COMP9121: Design of Networks and Distributed Systems

Week 5: Network Layer 2

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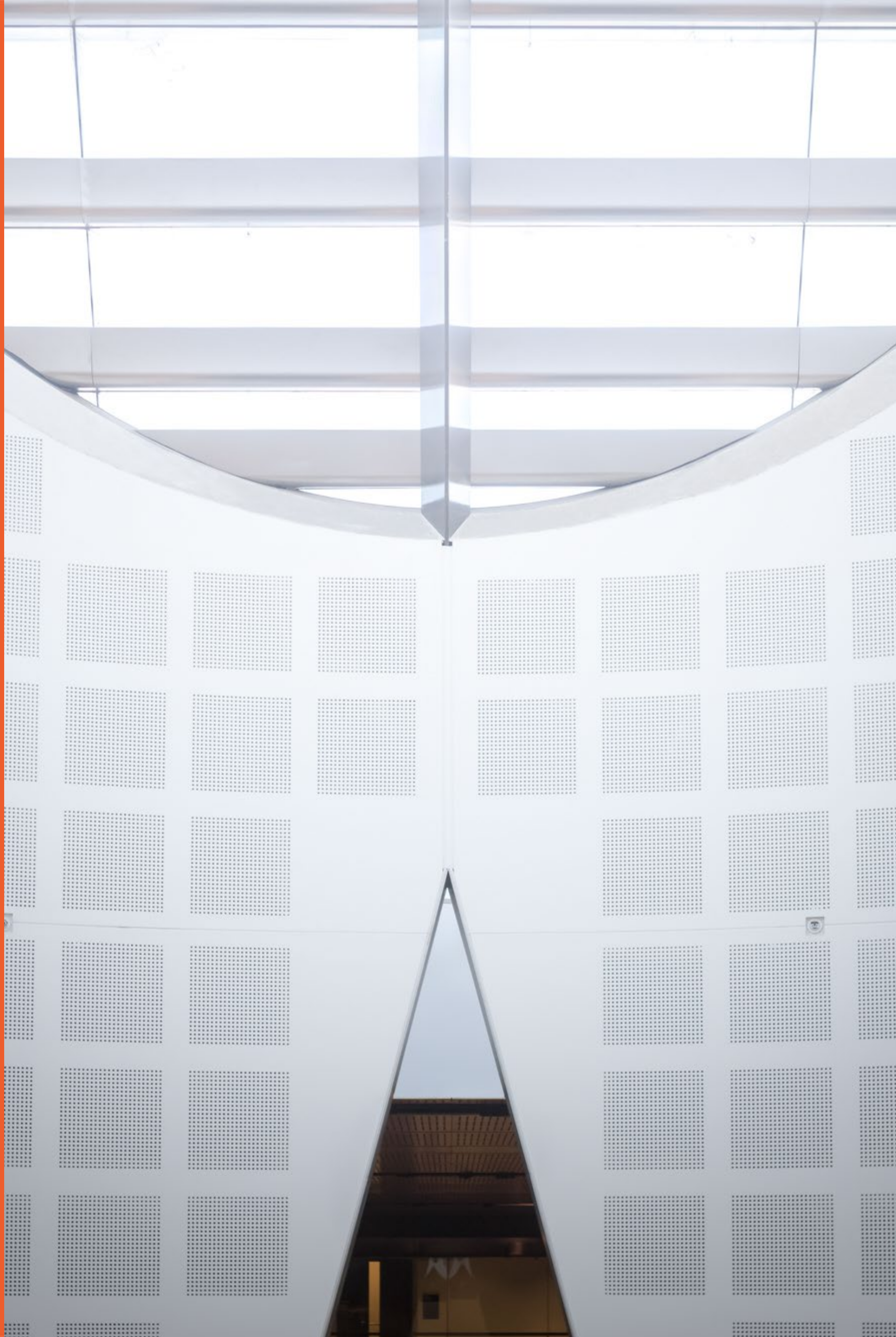
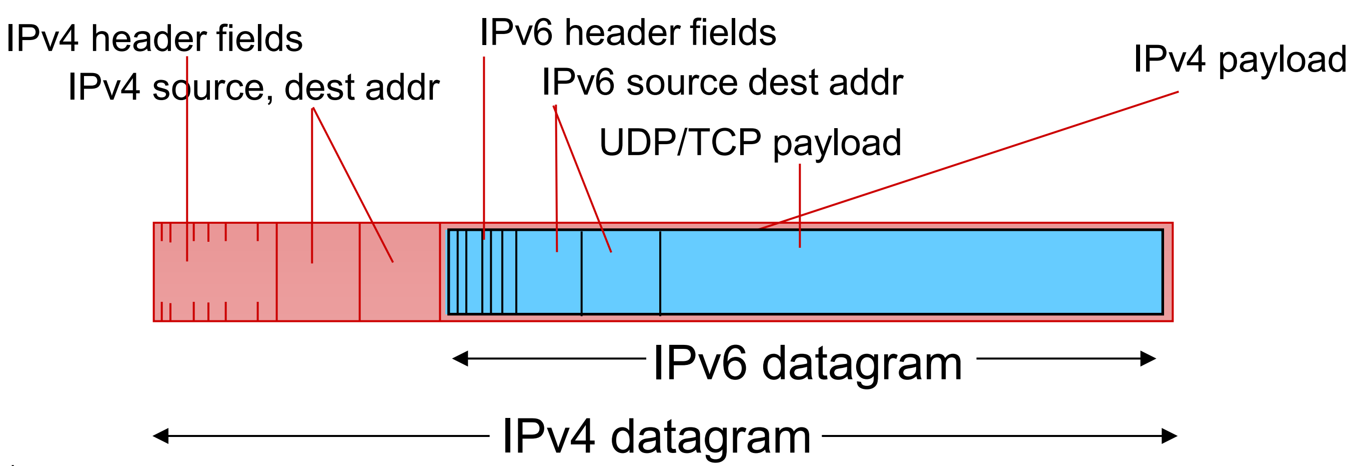
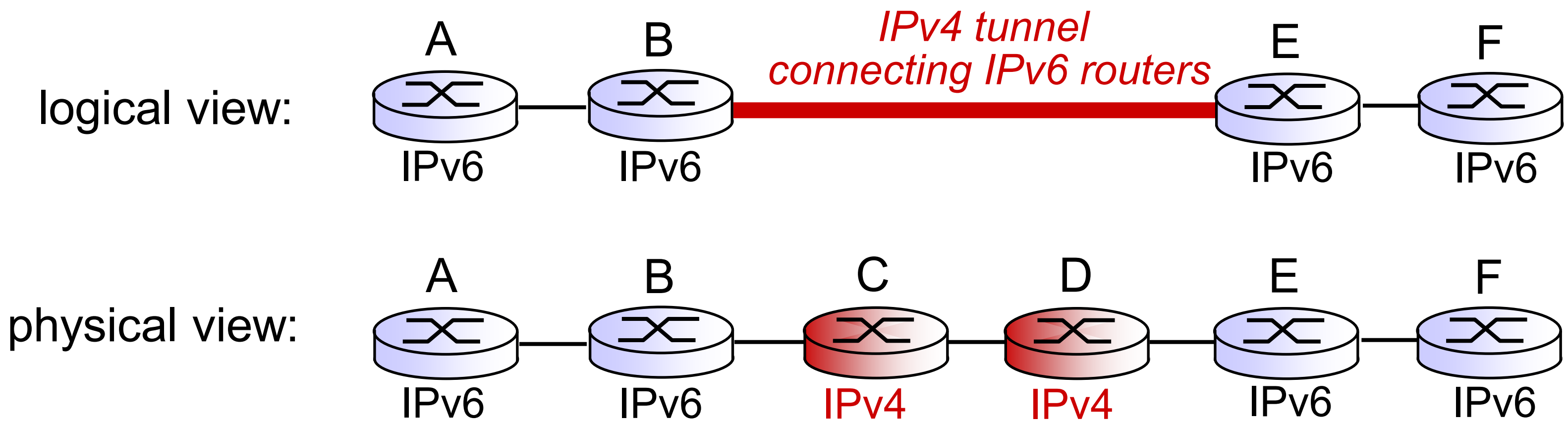


Transition from IPv4 to IPv6

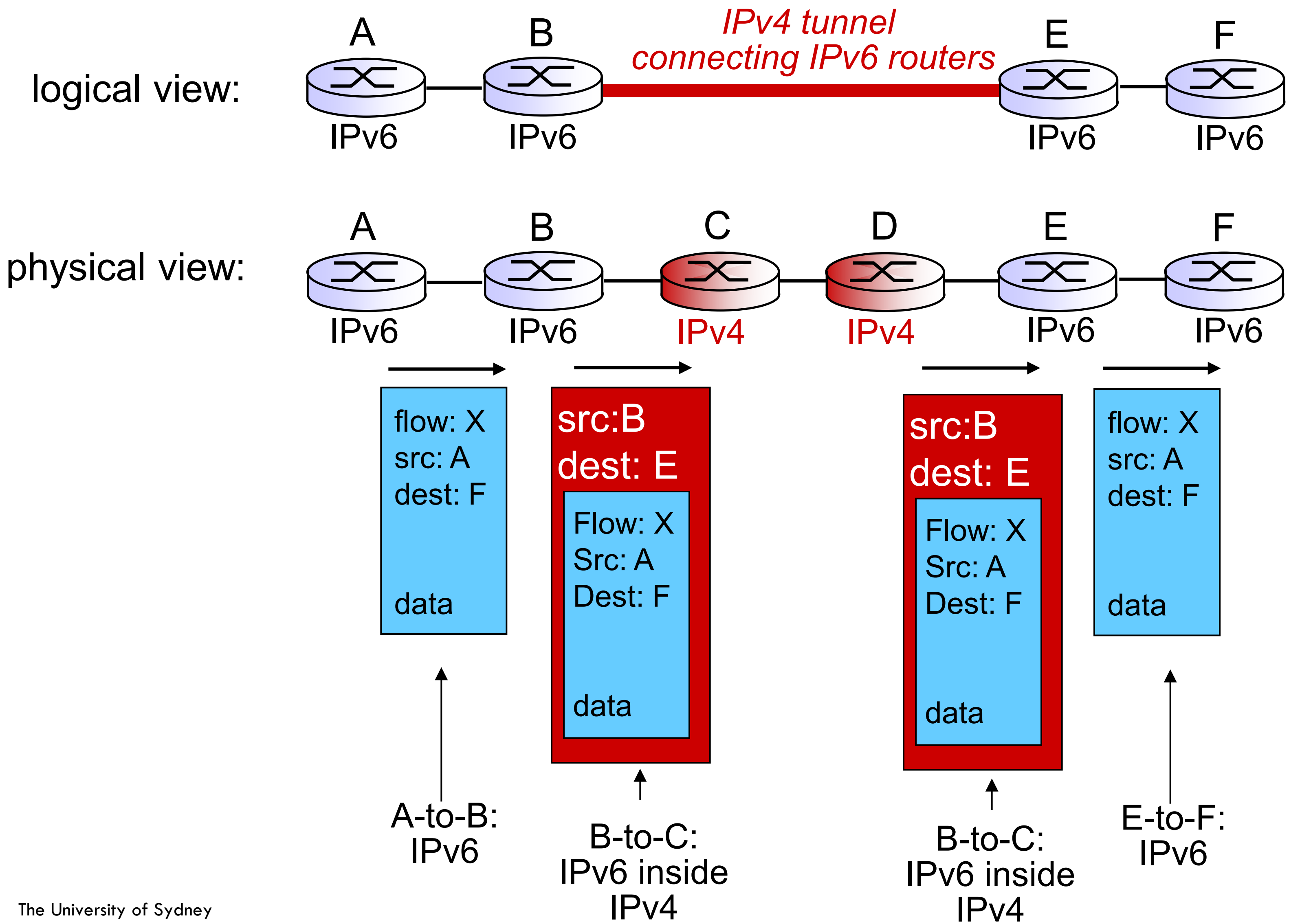
- not all routers can be upgraded simultaneously
  - no "flag days"
  - how will network operate with mixed IPv4 and IPv6 routers?
- *tunneling:* IPv6 datagram carried as *payload* in IPv4 datagram among IPv4 routers



Tunneling


IPv4 tunnel
connecting IPv6 routers
A
B
E
F
logical view:
IPv6
IPv6
IPv6
IPv6
A
B
C
D
E
F
physical view:
IPv6
IPv6
IPv4
IPv4
IPv6
IPv6

Tunneling

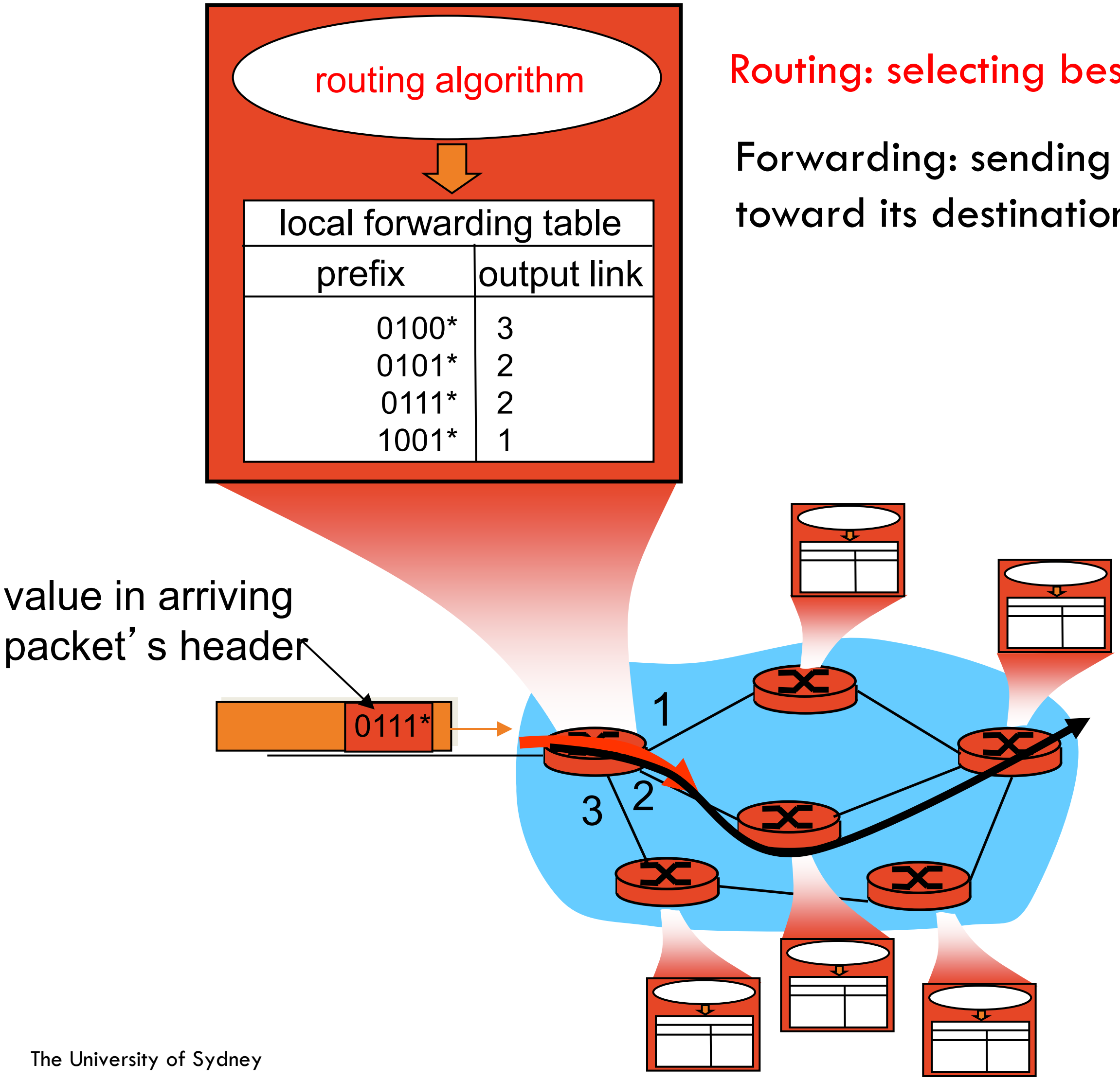


logical view:
A
B
IPv4 tunnel
connecting IPv6 routers
E
F
IPv6
IPv6
IPv6
IPv6
physical view:
A
B
C
D
E
F
IPv6
IPv6
IPv4
IPv4
IPv6
IPv6
flow: X
src: A
dest: F
data
src:B
dest: E
Flow: X
Src: A
Dest: F
data
src:B
dest: E
Flow: X
Src: A
Dest: F
data
flow: X
src: A
dest: F
data
A-to-B:
IPv6
B-to-C:
IPv6 inside
IPv4
B-to-C:
IPv6 inside
IPv4
E-to-F:
IPv6

Routing and forwarding

Routing: selecting best paths in a network.

Forwarding: sending the packet to the next-hop toward its destination

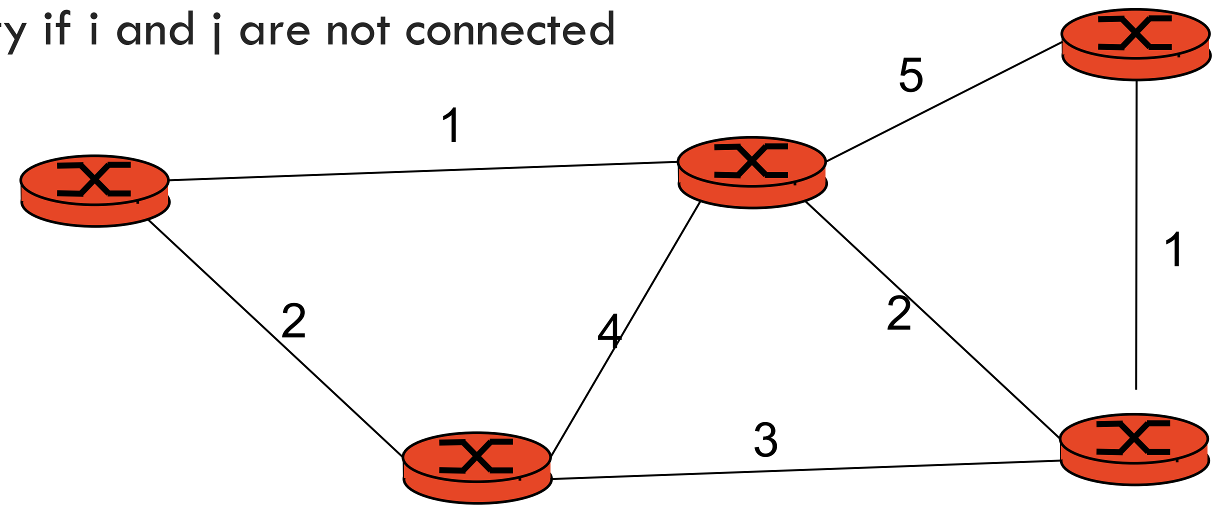


Link Cost

i: i-th node (router).

C_{ij}: link cost between i and j

C_{ij} = infinity if i and j are not connected



Aim: Shortest path.

Classification

Global or decentralized information?

Global:

- all routers have complete topology, link cost info
- “link state” algorithms

Decentralized:

- router only knows physically-connected neighbors, link costs to neighbors
- “distance vector” algorithms

Link State Algorithm: Dijkstra

Link-State Algorithm

- Basic idea: **two step** procedure
  - 1 Each source node gets a **map** of all nodes and link costs of the entire network
  - 2 Find the **shortest path** on the map from the source node to all destination nodes
- Step 1: Broadcast of link-state information
  - Every node *i* in the network broadcasts to every other node in the network:
    - ID's of its neighbors: $\mathcal{N}_i$=set of neighbors of i
    - Distances to its neighbors: $\{C_{ij} \mid j \in N_i\}$
  - Flooding is a popular method of broadcasting packets
- Step 2: Dijkstra

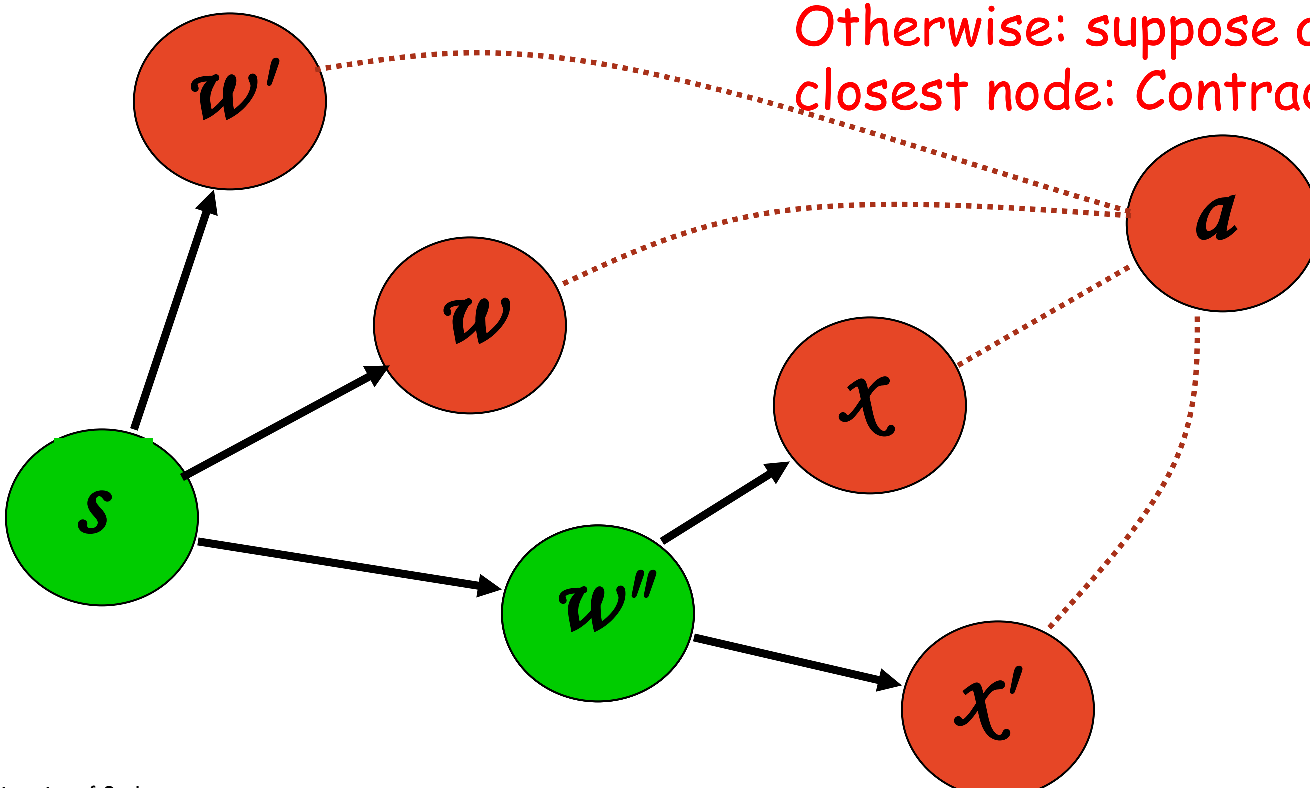
Dijkstra Algorithm: Finding shortest paths in order

Find shortest paths from source s to all other destinations

Closest node to s is 1 hop away

2nd closest node to s is 1 hop away from s or w"

Otherwise: suppose a is the 2nd closest node: Contradiction!



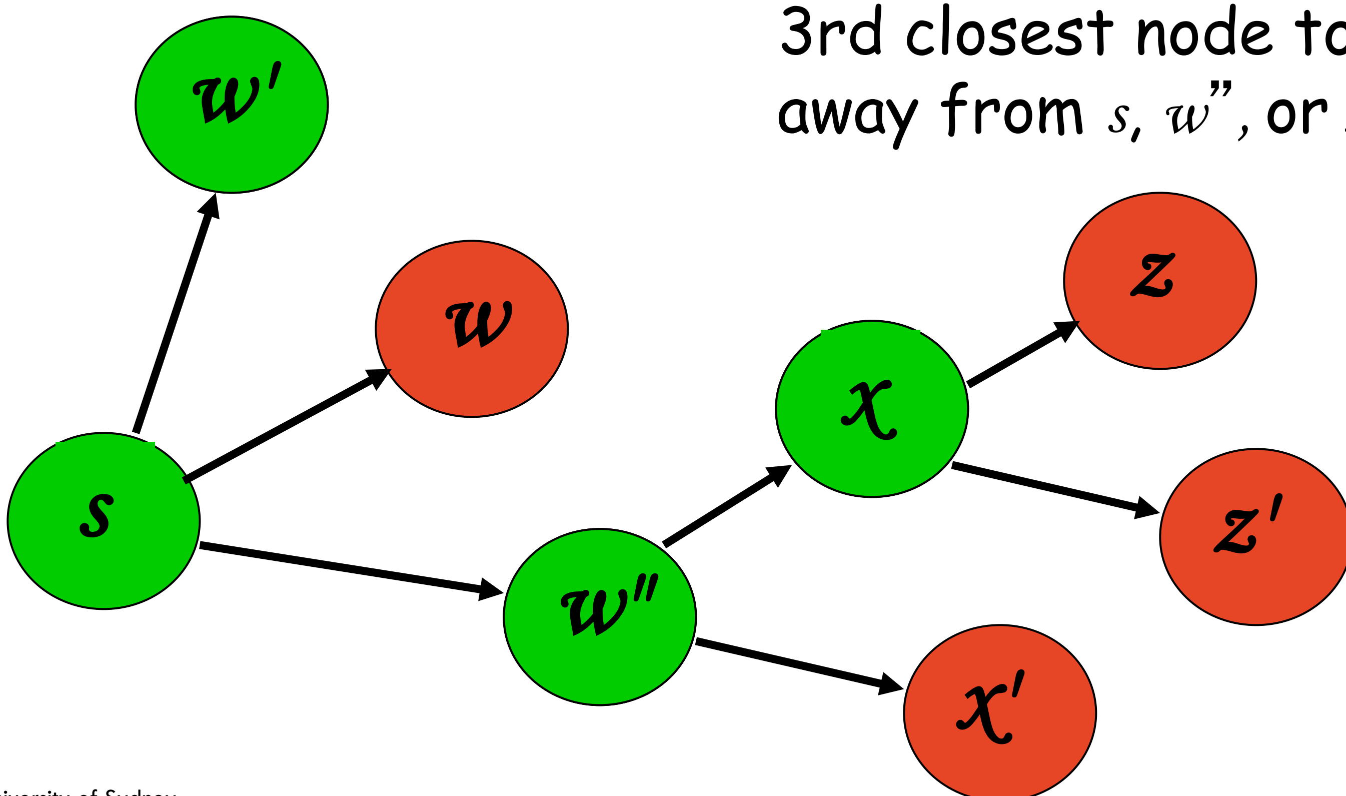
Dijkstra Algorithm: Finding shortest paths in order

Find shortest paths from source s to all other destinations

Closest node to s is 1 hop away

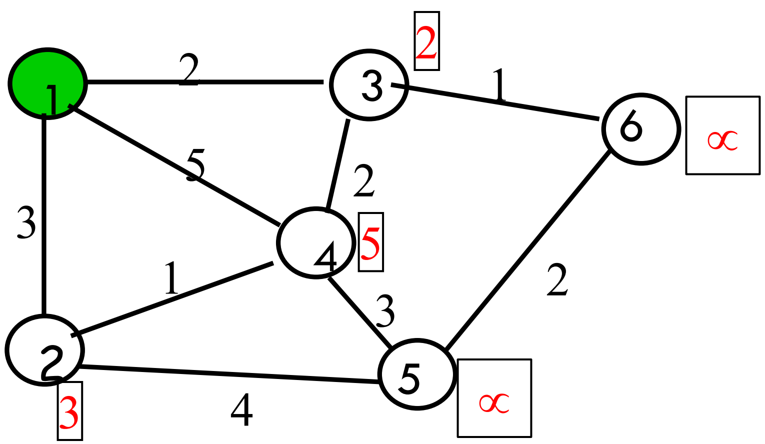
2nd closest node to s is 1 hop away from s or w"

3rd closest node to s is 1 hop away from s, w", or x



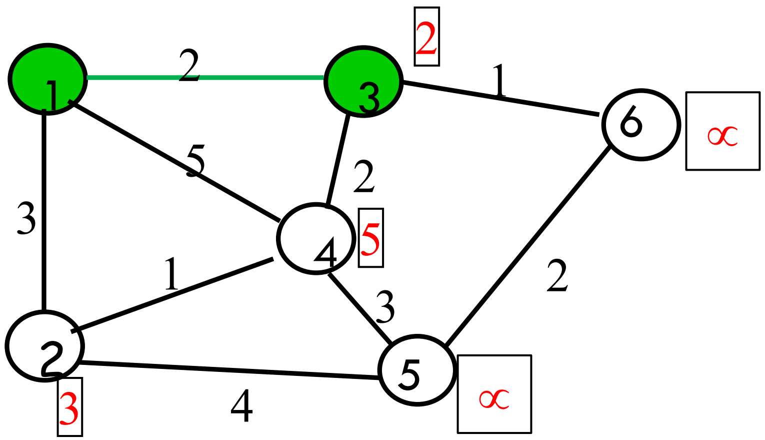
Dijkstra's algorithm

- C_{ij}: distance/cost from i to j
- D_j: current shortest distance from s to j
- N: set of nodes for which shortest path already found
- **Initialization: *(Start with source node s)***
  - $N = \{s\}$, $D_s = 0$, "*s* is distance zero from itself"
  - $D_j = C_{sj}$ for all $j \neq s$, distances of directly-connected neighbors



Dijkstra's algorithm

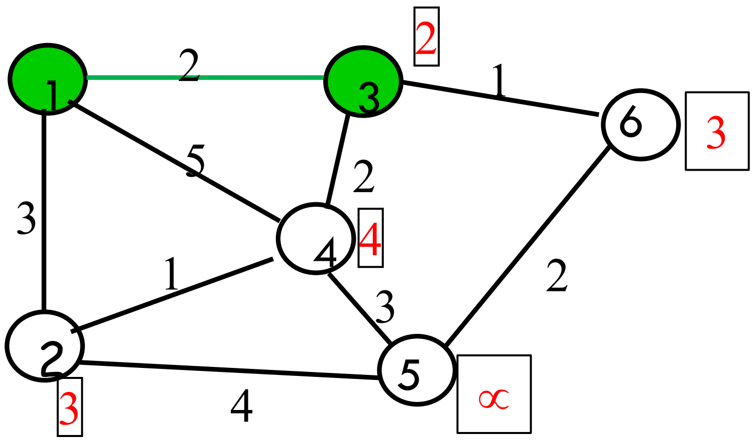
- **Step A: (*Find next closest node i*)**
  - Find $i \notin N$ such that
  - $D_i = \min D_j \quad$ for $j \notin N$
  - Add i to N
  - If N contains all the nodes, stop



Dijkstra’s algorithm

- **(node i was added to N last step)**
- **Other nodes may find a better way via the newly added**
- **Step B: *(update minimum costs)***
  - For each node $j \notin N$
  - $D_j = \min(D_j, D_i + C_{ij})$

*Minimum distance from s to j through node **i** in N*



Dijkstra's algorithm

- N: set of nodes for which shortest path already found
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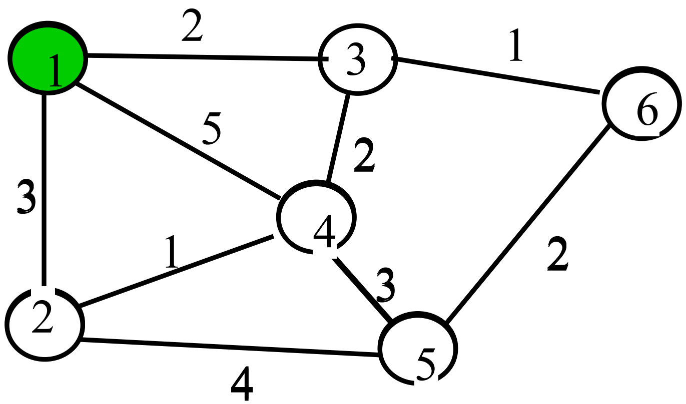
  - Find $i \notin N$ such that
  - $D_i = \min D_j$ for $j \notin N$
  - Add i to N
  - If N contains all the nodes, stop
- **Step B: *(update minimum costs)***
  - For each node $j \notin N$
  - $D_j = \min (D_j, D_i + C_{ij})$
  - Go to Step A

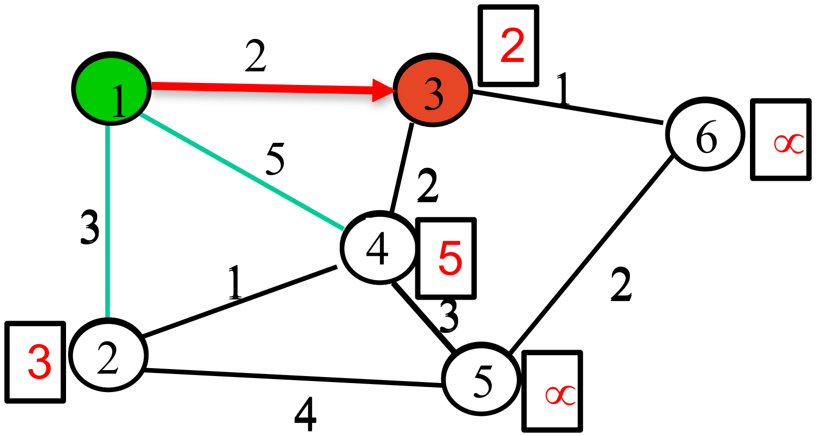
Dijkstra's algorithm: Example



Find the shortest path from 1 to all other nodes.

Iteration	Tree	N_2	N_3	N_4	N_5	N_6
Initial						
1						
2						
3						
4						
5						

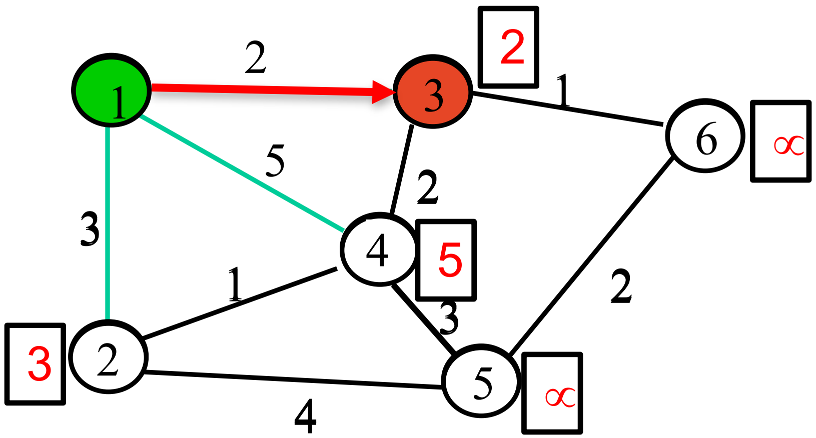
Dijkstra's algorithm: Example



(next node/last node, cost D_j)

Iteration	**Tree**	N_2	N_3	N_4	N_5	N_6
Initial	{1}	(1,3)	(1,2)	(1,5)	(-1,∝)	(-1,∝)
1						
2						
3						
4						
5						

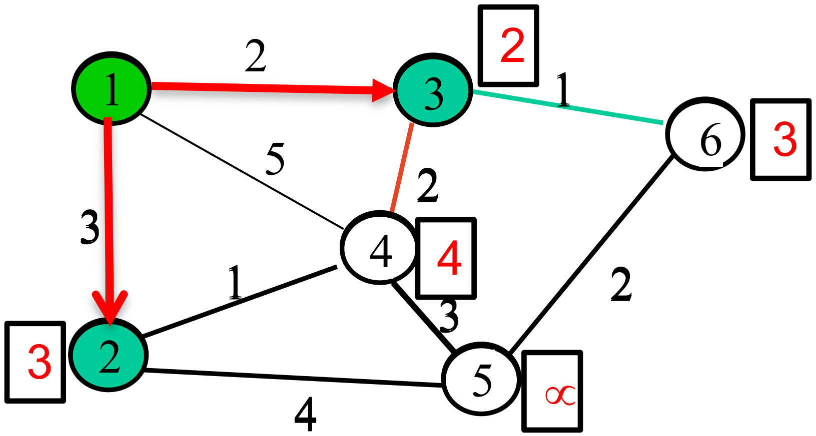
Dijkstra's algorithm: Example



(next node/last node, cost)

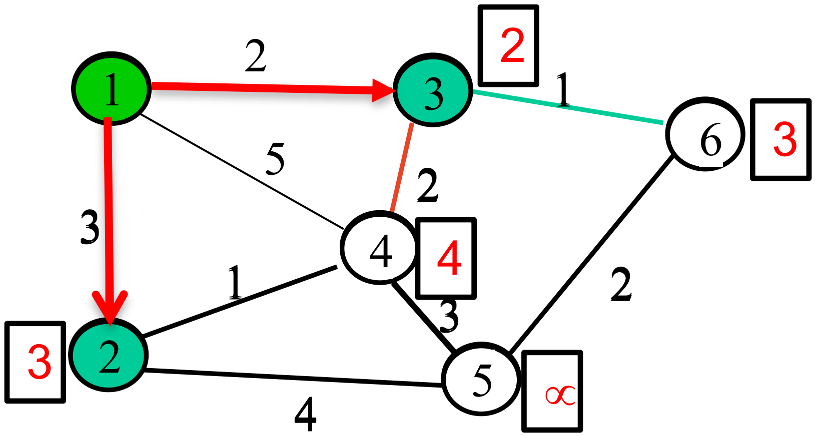
Iteration	**Tree**	N_2	N_3	N_4	N_5	N_6
Initial	{1}	(1,3)	(1,2)	(1,5)	(-1,∝)	(-1,∝)
1	{1, 3}					
2						
3						
4						
5						

Dijkstra's algorithm: Example



Iteration	**Tree**	N_2	N_3	N_4	N_5	N_6
Initial	{1}	(1,3)	(1,2)	(1,5)	(-1,∝)	(-1,∝)
1	{1,3}	(1,3)		(3,4)	(-1,∝)	(3,3)
2						
3						
4						
5						

Dijkstra's algorithm: Example



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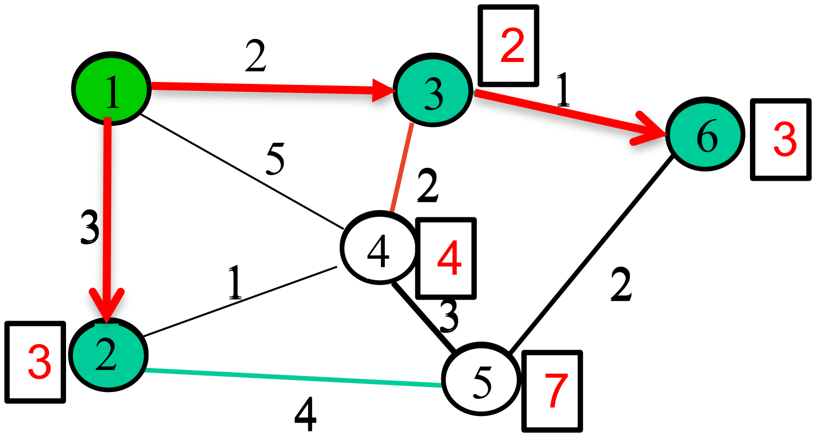
2	{1,2,3}					
3						
4						
5						

Dijkstra's algorithm: Example



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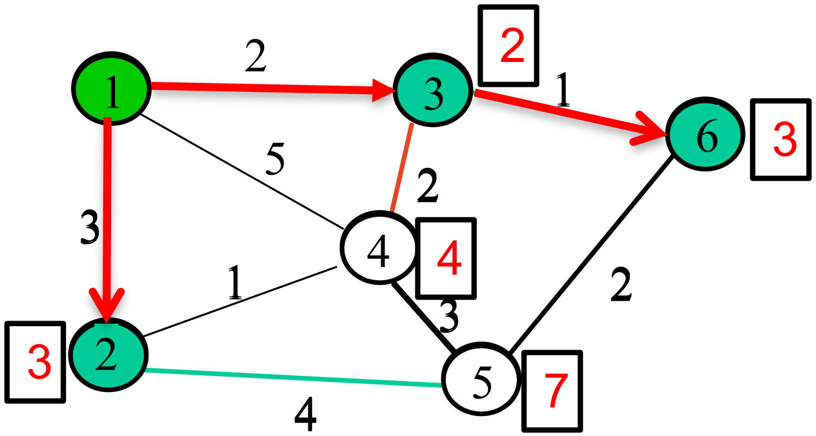
1	{1,3}	(1,3)		(3,4)	(-1,∝)	(3,3)
2	{1,2,3}			(3,4)	(2,7)	(3,3)
3						
4						
5						

Dijkstra's algorithm: Example



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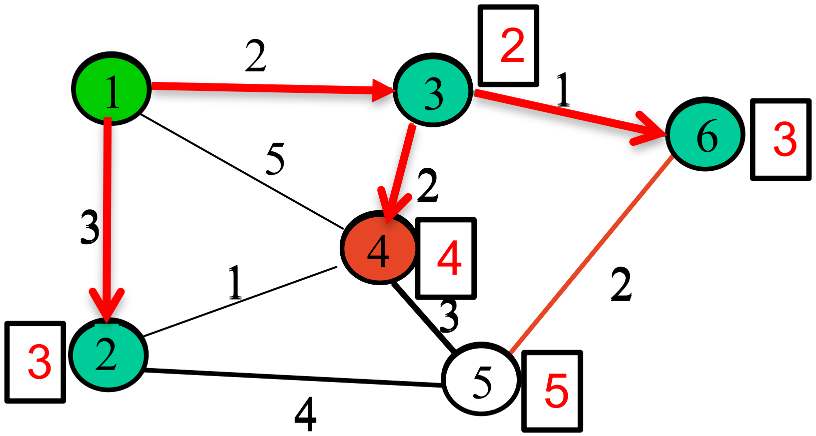
4						
5						

Dijkstra's algorithm: Example



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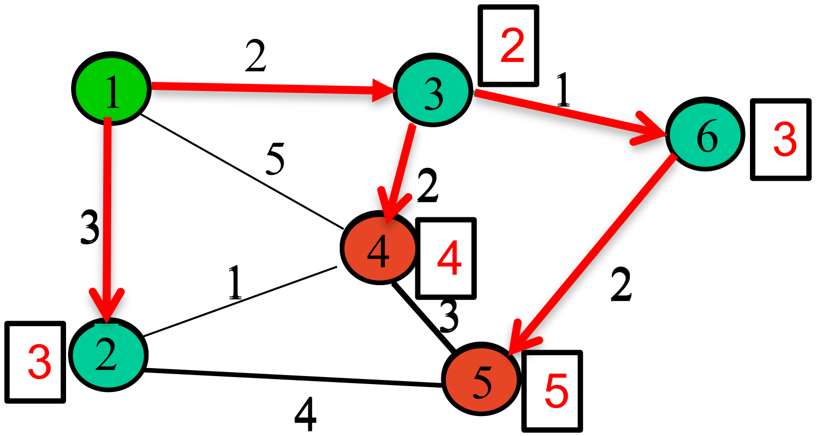
3	{1,2,3,6}			(3,4)	(6,5)	
4						
5						

Dijkstra's algorithm: Example



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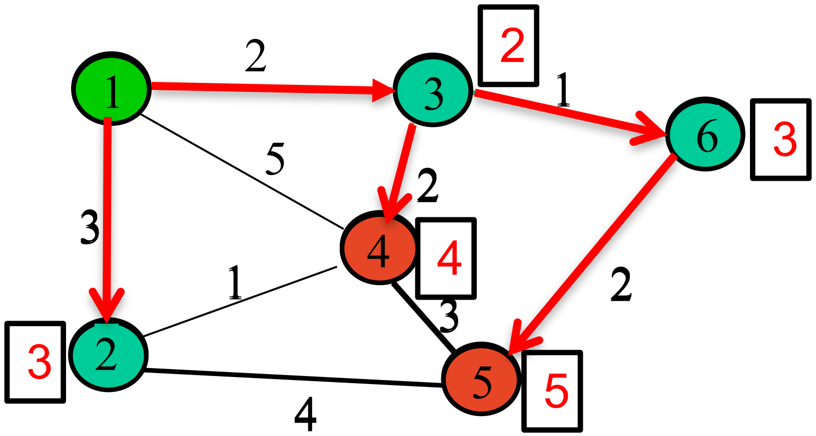
3	{1,2,3,6}			(3,4)	(6,5)	
4	{1,2,3,4,6}				(6,5)	

Dijkstra's algorithm: Example



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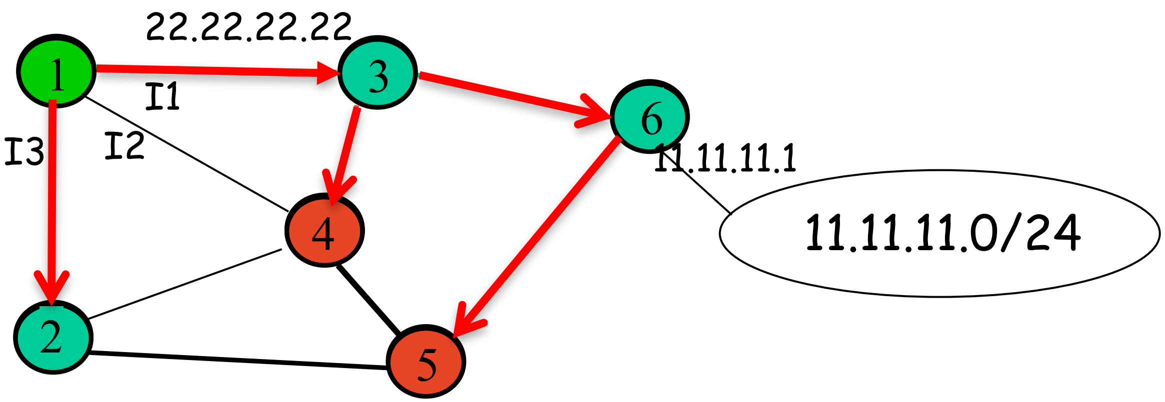
1	{1,3}	(1,3)		(3,4)	(-1,∝)	(3,3)
2	{1,2,3}			(3,4)	(2,7)	(3,3)
3	{1,2,3,6}			(3,4)	(6,5)	
4	{1,2,3,4,6}				(6,5)	
5	{1,2,3,4,5,6}	(1,3)	(1,2)	(3,4)	(6,5)	(3,3)

Forwarding table



For presentation convenance
Destination can be: Node name,
IP address, IP prefix, etc.

routing algorithm

local forwarding table at 1

Destination	Next Node
2	2
3	3
4	3
5	3
6	3

Destination can be: Node name,
IP address, interface, etc.

routing algorithm

local forwarding table at 1

Destination	Next Node/Hop/ Router
11.11.11.0/24 Or 11.11.11.1 Or Node 6	Node 3 Or Interface I1 Or 22.22.22.22

Reaction to Failure

- If a link fails,
  - Router sets link distance to infinity & floods the network with an update packet
  - All routers immediately update their link database & recalculate their shortest paths
  - Recovery very quick
- But watch out for old update messages
  - Add time stamp or sequence # to each update message
  - Check whether each received update message is new
  - If new, add it to database and broadcast
  - If older, send update message on arriving link

Dijkstra's algorithm, discussion

Algorithm complexity: n nodes

- each iteration: need to check all nodes, w, not in N
- operations: $O(n^2)$
- more efficient implementations possible: $O(n\log n)$
  - Using a heap to find the min.

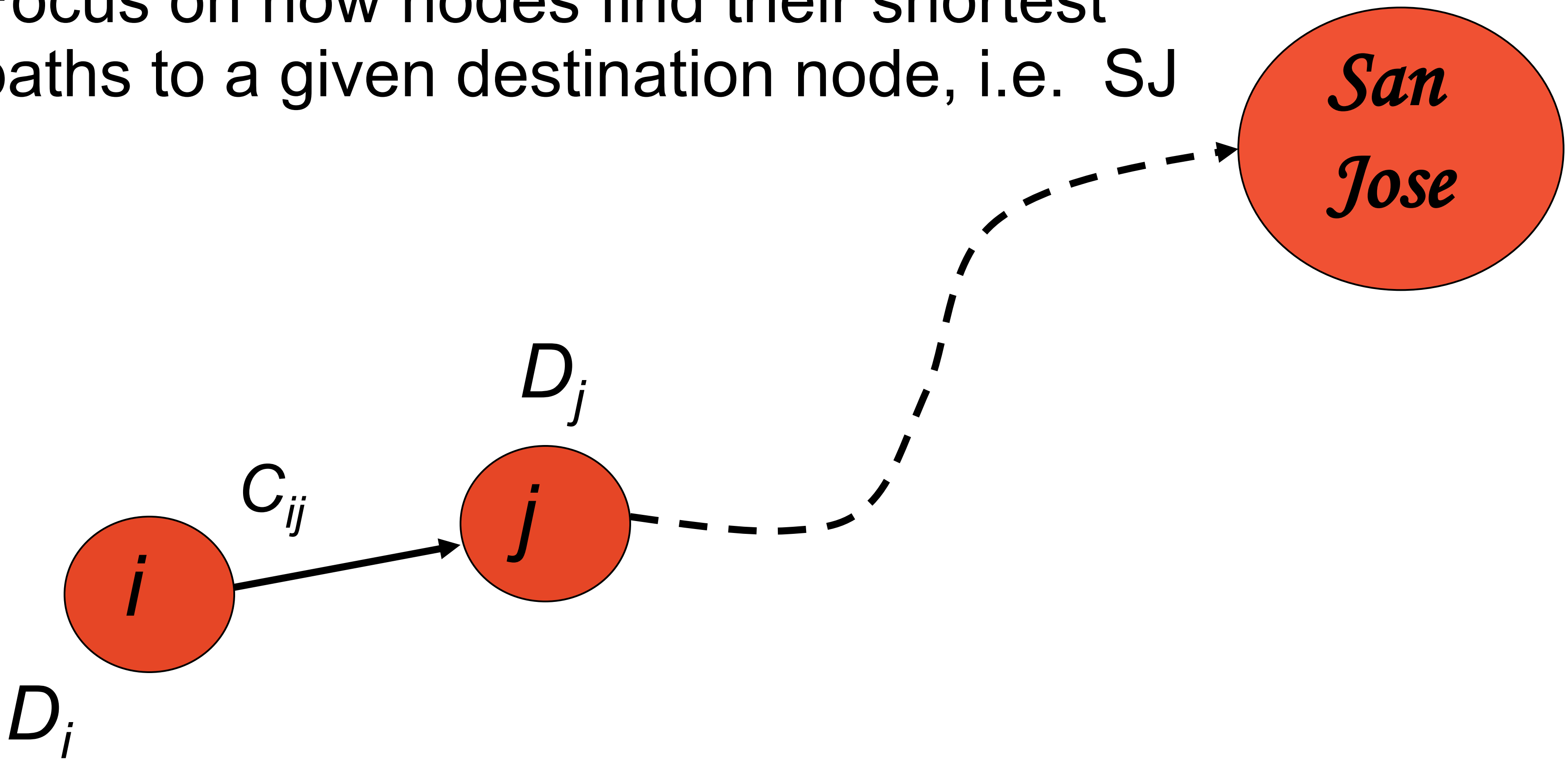
Important Concepts

- Link-state is a two-step procedure
  - Learn the map (by flooding)
  - Find the shortest path (use Dijkstra)
- LS is centralized!

Distance Vector Algorithm

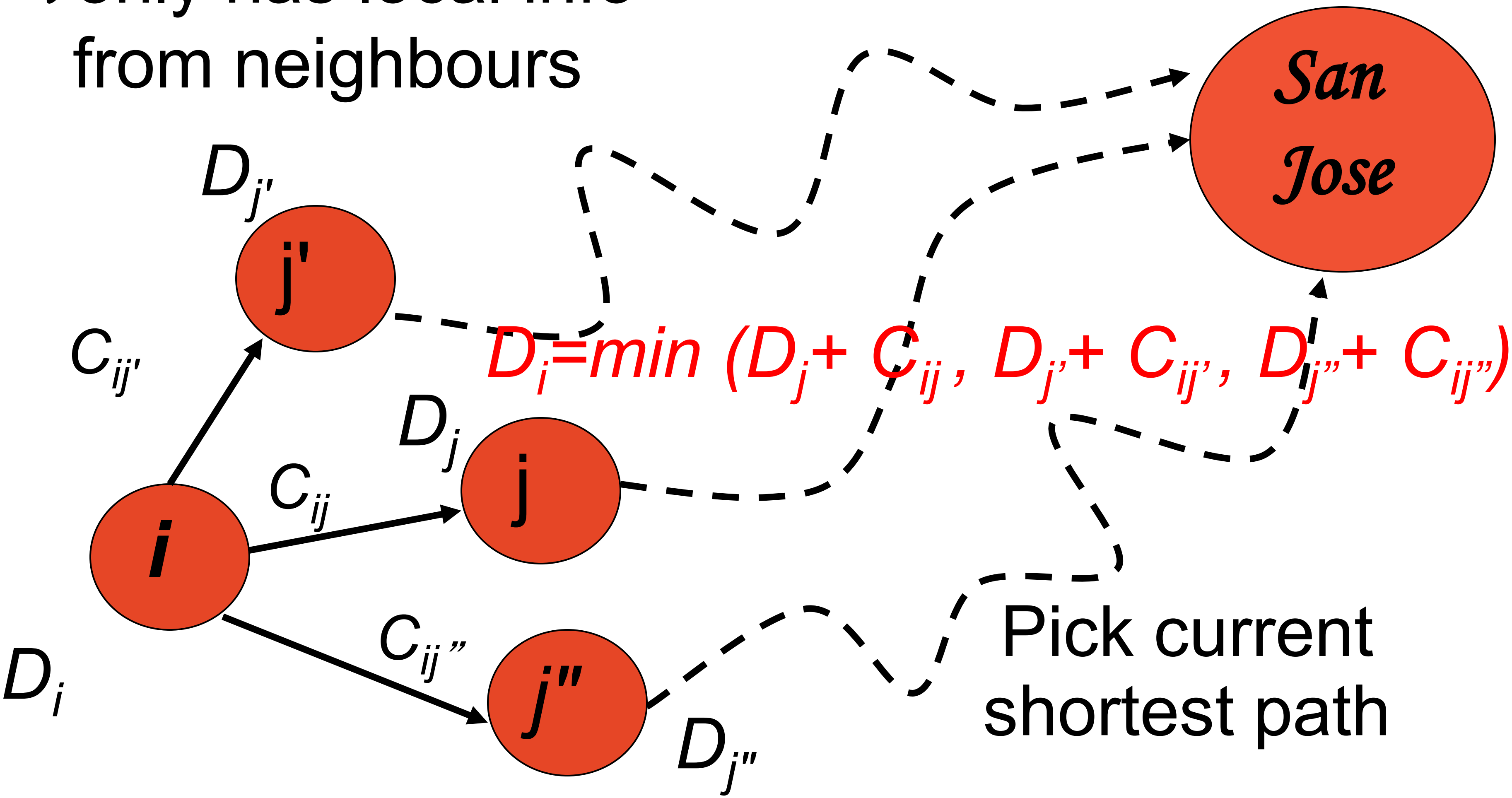
Shortest Path to SJ

Focus on how nodes find their shortest paths to a given destination node, i.e. SJ



But we don't know the shortest paths

i only has local info from neighbours



Distance Vector Algorithm

Bellman-Ford Equation (dynamic programming)

Define

$D_x(y)$:= cost of shortest path from x to y

Then

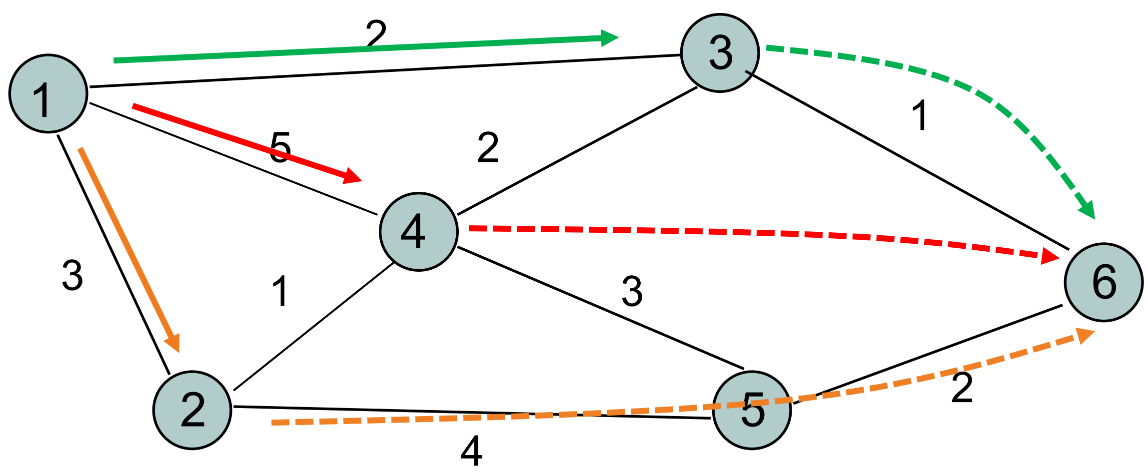
$$\boxed{D_x(y) = \min_v \{C(x,v) + D_v(y)\}}$$

where min is taken over all neighbors v of x

Destination node 6

D1 = min { 3+D2 , 2+D3 , 5+D4 }
D2 = min { 3+D1 , 1+D4 , 4+D5 }
D3 = min { 2+D1 , 2+D4 , 1 }
D4 = min { 5+D1 , 1+D2 , 2+D3 , 3+D5 }
D5 = min { 4+D2 , 3+D4 , 2 }

How to solve: Use an iterative procedure!
Use this Bellman-ford equation every round, until convergence.



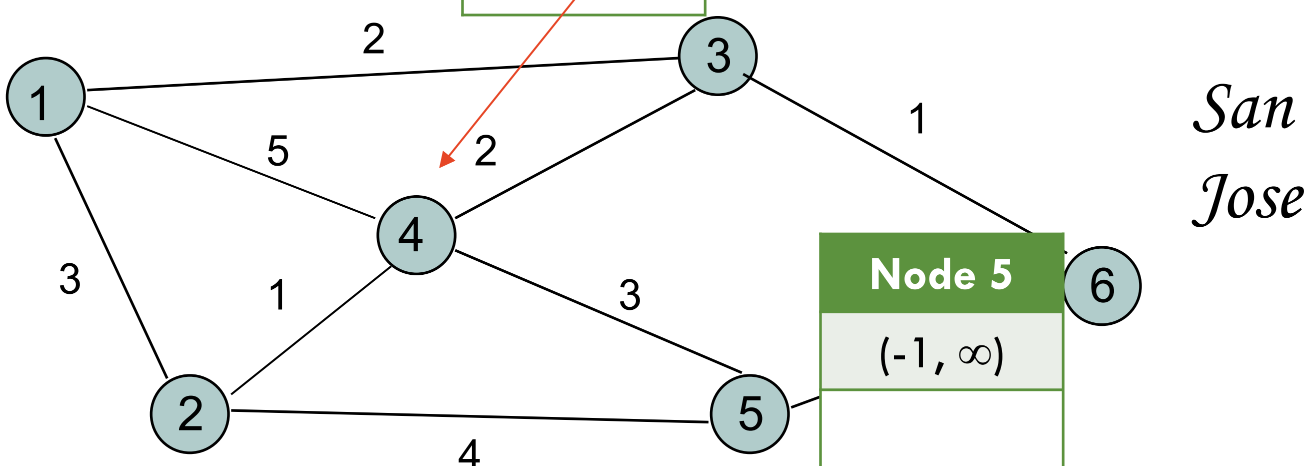
Iteration
Initial
1
2
3

Node 4
(-1, ∞)

Node 3
(-1, ∞)

Node 1
(-1, ∞)

Node 2
(-1, ∞)

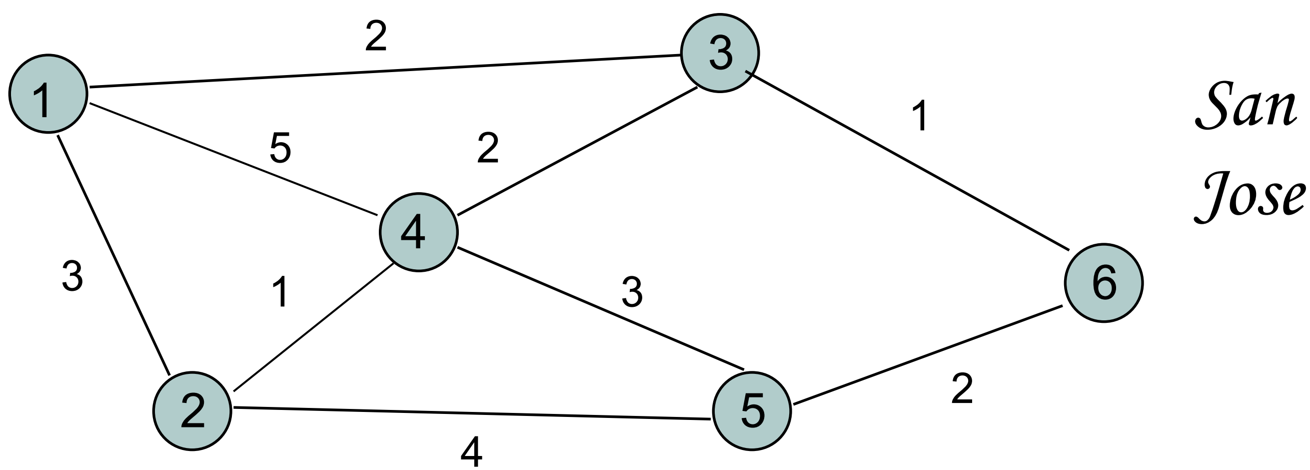


Node 5
(-1, ∞)

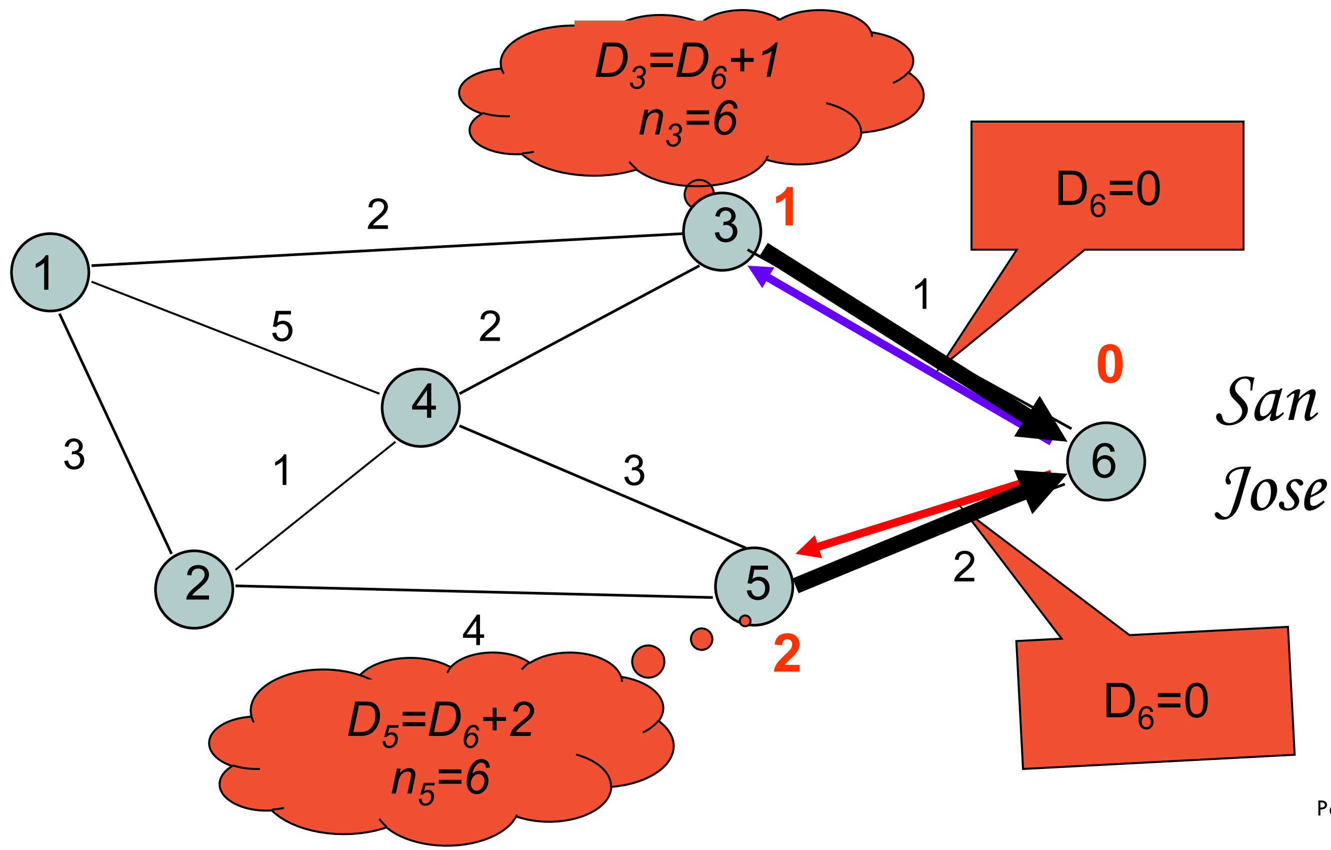
Iteration	Node 1	Node 2	Node 3	Node 4	Node 5
Initial	(-1, ∞)	(-1, ∞)	(-1, ∞)	(-1, ∞)	(-1, ∞)
1					
2					
3					

Table entry @ node 1 for dest SJ

Table entry @ node 3 for dest SJ



Iteration	Node 1	Node 2	Node 3	Node 4	Node 5
Initial	(-1, ∞)	(-1, ∞)	(-1, ∞)	(-1, ∞)	(-1, ∞)
1	(-1, ∞)	(-1, ∞)	(6,1)	(-1, ∞)	(6,2)
2					
3					



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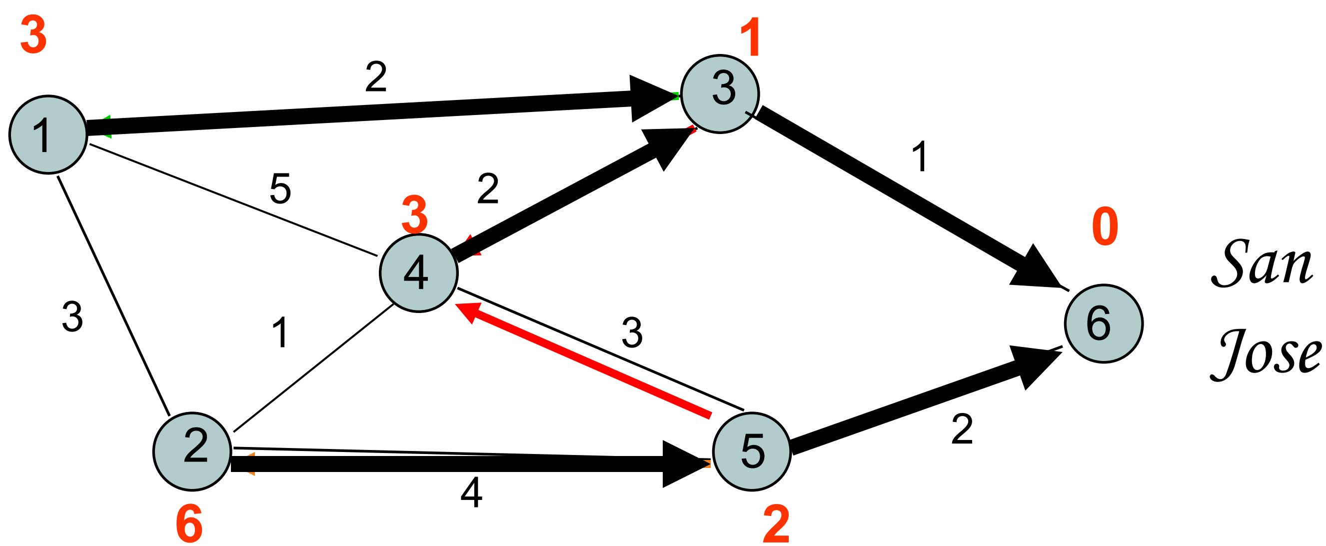
3					



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Initial	(-1, ∞)	(-1, ∞)	(-1, ∞)	(-1, ∞)	(-1, ∞)
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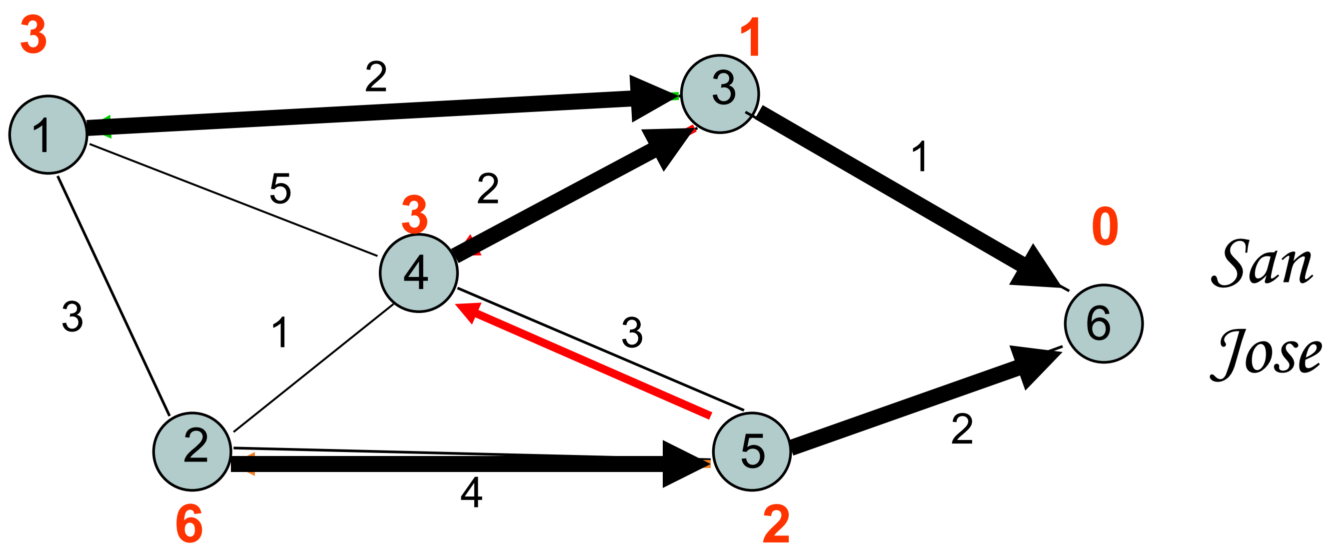

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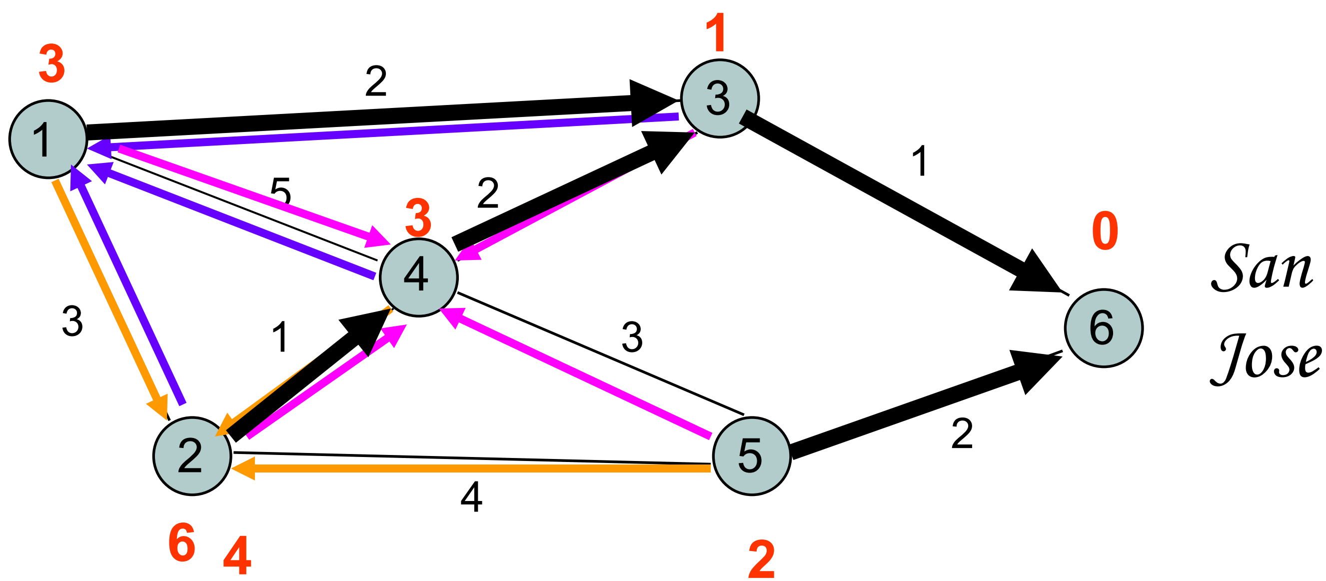


Distance vector algorithm

Basic idea:

- From time-to-time (ex. 30 sec), each node sends its own distance vector estimate to neighbours
- Distance vector: (Current shortest distance to 1, Current shortest distance to 2, … Current shortest distance to N)
- When a node x receives new DV estimate from neighbor, it updates its own DV using B-F equation:

$$D_x(y) \leftarrow \min_v\{C(x,v) + D_v(y)\} \quad \text{for each node } y \in N$$

- Under minor, natural conditions, the estimate $D_x(y)$ *converges to the actual least cost* $d_x(y)$

Example

Consider the following network in which distance vector routing is used. Each node in this network sends its routing table using a vector of size 6 where each entity of the vector represents the cost to the corresponding node, i.e. (Cost-to-Node1, Cost-to-Node2, Cost-to-Node3, Cost-to-Node4, Cost-to-Node5, Cost-to-Node6).

The following cost vectors have just arrived at router 1 from its neighbours:

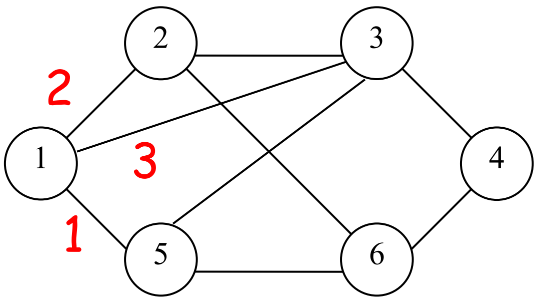
from 2: (2,0,2,7,4,1);

from 3: (3,2,0,3,1,4);

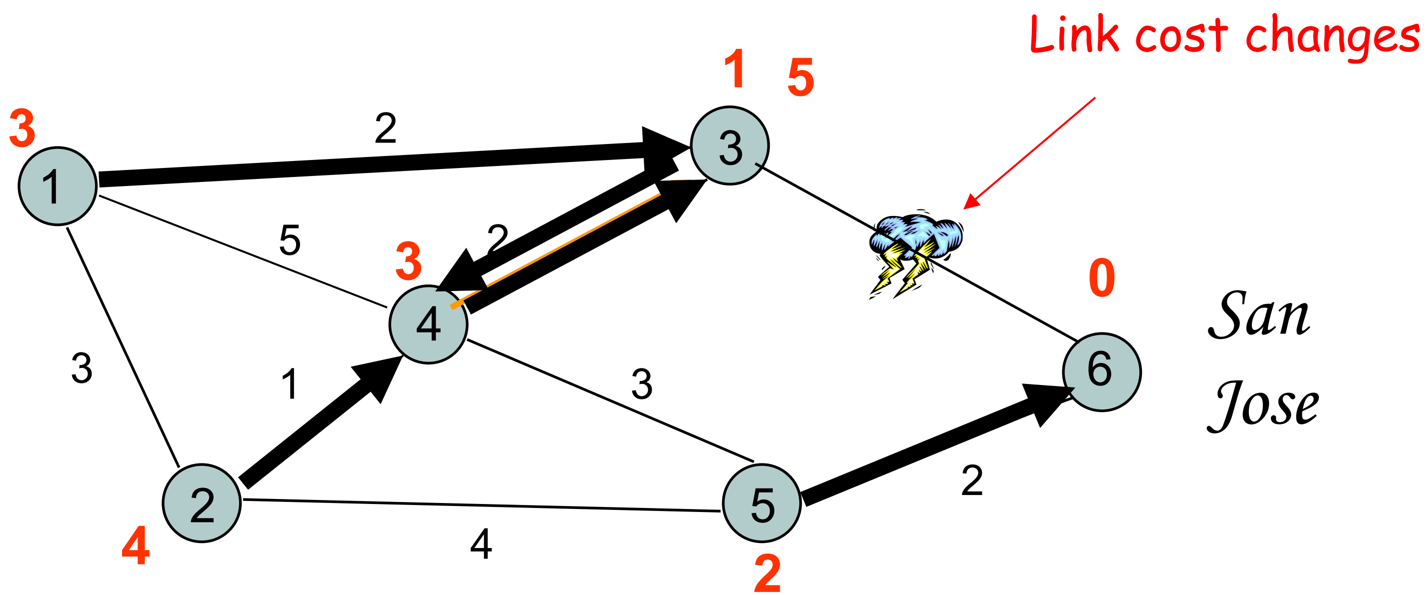
from 5: (1,3,1,4,0,3).

The link costs between node 1 and nodes 2, 3, and 5 are 2, 3, and 1, respectively. What is the routing table at node 1?

	Cost	Next Node
For Node 2: min {2+0, 3+2, 1+3} = 2		2
For Node 3: min {2+2, 3+0, 1+1} = 2		5
For Node 4: min {2+7, 3+3, 1+4} = 5		5
For Node 5: min {2+4, 3+1, 1+0} = 1		5
For Node 6: min {2+1, 3+4, 1+3} = 3		2

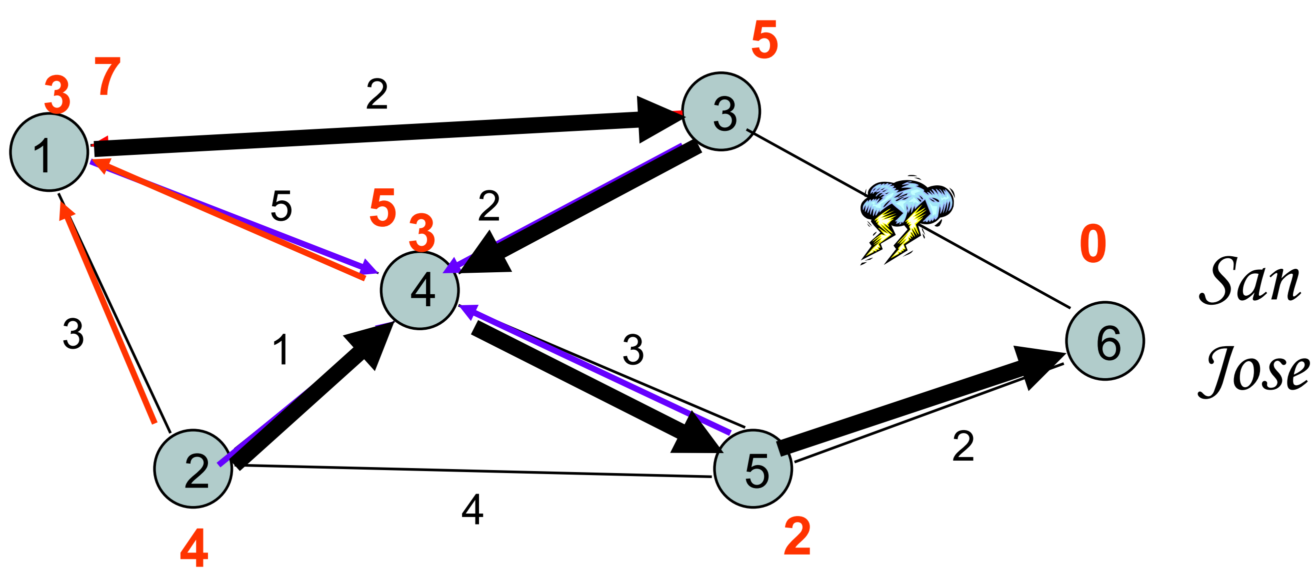


Iteration	Node 1	Node 2	Node 3	Node 4	Node 5
Initial	(3,3)	(4,4)	(6, 1)	(3,3)	(6,2)
1	(3,3)	(4,4)	(4, 5)	(3,3)	(6,2)
2					
3					



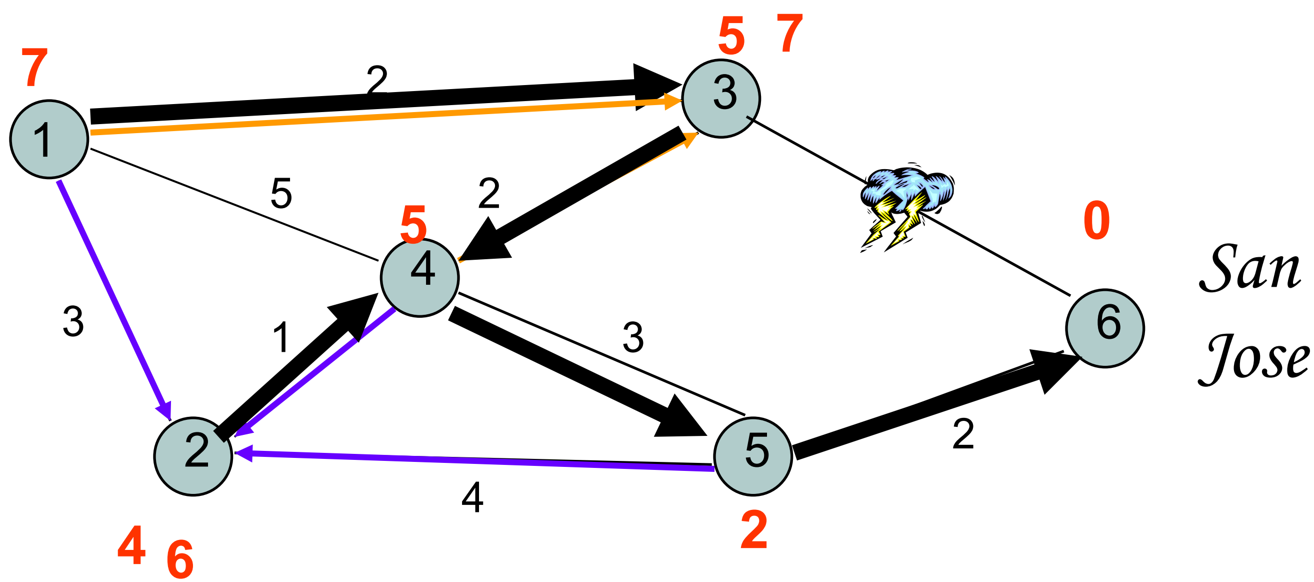
Network disconnected; Loop created between nodes 3 and 4

Iteration	Node 1	Node 2	Node 3	Node 4	Node 5
Initial	(3,3)	(4,4)	(6, 1)	(3,3)	(6,2)
1	(3,3)	(4,4)	(4, 5)	(3,3)	(6,2)
2	(3,7)	(4,4)	(4, 5)	(5,5)	(6,2)
3					



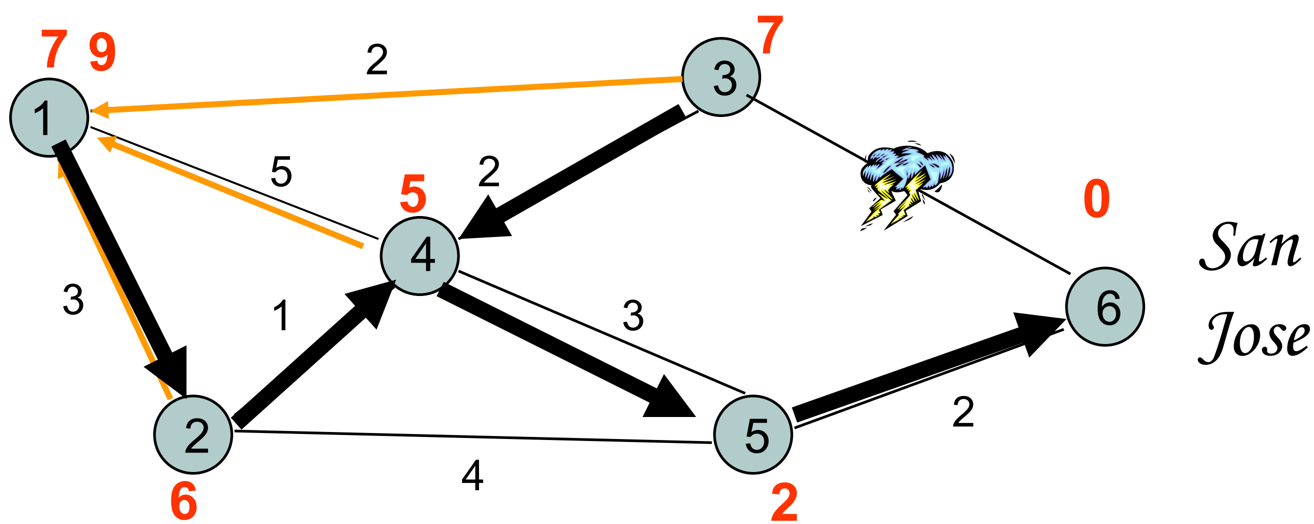
Node 4 could have chosen 2 as next node because of tie

Iteration	Node 1	Node 2	Node 3	Node 4	Node 5
Initial	(3,3)	(4,4)	(6, 1)	(3,3)	(6,2)
1	(3,3)	(4,4)	(4, 5)	(3,3)	(6,2)
2	(3,7)	(4,4)	(4, 5)	(5,5)	(6,2)
3	(3,7)	(4,6)	(4, 7)	(5,5)	(6,2)



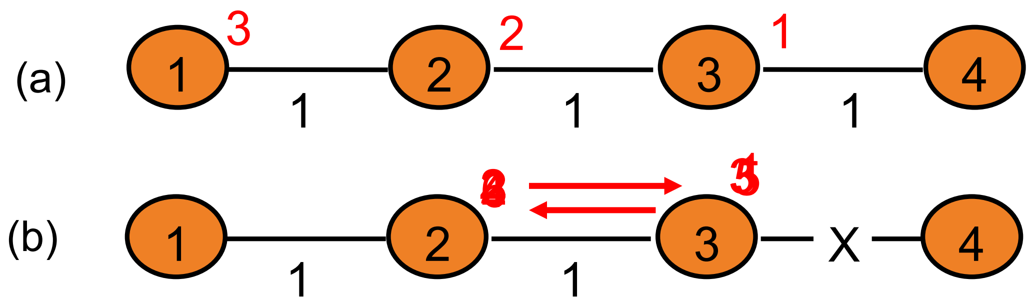
Node 2 could have chosen 5 as next node because of tie

Iteration	Node 1	Node 2	Node 3	Node 4	Node 5
1	(3,3)	(4,4)	(4, 5)	(3,3)	(6,2)
2	(3,7)	(4,4)	(4, 5)	(2,5)	(6,2)
3	(3,7)	(4,6)	(4, 7)	(5,5)	(6,2)
4	(2,9)	(4,6)	(4, 7)	(5,5)	(6,2)



Node 1 could have chosen 3 as next node because of tie

Counting to Infinity Problem



Nodes believe best path is through each other

(Destination is node 4)

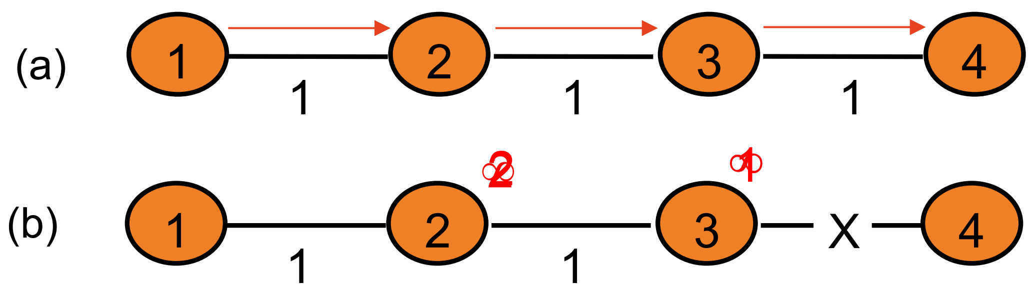
Update	Node 1	Node 2	Node 3
Before break	(2,3)	(3,2)	(4, 1)
After break	(2,3)	(3,2)	(2,3)
1	(2,3)	(3,4)	(2,3)
2	(2,5)	(3,4)	(2,5)
3	(2,5)	(3,6)	(2,5)
4	(2,7)	(3,6)	(2,7)
5	(2,7)	(3,8)	(2,7)
…	…	…	…

Problem: Bad News Travels Slowly

Remedies

- Split Horizon
  - Do not report route to a destination to the neighbor from which route was learned
- Poisoned Reverse
  - Report route to a destination to the neighbor from which route was learned, but with infinite distance

Split Horizon with Poison Reverse



Don’t learn from 1Don’t learn from 2

Nodes believe best path is through each other

Update	Node 1	Node 2	Node 3	
Before break	(2, 3)	(3, 2)	(4, 1)	
After break	(2, 3)	(3, 2)	(-1, ∞)	Node 2 advertizes its route to 4 to node 3 as having distance infinity; node 3 finds there is no route to 4
1	(2, 3)	(-1, ∞)	(-1, ∞)	Node 1 advertizes its route to 4 to node 2 as having distance infinity; node 2 finds there is no route to 4
2	(-1, ∞)	(-1, ∞)	(-1, ∞)	Node 1 finds there is no route to 4

Important Concepts

- *Link State* is <u>centralized</u>
  - Dijkstra
- *Distance Vector* is <u>decentralized</u>
  - Split Horizon/Poison Reverse