Computer Communication Networks

Chapter 5: Network Layer

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Outline

- Network Layer Services
- Major Network Layer Functions
  - Routing
  - Forwarding
  - Prioritizing and scheduling – packet-level traffic management
  - Congestion control – flow-level traffic management
    - Open-loop: admission control, policing, traffic shaping
    - Close-loop: flow control
- Protocols in the Network Layer
  - Internet protocol (IP)
  - ATM

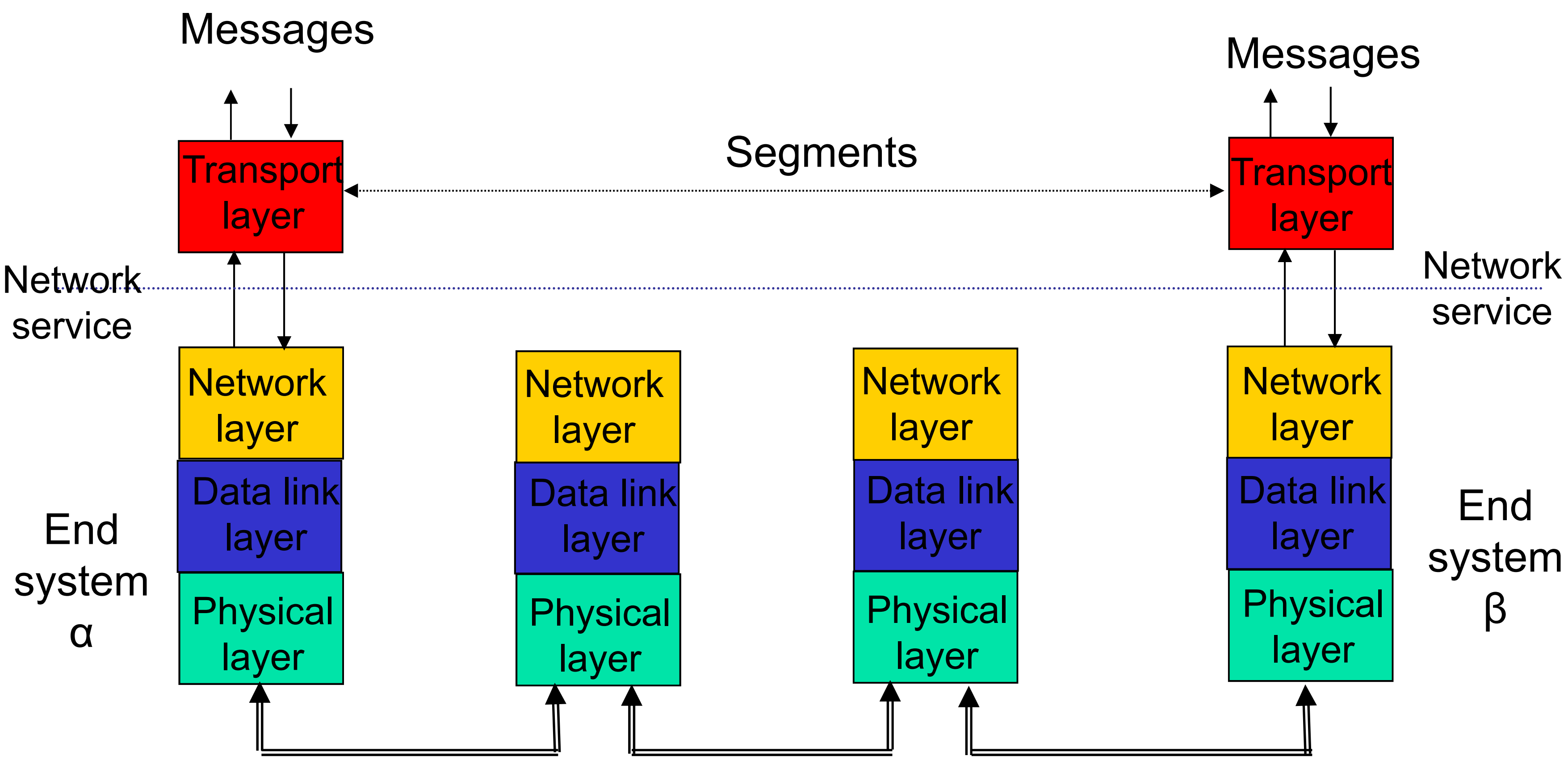
Network Layer Services

Network Layer Challenges

- Network Layer: the complicated 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?

Network Service

- Network layer can offer a variety of services to transport layer
- Connection-oriented service or connectionless service
- Best-effort or delay/loss guarantees



The End-to-End Argument for System Design

- An end-to-end function is best implemented at a higher level than at a lower level
  - End-to-end service requires all intermediate components to work properly
  - Higher-level better positioned to ensure correct operation
- Example: stream transfer service
  - Establishing an explicit connection for each stream across network requires all network elements (NEs) to be aware of connection; All NEs have to be involved in re-establishment of connections in case of network fault
  - In connectionless network operation, NEs do not deal with each explicit connection and hence are much simpler in design

End-to-End Packet Network

- Packet networks very different than telephone networks
- Individual packet streams are highly bursty
  - Statistical multiplexing is used to concentrate streams
- User demand can undergo dramatic change
  - Peer-to-peer applications stimulated huge growth in traffic volumes
- Internet structure highly decentralized
  - Paths traversed by packets can go through many networks controlled by different organizations
  - No single entity responsible for end-to-end service

Network Layer Functions

- **Routing**: mechanisms for determining the set of best paths for routing packets requires the collaboration of network elements
- **Forwarding**: transfer of packets from NE inputs to outputs
- **Priority & Scheduling**: determining order of packet transmission in each NE

Optional: congestion control, segmentation & reassembly, security

Routing in the Network Layer

Key Roles of Routing

How to get packet from here to there?

- Decentralized nature of Internet makes routing a major challenge
  - Interior gateway protocols (IGPs) are used to determine routes within a domain
  - Exterior gateway protocols (EGPs) are used to determine routes across domains
  - Routes must be consistent & produce stable flows
- Scalability required to accommodate growth
  - Hierarchical structure of IP addresses essential to keeping size of routing tables manageable

Packet Switching Network

Packet switching network

- Transfers packets between users
- Transmission lines + packet switches (routers)
- Origin in message switching

Two modes of operation:

- Connectionless
- Virtual Circuit

Packet Switching - Datagram

- Messages broken into smaller units (packets)
- Source & destination addresses in packet header
- Connectionless, packets routed independently (datagram)
- Packet may arrive out of order
- Pipelining of packets across network can reduce delay, increase throughput
- Lower delay than message switching, suitable for interactive traffic

Routing Tables in Datagram Networks

- Route determined by table lookup
- Routing decision involves finding next hop in route to given destination
- Routing table has an entry for each destination specifying output port that leads to next hop
- Size of table becomes impractical for very large number of destinations

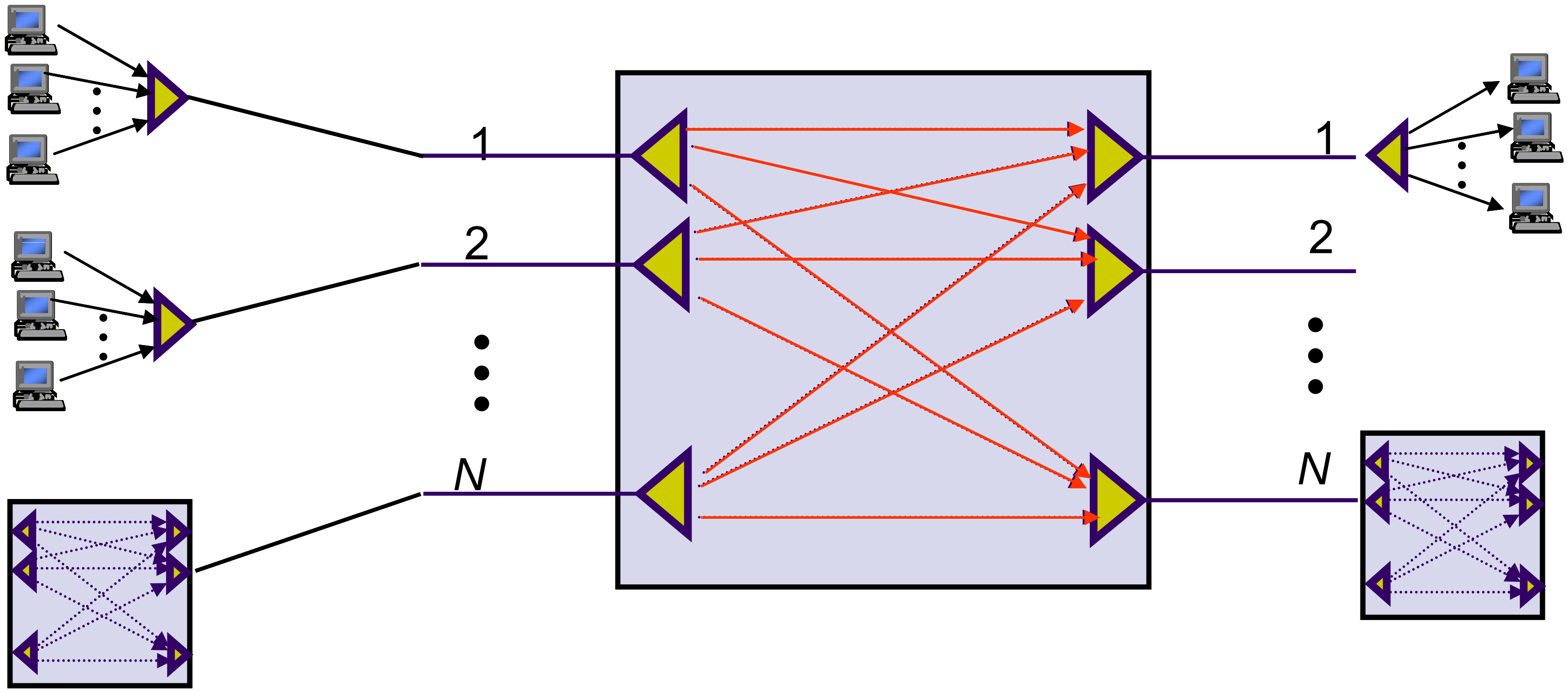
Destination address	Output port
0785	7
1345	12
1566	6
2458	12

Example: Internet Routing

- Internet protocol uses datagram packet switching *across networks*
  - Networks are treated as data links
- Hosts have two-part IP address:
  - Network address + Host address
- Routers do table lookup on network address
  - This reduces size of routing table
- In addition, network addresses are assigned so that they can also be aggregated

Packet Switch: Intersection where Traffic Flows Meet

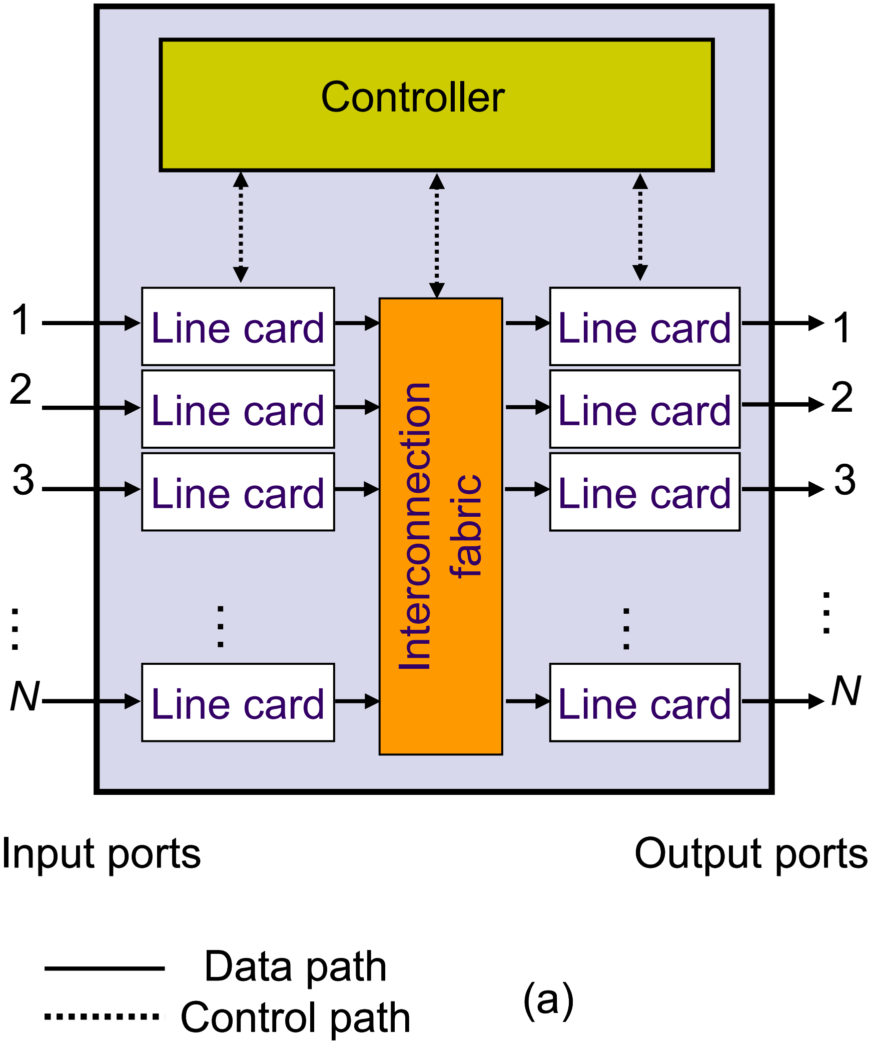
- Inputs contain multiplexed flows from access muxs & other packet switches
- Flows demultiplexed at input, routed and/or forwarded to output ports
- Packets buffered, prioritized, and multiplexed on output lines



Generic Packet Switch

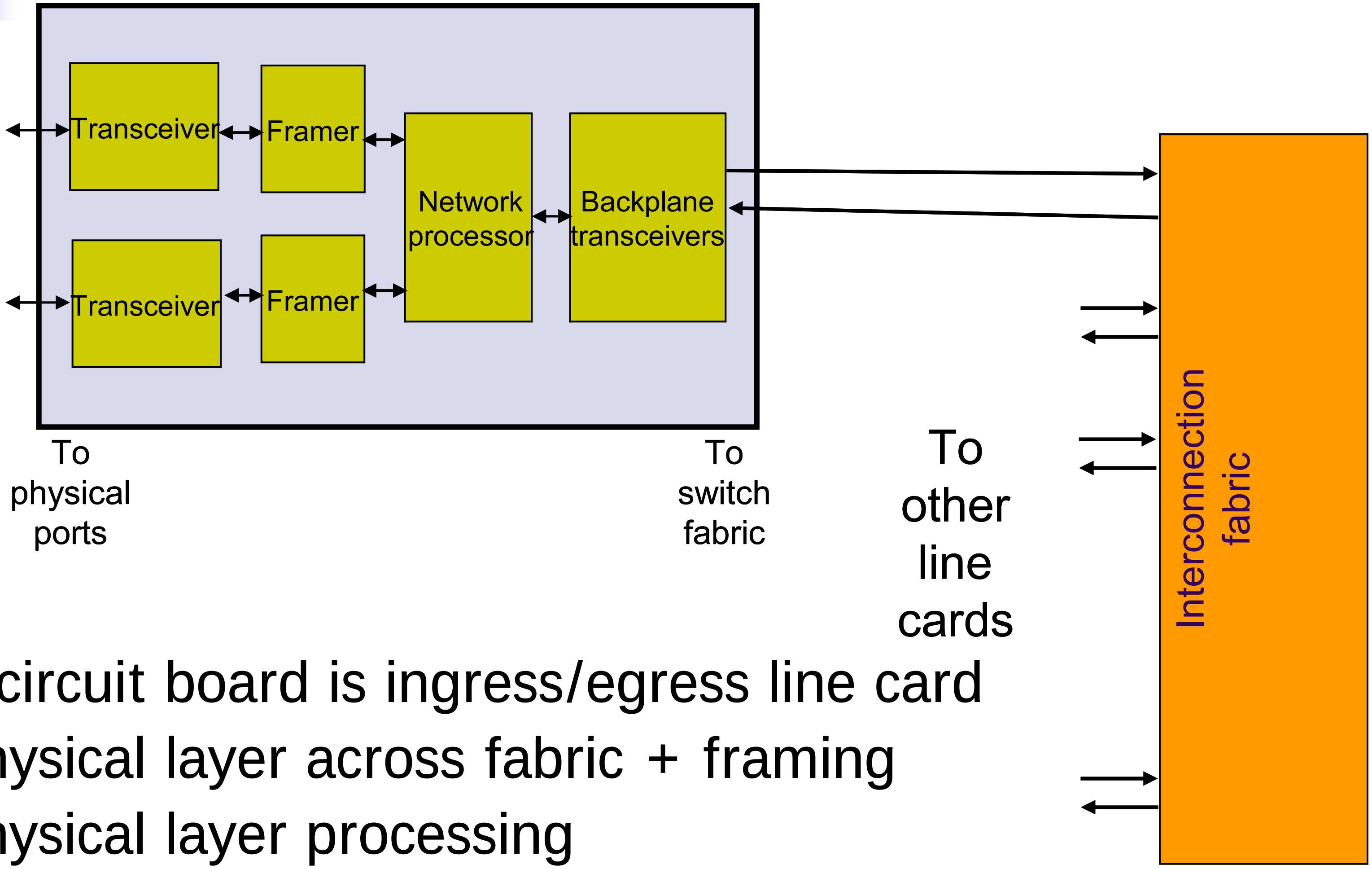
"Unfolded" View of Switch

- Ingress Line Cards
  - Header processing
  - Demultiplexing
  - Routing in large switches
- Controller
  - Routing in small switches
  - Signalling & resource allocation
- Interconnection Fabric
  - Transfer packets between line cards
- Egress Line Cards
  - Scheduling & priority
  - Multiplexing



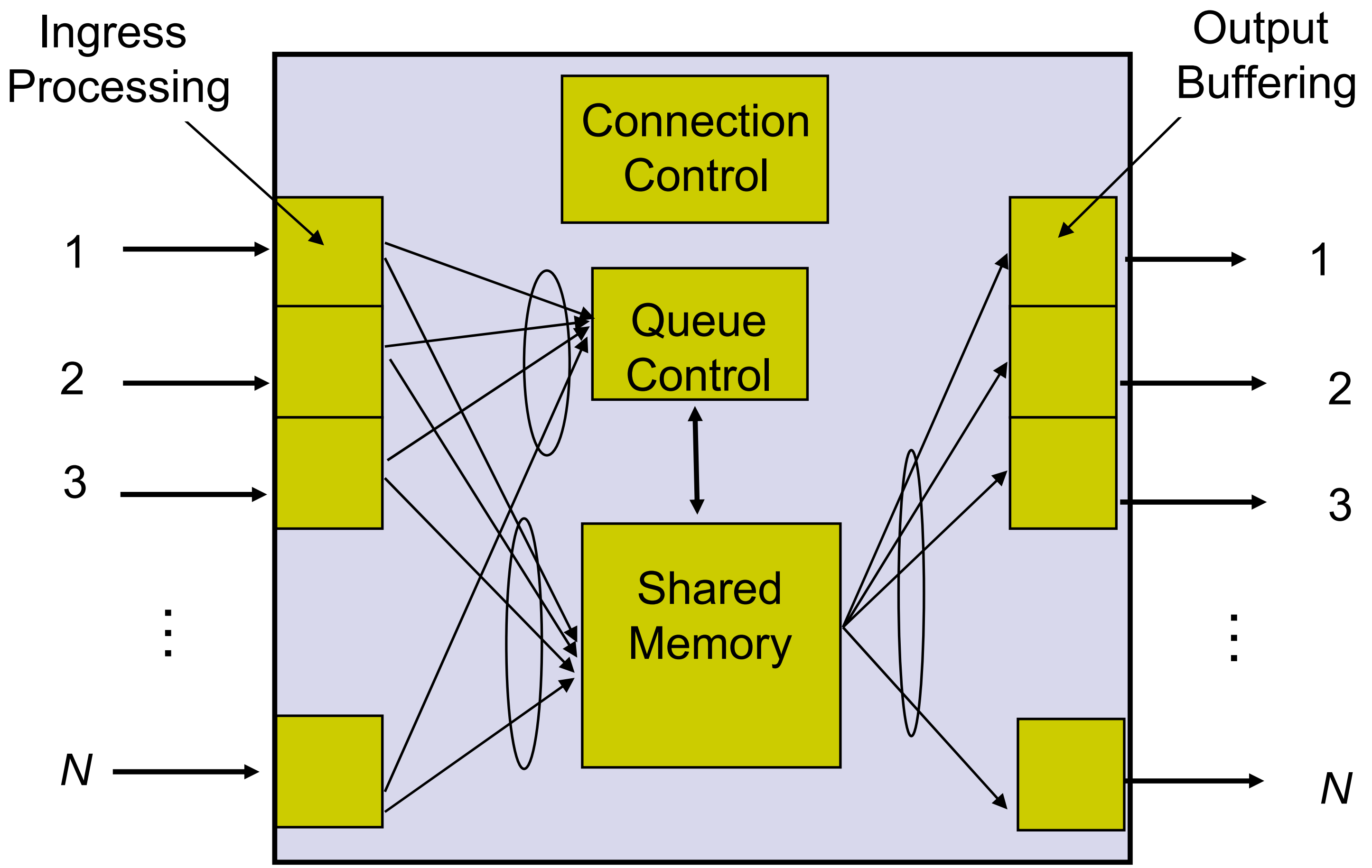
(a)

Line Cards



- 1 circuit board is ingress/egress line card
- Physical layer across fabric + framing
- Physical layer processing
- Data link layer processing
- Network header processing

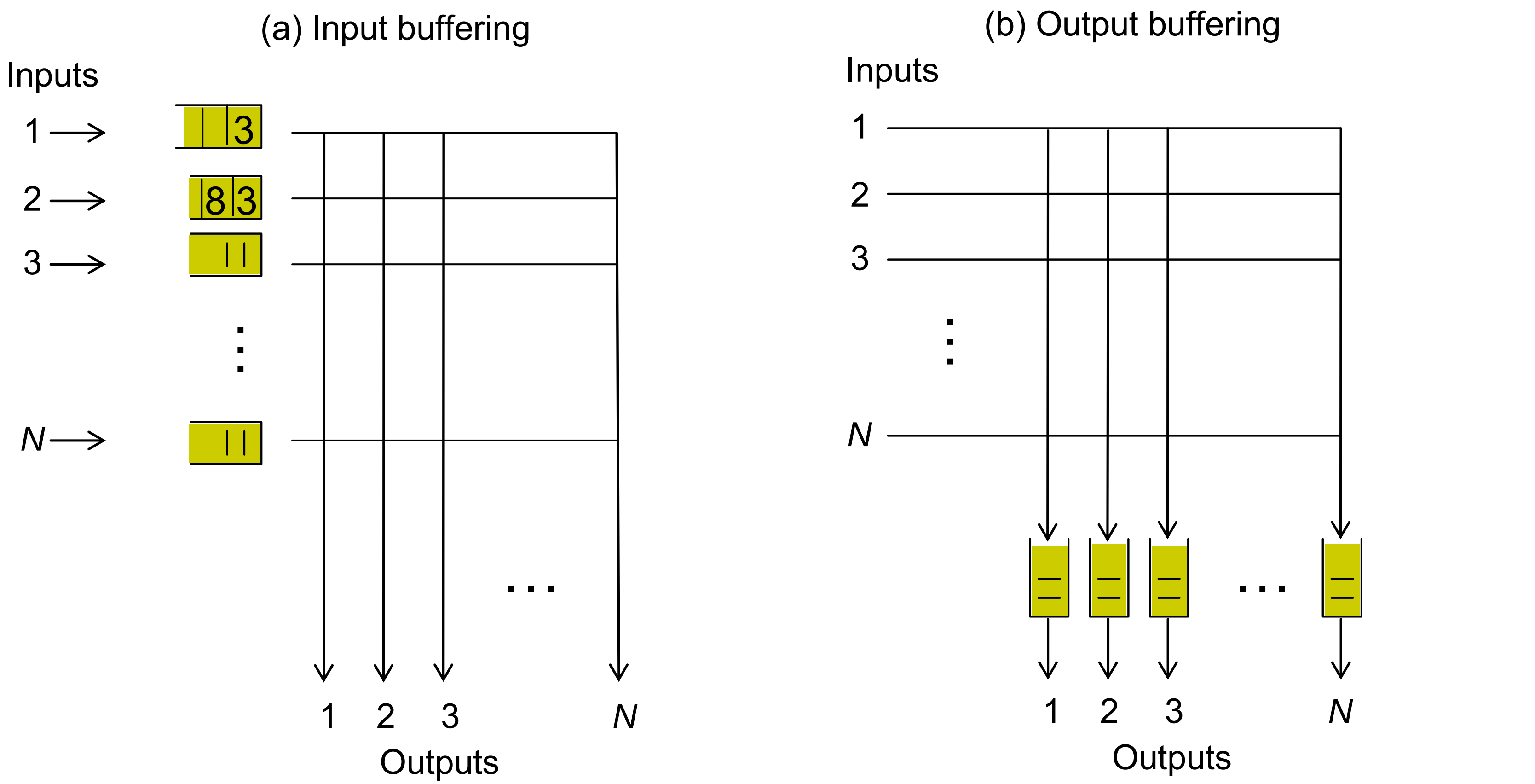
Shared Memory Packet Switch



Small switches can be built by reading/writing into shared memory

Crossbar Switches

- Large switches built from crossbar & multistage space switches
- Requires centralized controller/scheduler (who sends to whom when)
- Can buffer at input, output, or both (performance vs complexity)

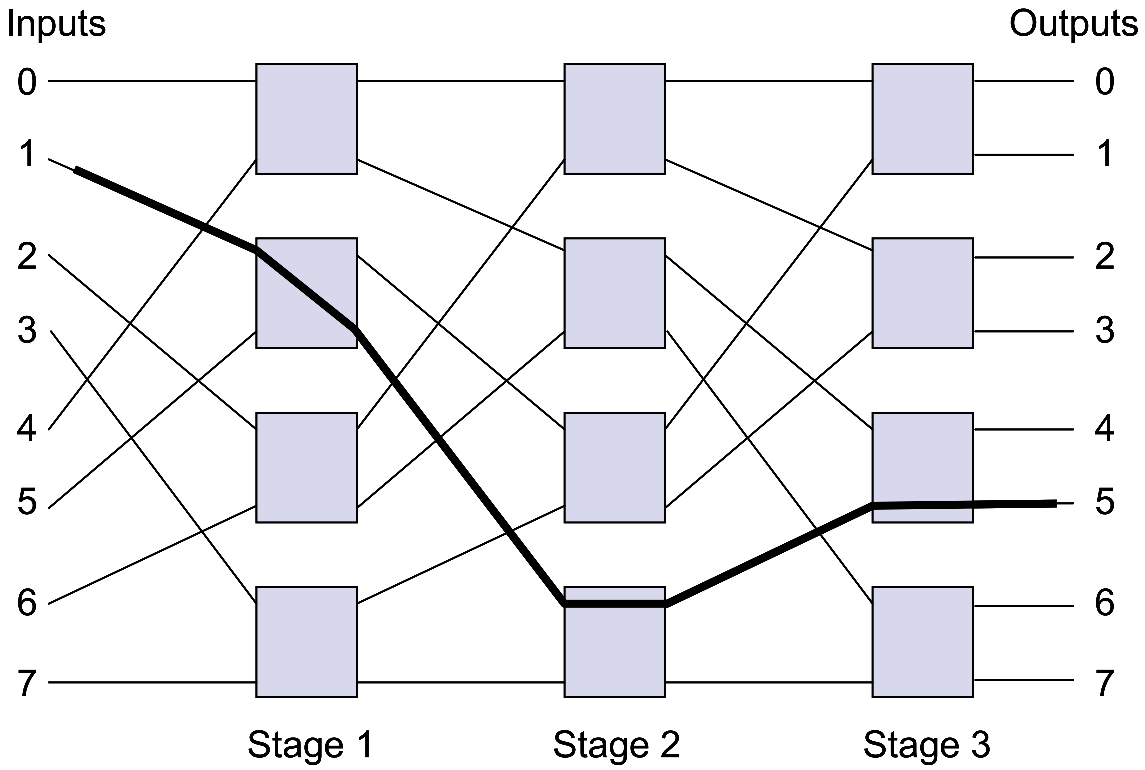


(a) Input buffering

(b) Output buffering

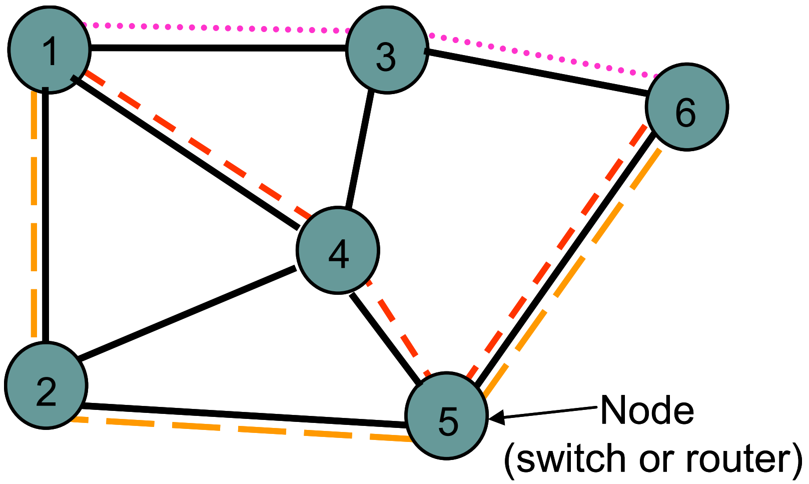
Self-Routing Switches

- Self-routing switches do not require controller
- Output port number determines route
- 101 → (1) lower port, (2) upper port, (3) lower port



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?



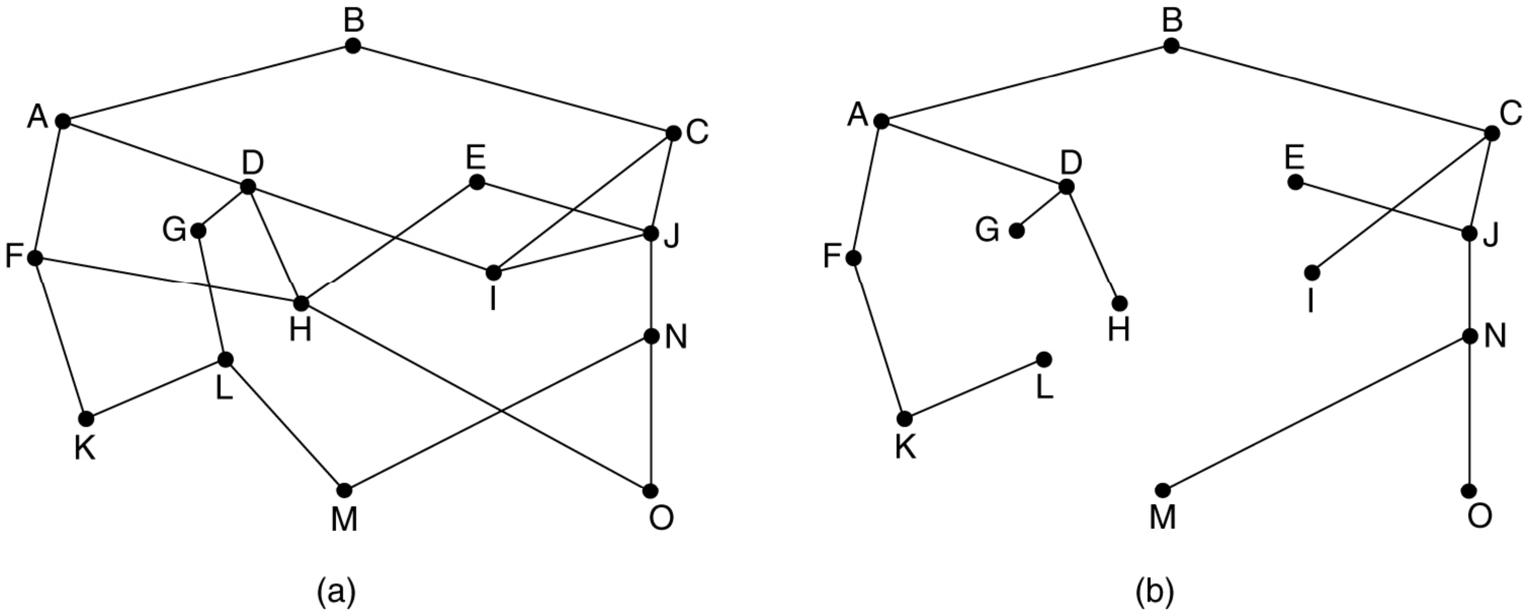
Creating the Routing Tables

- Need information on state of links
  - Link up/down; congested; delay or other metrics
- Need to distribute link state information using a routing protocol
  - What information is exchanged? How often?
  - Exchange with neighbors; Broadcast or flood
- Need to compute routes based on information
  - Single metric; multiple metrics
  - Single route; alternate routes

Routing Algorithm Requirements

- Responsiveness to changes
  - Topology or bandwidth changes, congestion
  - Rapid convergence of routers to consistent set of routes
  - Freedom from persistent loops
- Optimality
  - Resource utilization, path length
- Robustness
  - Continues working under high load, congestion, faults, equipment failures, incorrect implementations
- Simplicity
  - Efficient software implementation, reasonable processing load

The Optimality Principle



(a) A subnet. (b) A sink tree for router B.

If router J is on the optimal path from router I to router K, then the optimal path from J to K also falls along the same route

Routing Algorithms

- Flooding
- Shortest Path Routing
- Distance Vector Routing
- Link State Routing
- Hierarchical Routing
- Broadcast Routing
- Multicast Routing
- Routing for Mobile Hosts
- Routing in Ad Hoc Networks

The above is not mutually exclusive classification

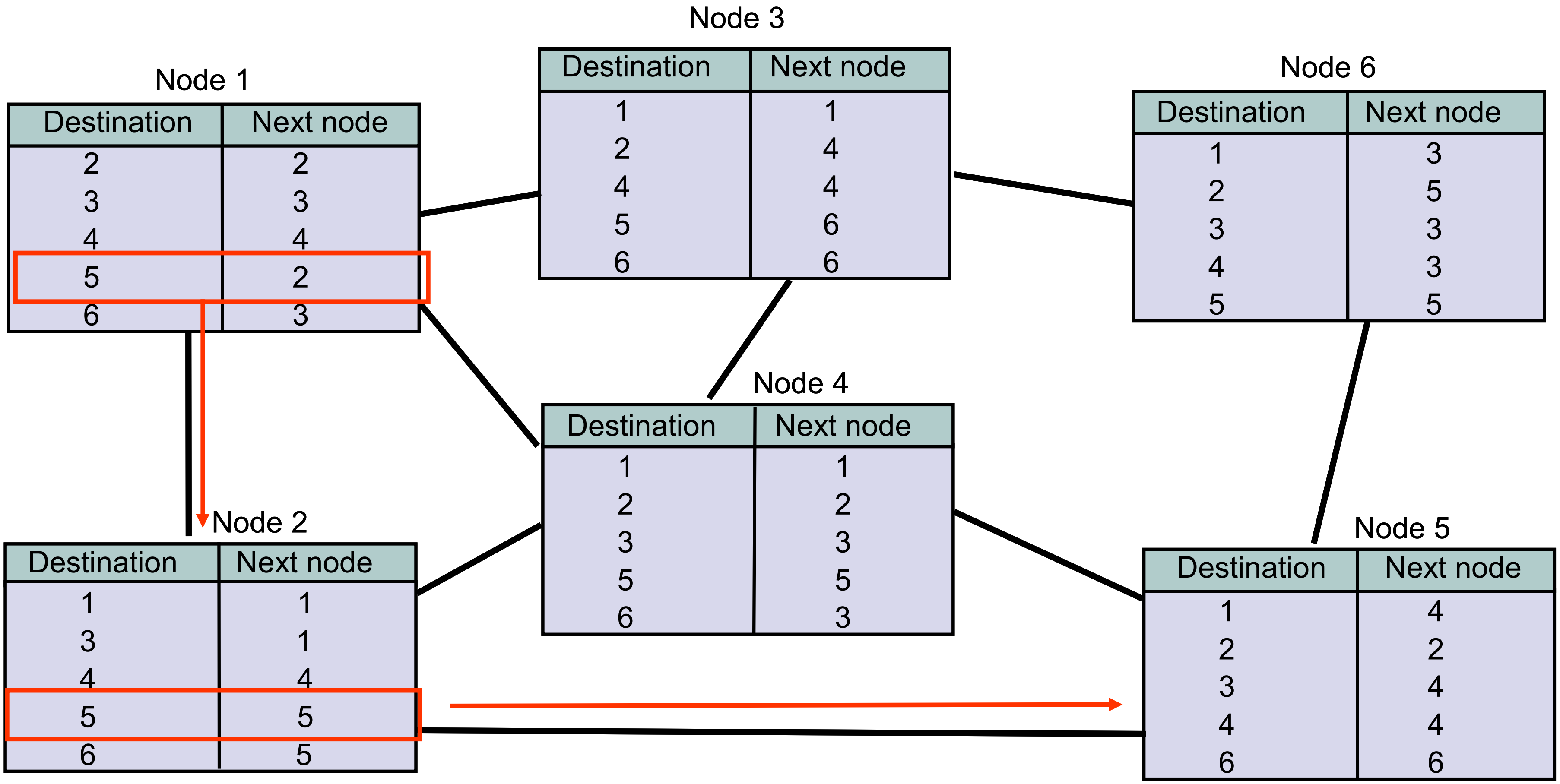
Centralized vs Distributed Routing

- 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

Static vs Dynamic Routing

- Static Routing
  - Set up manually, do not change; requires administration
  - Works when traffic predictable & network is simple
  - Used to override some routes set by dynamic algorithm
  - Used to provide default router
- Dynamic Routing
  - Adapt to changes in network conditions
  - Automated
  - Calculates routes based on received updated network state information

Routing Tables in Datagram Packet Networks



Node 1

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

Node 3

Destination	Next node
1	1
2	4
4	4
5	6
6	6

Node 6

Destination	Next node
1	3
2	5
3	3
4	3
5	5

Node 4

Destination	Next node
1	1
2	2
3	3
5	5
6	3

Node 2

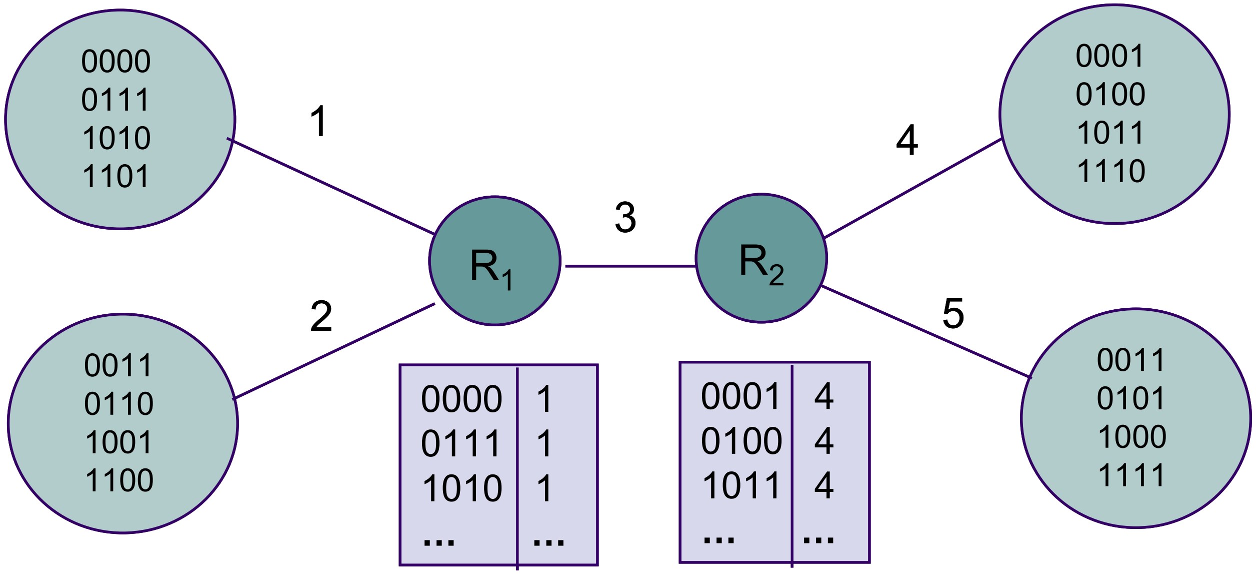
Destination	Next node
1	1
3	1
4	4
5	5
6	5

Node 5

Destination	Next node
1	4
2	2
3	4
4	4
6	6

Non-Hierarchical Addresses and Routing

- No relationship between addresses & routing proximity
- Routing tables require 16 entries each

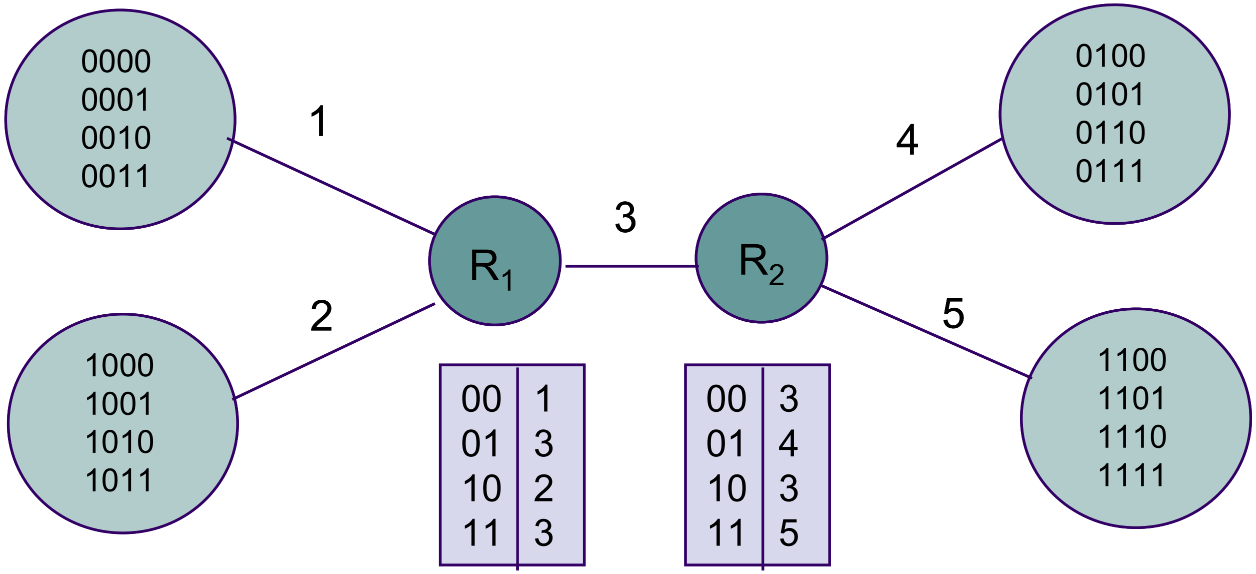


0000	1
0111	1
1010	1
…	…

0001	4
0100	4
1011	4
…	…

Hierarchical Addresses and Routing

- Prefix indicates network where host is attached
- Routing tables require 4 entries each



00	1
01	3
10	2
11	3

00	3
01	4
10	3
11	5

Flat vs Hierarchical Routing

- Flat Routing
  - All routers are peers
  - Does not scale
- Hierarchical Routing
  - Partitioning: Domains, autonomous systems, areas...
  - Some routers part of routing backbone
  - Some routers only communicate within an area
  - Efficient because it matches typical traffic flow patterns
  - Scales

Specialized Routing

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

- Deflection Routing
  - Fixed, preset routing procedure
  - No route synthesis

Flooding

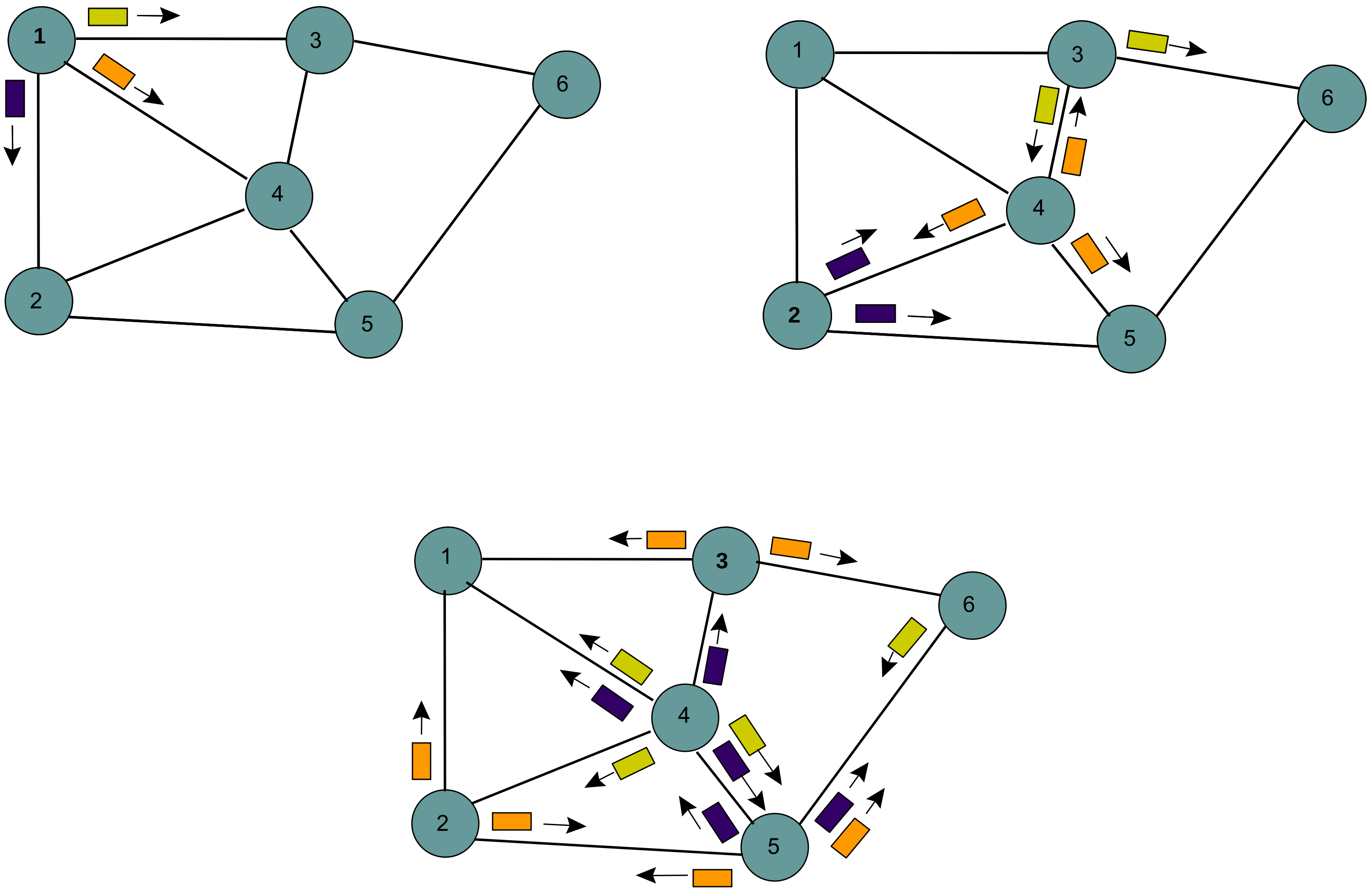
Send a packet to all nodes in a network

- 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

Example of Flooding



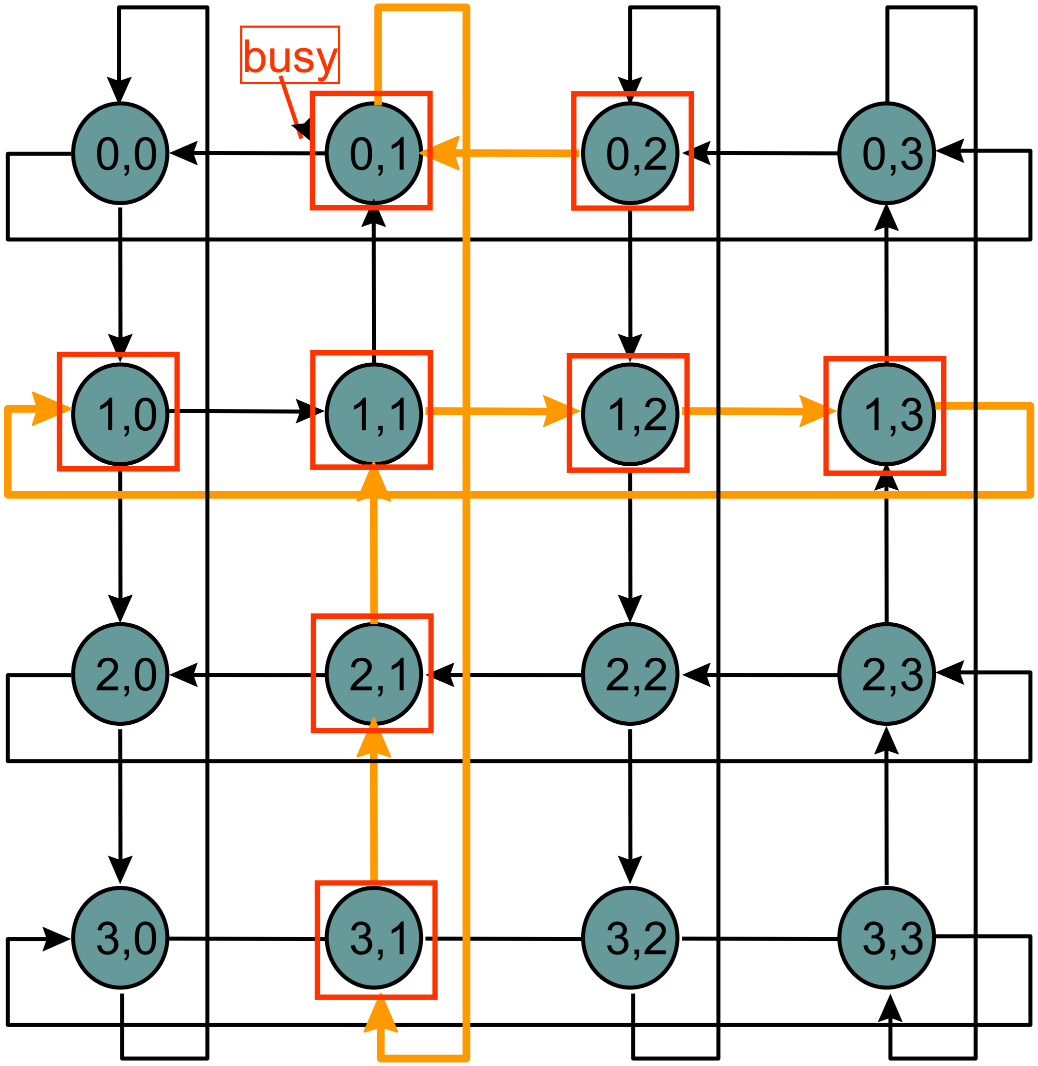
Limited Flooding

- 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 record source address and sequence number and discards repeats

Deflection Routing

- Network nodes forward packets to preferred port
- If preferred port busy, deflect packet to another port
- Works well with regular topologies
  - Manhattan street network
  - Rectangular array of nodes
  - Nodes designated (i,j)
  - Rows alternate as one-way streets
  - Columns alternate as one-way avenues
- Bufferless operation is possible
  - Proposed for optical packet networks
  - All-optical buffering currently not viable

Example: (0,2)→(1,0)



Paths versus 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 an optimal 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
  - Bellman-ford 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

Local Signpost

- Direction
- Distance

Routing Table

For each destination list:

- Next Node
- Distance

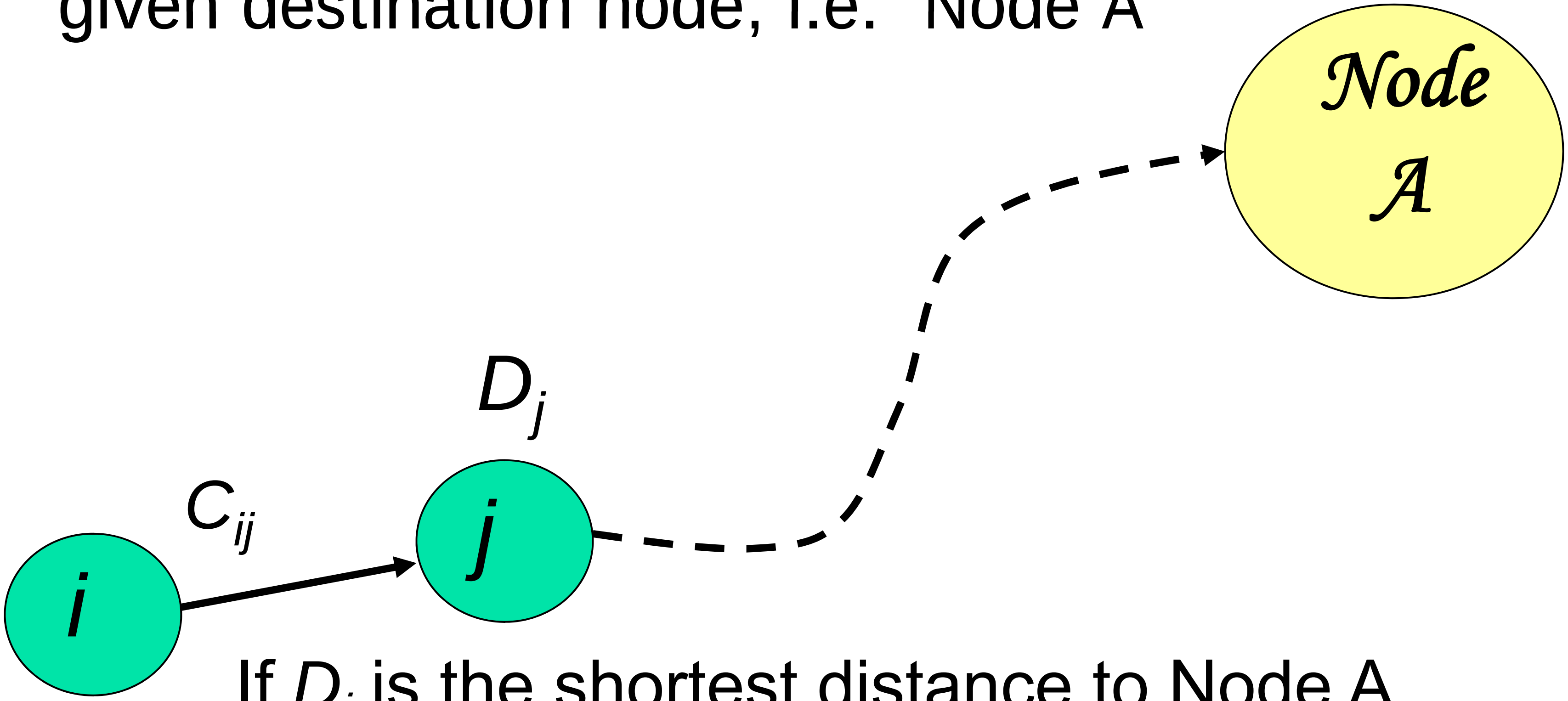
dest	next	dist

Table Synthesis

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

Shortest Path to a Node

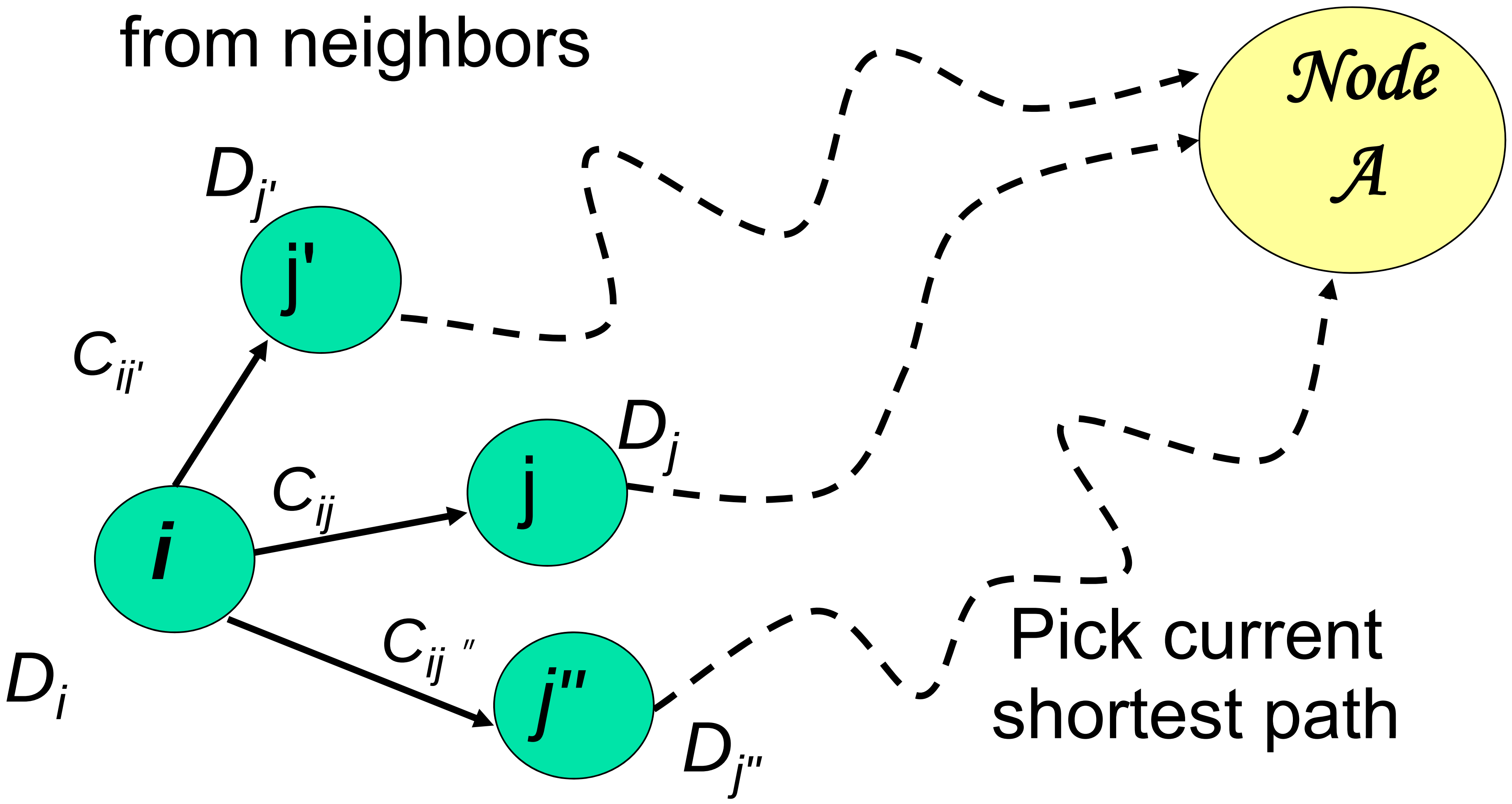
- Focus on how nodes find their shortest path to a given destination node, i.e. Node A



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

Why Distance Vector Work?

Node i only has local info from neighbors



Pick current shortest path

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: $D_j=\propto$, 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 *i*, 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 (continued)

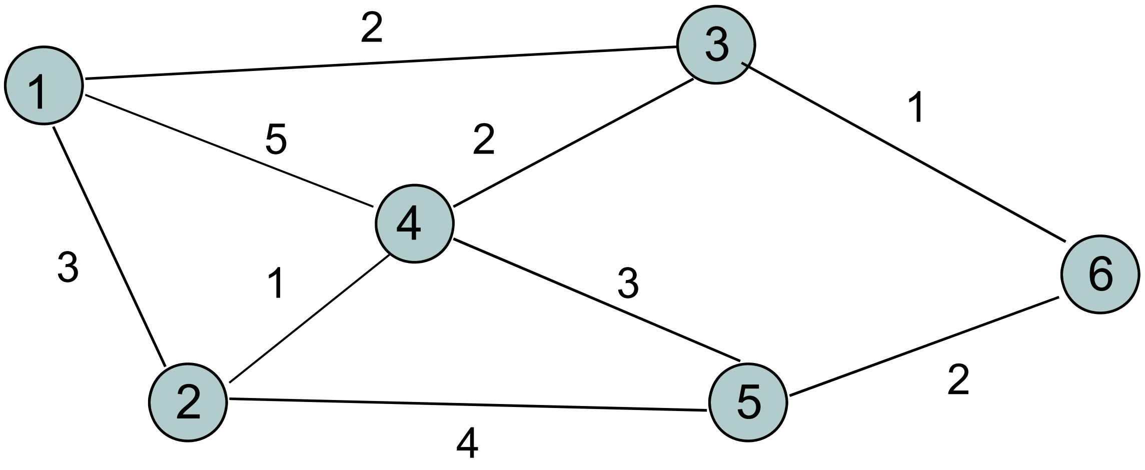
- *Now consider parallel computations for all destinations d*
- *Initialization*
  - Each node has 1 row for each destination *d*
  - Distance of node *d* to itself is zero: $D_d(d)=0$
  - Distance of other node *j* to *d* is infinite: $D_j(d)= \propto$, for $j \neq d$
  - Next node $n_j\ (d)$= -1 since 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 $(n_j(d), D_i(d))$ by new $(n_j*, D_j*(d))$ if new next node or distance found
  - Go to send step

Example

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 A

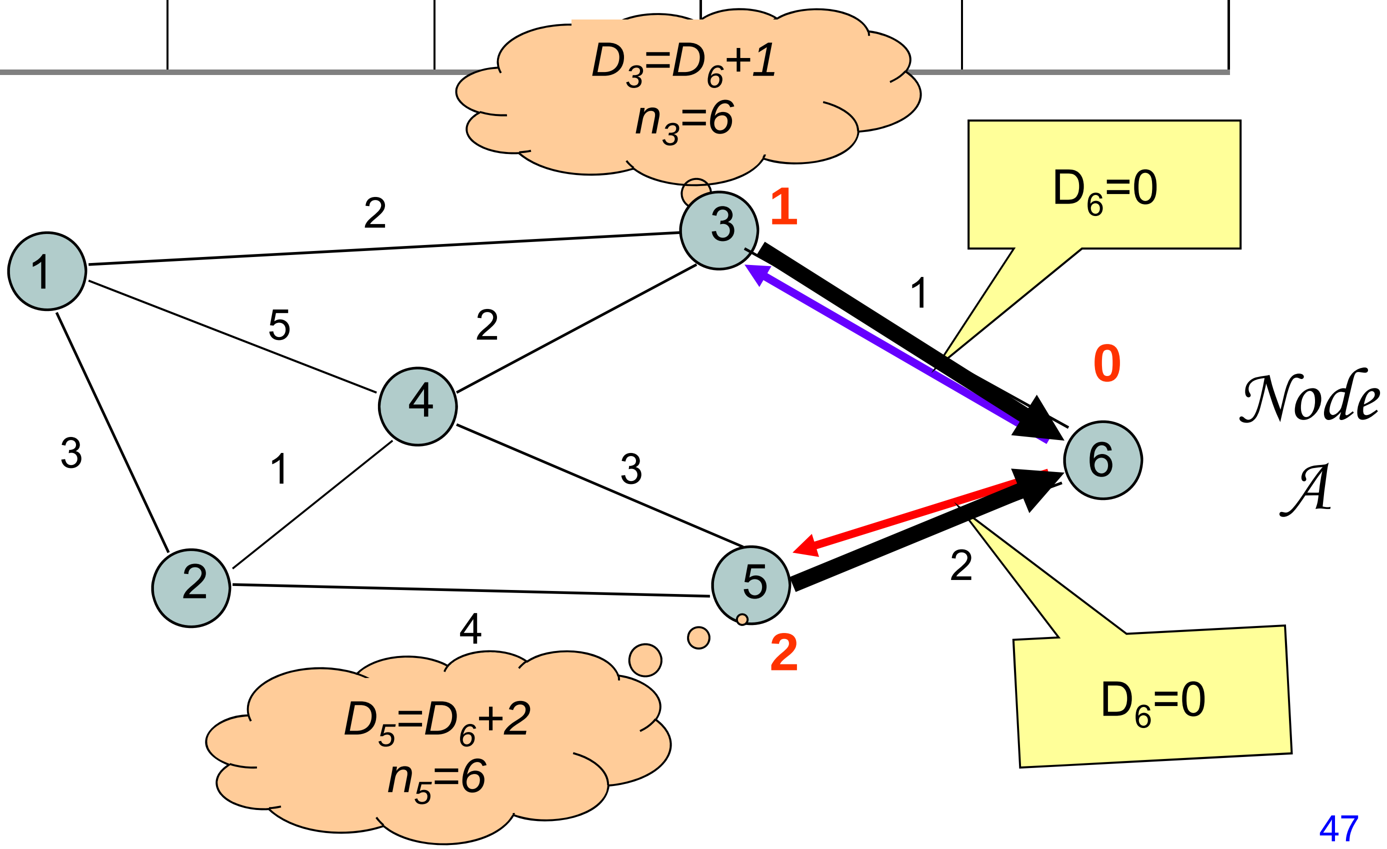
Table entry
@ node 3
for dest A



Node A

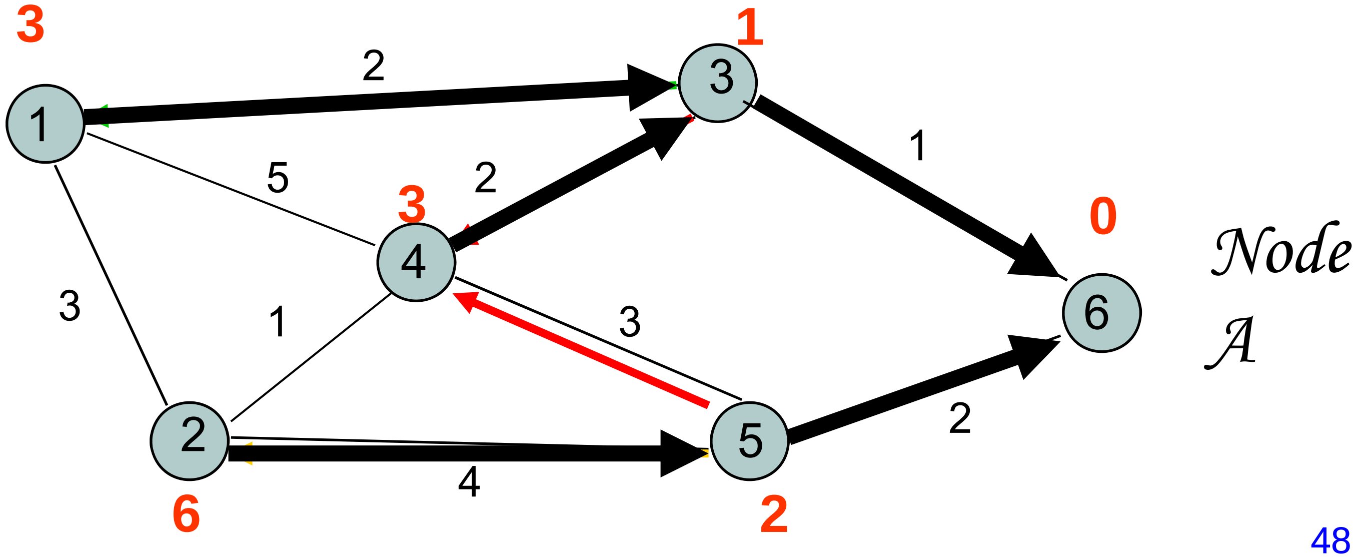
Example (continued)

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					



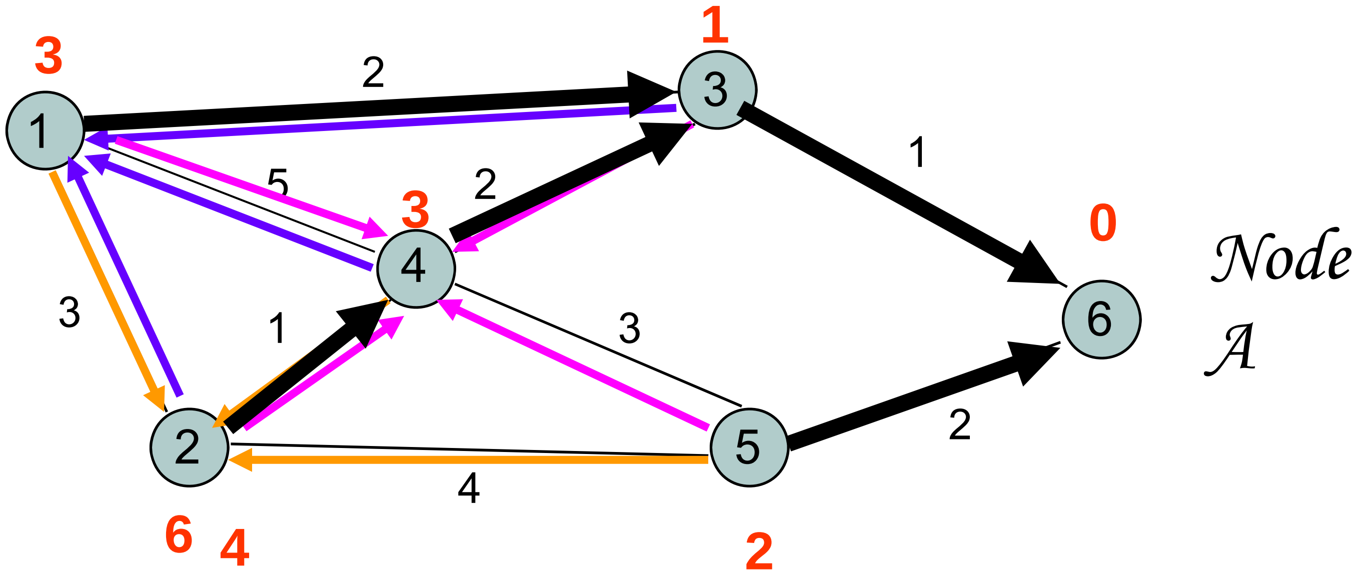
Example (Continued)

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					



Example (Continued)

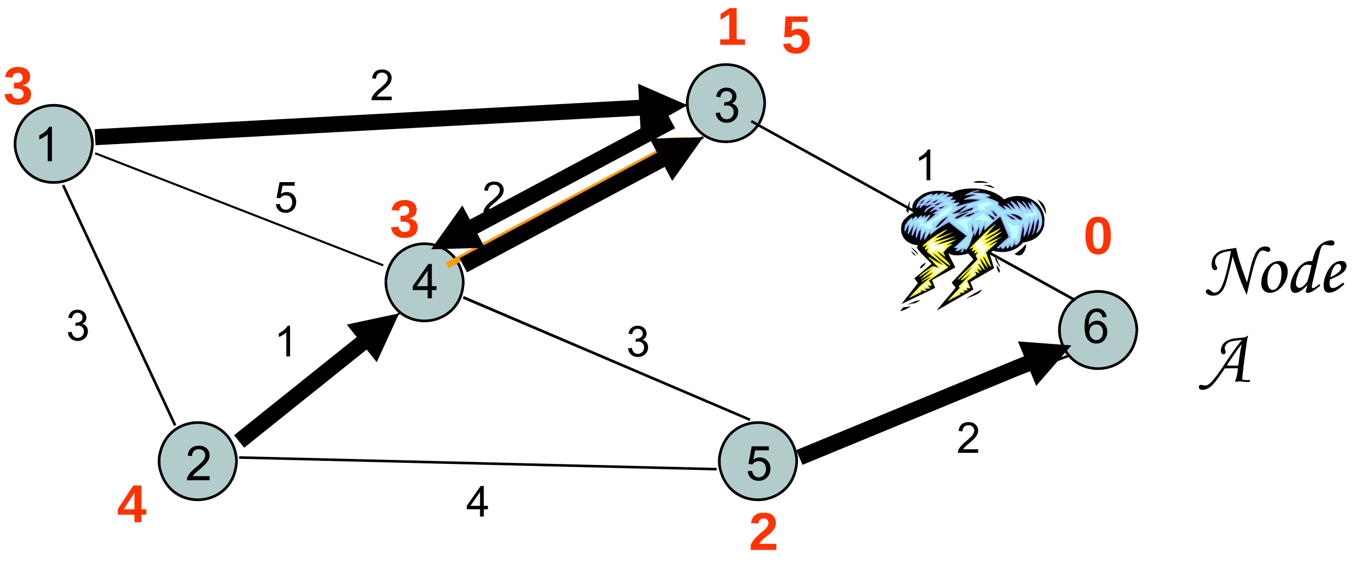
Iteration	Node 1	Node 2	Node 3	Node 4	Node 5
Initial	(-1, ∞)	(-1, ∞)	(-1, ∞)	(-1, ∞)	(-1, ∞)
1	(-1, ∞)	(-1, ∞)	(6, 1)	(-1, ∞)	(6,2)
2	(3,3)	(5,6)	(6, 1)	(3,3)	(6,2)
3	(3,3)	(4,4)	(6, 1)	(3,3)	(6,2)



Example (Continued)

Iteratio n	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					

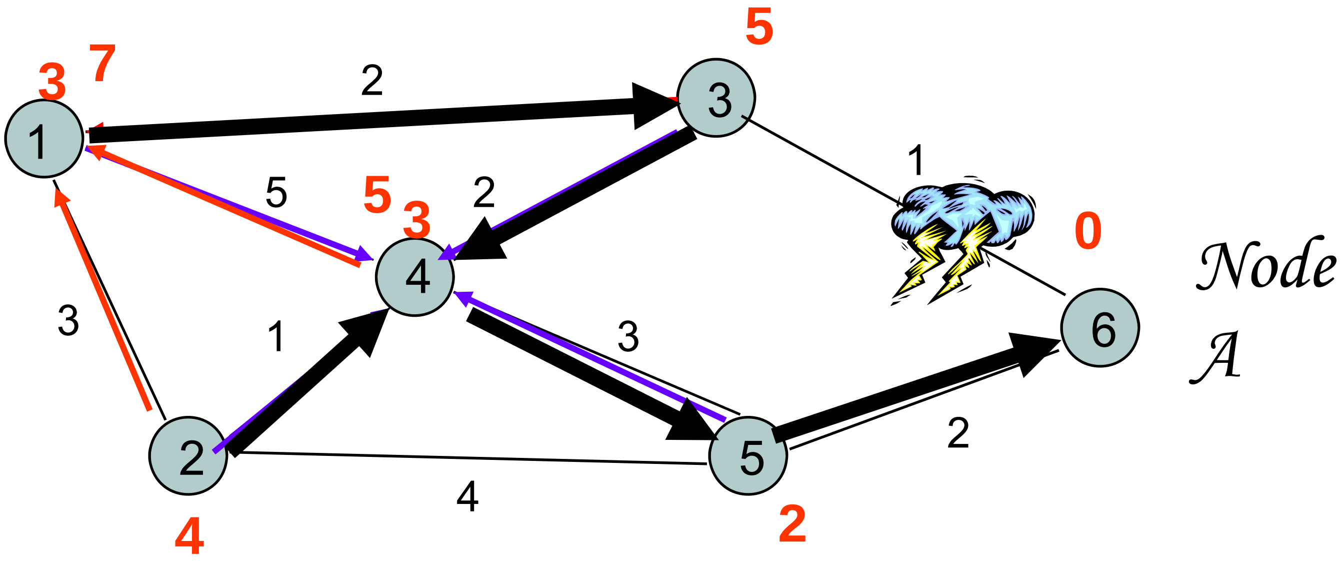
Network disconnected; Loop created between nodes 3 and 4



Example (continued)

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					

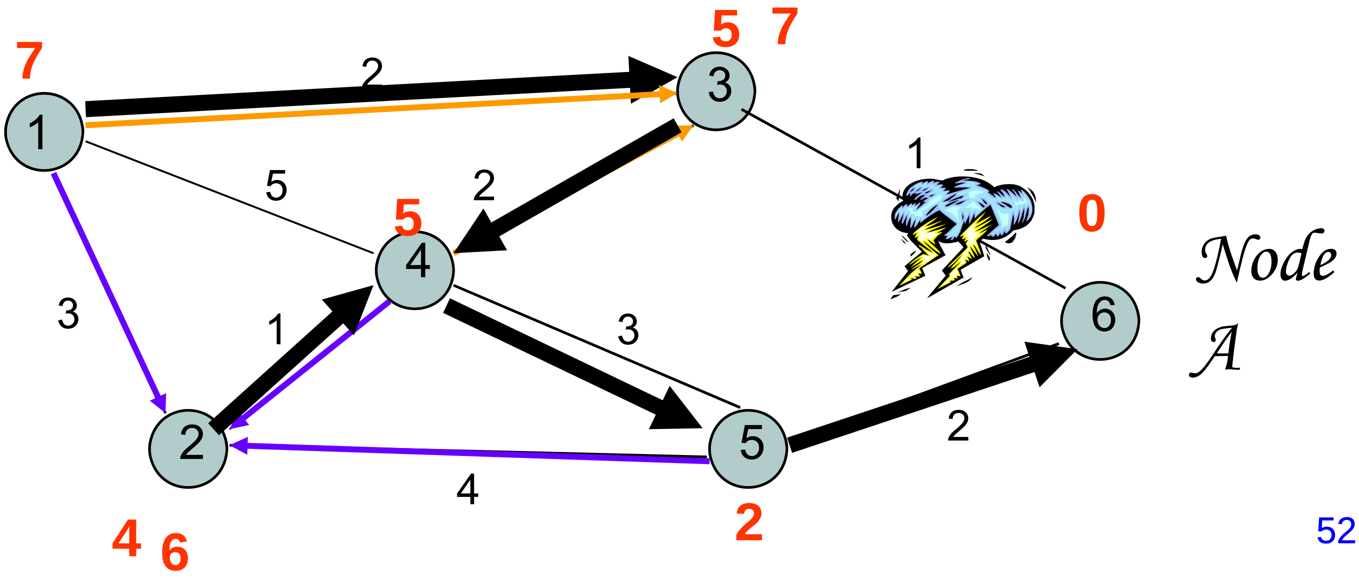
Node 4 could have chosen 2 as next node because of tie



Example (Continued)

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)

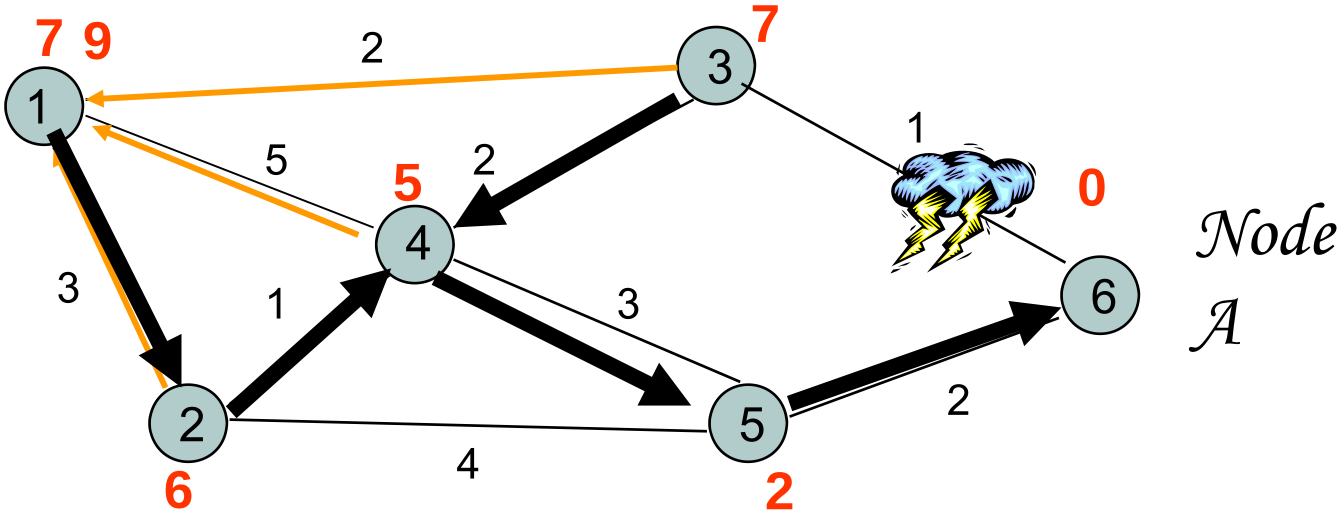
Node 2 could have chosen 5 as next node because of tie



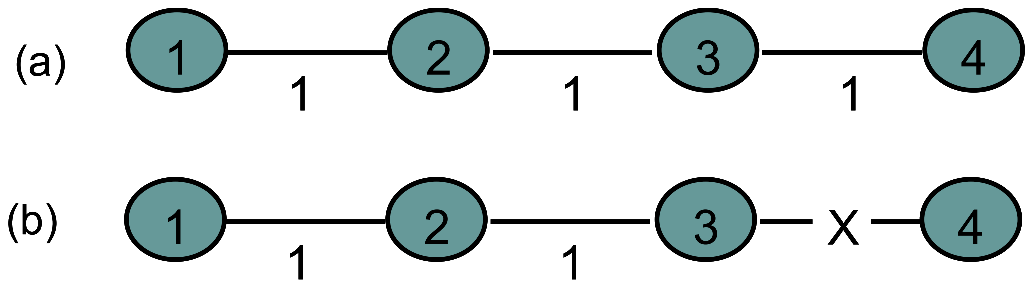
Example (Continued)

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)

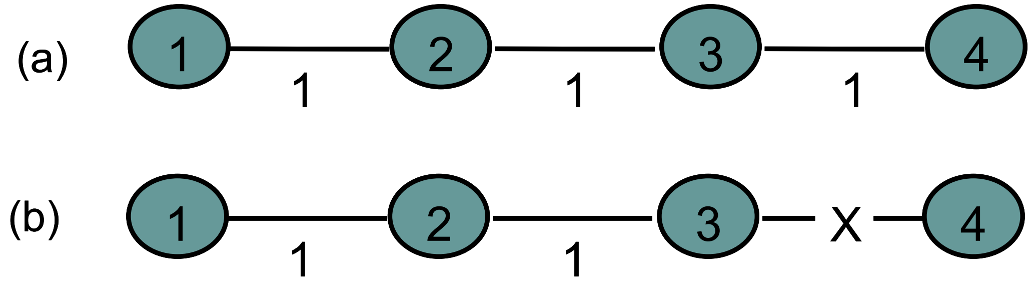
Update	Node 1	Node 2	Node 3
Before break	(2,3)	(3,2)	(4, 1)
After break	(2,3)	(3,2)	(2,3)
1	(2,3)	(3,4)	(2,3)
2	(2,5)	(3,4)	(2,5)
3	(2,5)	(3,6)	(2,5)
4	(2,7)	(3,6)	(2,7)
5	(2,7)	(3,8)	(2,7)
…	…	…	…

Problem: Bad News Travels Slowly

Remedies

- Split Horizon
  - Do not report *route to a destination* to the neighbor from which route was learned
- Split Horizon with 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
- Another solution?
  - Report (distance, via node)?

Split Horizon with Poisoned 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

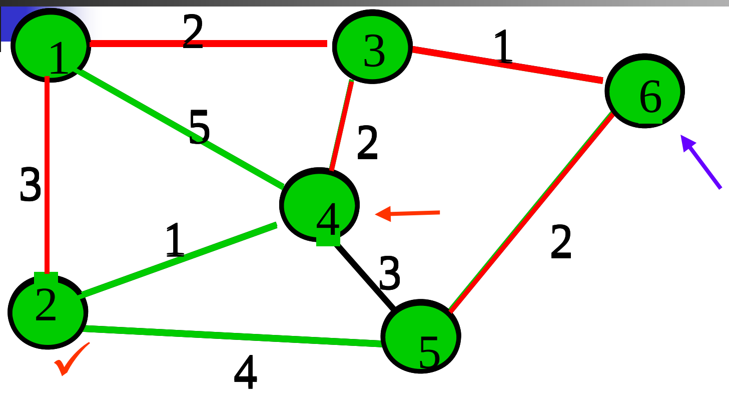
Link-State Algorithm

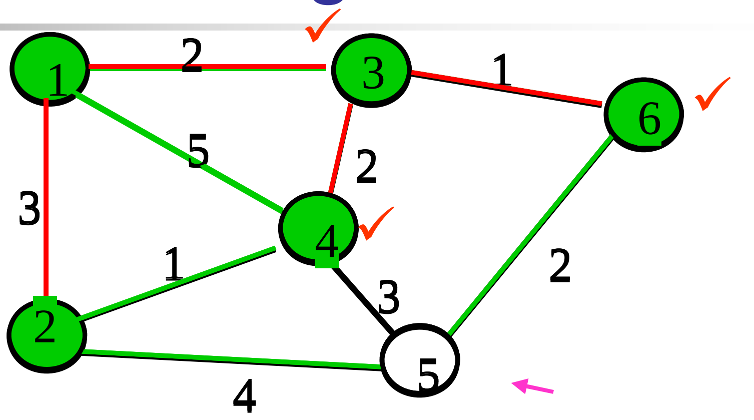
- Basic idea: two step procedure
  - Each source node gets a map of all nodes and link metrics (link state) of the entire network
  - Find the shortest path on the map from the source node to all destination nodes
- Broadcast of link-state information
  - Every node *i* in the network broadcasts to every 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's algorithm

- *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
- 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*
- Step B: (*update minimum costs)*
  - For each node $j \notin N$
  - $D_j = \min_i (D_j, D_i + C_{ij})$ ← *Minimum distance from s* to *j through node* ***i*** *in N*
  - If *N* contains all the nodes, stop
  - Else go to Step A

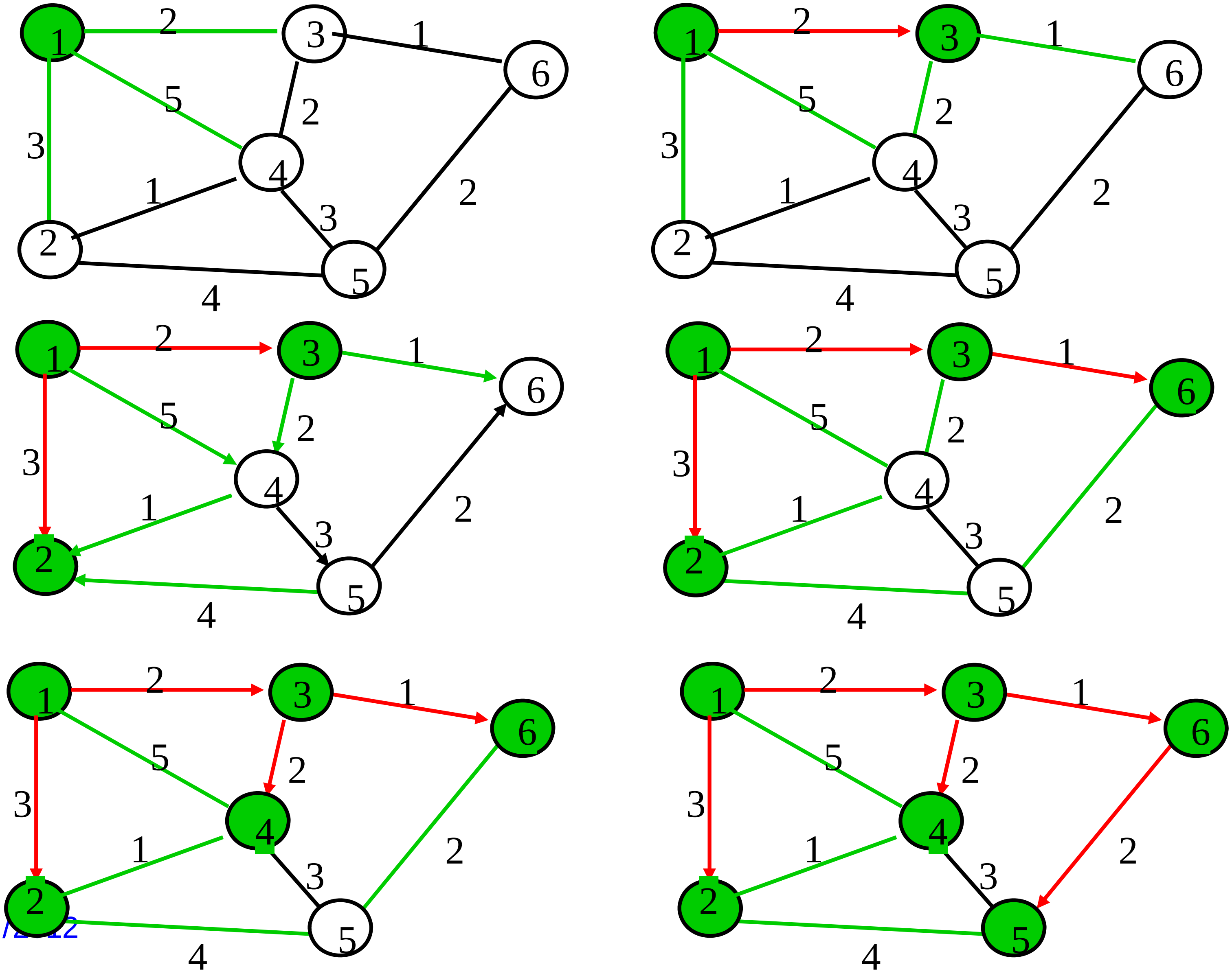
Example of the Dijkstra's algorithm





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



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 could be very quick (but depending on network size)
- 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

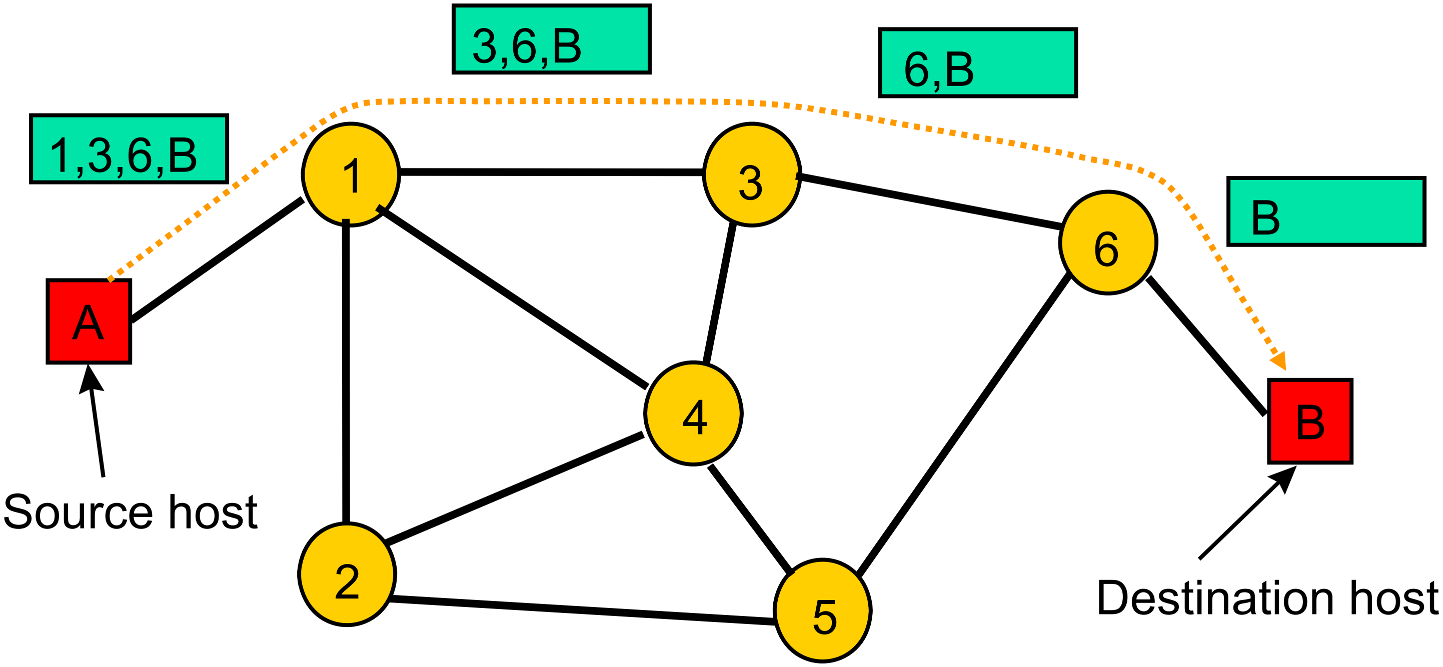
Why is Link State Better?

- Fast, loopless convergence
- Support for precise metrics, and multiple metrics if necessary (throughput, delay, cost, reliability)
- Support for multiple paths to a destination
  - algorithm can be modified to find best two paths

Source Routing

- Source host selects path that is to be followed by a packet
  - Strict: sequence of nodes in path inserted into header
  - Loose: subsequence of nodes in path specified
- Intermediate switches read next-hop address and remove address
- Source host needs link state information or access to a route server
- Source routing allows the host to control the paths that its information traverses in the network
- Potentially that means for customers to select what service providers they use

Example



Prioritization and Scheduling – Packet-Level Traffic Management

Traffic Management

Vehicular traffic management

- Traffic lights & signals control flow of traffic in city street system
- Objective is to maximize flow with tolerable delays
- Priority Services
  - Police sirens
  - Cavalcade for dignitaries
  - Bus & High-usage lanes
  - Trucks allowed only at night

Packet traffic management

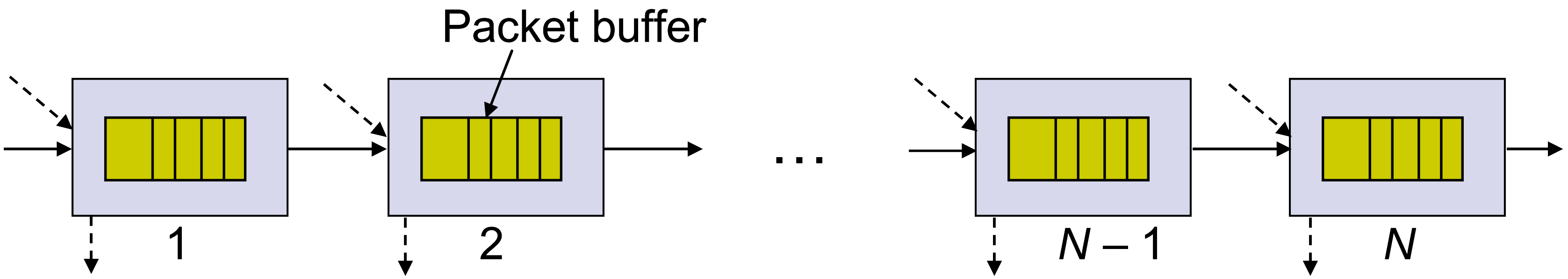
- Multiplexing & access mechanisms to control flow of packet traffic
- Objective is make efficient use of network resources & deliver QoS
- Priority
  - Fault-recovery packets
  - Real-time traffic
  - Enterprise (high-revenue) traffic
  - High bandwidth traffic

Time Scales & Granularities

- Packet Level
  - Queueing & scheduling at multiplexing points
  - Determines relative performance offered to packets over a short time scale (microseconds)
- Flow Level
  - Management of traffic flows & resource allocation to ensure delivery of QoS (milliseconds to seconds)
  - Matching traffic flows to resources available; congestion control
- Flow-Aggregate Level
  - Routing of aggregate traffic flows across the network for efficient utilization of resources and meeting of service levels
  - “Traffic Engineering”, at scale of minutes to days

End-to-End QoS

- A packet traversing network encounters delay and possible loss at various multiplexing points
- End-to-end performance is accumulation of per-hop performance

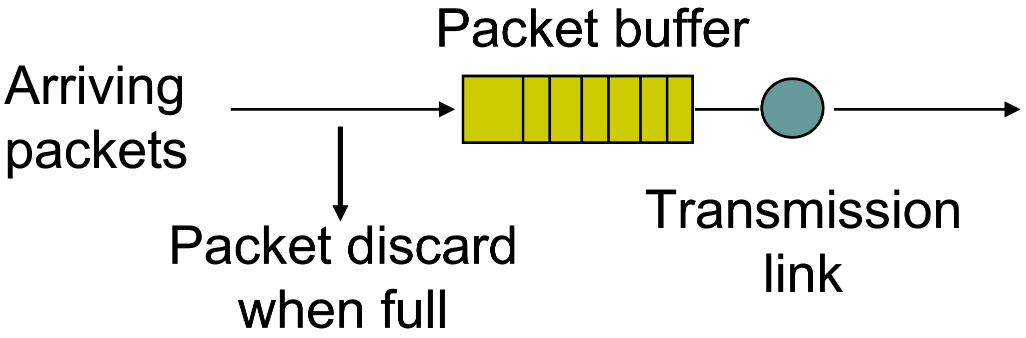


Scheduling & QoS

- End-to-End QoS & Resource Control
  - Buffer & bandwidth control → Performance
  - Admission control to regulate traffic level
- Scheduling Concepts
  - fairness/isolation
  - priority, aggregation,
- Fair Queueing & Variations
  - WFQ, PGPS
- Guaranteed Service
  - WFQ, Rate-control
- Packet Dropping
  - aggregation, drop priorities

FIFO Queueing

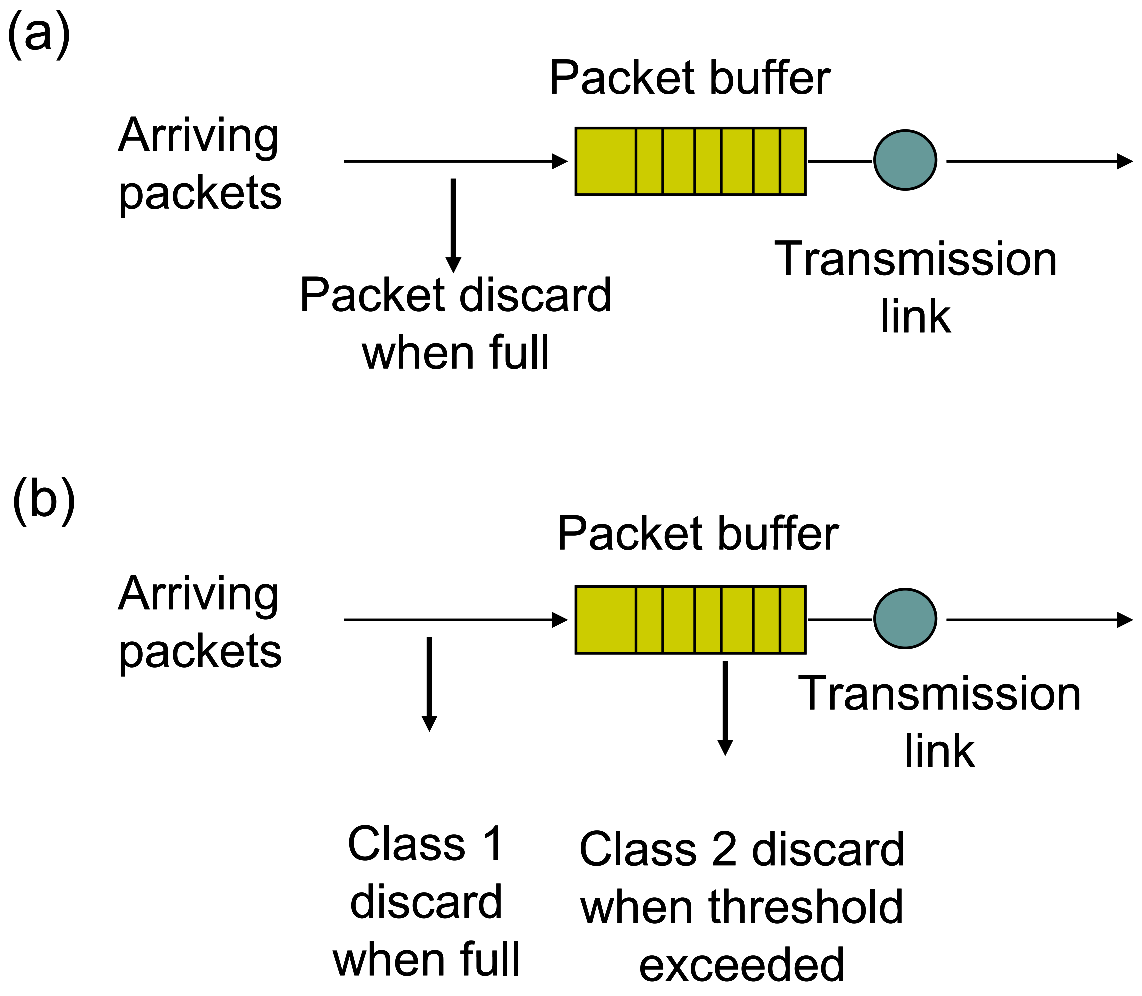
- All packet flows share the same buffer
- Transmission Discipline: First-In, First-Out
- Buffering Discipline: Discard arriving packets if buffer is full (Alternative: random discard; pushout head-of-line, i.e. oldest, packet)



FIFO Queueing

- Cannot provide differential QoS to different packet flows
  - Different packet flows interact strongly
- Statistical delay guarantees via load control
  - Restrict number of flows allowed (connection admission control)
  - Difficult to determine performance delivered
- Finite buffer determines a maximum possible delay
- Buffer size determines loss probability
  - But depends on arrival & packet length statistics
- Variation: packet enqueueing based on queue thresholds
  - some packet flows encounter blocking before others
  - higher loss, lower delay

FIFO Queueing with Discard Priority



(a)

Packet buffer

Arriving packets

Packet discard when full

Transmission link

(b)

Packet buffer

Arriving packets

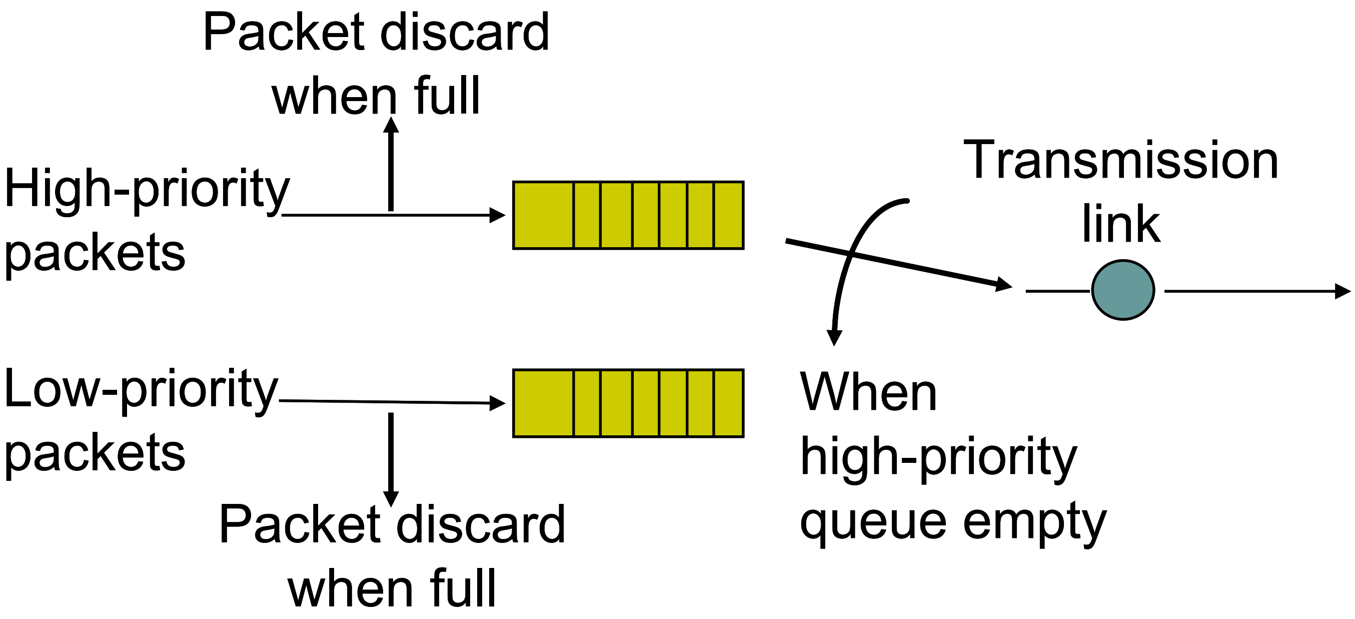
Transmission link

Class 1 discard when full

Class 2 discard when threshold exceeded

HOL Priority Queueing

- High priority queue serviced until empty
- High priority queue has lower waiting time
- Buffers can be dimensioned for different loss probabilities
- Surge in high priority queue can cause low priority queue to saturate



Packet discard when full

High-priority packets

Transmission link

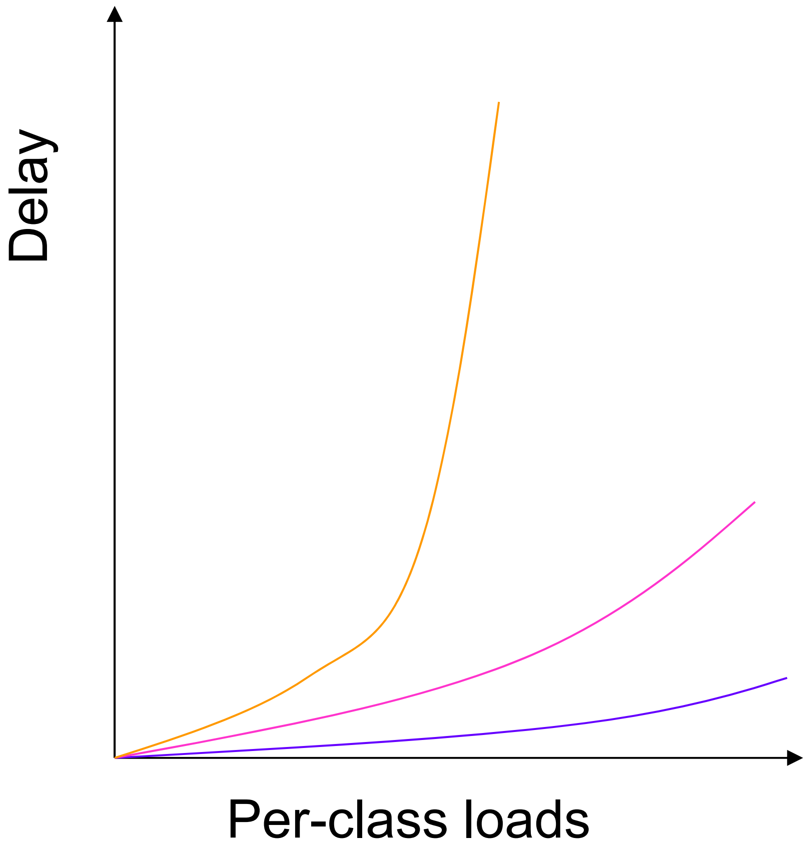
When high-priority queue empty

Low-priority packets

Packet discard when full

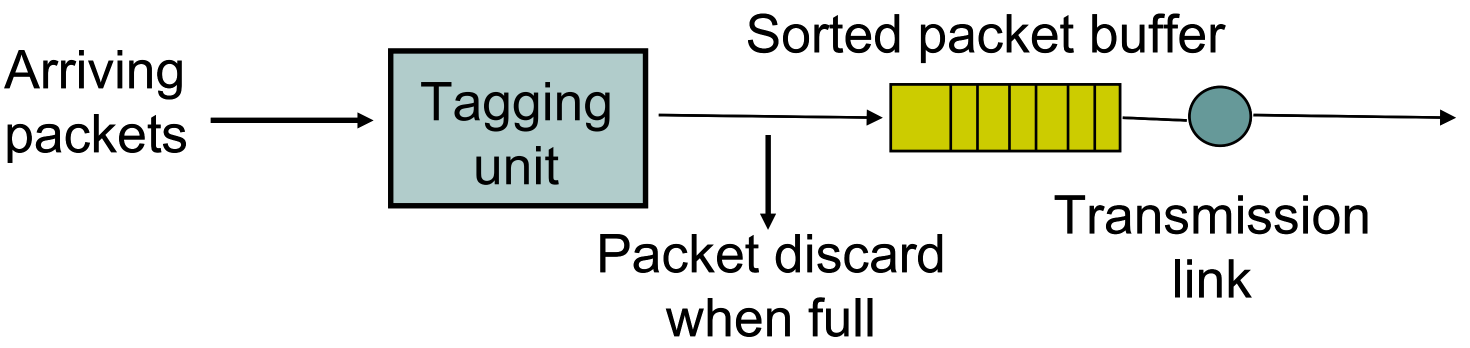
HOL Priority Features

- Provides differential QoS
- Pre-emptive priority: lower classes invisible
- Non-preemptive priority: lower classes impact higher classes through residual service times
- High-priority classes can hog all of the bandwidth & starve lower priority classes
- Need to provide some isolation between classes



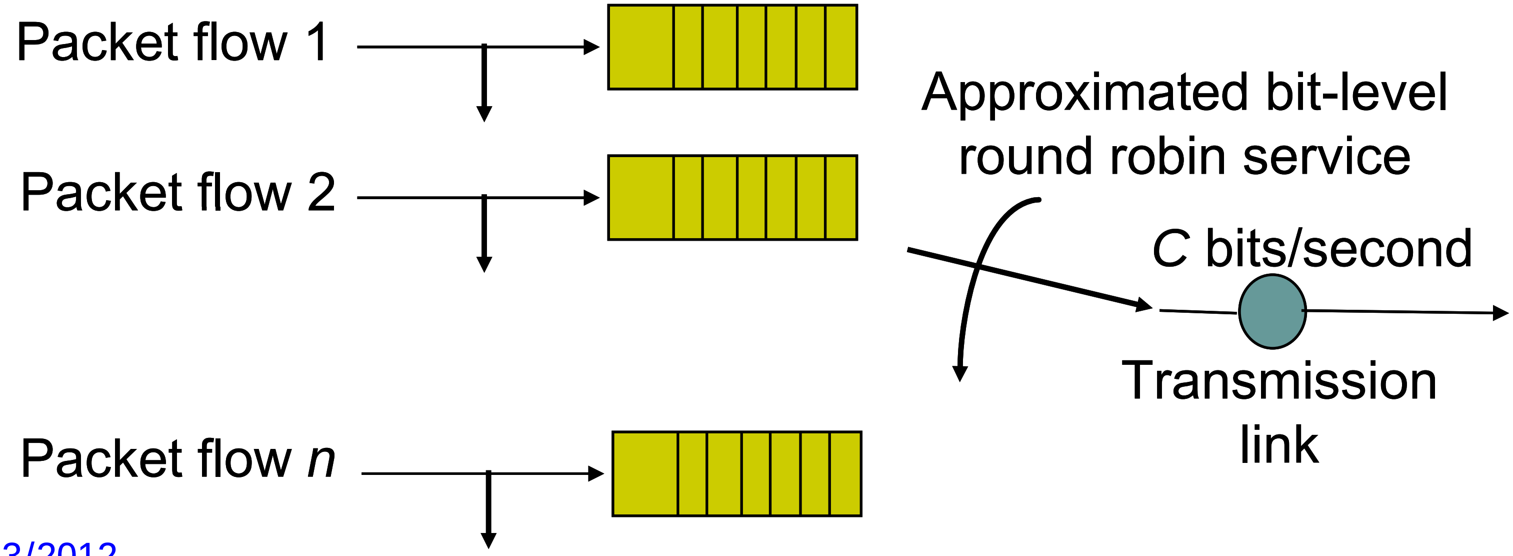
Earliest Due Date Scheduling

- Queue in order of "due date"
  - packets requiring low delay get earlier due date
  - packets without delay get indefinite or very long due dates



Fair Queueing / Generalized Processor Sharing

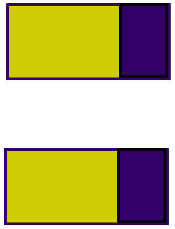
- Each flow has its own logical queue: prevents hogging; allows differential loss probabilities
- C bits/sec allocated equally among non-empty queues
  - transmission rate = C / n(t), where n(t)=# non-empty queues
- Idealized system assumes fluid flow from queues
- Implementation requires approximation: simulate fluid system; sort packets according to completion time in ideal system

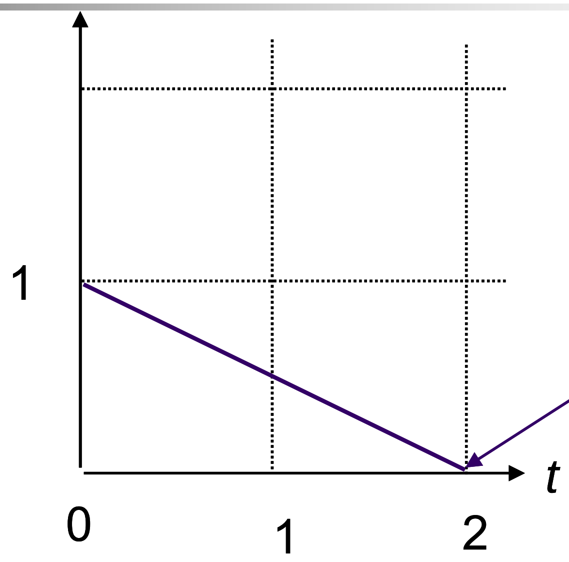


Fluid-Flow versus Packet-by-Packet Service

Buffer 1
at *t*=0

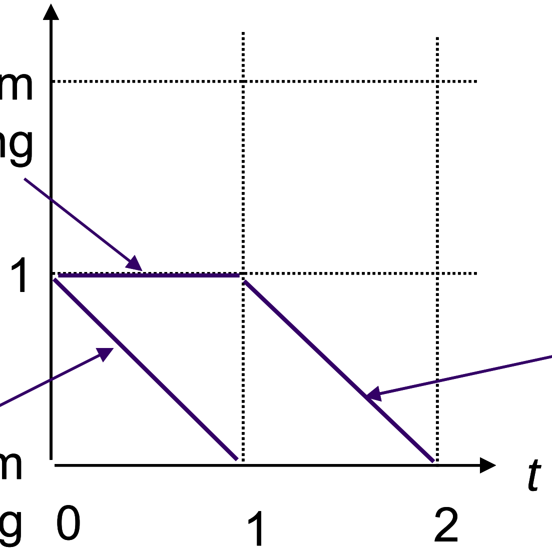
Buffer 2
at *t*=0





Fluid-flow system:
both packets served
at rate 1/2

Both packets
complete service
at *t* = 2



Packet from
buffer 2 waiting

Packet-by-packet system:
buffer 1 served first at rate 1;
then buffer 2 served at rate 1.

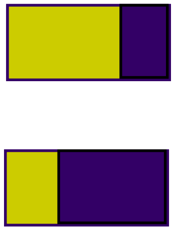
Packet from buffer 2
being served

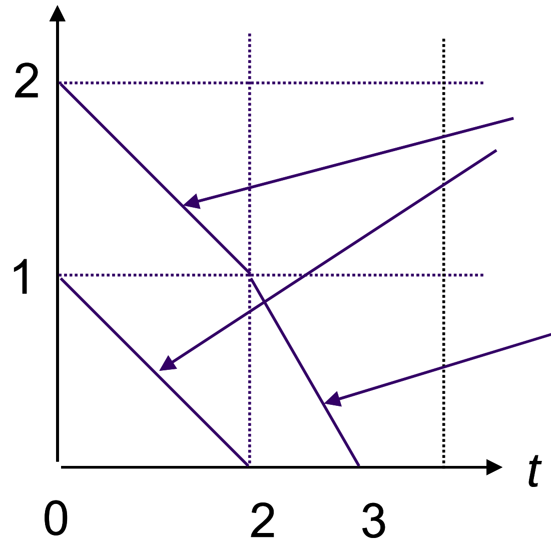
Packet from
buffer 1 being
served

Fluid-Flow versus Packet-by-Packet Service (continued)

Buffer 1
at *t*=0

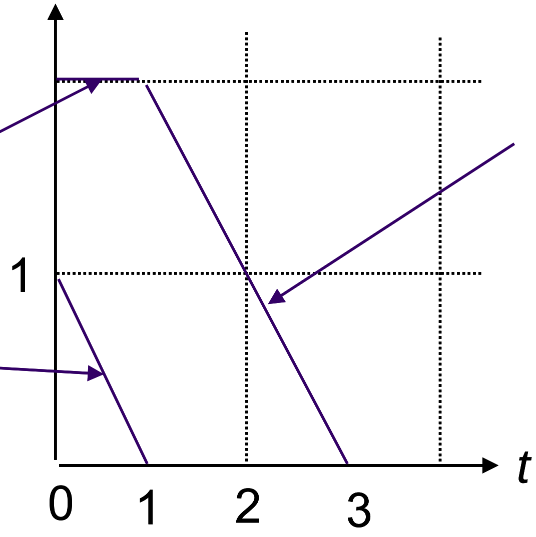
Buffer 2
at *t*=0





Fluid-flow system:
both packets served
at rate 1/2

Packet from buffer 2
served at rate 1



Packet from
buffer 2
waiting

Packet from
buffer 1
served at
rate 1

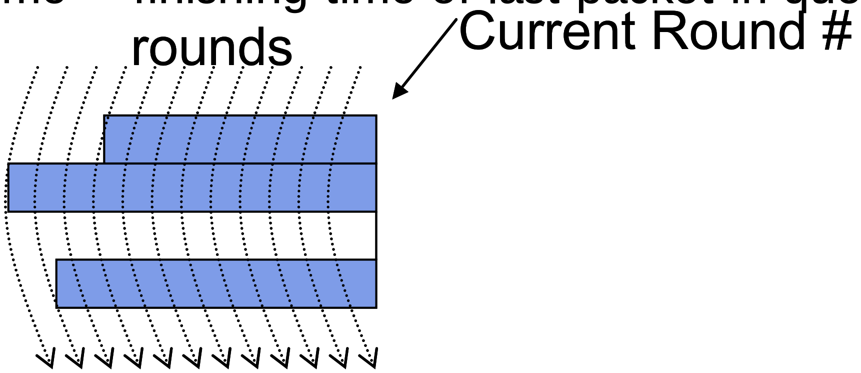
Packet-by-packet
fair queueing:
buffer 2 served at rate 1

Bit-by-Bit Fair Queueing

- Assume n flows, n queues
- 1 round = 1 cycle serving all n queues
- If each queue gets 1 bit per cycle, then 1 round = # active queues
  - Actual duration of a round is determined by active queues.
- Round number = number of cycles of service that have been completed
- If packet arrives to idle queue:

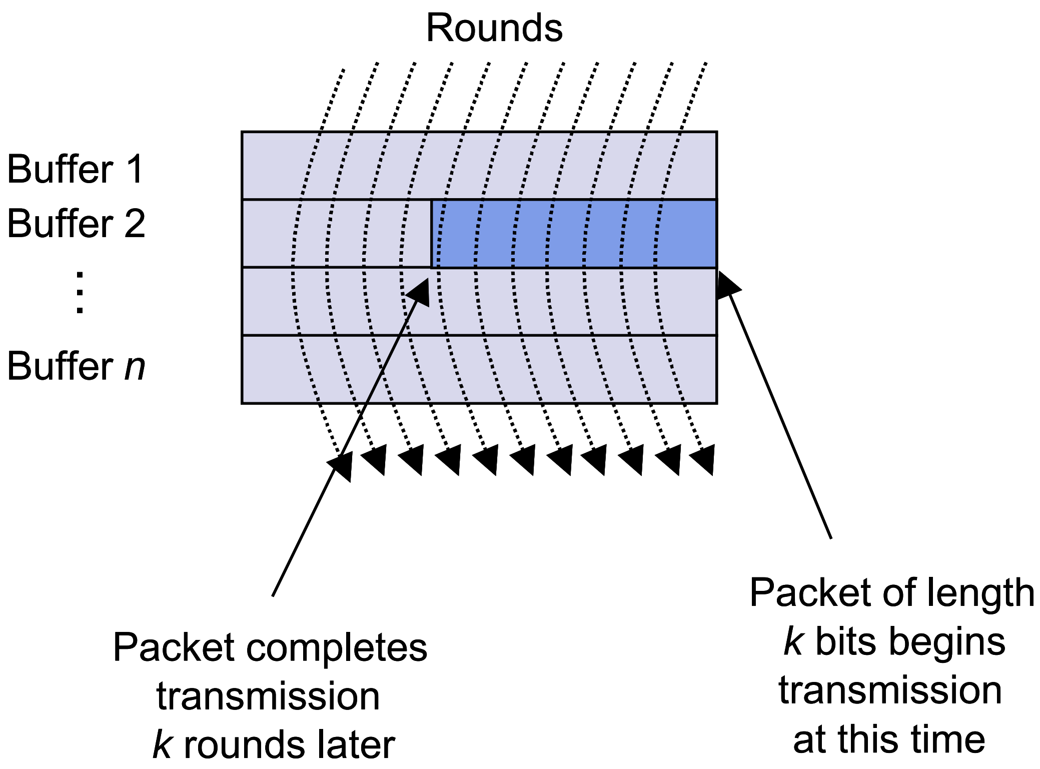
  Finishing time = round number + packet size in bits
- If packet arrives to active queue:

  Finishing time = finishing time of last packet in queue + packet size



More Details

Number of rounds = Number of bit transmission opportunities



Rounds

Buffer 1

Buffer 2

⋮

Buffer *n*

Packet completes
transmission
k rounds later

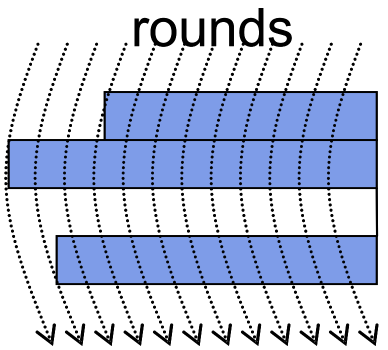
Packet of length
k bits begins
transmission
at this time

Differential Service:

If a traffic flow is to receive twice as much bandwidth as a regular flow, then its packet completion time would be half

Computing the Finishing Time

- *F(i,k,t)* = finish time of *k*th packet that arrives at time *t* to flow *i*
- *P(i,k,t)* = size of *k*th packet that arrives at time t to flow *i*
- *R(t)* = round number at time *t*



Generalize so *R(t)* continuous, not discrete

R(t) grows at rate inversely proportional to *n(t)*

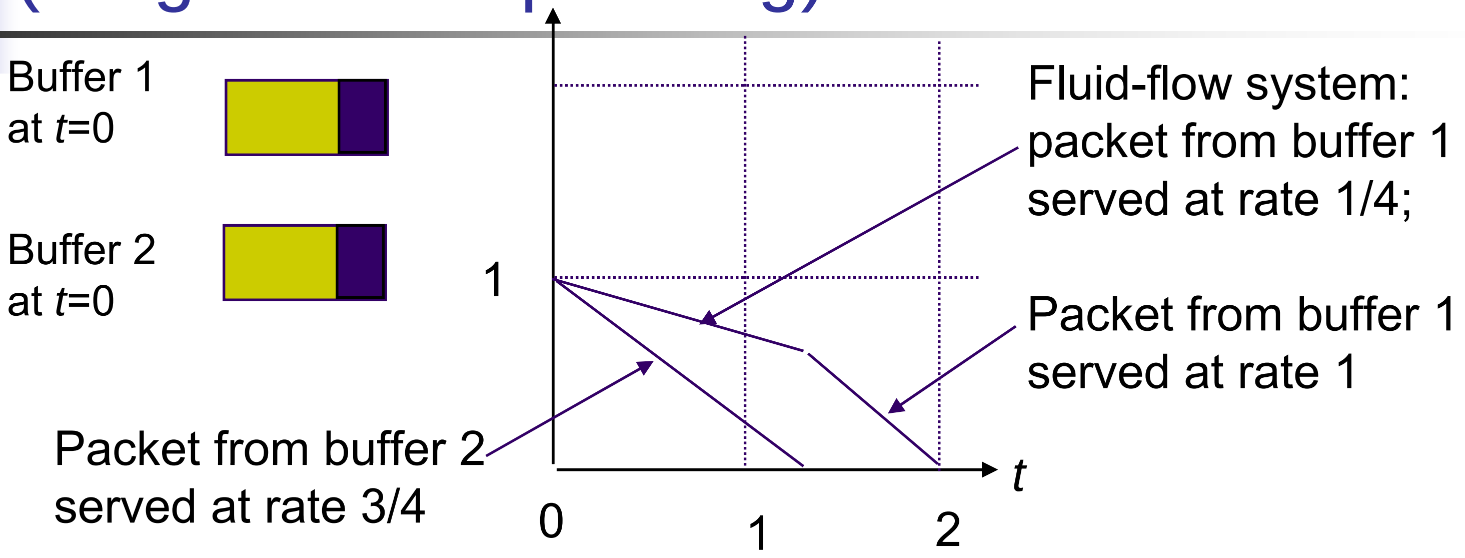
- Packet-by-Packet Fair Queueing:

$$F(i,k,t) = \max\{F(i,k-1,t^{k-1}),\ R(t)\} + P(i,k,t)$$

- Weighted Fair Queueing:

$$F(i,k,t) = \max\{F(i,k-1,t^{k-1}), R(t)\} + P(i,k,t)/w_i$$

Fluid-Flow versus Packet-by-Packet Service (weighted fair queueing)



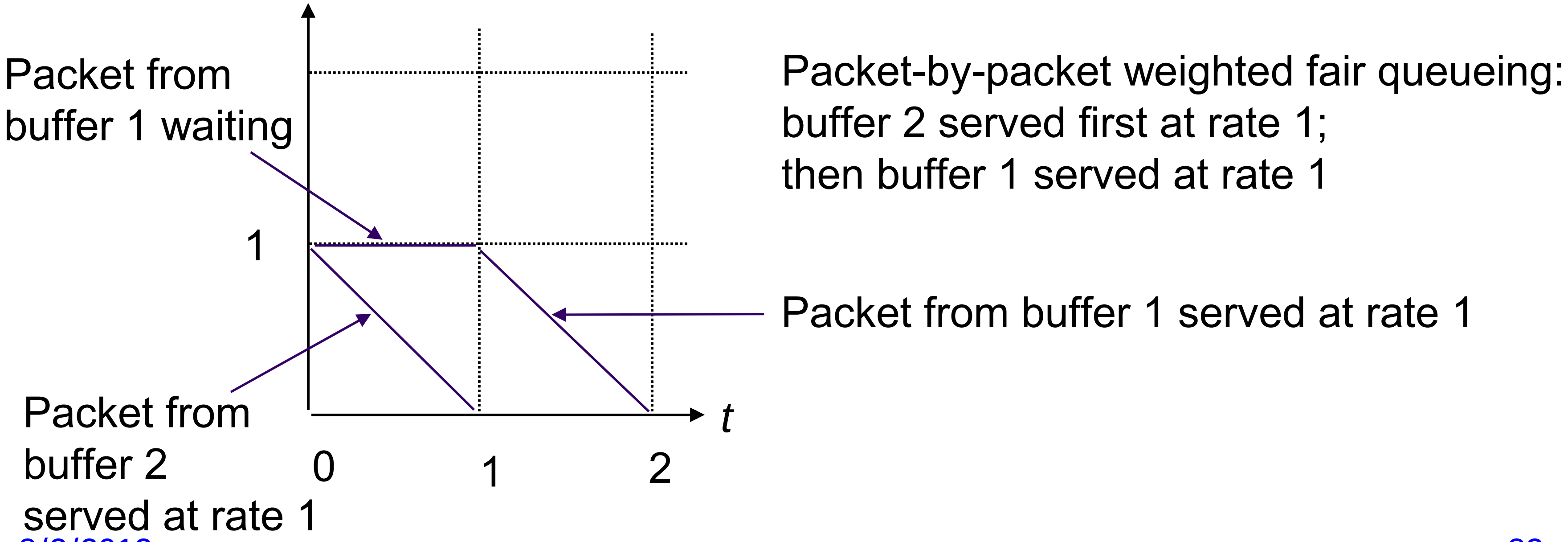
Buffer 1 at *t*=0

Buffer 2 at *t*=0

Fluid-flow system: packet from buffer 1 served at rate 1/4;

Packet from buffer 1 served at rate 1

Packet from buffer 2 served at rate 3/4



Packet from buffer 1 waiting

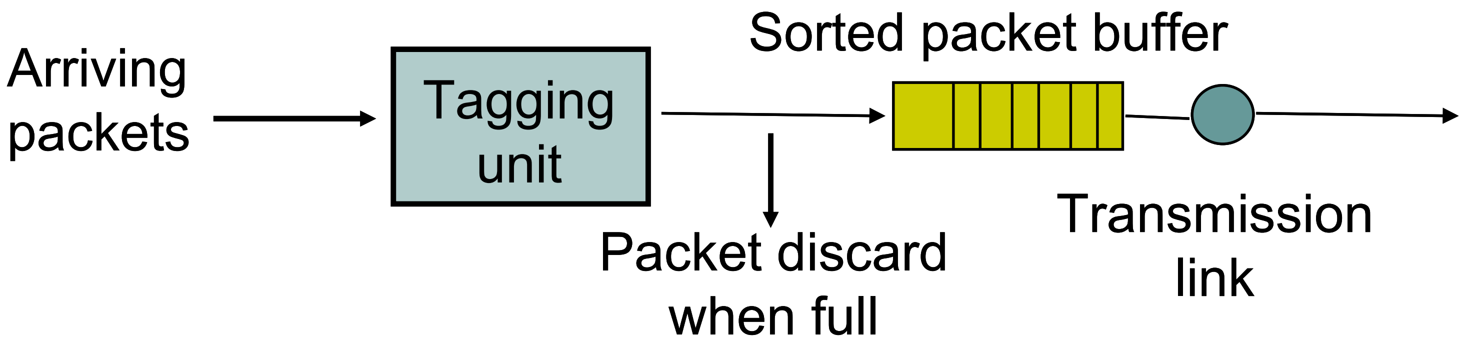
Packet-by-packet weighted fair queueing: buffer 2 served first at rate 1; then buffer 1 served at rate 1

Packet from buffer 1 served at rate 1

Packet from buffer 2 served at rate 1

Packetized GPS/WFQ

- Compute packet completion time in ideal system
  - add tag to packet
  - sort packet in queue according to tag
  - serve according to HOL



WFQ and Packet QoS

- WFQ and its many variations form the basis for providing QoS in packet networks
- Very high-speed implementations available, up to 10 Gbps and possibly higher
- WFQ must be combined with other mechanisms to provide end-to-end QoS

Buffer Management

- Packet drop strategy: Which packet to drop when buffers full
- Fairness: protect well-behaving sources from misbehaving sources
- Aggregation:
  - Per-flow buffers protect flows from misbehaving flows
  - Full aggregation provides no protection
  - Aggregation into classes provided intermediate protection
- Drop priorities:
  - Drop packets from buffer according to priorities
  - Maximizes network utilization & application QoS
  - Examples: layered video, policing at network edge
- Controlling sources at the edge

Early or Overloaded Drop

Random early detection:

- Drop packets if short-term avg of queue exceeds threshold
- Packet drop probability increases linearly with queue length
- Dropped packets provide feedback to sources to reduce rate
- Why random?
  - Higher rate gets a higher chance of packet drop
- Improves performance of cooperating sources
- Increases loss probability of misbehaving sources

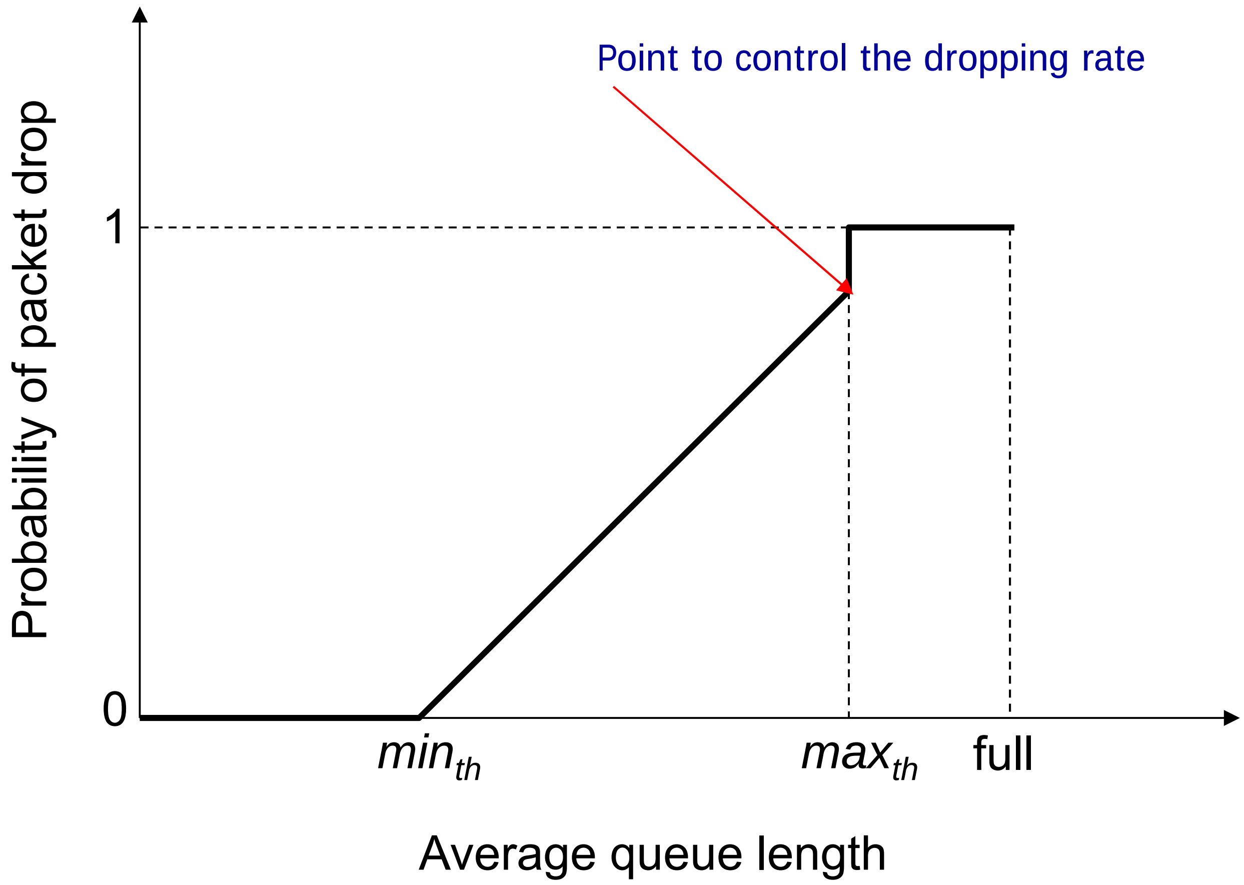
Random Early Detection (RED)

- Packets produced by TCP will reduce input rate in response to network congestion
- Early drop: discard packets before buffers are full
- Random drop causes some sources to reduce rate before others, causing gradual reduction in aggregate input rate

Algorithm:

- Maintain running average of queue length
- If Q_{avg} < minthreshold, do nothing
- If Q_{avg} > maxthreshold, drop packet
- If in between, drop packet according to probability
- Flows that send more packets are more likely to have packets dropped

Packet Drop Profile in RED

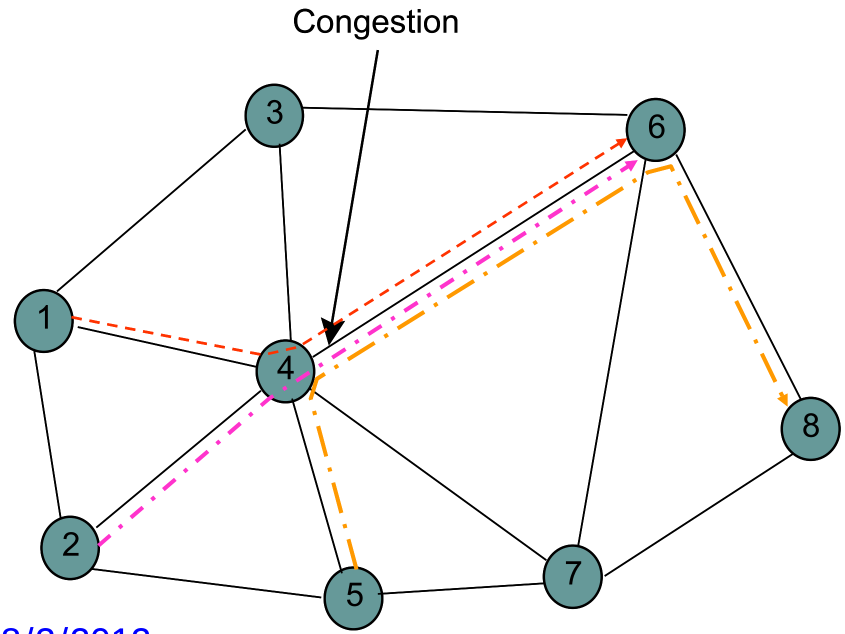


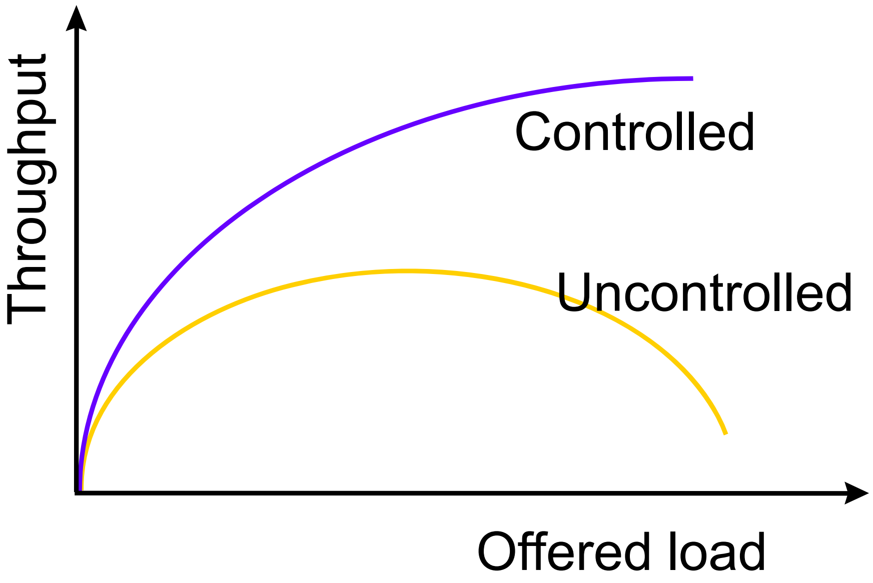
Congestion Control –
Flow-Level Traffic Management

Congestion

Congestion occurs when a surge of traffic overloads network resources

- Approaches to Congestion Control:
  - Preventive Approaches: Scheduling & Reservations
  - Reactive Approaches: Detect & Throttle/Discard



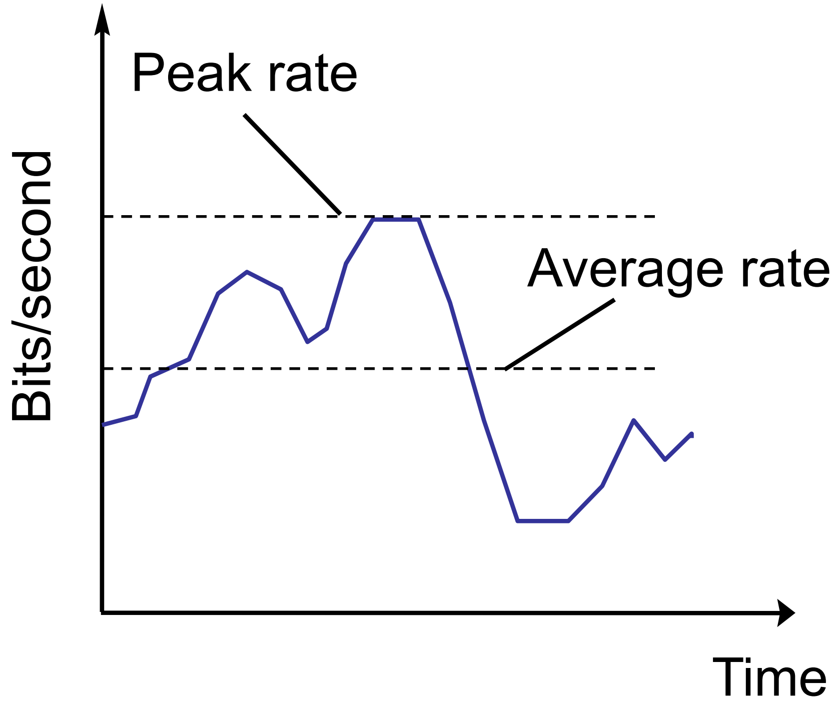


Open-Loop Control

- Network performance is guaranteed to all traffic flows that have been admitted into the network
- Initially for connection-oriented networks
- Key Mechanisms
  - Admission Control
  - Policing
  - Traffic Shaping
  - Traffic Scheduling

Admission Control

- Flows negotiate contract with network
- Specify requirements:
  - Peak, Avg., Min Bit rate
  - Maximum burst size
  - Delay, Loss requirement
- Network computes resources needed
  - “Effective” bandwidth
- If flow accepted, network allocates resources to ensure QoS delivered as long as source conforms to contract



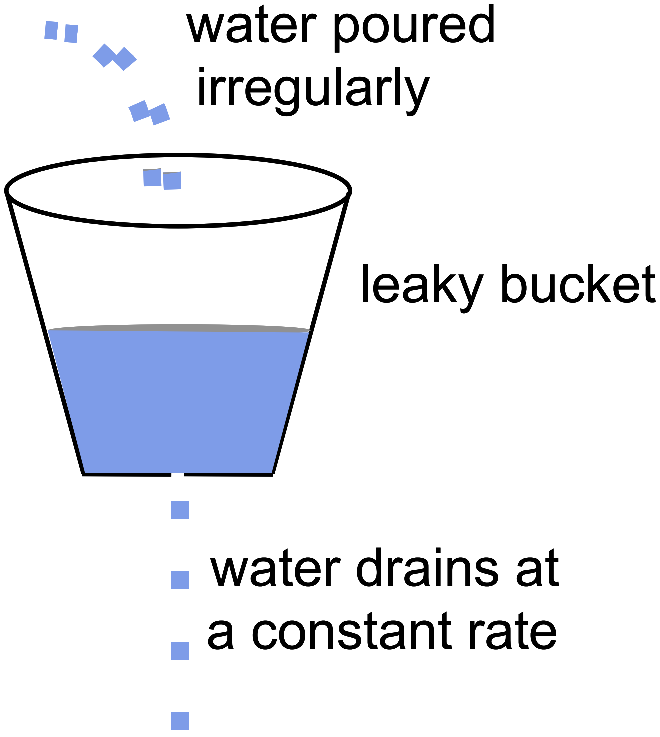
Typical bit rate demanded by a variable bit rate information source

Policing

- Network monitors traffic flows continuously to ensure they meet their traffic contract
- When a packet violates the contract, network can discard or tag the packet giving it lower priority
- If congestion occurs, tagged packets are discarded first
- *Leaky Bucket Algorithm* is the most commonly used policing mechanism
  - Bucket has specified leak rate for average contracted rate
  - Bucket has specified depth to accommodate variations in arrival rate
  - Arriving packet is *conforming* if it does not result in overflow

Leaky Bucket Algorithm

Leaky Bucket algorithm can be used to police arrival rate of a packet stream



Leak rate corresponds to long-term rate

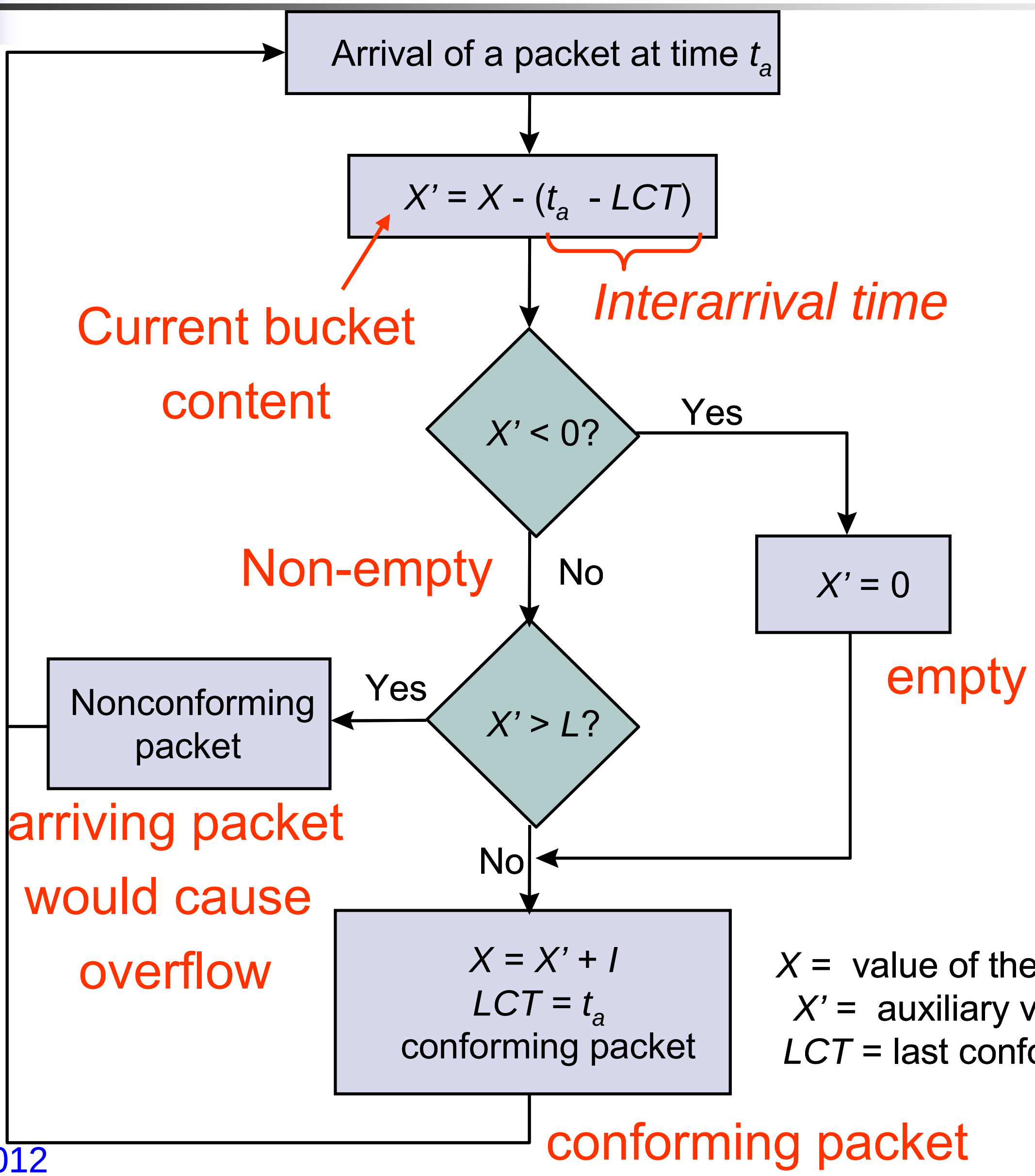
Bucket depth corresponds to maximum allowable burst arrival

1 packet per unit time
Assume constant-length packet as in ATM

Let X = bucket content at last conforming packet arrival

Let t_a – last conforming packet arrival time = depletion in bucket

Details of the Algorithm



Arrival of a packet at time t_a

$X' = X - (\underbrace{t_a - LCT}_{\text{Interarrival time}})$

Current bucket content

$X' < 0$?

Yes

$X' = 0$

empty

No

Non-empty

$X' > L$?

Yes

Nonconforming packet

arriving packet would cause overflow

No

$X = X' + I$
$LCT = t_a$
conforming packet

conforming packet

Depletion rate:
1 packet per unit time

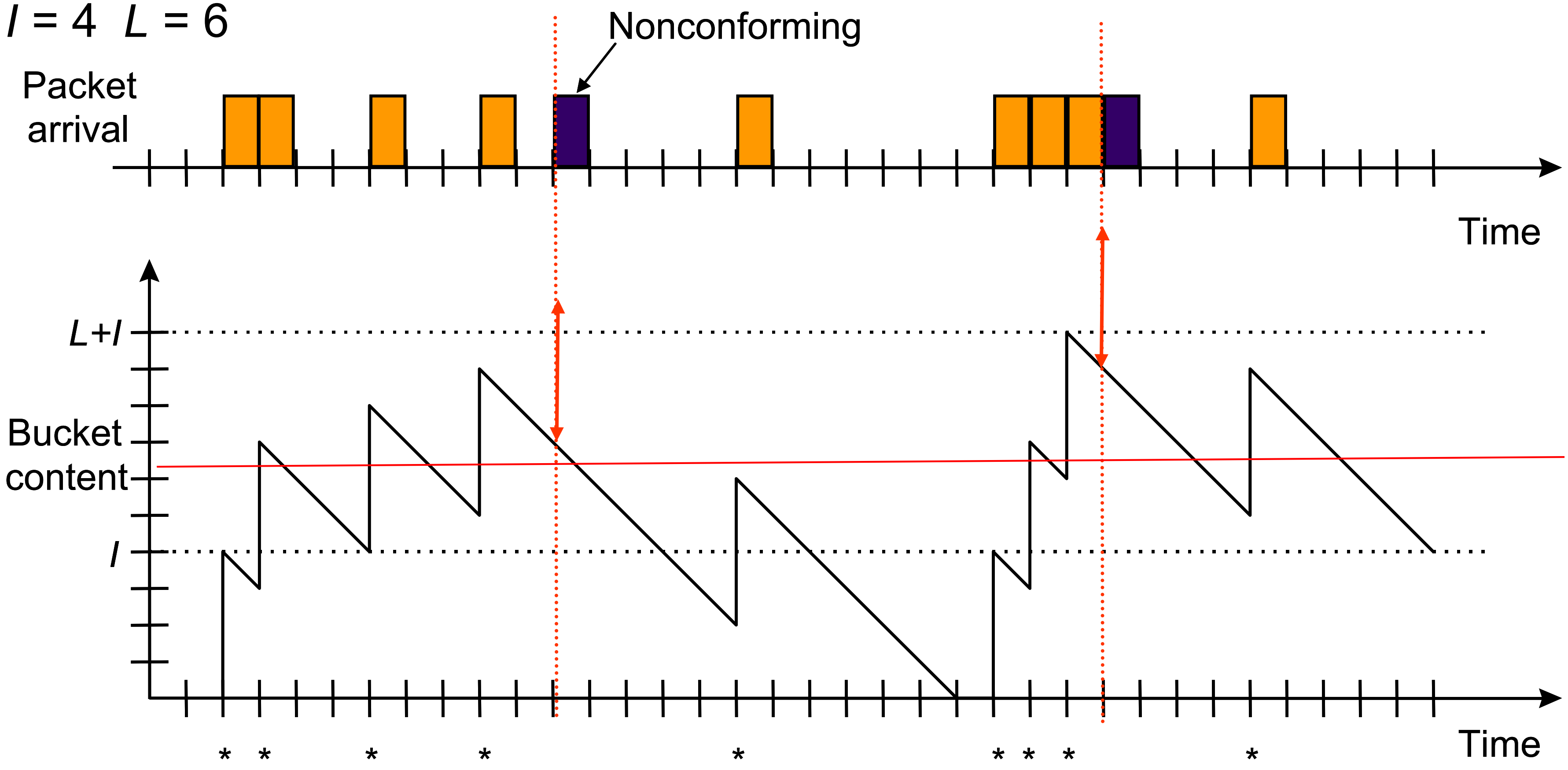
$L+I$ = Bucket Depth

I = increment per arrival, nominal interarrival time

X = value of the leaky bucket counter
X' = auxiliary variable
LCT = last conformance time

Leaky Bucket Example

I = 4 *L* = 6



Non-conforming packets not allowed into bucket & hence not included in calculations

Policing Parameters

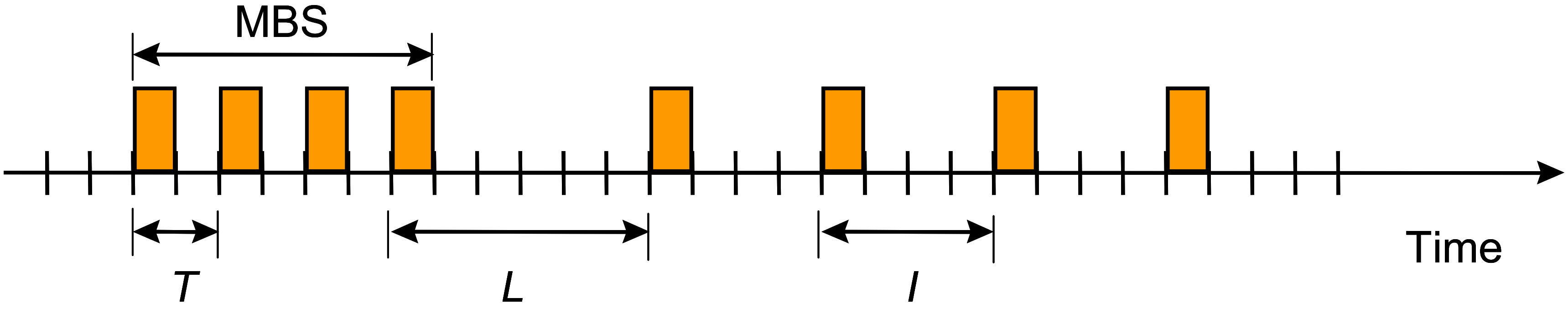
T = 1 / peak rate

MBS = maximum burst size

I = nominal interarrival time = 1 / sustainable rate

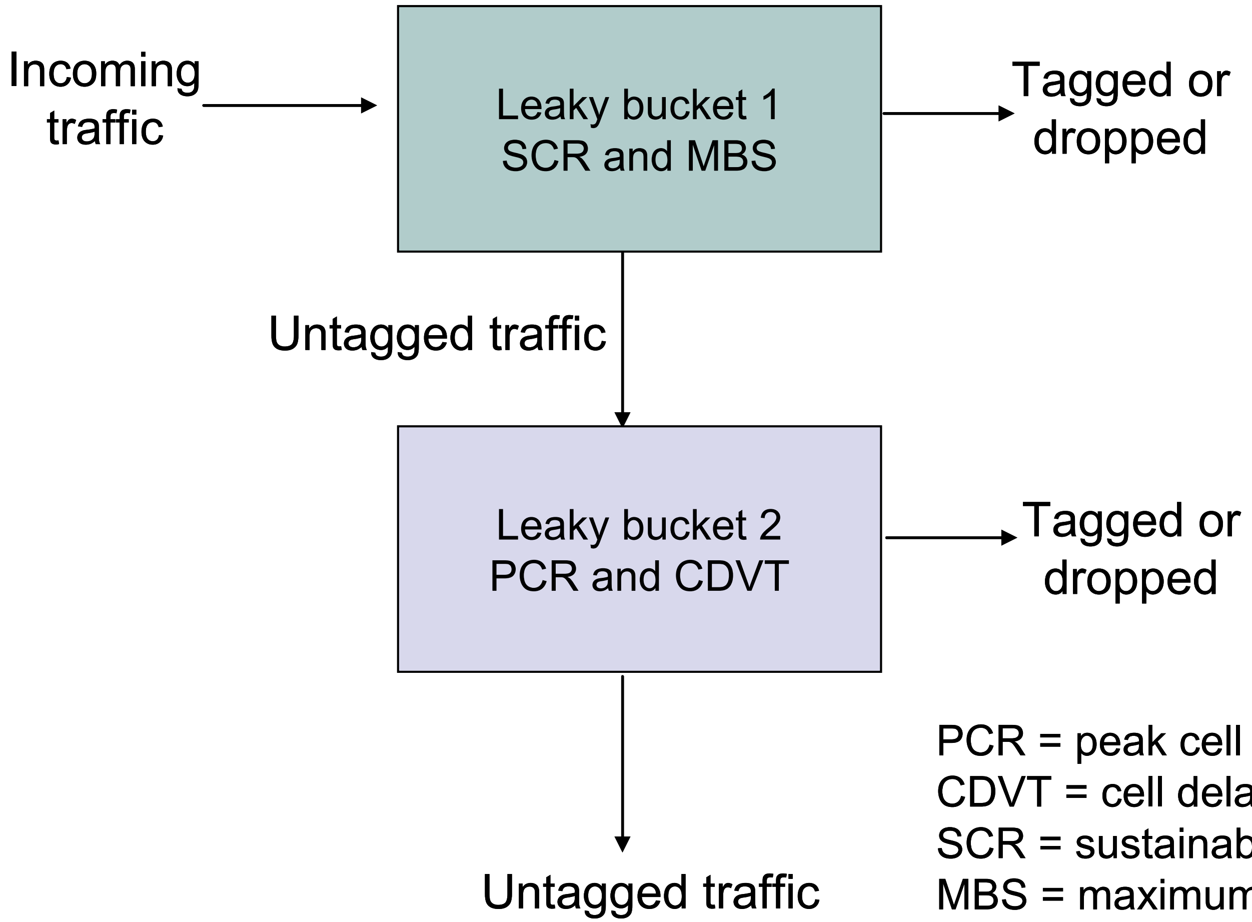
$$MBS = 1 + \left[\frac{L}{I - T} \right]$$

After 1st packet, the content increases by I – T per packet arrival



Dual Leaky Bucket

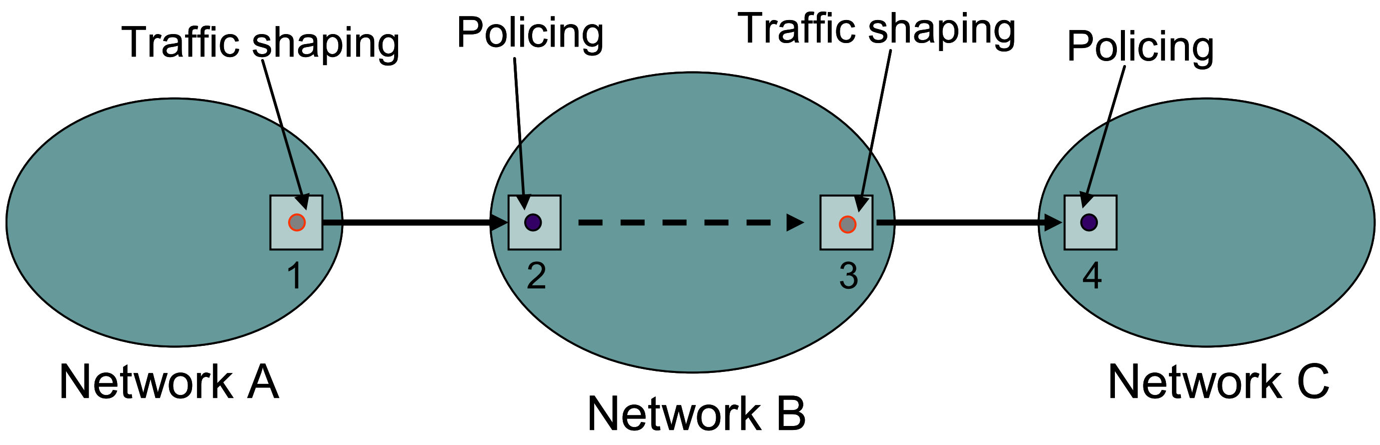
Dual leaky bucket to police PCR, SCR, and MBS:



PCR = peak cell rate
CDVT = cell delay variation tolerance
SCR = sustainable cell rate
MBS = maximum burst size

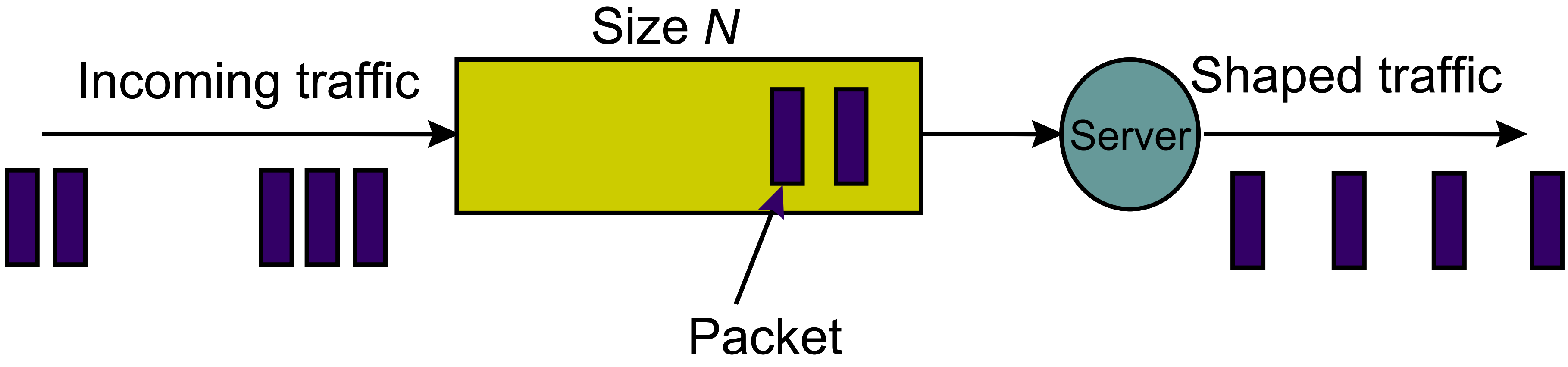
Traffic Shaping

- Networks police the incoming traffic flow
- *Traffic shaping* is used to ensure that a packet stream conforms to specific parameters
- Networks can shape their traffic prior to passing it to another network



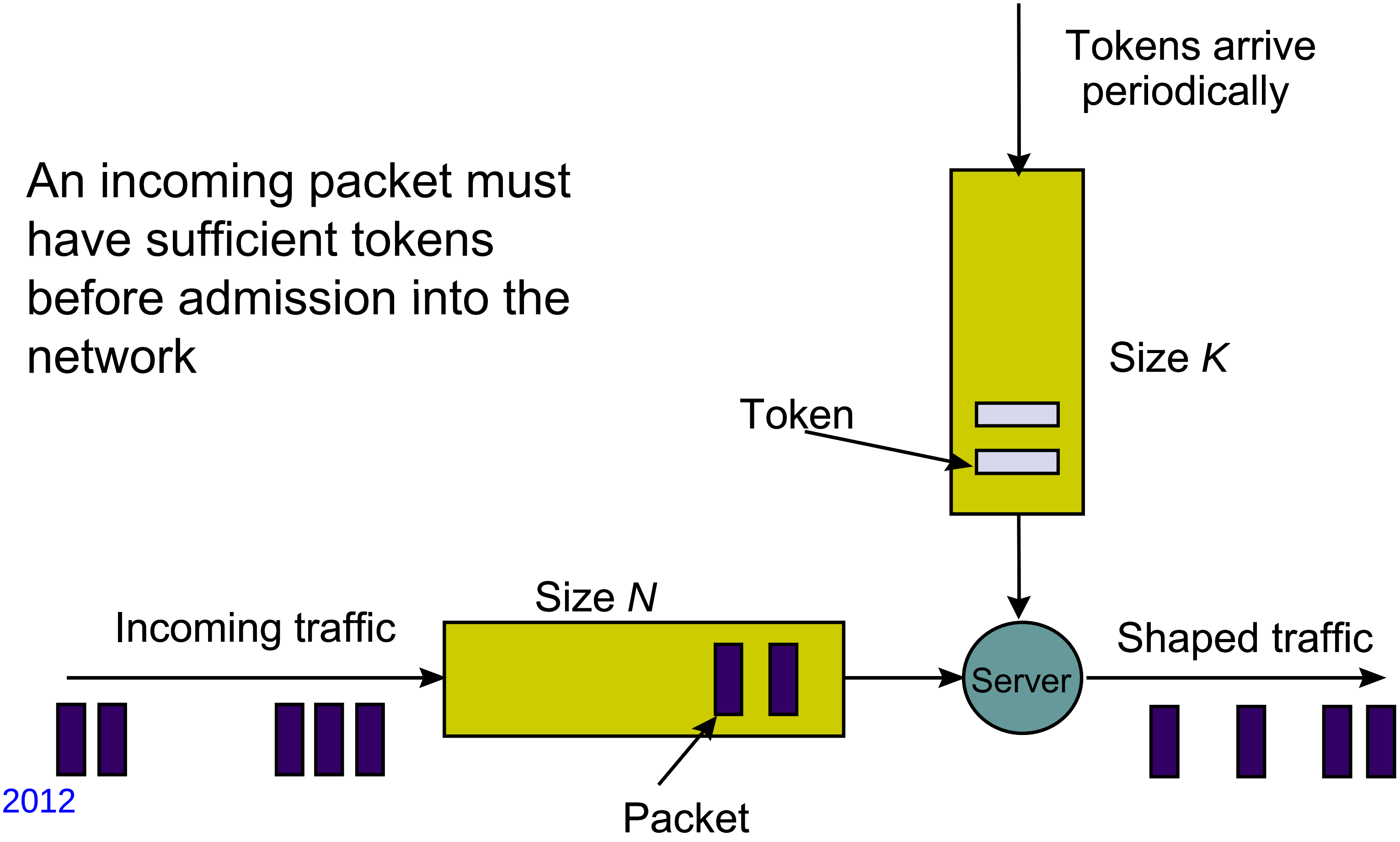
Leaky Bucket Traffic Shaper

- Buffer incoming packets
- Play out periodically to conform to parameters
- Surges in arrivals are buffered & smoothed out
- Possible packet loss due to buffer overflow
- Too restrictive, since conforming traffic does not need to be completely smooth



Token Bucket Traffic Shaper

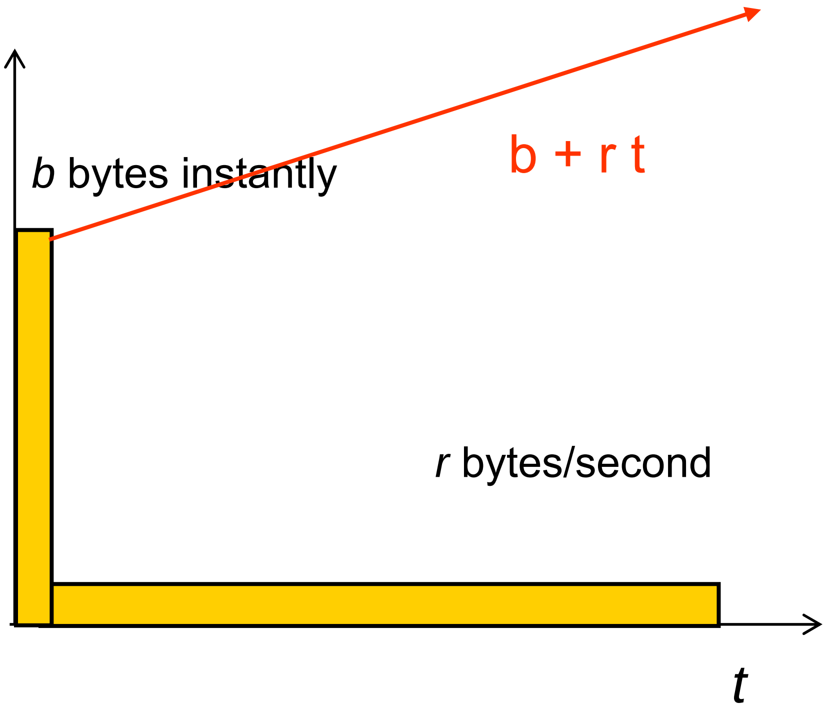
- Token rate regulates transfer of packets
- If sufficient tokens available, packets enter network without delay
- K determines how much burstiness allowed into the network



An incoming packet must have sufficient tokens before admission into the network

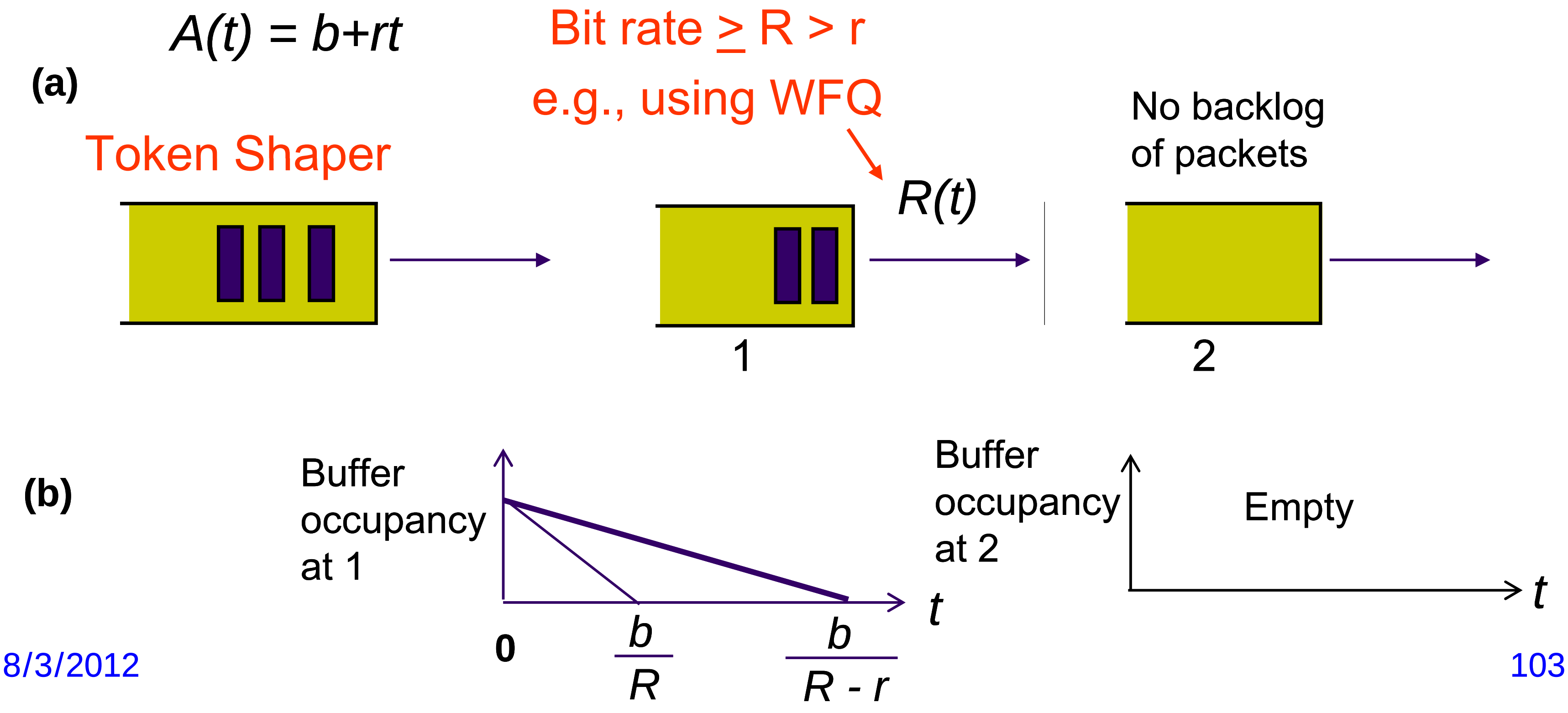
Token Bucket Shaping Effect

The token bucket constrains the traffic from a source to be limited to *b* + *r t* bytes in an interval of length *t. r is the token rate in bytes/second.*



Packet transfer with Delay Guarantees

- Assume fluid flow for information
- Token bucket allows burst of b bytes & then r bytes/second
  - Since R>r, buffer content @ 1 never greater than b bytes
  - Thus delay @ mux < b/R
- Rate into second mux is r < R, so bytes are never delayed



Delay Bounds with WFQ / PGPS

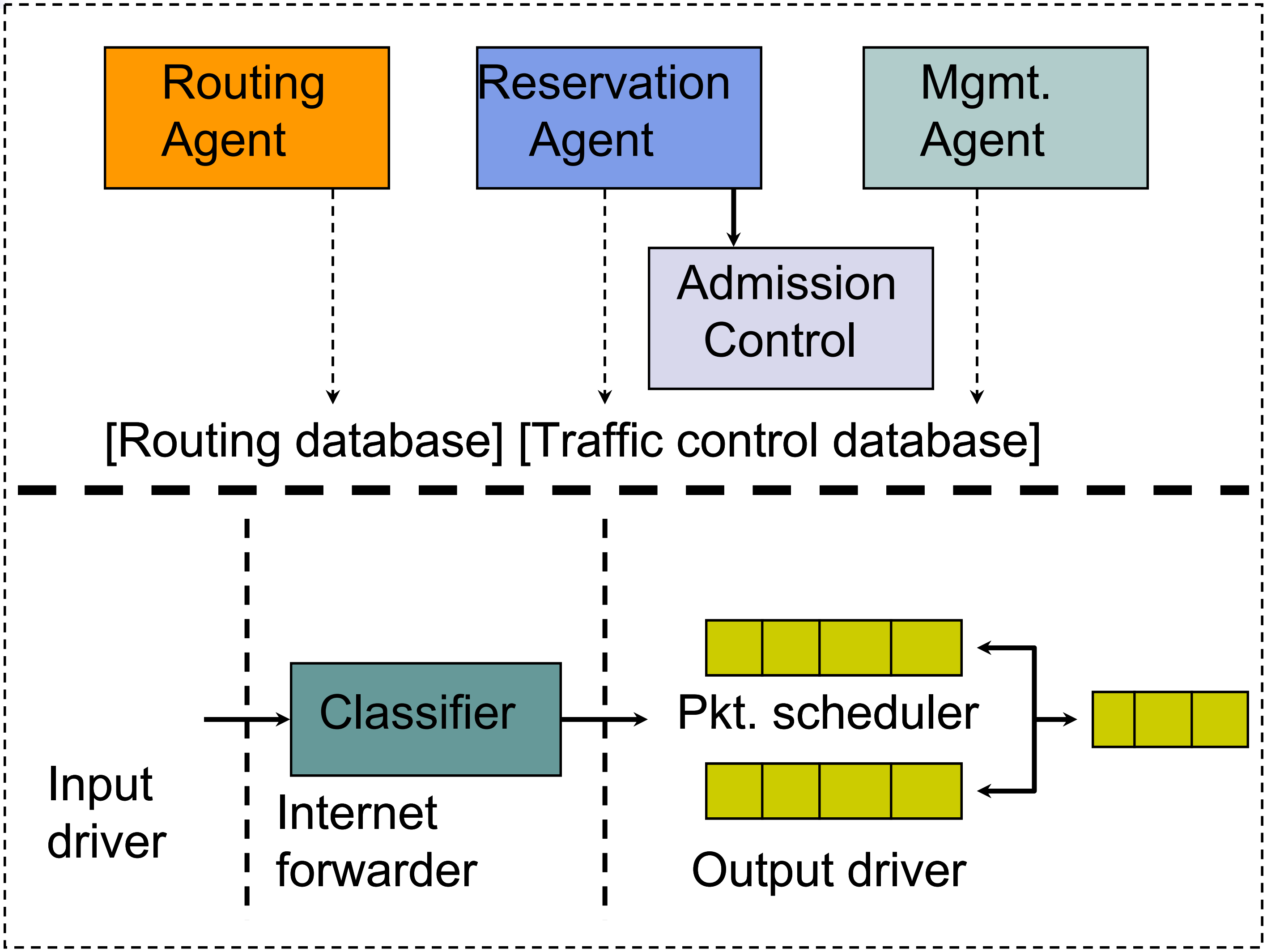
- Assume
  - traffic shaped to parameters b & r
  - schedulers give flow at least rate R>r
  - H hop path
  - m is maximum packet size for the given flow
  - M maximum packet size in the network
  - R_j transmission rate in jth hop
- Maximum end-to-end delay that can be experienced by a packet from flow i is:

$$D \leq \frac{b}{R} + \frac{(H-1)m}{R} + \sum_{j=1}^{H} \frac{M}{R_j}$$

Scheduling for Guaranteed Service

- Suppose guaranteed bounds on end-to-end delay across the network are to be provided
- A call admission control procedure is required to allocate resources & set schedulers
- Traffic flows from sources must be shaped/regulated so that they do not exceed their allocated resources
- Strict delay bounds can be met

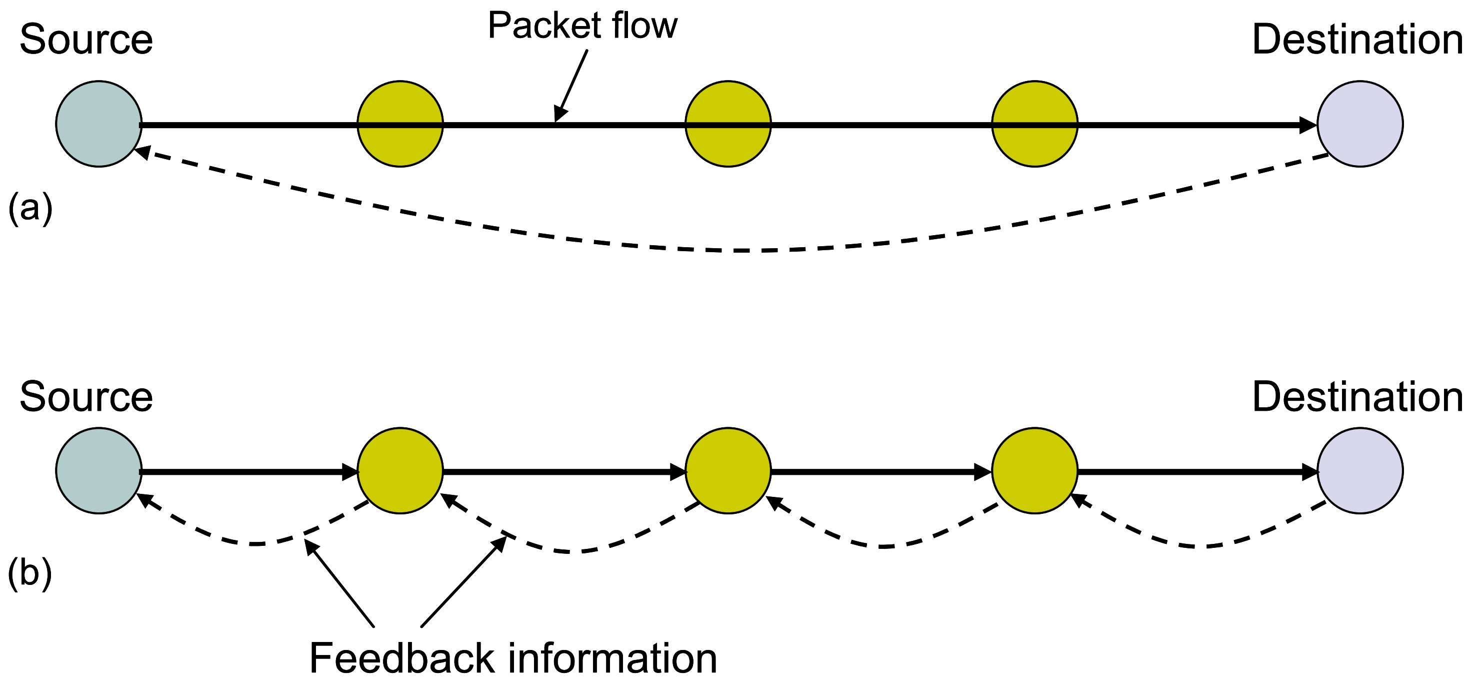
Current View of Router Function



Closed-Loop Flow Control

- Closed-Loop Congestion control
  - feedback information to regulate flow from sources into network
  - Based on buffer content, link utilization, etc.
  - Examples: TCP at transport layer; congestion control at ATM level
- End-to-end vs. Hop-by-hop
  - Delay in effecting control
- Implicit vs. Explicit Feedback
  - Source deduces congestion from observed behavior
  - Routers/switches generate messages alerting to congestion

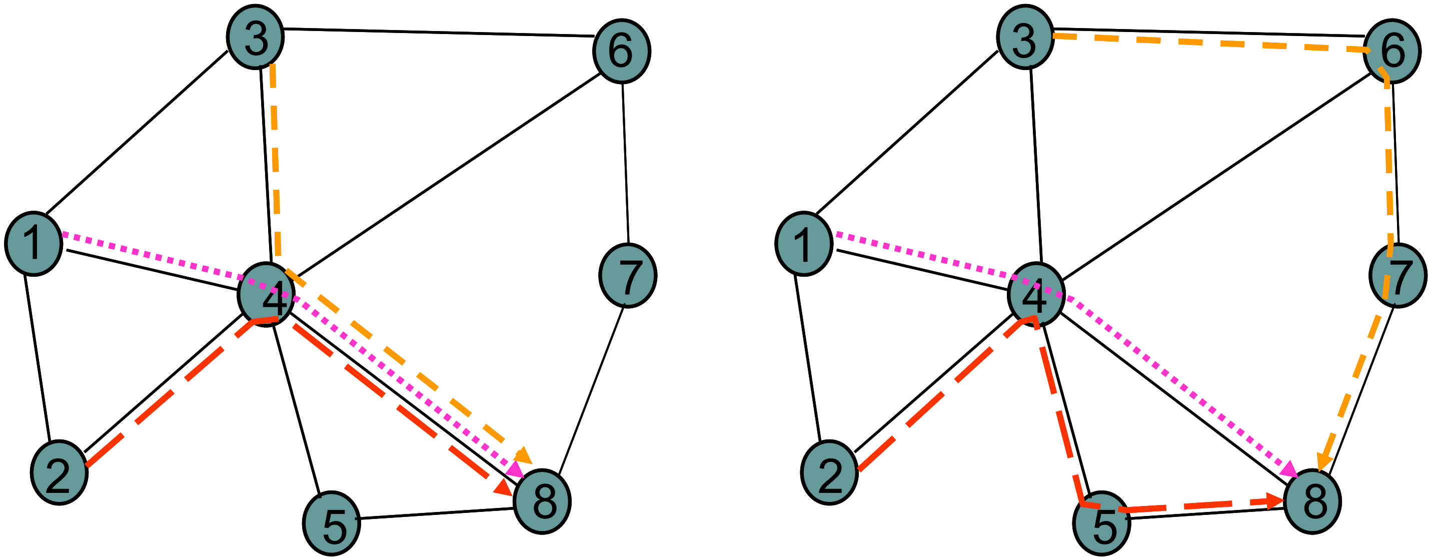
End-to-End vs. Hop-by-Hop Congestion Control



Traffic Engineering

- Management exerted at flow aggregate level
- Distribution of flows in network to achieve efficient utilization of resources (bandwidth)
- Shortest path algorithm to route a given flow not enough
  - Does not take into account requirements of a flow, e.g. bandwidth requirement
  - Does not take account interplay between different flows
- Must take into account aggregate demand from all flows

Example



(a)

(b)

Shortest path routing congests link 4 to 8

Better flow allocation distributes flows more uniformly