Lecture 2-2
Routing

Routing in Packet Networks
Shortest Path Routing

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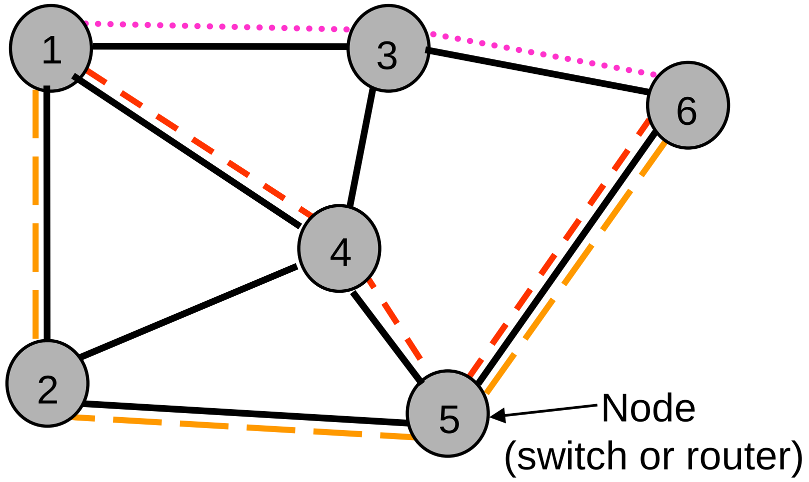
Routing

Routing in Packet Networks

Network Layer

- Network Layer: the most complex layer
  - Requires the coordinated actions of multiple, geographically distributed network elements (switches & routers)
  - Must be able to deal with very large scales
    - Billions of users (people & communicating devices)
  - Biggest Challenges
    - Addressing: where should information be directed to?
    - Routing: what path should be used to get information there?

Routing in Packet Networks



- Three possible (loopfree) routes from 1 to 6:
  - 1-3-6, 1-4-5-6, 1-2-5-6
- Which is "best"?
  - Min delay? Min hop? Max bandwidth? Min cost? Max reliability?

Centralized vs Distributed Routing

- Centralized Routing
  - All routes determined by a central node
  - All state information sent to central node
  - Problems adapting to frequent topology changes
  - Does not scale
- Distributed Routing
  - Routes determined by routers using distributed algorithm
  - State information exchanged by routers
  - Adapts to topology and other changes
  - Better scalability

Specialized Routing

- Flooding
  - Useful in starting up network
  - Useful in propagating information to all nodes

Flooding (1)

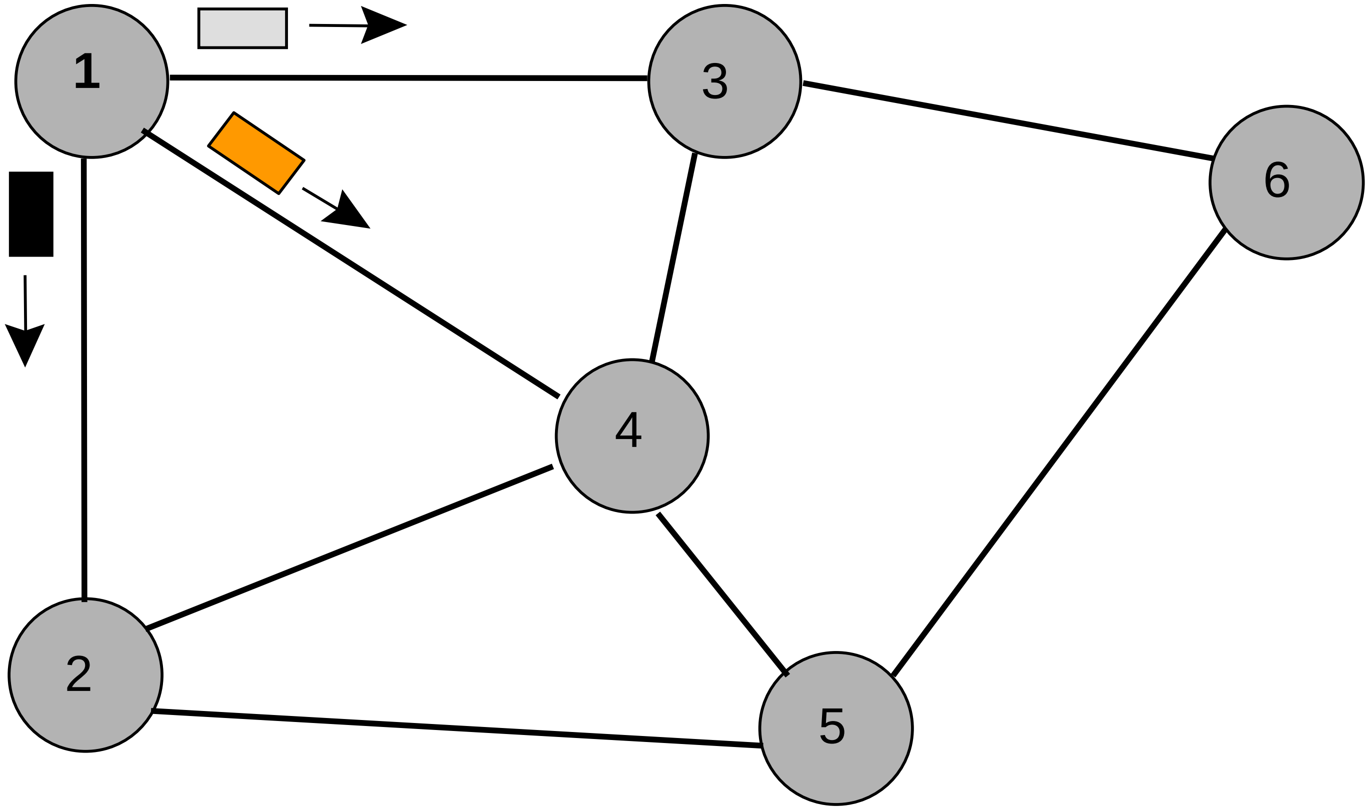
Send a packet to all nodes in a network

- No routing tables available
- Need to broadcast packet to all nodes (e.g. to propagate link state information)

Approach

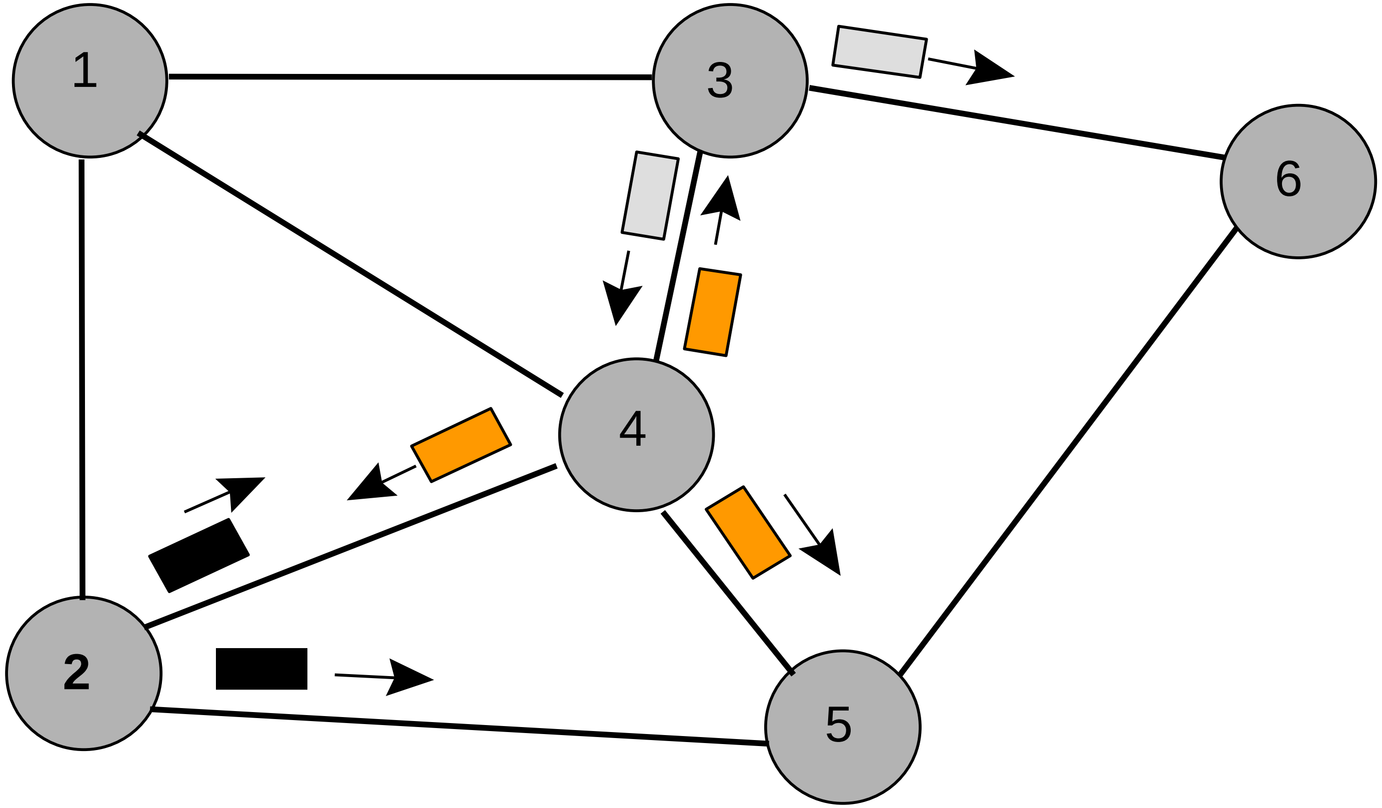
- Send packet on all ports except one where it arrived
- Exponential growth in packet transmissions

Flooding (2)



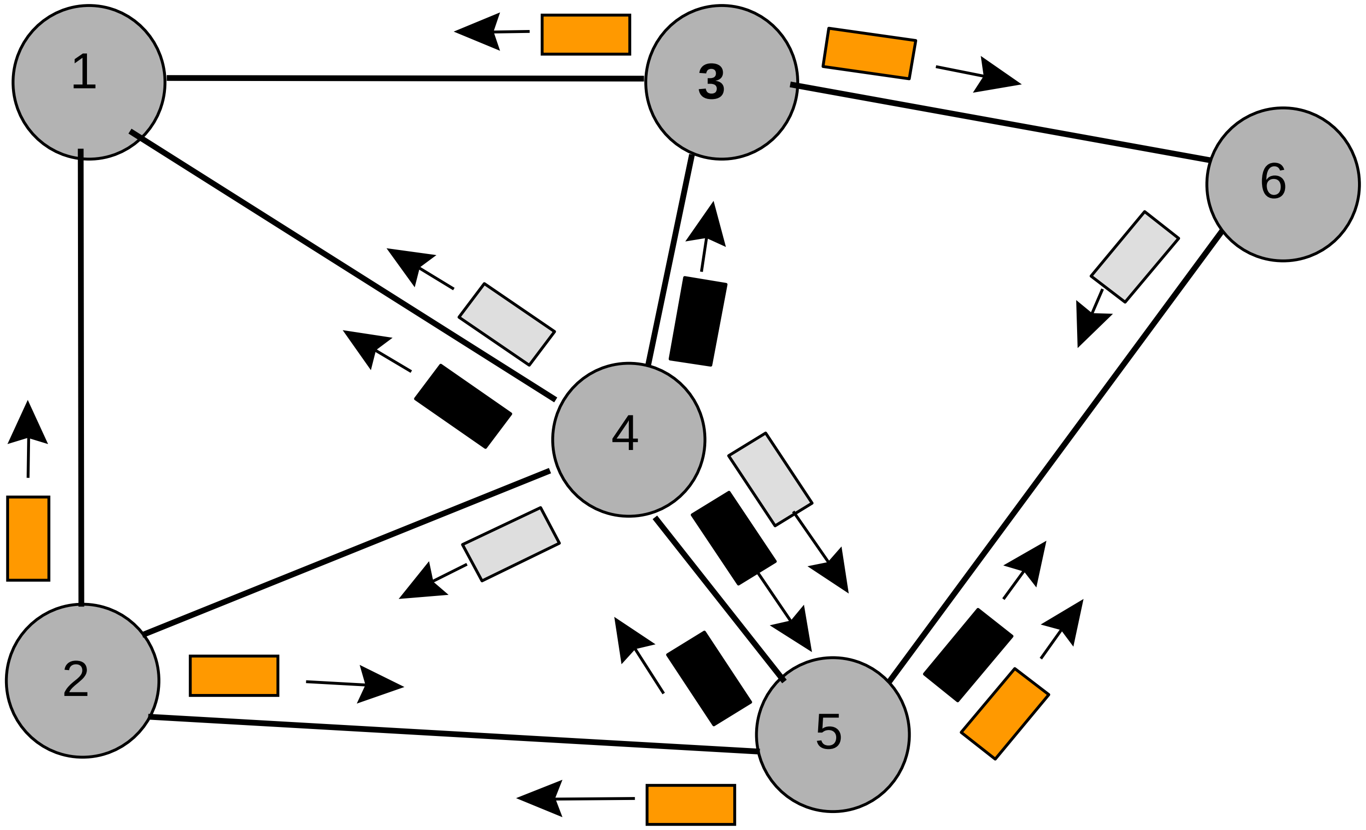
Flooding is initiated from Node 1: Hop 1 transmissions

Flooding (3)



Flooding is initiated from Node 1: Hop 2 transmissions

Flooding (4)



Flooding is initiated from Node 1: Hop 3 transmissions

Limited Flooding

- Time-to-Live field in each packet limits number of hops to certain diameter
- Each switch adds its ID before flooding; discards repeats
- Source puts sequence number in each packet; switches records source address and sequence number and discards repeats

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Routing in Packet Networks
Shortest Path Routing

Lecture 2-2
Routing

Shortest Path Routing

Shortest Paths & Routing

- Many possible paths connect any given source and to any given destination
- Routing involves the selection of the path to be used to accomplish a given transfer
- Typically it is possible to attach a cost or distance to a link connecting two nodes
- Routing can then be posed as a shortest path problem

Routing Metrics

Means for measuring desirability of a path

- Path Length = sum of costs or distances
- Possible metrics
  - Hop count: rough measure of resources used
  - Reliability: link availability; BER
  - Delay: sum of delays along path; complex & dynamic
  - Bandwidth: "available capacity" in a path
  - Load: Link & router utilization along path
  - Cost: $$$

Shortest Path Approaches

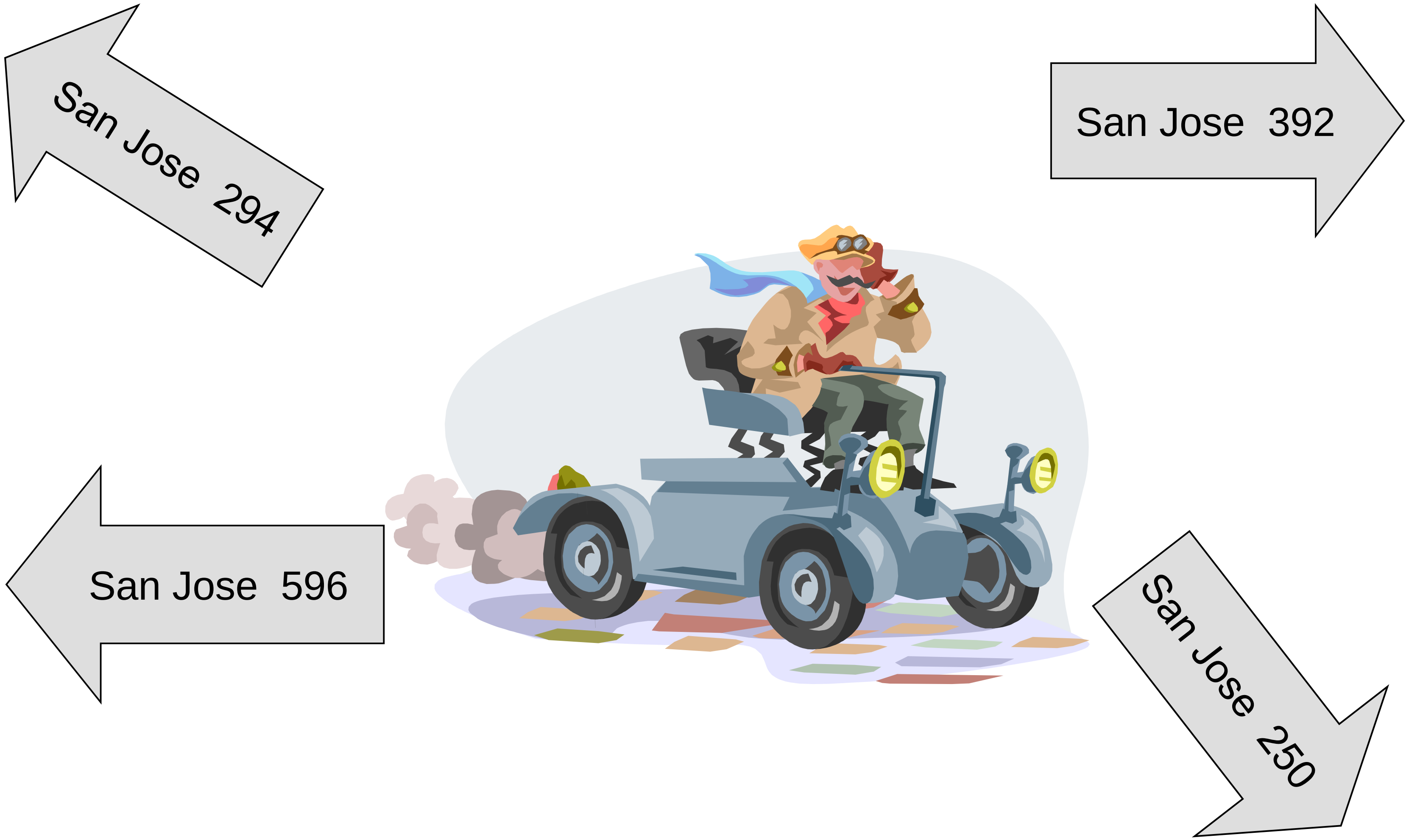
Distance Vector Protocols

- Neighbors exchange list of distances to destinations
- Best next-hop determined for each destination
- Ford-Fulkerson (distributed) shortest path algorithm

Link State Protocols

- Link state information flooded to all routers
- Routers have complete topology information
- Shortest path (& hence next hop) calculated
- Dijkstra (centralized) shortest path algorithm

Distance Vector Do you know the way to San Jose?



Distance Vector

Local Signpost

- Direction
- Distance

Routing Table

For each destination list:

- Next Node
- Distance

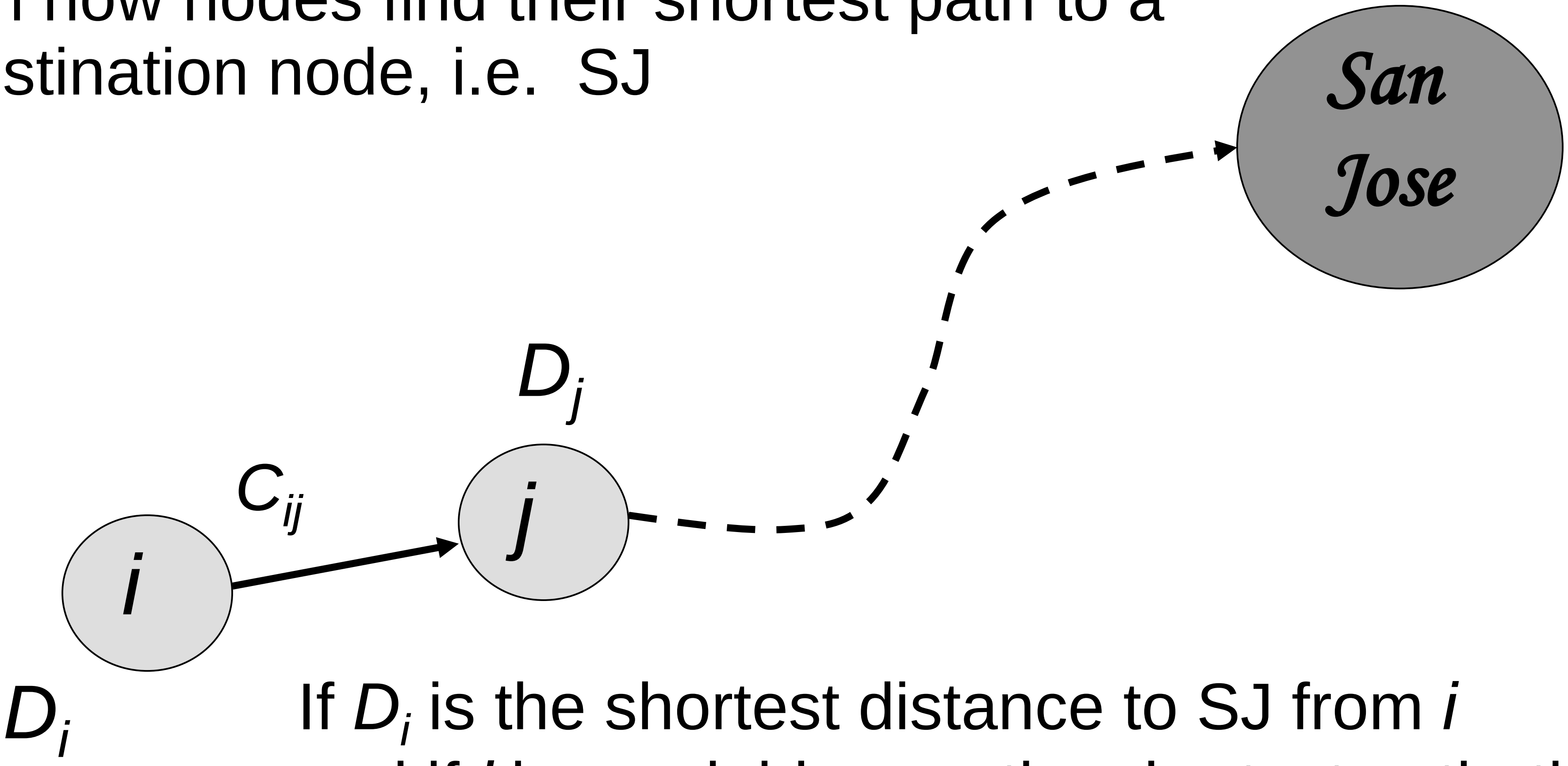
dest	next	dist

Table Synthesis

- Neighbors exchange table entries
- Determine current best next hop
- Inform neighbors
  - Periodically
  - After changes

Shortest Path to SJ

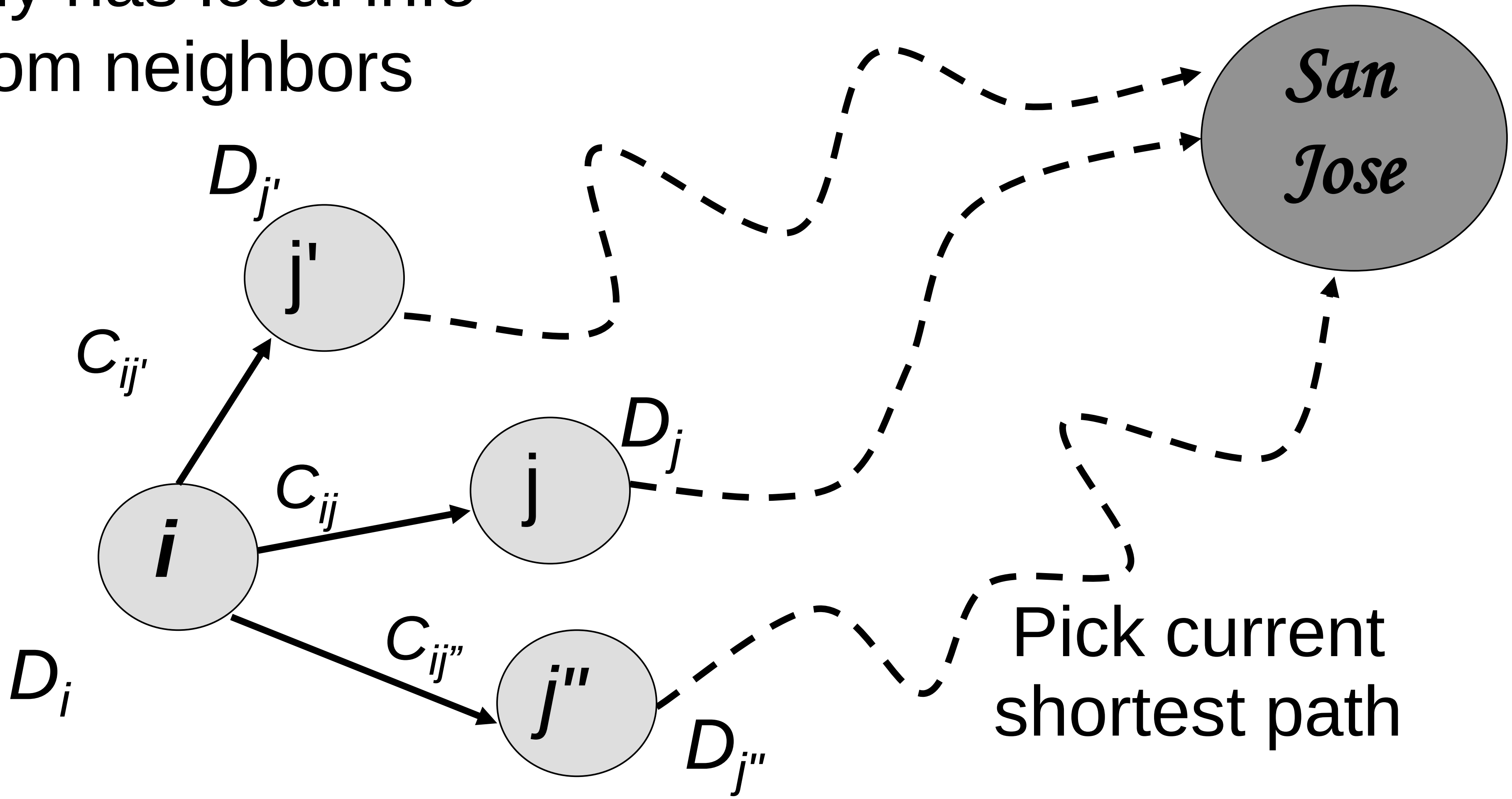
Focus on how nodes find their shortest path to a given destination node, i.e. SJ



If D_i is the shortest distance to SJ from i and if j is a neighbor on the shortest path, then $D_i = C_{ij} + D_j$

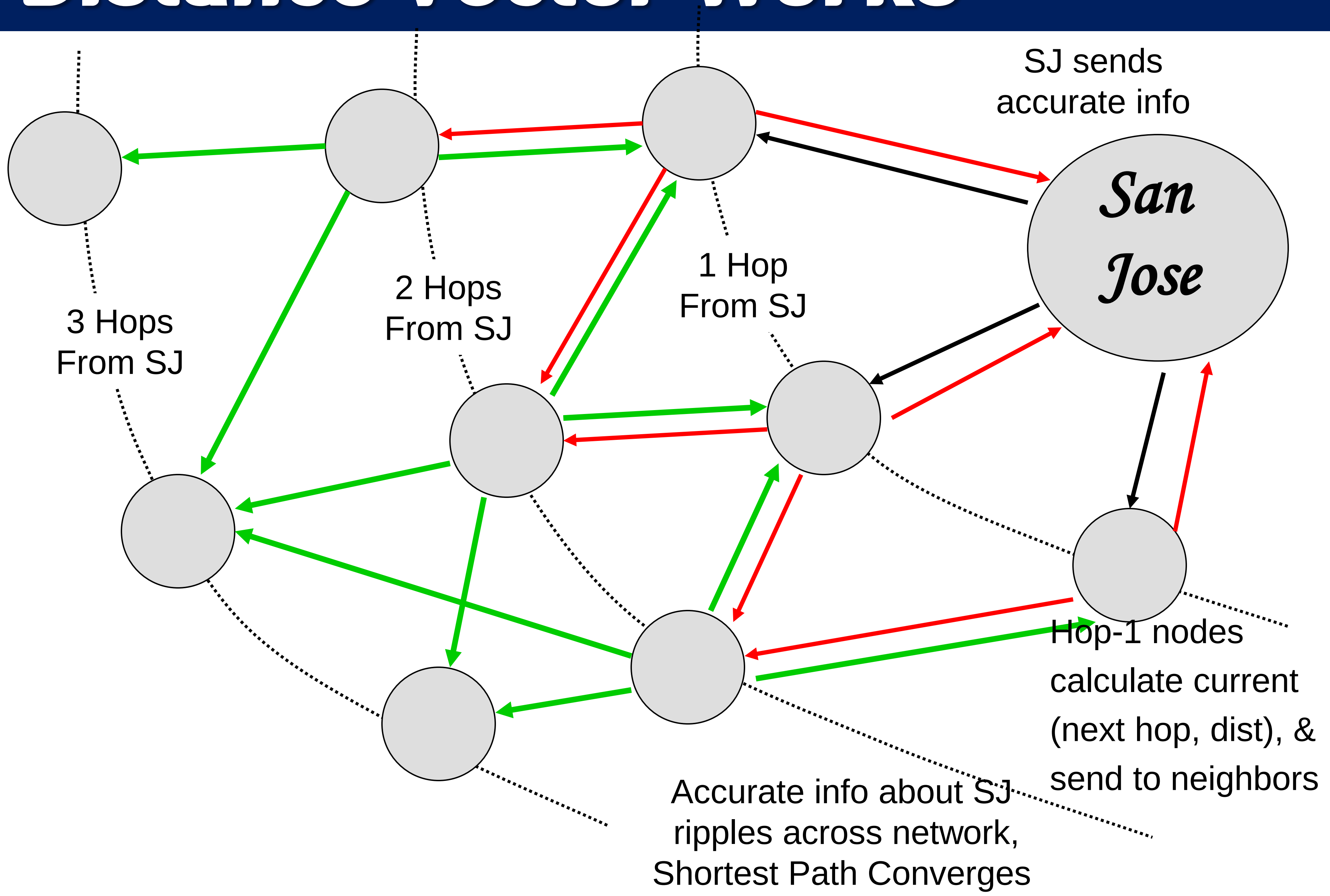
But we don't know the shortest paths

i only has local info from neighbors



Pick current shortest path

Why Distance Vector Works



Bellman-Ford Algorithm

- *Consider computations for one destination d*
- *Initialization*
  - Each node table has 1 row for destination *d*
  - Distance of node *d* to itself is zero: $D_d=0$
  - Distance of other node *j* to *d* is infinite: $D_j=\infty$, for $j \neq d$
  - Next hop node $n_j = -1$ to indicate not yet defined for $j \neq d$
- *Send Step*
  - Send new distance vector to immediate neighbors across local link
- *Receive Step*
  - At node *j*, find the next hop that gives the minimum distance to *d*,
    - $Min_j \{ C_{ij} + D_j \}$
    - Replace old $(n_j, D_j(d))$ by new $(n_j^*, D_j^*(d))$ if new next node or distance
  - Go to send step

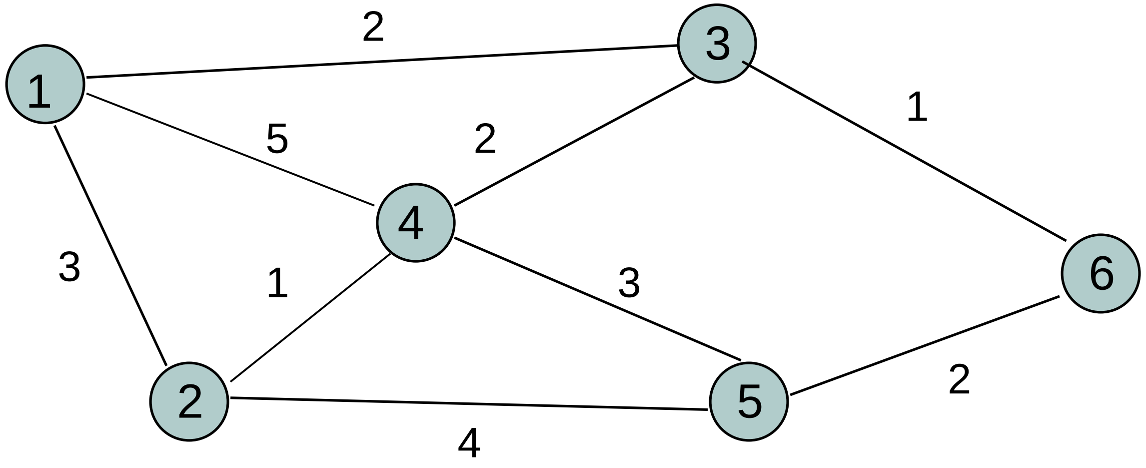
Bellman-Ford Algorithm

- *Now consider parallel computations for all destinations d*
- *Initialization*
  - Each node has 1 row for each destination *d*
  - Distance of node *d* to itself is zero: $D_d(d)=0$
  - Distance of other node *j* to *d* is infinite: $D_j(d)= \propto$, for $j \neq d$
  - Next node n_j = -1 since not yet defined
- *Send Step*
  - Send new distance vector to immediate neighbors across local link
- *Receive Step*
  - For each destination *d*, find the next hop that gives the minimum distance to *d*,
    - $Min_j \{ C_{ij} + D_j(d) \}$
    - Replace old $(n_j, D_i(d))$ by new $(n_j^*, D_j^*(d))$ if new next node or distance found
  - Go to send step

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

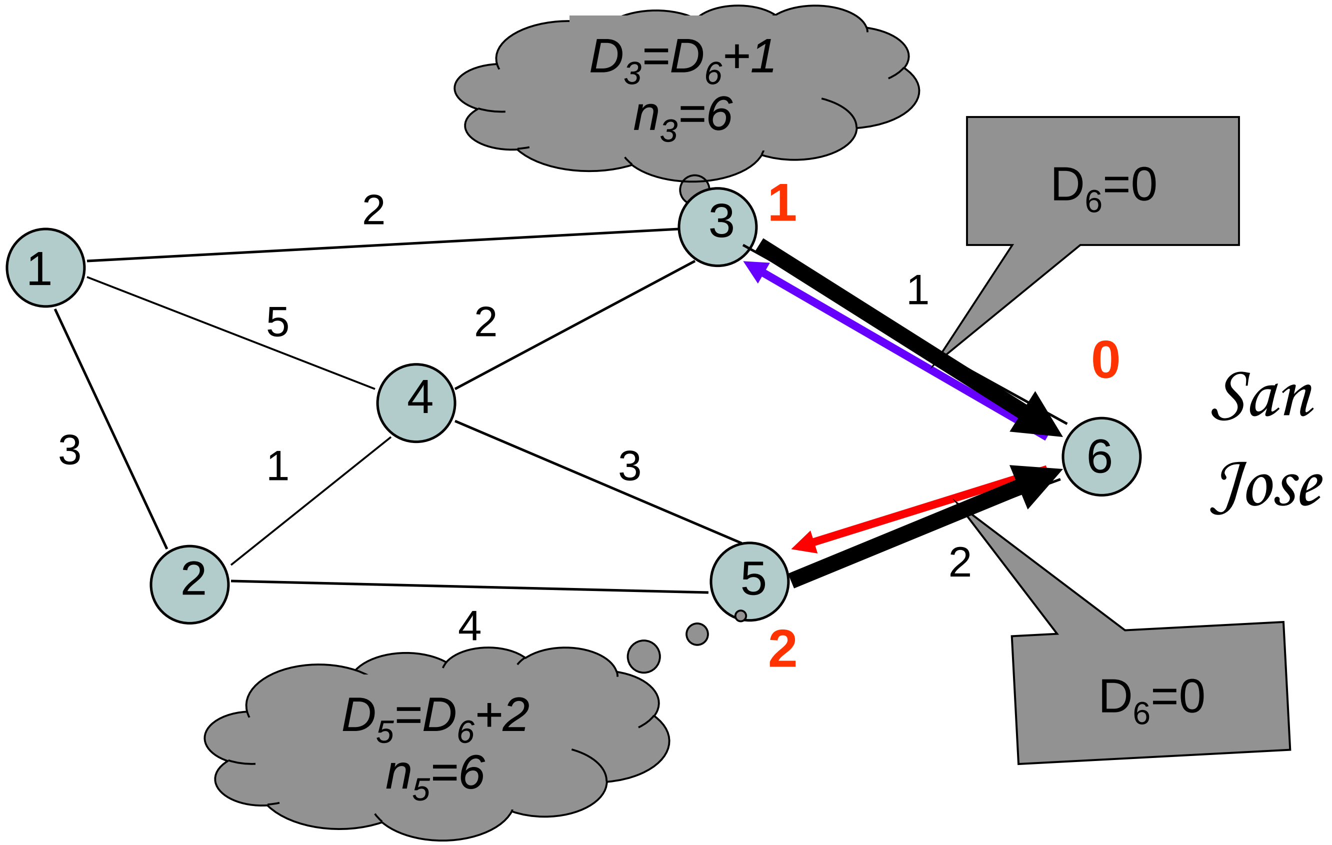
Table entry @ node 1 for dest SJ

Table entry @ node 3 for dest SJ

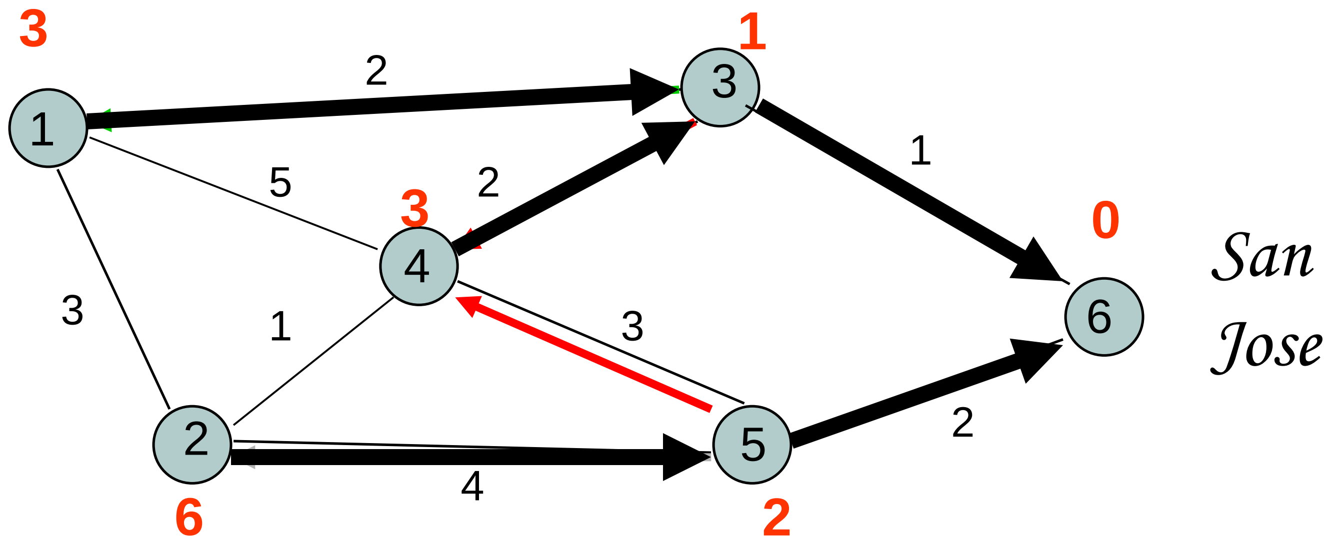


San Jose

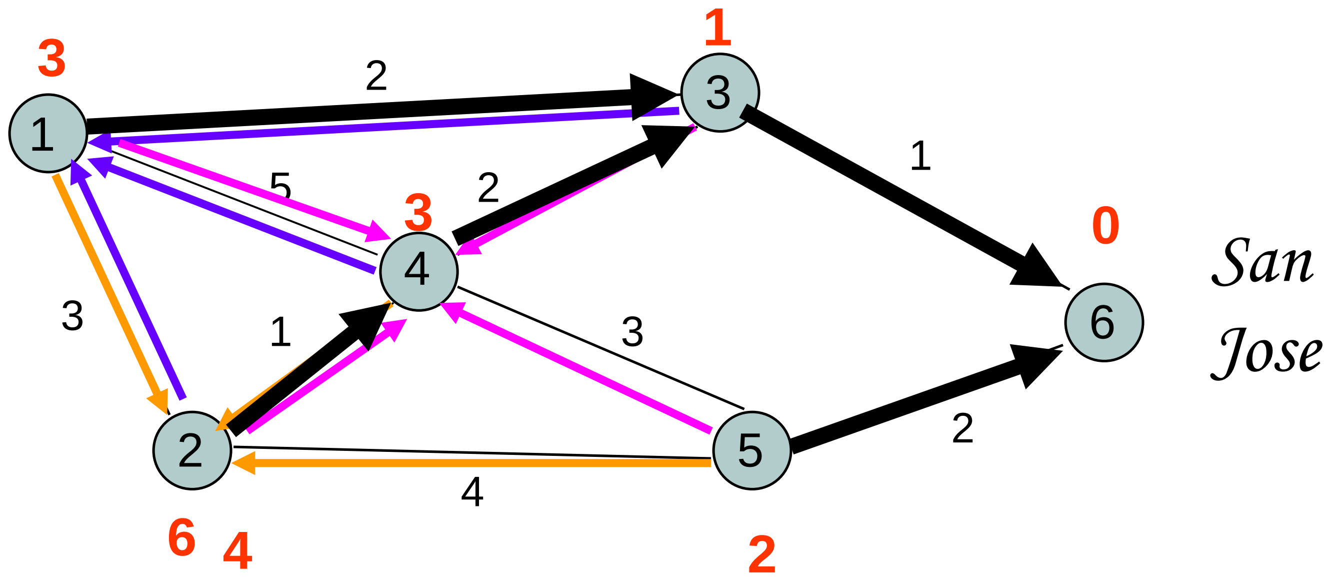
Iteration	Node 1	Node 2	Node 3	Node 4	Node 5
Initial	(-1, ∞)	(-1, ∞)	(-1, ∞)	(-1, ∞)	(-1, ∞)
1	(-1, ∞)	(-1, ∞)	(6,1)	(-1, ∞)	(6,2)
2					
3					



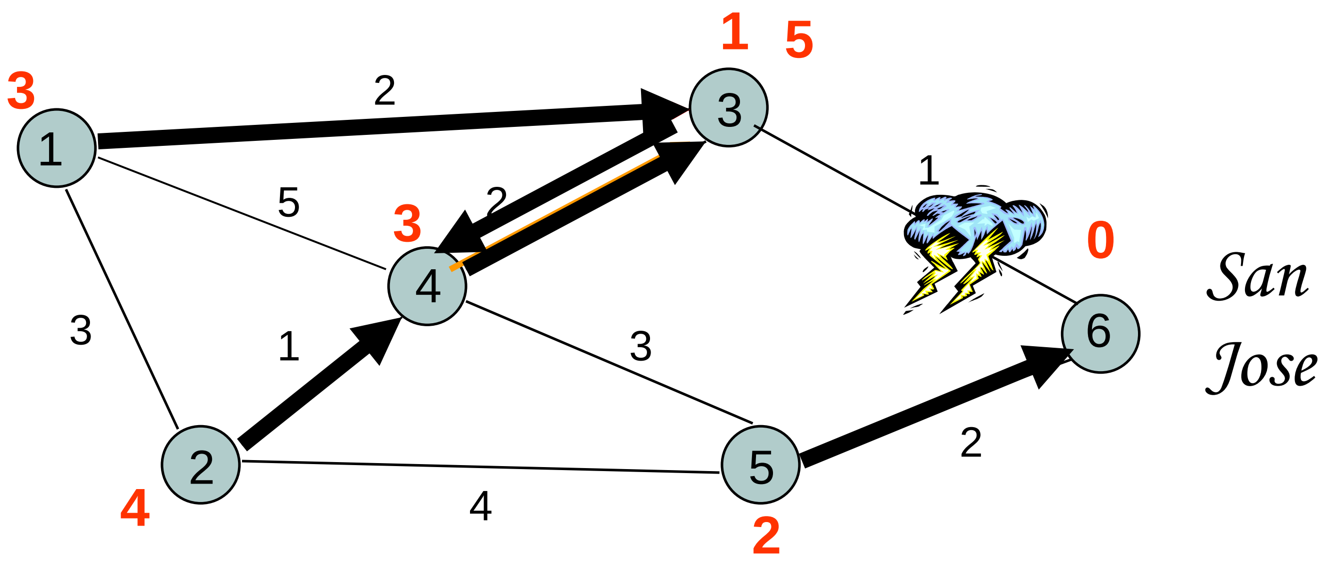
Iteration	Node 1	Node 2	Node 3	Node 4	Node 5
Initial	(-1, ∞)	(-1, ∞)	(-1, ∞)	(-1, ∞)	(-1, ∞)
1	(-1, ∞)	(-1, ∞)	(6, 1)	(-1, ∞)	(6,2)
2	(3,3)	(5,6)	(6, 1)	(3,3)	(6,2)
3					



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

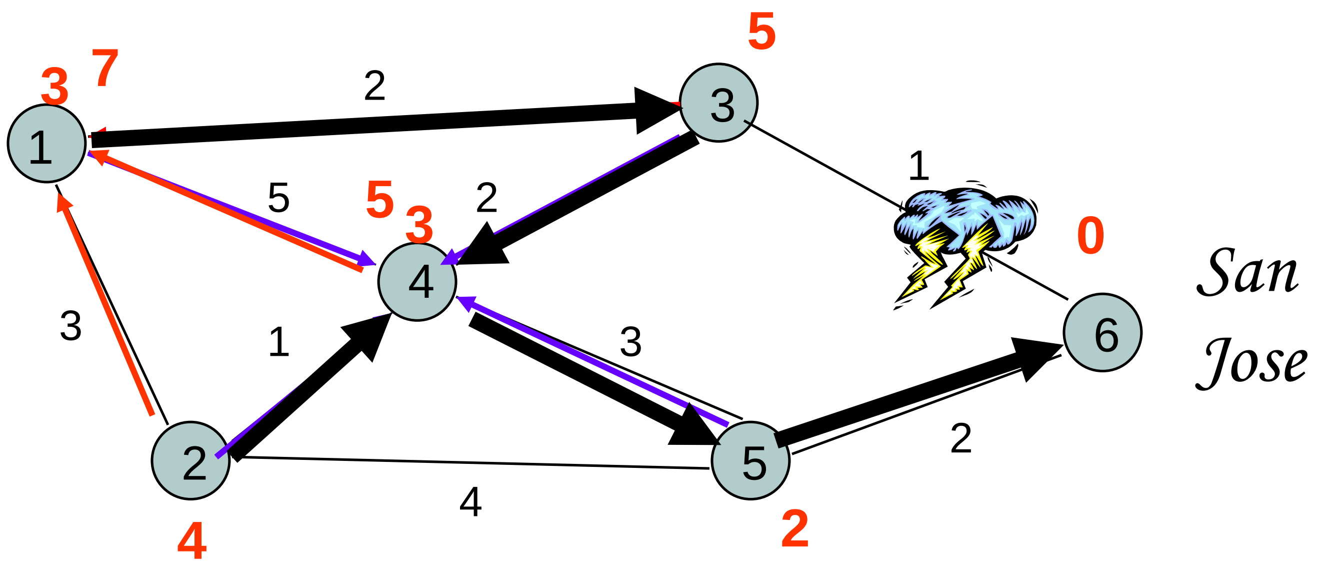


Iteration	Node 1	Node 2	Node 3	Node 4	Node 5
Initial	(3,3)	(4,4)	(6, 1)	(3,3)	(6,2)
1	(3,3)	(4,4)	(4, 5)	(3,3)	(6,2)
2					
3					



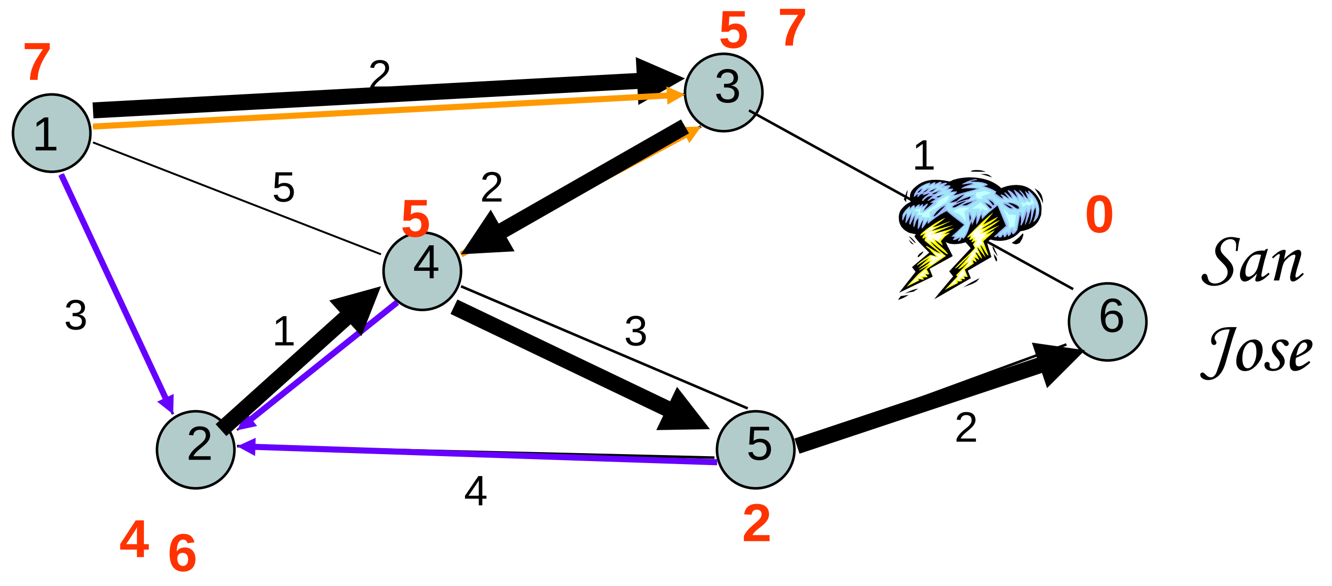
Network disconnected; Loop created between nodes 3 and 4

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					



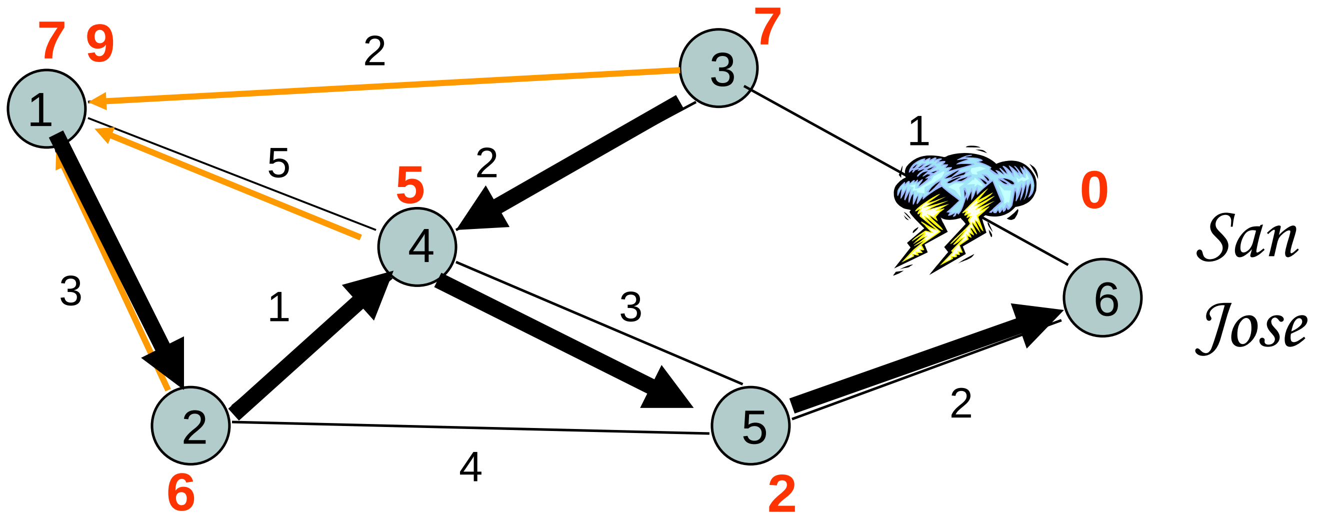
Node 4 could have chosen 2 as next node because of tie

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)



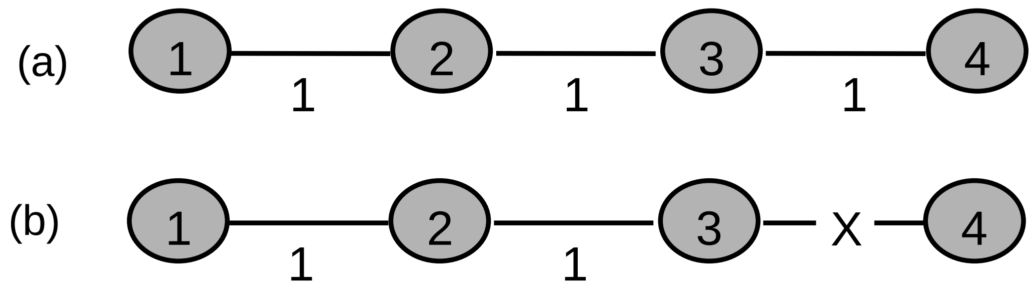
Node 2 could have chosen 5 as next node because of tie

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 chose 3 as next node because of tie

Counting to Infinity Problem



Nodes believe best path is through each other

(Destination is node 4)

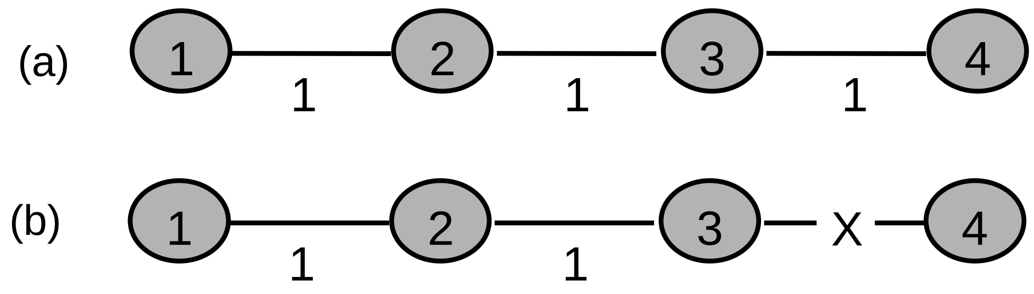
Update	Node 1	Node 2	Node 3
Before break	(2,3)	(3,2)	(4, 1)
After break	(2,3)	(3,2)	(2,3)
1	(2,3)	(3,4)	(2,3)
2	(2,5)	(3,4)	(2,5)
3	(2,5)	(3,6)	(2,5)
4	(2,7)	(3,6)	(2,7)
5	(2,7)	(3,8)	(2,7)
…	…	…	…

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
  - Breaks erroneous direct loops immediately
  - Does not work on some indirect loops

Split Horizon with Poison Reverse



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

Link-State Algorithm

- Basic idea: two step procedure
  - Each source node gets a map of all nodes and link metrics (link state) of the entire network
  - Find the shortest path on the map from the source node to all destination nodes
- 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

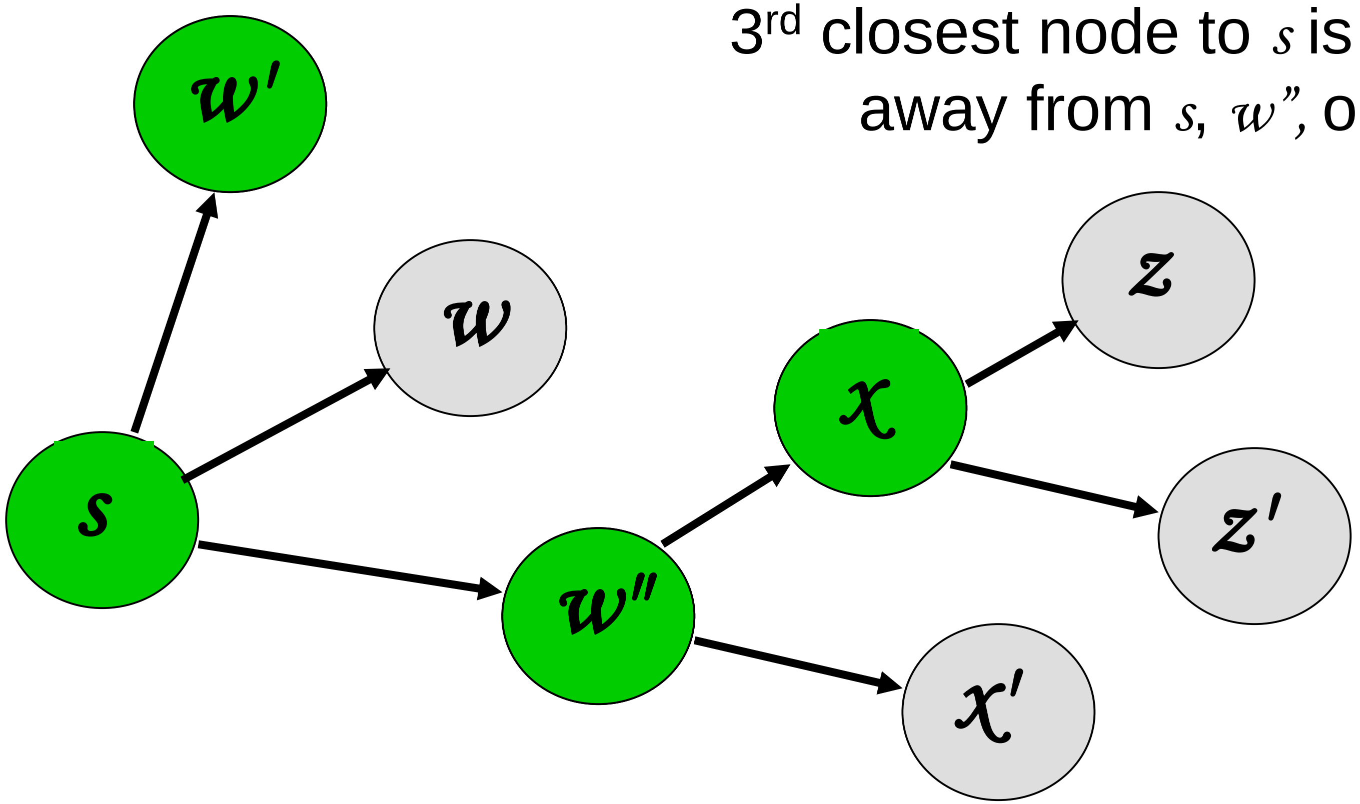
Dijkstra Algorithm: Finding shortest paths in order

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''

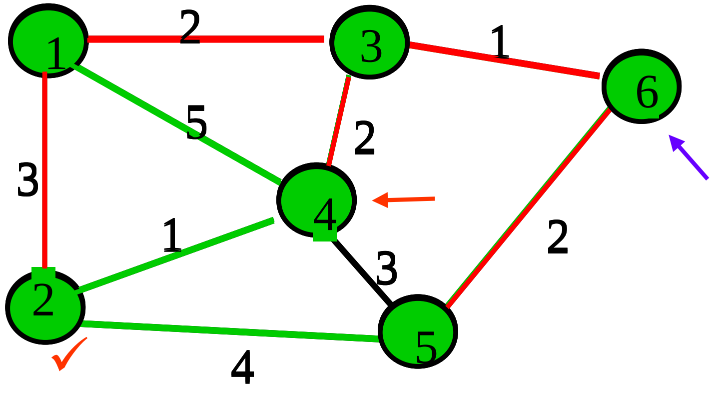
3rd closest node to s is 1 hop away from s, w'', or x

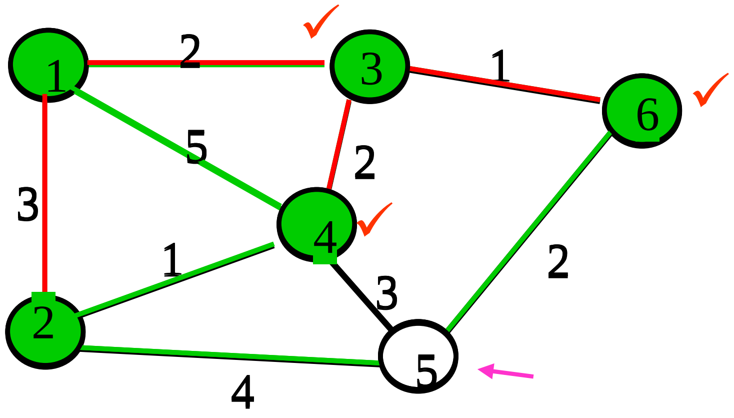


Dijkstra's algorithm

- N: set of nodes for which shortest path already found
- Initialization: (S*tart 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
- Step A: (*Find next closest node i*)
  - 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 $j \notin N$
  - $D_j = \min (D_j, D_i + C_{ij})$ ← *Minimum distance from s to j through node **i** in N*
  - Go to Step A

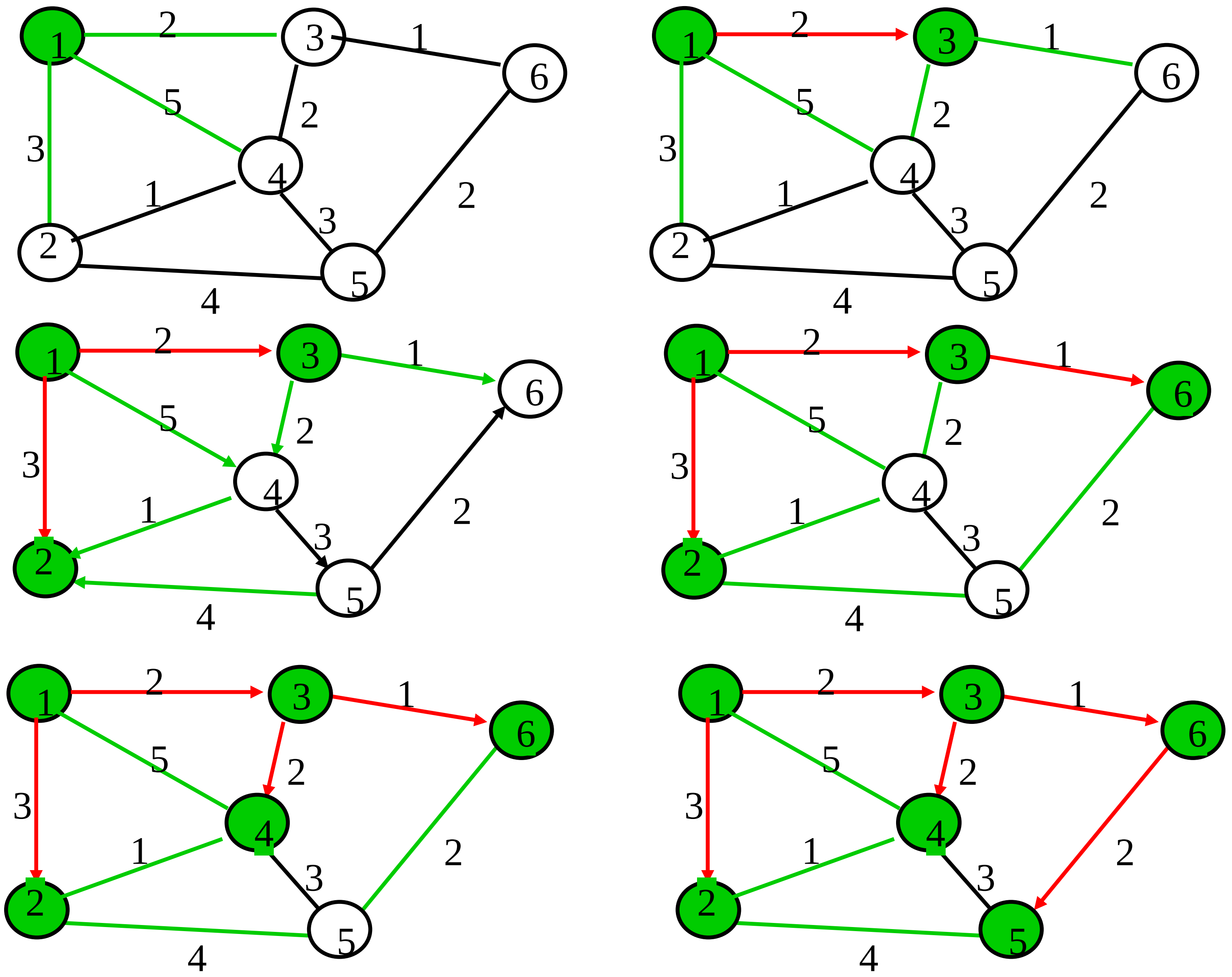
Execution of Dijkstra's algorithm





Iteration	**N**	D_2	D_3	D_4	D_5	D_6
Initial	{1}	3	2 ✓	5	∝	∝
1	{1,3}	3 ✓	2	4	∝	3
2	{1,2,3}	3	2	4	7	3 ✓
3	{1,2,3,6}	3	2	4 ✓	5	3
4	{1,2,3,4,6}	3	2	4	5 ✓	3
5	{1,2,3,4,5,6}	3	2	4	5	3

Shortest Paths in Dijkstra's Algorithm



Routing table at node 1

Destination	Next node	Cost
2	2	3
3	3	2
4	3	4
5	3	5
6	3	3

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