Computer Networks

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Fall 2014

Chapter 3. Packet Switching Networks

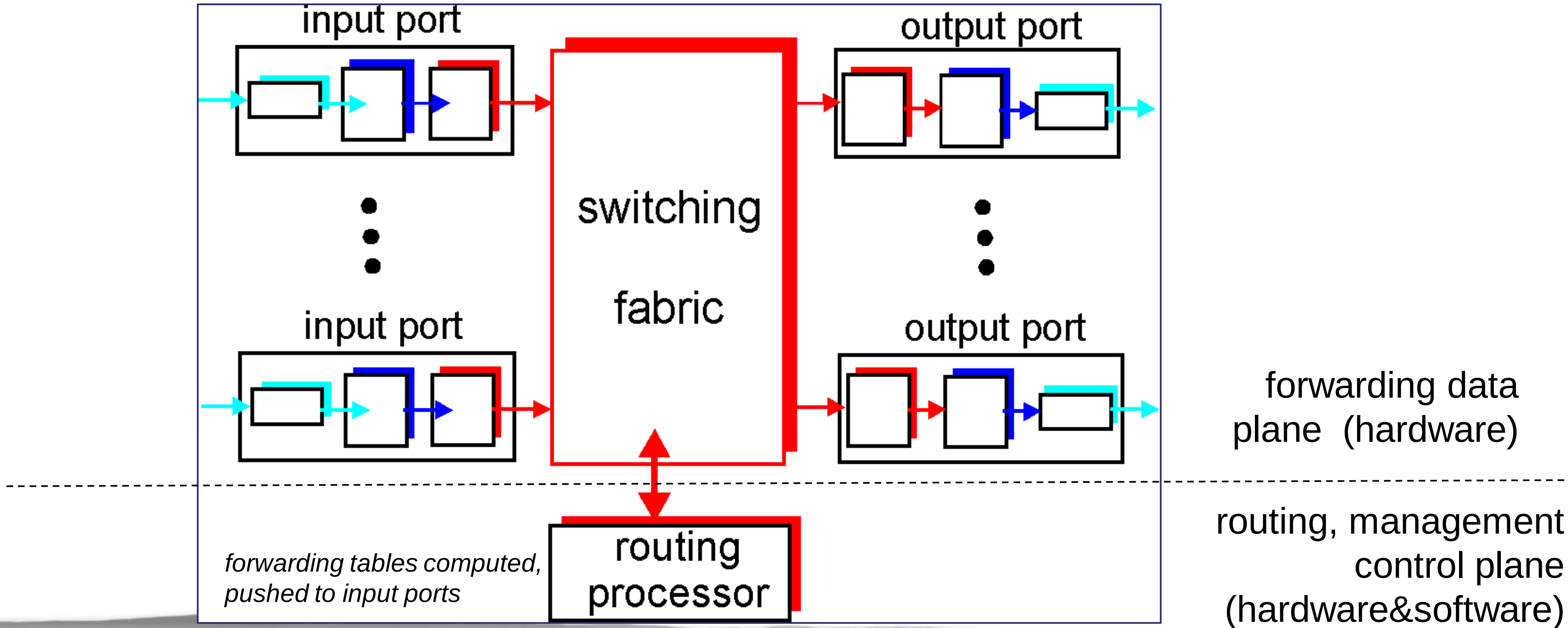
- Switching and Forwarding
- Virtual Circuit and Datagram Networks
- ATM and Cell Switching
- X.25 and Frame Relay
- Routing

What's Inside a Router/Switch?

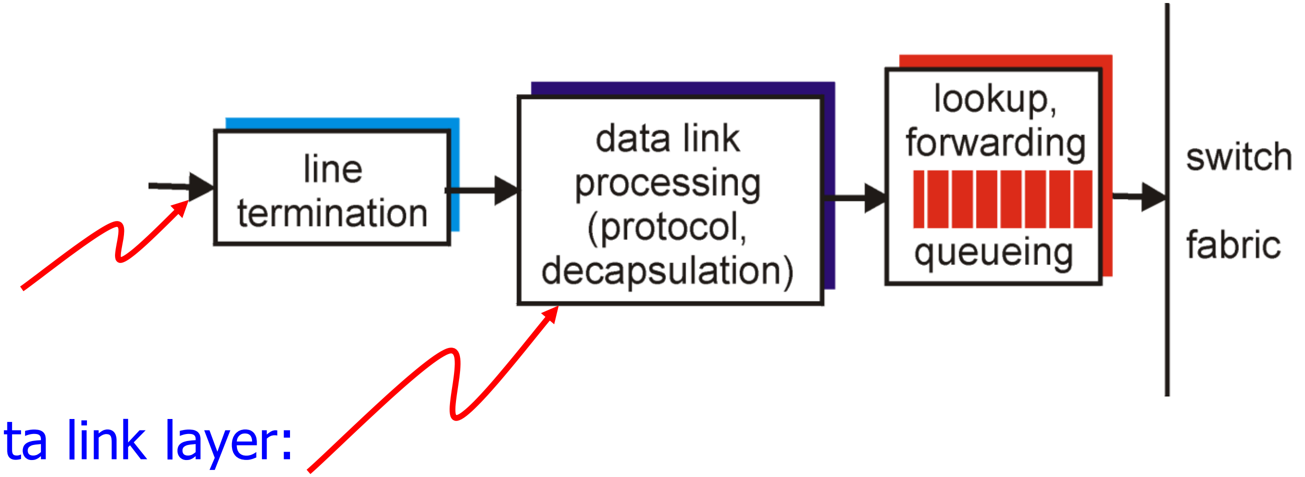
Inside a Switch: Architecture Overview

Two key switch functions:

- Run routing algorithms/protocol
- Forwarding packets from incoming to outgoing link



Input Port Functions



Physical layer:
Bit-level reception

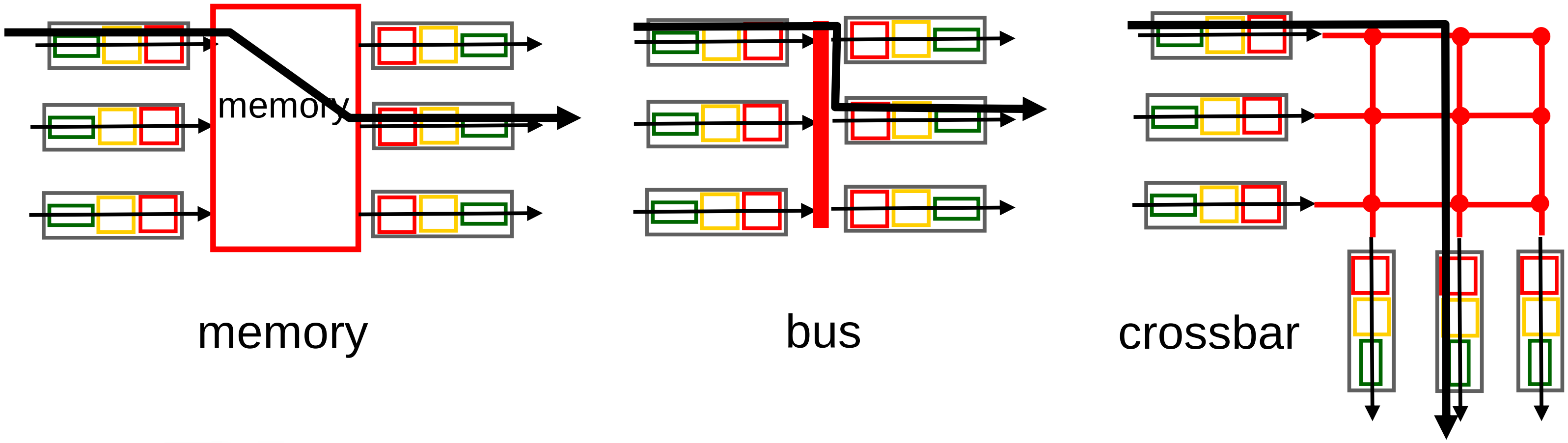
Data link layer:
Error handling

Decentralized switching

- Lookup output port using forwarding table
- Complete input port processing at "line speed"
- Queuing: if packets arrive faster than forwarding rate into switch fabric

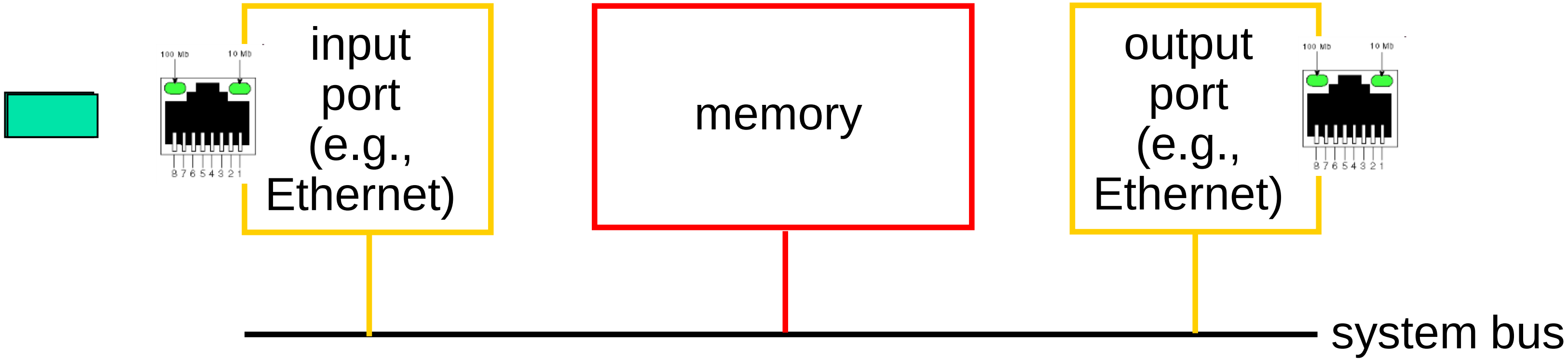
Three Types of Switching Fabrics

- Transfer packet from input buffer to appropriate output buffer
- Switching rate: rate at which packets can be transfer from inputs to outputs
  - often measured as multiple of input/output line rate
  - N inputs: switching rate N times line rate desirable
- Three types of switching fabrics



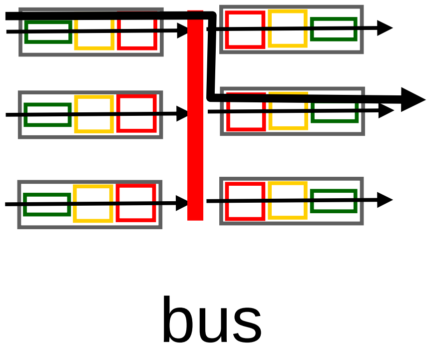
Switching via Memory

- First generation routers:
- Traditional computers with switching under direct control of CP
- Packet copied to system's memory
- Speed limited by memory bandwidth (2 bus crossings per datagram)



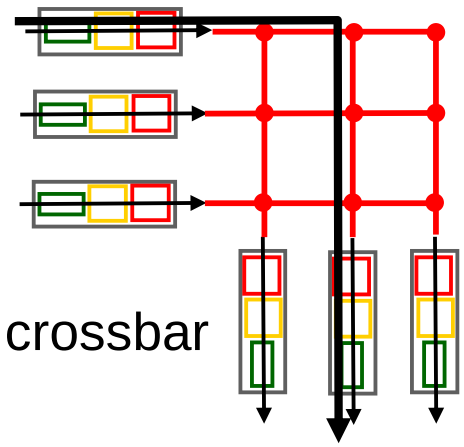
Switching via a Bus

- Datagram from input port memory
  to output port memory via a shared bus
- *Bus contention:* switching speed limited by bus bandwidth
- 32 Gbps bus, Cisco 5600: sufficient speed for access and enterprise routers

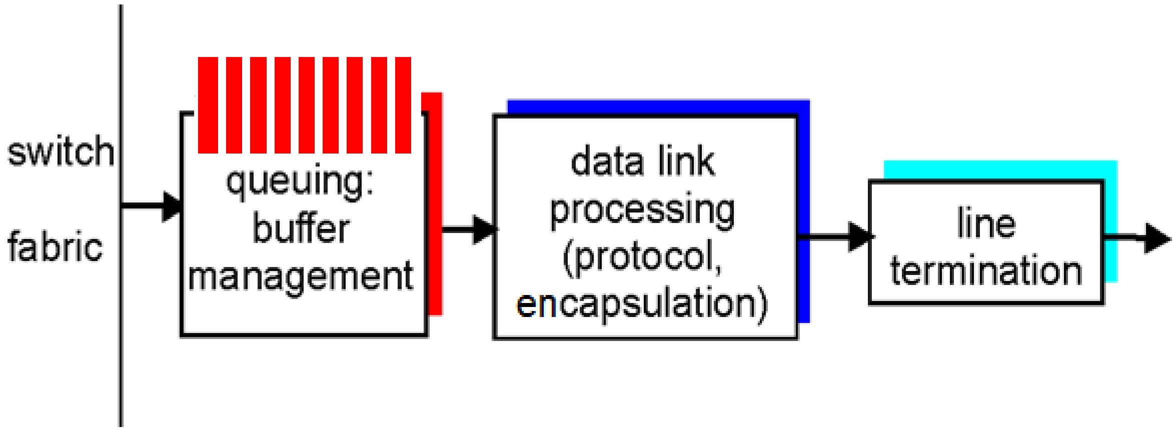


Switching via a Mesh

- Overcome bus bandwidth limitations
- Banyan networks, crossbar, other interconnection nets initially developed to connect processors in multiprocessor
- Advanced design: fragmenting datagram into fixed length cells, switch cells through the fabric.
- Cisco 12000: switches 60 Gbps through the interconnection network



Output Port Functions



- Buffering
  - Required when packets arrive from fabric faster than the transmission rate

Datagram (packets) can be lost due to congestion, lack of buffers

- Scheduling discipline
  - Chooses among queued packets for transmission
  - Select packets to drop when buffer saturates

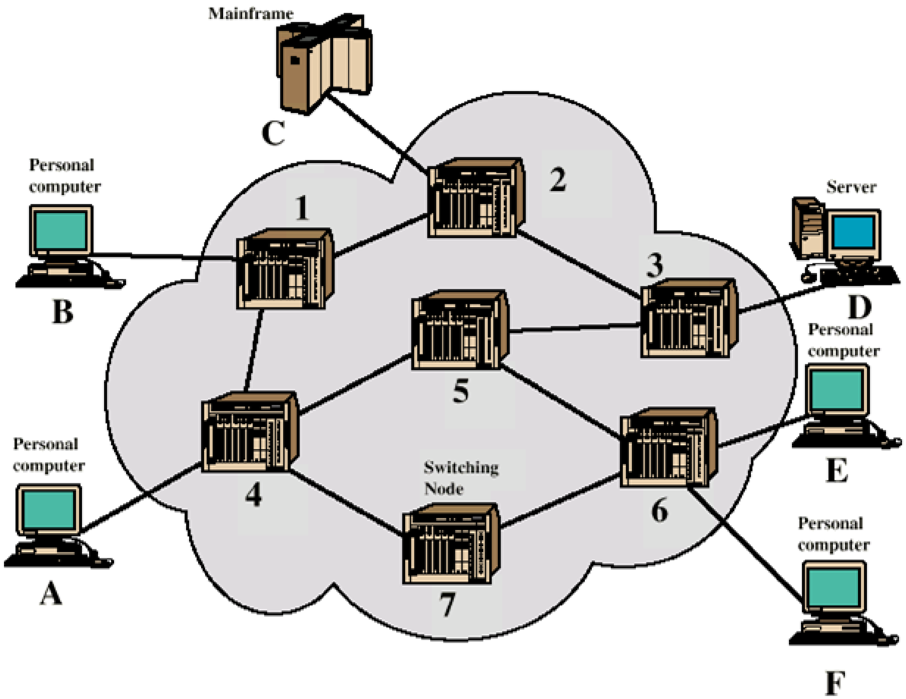
Priority scheduling – who gets best performance

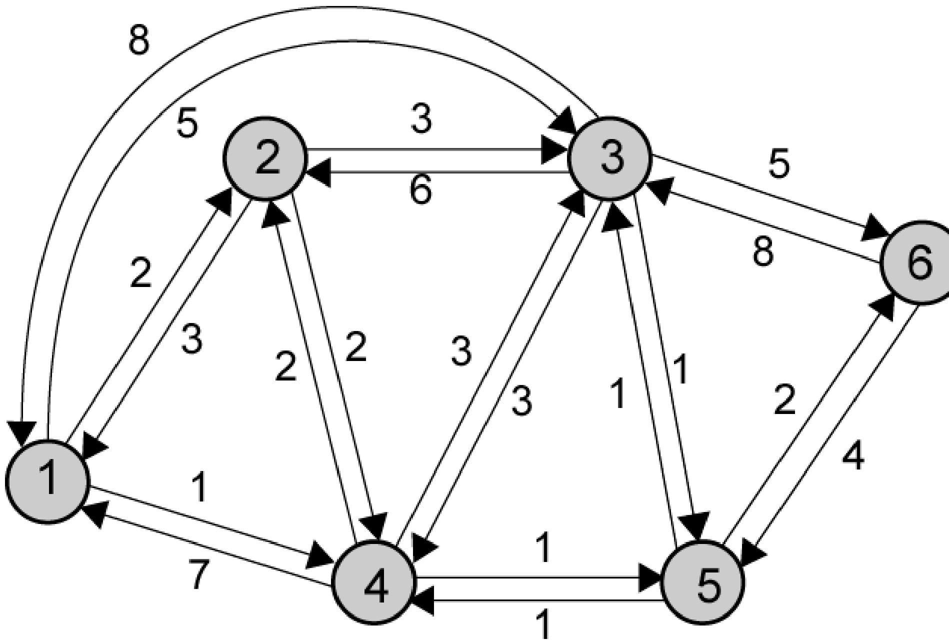
Routing

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



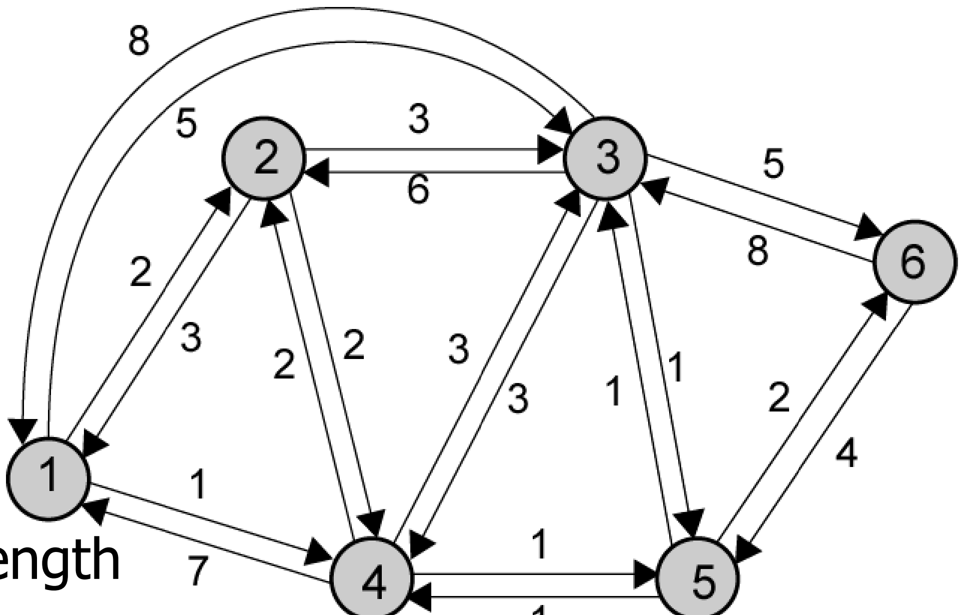


Routing Elements

- 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

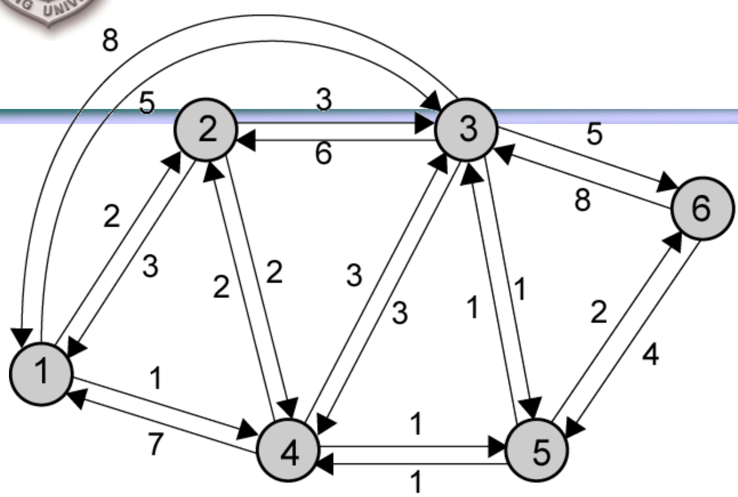
- Central (static)
  - Fixed and configured
- Distributed
  - Flooding
  - Random
  - Adaptive

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

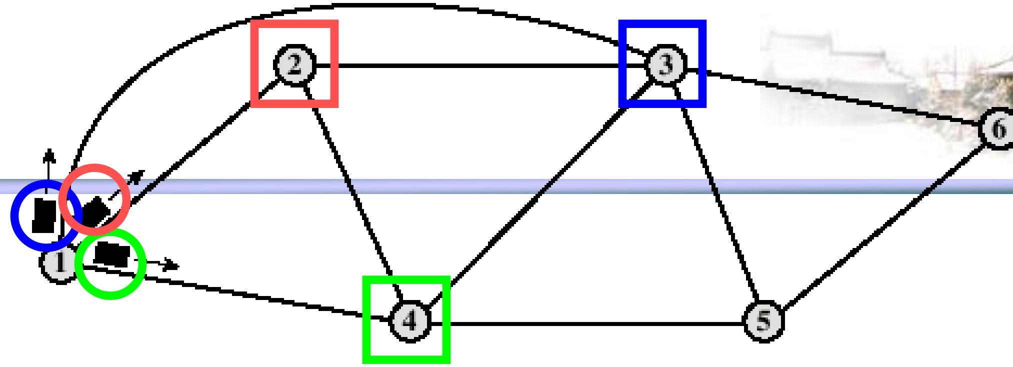
- No network info required
- Packet sent by switch to every neighbor
  - Packets retransmitted on every link except incoming link
- Eventually a number of copies will arrive at destination

- 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

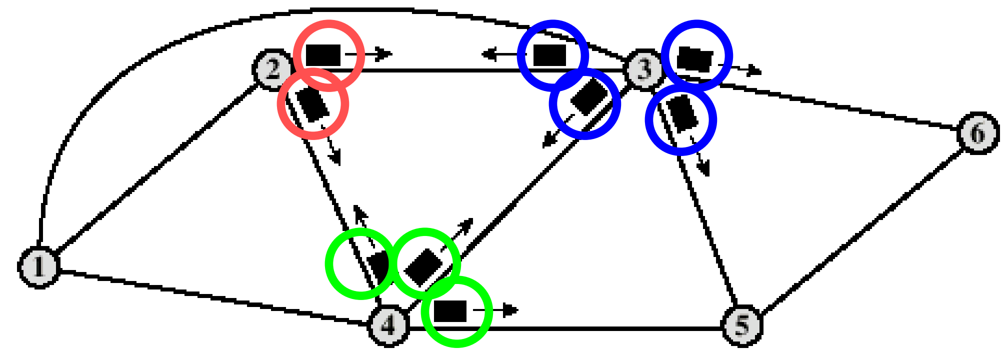
Flooding Example

Hop count = 3

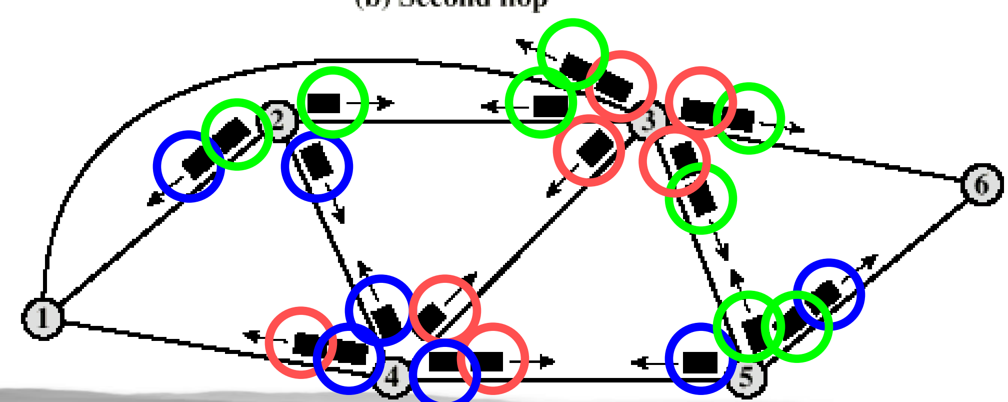
- Initial
  - 3 packets
- 1st hop
  - 9 packets
- 2nd hop
  - 23 packets



(a) First hop



(b) Second hop



(c) Third hop

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

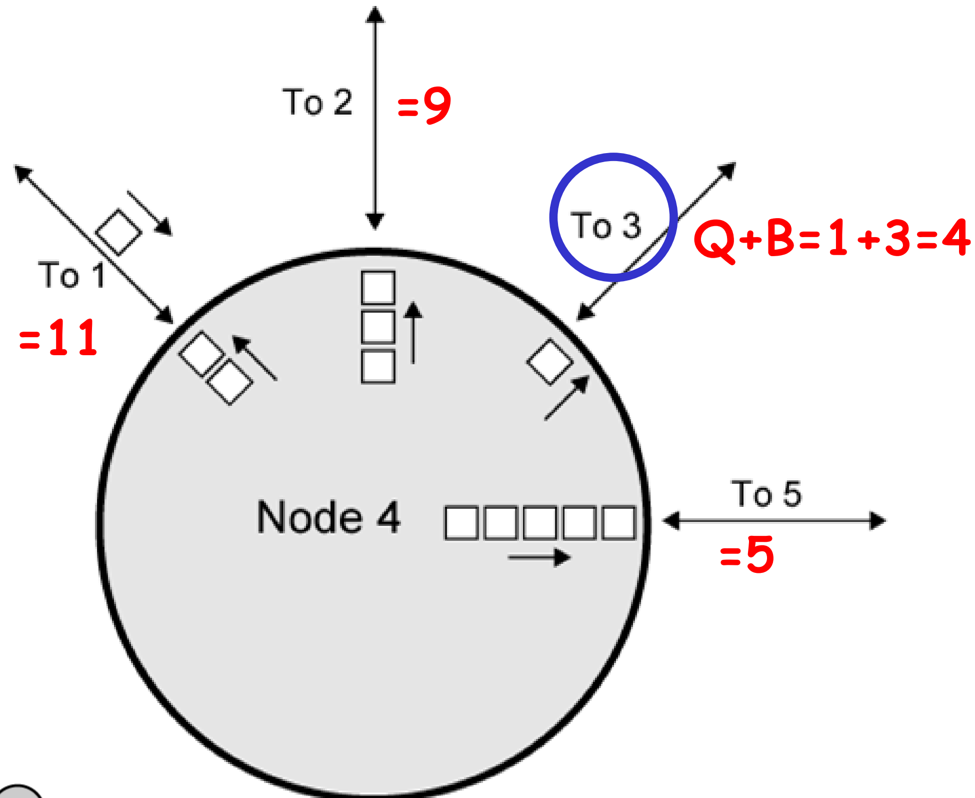
- Used by almost all packet switching networks
- Routing decisions change as conditions on the network change
- Requires info about network
  - Tradeoff between quality of network info and overhead
- Aid in congestion control

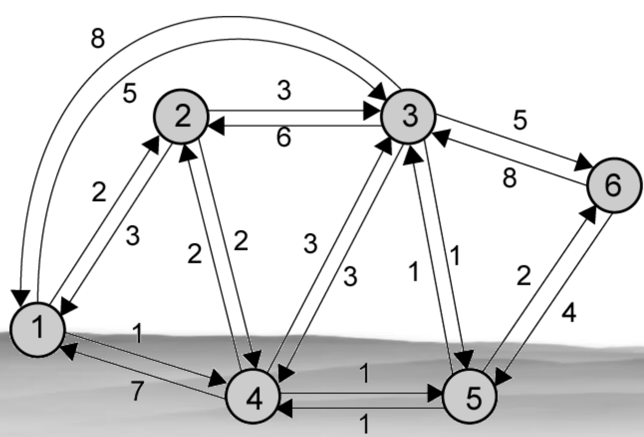
An Isolated Adaptive Routing

- 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

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

- **L(n)** = cost of least-cost path from source **s** to node **n** currently known
  - At termination, **L(n)** is cost of least-cost path from **s** to **n**
- Step 1 [Initialization]
  - **T** = **{s}** set of nodes incorporated consists of only source node
  - **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 **T** with least-cost path from **s** (i.e. **min L(*x*)**)
  - Incorporate node ***x*** into **T**
  - Also incorporate the edge that links ***x*** with the node in **T** that contributes to the path

Dijkstra’s Algorithm Method

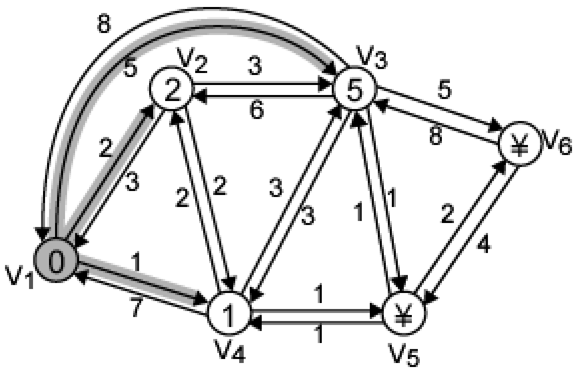
- Step 3 [Update Least-Cost Paths]
  - $\mathbf{L(n) = min[L(n), L(}x\mathbf{) + w(}x\mathbf{, n)]}$ for all $\mathbf{n \notin T}$
  - If latter term is minimum, path from $\mathbf{s}$ to $\mathbf{n}$ is path from $\mathbf{s}$ to x concatenated with link from x to $\mathbf{n}$

- Algorithm terminates when all nodes have been added to $\mathbf{T}$

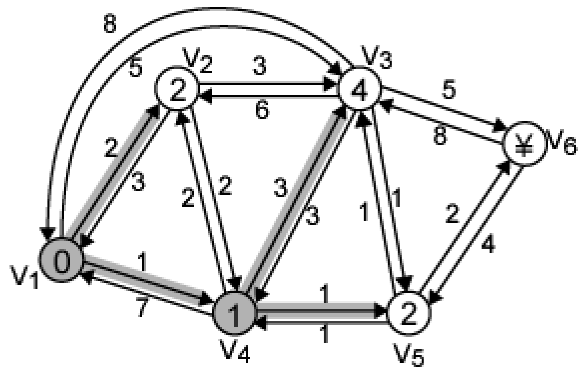
Dijkstra's Algorithm Notes

- 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

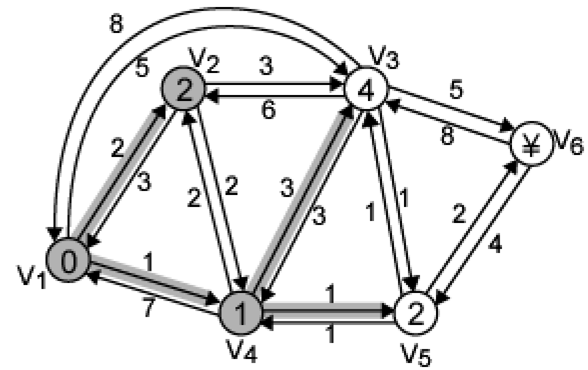
Example of Dijkstra's Algorithm



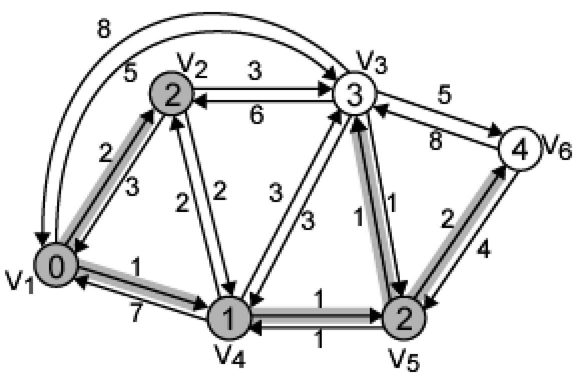
T = {1}



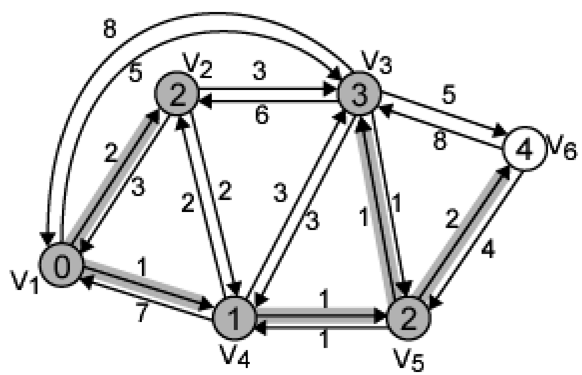
T = {1, 4}



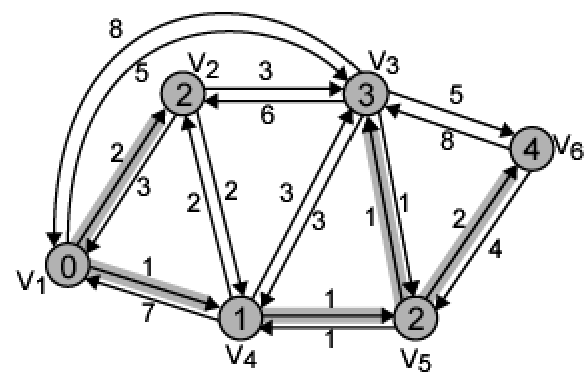
T = {1, 2, 4}



T = {1, 2, 4, 5}



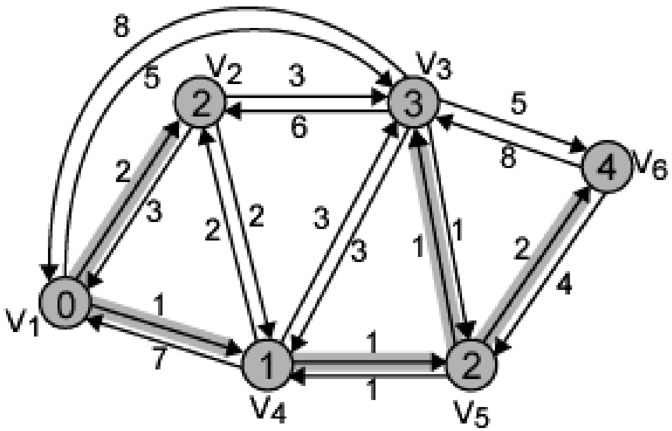
T = {1, 2, 3, 4, 5}



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

Results of Example 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



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

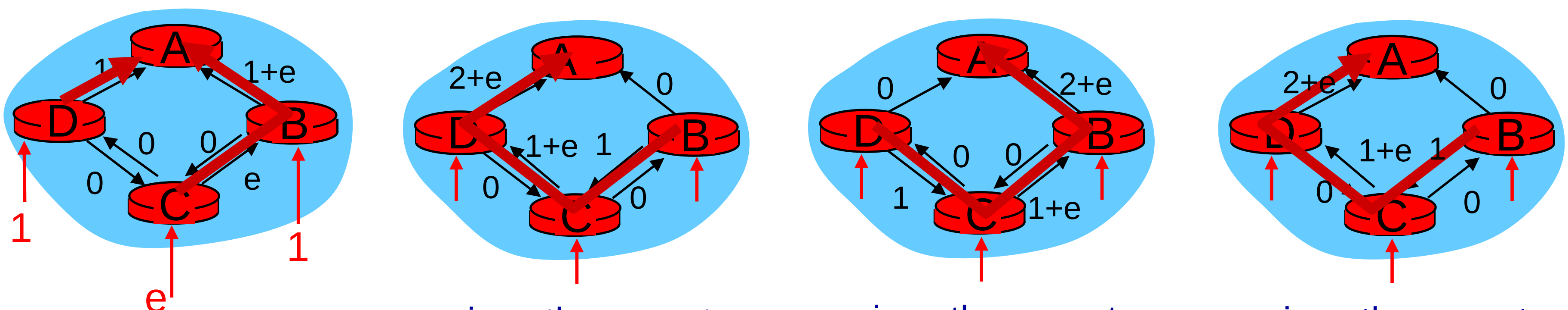
Dijkstra's algorithm discussion

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:



initially

given these costs, find new routing…. resulting in new costs

given these costs, find new routing…. resulting in new costs

given these costs, find new routing…. resulting in new costs

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**
  - $w(i, i) = 0$
  - $w(i, j) = \infty$ if the two nodes are not directly connected
  - $w(i, j) > 0$ if the two nodes are directly connected

Bellman-Ford Algorithm Method

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

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

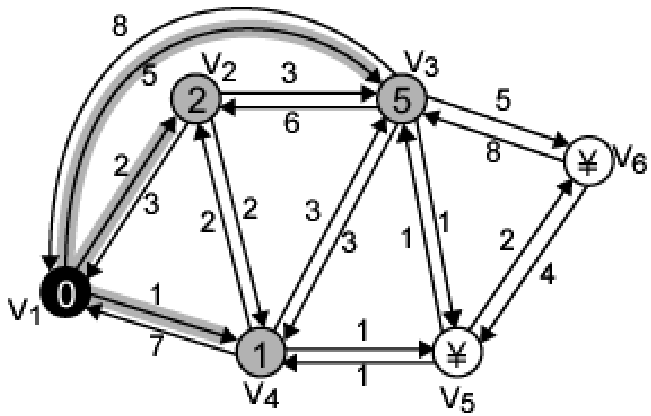
Bellman-Ford Algorithm Method

- 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)

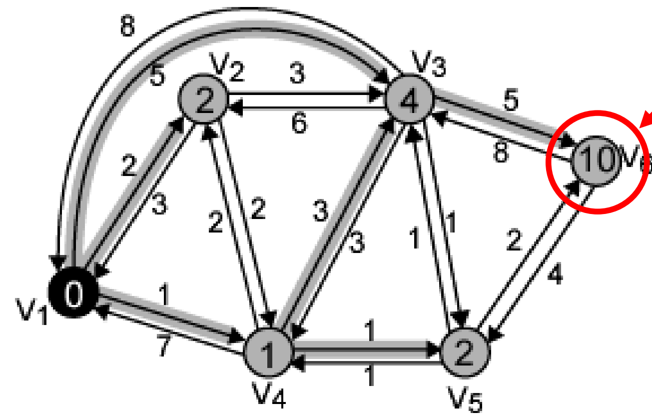
Bellman-Ford Algorithm Notes

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

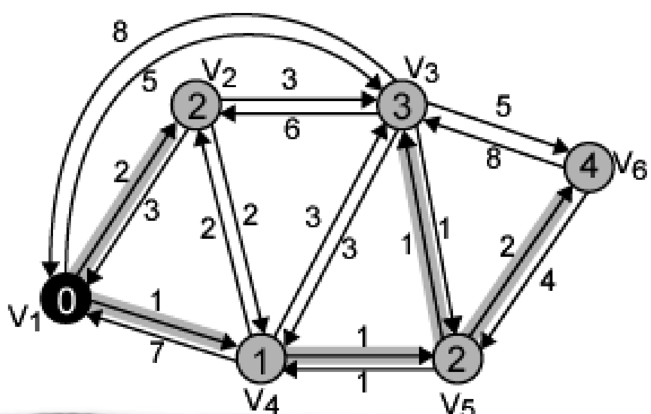
Example of Bellman-Ford Algorithm



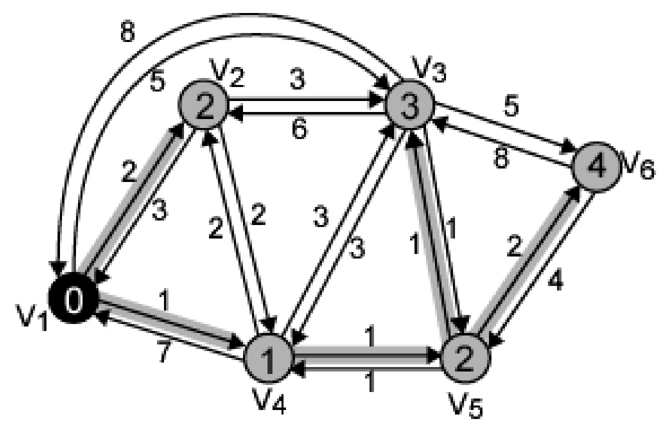
h = 1



h = 2



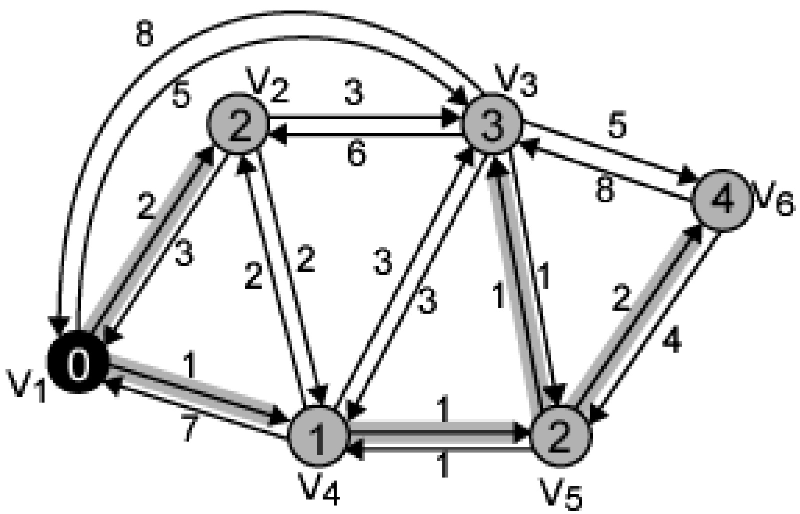
h = 3



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			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

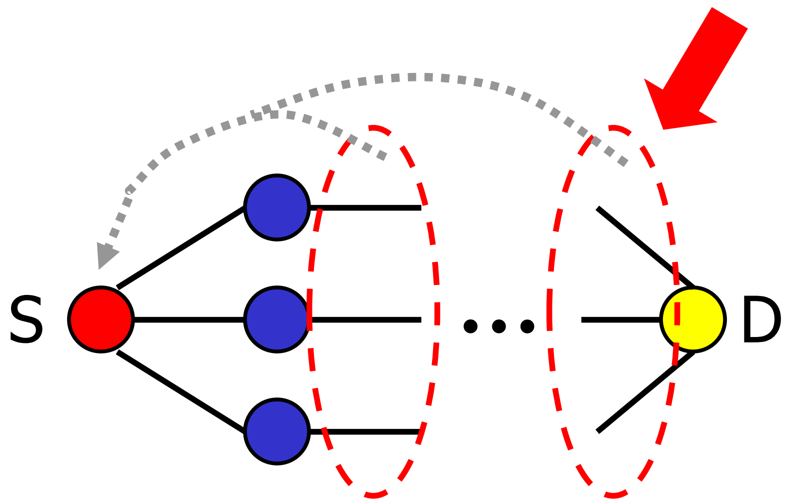


Destination	Next-Hop	Distance
2	2	2
3	4	3
4	4	1
5	4	2
6	4	4

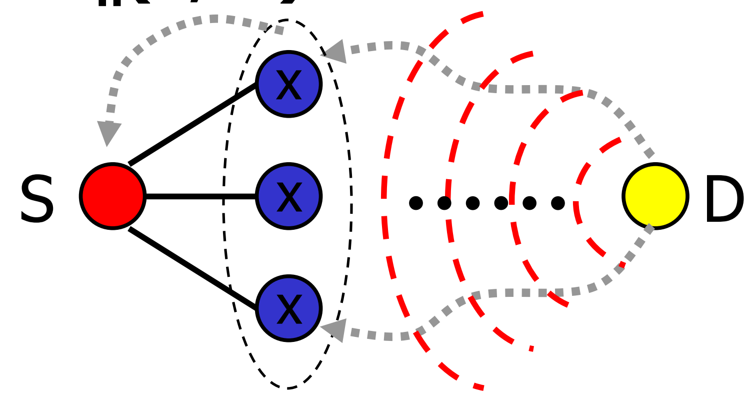
Dijkstra vs. Bellman-Ford

- Routing based on Dijkstra
  - Link states flood to all other nodes
  - Each node will have complete topology and build its own routing table
- 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

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



Dijkstra's
(Link State)



Bellman-Ford
(Distance Vector)

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

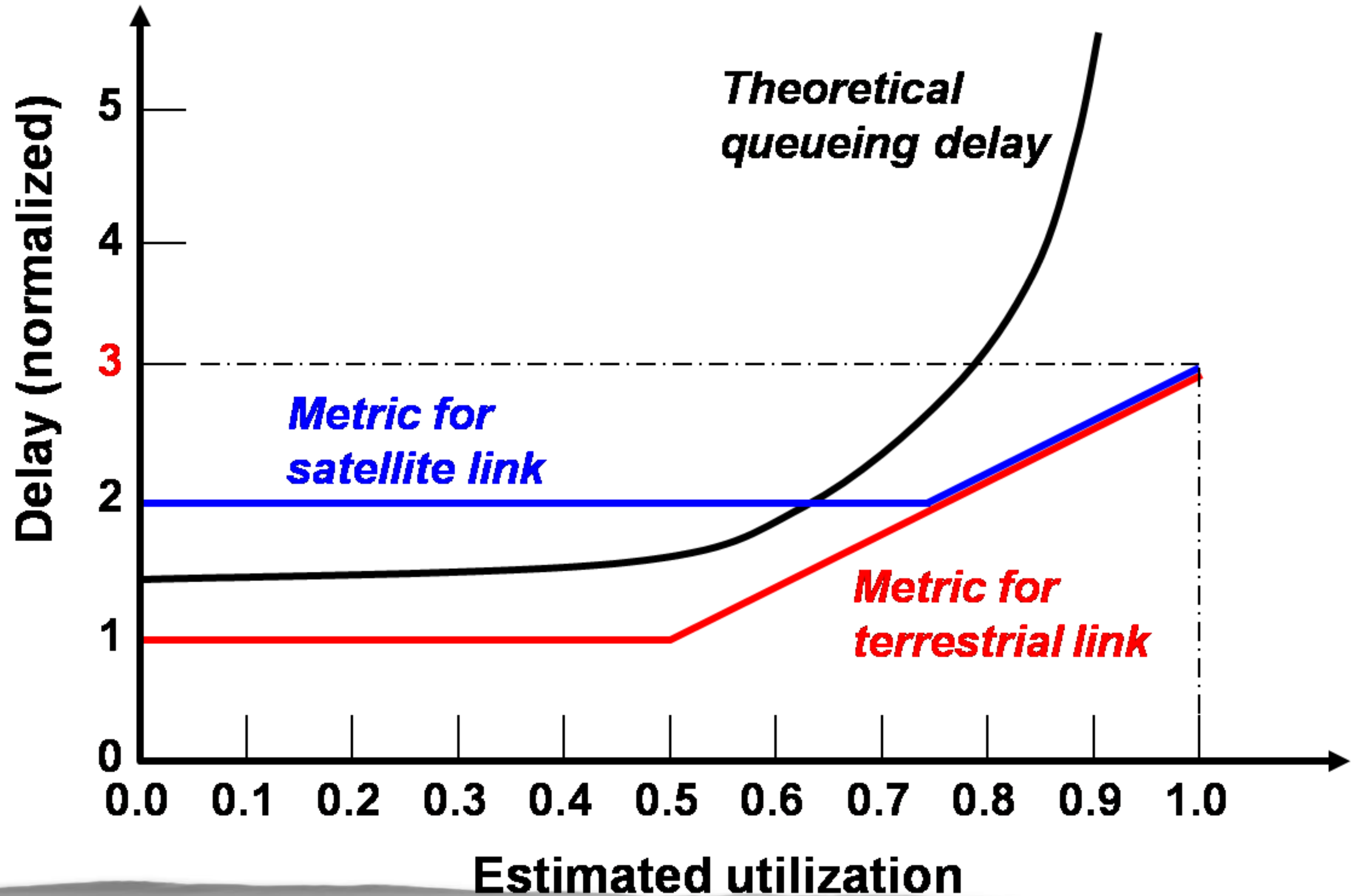
- Apply Link utilization to represent a link's state
- Leveling based on previous value and new utilization
- Use hop normalized metric to calculate link cost

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

Calculate Link Cost

- Set link cost based on leveled utilization



Summary

- 路由器的构成
- 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

- 书第12章习题：12.2~5，12.9, 12.10, 12.12, 12.16