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Data and Computer Communications
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Chapter 12

Routing

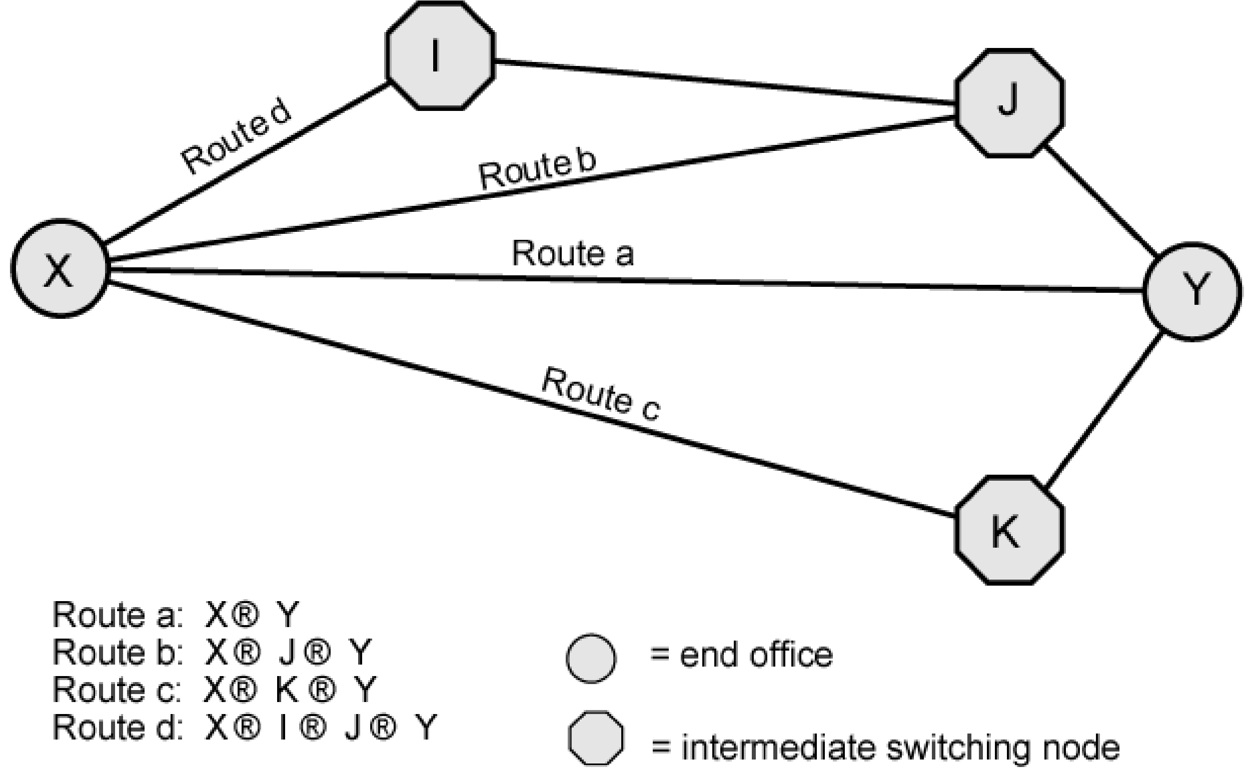
Routing in Circuit Switched Network

- Many connections will need paths through more than one switch
- Need to find a route
  - Efficiency
  - Resilience
- Public telephone switches are a tree structure
  - Static routing uses the same approach all the time
- Dynamic routing allows for changes in routing depending on traffic
  - Uses a peer structure for nodes

Alternate Routing

- Possible routes between end offices predefined
- Originating switch selects appropriate route
- Routes listed in preference order
- Different sets of routes may be used at different times

Alternate Routing Diagram



(a) Topology

Time Period	First route	Second route	Third route	Fourth and final route
Morning	a	b	c	d
Afternoon	a	d	b	c
Evening	a	d	c	b
Weekend	a	c	b	d

(b) Routing table

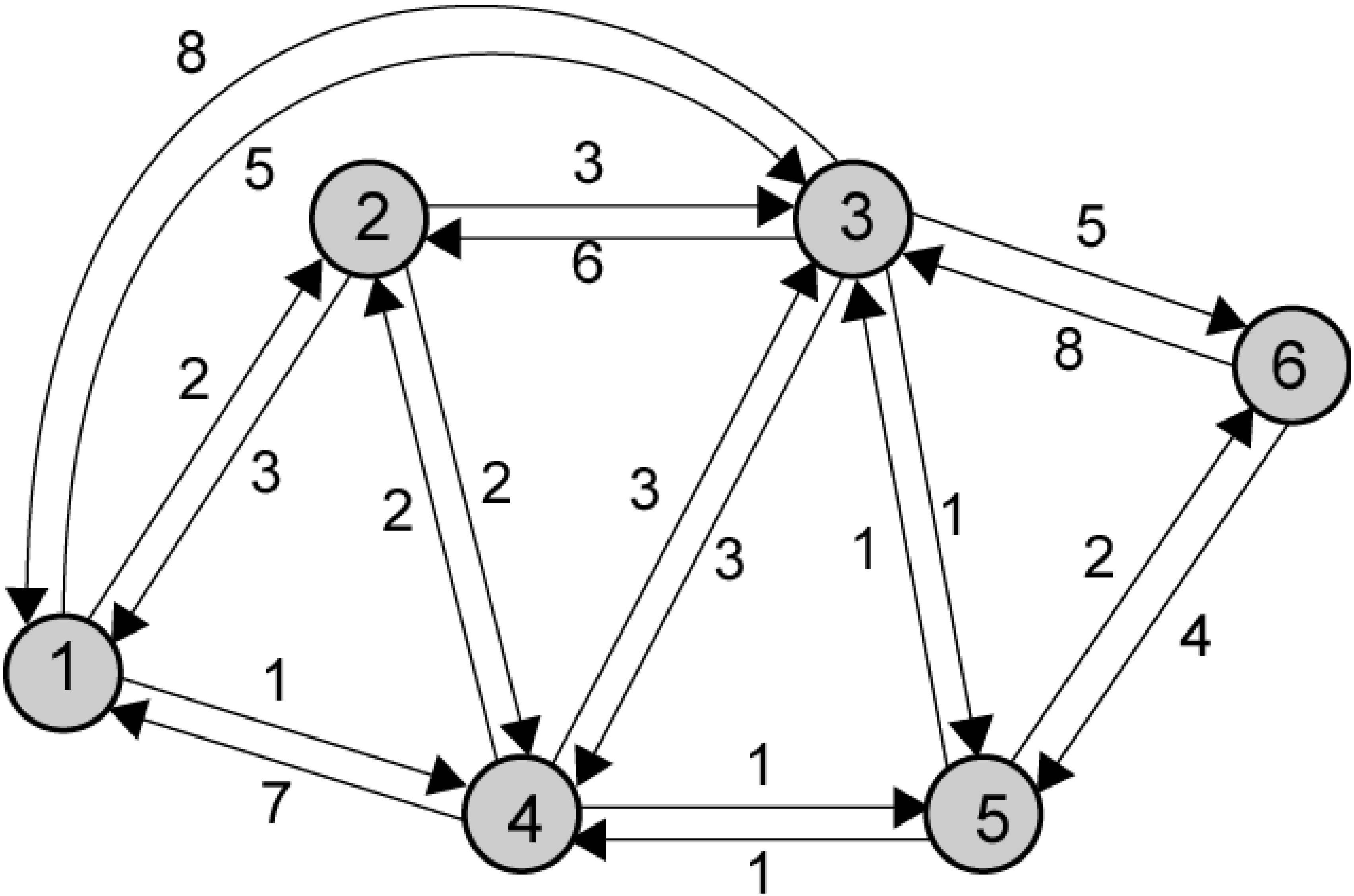
Routing in Packet Switched Network

- Complex, crucial aspect of packet switched networks
- Characteristics required
  - Correctness
  - Simplicity
  - Robustness
  - Stability
  - Fairness
  - Optimality
  - Efficiency

Performance Criteria

- Used for selection of route
- Minimum hop
- Least cost
    - See Stallings appendix 10A for routing algorithms

Example Packet Switched Network



Decision Time and Place

- Time
  - Packet or virtual circuit basis
- Place
  - Distributed
    - Made by each node
  - Centralized
  - Source

Network Information Source and Update Timing

- Routing decisions usually based on knowledge of network (not always)
- Distributed routing
  - Nodes use local knowledge
  - May collect info from adjacent nodes
  - May collect info from all nodes on a potential route
- Central routing
  - Collect info from all nodes
- Update timing
  - When is network info held by nodes updated
  - Fixed - never updated
  - Adaptive - regular updates

Routing Strategies

- Fixed
- Flooding
- Random
- Adaptive

Fixed Routing

- Single permanent route for each source to destination pair
- Determine routes using a least cost algorithm (appendix 10A)
- Route fixed, at least until a change in network topology

Fixed Routing Tables

CENTRAL ROUTING DIRECTORY

To Node \ From Node	1	2	3	4	5	6
1	—	1	5	2	4	5
2	2	—	5	2	4	5
3	4	3	—	5	3	5
4	4	4	5	—	4	5
5	4	4	5	5	—	5
6	4	4	5	5	6	—

Node 1 Directory

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

Node 2 Directory

Destination	Next Node
1	1
3	3
4	4
5	4
6	4

Node 3 Directory

Destination	Next Node
1	5
2	5
4	5
5	5
6	5

Node 4 Directory

Destination	Next Node
1	2
2	2
3	5
5	5
6	5

Node 5 Directory

Destination	Next Node
1	4
2	4
3	3
4	4
6	6

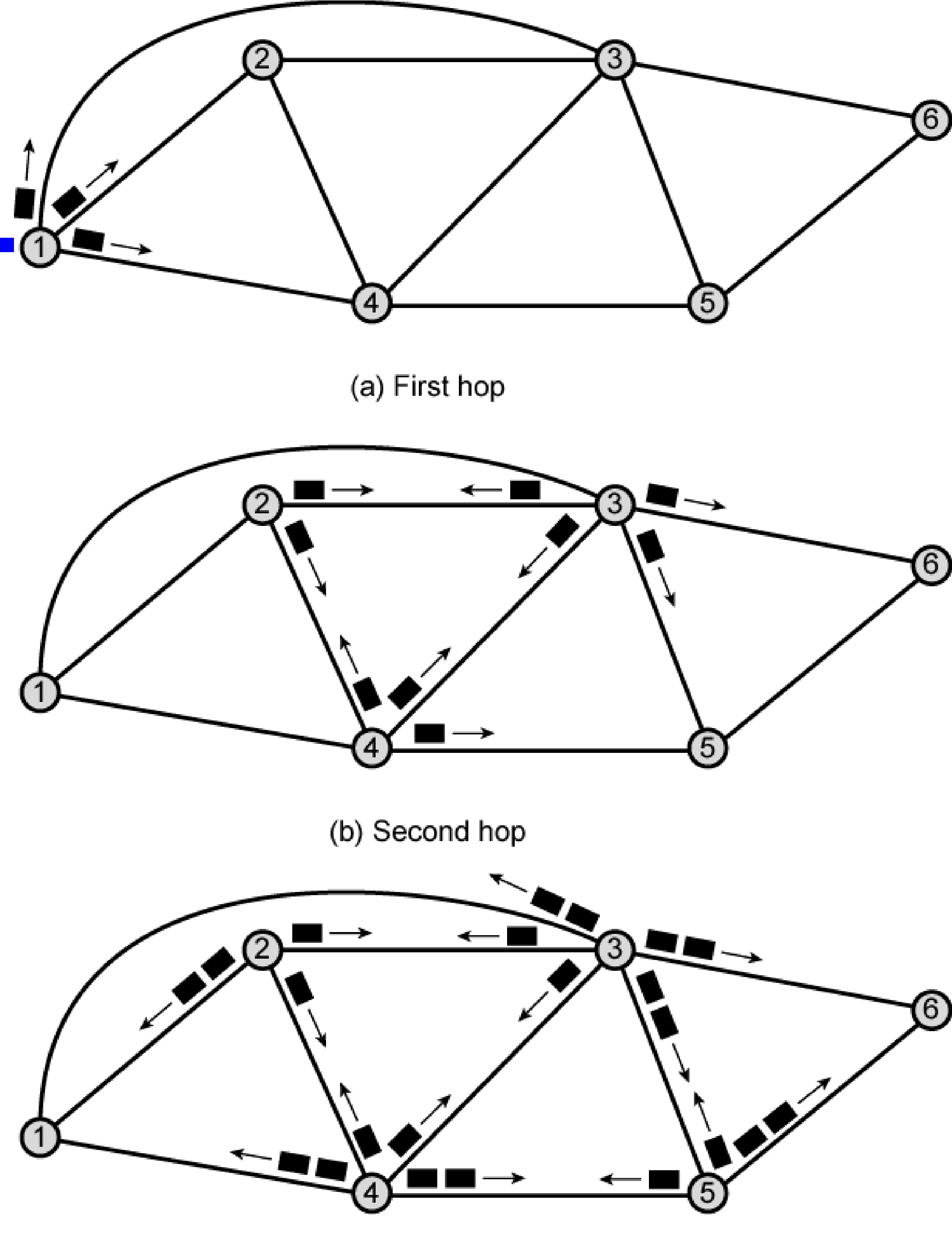
Node 6 Directory

Destination	Next Node
1	5
2	5
3	5
4	5
5	5

Flooding

- No network info required
- Packet sent by node to every neighbor
- Incoming packets retransmitted on every link except incoming link
- Eventually a number of copies will arrive at destination
- Each packet is uniquely numbered so duplicates can be discarded
- Nodes can remember packets already forwarded to keep network load in bounds
- Can include a hop count in packets

Flooding Example



(a) First hop

(b) Second hop

(c) Third hop

Properties of Flooding

- All possible routes are tried
  - Very robust
- At least one packet will have taken minimum hop count route
  - Can be used to set up virtual circuit
- All nodes are visited
  - Useful to distribute information (e.g. routing)

Random Routing

- Node selects one outgoing path for retransmission of incoming packet
- Selection can be random or round robin
- Can select outgoing path based on probability calculation
- No network info needed
- Route is typically not least cost nor minimum hop

Adaptive Routing

- Used by almost all packet switching networks
- Routing decisions change as conditions on the network change
  - Failure
  - Congestion
- Requires info about network
- Decisions more complex
- Tradeoff between quality of network info and overhead
- Reacting too quickly can cause oscillation
- Too slowly to be relevant

Adaptive Routing - Advantages

- Improved performance
- Aid congestion control (See chapter 13)
- Complex system
  - May not realize theoretical benefits

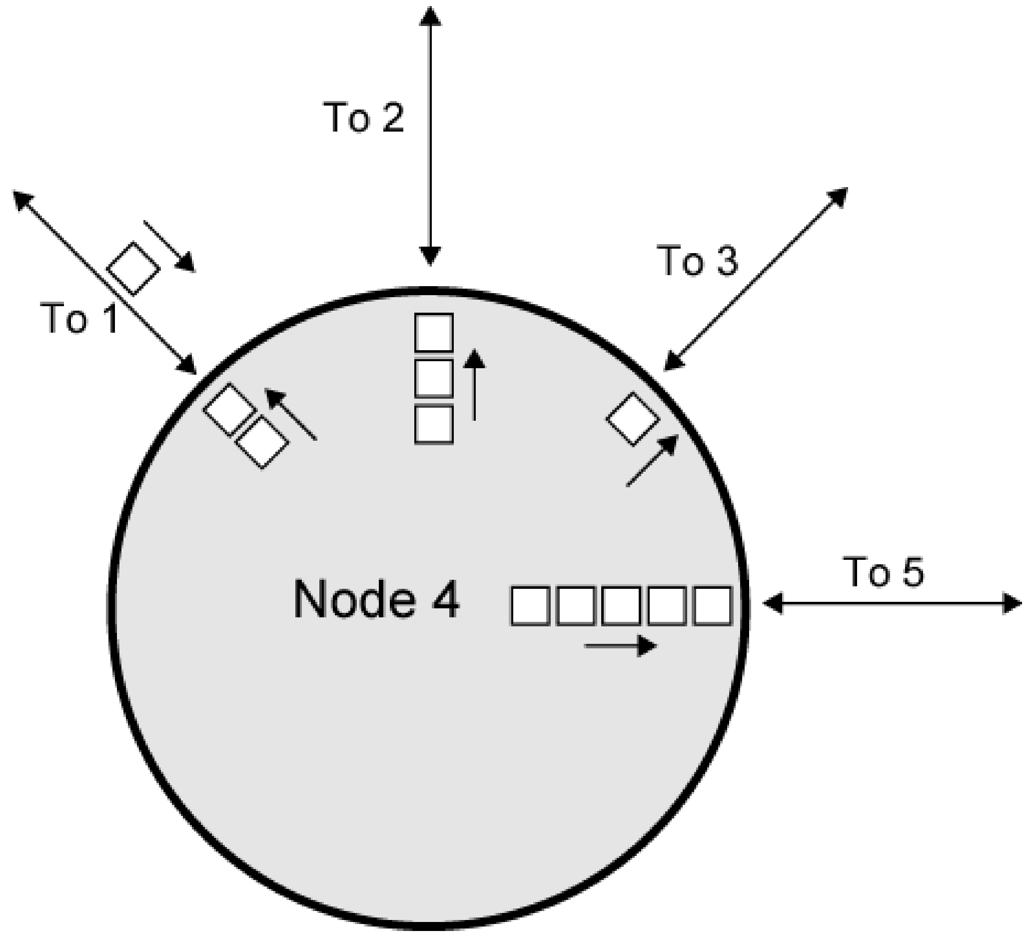
Classification

- Based on information sources
  - Local (isolated)
    - Route to outgoing link with shortest queue
    - Can include bias for each destination
    - Rarely used - do not make use of easily available info
  - Adjacent nodes
  - All nodes

Isolated Adaptive Routing

Node 4's Bias
Table for
Destination 6

Next Node	Bias
1	9
2	6
3	3
5	0



ARPANET Routing Strategies(1)

- First Generation
  - 1969
  - Distributed adaptive
  - Estimated delay as performance criterion
  - Bellman-Ford algorithm (appendix 10a)
  - Node exchanges delay vector with neighbors
  - Update routing table based on incoming info
  - Doesn't consider line speed, just queue length
  - Queue length not a good measurement of delay
  - Responds slowly to congestion

ARPANET Routing Strategies(2)

- Second Generation
  - 1979
  - Uses delay as performance criterion
  - Delay measured directly
  - Uses Dijkstra's algorithm (appendix 10a)
  - Good under light and medium loads
  - Under heavy loads, little correlation between reported delays and those experienced

ARPANET Routing Strategies(3)

- Third Generation
  - 1987
  - Link cost calculations changed
  - Measure average delay over last 10 seconds
  - Normalize based on current value and previous results

Least Cost Algorithms

- Basis for routing decisions
  - Can minimize hop with each link cost 1
  - Can have link value inversely proportional to capacity
- Given network of nodes connected by bi-directional links
- Each link has a cost in each direction
- Define cost of path between two nodes as sum of costs of links traversed
- For each pair of nodes, find a path with the least cost
- Link costs in different directions may be different
  - E.g. length of packet queue

Dijkstra's Algorithm Definitions

- Find shortest paths from given source node to all other nodes, by developing paths in order of increasing path length
- N = set of nodes in the network
- s = source node
- T = set of nodes so far incorporated by the algorithm
- w(i, j) = link cost from node i to node j
  - w(i, i) = 0
  - w(i, j) = ∞ if the two nodes are not directly connected
  - w(i, j) ≥ 0 if the two nodes are directly connected
- L(n) = cost of least-cost path from node s to node n currently known
  - At termination, L(n) is cost of least-cost path from s to n

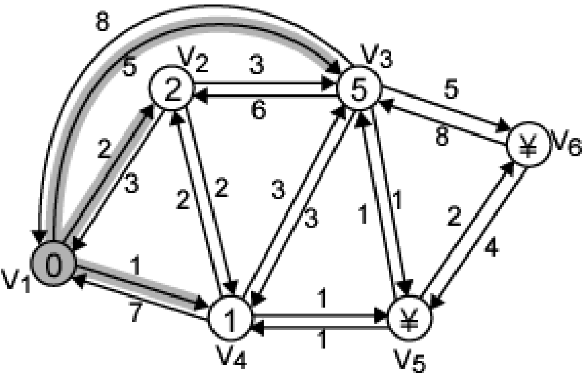
Dijkstra's Algorithm Method

- Step 1 [Initialization]
  - T = {s} Set of nodes so far incorporated consists of only source node
  - $L(n) = w(s, n)$ for $n \neq s$
  - Initial path costs to neighboring nodes are simply link costs
- Step 2 [Get Next Node]
  - Find neighboring node not in T with least-cost path from s
  - Incorporate node into T
  - Also incorporate the edge that is incident on that node and a node in T that contributes to the path
- Step 3 [Update Least-Cost Paths]
  - $L(n) = \min[L(n), L(x) + w(x, n)]$ for all $n \notin T$
  - If latter term is minimum, path from s to n is path from s to x concatenated with edge from x to n
- Algorithm terminates when all nodes have been added to T

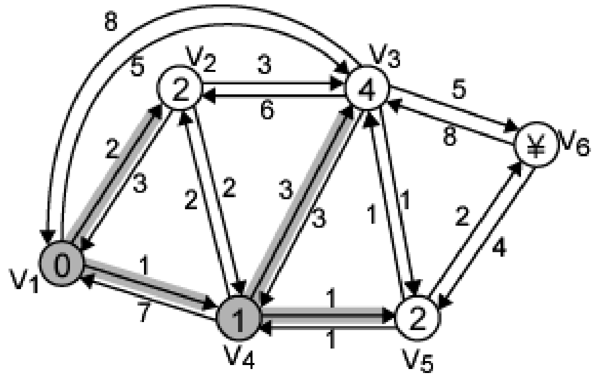
Dijkstra's Algorithm Notes

- At termination, value L(x) associated with each node x is cost (length) of least-cost path from s to x.
- In addition, T defines least-cost path from s to each other node
- One iteration of steps 2 and 3 adds one new node to T
  - Defines least cost path from s tothat node

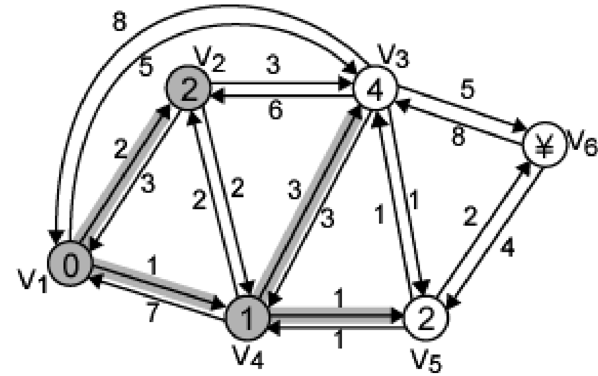
Example of Dijkstra's Algorithm



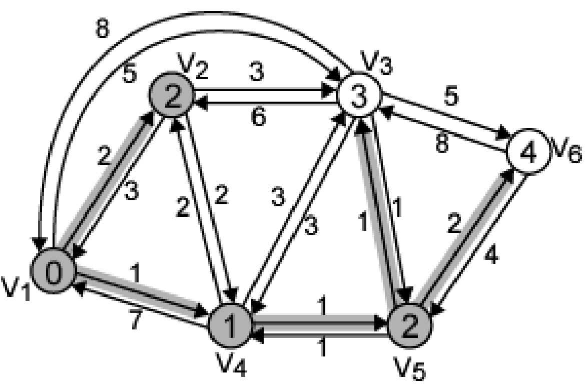
T = {1}



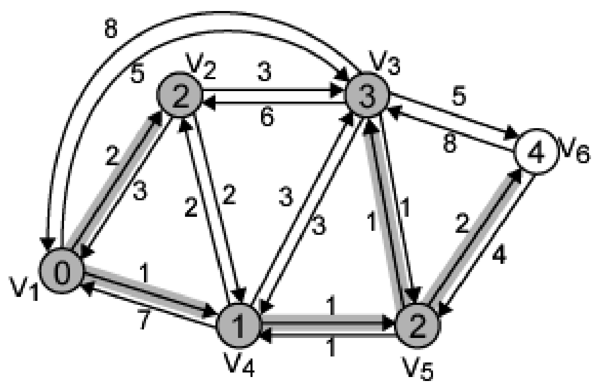
T = {1, 4}



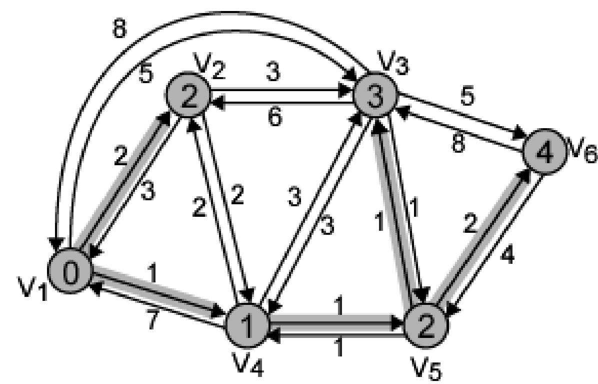
T = {1, 2, 4}



T = {1, 2, 4, 5}



T = {1, 2, 3, 4, 5}



T = {1, 2, 3, 4, 5, 6}

Results of Example Dijkstra's Algorithm

Iteration	T	L(2)	Path	L(3)	Path	L(4)	Path	L(5)	Path	L(6)	Path
1	{1}	2	1–2	5	1-3	1	1–4	∞	-	∞	-
2	{1,4}	2	1–2	4	1-4-3	1	1–4	2	1-4–5	∞	-
3	{1, 2, 4}	2	1–2	4	1-4-3	1	1–4	2	1-4–5	∞	-
4	{1, 2, 4, 5}	2	1–2	3	1-4-5–3	1	1–4	2	1-4–5	4	1-4-5–6
5	{1, 2, 3, 4, 5}	2	1–2	3	1-4-5–3	1	1–4	2	1-4–5	4	1-4-5–6
6	{1, 2, 3, 4, 5, 6}	2	1-2	3	1-4-5-3	1	1-4	2	1-4–5	4	1-4-5-6

Bellman-Ford Algorithm Definitions

- Find shortest paths from given node subject to constraint that paths contain at most one link
- Find the shortest paths with a constraint of paths of at most two links
- And so on
- s = source node
- w(i, j) = link cost from node i to node j
  - w(i, i) = 0
  - w(i, j) = ∞ if the two nodes are not directly connected
  - w(i, j) $\geq$ 0 if the two nodes are directly connected
- h = maximum number of links in path at current stage of the algorithm
- $L_h(n)$ = cost of least-cost path from s to n under constraint of no more than h links

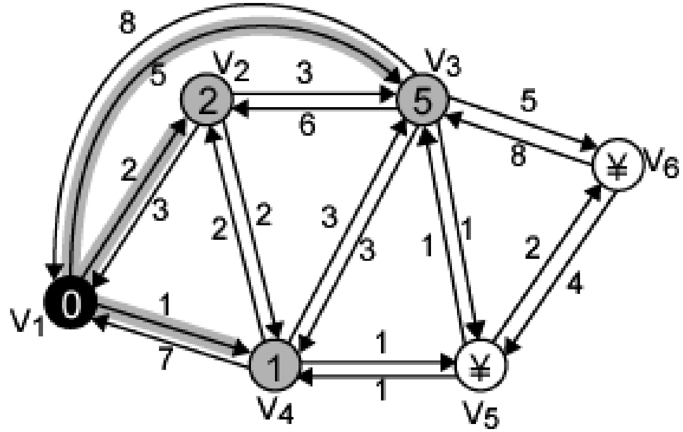
Bellman-Ford Algorithm Method

- Step 1 [Initialization]
  - $L_0(n) = \infty$, for all $n \neq s$
  - $L_h(s) = 0$, for all h
- Step 2 [Update]
- For each successive $h \geq 0$
  - For each $n \neq s$, compute
  - $L_{h+1}(n) = \min_j [L_h(j) + w(j,n)]$
- Connect n with predecessor node j that achieves minimum
- Eliminate any connection of n with different predecessor node formed during an earlier iteration
- Path from s to n terminates with link from j to n

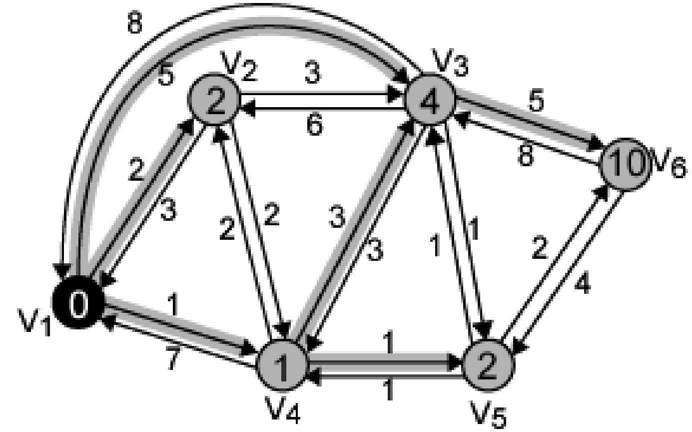
Bellman-Ford Algorithm Notes

- For each iteration of step 2 with h=K and for each destination node n, algorithm compares paths from s to n of length K=1 with path from previous iteration
- If previous path shorter it is retained
- Otherwise new path is defined

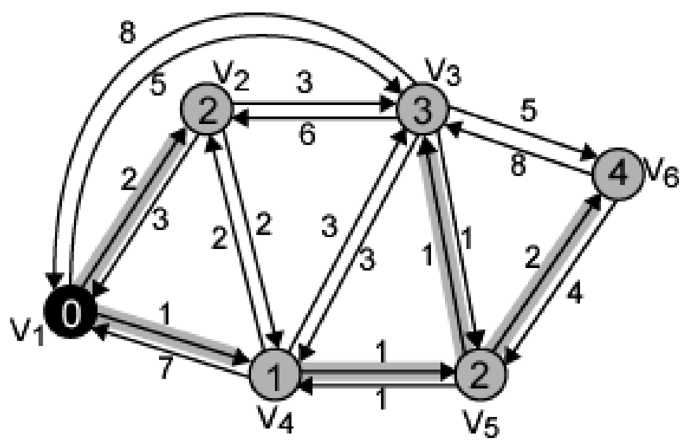
Example of Bellman-Ford Algorithm



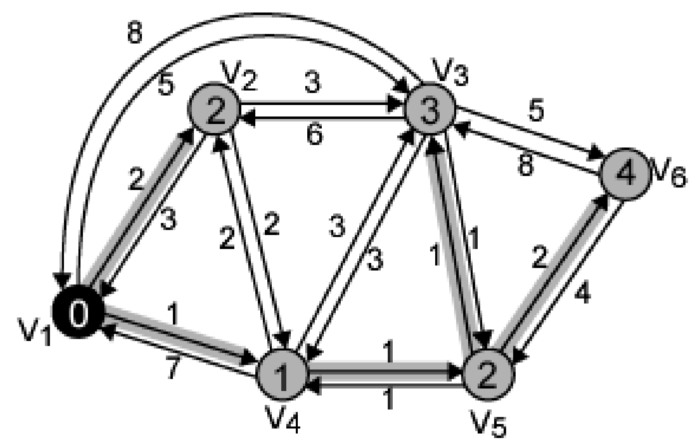
h = 1



h = 2



h = 3



h = 4

Results of Bellman-Ford Example

h	$L_h(2)$	Path	$L_h(3)$	Path	$L_h(4)$	Path	$L_h(5)$	Path	$L_h(6)$	Path
0	∞	-	∞	-	∞	-	∞	-	∞	-
1	2	1-2	5	1-3	1	1-4	∞	-	∞	-
2	2	1-2	4	1-4-3	1	1-4	2	1-4-5	10	1-3-6
3	2	1-2	3	1-4-5-3	1	1-4	2	1-4-5	4	1-4-5-6
4	2	1-2	3	1-4-5-3	1	1-4	2	1-4-5	4	1-4-5-6

Comparison

- Results from two algorithms agree
- Information gathered
  - Bellman-Ford
    - Calculation for node n involves knowledge of link cost to all neighboring nodes plus total cost to each neighbor from s
    - Each node can maintain set of costs and paths for every other node
    - Can exchange information with direct neighbors
    - Can update costs and paths based on information from neighbors and knowledge of link costs
  - Dijkstra
    - Each node needs complete topology
    - Must know link costs of all links in network
    - Must exchange information with all other nodes

Evaluation

- Dependent on processing time of algorithms
- Dependent on amount of information required from other nodes
- Implementation specific
- Both converge under static topology and costs
- Converge to same solution
- If link costs change, algorithms will attempt to catch up
- If link costs depend on traffic, which depends on routes chosen, then feedback
  - May result in instability