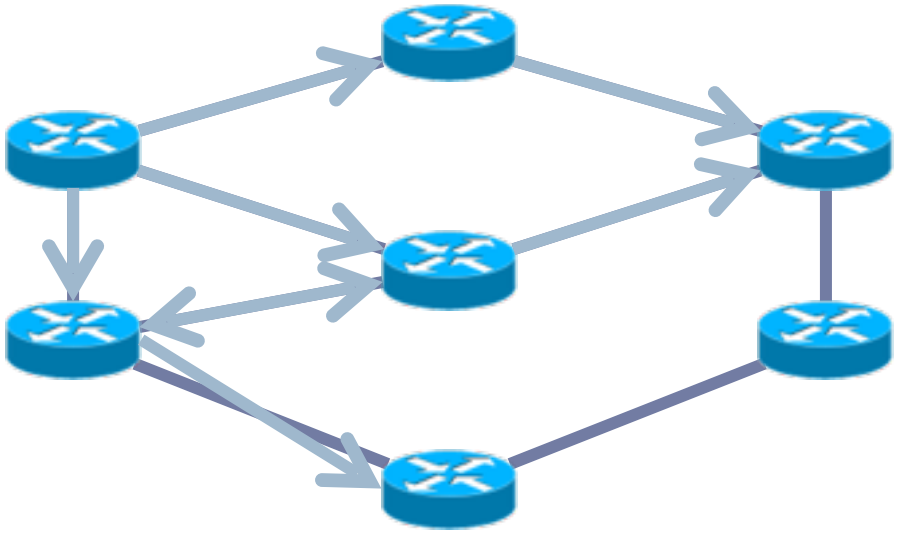
Link State Routing

- Each node knows its connectivity and cost to direct neighbors
- Each node tells every other node this information



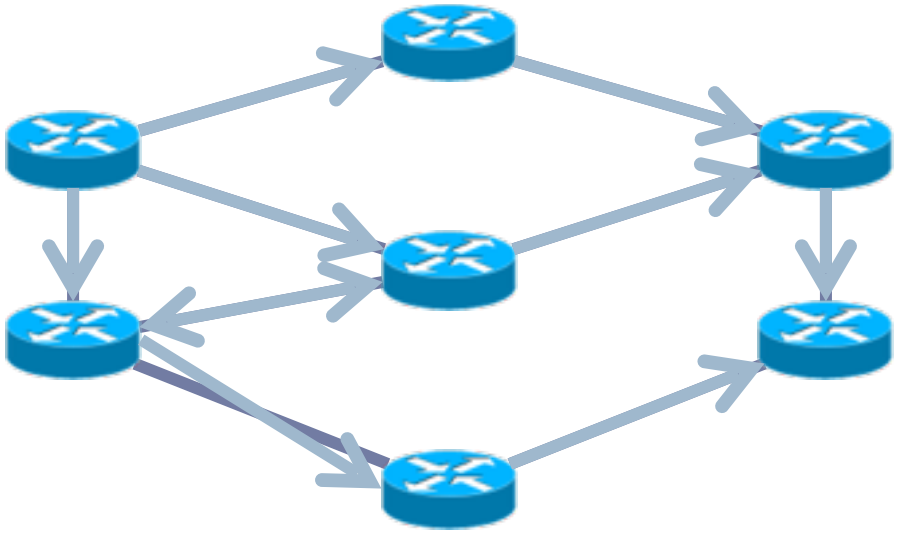
Link State Routing

- Each node knows its connectivity and cost to direct neighbors
- Each node tells every other node this information



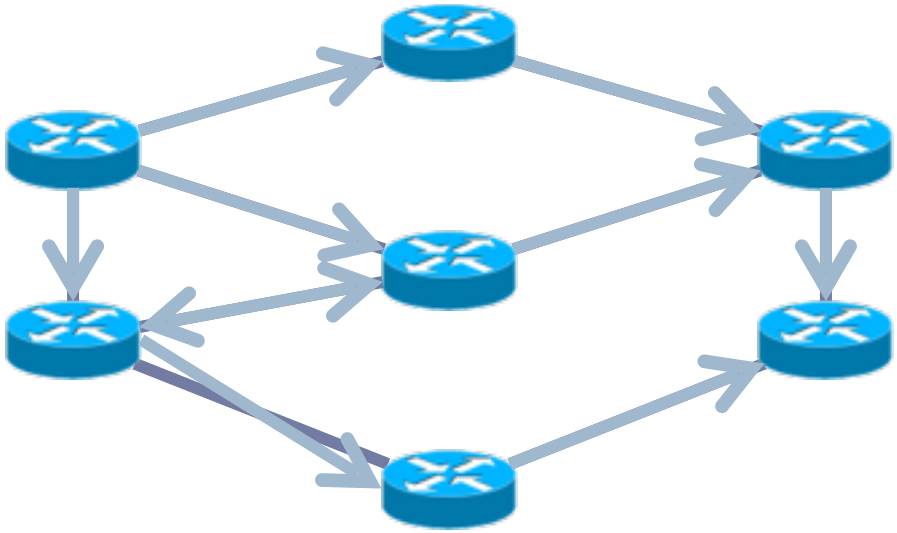
Link State Routing

- Each node knows its connectivity and cost to direct neighbors
- Each node tells every other node this information



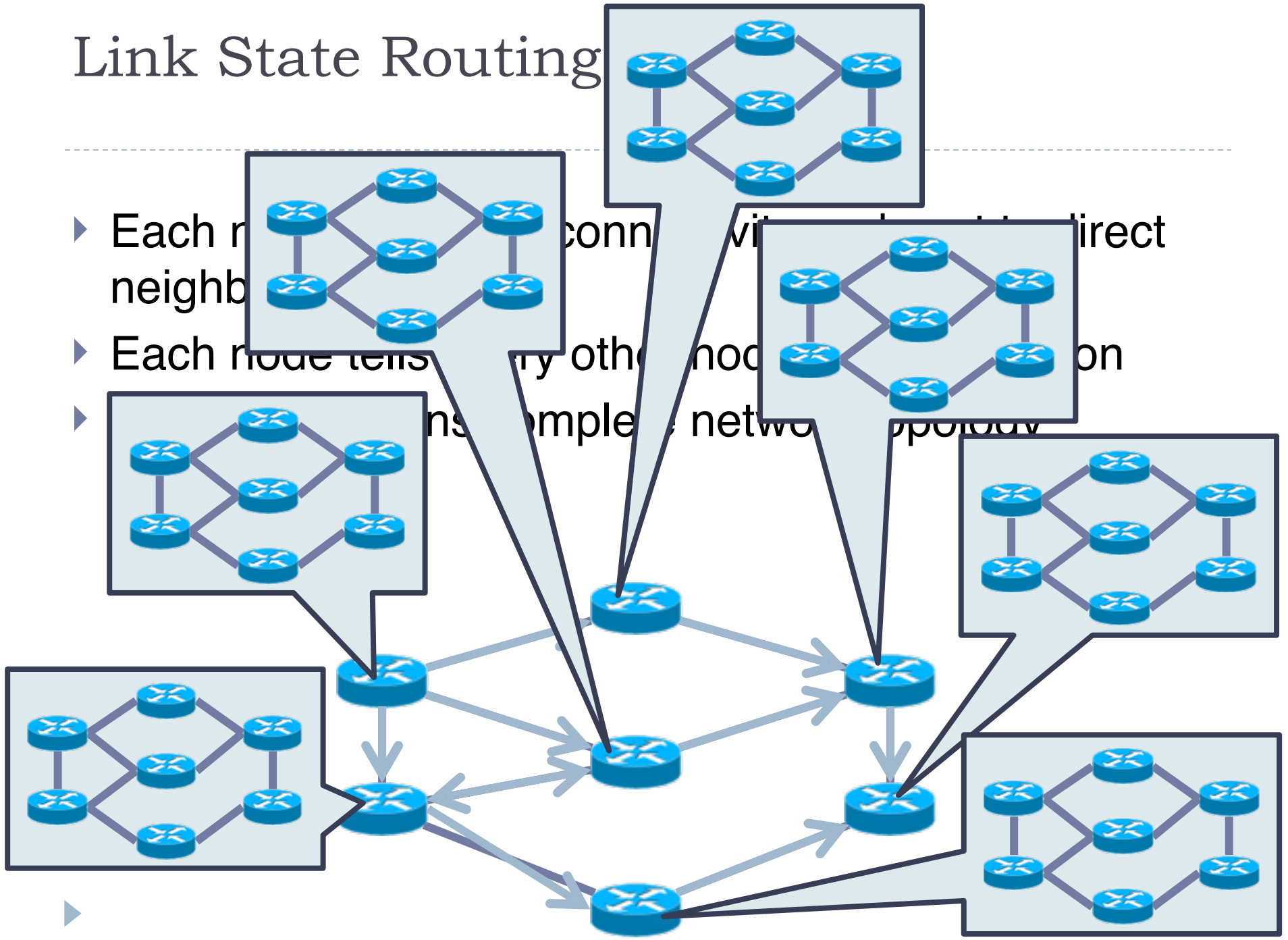
Link State Routing

- Each node knows its connectivity and cost to direct neighbors
- Each node tells every other node this information
- Each node learns complete network topology



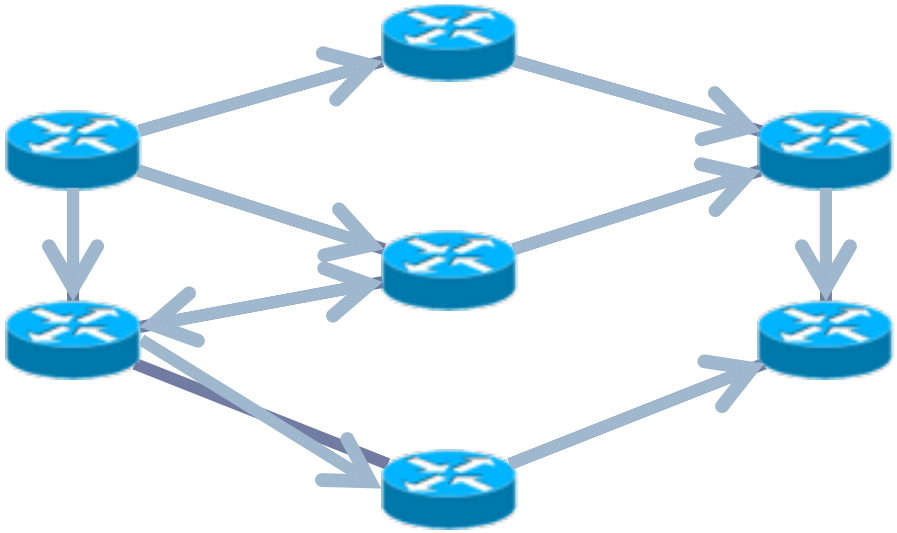
Link State Routing

- Each r… conn… vi… direct neighb…
- Each node tells … ry othe… nod… on
- …ns… omple… netwo… oppoday



Link State Routing

- Each node knows its connectivity and cost to direct neighbors
- Each node tells every other node this information
- Each node learns complete network topology
- Use Dijkstra to compute shortest paths



Flooding Details

- Each node periodically generates Link State Packet
  - ID of node generating the LSP
  - List of direct neighbors and costs
  - Sequence number (64-bit, assumed to never wrap)
  - Time to live

Flooding Details

- Each node periodically generates Link State Packet
  - ID of node generating the LSP
  - List of direct neighbors and costs
  - Sequence number (64-bit, assumed to never wrap)
  - Time to live
- Flood is reliable (ack + retransmission)

Flooding Details

- Each node periodically generates Link State Packet
  - ID of node generating the LSP
  - List of direct neighbors and costs
  - Sequence number (64-bit, assumed to never wrap)
  - Time to live
- Flood is reliable (ack + retransmission)
- Sequence number “versions” each LSP

Flooding Details

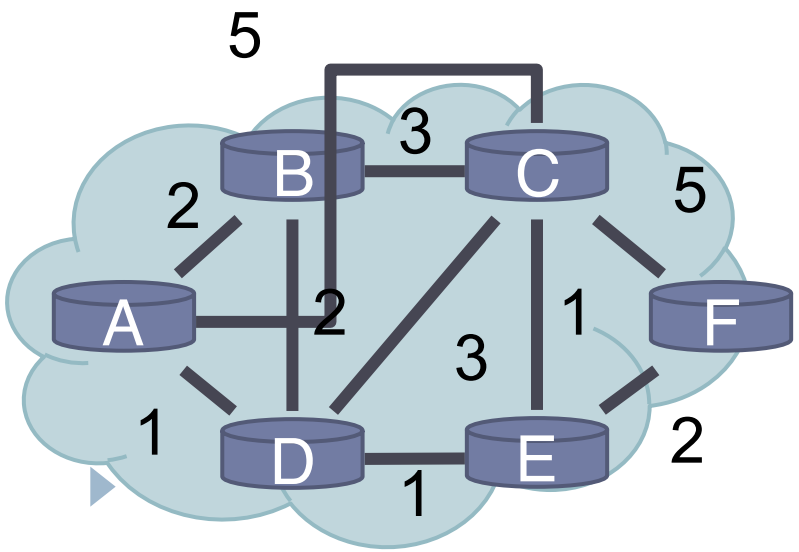
- Each node periodically generates Link State Packet
  - ID of node generating the LSP
  - List of direct neighbors and costs
  - Sequence number (64-bit, assumed to never wrap)
  - Time to live
- Flood is reliable (ack + retransmission)
- Sequence number “versions” each LSP
- Receivers flood LSPs to their own neighbors
  - Except whoever originated the LSP

Flooding Details

- Each node periodically generates Link State Packet
  - ID of node generating the LSP
  - List of direct neighbors and costs
  - Sequence number (64-bit, assumed to never wrap)
  - Time to live
- Flood is reliable (ack + retransmission)
- Sequence number “versions” each LSP
- Receivers flood LSPs to their own neighbors
  - Except whoever originated the LSP
- LSPs also generated when link states change

Dijkstra's Algorithm

Step	Start S	→B	→C	→D	→E	→F
0	A	2, A	5, A	1, A	∞	∞

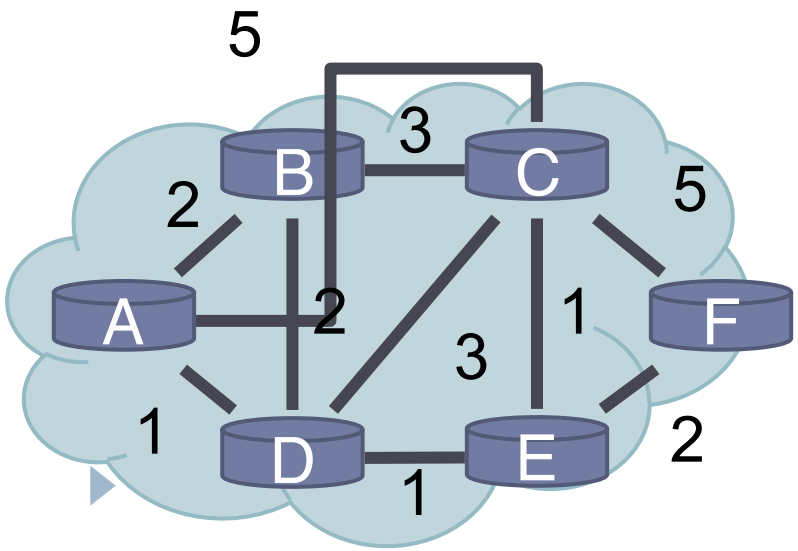


1. ***Initialization:***
2. S = {A};
3. for all nodes *v*
4. if *v* adjacent to *A*
5. then D(v) = c(A,v);
6. else D(v) = ∞;

…

Dijkstra's Algorithm

Step	Start S	→B	→C	→D	→E	→F
0	A	2, A	5, A	1, A	∞	∞

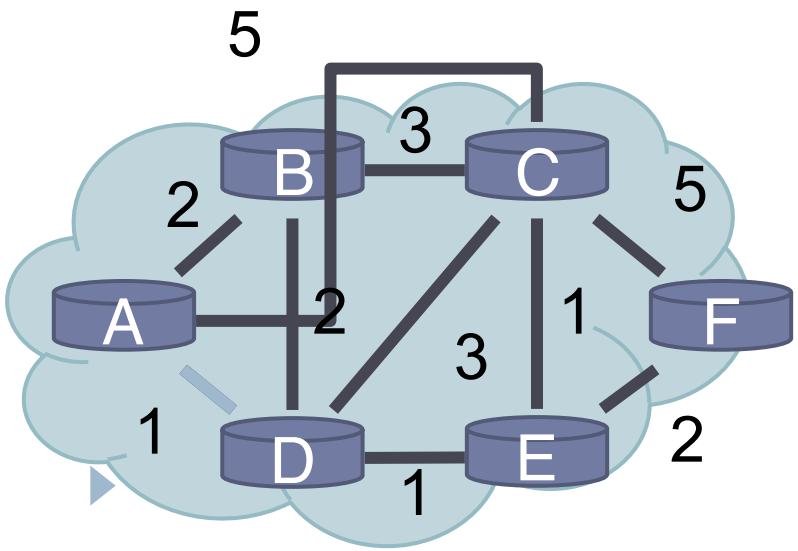


…

8. ***Loop***
9. find w not in S s.t. D(w) is a minimum;
10. add w to S;
11. update D(v) for all v adjacent to w and not in S:
12. D(v) = min(D(v), D(w) + c(w,v));
13. ***until all nodes in S;***

Dijkstra's Algorithm

Step	Start S	→B	→C	→D	→E	→F
0	A	2, A	5, A	1, A	∞	∞
1	AD		4, D		2, D	∞

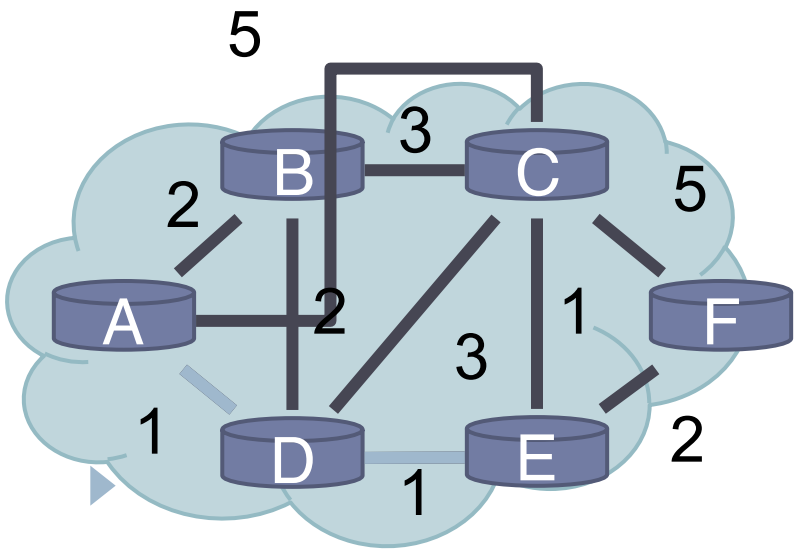


…

8. ***Loop***
9. find w not in S s.t. D(w) is a minimum;
10. add w to S;
11. update D(v) for all v adjacent to w and not in S:
12. D(v) = min(D(v), D(w) + c(w,v));
13. ***until all nodes in S;***

Dijkstra's Algorithm

Step	Start S	→B	→C	→D	→E	→F
0	A	2, A	5, A	1, A	∞	∞
1	AD		4, D		2, D	∞
2	ADE		3, E			4, E

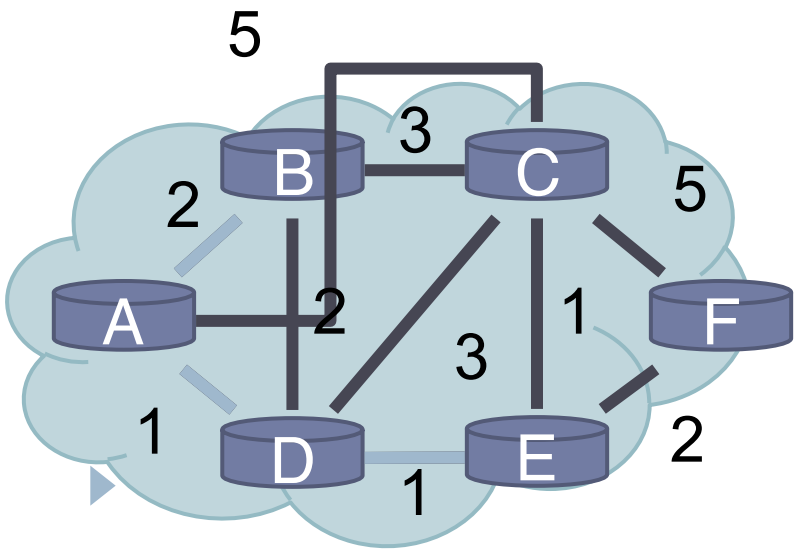


…

8. ***Loop***
9. find w not in S s.t. D(w) is a minimum;
10. add w to S;
11. update D(v) for all v adjacent to w and not in S:
12. D(v) = min(D(v), D(w) + c(w,v));
13. ***until all nodes in S;***

Dijkstra's Algorithm

Step	Start S	→B	→C	→D	→E	→F
0	A	2, A	5, A	1, A	∞	∞
1	AD		4, D		2, D	∞
2	ADE		3, E			4, E
3	ADEB					

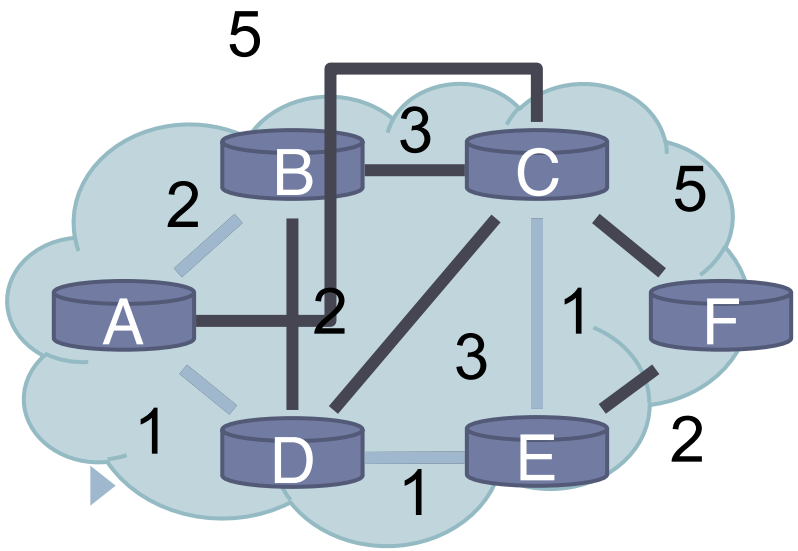


…

8. ***Loop***
9. find w not in S s.t. D(w) is a minimum;
10. add w to S;
11. update D(v) for all v adjacent to w and not in S:
12. D(v) = min(D(v), D(w) + c(w,v));
13. ***until all nodes in S;***

Dijkstra's Algorithm

Step	Start S	→B	→C	→D	→E	→F
0	A	2, A	5, A	1, A	∞	∞
1	AD		4, D		2, D	∞
2	ADE		3, E			4, E
3	ADEB					
4	ADEBC					

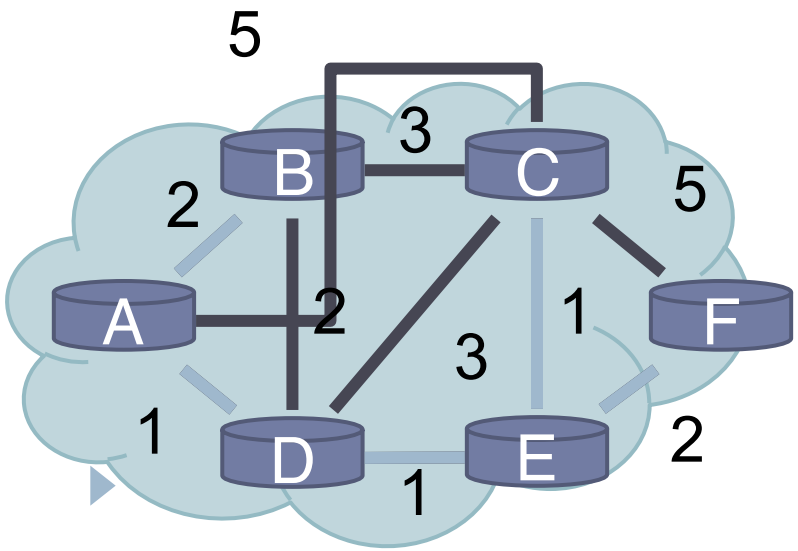


…

8. ***Loop***
9. find w not in S s.t. D(w) is a minimum;
10. add w to S;
11. update D(v) for all v adjacent to w and not in S:
12. D(v) = min(D(v), D(w) + c(w,v));
13. ***until all nodes in S;***

Dijkstra's Algorithm

Step	Start S	→B	→C	→D	→E	→F
0	A	2, A	5, A	1, A	∞	∞
1	AD		4, D		2, D	∞
2	ADE		3, E			4, E
3	ADEB					
4	ADEBC					
5	ADEBCF					



…

8. ***Loop***
9. find w not in S s.t. D(w) is a minimum;
10. add w to S;
11. update D(v) for all v adjacent to w and not in S:
12. D(v) = min(D(v), D(w) + c(w,v));
13. ***until all nodes in S;***

OSPF vs. IS-IS

- Two different implementations of link-state routing

OSPF	IS-IS

OSPF vs. IS-IS

- Two different implementations of link-state routing

OSPF	IS-IS
Favored by companies, datacenters	

OSPF vs. IS-IS

- Two different implementations of link-state routing

OSPF	IS-IS
Favored by companies, datacenters More optional features	

OSPF vs. IS-IS

- Two different implementations of link-state routing

OSPF

- Favored by companies, datacenters
- More optional features
- Built on top of IPv4
  - LSAs are sent via IPv4
  - OSPFv3 needed for IPv6

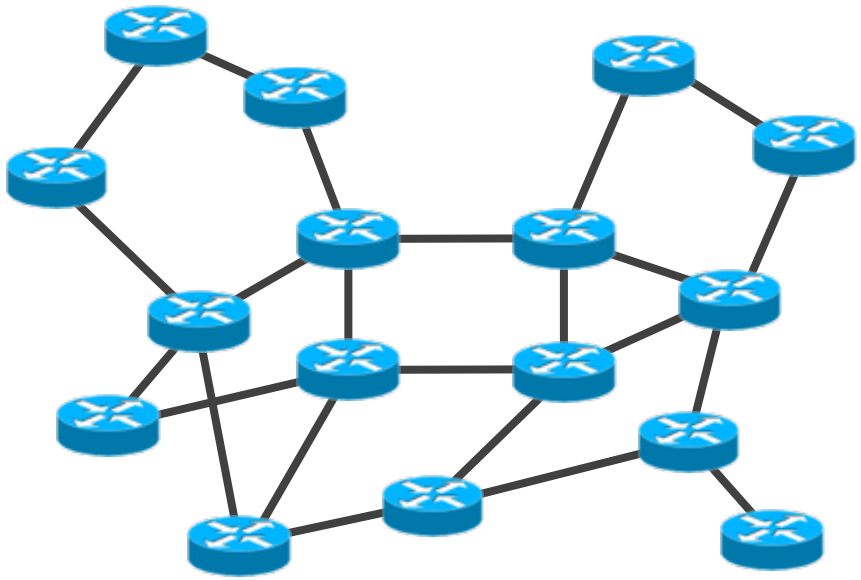
IS-IS

- Favored by ISPs
- Less “chatty”
  - Less network overhead
  - Supports more devices
- Not tied to IP
  - Works with IPv4 or IPv6

Different Organizational Structure

OSPF

- Organized around overlapping areas
- Area 0 is the core network

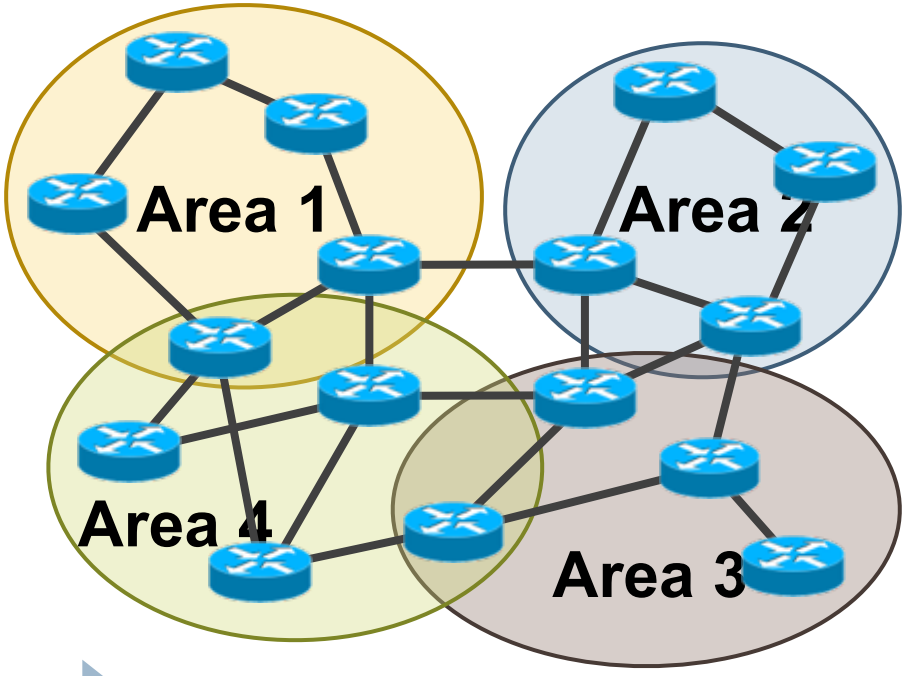


IS-IS

Different Organizational Structure

OSPF

- Organized around overlapping areas
- Area 0 is the core network

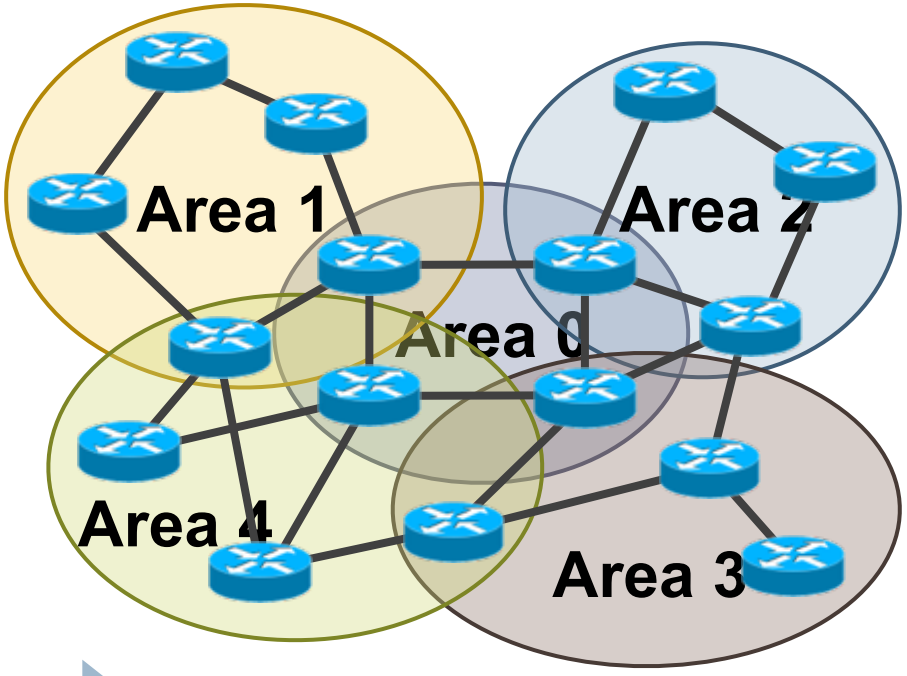


IS-IS

Different Organizational Structure

OSPF

- Organized around overlapping areas
- Area 0 is the core network

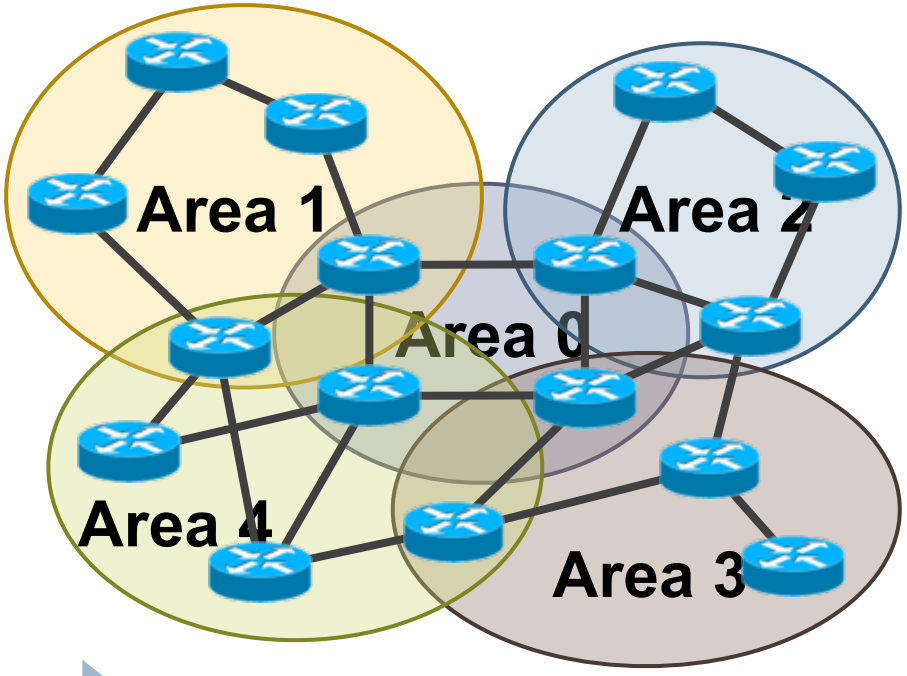


IS-IS

Different Organizational Structure

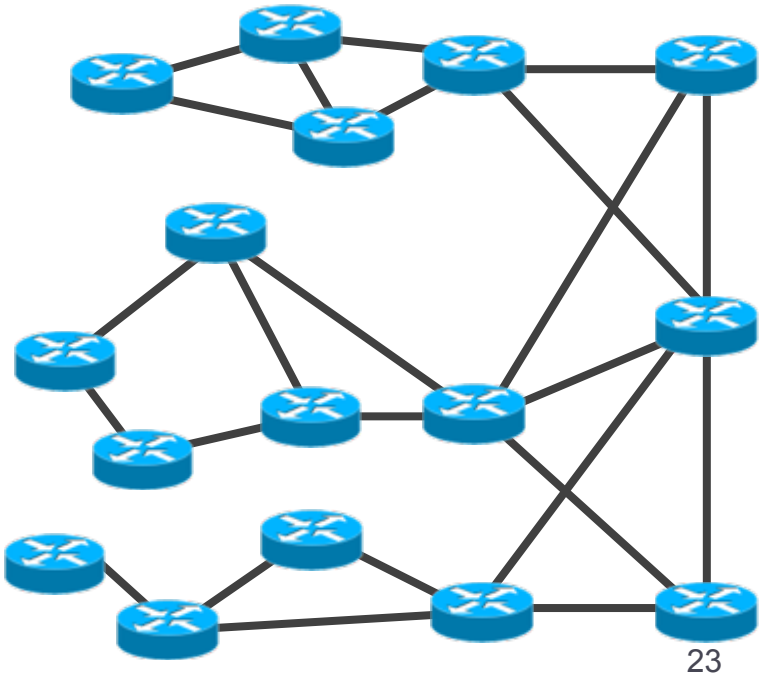
OSPF

- Organized around overlapping areas
- Area 0 is the core network



IS-IS

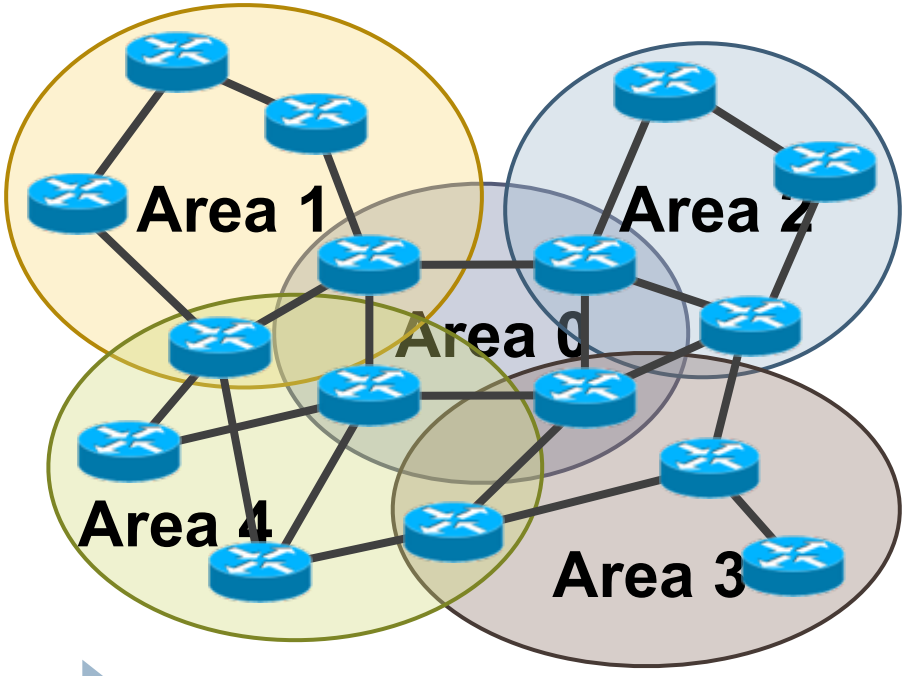
- Organized as a 2-level hierarchy



Different Organizational Structure

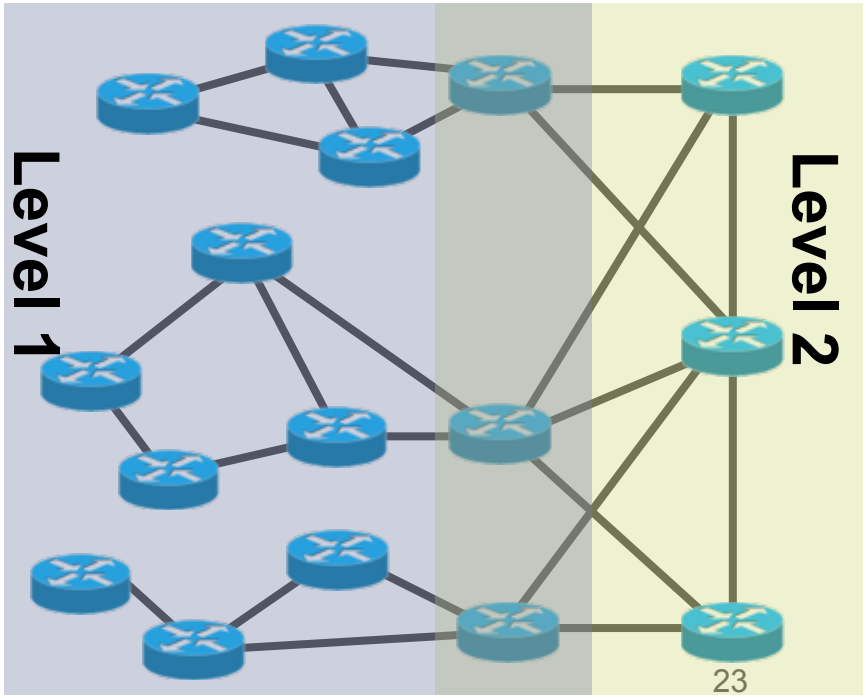
OSPF

- Organized around overlapping areas
- Area 0 is the core network



IS-IS

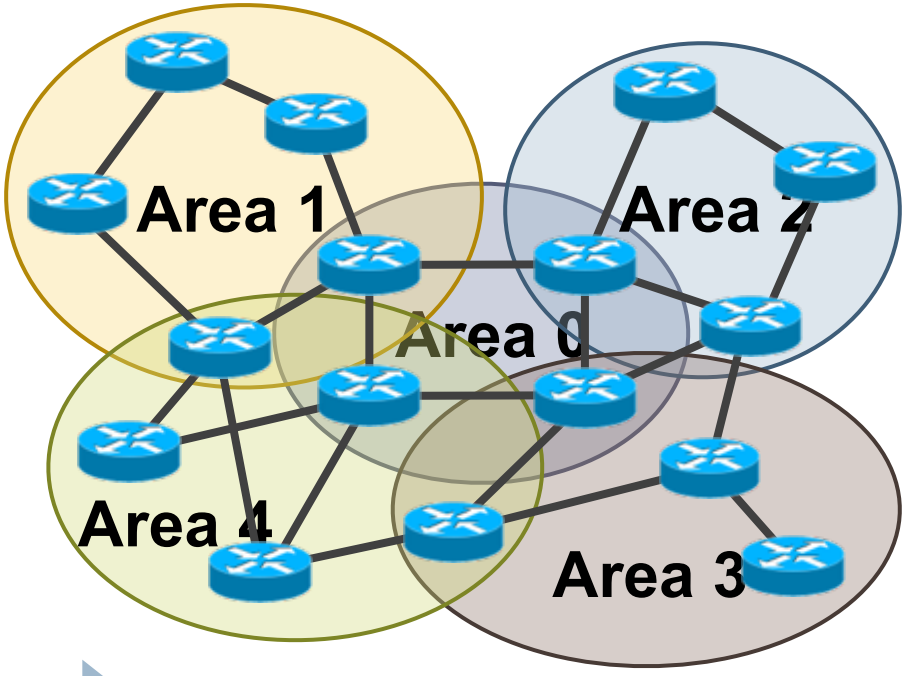
- Organized as a 2-level hierarchy



Different Organizational Structure

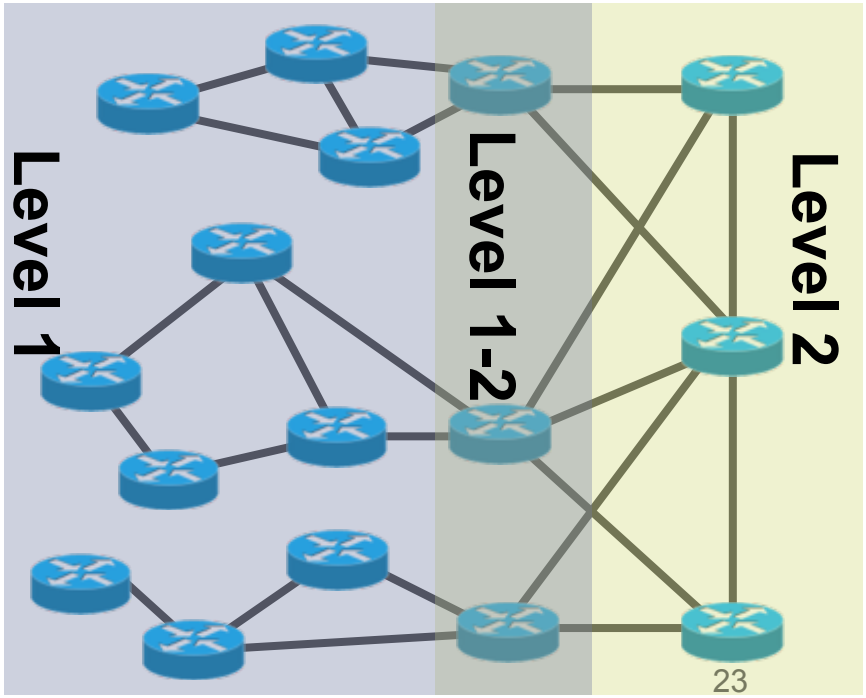
OSPF

- Organized around overlapping areas
- Area 0 is the core network



IS-IS

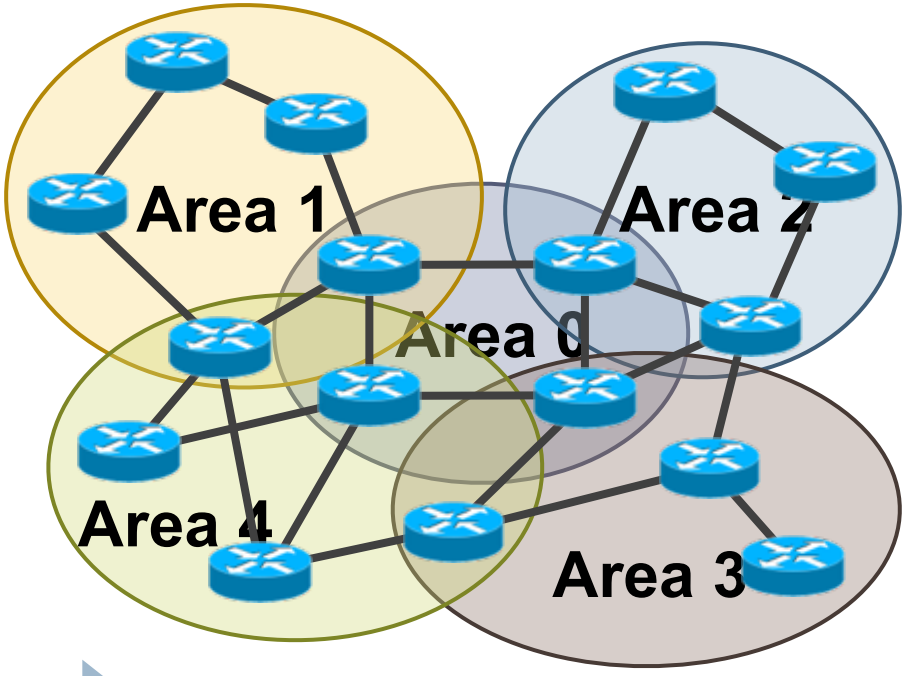
- Organized as a 2-level hierarchy



Different Organizational Structure

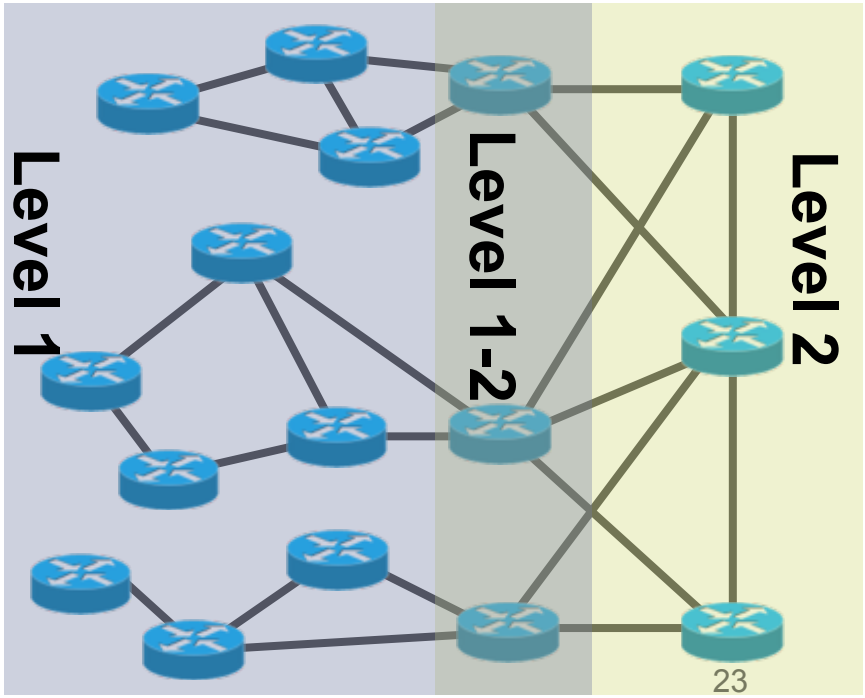
OSPF

- Organized around overlapping areas
- Area 0 is the core network



IS-IS

- Organized as a 2-level hierarchy
- Level 2 is the backbone



Link State vs. Distance Vector

	Link State	Distance Vector
Message Complexity	$O(n^2*e)$	O(d*n*k)
Time Complexity	O(n*log n)	O(n)
Convergence Time	O(1)	O(k)
Robustness	• Nodes may advertise incorrect link costs • Each node computes their own table	• Nodes may advertise incorrect path cost • Errors propagate due to sharing of DV tables

n = number of nodes in the graph
d = degree of a given node
k = number of rounds

Link State vs. Distance Vector

	Link State	Distance Vector
Message Complexity	$O(n^2*e)$	O(d*n*k)
Time Complexity	O(n*log n)	O(n)
Convergence Time	O(1)	O(k)
Robustness	• Nodes may advertise incorrect link costs • Each node computes their own table	• Nodes may advertise incorrect path cost • Errors propagate due to sharing of DV tables

- Which is best?
- In practice, it depends.
- In general, link state is more popular.