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Computer Networks

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Material with thanks to James F. Kurose, Mosharaf Chowdhury, and other colleagues.

Chapter 3. Network Layer

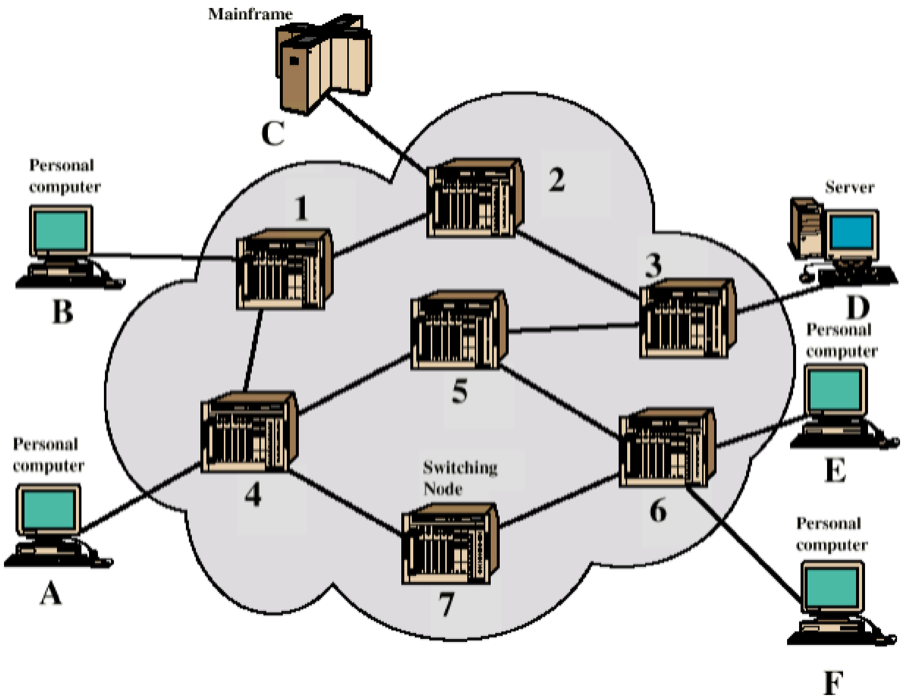
- Network Layer Functions
- IP Protocol Basic
- IP Protocol Suit
- Routing Fundamentals
- Internet Routing Protocols
- IP Multicasting

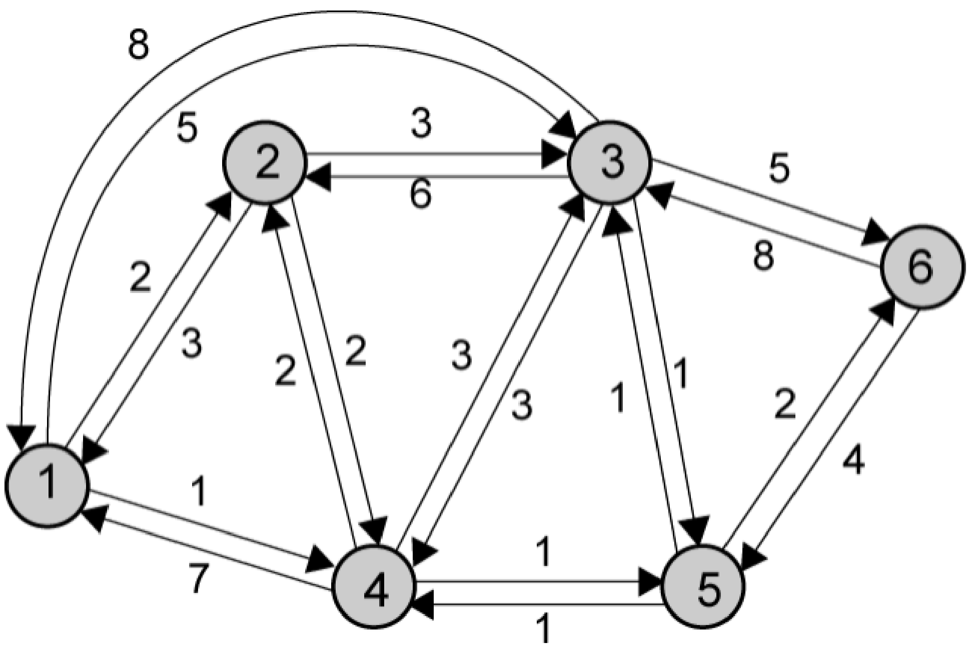
Routing Fundamentals

Routing

- Objective
  - Build routing tables on switches for datagram networks
  - Choose paths and build forwarding tables when setting up connections for VC networks
- Characteristics required
  - Efficiency: e.g. smallest possible line or switch
  - Resilience: peak load, switch or line failure
  - Stability: avoid oscillation

Network Abstraction



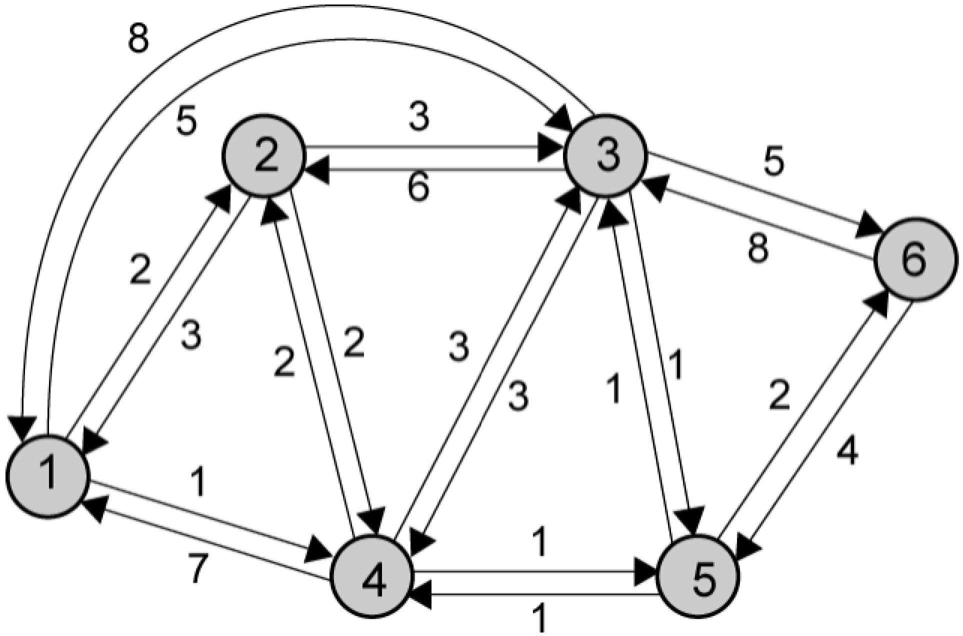


Routing Elements

- Performance criteria
- Decision time
- Decision place
- Network info source
- Network info update timing

Performance Criteria

- Minimum hop
  - e.g. 1–3–6
- Least cost
  - e.g. 1–4–5–6
- Determine cost
  - Minimum delay: queue length
  - Largest throughput: reverse of transmission rate



Decision Time and Place

- Time
  - For each packet --- datagram networks
  - At the start of each virtual circuit --- VC networks
- Place
  - Centralized
  - Source --- source routing
  - Distributed --- by each switch node

Network Info Source and Update Timing

- Info source
  - Local information
  - Adjacent switches
  - All switches in the network
- Update timing
  - Update periodically
  - Upon major changes in switches or links
  - Fixed (manual configuration)

Different Routing Strategies

- Central (static)
  - Fixed and configured
- Distributed
  - Flooding
  - Random
  - Adaptive

Central Routing

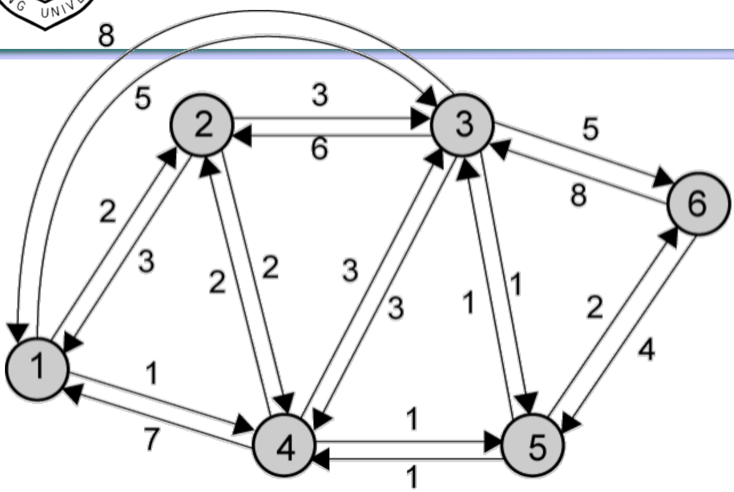
- Single fixed route for each source to destination pair

- Determine routes using a least cost algorithm

- Routes re-config upon major changes in network topology

Fixed Routing Tables

1 → 6



CENTRAL ROUTING DIRECTORY

From Node

To 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	—

Centralized

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

Distributed

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

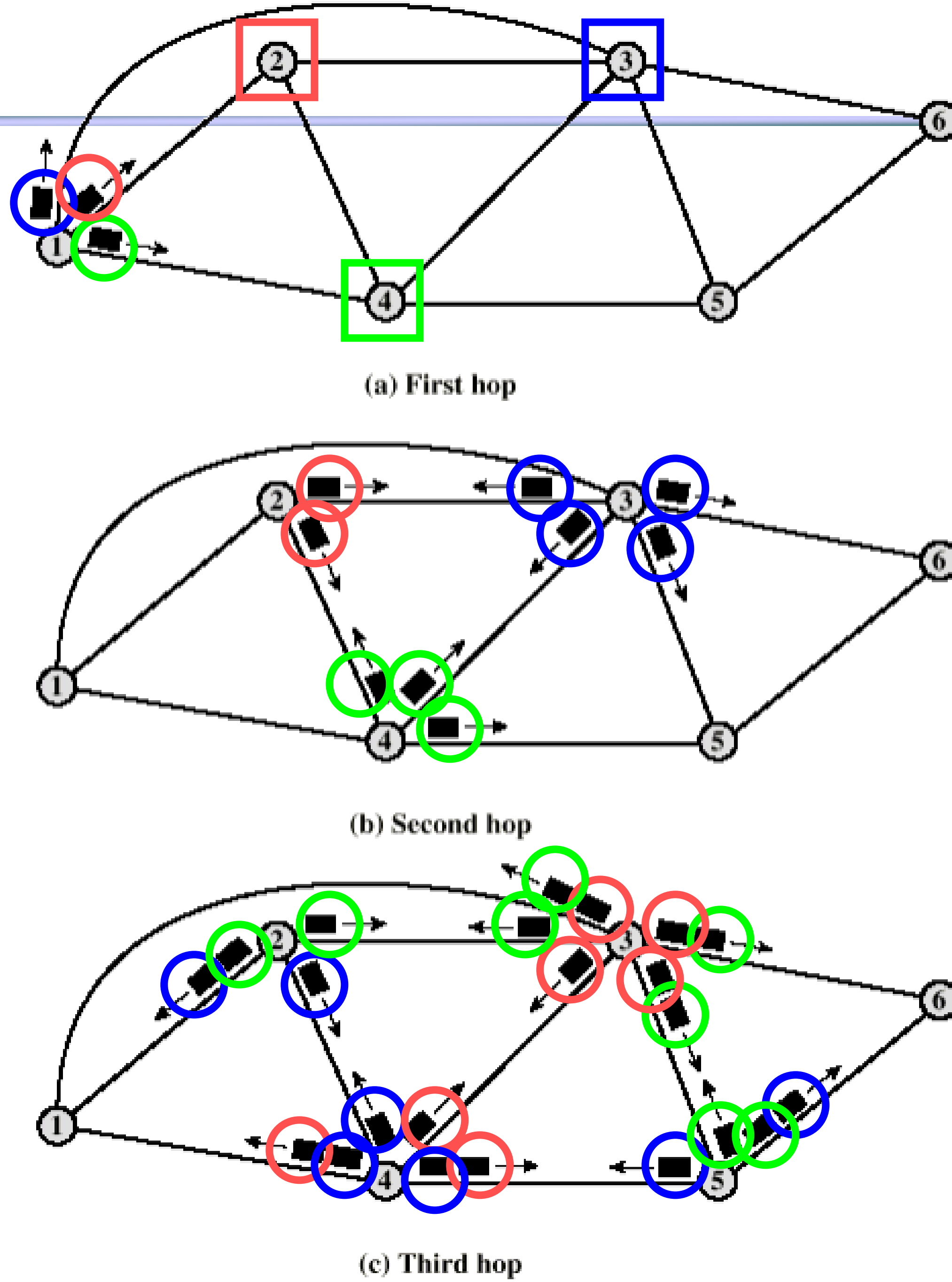
Flooding

- No network info required
- Packet sent by switch to every neighbor
  - Packets retransmitted on every link except incoming link
- Eventually a number of copies will arrive at destination
- Duplicates
  - Many copies of the same packet is created
- Cycle problem
  - These copies may circling around the network forever
  - A hop count in packets can handle the problem

Flooding Example

Hop count = 3

- Initial
  - 3 packets
- 1st hop
  - 9 packets
- 2nd hop
  - 23 packets



Properties of Flooding

- All possible routes are tried
  - Very robust
- At least one packet will take minimum cost route
  - Can be used to set up virtual circuit
- All switches 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
  - Or based on probability calculation
- No network info needed
- Suitable for strongly-connected network
- Route is typically not optimal

Assign Probabilities

- $P_i = R_i / \Sigma_j R_j$
  - P_i – Probability of selecting out-link i
  - R_i – Cost factor of link i

- Possible cost factor
  - Transmission rate – for throughput
  - Reverse of queue size – for delay

Adaptive Routing

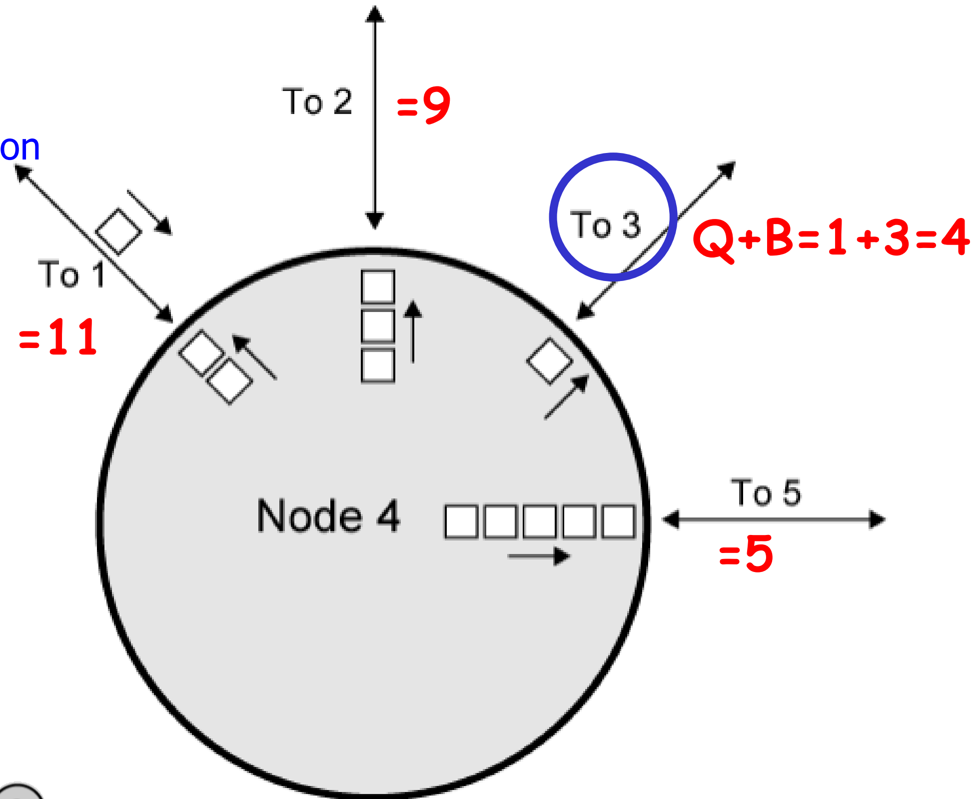
- Used by almost all packet switching networks
- Routing decisions change as conditions on the network change
- Requires info about network
  - Tradeoff between quality of network info and overhead
- Aid in congestion control

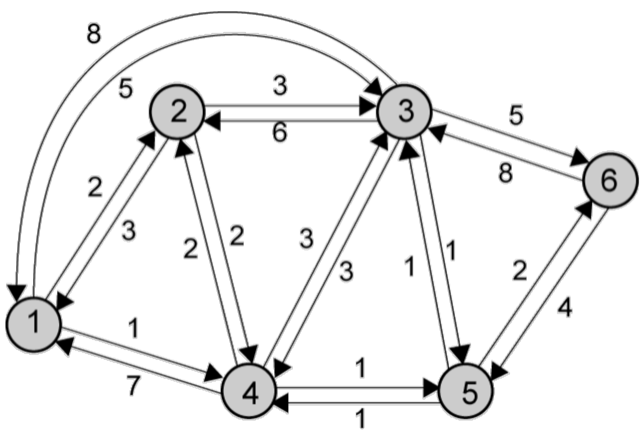
An Isolated Adaptive Routing

- Only local info used
- Strategy 1: route to the outgoing link with shortest queue length Q
  - Pros. Load balancing
  - Cons. May away from the destination
- Strategy 2: take direction into account
  - Each link has a bias B for the destination
  - Route to minimize Q+B

Node 4's Bias
Table for
Destination 6

Next Node	Bias
1	9
2	6
3	3
5	0





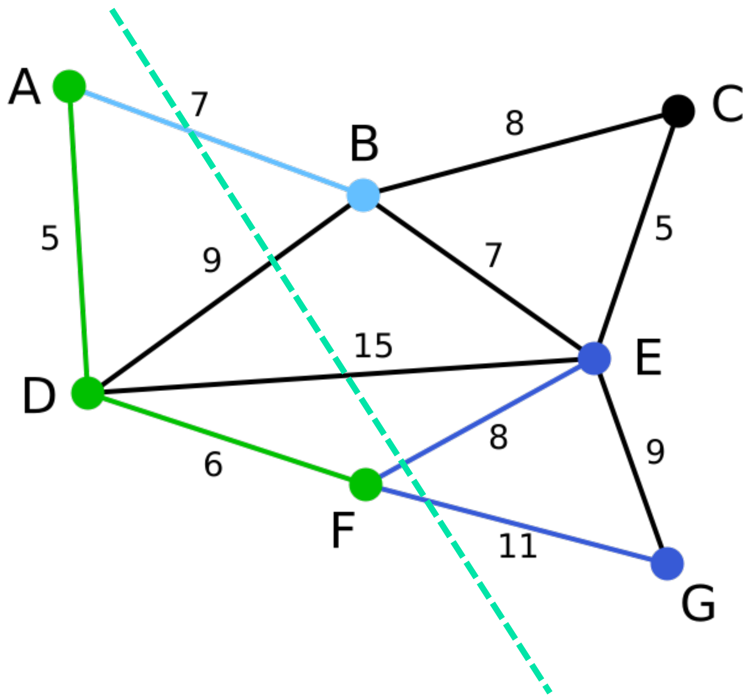
2 Least Cost Algorithms

- For each pair of nodes, find a path with the least cost

- Dijkstra's Algorithm
- Bellman-Ford Algorithm

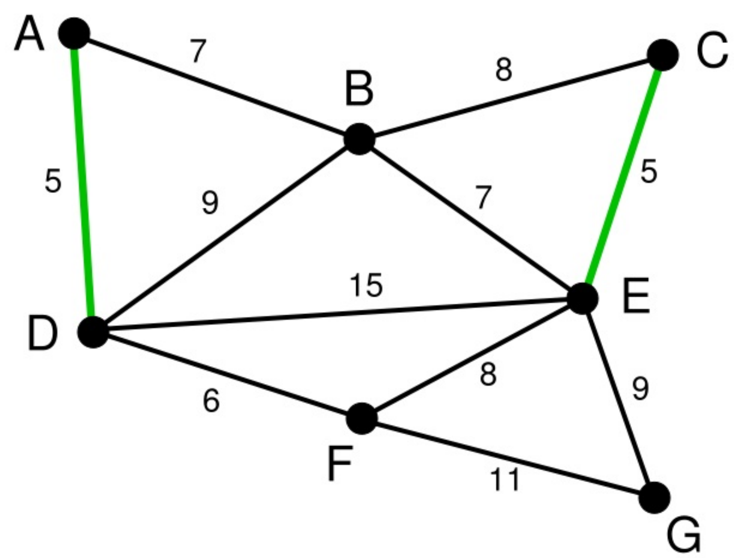
Recap: Prim's and Kruskal's algorithm

- Minimum Spanning Tree Algorithm



Prim's algorithm

Explored node set {A,D,F}
To be explored set {B,E,G}
Next node chosen: B



Kruskal's algorithm

Sort according to edge weight (ascending)
Add edges one-by-one (without loop)

Dijkstra's Algorithm

- Find shortest paths from given source to all other nodes
  - Developing paths in order of increasing path cost (length)

- Denote
  - **N** = set of nodes in the network
  - **s** = the 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

Dijkstra's Algorithm Method

- $\mathbf{L(n)}$ = cost of least-cost path from source $\mathbf{s}$ to node $\mathbf{n}$ currently known
  - At termination, $\mathbf{L(n)}$ is cost of least-cost path from $\mathbf{s}$ to $\mathbf{n}$

- Step 1 [Initialization]
  - $\mathbf{T} = \{\mathbf{s}\}$ set of nodes incorporated consists of only source node
  - $\mathbf{L(n) = w(s, n)}$ for $\mathbf{n \neq s}$
  - Initial path costs to neighboring nodes are simply link costs

- Step 2 [Get Next Node]
  - Find node x not in $\mathbf{T}$ with least-cost path from $\mathbf{s}$ (i.e. $\mathbf{min\ L(}x\mathbf{)}$)
  - Incorporate node x into $\mathbf{T}$
  - Also incorporate the edge that links x with the node in $\mathbf{T}$ that contributes to the path

Dijkstra’s Algorithm Method

- Step 3 [Update Least-Cost Paths]
  - $\mathbf{L(n) = min[L(n), L(\mathit{x}) + w(\mathit{x}, n)]}$ for all $\mathbf{n \notin T}$
  - If latter term is minimum, path from **s** to **n** is path from **s** to $\boldsymbol{x}$ concatenated with link from $\boldsymbol{x}$ to **n**

- Algorithm terminates when all nodes have been added to **T**

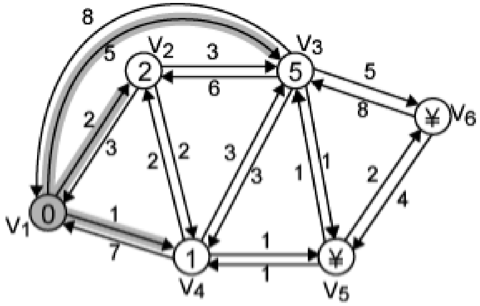
Dijkstra's Algorithm Notes

- One iteration of steps 2 and 3 adds one new node to **T**
  - Defines least cost path from **s** to that node

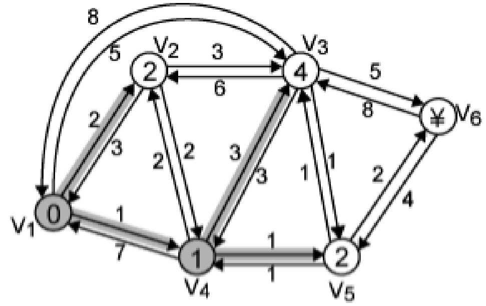
- Value **L(n)** for each node **n** is the cost (length) of least-cost path from **s** to **n**

- At last, **T** defines the least-cost path from **s** to each other node

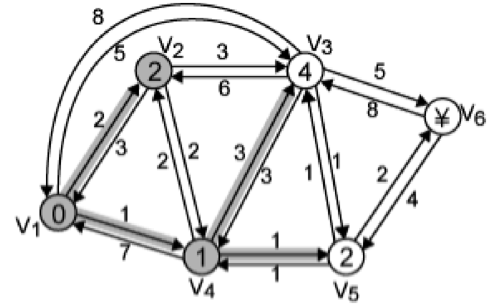
Example of Dijkstra's Algorithm



T = {1}

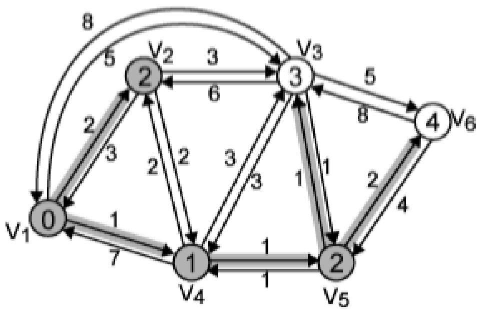


T = {1, 4}

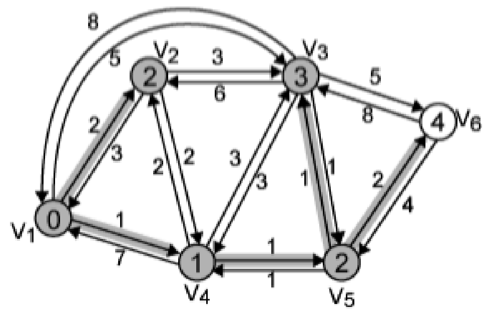


T = {1, 2, 4}

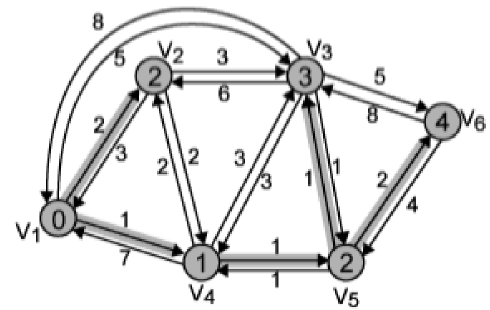
L(3)=min{L(3),L(4)+w(4,3)}=min{5,1+3}=4



T = {1, 2, 4, 5}



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

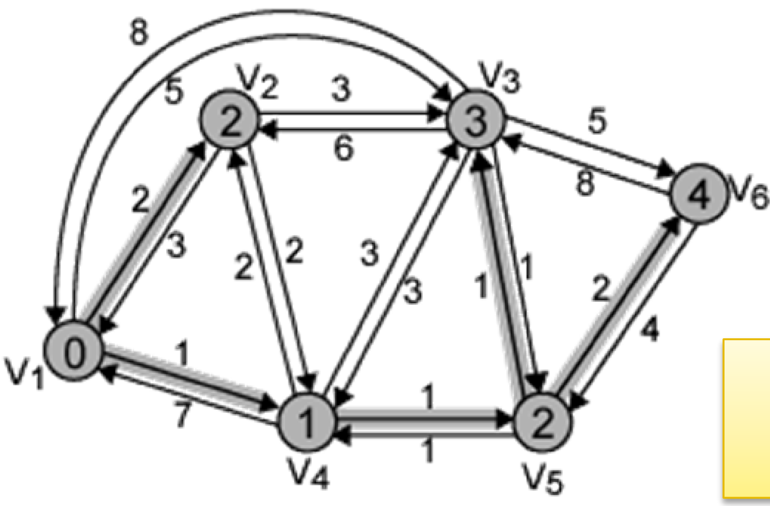


T = {1, 2, 3, 4, 5, 6}

L(3)=min{L(3),L(5)+w(5,3)}=min{4,2+1}=3

No	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			2	1-4-5	∞	–
3	{1, 2, 4}			4	1-4-3			2	1-4-5	∞	–
4	{1, 2, 4, 5}			3	1-4-5-3					4	1-4-5-6
5	{1, 2, 3, 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

Exercise



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

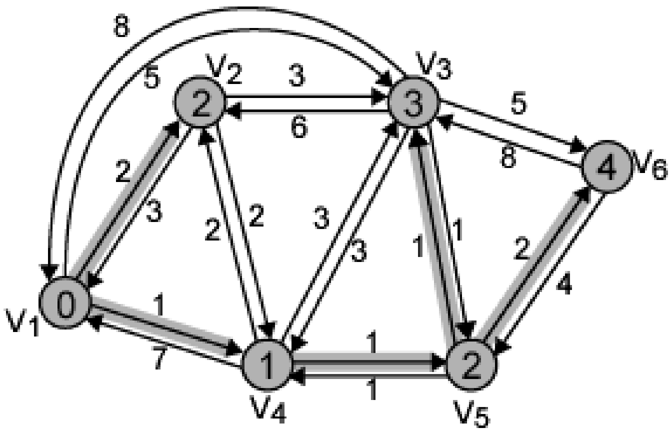
T=T+{x} //x is the min cost in N-T

L(n) = min[L(n), L(x) + w(x, n)] for all n ∉ T

No	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			2	1-4-5	∞	–
3											
4											
5											
6											

Results of Dijkstra's Algorithm

No	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			2	1-4-5	∞	–
3	{1, 2, 4}			4	1-4-3			2	1-4-5	∞	–
4	{1, 2, 4, 5}			3	1-4-5-3					4	1-4-5-6
5	{1, 2, 3, 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



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

Destination	Next-Hop	Distance
2	2	2
3	4	3
4	4	1
5	4	2
6	4	4

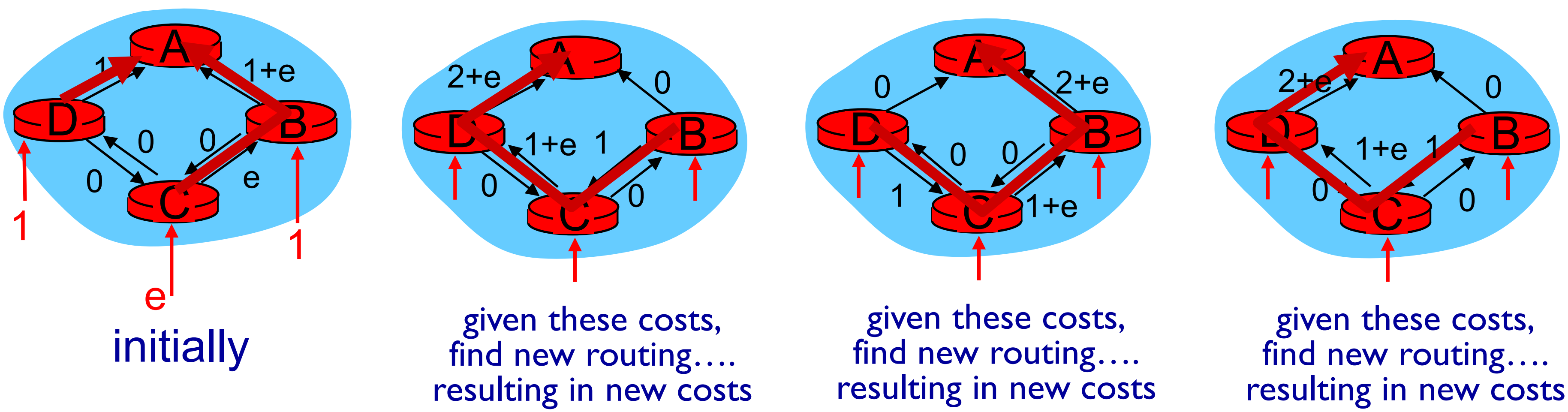
Dijkstra's algorithm discussion

algorithm complexity: n nodes

- each iteration: need to check all nodes, w, not in N
- n(n+1)/2 comparisons: $O(n^2)$
- more efficient implementations possible: O(nlogn)

oscillations possible:

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



震荡：解决办法-非同步运行路由算法，链路代价更新随机化

Bellman-Ford Algorithm

- Find shortest paths from given node containing at most 1 link
- Find the shortest paths that containing at most 2 links, based on the result of 1 link
- Find the shortest paths of 3 links based on result of 2 links, and so on

- **s** = the 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) > 0** if the two nodes are directly connected

Bellman-Ford Algorithm Method

- $\mathbf{h}$ = maximum number of links in path at current stage of the algorithm
- $\mathbf{L_h(n)}$ = cost of least-cost path from $\mathbf{s}$ to $\mathbf{n}$ under constraint of no more than $\mathbf{h}$ links

- Step 1 [Initialization]
  - $\mathbf{L_0(n)} = \infty$, for all $\mathbf{n \neq s}$
  - $\mathbf{L_1(n) = w(s, n)}$
  - $\mathbf{L_h(s) = 0}$, for all $\mathbf{h}$

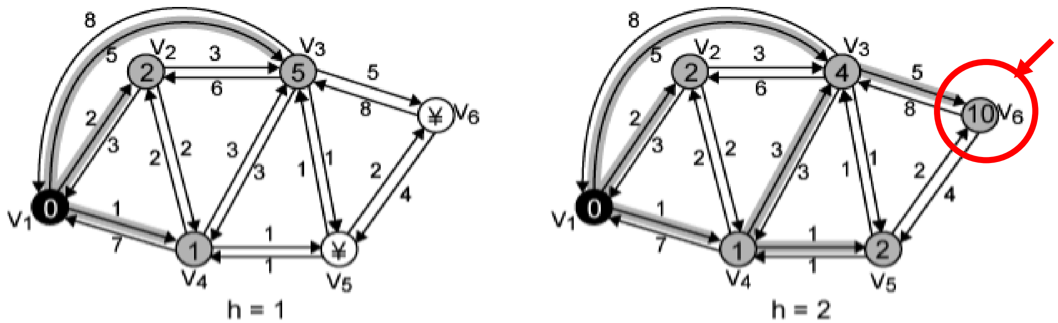
Bellman-Ford Algorithm Method

- Step 2 [Update]
  - For each successive $\mathbf{h > 0}$
  - For each $\mathbf{n \neq s}$, compute $\mathbf{L_{h+1}(n) = min_j[L_h(j)+w(j,n)]}$
  - Connect $\mathbf{n}$ with predecessor node $\mathbf{j}$ that achieves minimum
  - Eliminate any connection of $\mathbf{n}$ with different predecessor formed during earlier iterations
- Repeat until no change made to route (convergence)

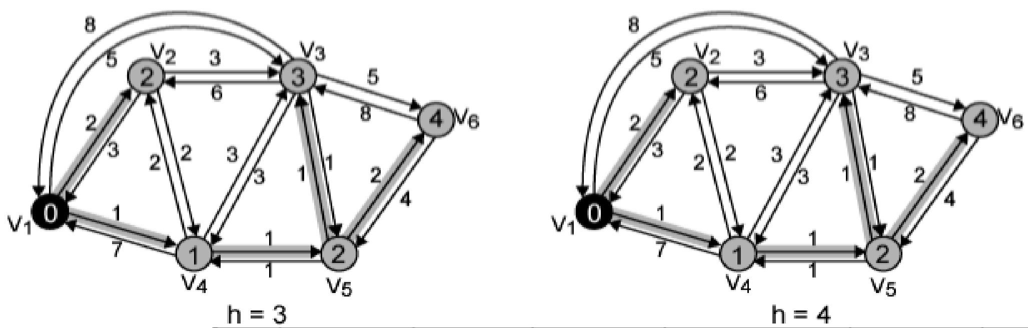
Bellman-Ford Algorithm Notes

- For each iteration with **h** and for each destination node **n**
  - Compares newly computed path from **s** to **n** of length **h** with path from previous iteration (**h–1**)
- If previous path shorter it is retained
- Otherwise new path is defined

Example of Bellman-Ford Algorithm

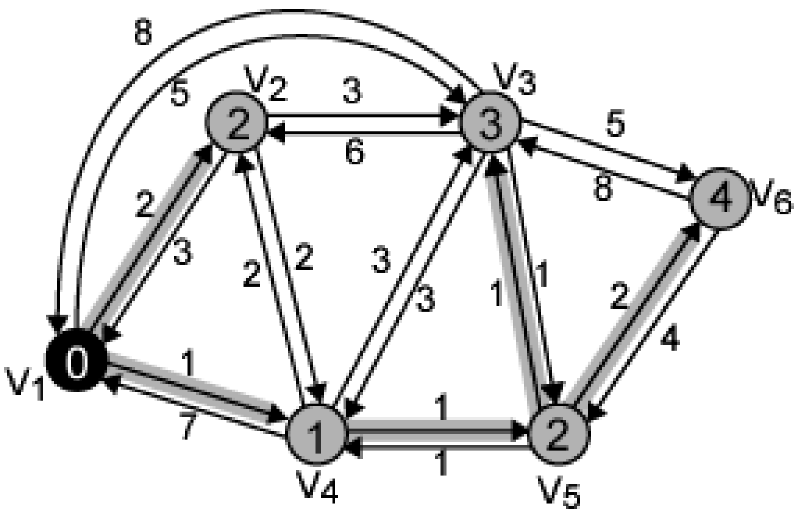


$$L_{h+1}(n) = \min_j[L_h(j)+w(j,n)]$$



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			4	1-4-3			2	1-4-5	10	1-3-6
3			3	1-4-5-3					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

Exercise

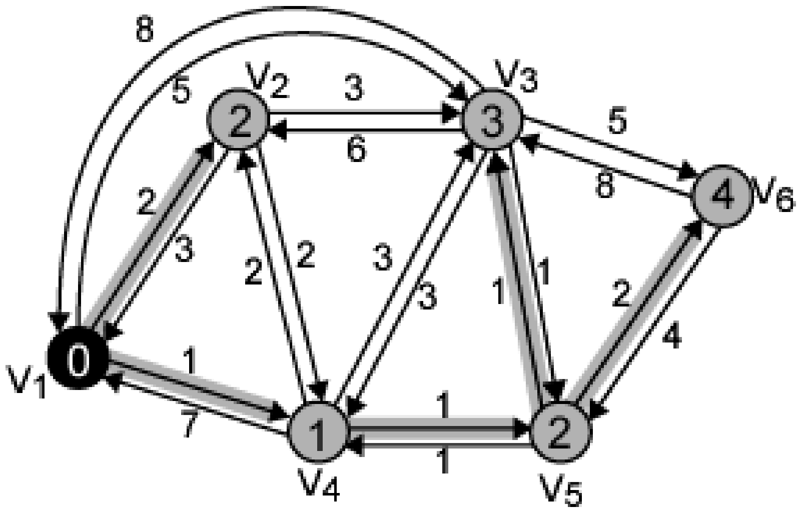


$$L_{h+1}(n) = \min_j[L_h(j)+w(j,n)]$$

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										
3										
4										

Results of Bellman-Ford Algorithm

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			4	1-4-3			2	1-4-5	10	1-3-6
3			3	1-4-5-3					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

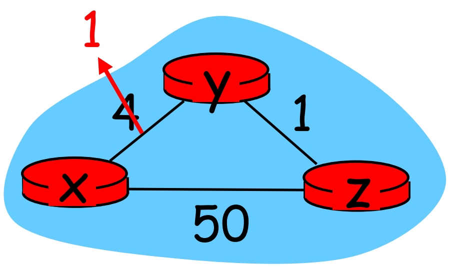


Destination	Next-Hop	Distance
2	2	2
3	4	3
4	4	1
5	4	2
6	4	4

Link cost changes

link cost changes:

- node detects local link cost change
- updates routing info, recalculates distance vector
- if DV changes, notify neighbors



"good news travels fast"

t_0 : *y* detects link-cost change, updates its DV, informs its neighbors.

t_1 : *z* receives update from *y*, updates its table, computes new least cost to *x* , sends its neighbors its DV.

t_2 : *y* receives *z*'s update, updates its distance table. *y*'s least costs do *not* change, so *y* does *not* send a message to *z*.

Link cost changes

link cost changes:

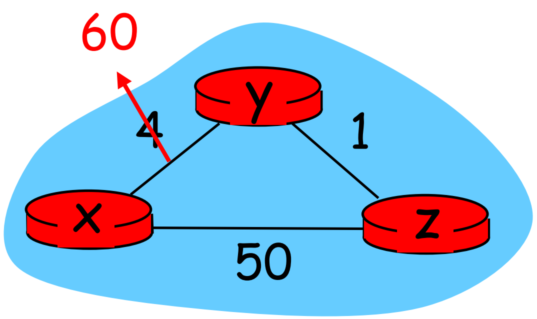
- node detects local link cost change
- *bad news travels slow* –

"count to infinity" problem!

- 44 iterations before algorithm stabilizes: see text

poisoned reverse:（毒性逆转）

- If Z routes through Y to get to X:
  - Z tells Y its (Z's) distance to X is infinite (so Y won't route to X via Z)
- will this completely solve count to infinity problem?
  - No,for 3 or more nodes circle it still exists.



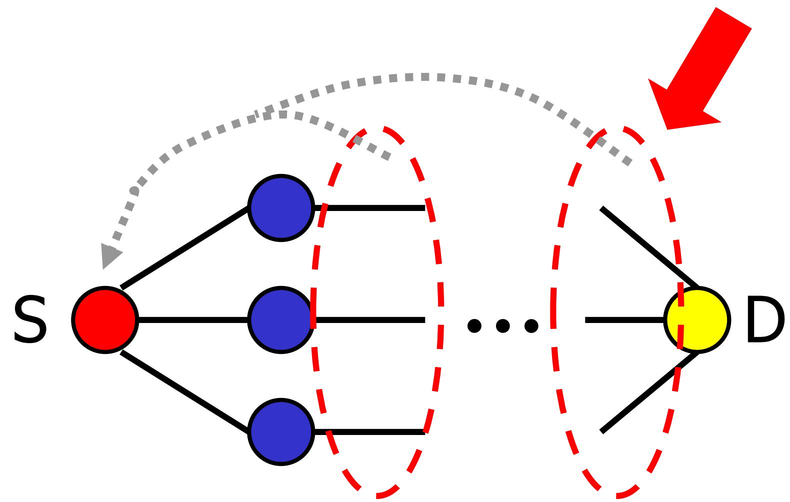
Before:
Dy(x)=4,
Dy(z)=1, Dz(y)=1, Dz(x)=5

After *:
Dy(x)=min{60, w(y,z)+Dz(x)}=6
Dy(z)=1, Dz(y)=1, Dz(x)=5

After **:
Dy(x)=6;
Dy(z)=1
Dz(y)=1,
Dz(x)=min{50, w(z,y)+Dy(x)}=7

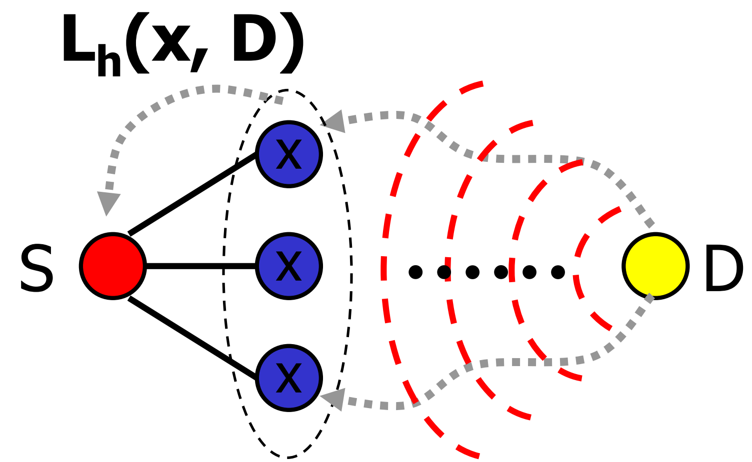
After ***:

$$L(n) = \min [\, L(n), L(x)+\underbrace{w(x, n)}\,]$$



Dijkstra's

(Link State)



Bellman-Ford

(Distance Vector)

Dijkstra vs. Bellman-Ford

- Routing based on Dijkstra
  - Link states flood to all other nodes
  - Each node will have complete topology and build its own routing table
  - Cannot deal with negative weight
- Routing based on Bellman-Ford
  - Each node maintain distance vectors to other known nodes
  - Vectors exchanged with direct neighbours to update the paths and costs
  - Routing tables built in a distributed way

Dijkstra vs. Bellman-Ford

Message complexity

- DK: **n** nodes, **e** links, **O(ne)** messages
- BF: Depends on convergence time

Speed of convergence

- DK: $O(n^2)$ and quick; May have oscillations
- BF: Slow and depends on changes; May contain routing loops

Robustness: what happens if node malfunctions

- DK: Advertise incorrect direct links cost; Error range constrained
- BF: Error node can exchange incorrect paths cost; Error may propagate through the network

Routing algorithm classification

Q: global or local information?

centralized:

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

decentralized:

- router knows physically-connected neighbors, link costs to neighbors
- iterative process of computation, exchange of info with neighbors
- "distance vector" algorithms

Q: static or dynamic?

static:

- routes change slowly over time

dynamic:

- routes change more quickly
  - periodic update
  - in response to link cost changes

Determine Link Cost

- 3 stages in ARPANET
- First stage in 1969
  - Output queue length is used to define a link cost
  - Bellman-Ford algorithm is used for routing

- Second stage in 1979
  - Measured delay is used to define a link cost
  - Mix queuing, transmission, and propagation
  - **Time of retransmit – Time of arrive + Transmission time + Propagation time**
  - Dijkstra's algorithm is used for routing

Determine Link Cost

- To handle the oscillation problem of Dijkstra
- Let some stay on loaded links to balance the traffic
- Apply Link utilization to represent a link's state
- Leveling based on previous value and new utilization
- Use hop normalized metric to calculate link cost

Calculate Link Cost

- Uses the single-server queuing model
- Link utilization
  - $\rho = 2(Ts - T)/(Ts - 2T)$
  - T – current measured delay
  - Ts – mean packet length (600 bit) / transmission rate of the link
- Leveling
  - $U_n = \alpha \times \rho_n + (1-\alpha) \times U_{n-1}$
  - U_n – leveled link utilization at time n
  - α – constant, now set 0.5

Summary

- 集中式路由
- 分布式路由：洪泛，随机行走，自适应路由
- 最小代价路由算法及其性能分析
  - Dijkstra Algorithm（集中式、全局信息）
  - Bellman-Ford（分布式、局部信息）
- 链路代价的计算

Homework

- 第5章: R4, P3, P5, P7, P11