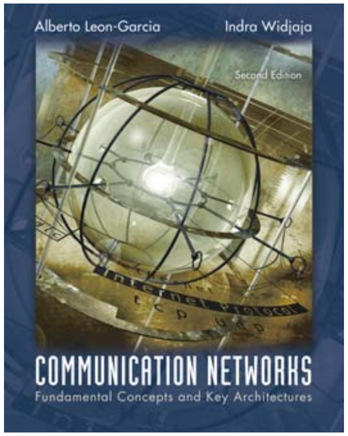
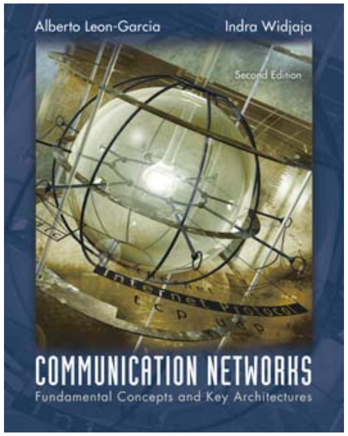
# Chapter 7 Packet-Switching Networks




Network Services and Internal Network Operation
Packet Network Topology
Datagrams and Virtual Circuits
Routing in Packet Networks
Shortest Path Routing
ATM Networks
Traffic Management

# Chapter 7
# Packet-Switching Networks

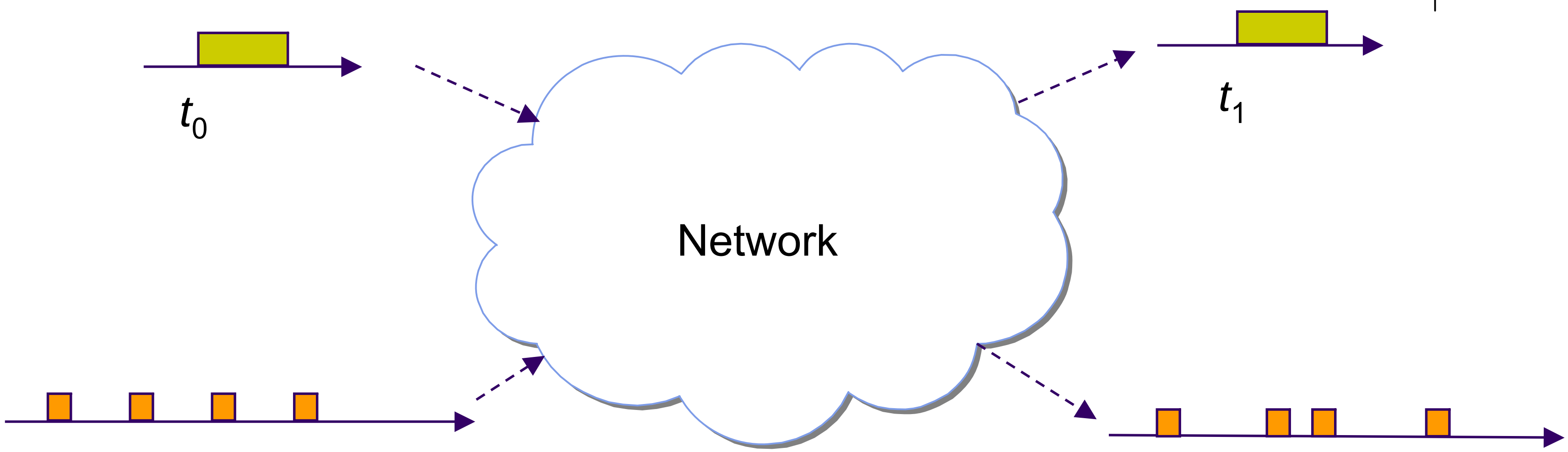



## *Network Services and Internal Network Operation*

# Network Layer

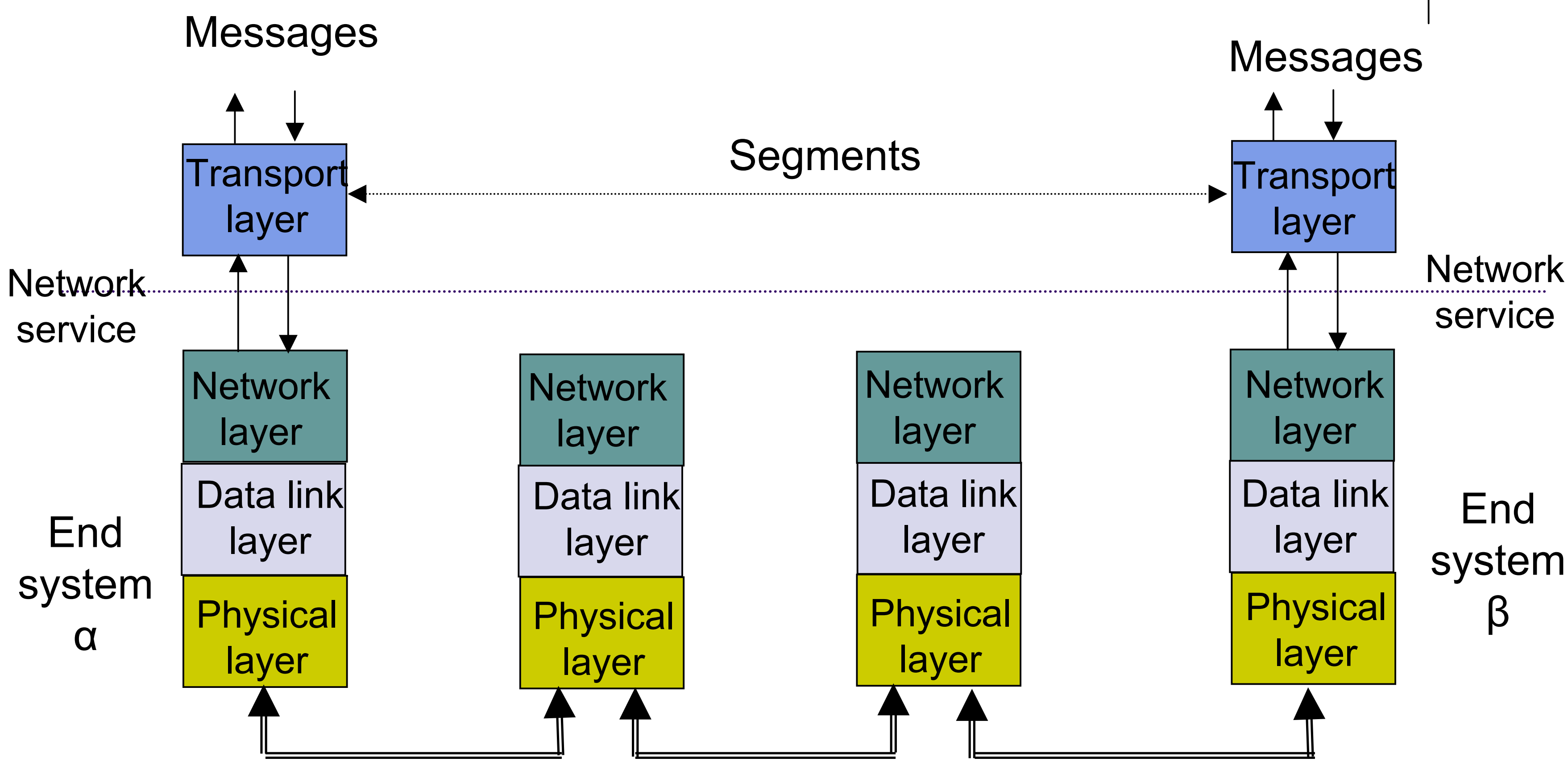
- Network Layer: the most complex layer
  - Requires the coordinated actions of multiple, geographically distributed network elements (switches & routers)
  - Must be able to deal with very large scales
    - Billions of users (people & communicating devices)
  - Biggest Challenges
    - Addressing: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

# Packet Switching




- Transfer of information as payload in data packets
- Packets undergo random delays & possible loss
- Different applications impose differing requirements on the transfer of information

# 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

# Network Service vs. Operation

Network Service

- Connectionless
  - Datagram Transfer
- Connection-Oriented
  - Reliable and possibly constant bit rate transfer

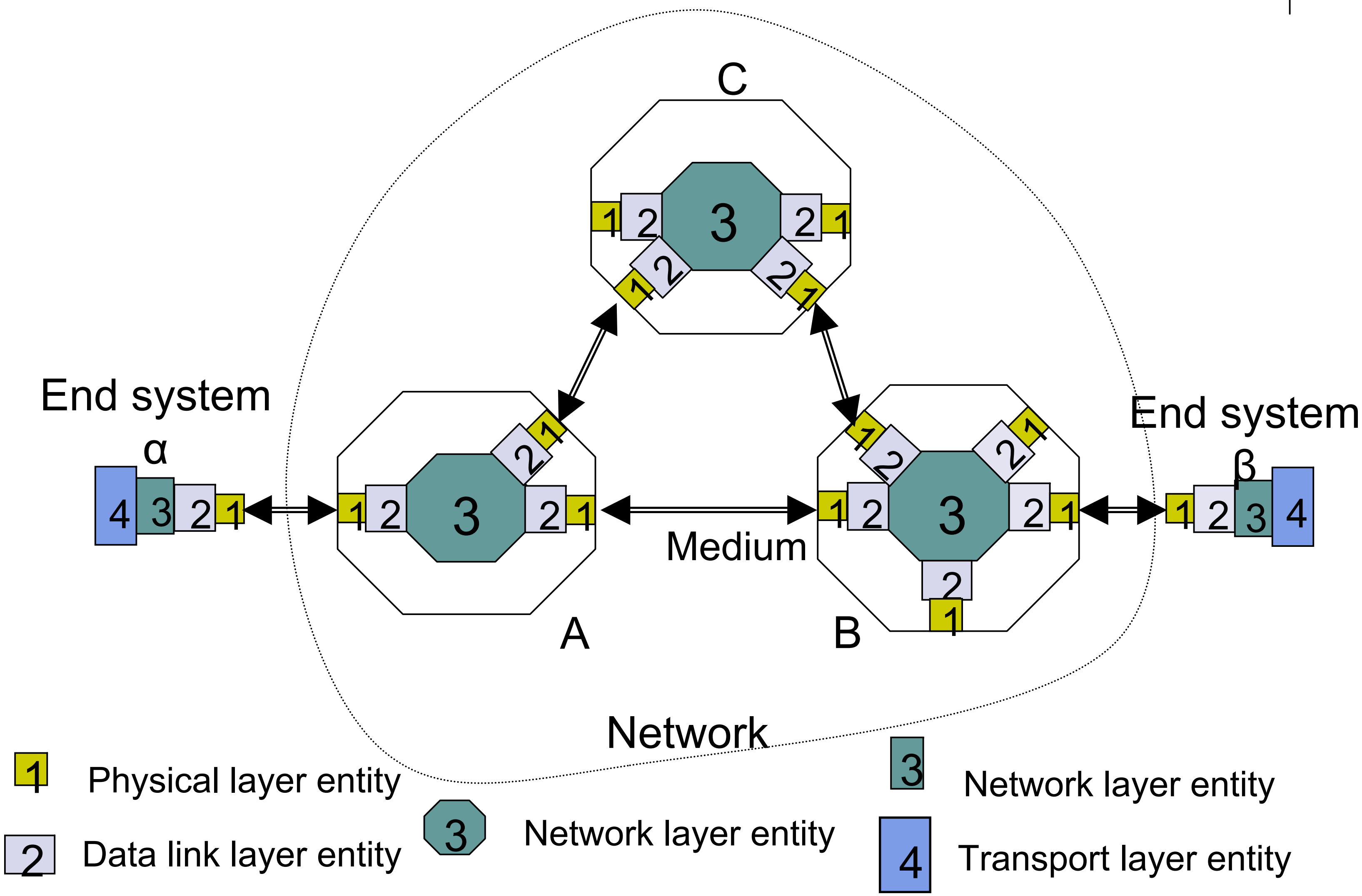
Internal Network Operation

- Connectionless
  - IP
- Connection-Oriented
  - Telephone connection
  - ATM

Various combinations are possible

- Connection-oriented service over Connectionless operation
- Connectionless service over Connection-Oriented operation
- Context & requirements determine what makes sense

# Complexity at the Edge or in the Core?



# 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

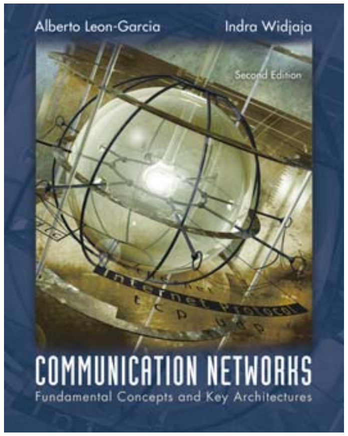
# Network Layer Functions

Essential

- **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

# Chapter 7
# Packet-Switching Networks

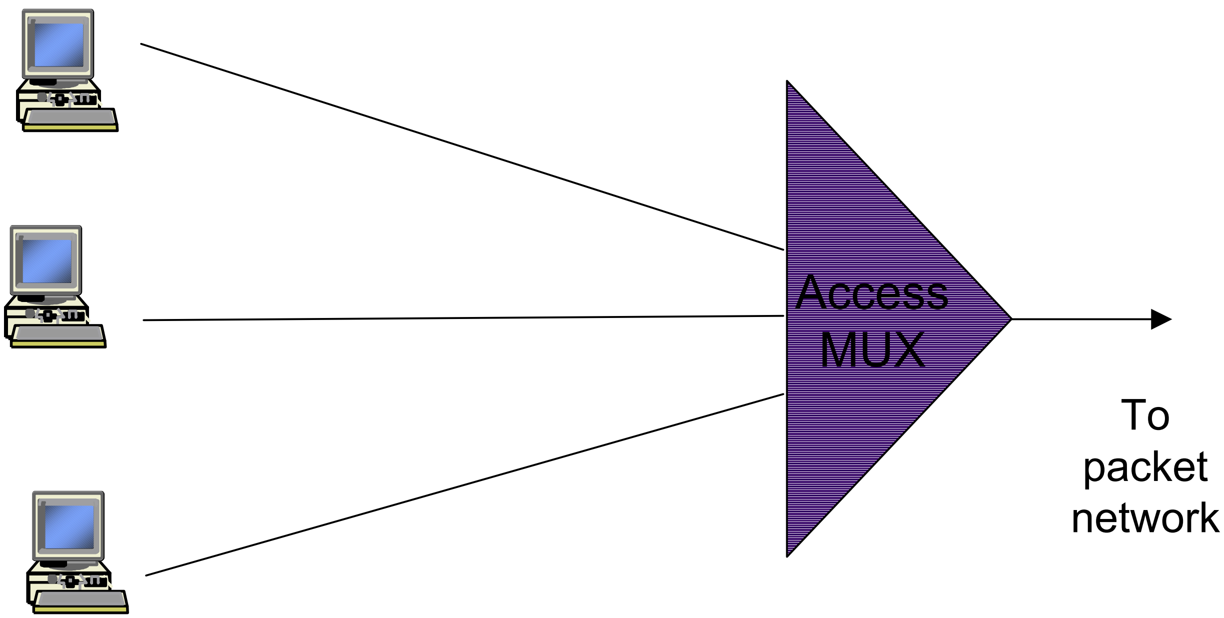



## *Packet Network Topology*

# End-to-End Packet Network

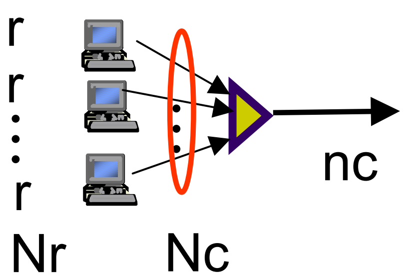
- Packet networks very different than telephone networks
- Individual packet streams are highly bursty
  - Statistical multiplexing is used to concentrate streams
- User demand can undergo dramatic change
  - Peer-to-peer applications stimulated huge growth in traffic volumes
- Internet structure highly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

# Access Multiplexing




- Packet traffic from users multiplexed at access to network into aggregated streams
- DSL traffic multiplexed at DSL Access Mux
- Cable modem traffic multiplexed at Cable Modem Termination System

# Oversubscription

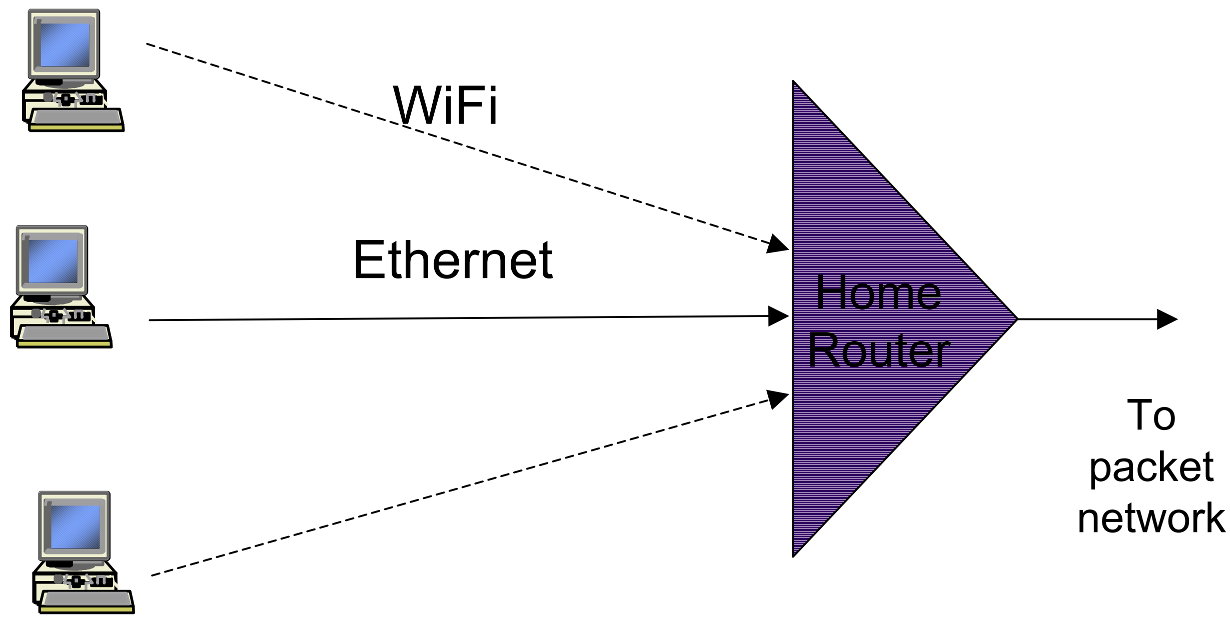



- Access Multiplexer
  - N subscribers connected @ c bps to mux
  - Each subscriber active r/c of time
  - Mux has C=nc bps to network
  - Oversubscription rate:  N/n
  - Find n so that at most 1% overflow probability

*Feasible oversubscription rate increases with size*

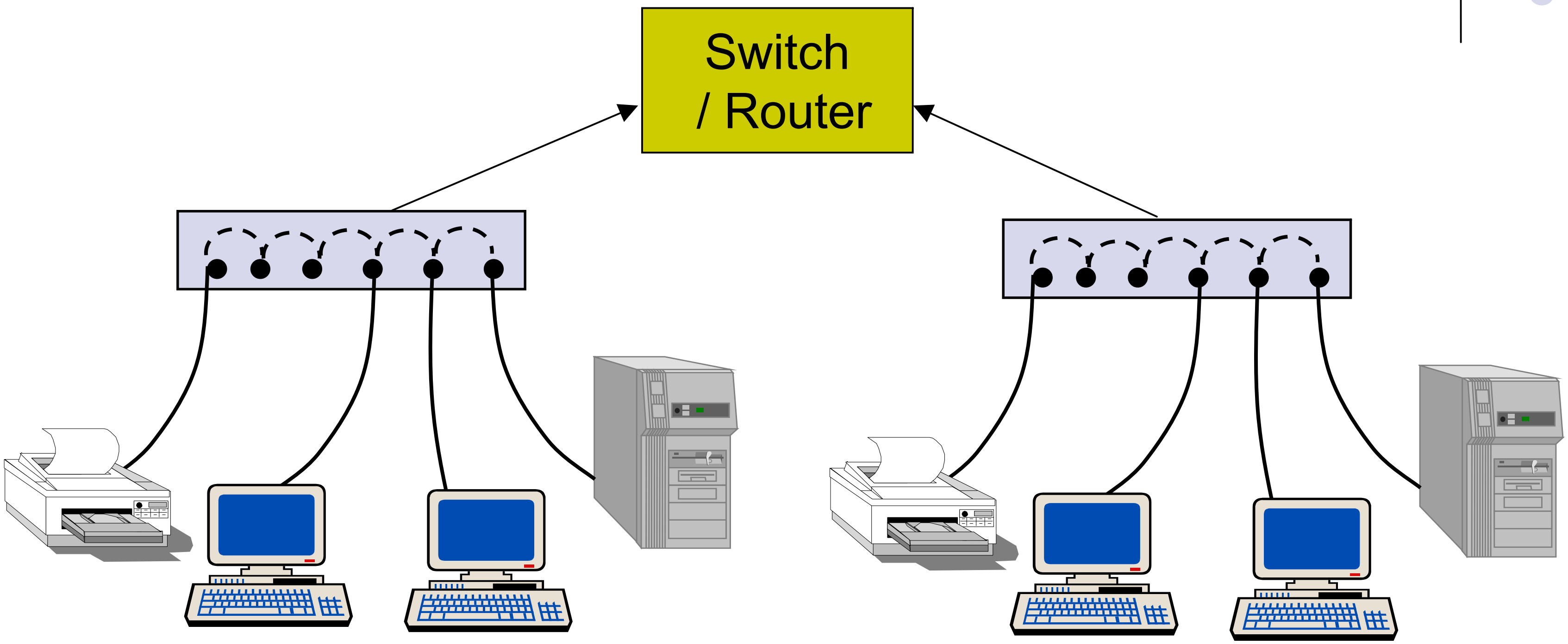
| ***N*** | ***r/c*** | ***n*** | ***N/n*** | |
|---|---|---|---|---|
| 10 | 0.01 | 1 | 10 | 10 extremely lightly loaded users |
| 10 | 0.05 | 3 | 3.3 | 10 very lightly loaded user |
| 10 | 0.1 | 4 | 2.5 | 10 lightly loaded users |
| 20 | 0.1 | 6 | 3.3 | 20 lightly loaded users |
| 40 | 0.1 | 9 | 4.4 | 40 lightly loaded users |
| 100 | 0.1 | 18 | 5.5 | 100 lightly loaded users |

# Home LANs




- Home Router
  - LAN Access using Ethernet or WiFi (IEEE 802.11)
  - Private IP addresses in Home (192.168.0.x) using Network Address Translation (NAT)
  - Single global IP address from ISP issued using Dynamic Host Configuration Protocol (DHCP)

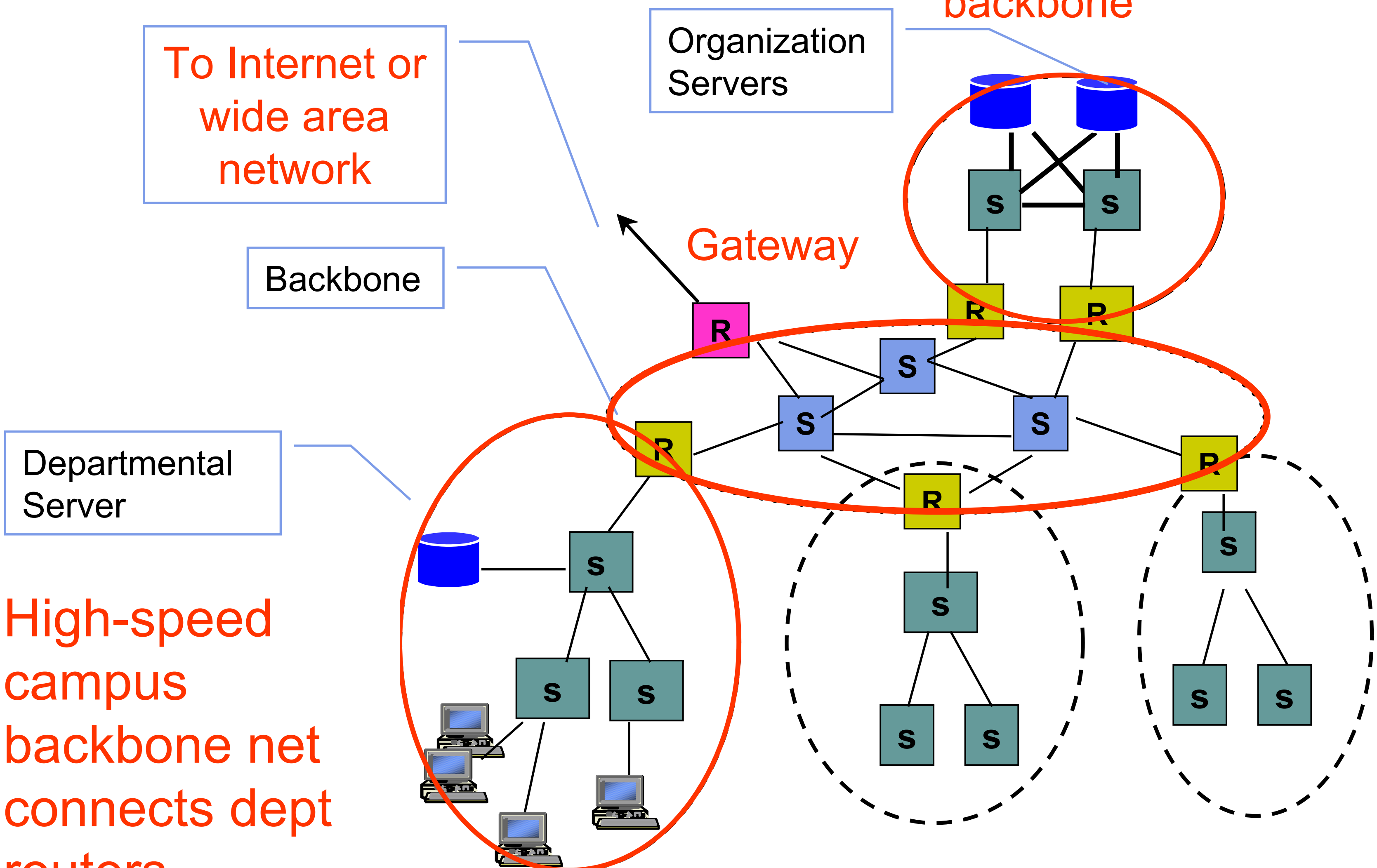
# LAN Concentration




- LAN Hubs and switches in the access network also aggregate packet streams that flows into switches and routers

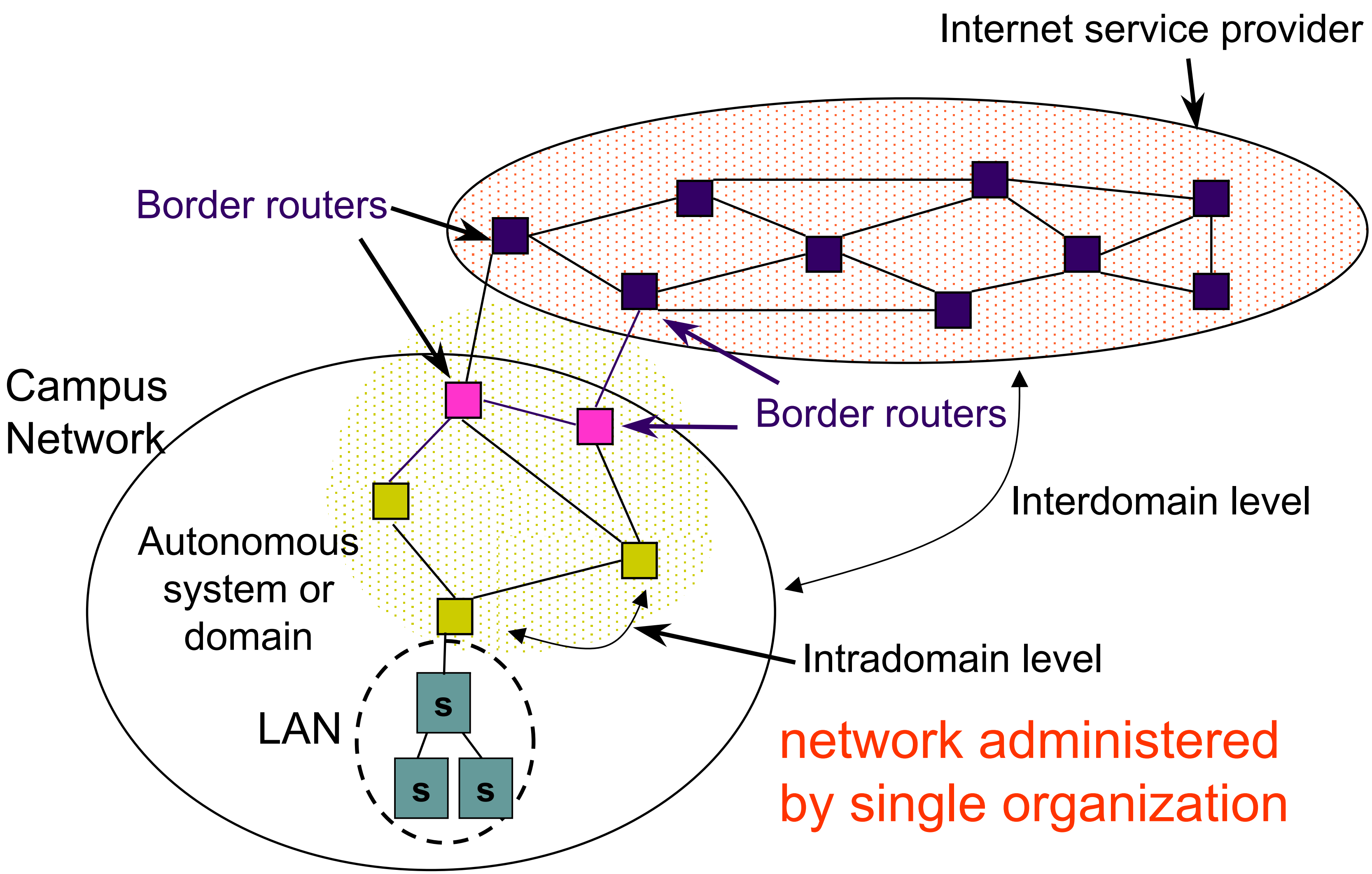
# Campus Network

Servers have redundant connectivity to backbone

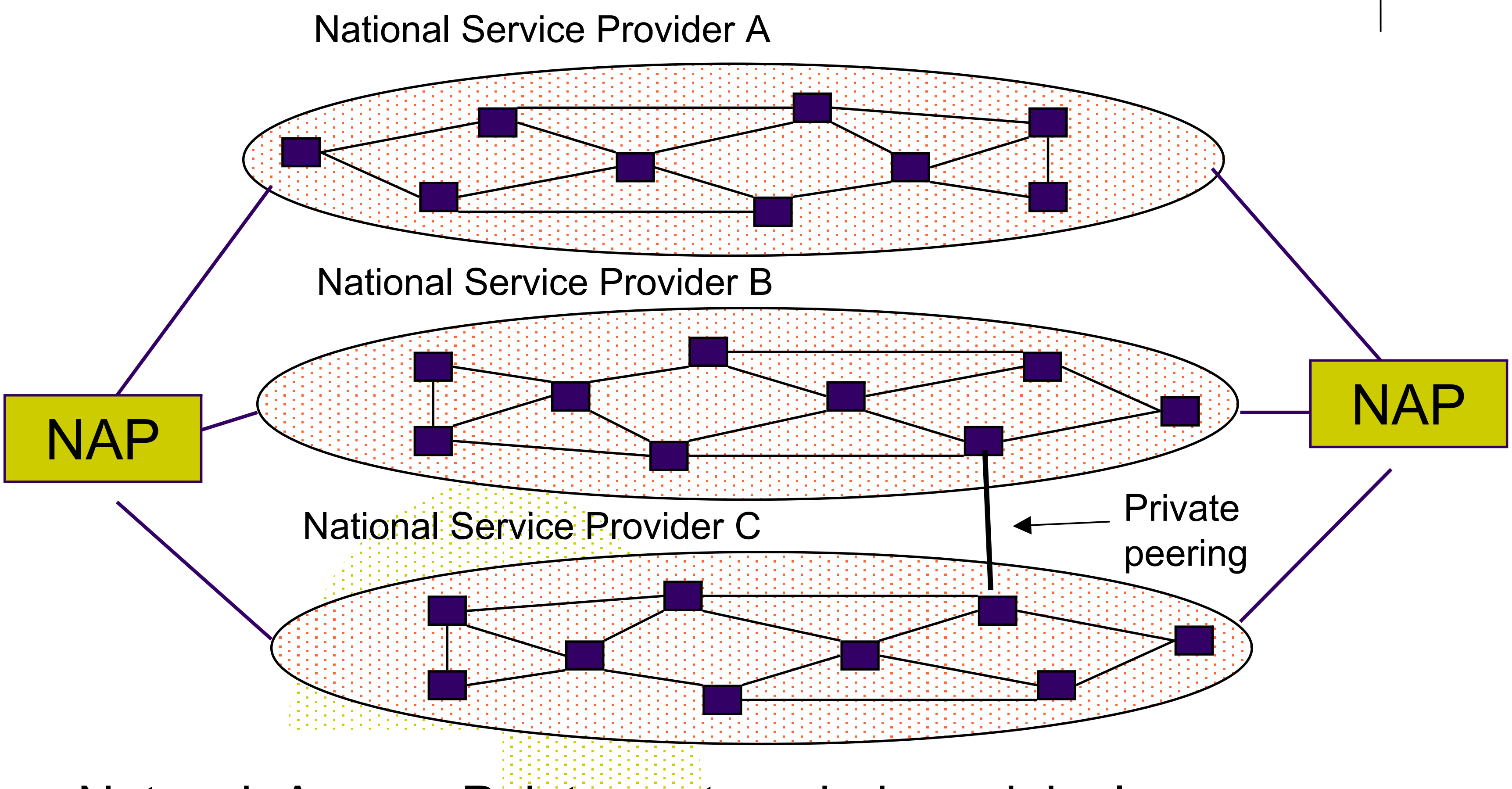



High-speed campus backbone net connects dept routers

# Connecting to Internet Service Provider

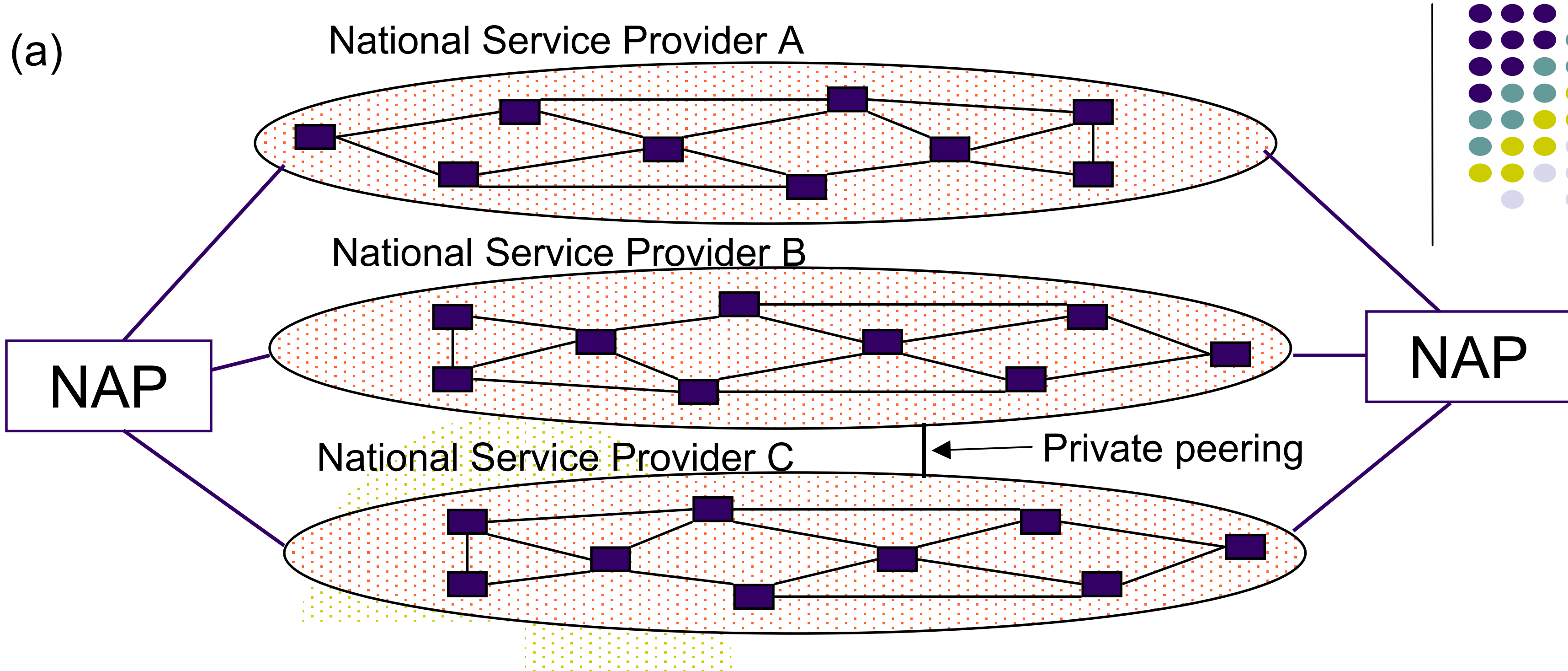


# Internet Backbone

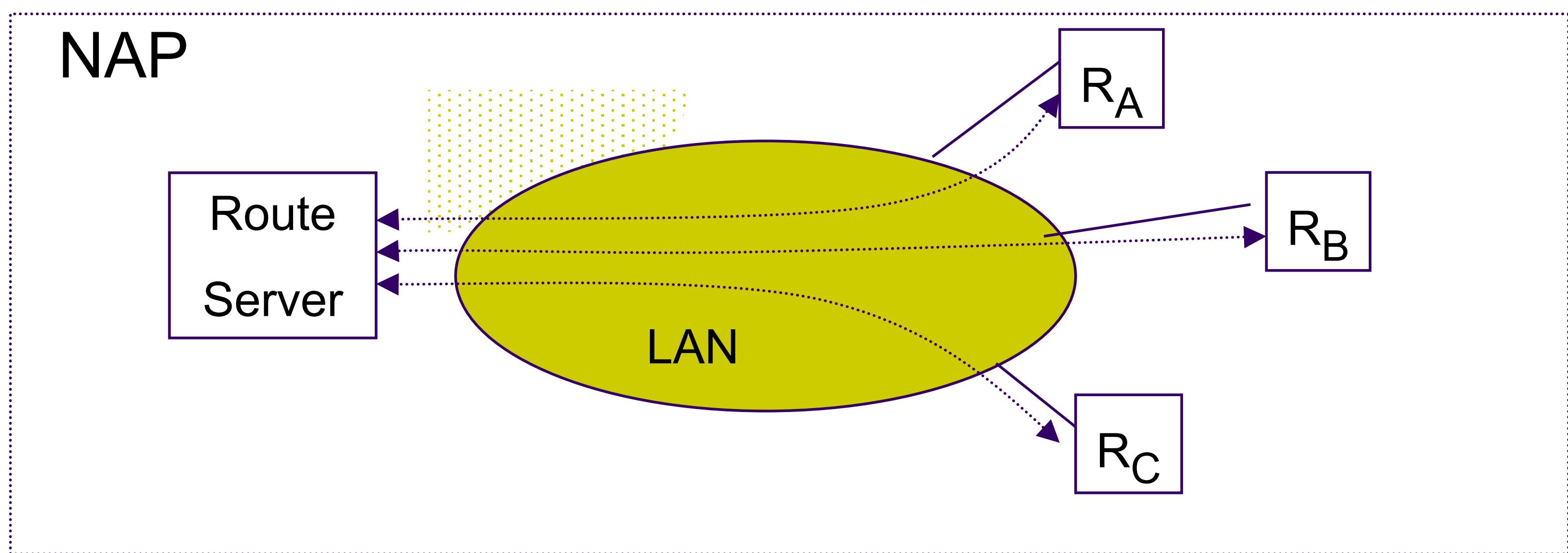



- Network Access Points: set up during original commercialization of Internet to facilitate exchange of traffic
- Private Peering Points: two-party inter-ISP agreements to exchange traffic

(a)


National Service Provider A
National Service Provider B
National Service Provider C
NAP
NAP
Private peering

(b)

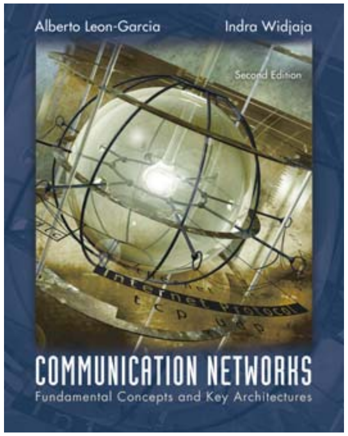

NAP
Route Server
LAN
$R_A$
$R_B$
$R_C$

# Key Role 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

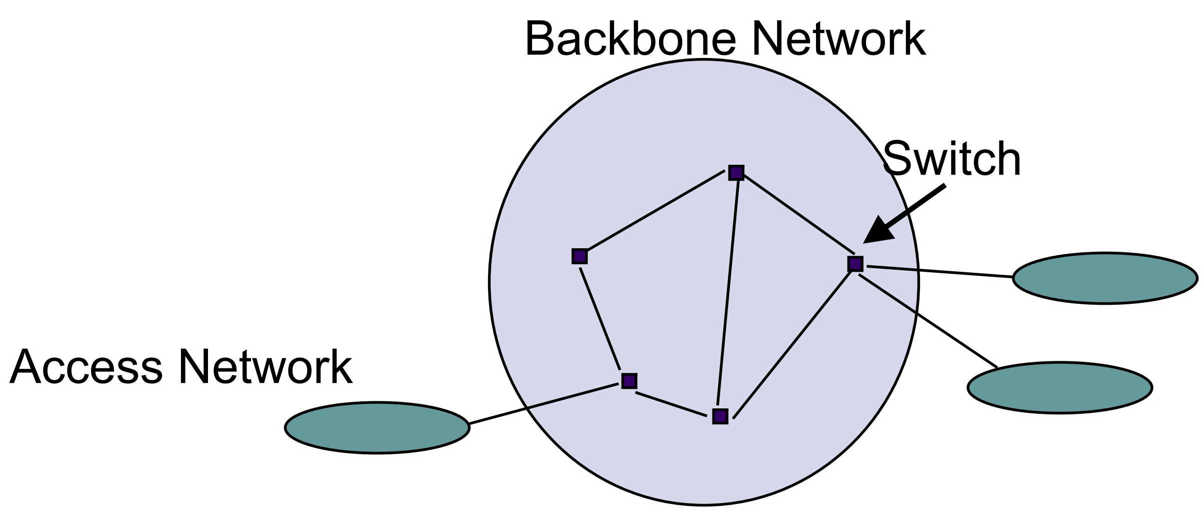
# Chapter 7
# Packet-Switching Networks



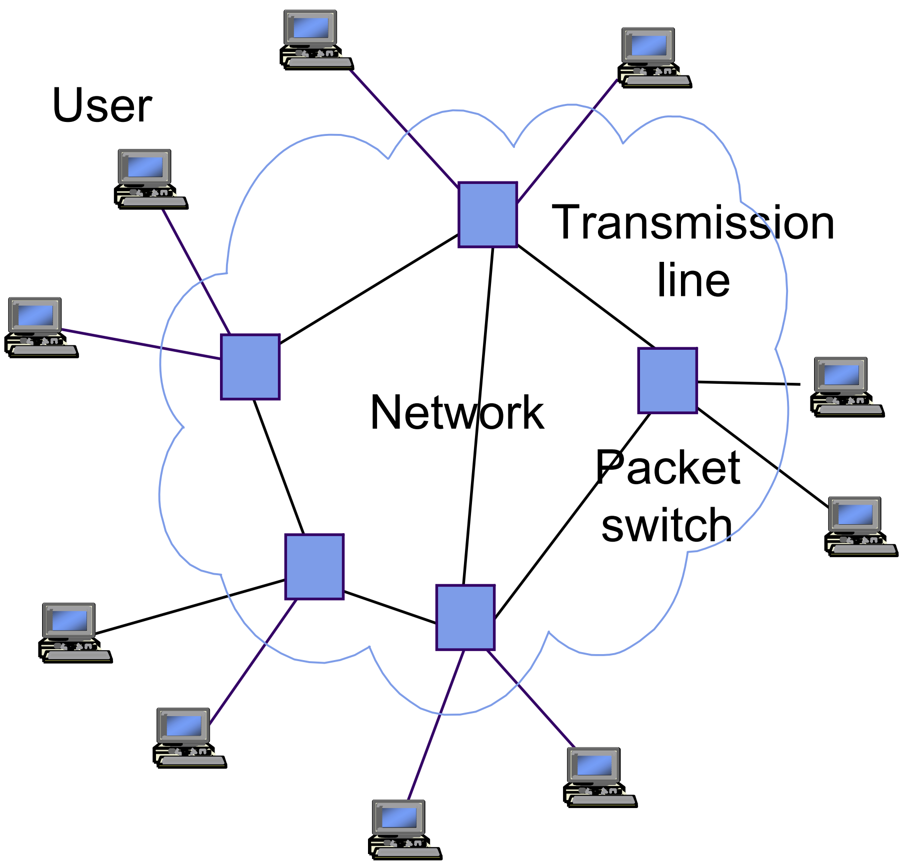

## *Datagrams and Virtual Circuits*

# The Switching Function

- Dynamic interconnection of inputs to outputs
- Enables dynamic sharing of transmission resource
- Two fundamental approaches:
  - Connectionless
  - Connection-Oriented:  Call setup control, Connection control



# Packet Switching Network



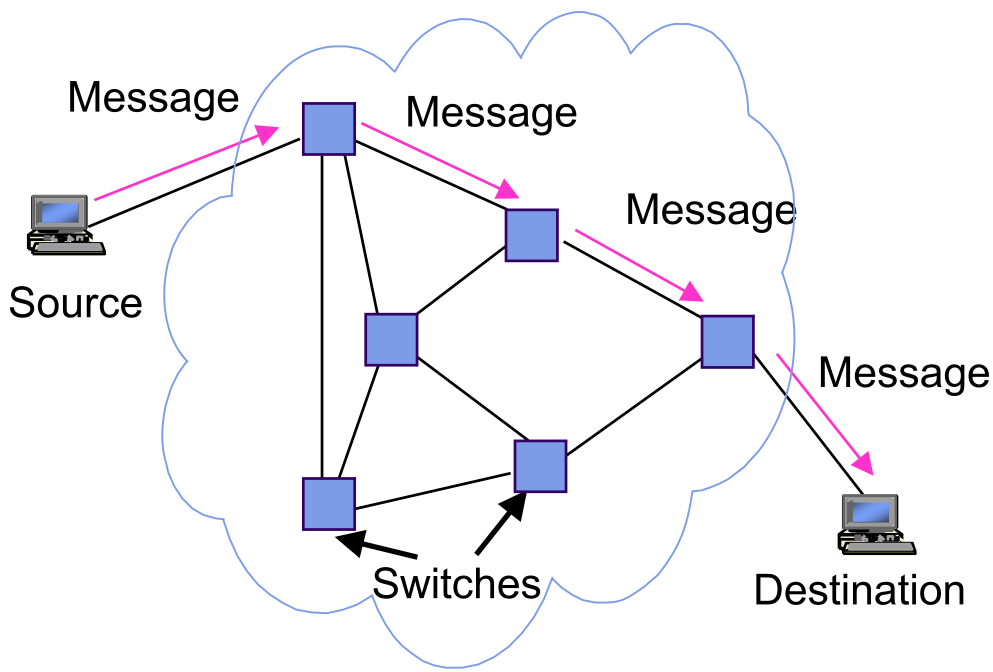

Packet switching network

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

Two modes of operation:

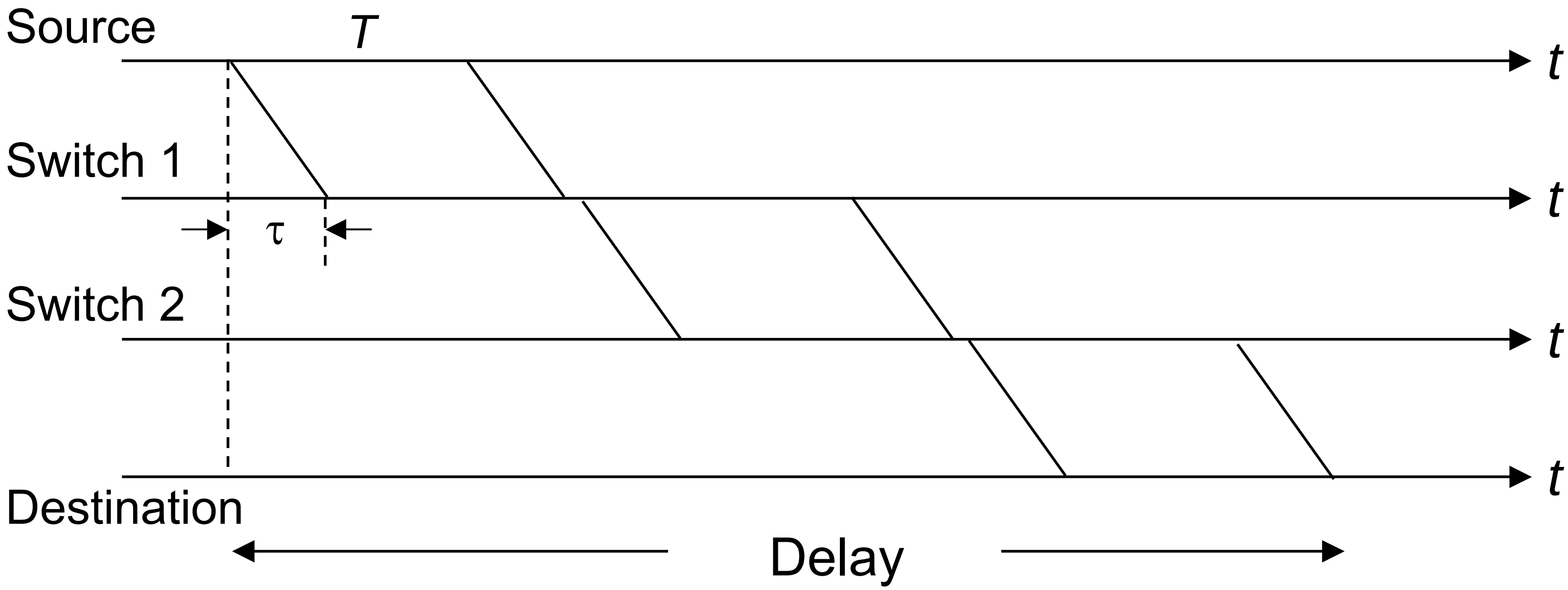
- Connectionless
- Virtual Circuit

# Message Switching




- Message switching invented for telegraphy
- Entire messages multiplexed onto shared lines, stored & forwarded
- Headers for source & destination addresses
- Routing at message switches
- Connectionless

# Message Switching Delay

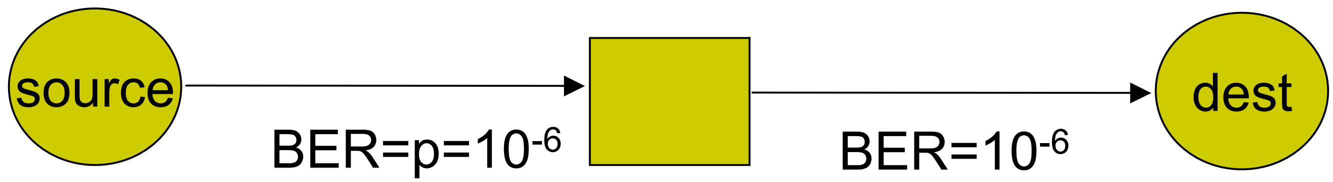



Minimum delay = $3\tau + 3T$

Additional queueing delays possible at each link

# Long Messages vs. Packets

1 Mbit message




How many bits need to be transmitted to deliver message?

- Approach 1: send 1 Mbit message
- Probability message arrives correctly

$$P_c = (1-10^{-6})^{10^6} \approx e^{-10^6 10^{-6}} = e^{-1} \approx 1/3$$

- On average it takes about 3 transmissions/hop
- Total # bits transmitted ≈ 6 Mbits

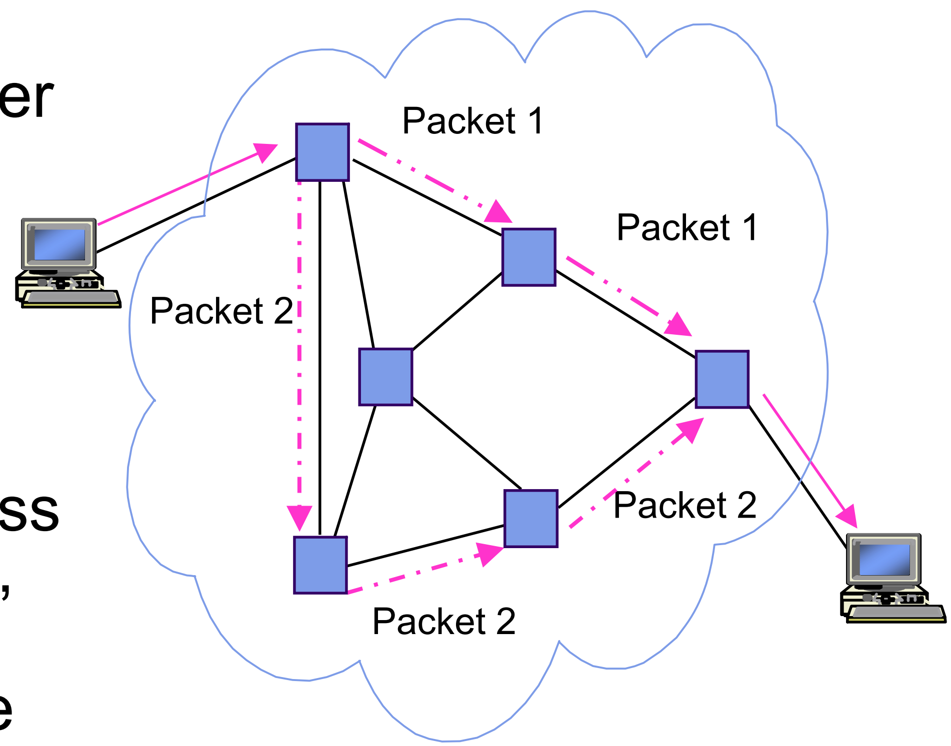
- Approach 2: send 10 100-kbit packets
- Probability packet arrives correctly

$$P_c' = (1-10^{-6})^{10^5} \approx e^{-10^5 10^{-6}} = e^{-0.1} \approx 0.9$$

- On average it takes about 1.1 transmissions/hop
- Total # bits transmitted ≈ 2.2 Mbits

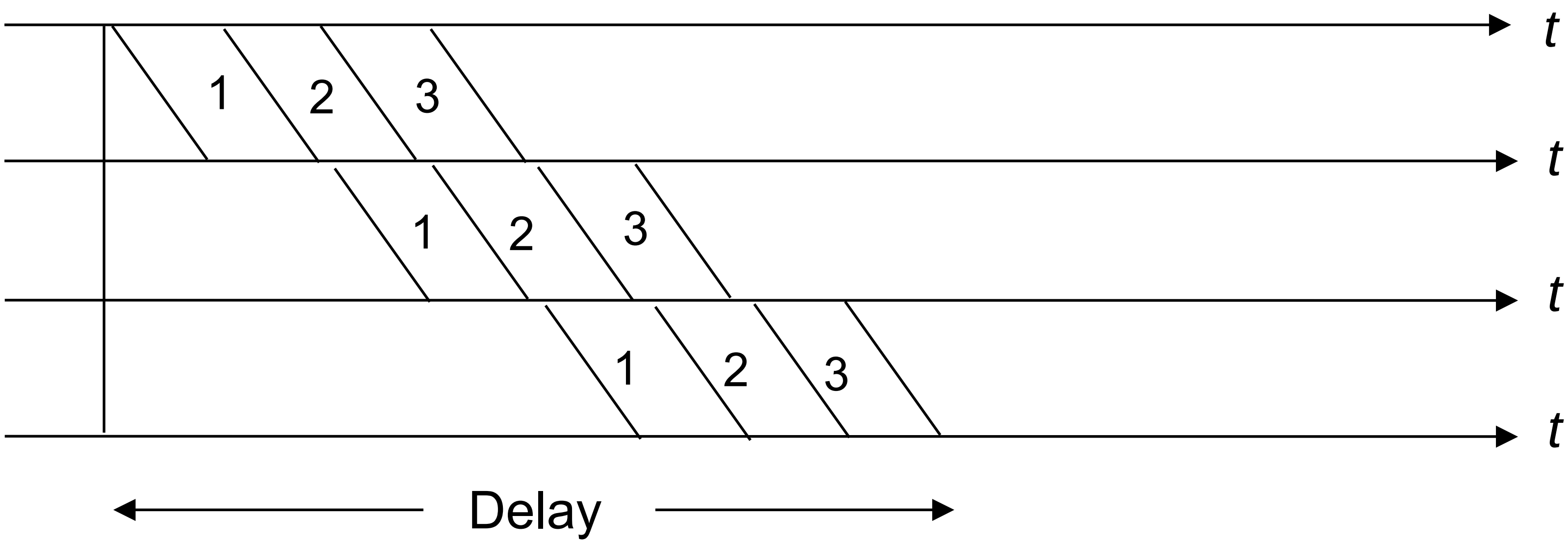
# Packet Switching - Datagram

- 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 that message switching, suitable for interactive traffic



# Packet Switching Delay

Assume three packets corresponding to one message traverse same path

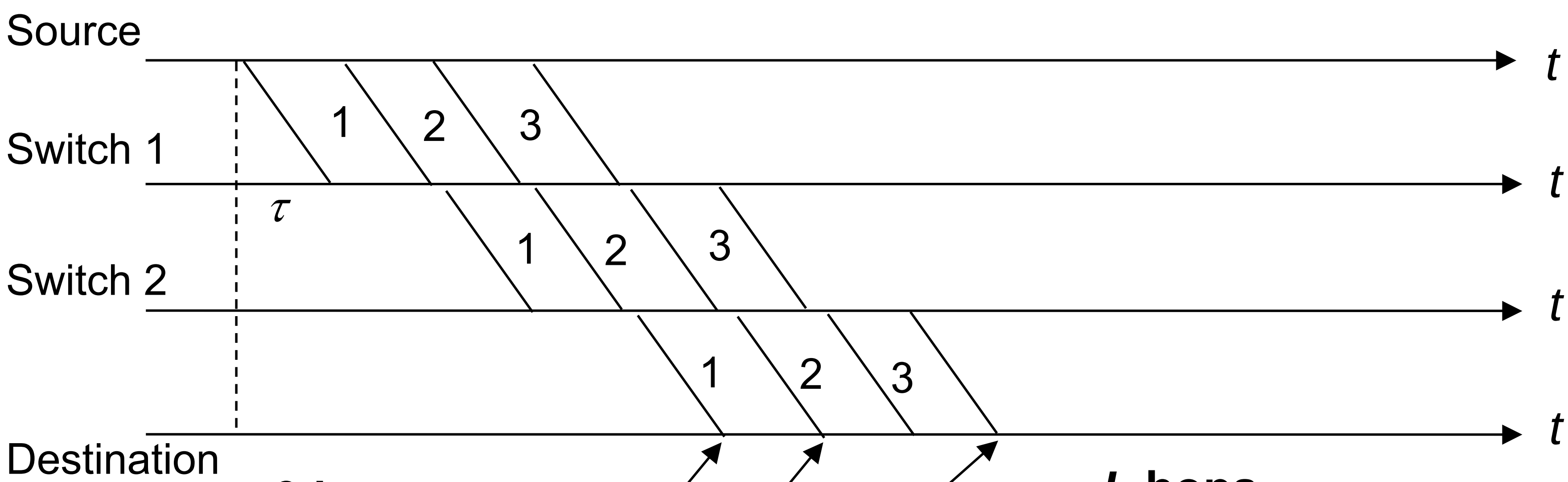



Minimum Delay = $3\tau + 5(T/3)$  (single path assumed)

Additional queueing delays possible at each link

Packet pipelining enables message to arrive sooner

# Delay for k-Packet Message over L Hops




**3 hops**

$3\tau + 2(T/3)$ first bit received

$3\tau + 3(T/3)$ first bit released

$3\tau + 5(T/3)$ last bit released

***L* hops**

$L\tau + (L-1)P$ first bit received

$L\tau + LP$ first bit released

$L\tau + LP + (k-1)P$ last bit released

where $T = k\,P$

# Routing Tables in Datagram Networks

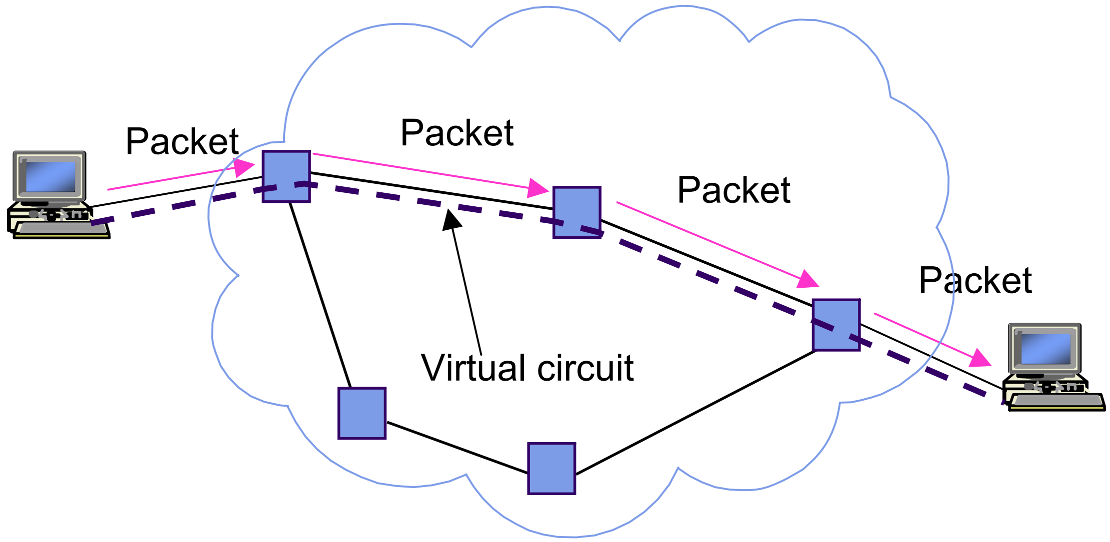
| Destination address | Output port |
|---|---|
| | |
| 0785 | 7 |
| | |
| 1345 | 12 |
| | |
| 1566 | 6 |
| | |
| 2458 | 12 |
| | |

- 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

# Example: Internet Routing

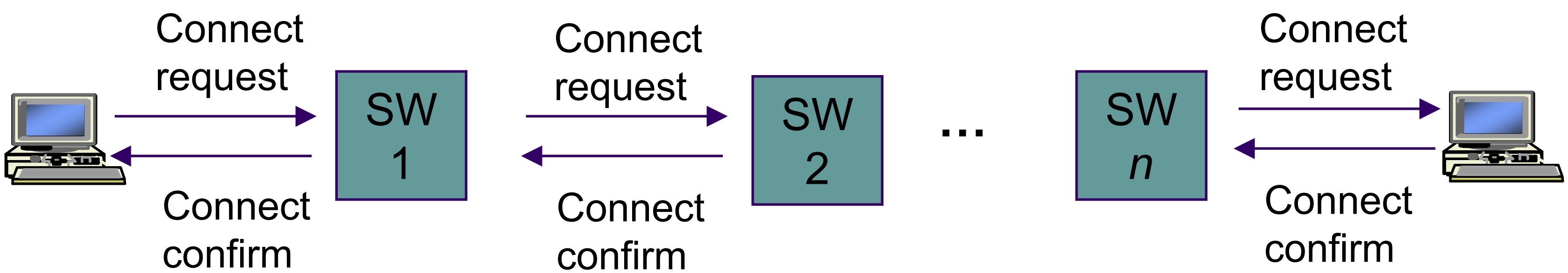
- Internet protocol uses datagram packet switching *across networks*
  - Networks are treated as data links
- Hosts have two-port IP address:
  - Network address + Host address
- Routers do table lookup on network address
  - This reduces size of routing table
- In addition, network addresses are assigned so that they can also be aggregated
  - Discussed as CIDR in Chapter 8

# Packet Switching – Virtual Circuit



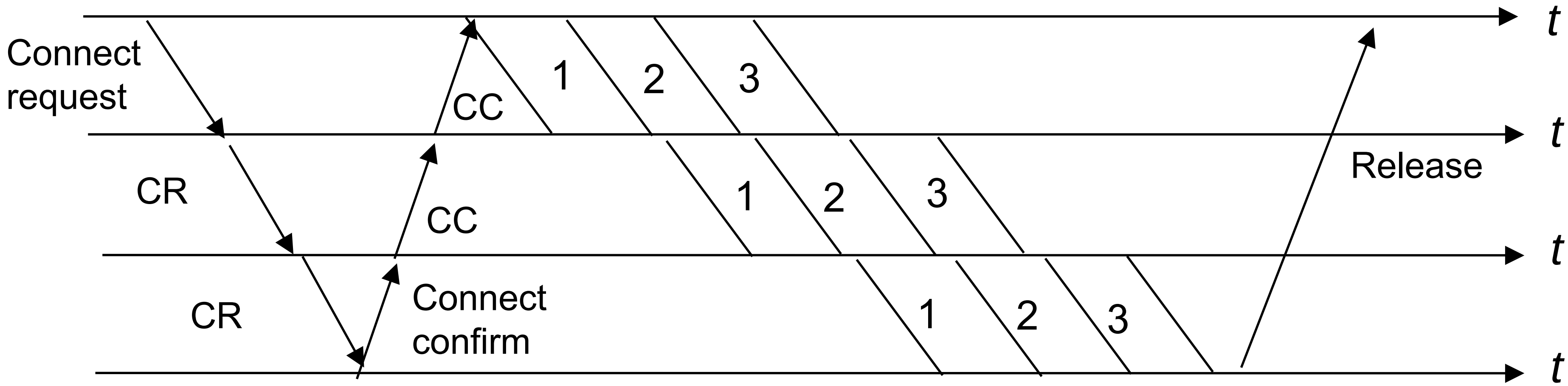

- Call set-up phase sets ups pointers in fixed path along network
- All packets for a connection follow the same path
- Abbreviated header identifies connection on each link
- Packets queue for transmission
- Variable bit rates possible, negotiated during call set-up
- Delays variable, cannot be less than circuit switching

# Connection Setup




- Signaling messages propagate as route is selected
- Signaling messages identify connection and setup tables in switches
- Typically a connection is identified by a local tag, Virtual Circuit Identifier (VCI)
- Each switch only needs to know how to relate an incoming tag in one input to an outgoing tag in the corresponding output
- Once tables are setup, packets can flow along path

# Connection Setup Delay



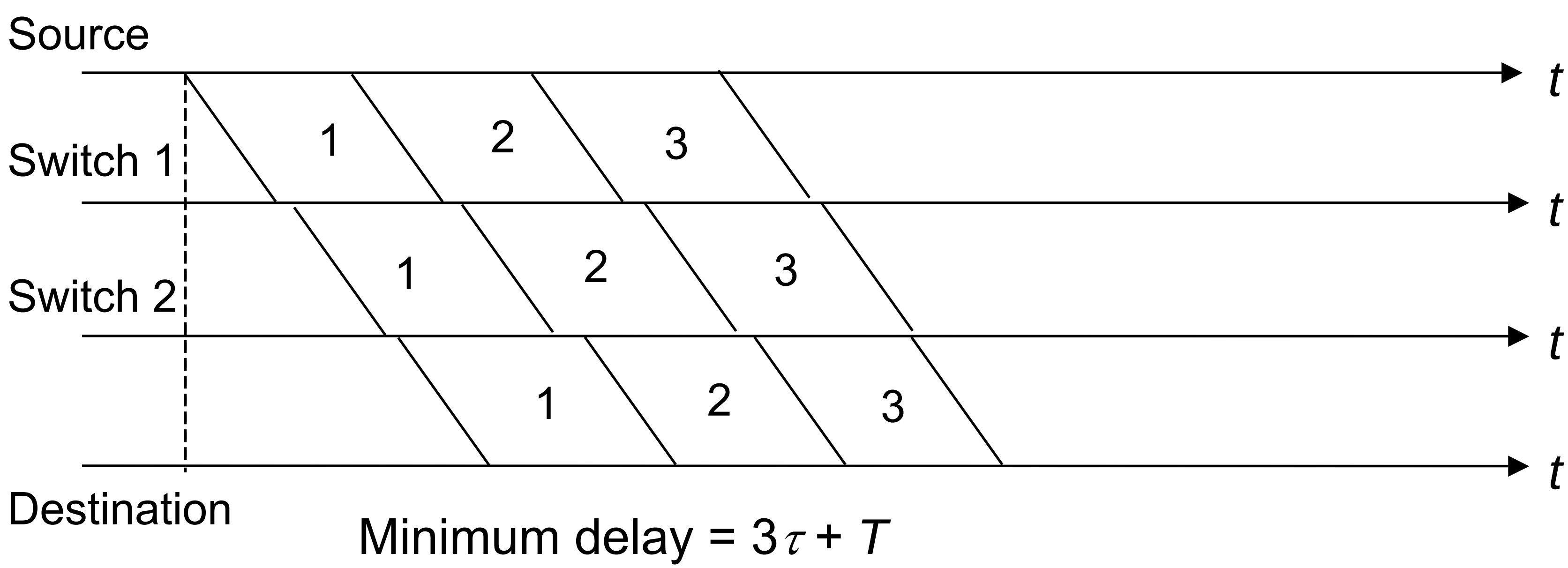

- Connection setup delay is incurred before any packet can be transferred
- Delay is acceptable for sustained transfer of large number of packets
- This delay may be unacceptably high if only a few packets are being transferred

# Virtual Circuit Forwarding Tables

| Input VCI | Output port | Output VCI |
|---|---|---|
| 12 | 13 | 44 |
| 15 | 15 | 23 |
| 27 | 13 | 16 |
| 58 | 7 | 34 |

- Each input port of packet switch has a forwarding table
- Lookup entry for VCI of incoming packet
- Determine output port (next hop) and insert VCI for next link
- Very high speeds are possible
- Table can also include priority or other information about how packet should be treated

# Cut-Through switching




- Some networks perform error checking on header only, so packet can be forwarded as soon as header is received & processed
- Delays reduced further with cut-through switching

# Message vs. Packet Minimum Delay

- Message:

  $L\ \tau + L\ T \qquad = L\ \tau + (L-1)\ T + T$

- Packet

  $L\ \tau + L\ P + (k-1)\ P \qquad = L\ \tau + (L-1)\ P + T$

- Cut-Through Packet (Immediate forwarding after header)

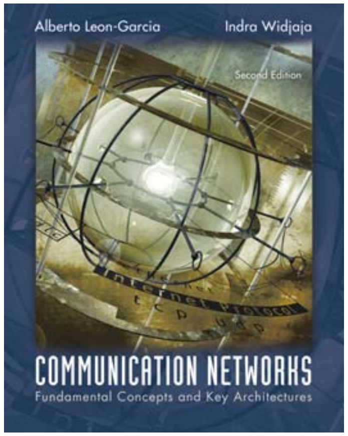
  $= L\ \tau + T$

Above neglect header processing delays

# Example: ATM Networks

- All information mapped into short fixed-length packets called *cells*
- Connections set up across network
  - Virtual circuits established across networks
  - Tables setup at ATM switches
- Several types of network services offered
  - Constant bit rate connections
  - Variable bit rate connections

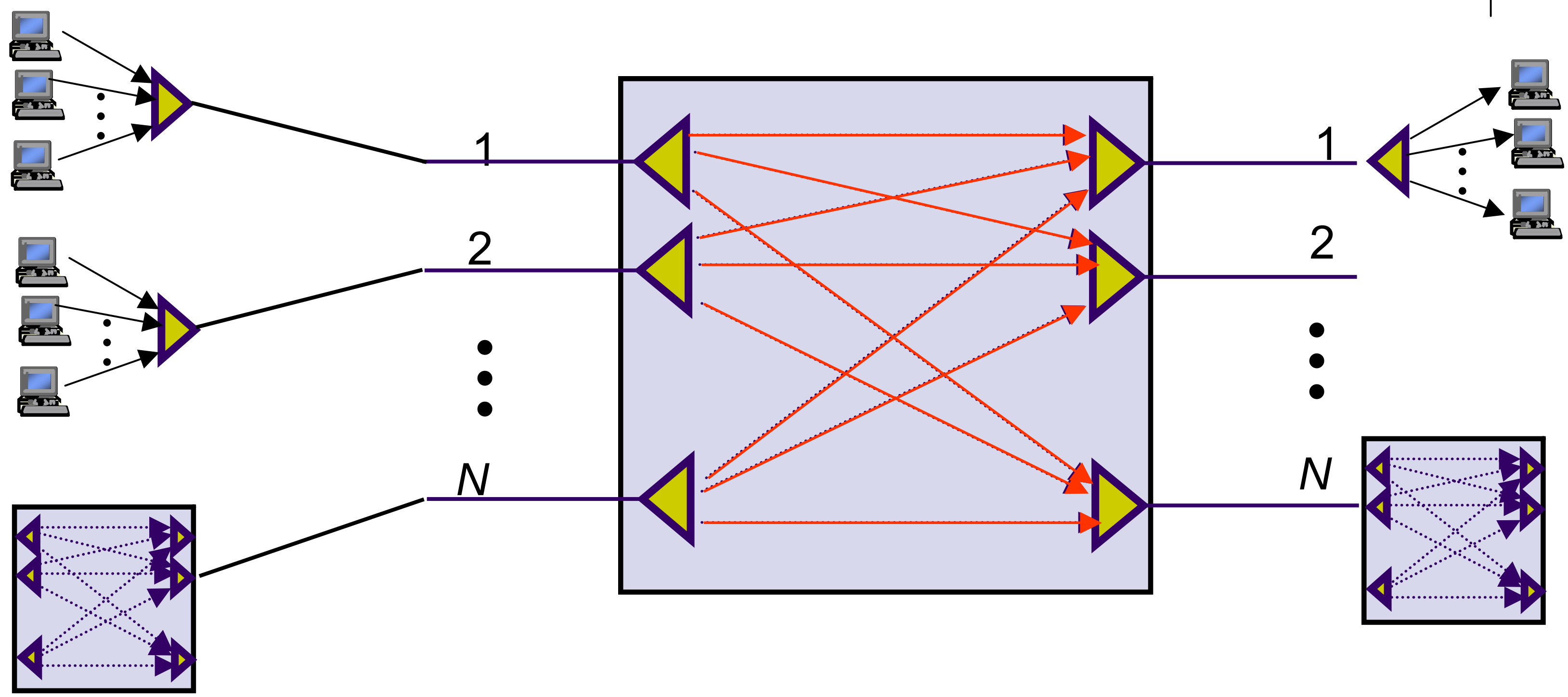
# Chapter 7
# Packet-Switching Networks




## *Datagrams and Virtual Circuits*

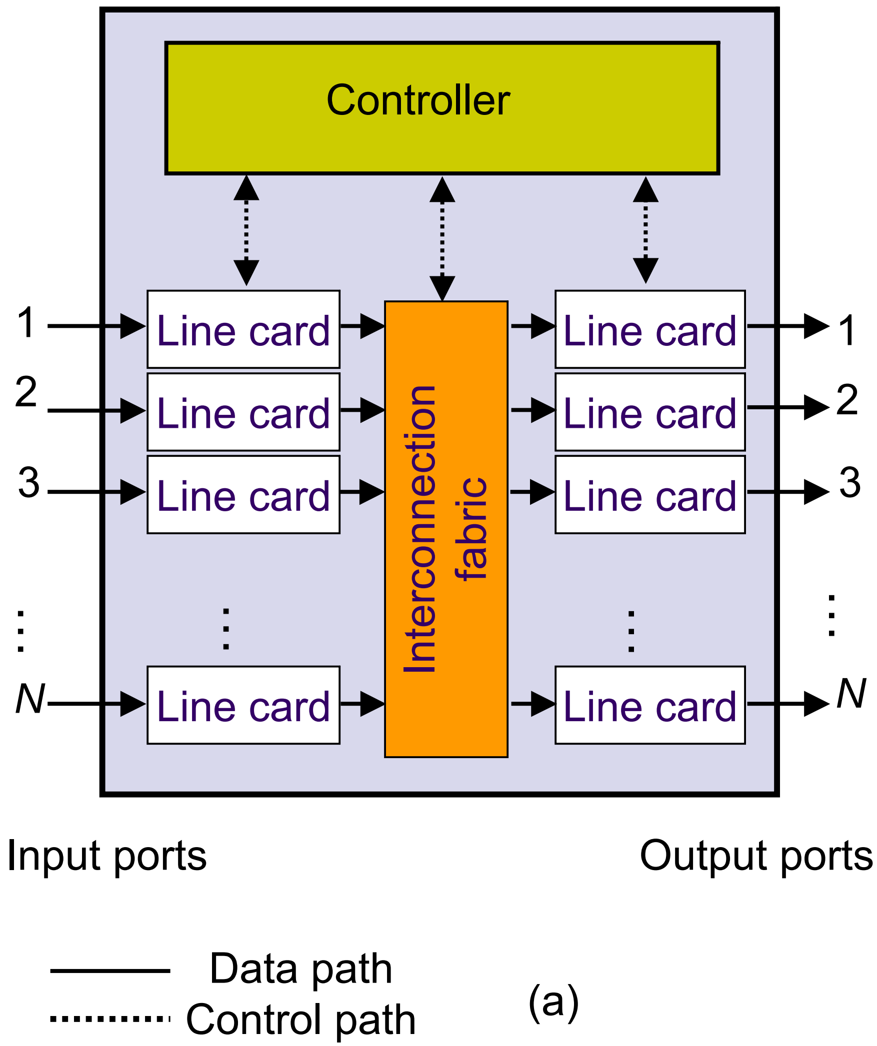
## *Structure of a Packet Switch*

# 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

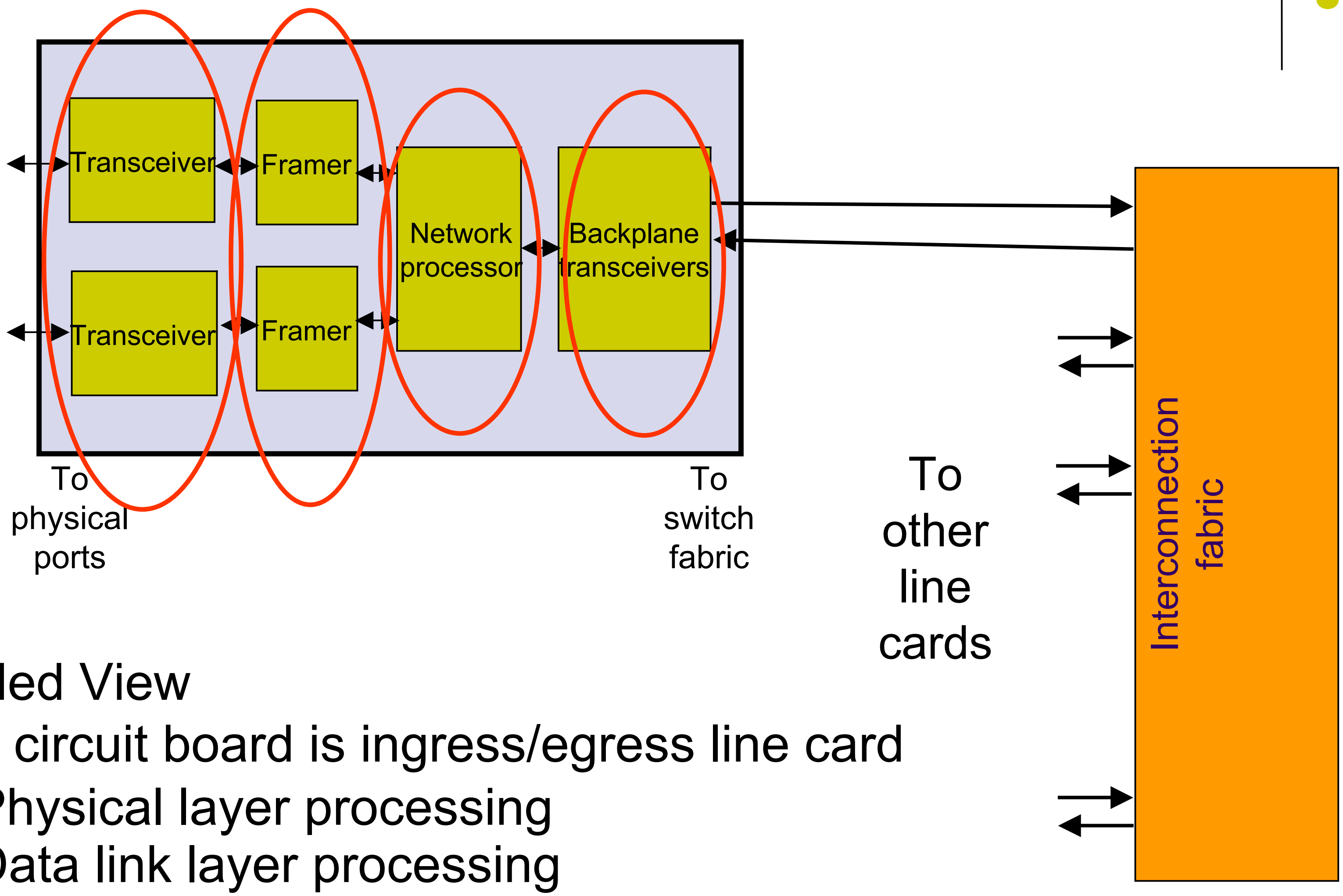


(a)

"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

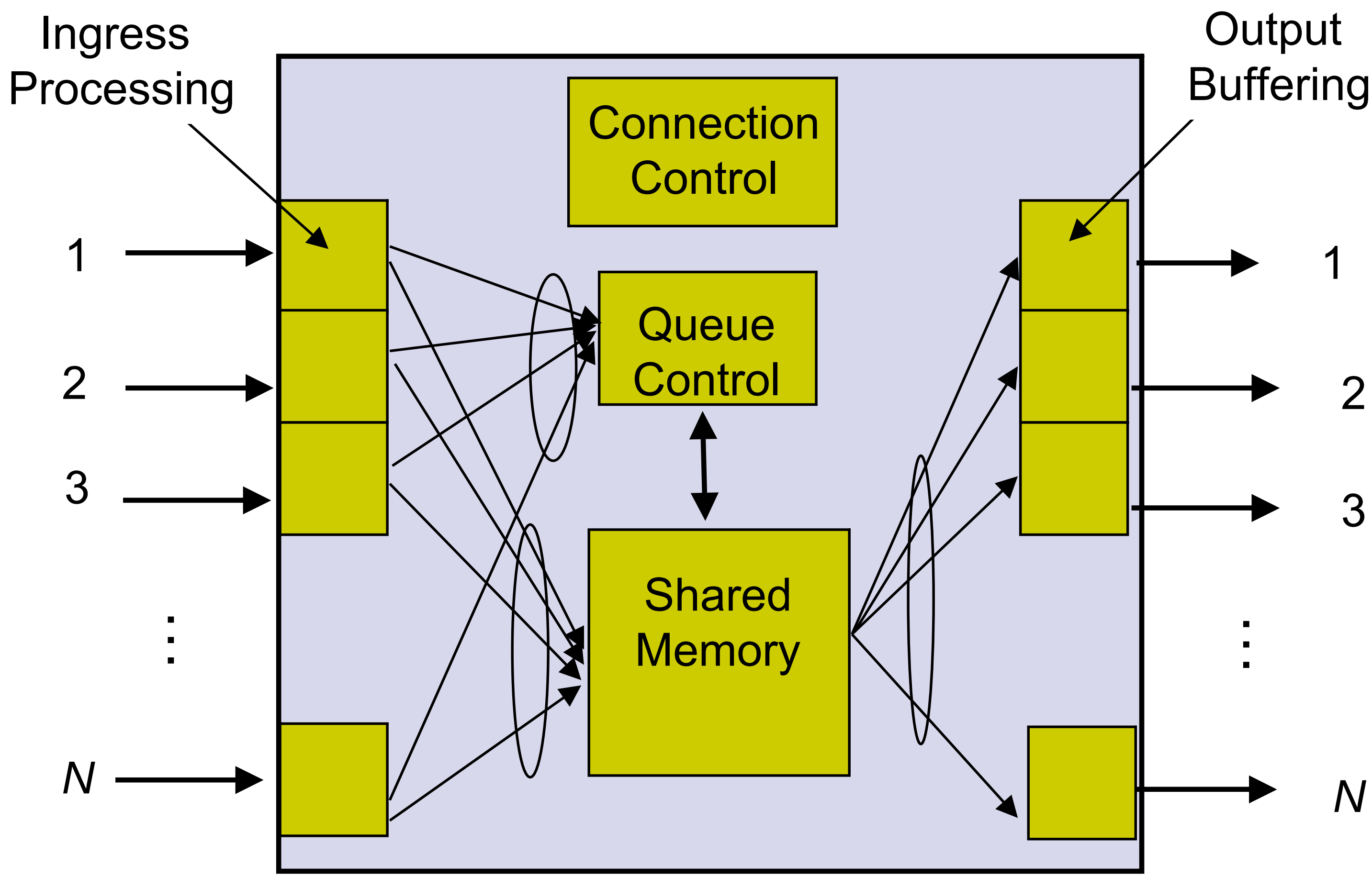
# Line Cards




Folded View

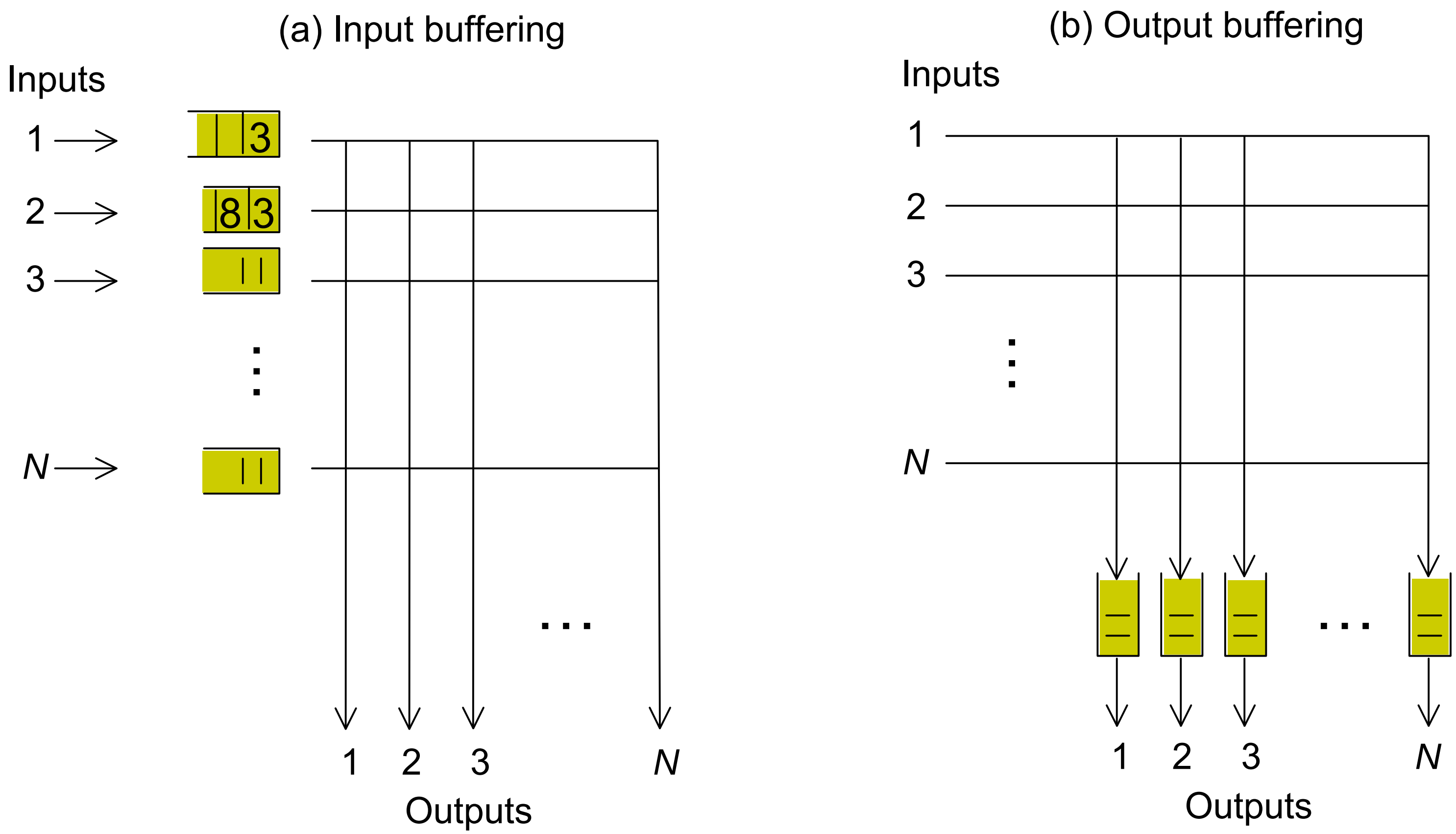
- 1 circuit board is ingress/egress line card
- Physical layer processing
- Data link layer processing
- Network header processing
- Physical layer across fabric + framing

# Shared Memory Packet Switch



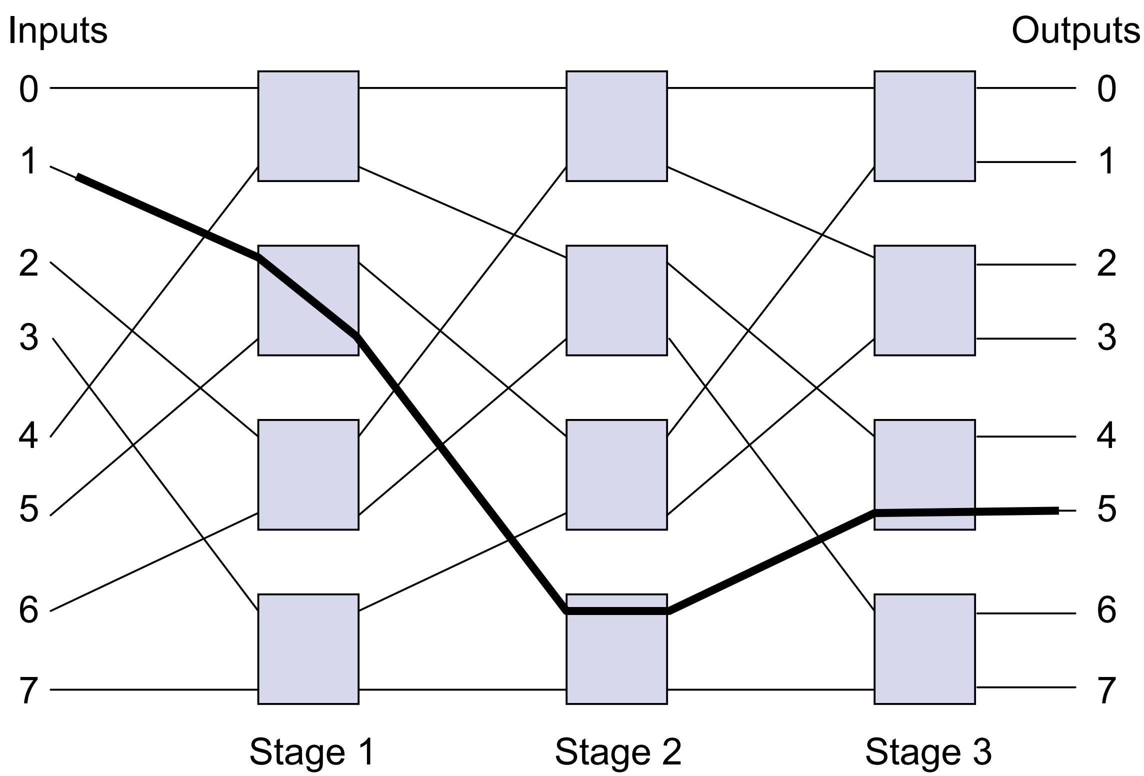

Small switches can be built by reading/writing into shared memory

# Crossbar Switches



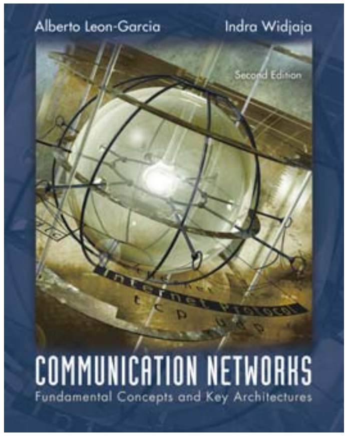

- Large switches built from crossbar & multistage space switches
- Requires centralized controller/scheduler (who sends to whom when)
- Can buffer at input, output, or both (performance vs complexity)

# Self-Routing Switches



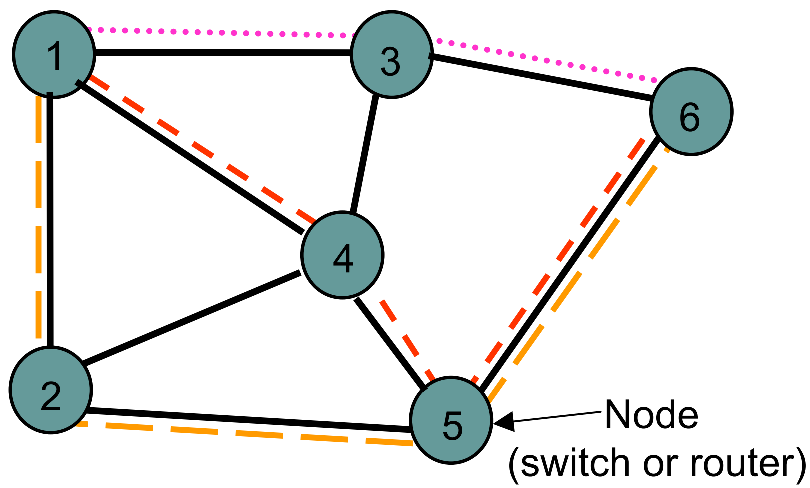

- Self-routing switches do not require controller
- Output port number determines route
- 101 → (1) lower port, (2) upper port, (3) lower port

# Chapter 7
# Packet-Switching Networks




## *Routing in Packet Networks*

# 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

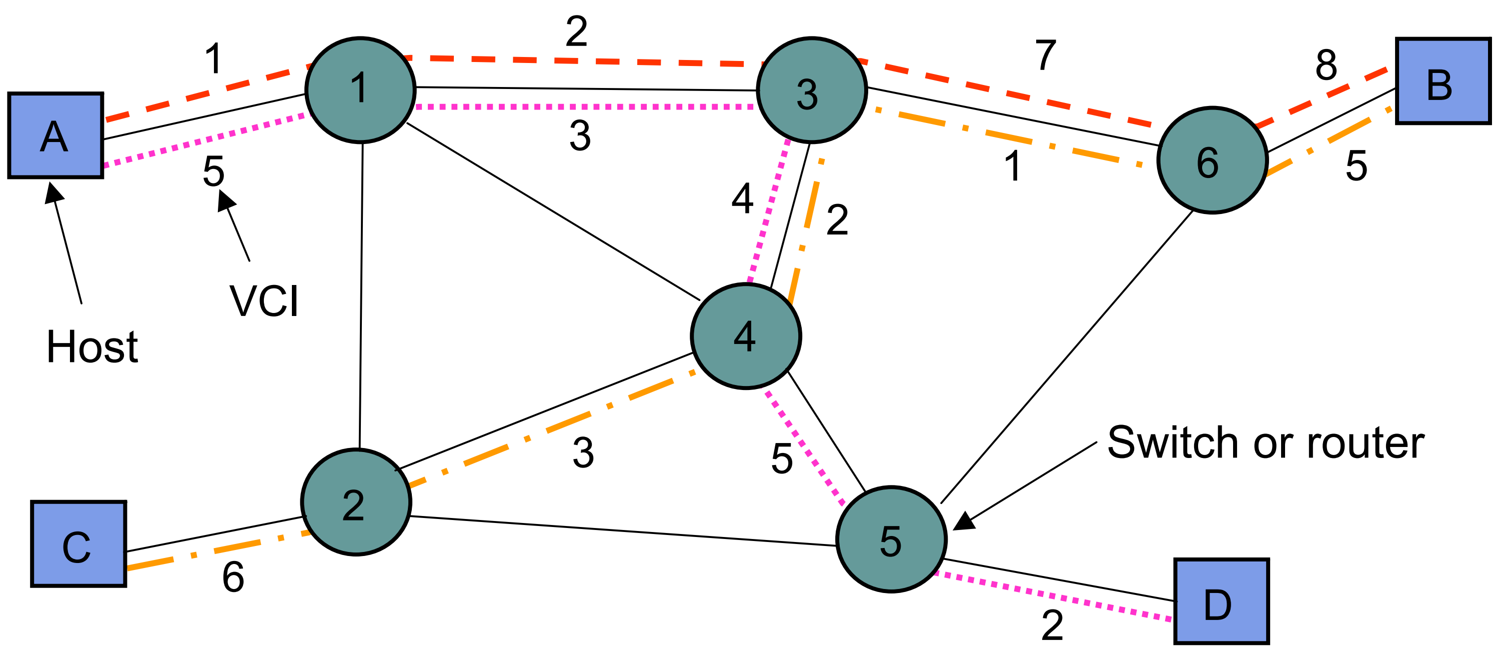
# Centralized vs Distributed Routing

- 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

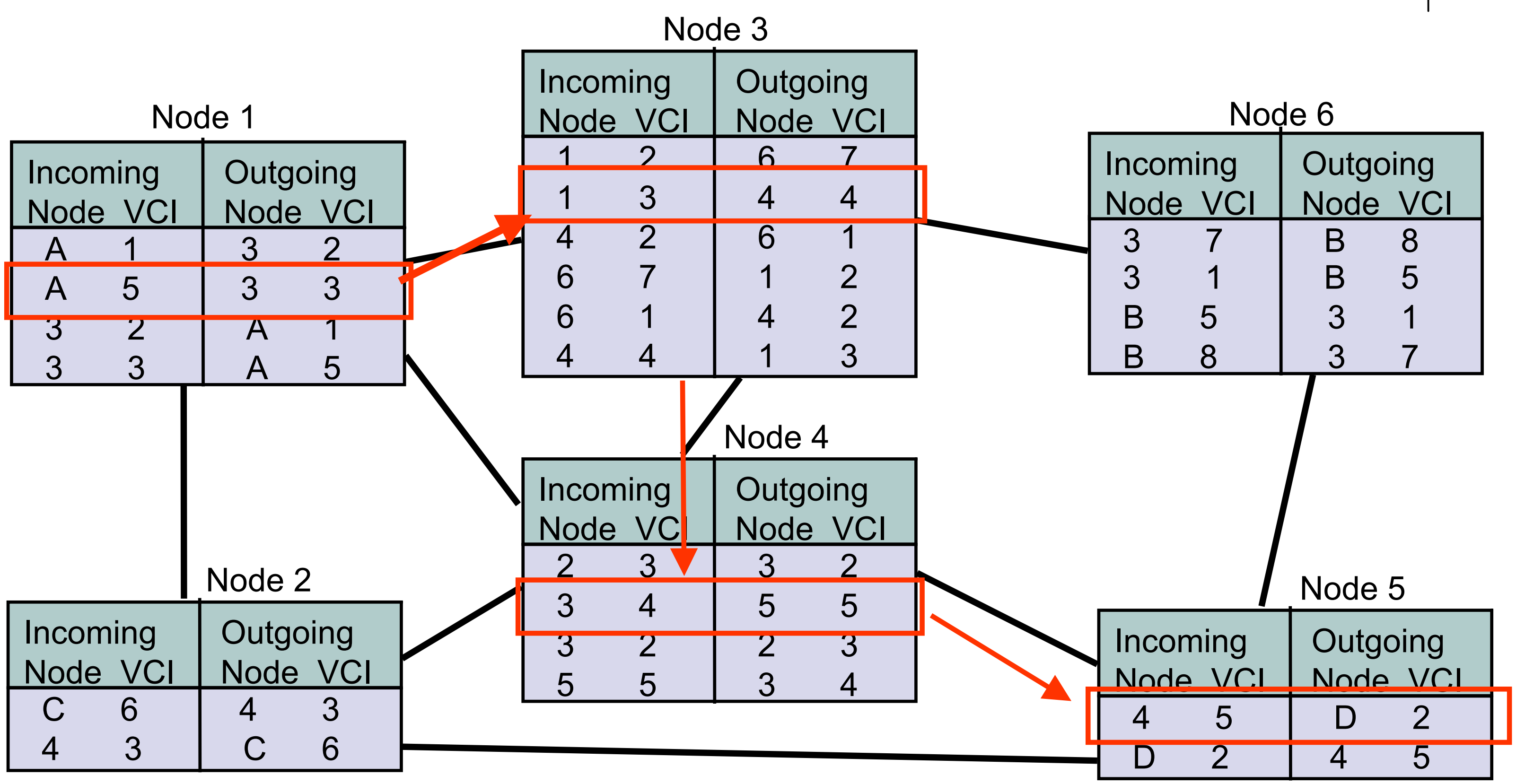
- Static Routing
  - Set up manually, do not change;  requires administration
  - Works when traffic predictable & network is simple
  - Used to override some routes set by dynamic algorithm
  - Used to provide default router
- Dynamic Routing
  - Adapt to changes in network conditions
  - Automated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

# Routing in Virtual-Circuit Packet Networks




- Route determined during connection setup
- Tables in switches implement forwarding that realizes selected route

# Routing Tables in VC Packet Networks




**Node 1**

| Incoming Node | Incoming VCI | Outgoing Node | Outgoing VCI |
|---|---|---|---|
| A | 1 | 3 | 2 |
| A | 5 | 3 | 3 |
| 3 | 2 | A | 1 |
| 3 | 3 | A | 5 |

**Node 2**

| Incoming Node | Incoming VCI | Outgoing Node | Outgoing VCI |
|---|---|---|---|
| C | 6 | 4 | 3 |
| 4 | 3 | C | 6 |

**Node 3**

| Incoming Node | Incoming VCI | Outgoing Node | Outgoing VCI |
|---|---|---|---|
| 1 | 2 | 6 | 7 |
| 1 | 3 | 4 | 4 |
| 4 | 2 | 6 | 1 |
| 6 | 7 | 1 | 2 |
| 6 | 1 | 4 | 2 |
| 4 | 4 | 1 | 3 |

**Node 4**

| Incoming Node | Incoming VCI | Outgoing Node | Outgoing VCI |
|---|---|---|---|
| 2 | 3 | 3 | 2 |
| 3 | 4 | 5 | 5 |
| 3 | 2 | 2 | 3 |
| 5 | 5 | 3 | 4 |

**Node 5**

| Incoming Node | Incoming VCI | Outgoing Node | Outgoing VCI |
|---|---|---|---|
| 4 | 5 | D | 2 |
| D | 2 | 4 | 5 |

**Node 6**

| Incoming Node | Incoming VCI | Outgoing Node | Outgoing VCI |
|---|---|---|---|
| 3 | 7 | B | 8 |
| 3 | 1 | B | 5 |
| B | 5 | 3 | 1 |
| B | 8 | 3 | 7 |

- Example: VCI from A to D
  - From A & VCI 5 → 3 & VCI 3 → 4 & VCI 4
  - → 5 & VCI 5 → D & VCI 2

# Routing Tables in Datagram Packet Networks

Node 1

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

Node 2

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

Node 3

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

Node 4

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

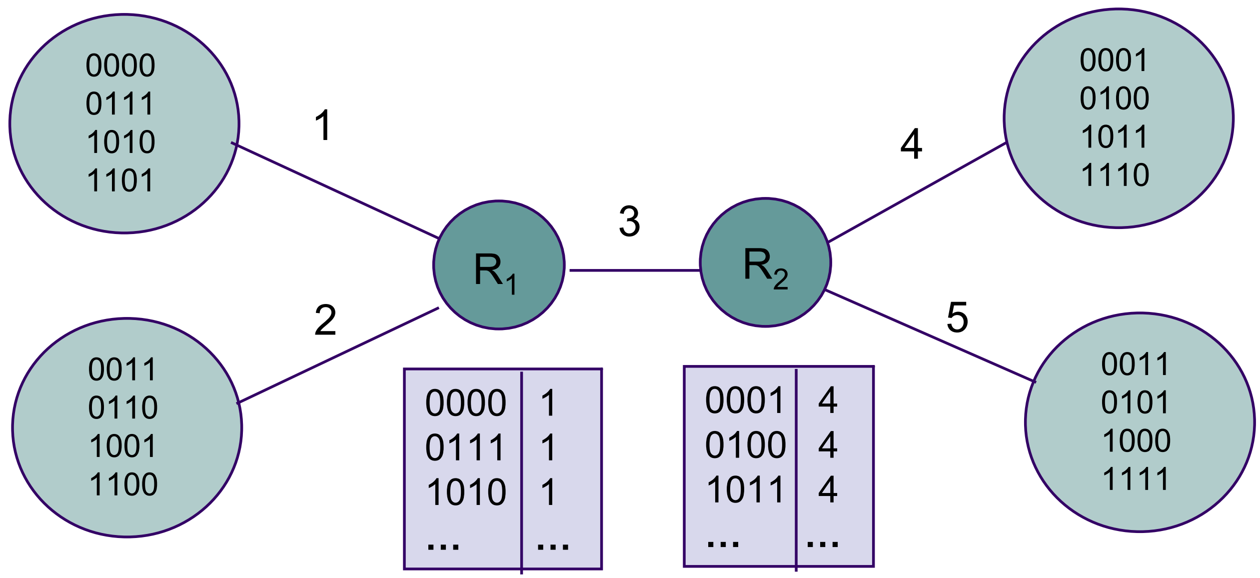
Node 5

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

Node 6

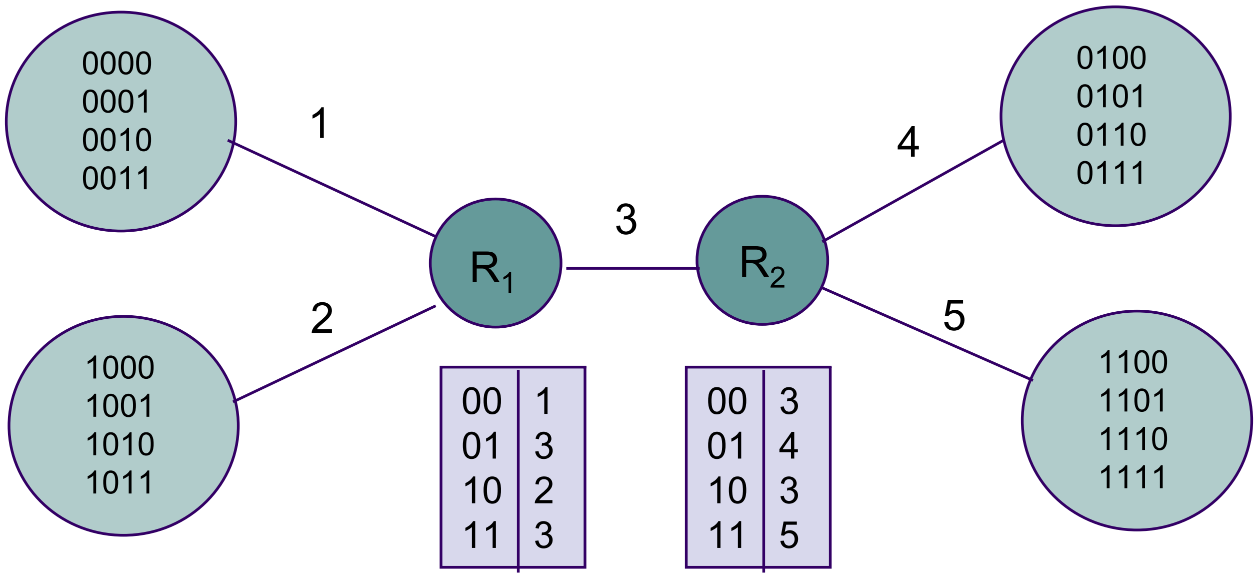
| Destination | Next node |
|---|---|
| 1 | 3 |
| 2 | 5 |
| 3 | 3 |
| 4 | 3 |
| 5 | 5 |

# Non-Hierarchical Addresses and Routing




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

# Hierarchical Addresses and Routing




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

# 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

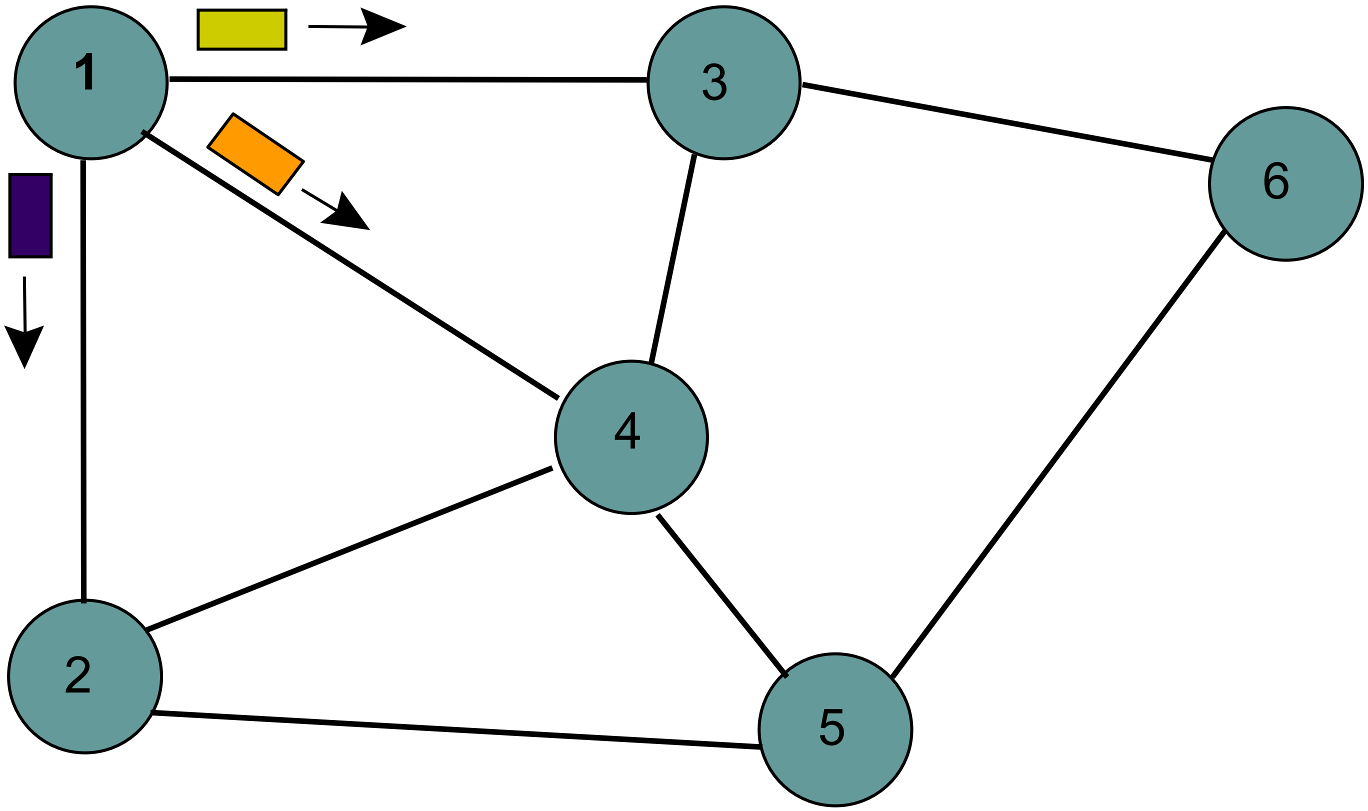
# Flooding

Send a packet to all nodes in a network

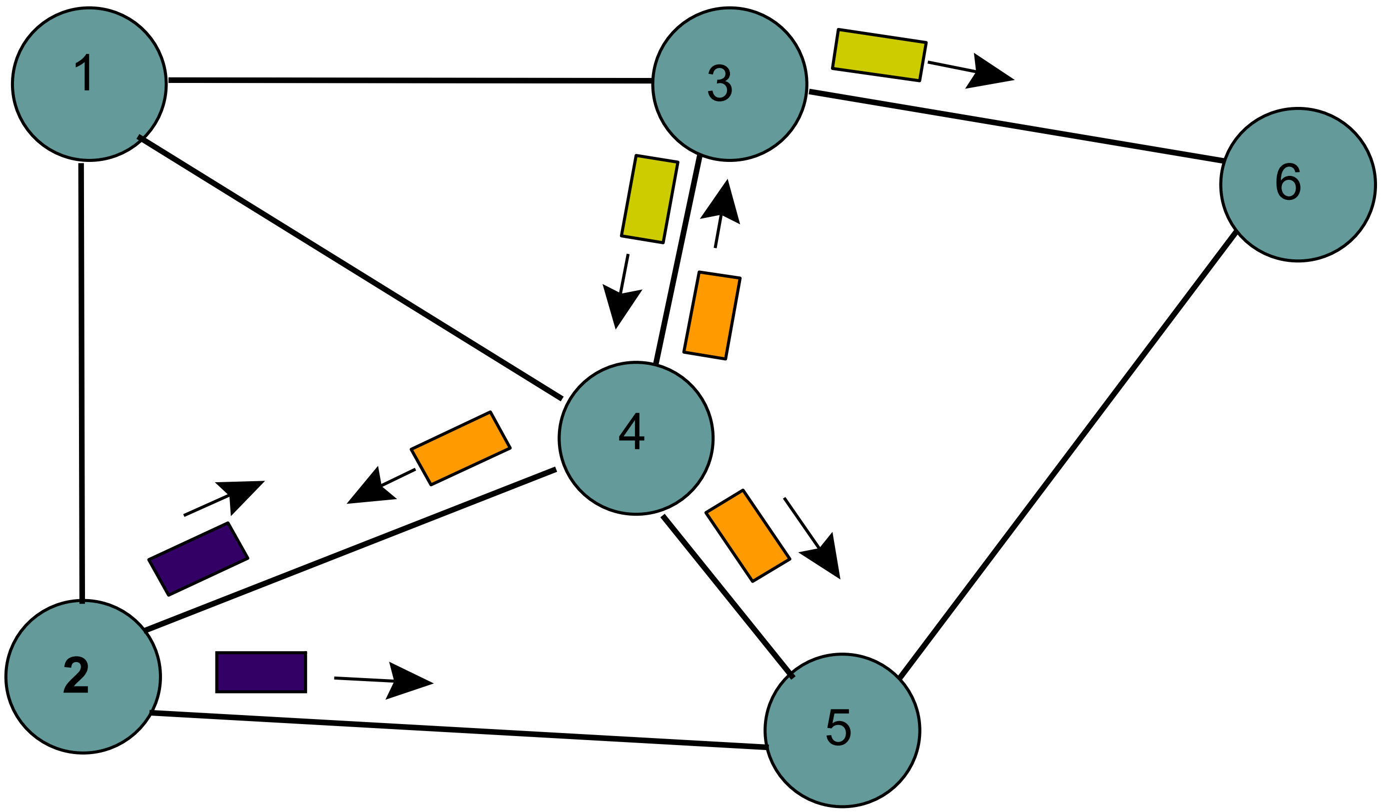
- No routing tables available
- Need to broadcast packet to all nodes (e.g. to propagate link state information)

Approach

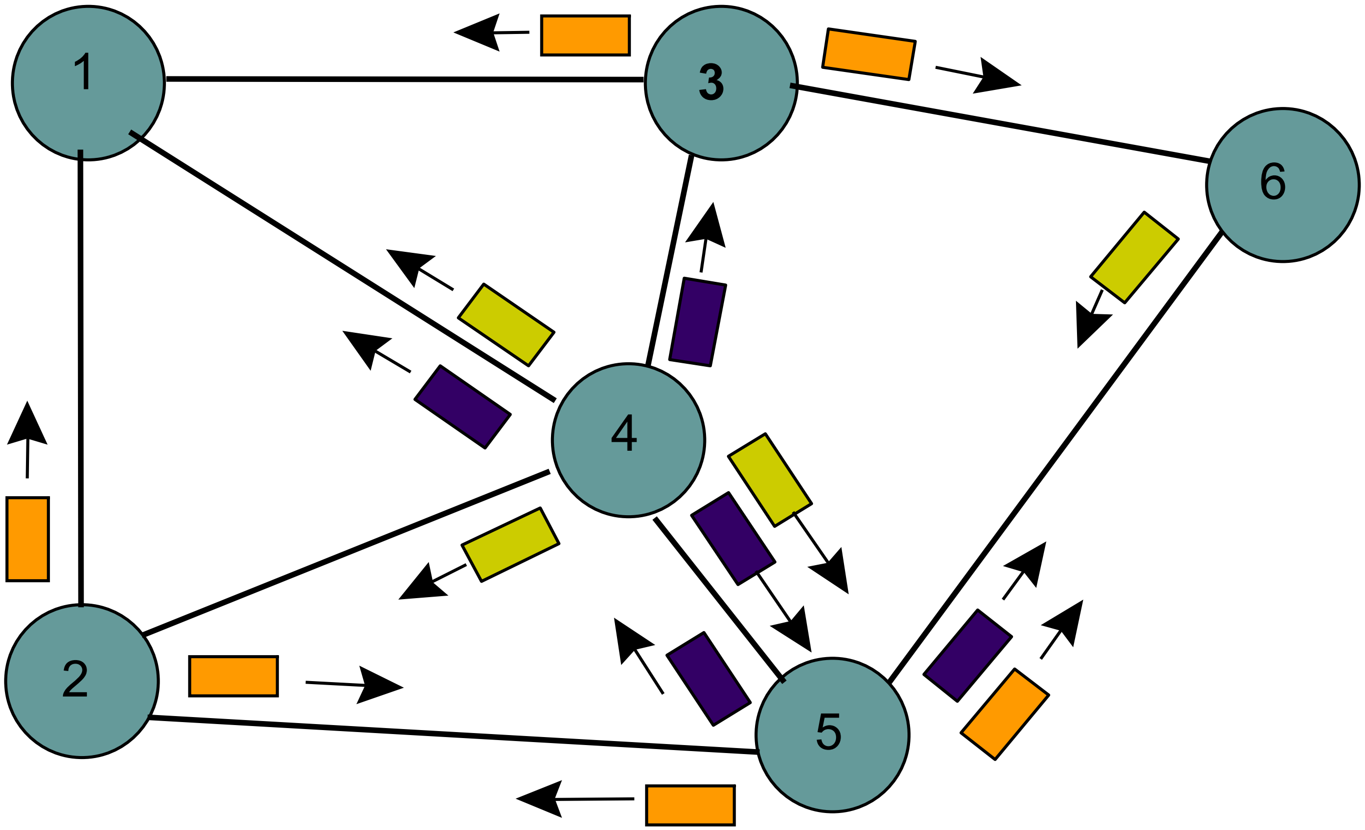
- Send packet on all ports except one where it arrived
- Exponential growth in packet transmissions




Flooding is initiated from Node 1:  Hop 1 transmissions




Flooding is initiated from Node 1:  Hop 2 transmissions



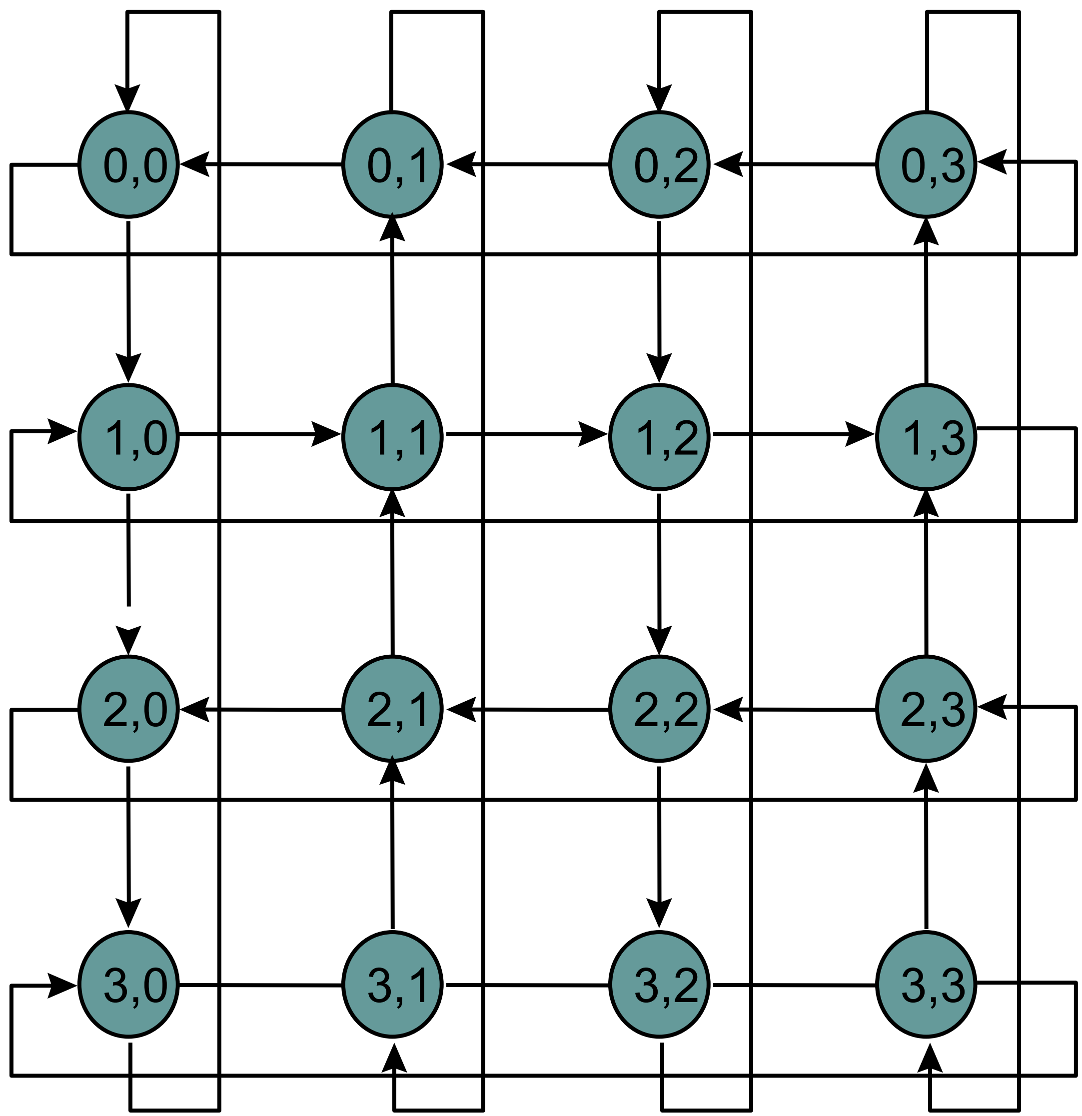

Flooding is initiated from Node 1: Hop 3 transmissions

# Limited Flooding

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

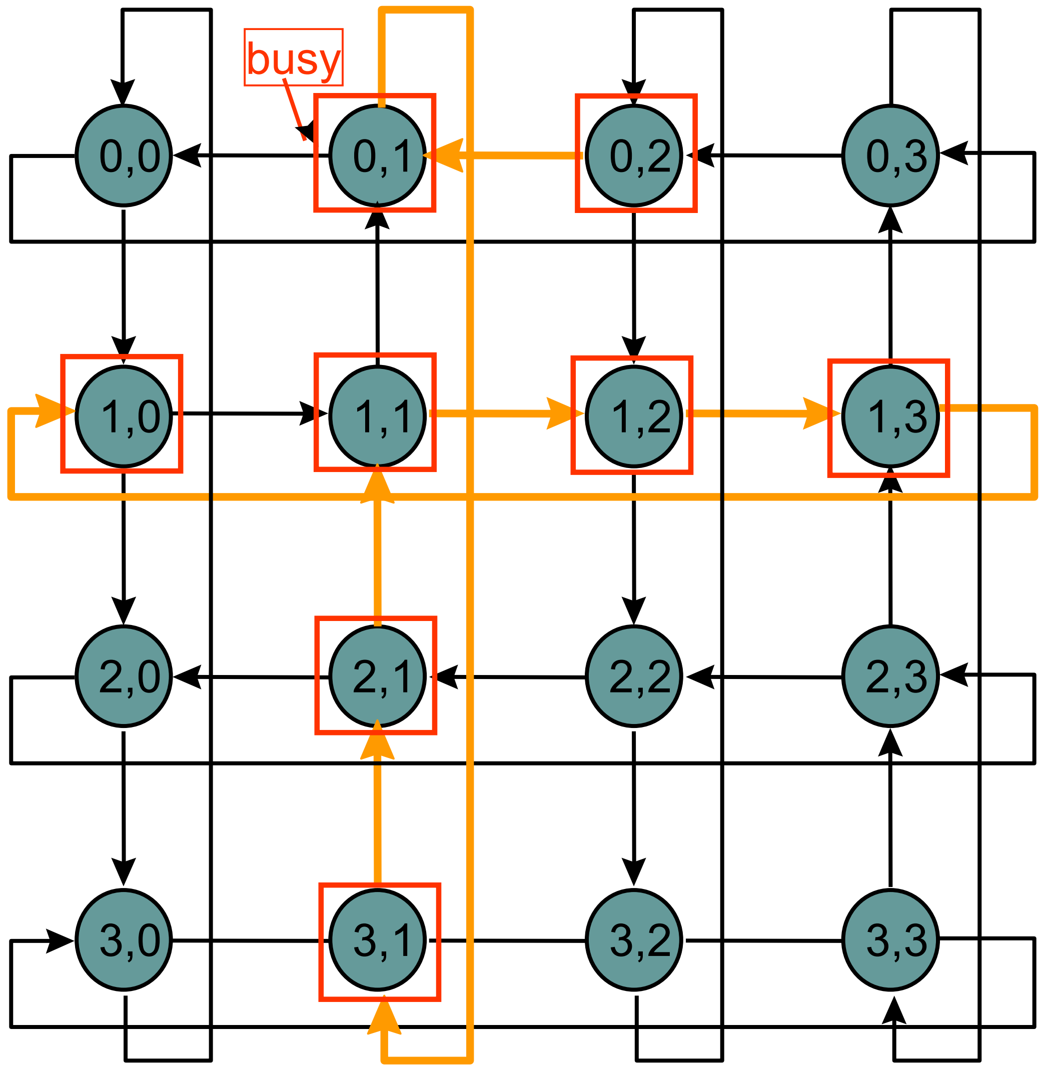
# Deflection Routing

- 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

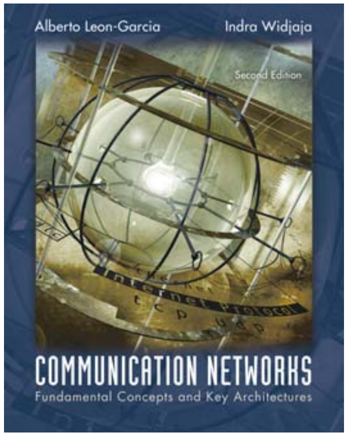



Tunnel from last column to first column or vice versa

# Example: Node (0,2)→(1,0)



# Chapter 7
# Packet-Switching Networks




## *Shortest Path Routing*

# Shortest Paths & Routing

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

# Routing Metrics

Means for measuring desirability of a path

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

# Shortest Path Approaches

**Distance Vector Protocols**

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

**Link State Protocols**

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

# Distance Vector
## *Do you know the way to San Jose?*

San Jose 294

San Jose 392

San Jose 596

San Jose 250

# Distance Vector

*Local Signpost*

- Direction
- Distance

*Routing Table*

For each destination list:

- Next Node
- Distance

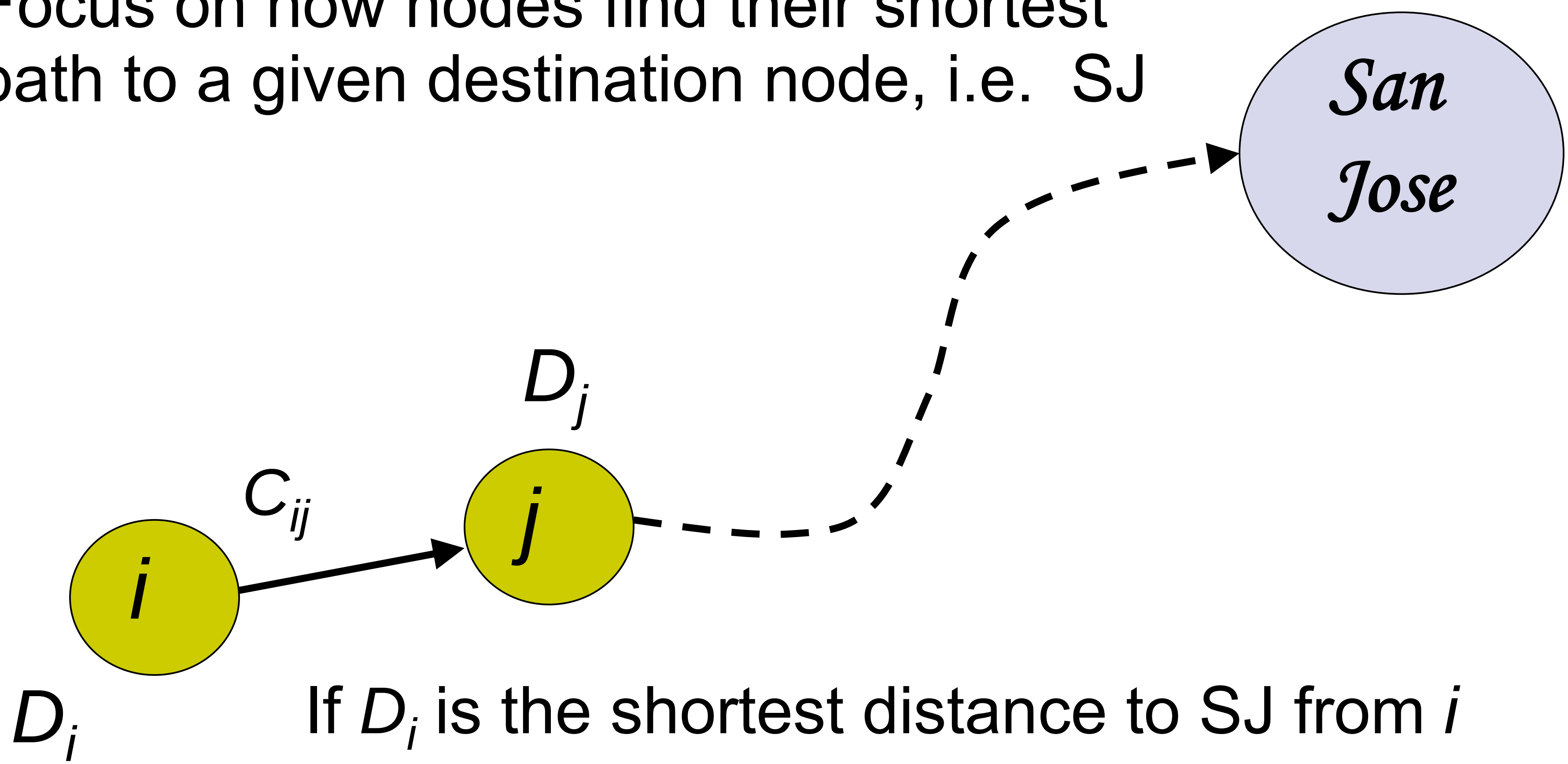
| dest | next | dist |
|---|---|---|
| | | |
| | | |
| | | |
| | | |
| | | |

*Table Synthesis*

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

# Shortest Path to SJ

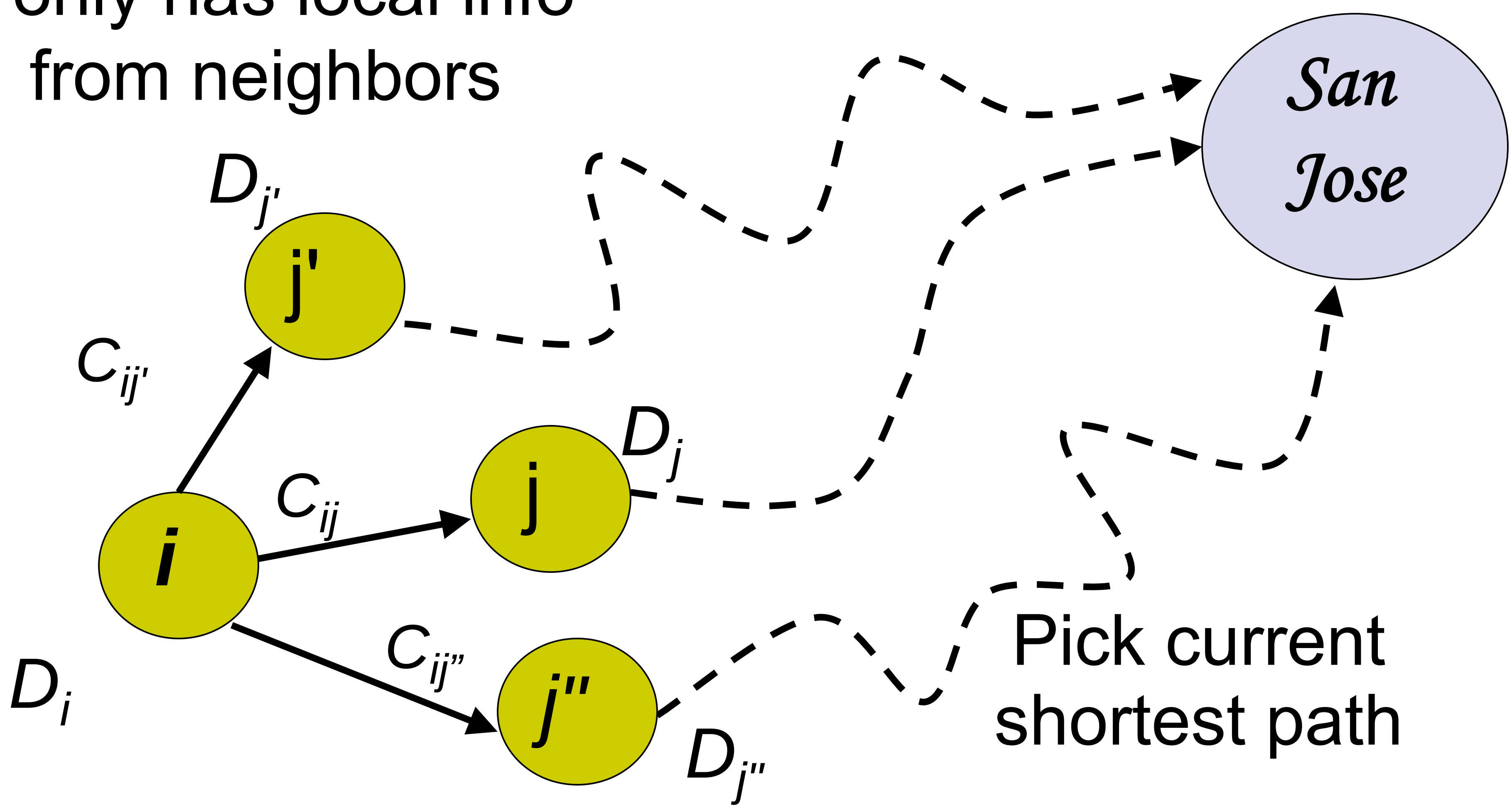
Focus on how nodes find their shortest path to a given destination node, i.e. SJ



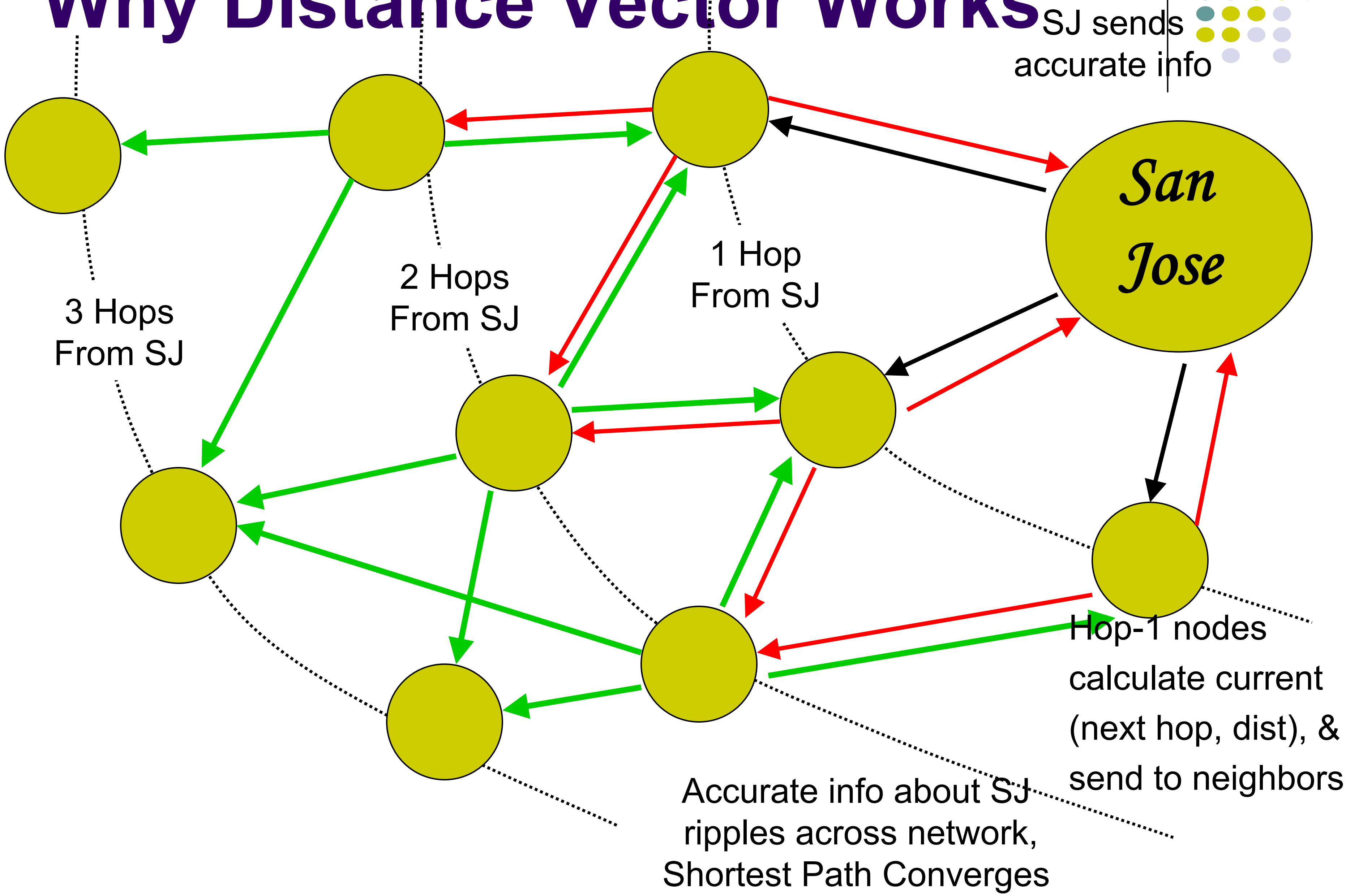

If $D_i$ is the shortest distance to SJ from $i$ and if $j$ is a neighbor on the shortest path, then $D_i = C_{ij} + D_j$

# But we don't know the shortest paths

*i* only has local info from neighbors



# Why Distance Vector Works



# Bellman-Ford Algorithm

- *Consider computations <u>for one destination</u> 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*
  - <u>At node *j*, find the next hop that gives the minimum distance to *d*</u>,
    - $Min_j \{ C_{ij} + D_j \}$
    - Replace old $(n_j, D_j(d))$ by new $(n_j^*, D_j^*(d))$ if new next node or distance
  - Go to send step

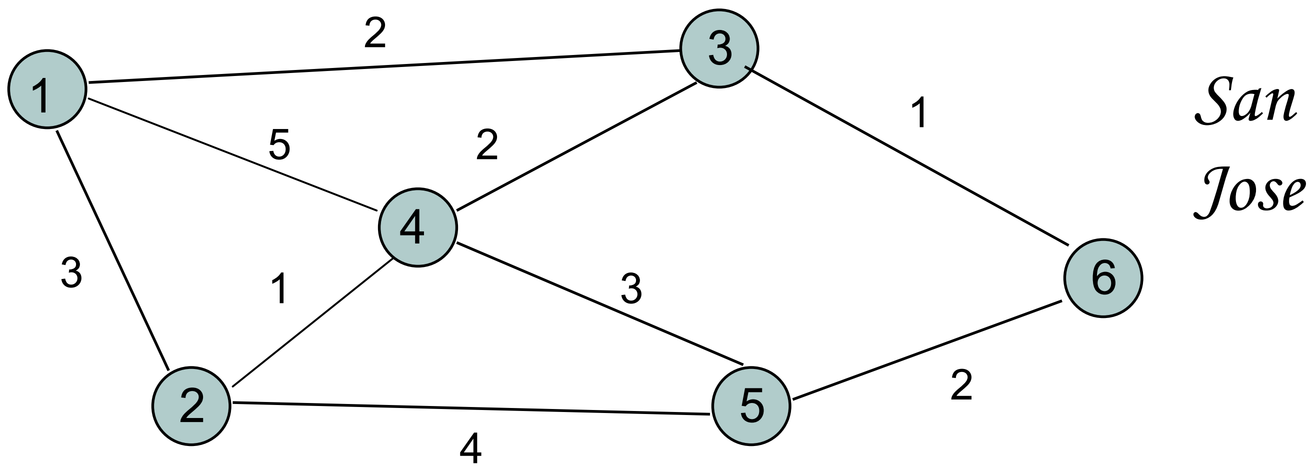
# Bellman-Ford Algorithm

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

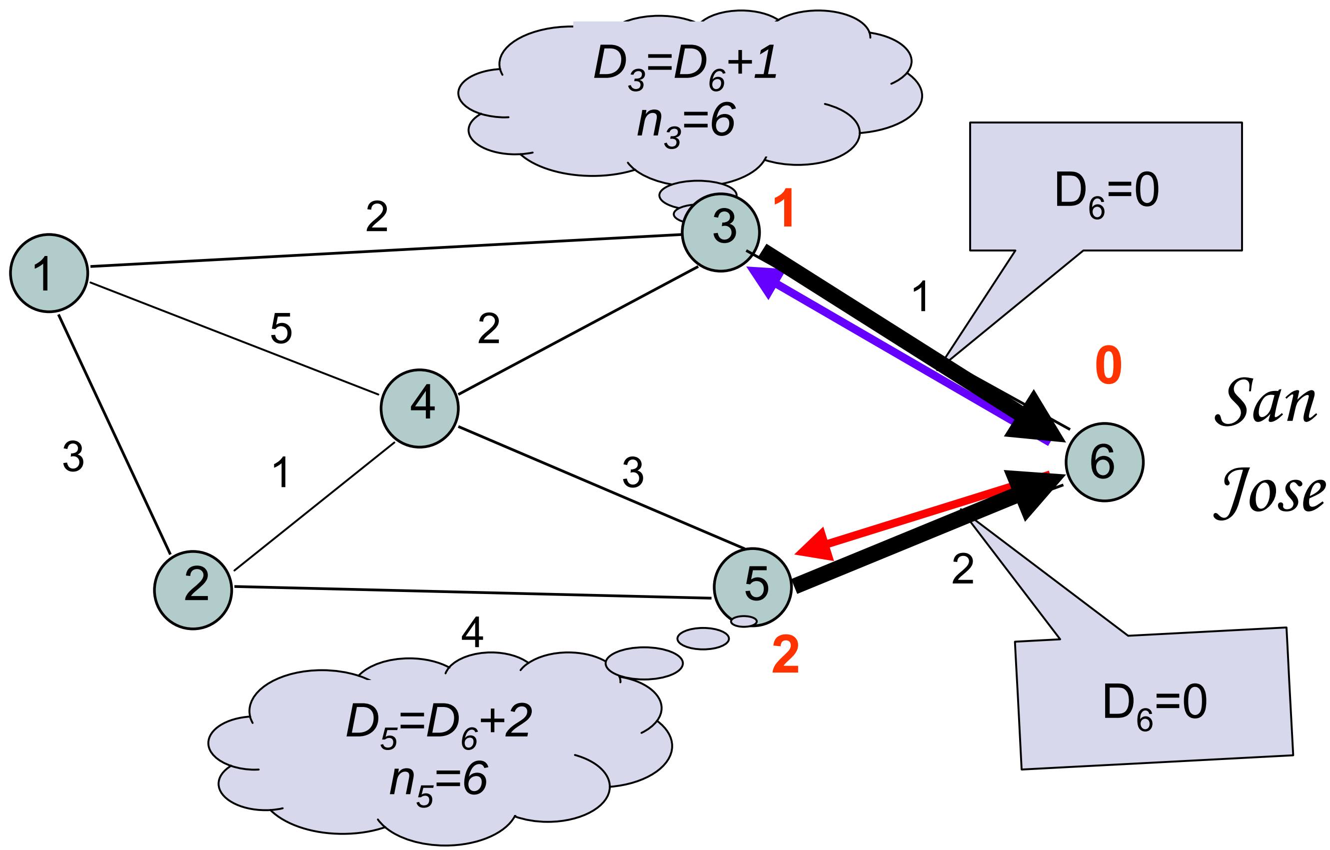
| Iteration | Node 1 | Node 2 | Node 3 | Node 4 | Node 5 |
|---|---|---|---|---|---|
| Initial | (-1, ∞) | (-1, ∞) | (-1, ∞) | (-1, ∞) | (-1, ∞) |
| 1 | | | | | |
| 2 | | | | | |
| 3 | | | | | |

Table entry @ node 1 for dest SJ

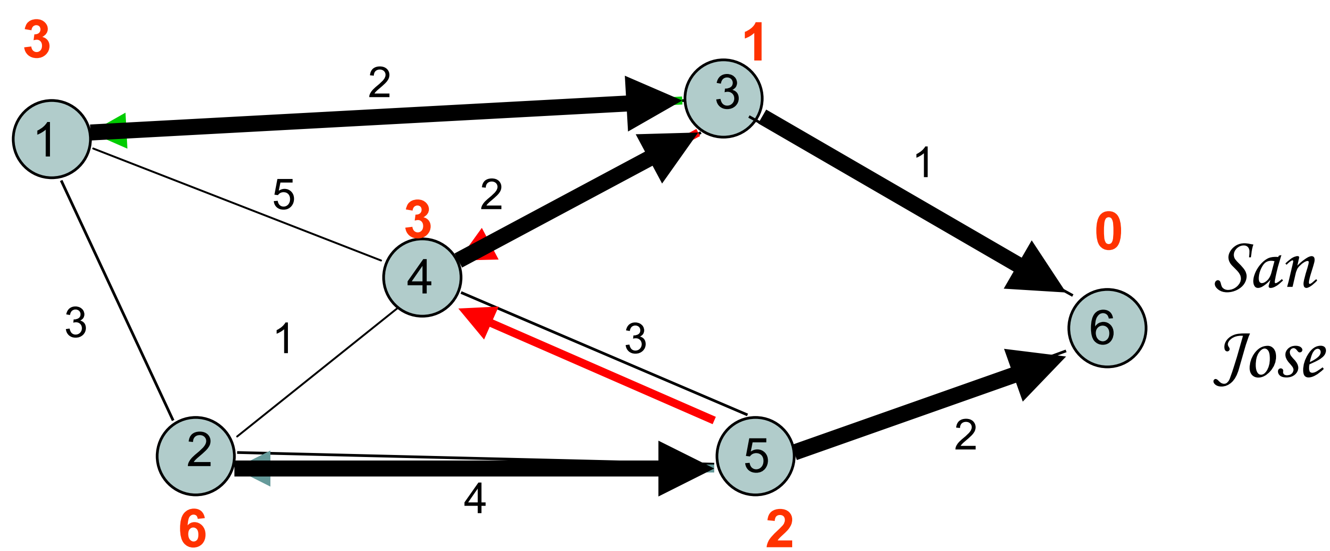
Table entry @ node 3 for dest SJ



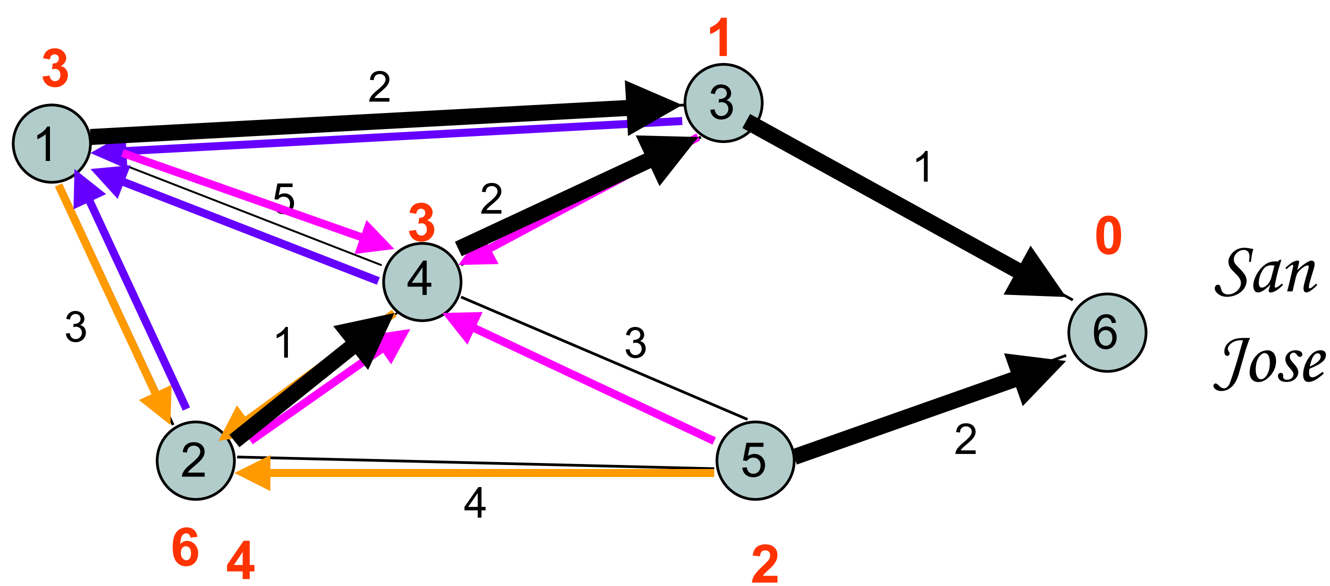
| Iteration | Node 1 | Node 2 | Node 3 | Node 4 | Node 5 |
|---|---|---|---|---|---|
| Initial | (-1, ∞) | (-1, ∞) | (-1, ∞) | (-1, ∞) | (-1, ∞) |
| 1 | (-1, ∞) | (-1, ∞) | (6,1) | (-1, ∞) | (6,2) |
| 2 | | | | | |
| 3 | | | | | |



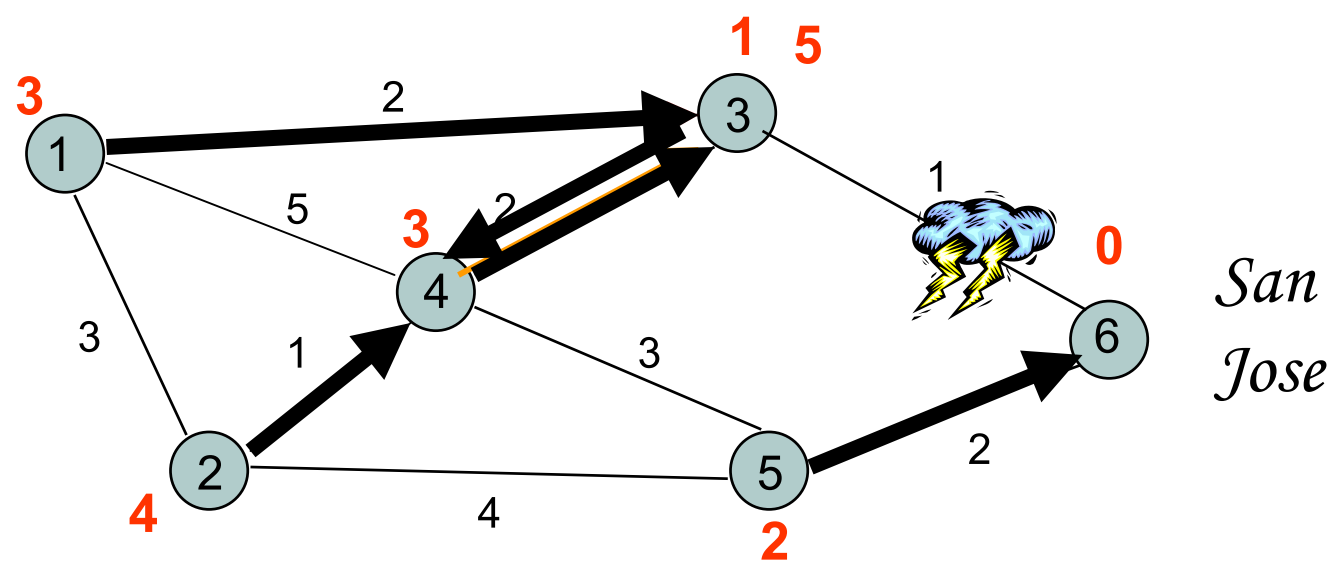
| Iteration | Node 1 | Node 2 | Node 3 | Node 4 | Node 5 |
|---|---|---|---|---|---|
| Initial | (-1, ∞) | (-1, ∞) | (-1, ∞) | (-1, ∞) | (-1, ∞) |
| 1 | (-1, ∞) | (-1, ∞) | (6, 1) | (-1, ∞) | (6,2) |
| 2 | (3,3) | (5,6) | (6, 1) | (3,3) | (6,2) |
| 3 | | | | | |



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

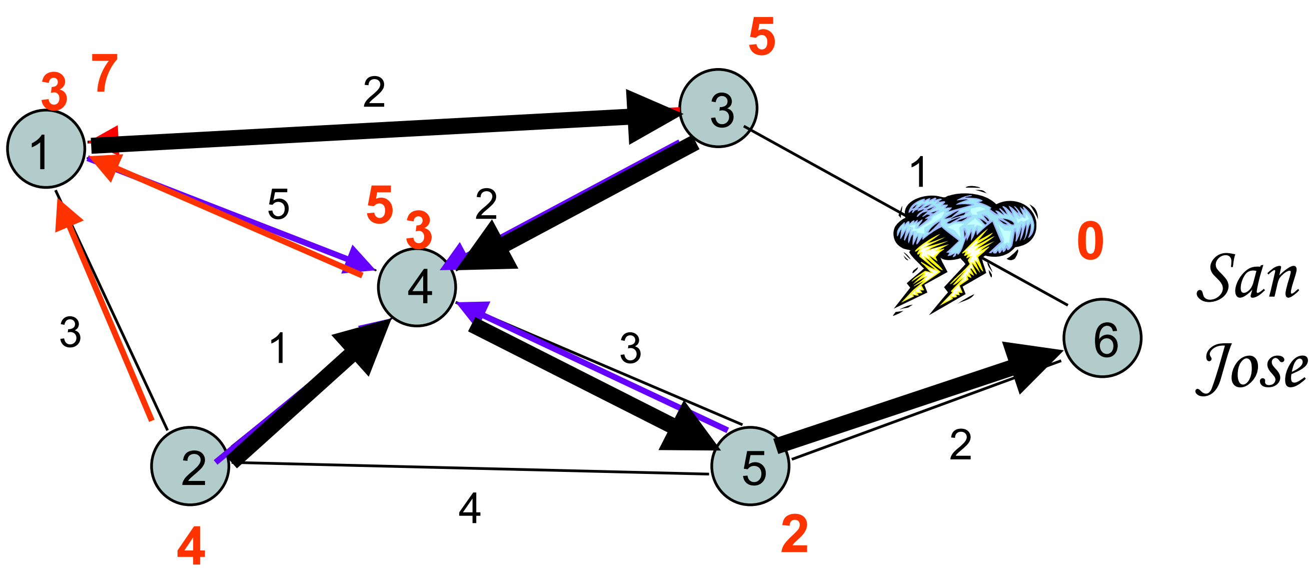


| Iteration | Node 1 | Node 2 | Node 3 | Node 4 | Node 5 |
|---|---|---|---|---|---|
| Initial | (3,3) | (4,4) | (6, 1) | (3,3) | (6,2) |
| 1 | (3,3) | (4,4) | (4, 5) | (3,3) | (6,2) |
| 2 | | | | | |
| 3 | | | | | |



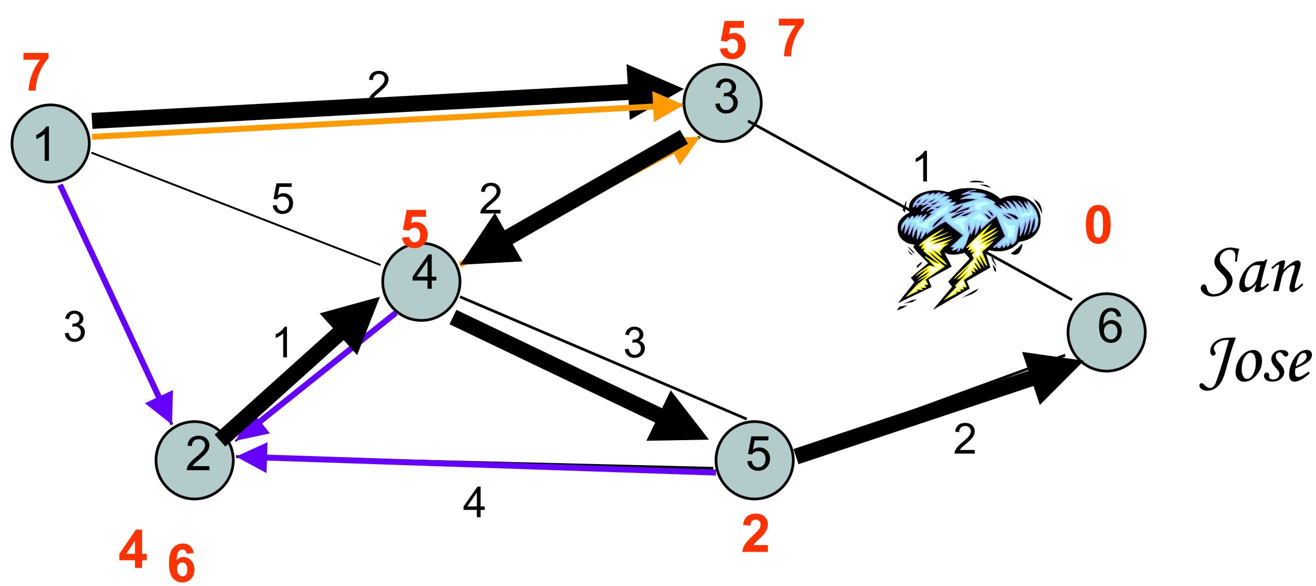

*Network disconnected; Loop created between nodes 3 and 4*

| Iteration | Node 1 | Node 2 | Node 3 | Node 4 | Node 5 |
|---|---|---|---|---|---|
| Initial | (3,3) | (4,4) | (6, 1) | (3,3) | (6,2) |
| 1 | (3,3) | (4,4) | (4, 5) | (3,3) | (6,2) |
| 2 | (3,7) | (4,4) | (4, 5) | (5,5) | (6,2) |
| 3 | | | | | |



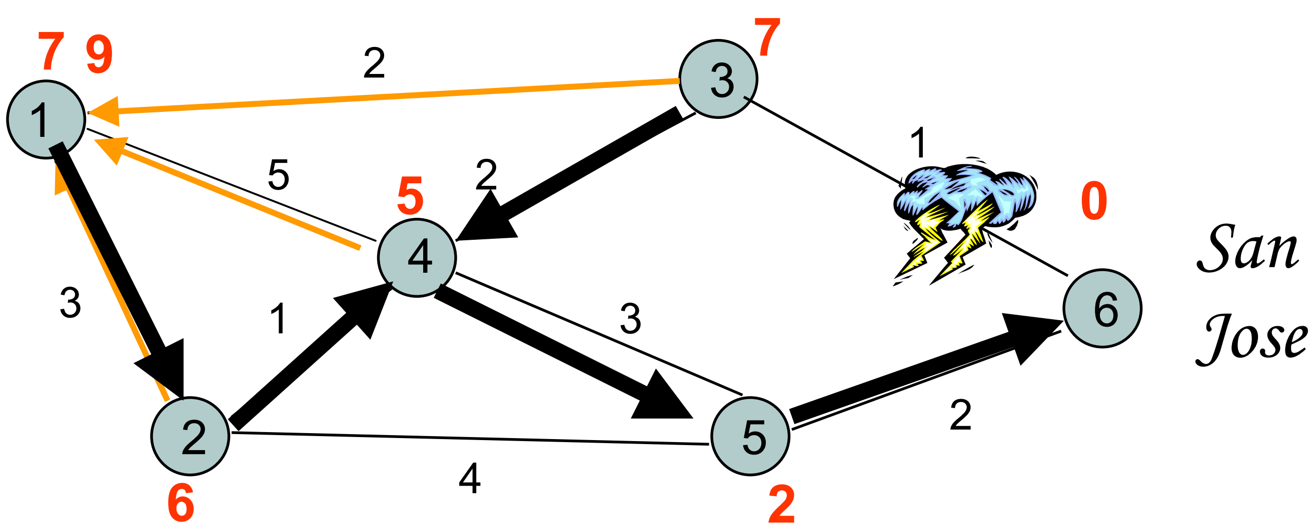

Node 4 could have chosen 2 as next node because of tie

| Iteration | Node 1 | Node 2 | Node 3 | Node 4 | Node 5 |
|---|---|---|---|---|---|
| Initial | (3,3) | (4,4) | (6, 1) | (3,3) | (6,2) |
| 1 | (3,3) | (4,4) | (4, 5) | (3,3) | (6,2) |
| 2 | (3,7) | (4,4) | (4, 5) | (5,5) | (6,2) |
| 3 | (3,7) | (4,6) | (4, 7) | (5,5) | (6,2) |



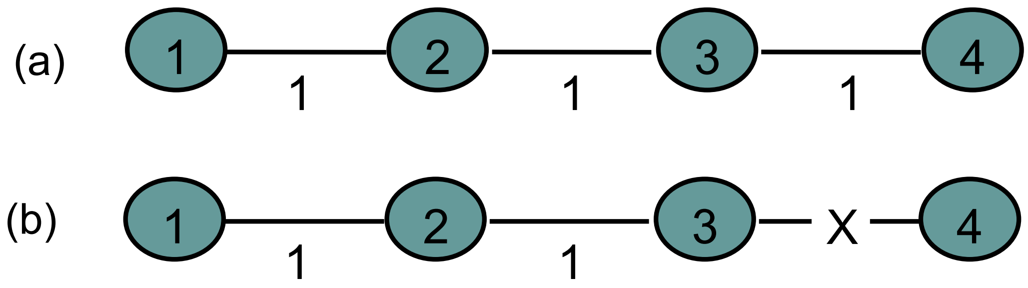

Node 2 could have chosen 5 as next node because of tie

| Iteration | Node 1 | Node 2 | Node 3 | Node 4 | Node 5 |
|---|---|---|---|---|---|
| 1 | (3,3) | (4,4) | (4, 5) | (3,3) | (6,2) |
| 2 | (3,7) | (4,4) | (4, 5) | (2,5) | (6,2) |
| 3 | (3,7) | (4,6) | (4, 7) | (5,5) | (6,2) |
| 4 | (2,9) | (4,6) | (4, 7) | (5,5) | (6,2) |
| | | | | | |




Node 1 could have chose 3 as next node because of tie

# Counting to Infinity Problem




Nodes believe best path is through each other

(Destination is node 4)

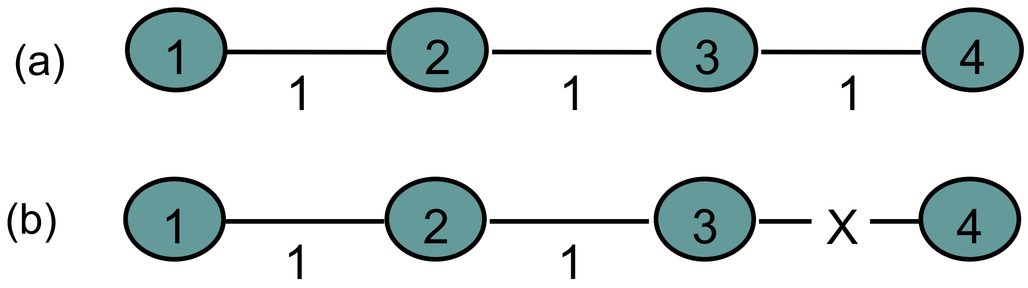
| Update | Node 1 | Node 2 | Node 3 |
|---|---|---|---|
| Before break | (2,3) | (3,2) | (4, 1) |
| After break | (2,3) | (3,2) | (2,3) |
| 1 | (2,3) | (3,4) | (2,3) |
| 2 | (2,5) | (3,4) | (2,5) |
| 3 | (2,5) | (3,6) | (2,5) |
| 4 | (2,7) | (3,6) | (2,7) |
| 5 | (2,7) | (3,8) | (2,7) |
| … | … | … |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

# Problem:  Bad News Travels Slowly

Remedies

- Split Horizon
  - Do not report route to a destination to the neighbor from which route was learned
- Poisoned Reverse
  - Report route to a destination to the neighbor from which route was learned, but with infinite distance
  - Breaks erroneous direct loops immediately
  - Does not work on some indirect loops

# Split Horizon with Poison Reverse




Nodes believe best path is through each other

| Update | Node 1 | Node 2 | Node 3 | |
|---|---|---|---|---|
| Before break | (2, 3) | (3, 2) | (4, 1) | |
| After break | (2, 3) | (3, 2) | (-1, ∞) | Node 2 advertizes its route to 4 to node 3 as having distance infinity; node 3 finds there is no route to 4 |
| 1 | (2, 3) | (-1, ∞) | (-1, ∞) | Node 1 advertizes its route to 4 to node 2 as having distance infinity; node 2 finds there is no route to 4 |
| 2 | (-1, ∞) | (-1, ∞) | (-1, ∞) | Node 1 finds there is no route to 4 |

# Link-State Algorithm

- Basic idea: two step procedure
  - Each source node gets a map of all nodes and link metrics (link state) of the entire network
  - Find the shortest path on the map from the source node to all destination nodes
- Broadcast of link-state information
  - Every node *i* in the network broadcasts to every other node in the network:
    - ID's of its neighbors: $\mathcal{N}_i$=set of neighbors of i
    - Distances to its neighbors: $\{C_{ij} \mid j \in N_i\}$
  - Flooding is a popular method of broadcasting packets

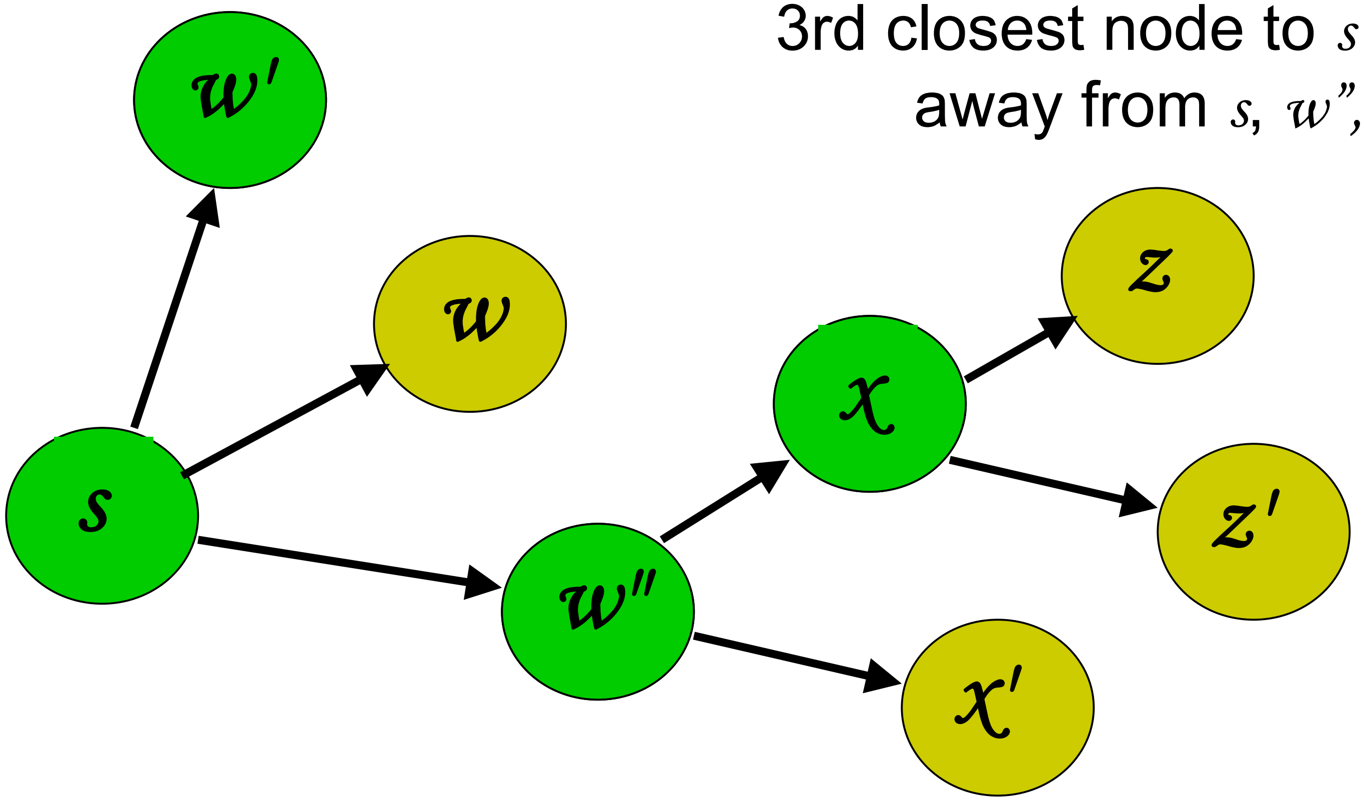
# Dijkstra Algorithm: Finding shortest paths in order

Find shortest paths from source s to all other destinations

Closest node to $s$ is 1 hop away

2nd closest node to $s$ is 1 hop away from $s$ or $w''$

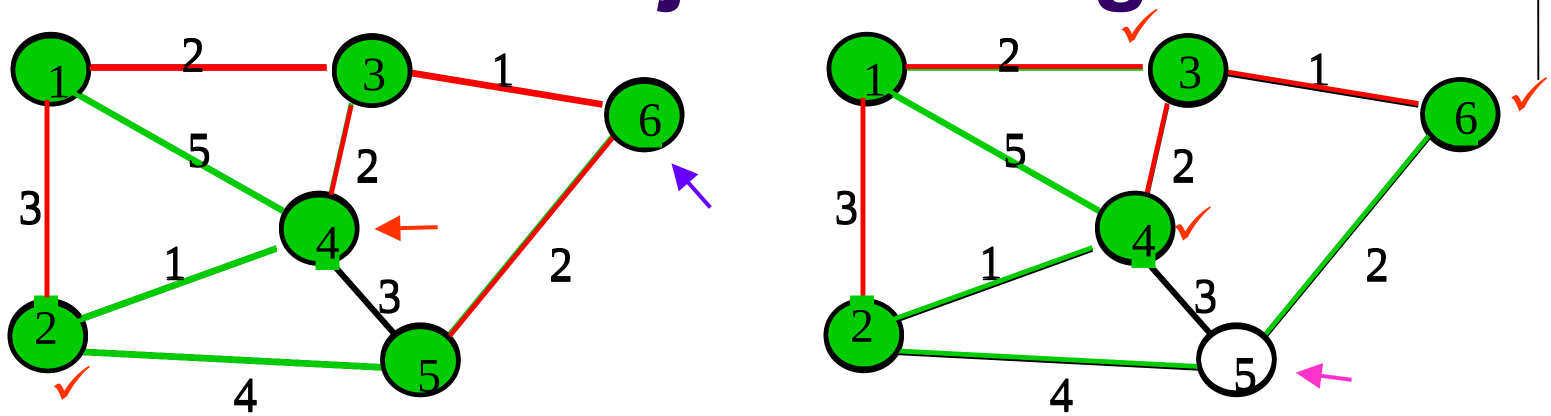
3rd closest node to $s$ is 1 hop away from $s$, $w''$, or $x$



# Dijkstra's algorithm

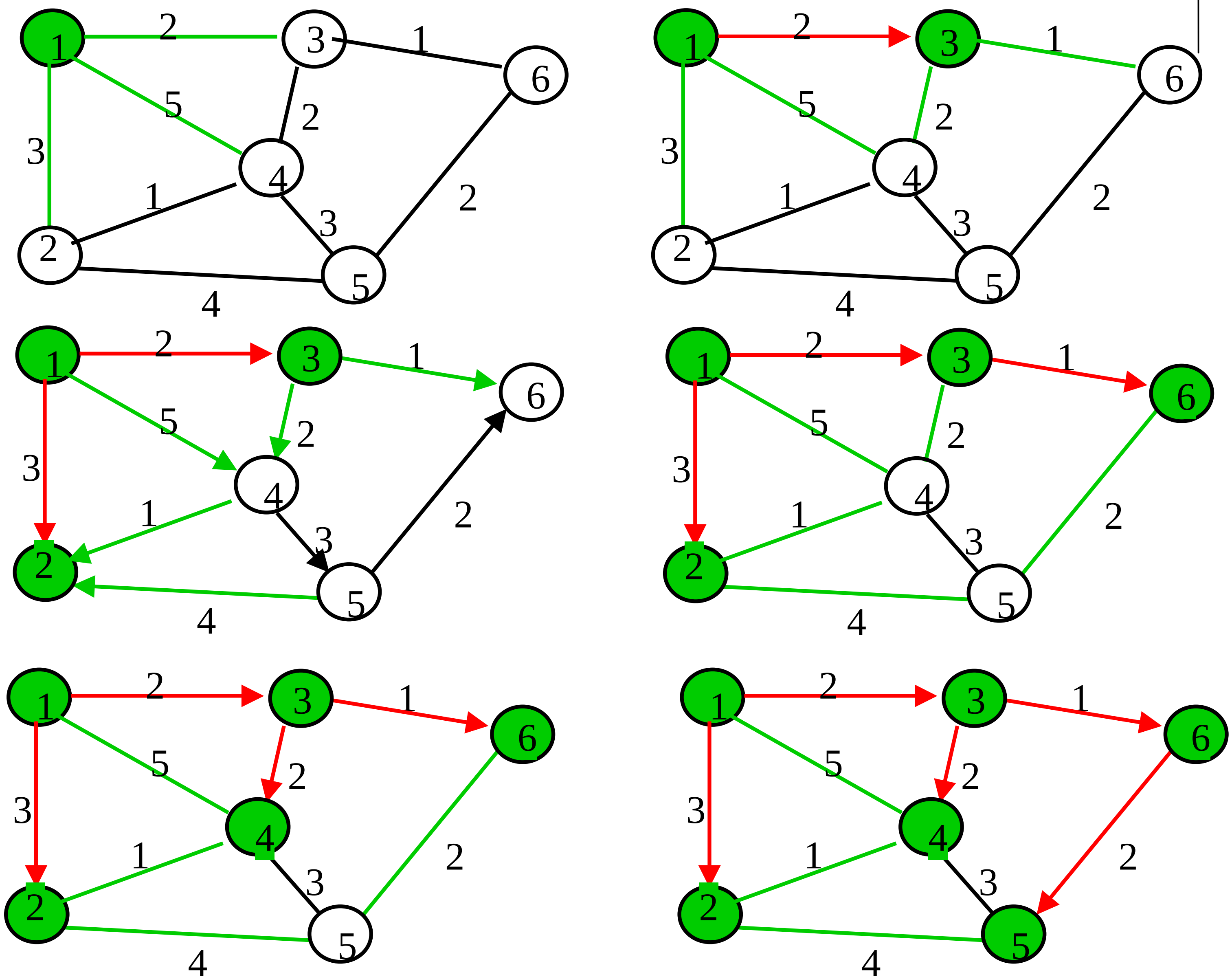
- *N*: set of nodes for which shortest path already found
- Initialization: (*Start with source node s)*
  - *N = {s}*, $D_s = 0$, "*s* is distance zero from itself"
  - $D_j = C_{sj}$ for all $j \neq s$, distances of directly-connected neighbors
- Step A: (*Find next closest node i*)
  - Find $i \notin N$ such that
  - $D_i = \min D_j$ for $j \notin N$
  - Add *i* to *N*
  - If *N* contains all the nodes, stop
- Step B: (*update minimum costs)*
  - For each node $j \notin N$
  - $D_j = \min(D_j, D_i + C_{ij})$ ← *Minimum distance from s* to *j through node **i** in N*
  - Go to Step A

# Execution of Dijkstra's algorithm




| Iteration | **N** | $D_2$ | $D_3$ | $D_4$ | $D_5$ | $D_6$ |
|---|---|---|---|---|---|---|
| Initial | {1} | 3 | 2 ✓ | 5 | $\propto$ | $\propto$ |
| 1 | {1,3} | 3 ✓ | 2 | 4 | $\propto$ | 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 very quick
- But watch out for old update messages
  - Add time stamp or sequence # to each update message
  - Check whether each received update message is new
  - If new, add it to database and broadcast
  - If older, send update message on arriving link

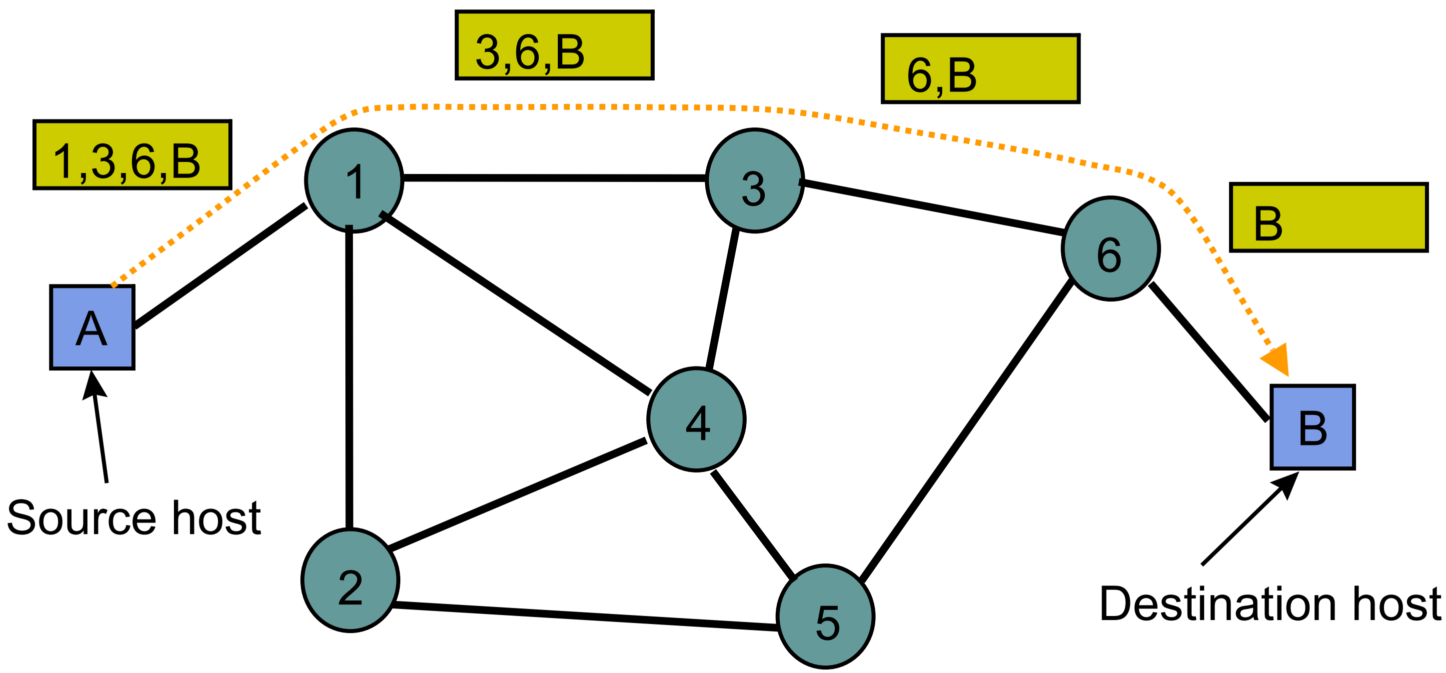
# Why is Link State Better?

- 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

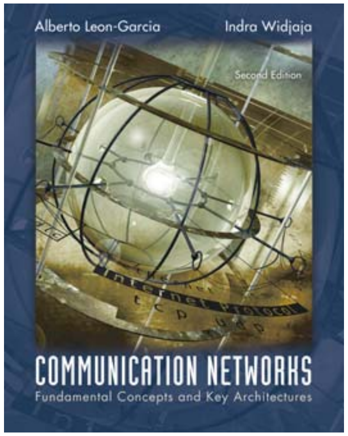
# Source Routing

- 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 the means for customers to select what service providers they use

# Example



# Chapter 7
# Packet-Switching Networks

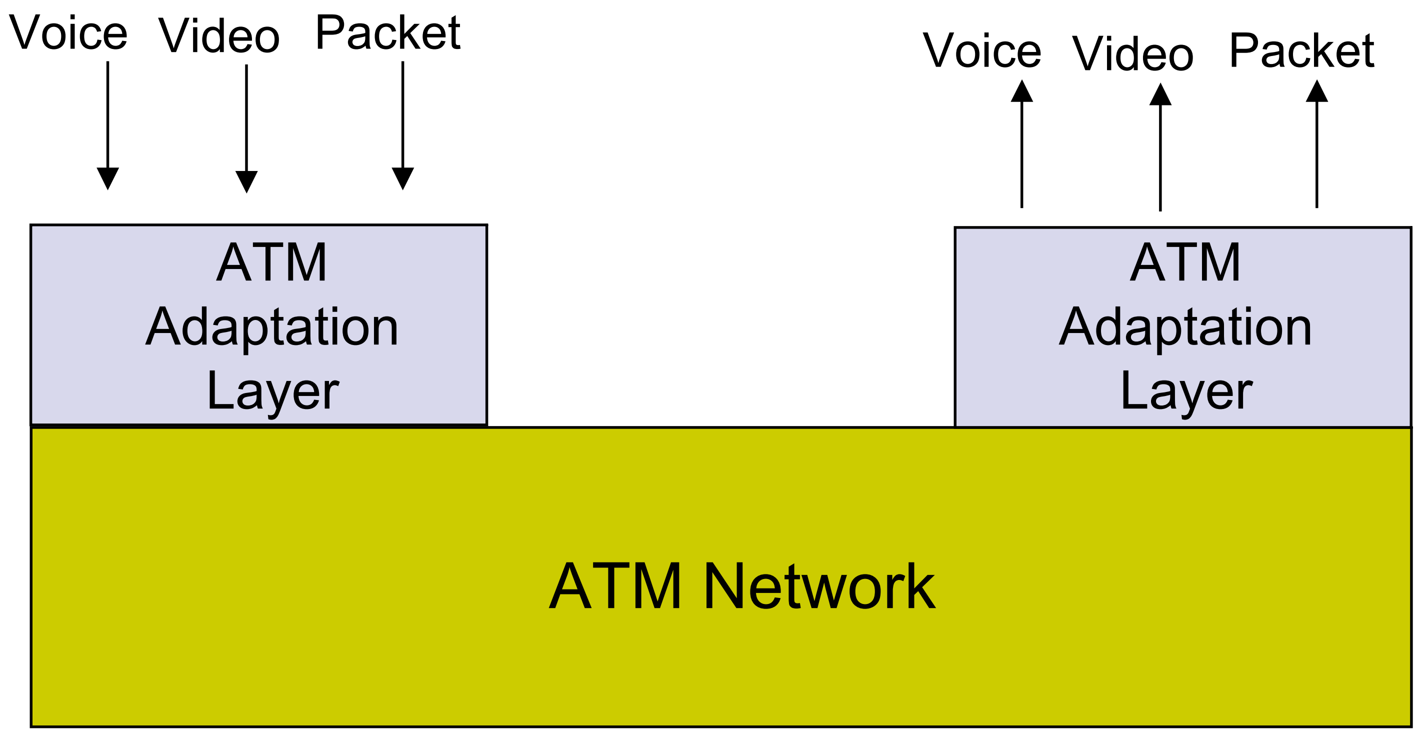



## *ATM Networks*

# Asynchronous Tranfer Mode (ATM)

- Packet multiplexing and switching
  - Fixed-length packets: “cells”
  - Connection-oriented
  - Rich Quality of Service support
- Conceived as end-to-end
  - Supporting wide range of services
    - Real time voice and video
    - Circuit emulation for digital transport
    - Data traffic with bandwidth guarantees
- Detailed discussion in Chapter 9

# ATM Networking



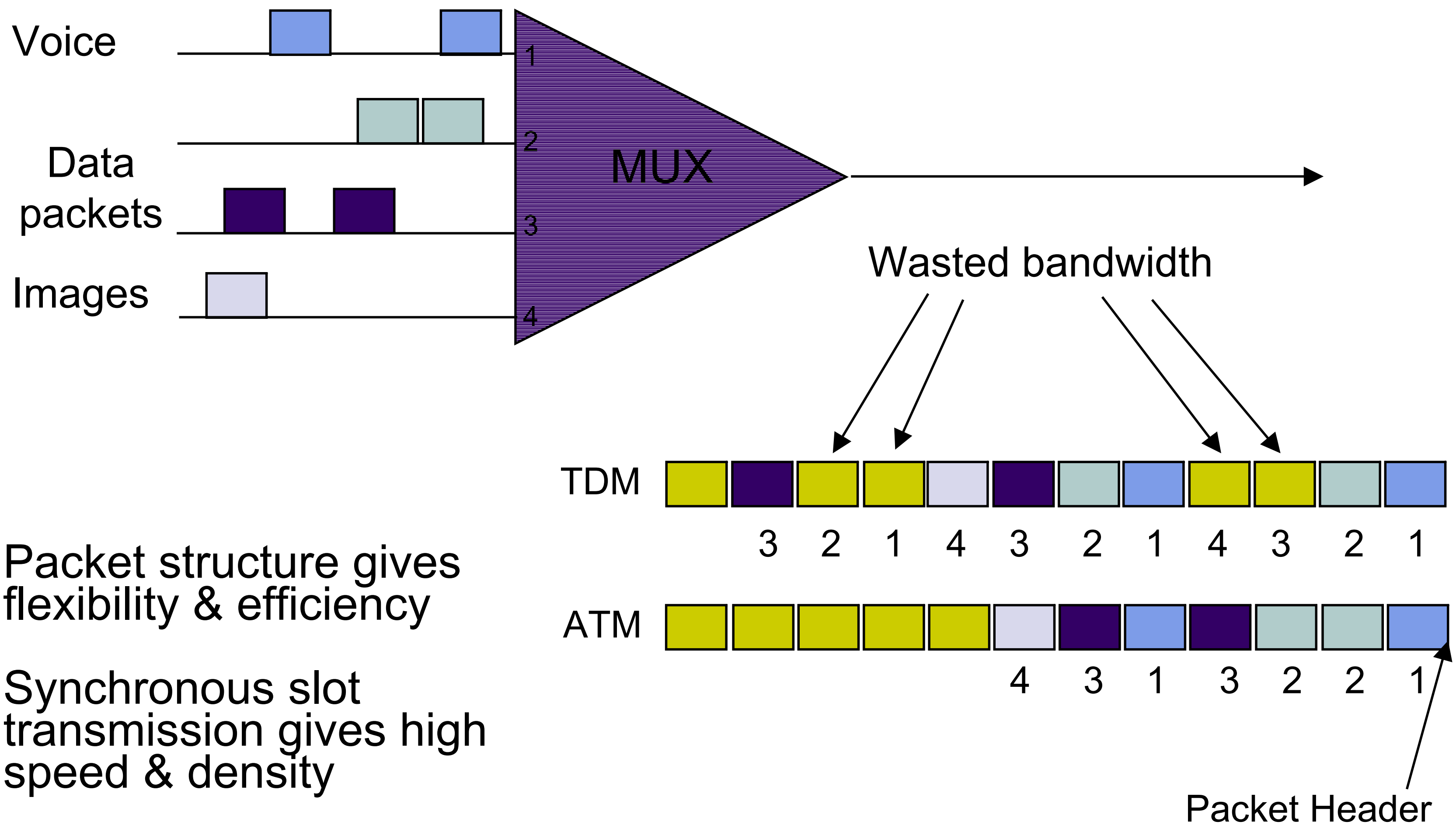

- End-to-end information transport using cells
- 53-byte cell provide low delay and fine multiplexing granularity
- Support for many services through ATM Adaptation Layer

# TDM vs. Packet Multiplexing

| | Variable bit rate | Delay | Burst traffic | Processing |
|---|---|---|---|---|
| TDM | Multirate only | Low, fixed ✓ | Inefficient | Minimal, very high speed |
| Packet | Easily handled ✓ | Variable | Efficient ✓ | Header & packet processing required* |

*In mid-1980s, packet processing mainly in software and hence slow; By late 1990s, very high speed packet processing possible

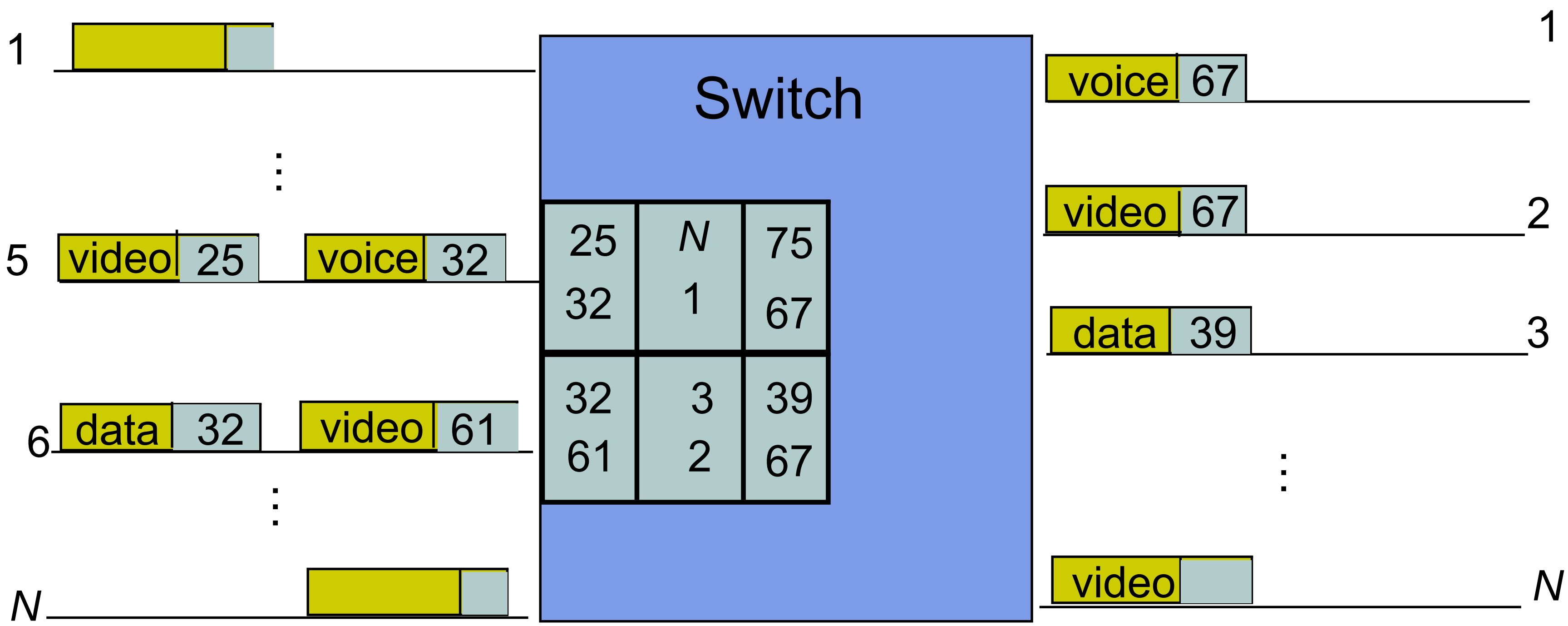
# ATM: Attributes of TDM & Packet Switching




- Packet structure gives flexibility & efficiency
- Synchronous slot transmission gives high speed & density

# ATM Switching

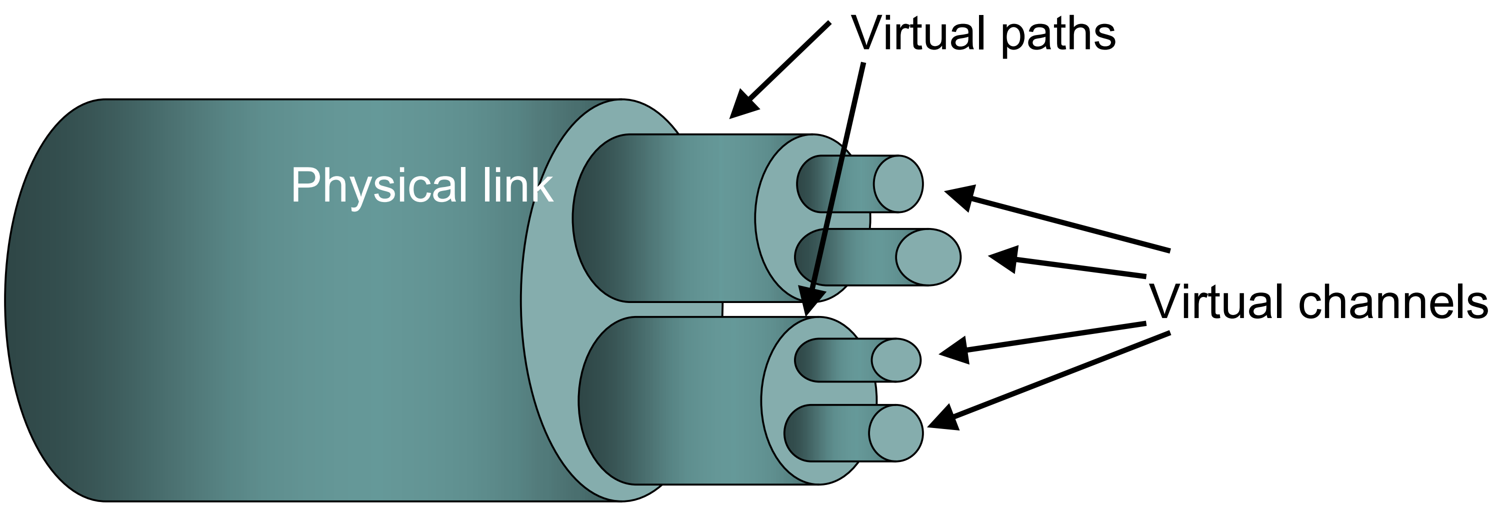
Switch carries out table translation and routing



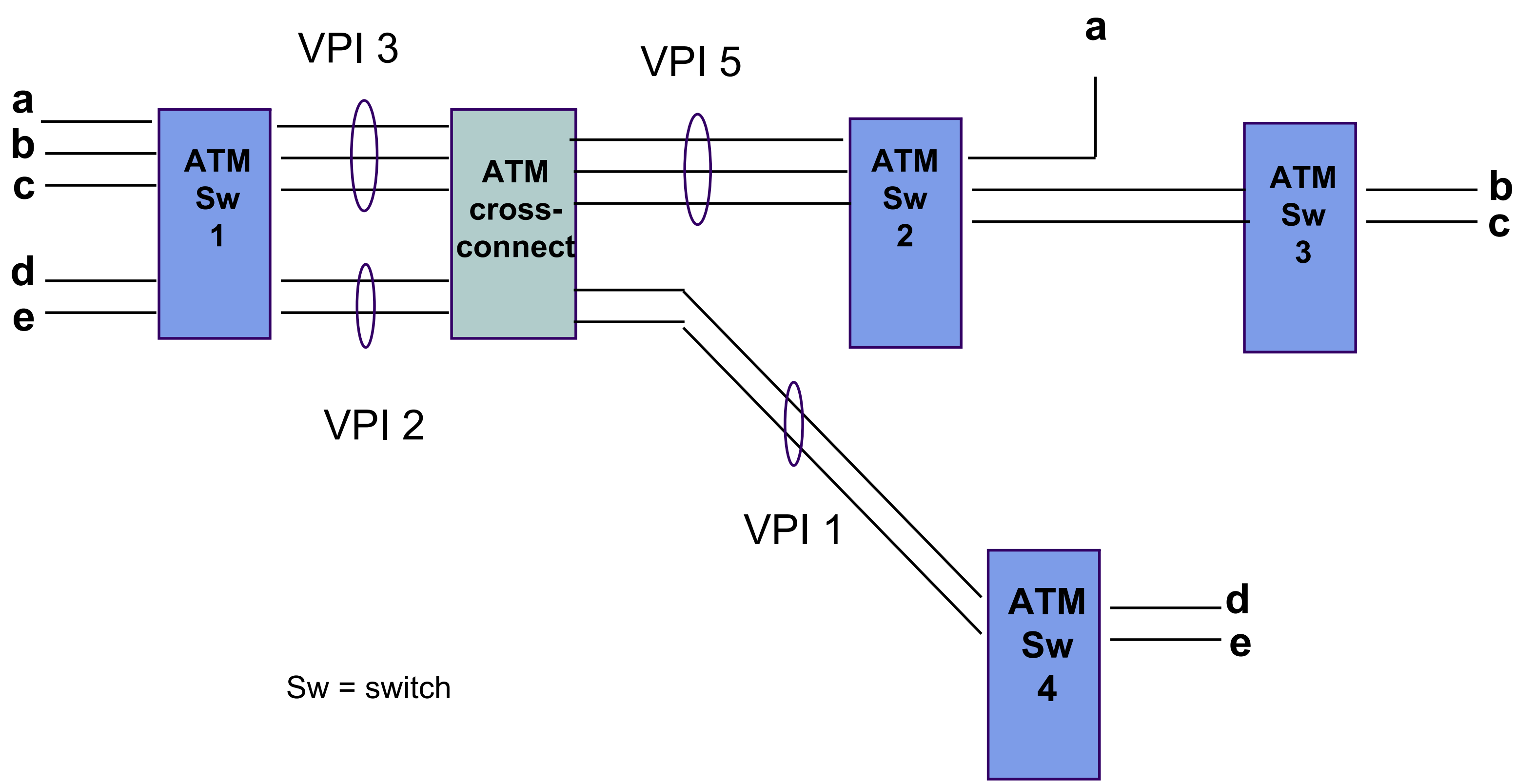

ATM switches can be implemented using shared memory, shared backplanes, or self-routing multi-stage fabrics

# ATM Virtual Connections

- Virtual connections setup across network
- Connections identified by locally-defined tags
- ATM Header contains virtual connection information:
  - 8-bit Virtual Path Identifier
  - 16-bit Virtual Channel Identifier
- Powerful traffic grooming capabilities
  - Multiple VCs can be bundled within a VP
  - Similar to tributaries with SONET, except variable bit rates possible



# VPI/VCI switching & multiplexing

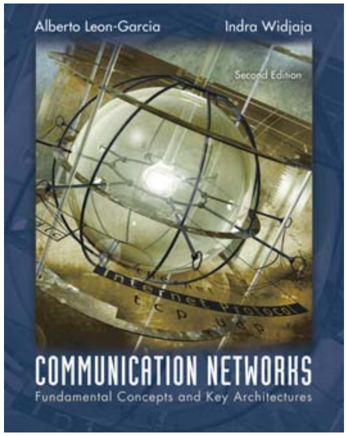



- Connections a,b,c bundled into VP at switch 1
  - Crossconnect switches VP without looking at VCIs
  - VP unbundled at switch 2; VC switching thereafter
- VPI/VCI structure allows creation virtual networks

# MPLS & ATM

- ATM initially touted as more scalable than packet switching
- ATM envisioned speeds of 150-600 Mbps
- Advances in optical transmission proved ATM to be the less scalable: @ 10 Gbps
  - Segmentation & reassembly of messages & streams into 48-byte cell payloads difficult & inefficient
  - Header must be processed every 53 bytes vs. 500 bytes on average for packets
  - Delay due to 1250 byte packet at 10 Gbps = 1 $\mu$sec; delay due to 53 byte cell @ 150 Mbps ≈ 3 $\mu$sec
- MPLS (Chapter 10) uses tags to transfer packets across virtual circuits in Internet

# Chapter 7
# Packet-Switching Networks




***Traffic Management***

***Packet Level***

***Flow Level***

***Flow-Aggregate Level***

# 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

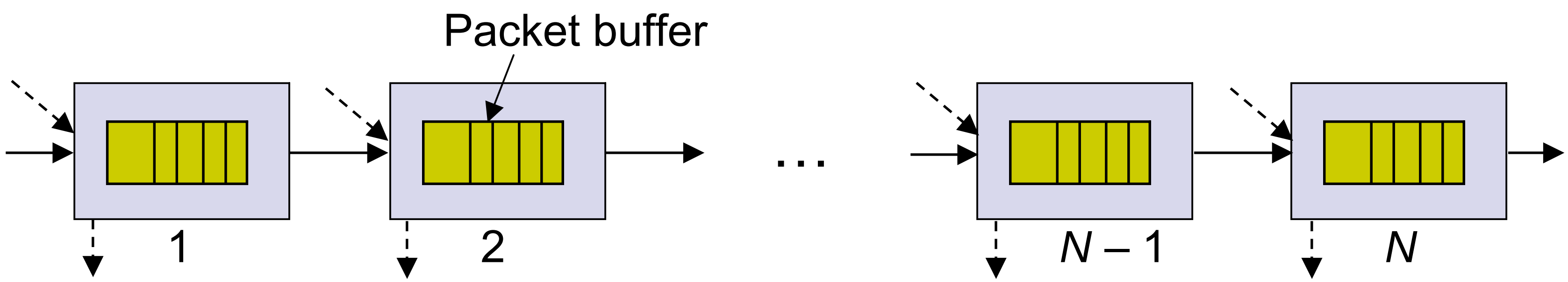
Packet traffic management

- 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

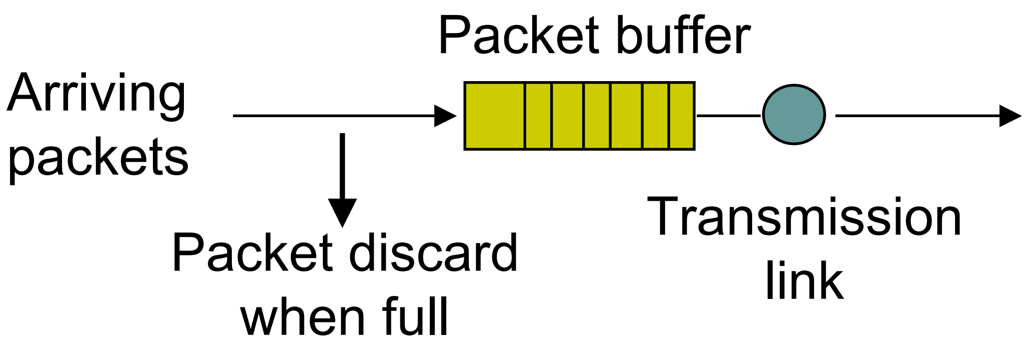



- A packet traversing network encounters delay and possible loss at various multiplexing points
- End-to-end performance is accumulation of per-hop performances

# 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

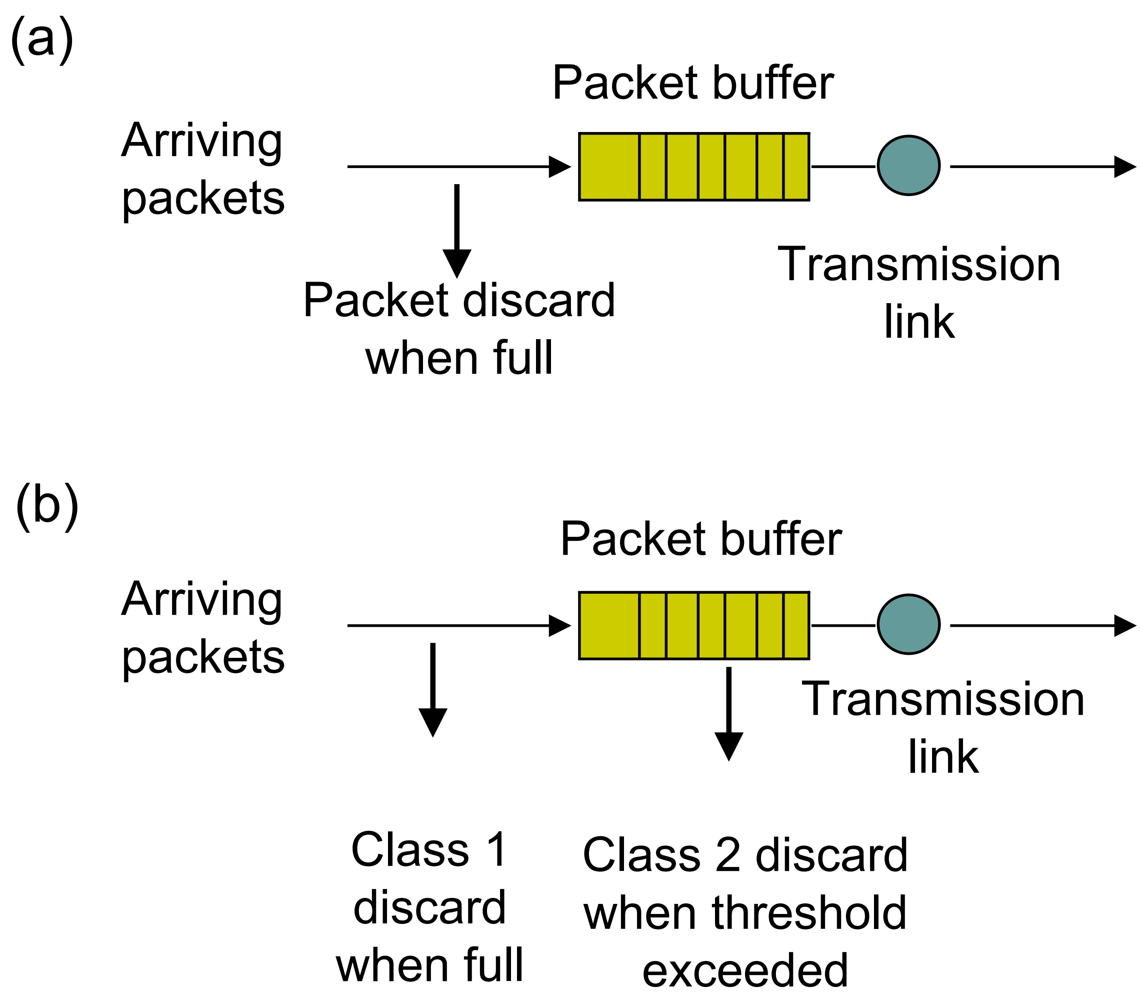



- All packet flows share the same buffer
- Transmission Discipline:  First-In, First-Out
- Buffering Discipline:  Discard arriving packets if buffer is full (Alternative:  random discard; pushout head-of-line, i.e. oldest, packet)

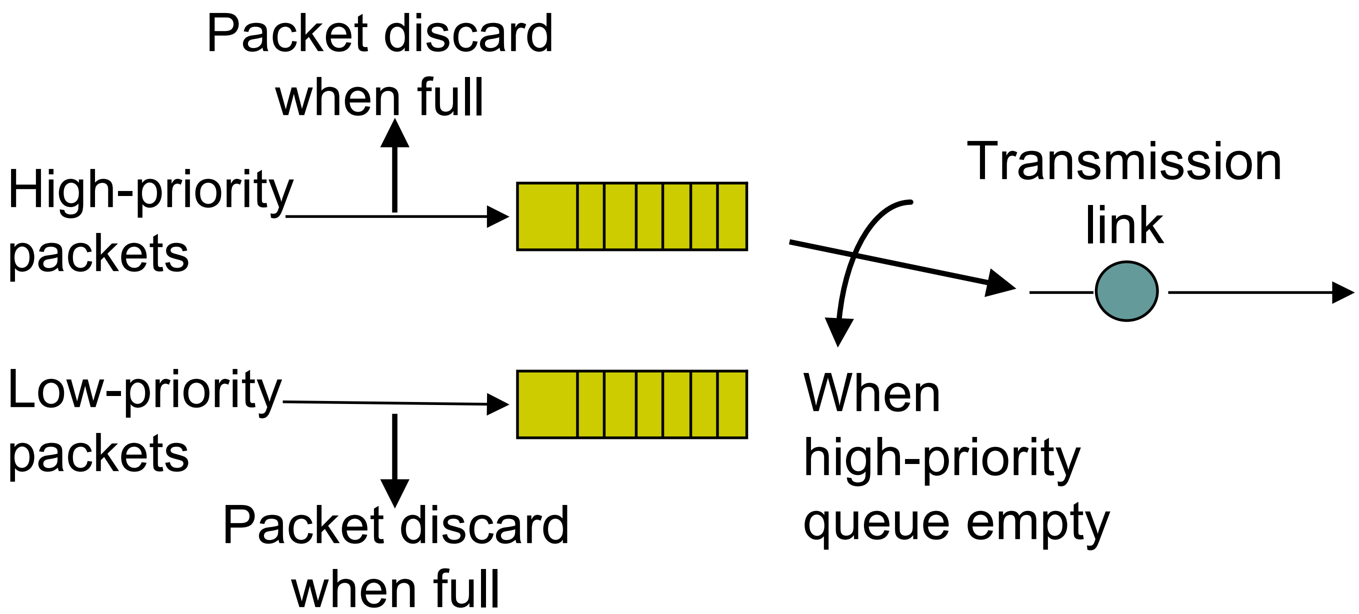
# FIFO Queueing

- 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

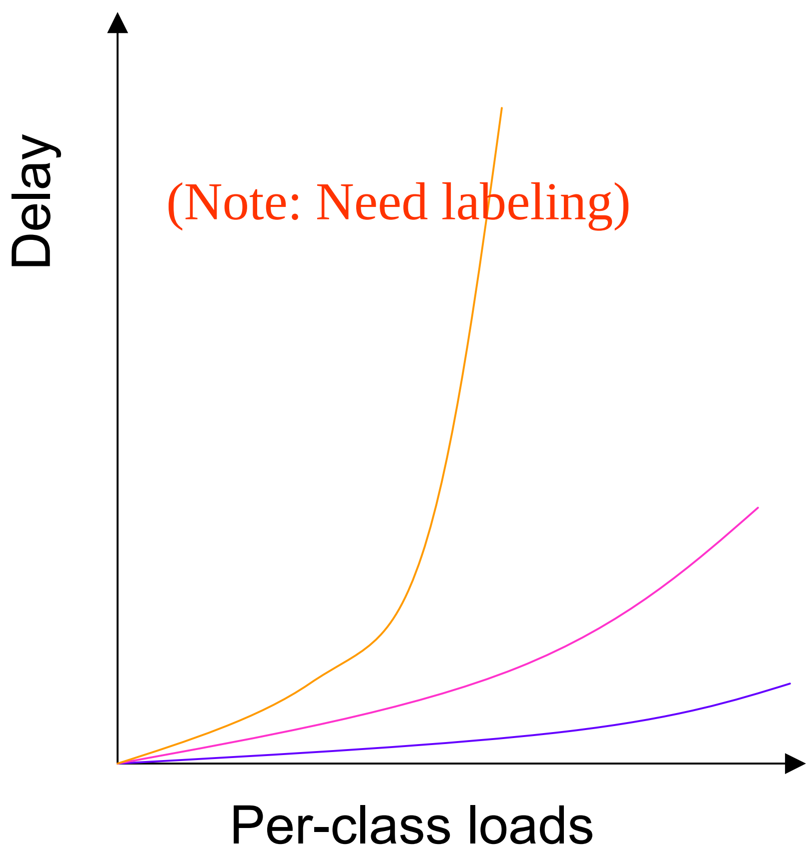


# HOL Priority Queueing



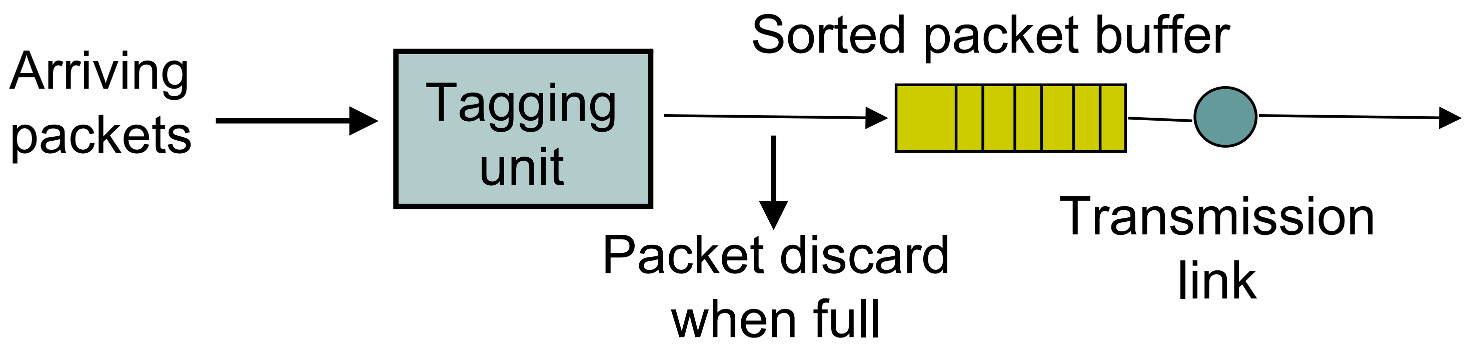

- High priority queue serviced until empty
- High priority queue has lower waiting time
- Buffers can be dimensioned for different loss probabilities
- Surge in high priority queue can cause low priority queue to saturate

# HOL Priority Features



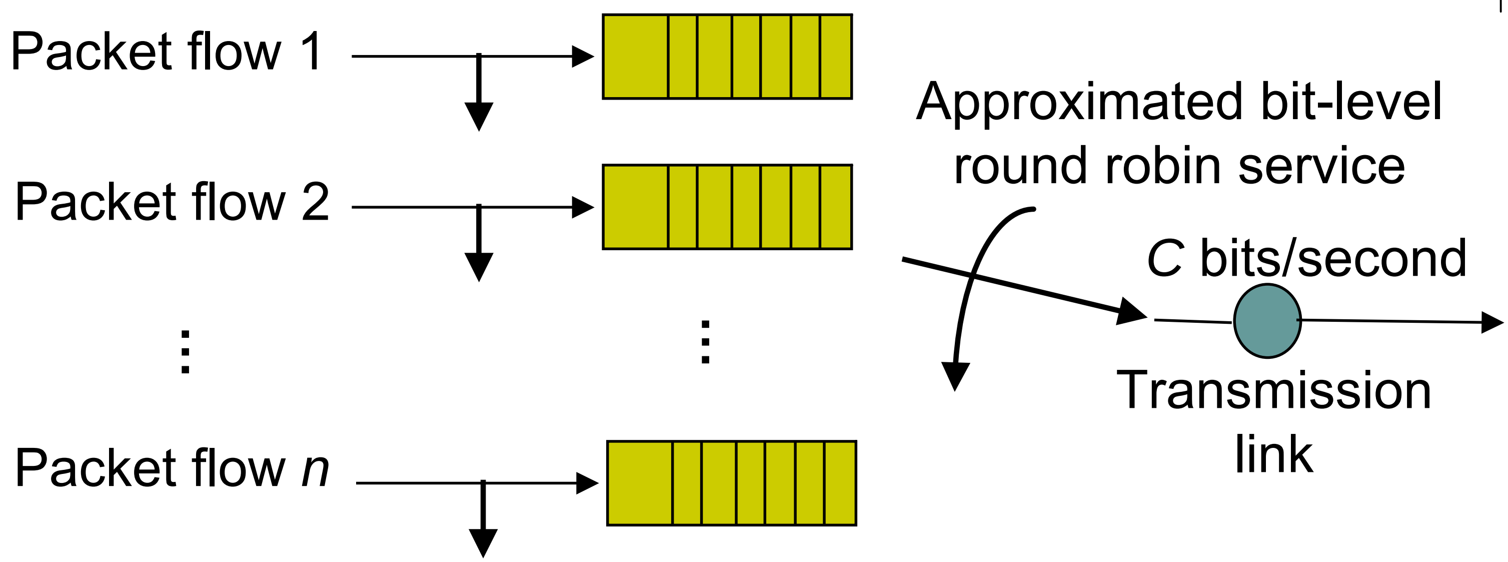

- Provides differential QoS
- Pre-emptive priority: lower classes invisible
- Non-preemptive priority: lower classes impact higher classes through residual service times
- High-priority classes can hog all of the bandwidth & starve lower priority classes
- Need to provide some isolation between classes

# Earliest Due Date Scheduling

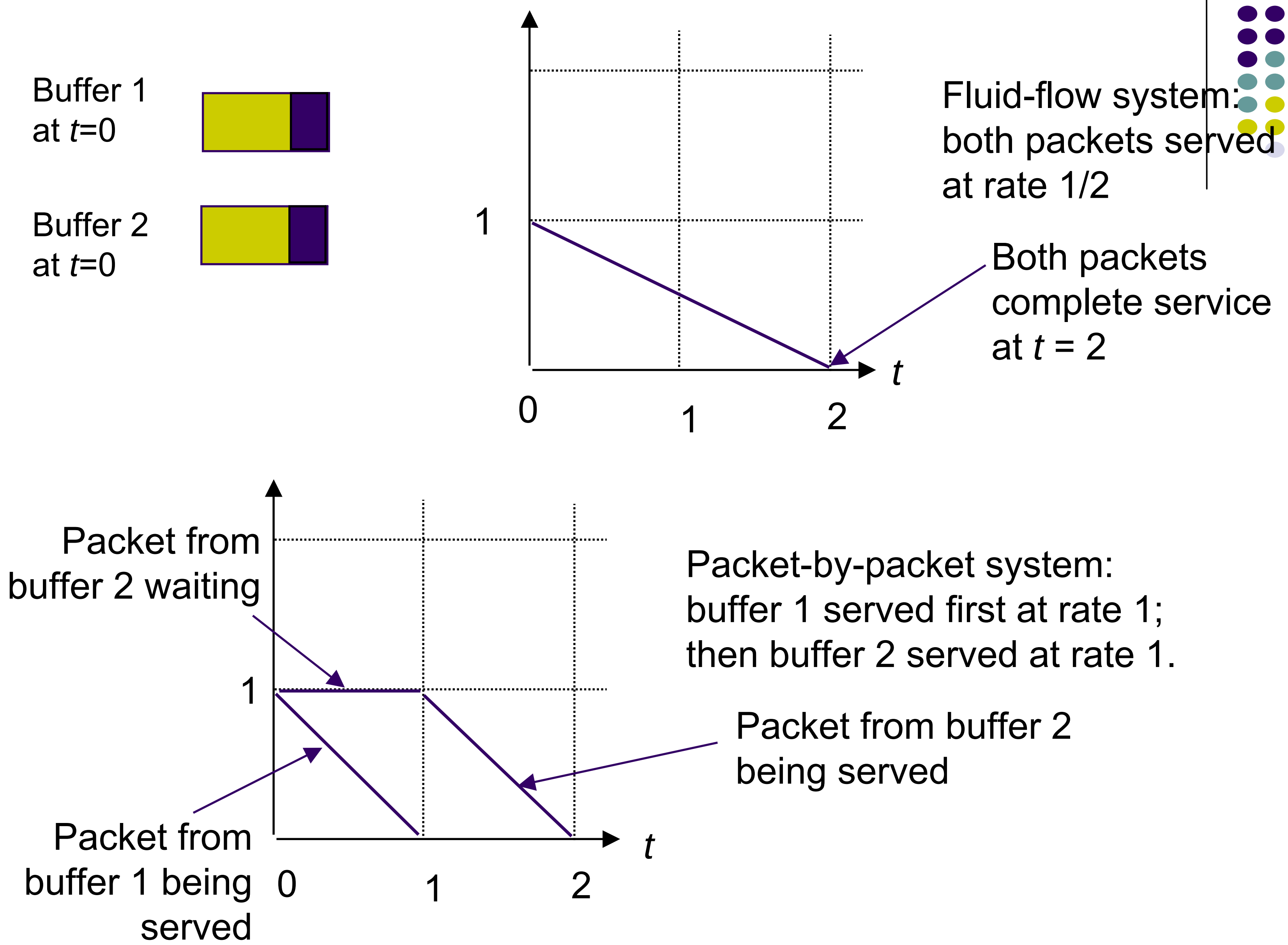


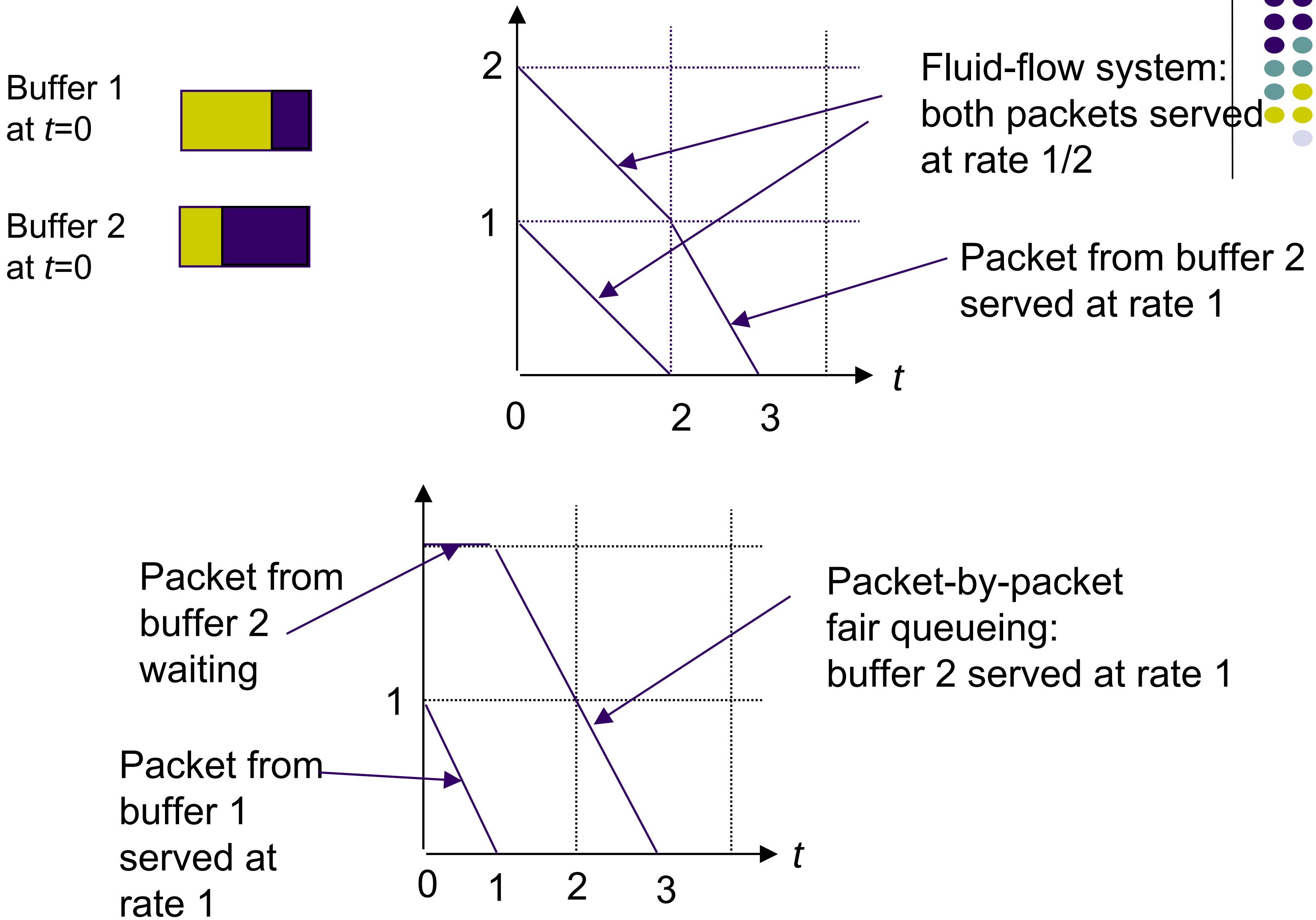

- Queue in order of "due date"
  - packets requiring low delay get earlier due date
  - packets without delay get indefinite or very long due dates

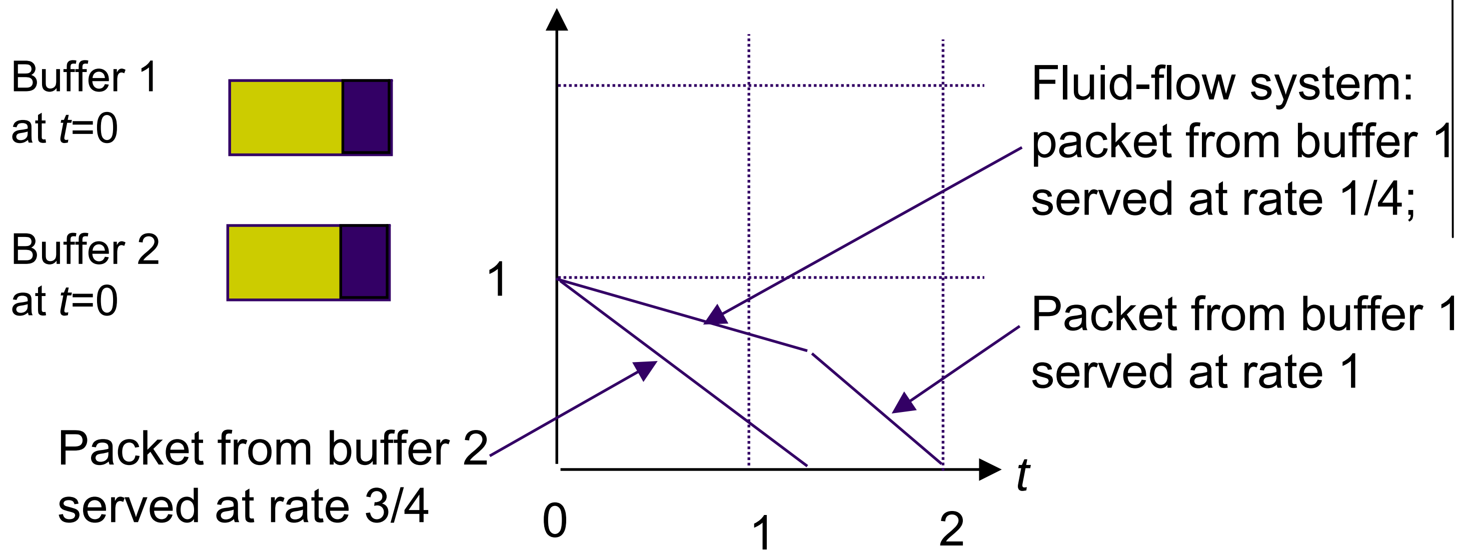
# Fair Queueing / Generalized Processor Sharing

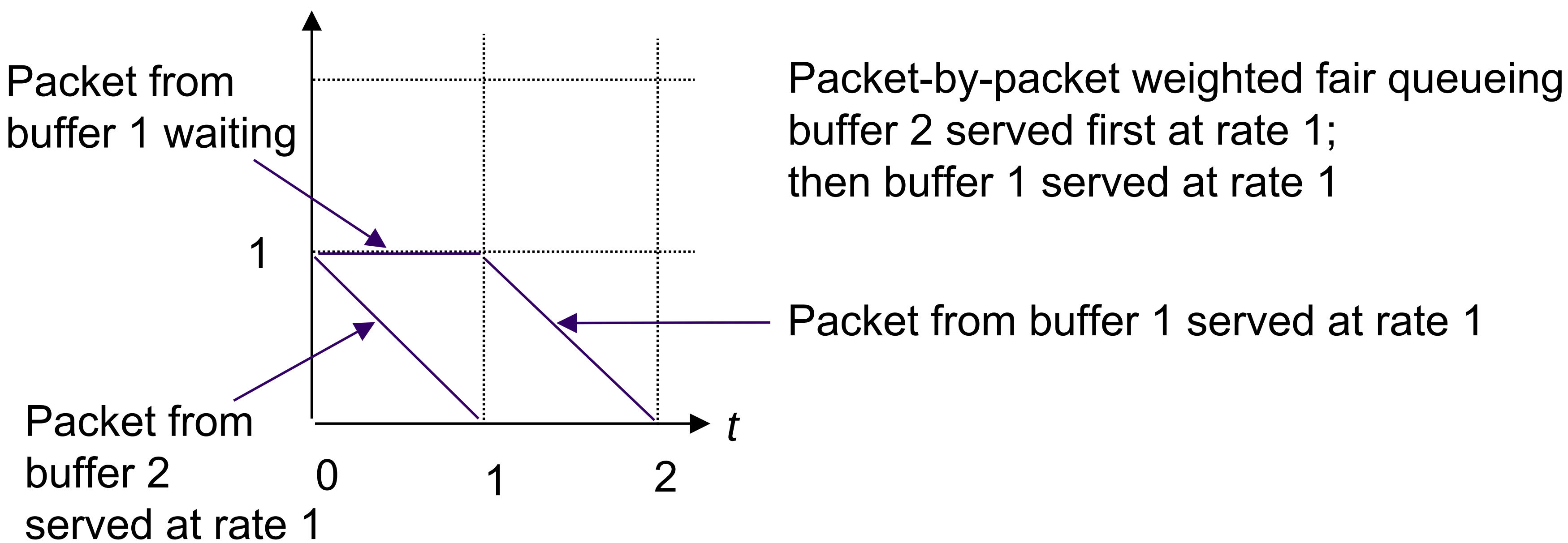



- Each flow has its own logical queue: prevents hogging; allows differential loss probabilities
- C bits/sec allocated equally among non-empty queues
  - transmission rate = C / n(t), where n(t)=# non-empty queues
- Idealized system assumes fluid flow from queues
- Implementation requires approximation: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

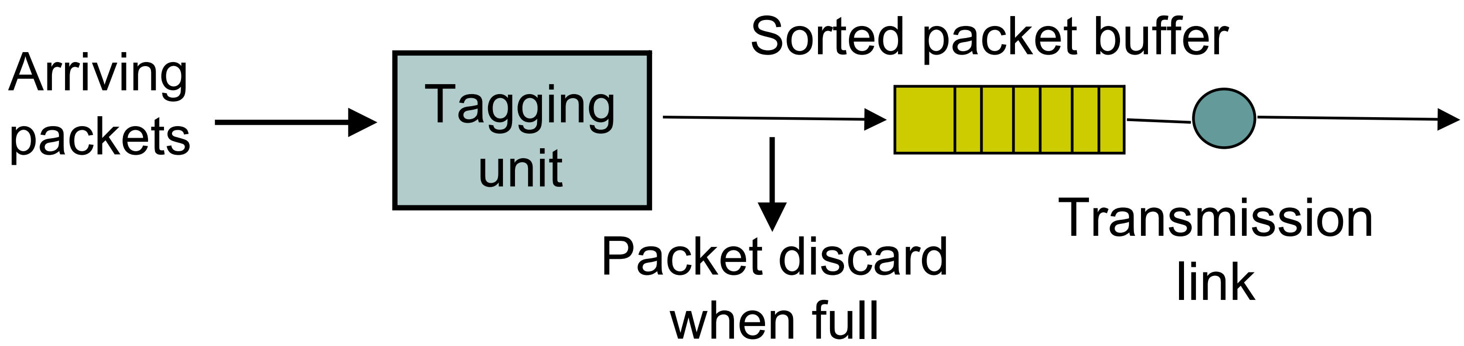

Buffer 1
at t=0
Buffer 2
at t=0
1
0
1
2
t
Fluid-flow system:
both packets served
at rate 1/2
Both packets
complete service
at t = 2
Packet from
buffer 2 waiting
1
Packet from
buffer 1 being
served
0
1
2
t
Packet-by-packet system:
buffer 1 served first at rate 1;
then buffer 2 served at rate 1.
Packet from buffer 2
being served


Buffer 1
at t=0
Buffer 2
at t=0
2
1
0
2
3
t
Fluid-flow system:
both packets served
at rate 1/2
Packet from buffer 2
served at rate 1
Packet from
buffer 2
waiting
1
Packet from
buffer 1
served at
rate 1
0
1
2
3
t
Packet-by-packet
fair queueing:
buffer 2 served at rate 1


Buffer 1
at t=0
Buffer 2
at t=0
1
0
1
2
t
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
1
0
1
2
t
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

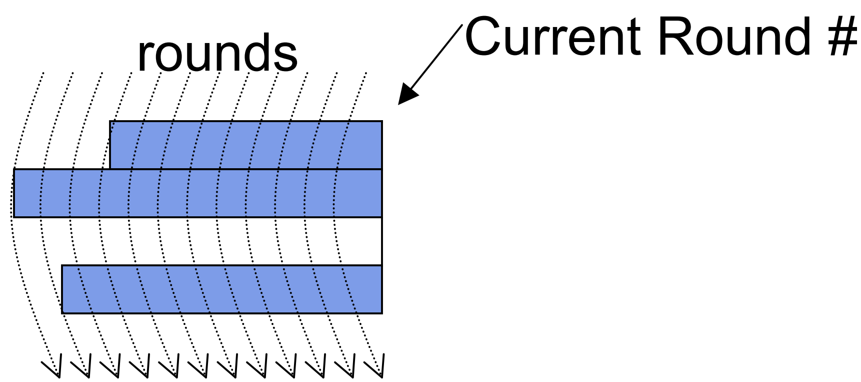
# Packetized GPS/WFQ




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

# 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
- Round number = number of cycles of service that have been completed

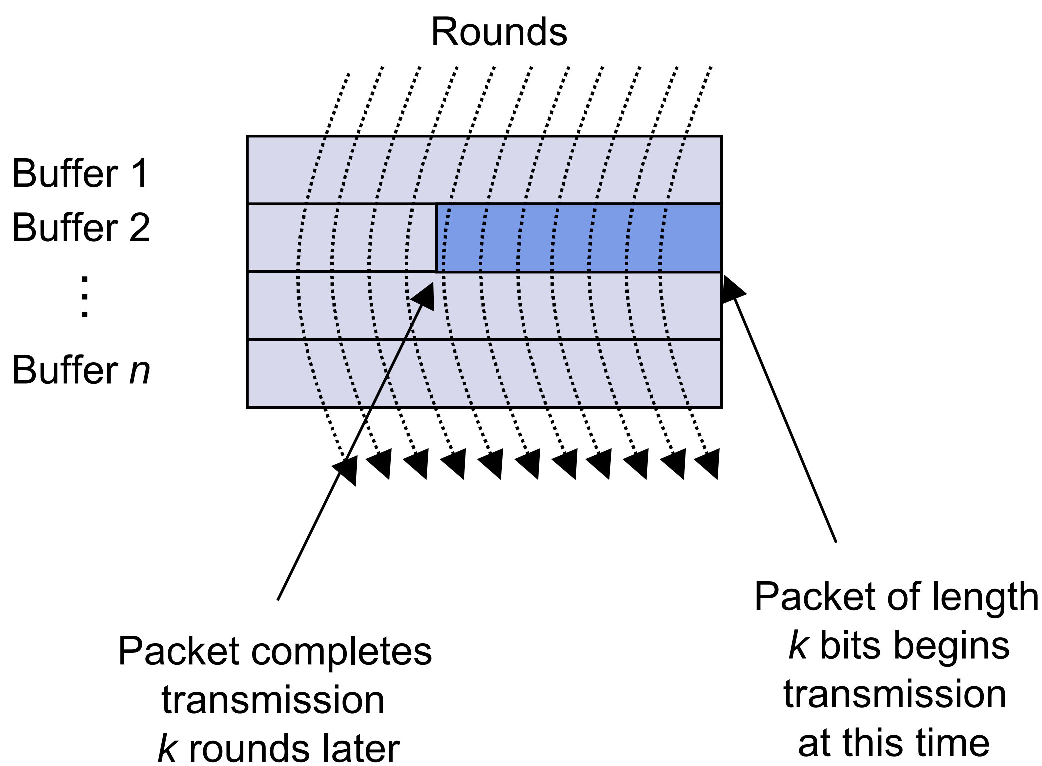



- If packet arrives to idle queue:

  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

Number of rounds = Number of bit transmission opportunities

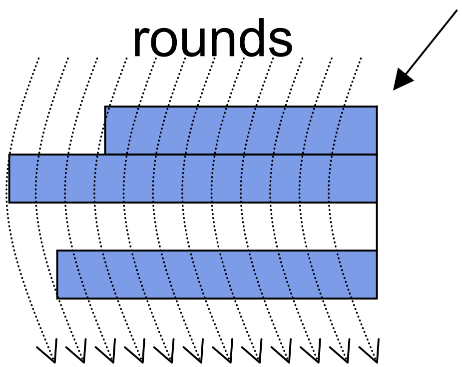



Differential Service:

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)*

- Fair Queueing:

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

- Weighted Fair Queueing:

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

# 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 (next section)

# Buffer Management

- Packet drop strategy:  Which packet to drop when buffers full
- Fairness:  protect 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 pkts if short-term avg of queue exceeds threshold
- pkt drop probability increases linearly with queue length
- mark offending pkts
- improves performance of cooperating TCP sources
- increases loss probability of misbehaving sources

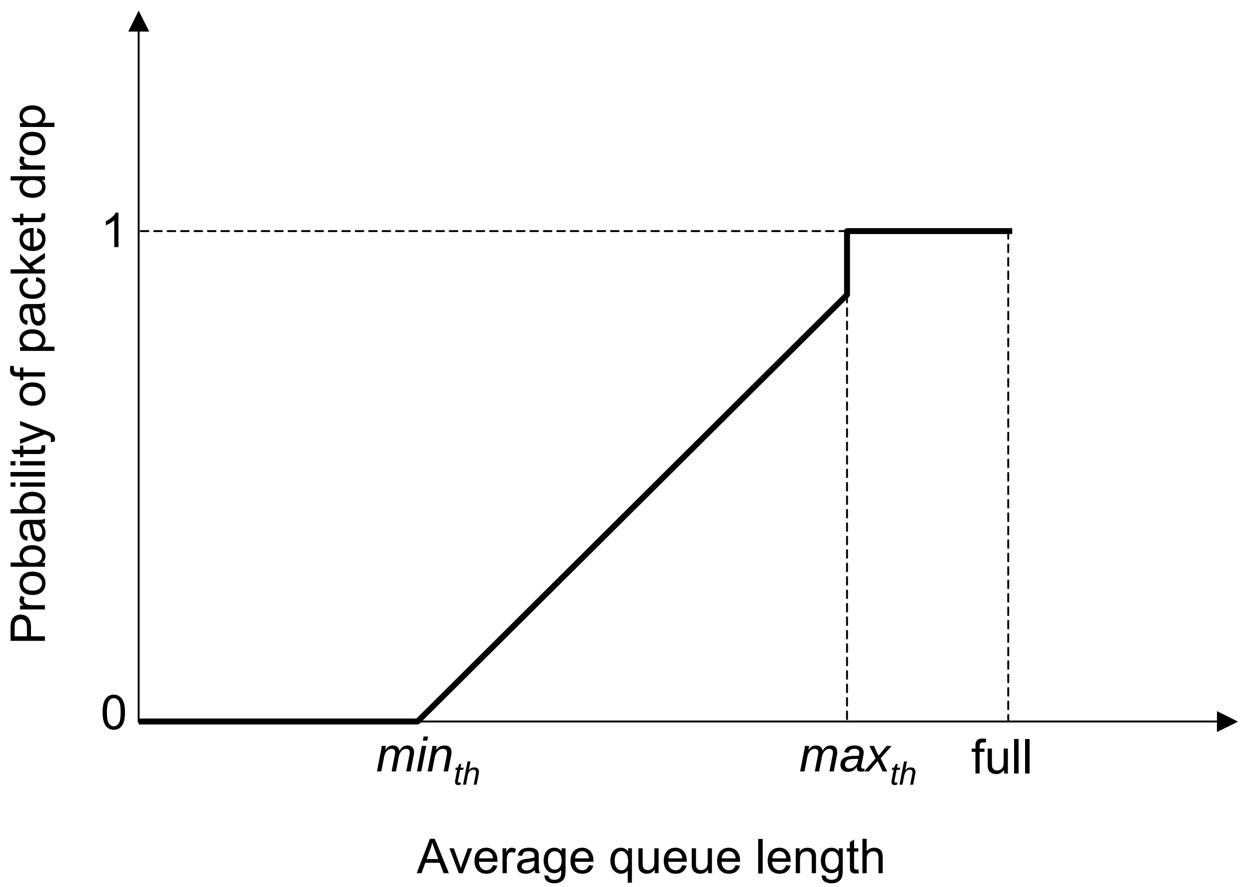
# Random Early Detection (RED)

- 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

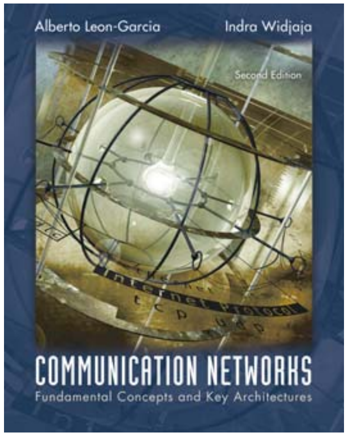
Algorithm:

- 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

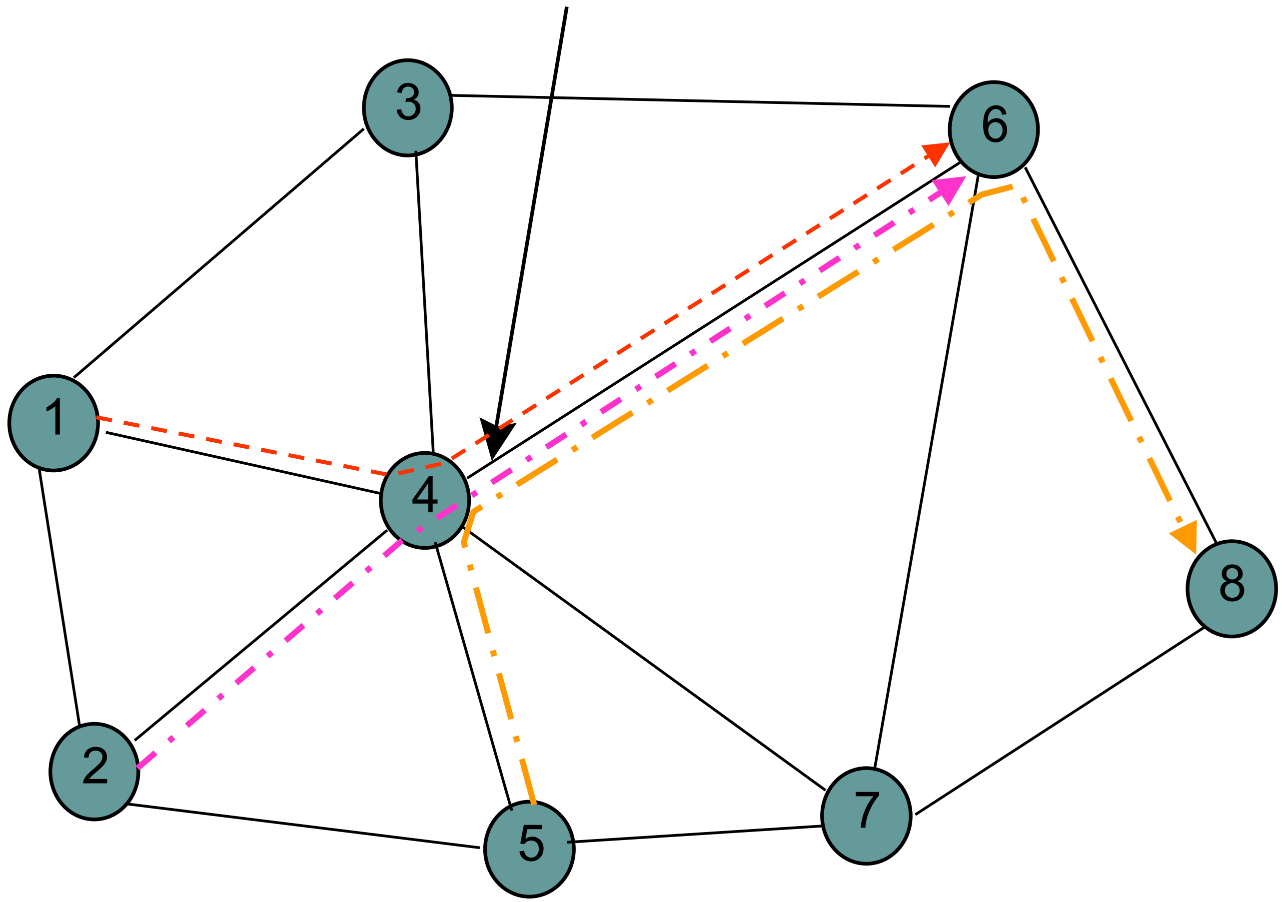


# Chapter 7
# Packet-Switching Networks




## *Traffic Management at the Flow Level*

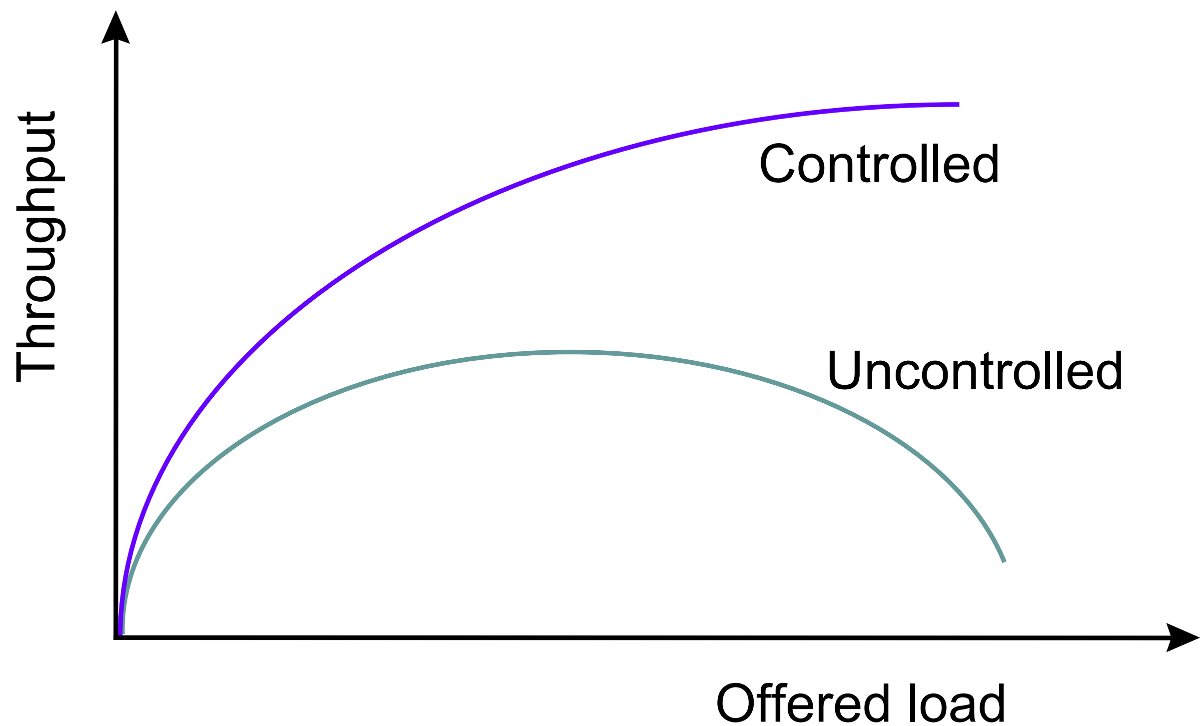
Congestion occurs when a surge of traffic overloads network resources




Approaches to Congestion Control:

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

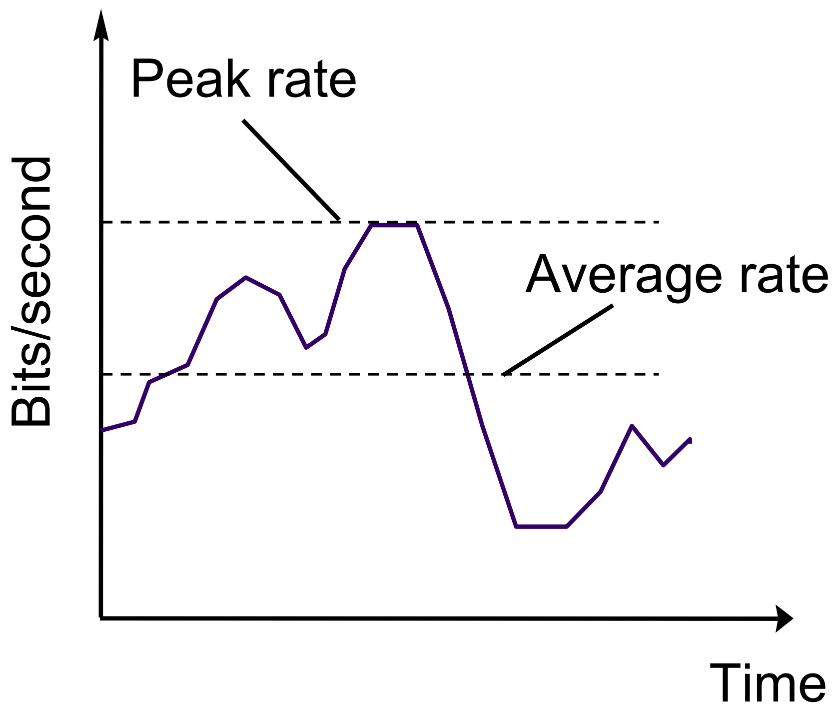
Ideal effect of congestion control:
Resources used efficiently up to capacity available



# 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



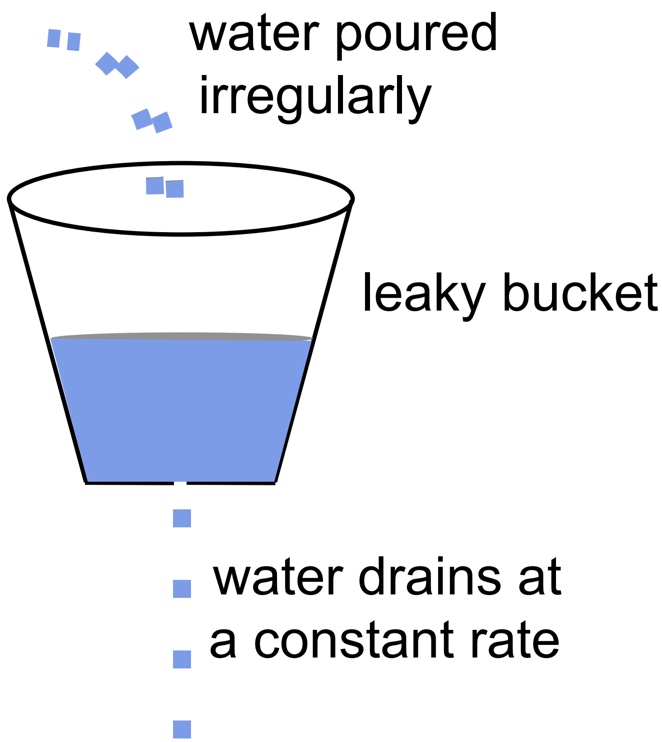

Typical bit rate demanded by a variable bit rate information source

- 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

# 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 can be used to police arrival rate of a packet stream




Leak rate corresponds to long-term rate

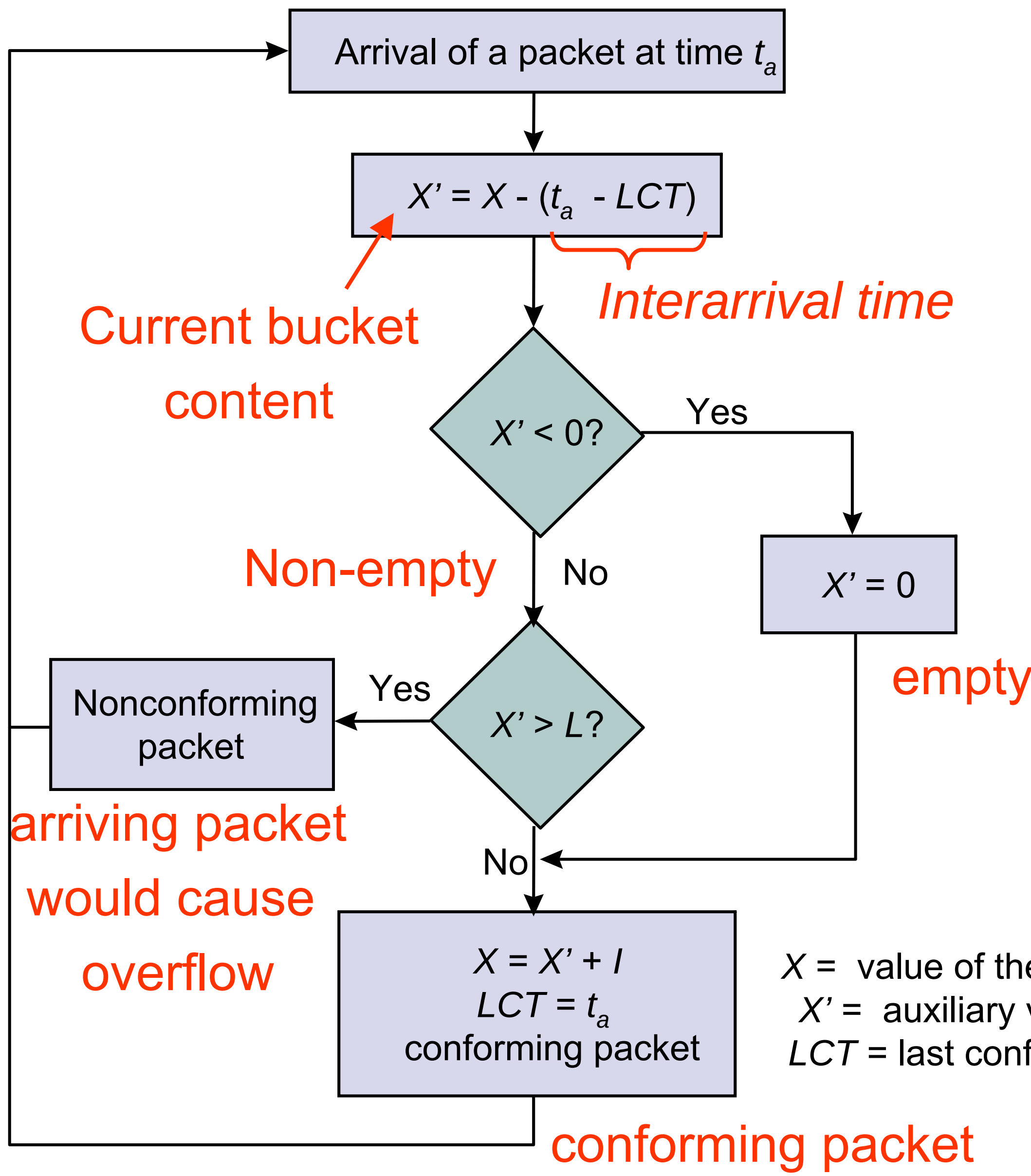
Bucket depth corresponds to maximum allowable burst arrival

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

# Leaky Bucket Algorithm




Depletion rate:
1 packet per unit time

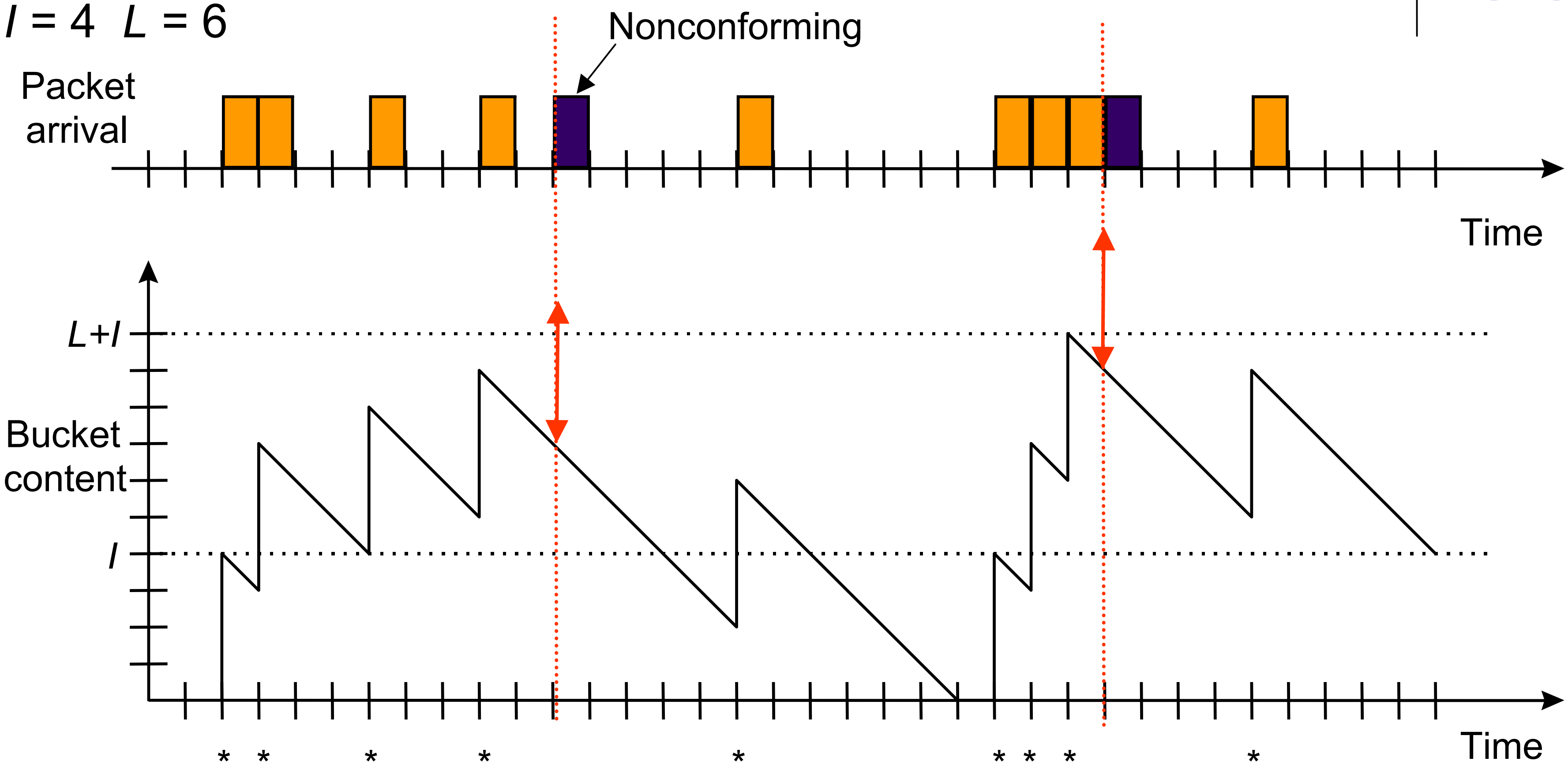
$L+I$ = Bucket Depth

$I$ = 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

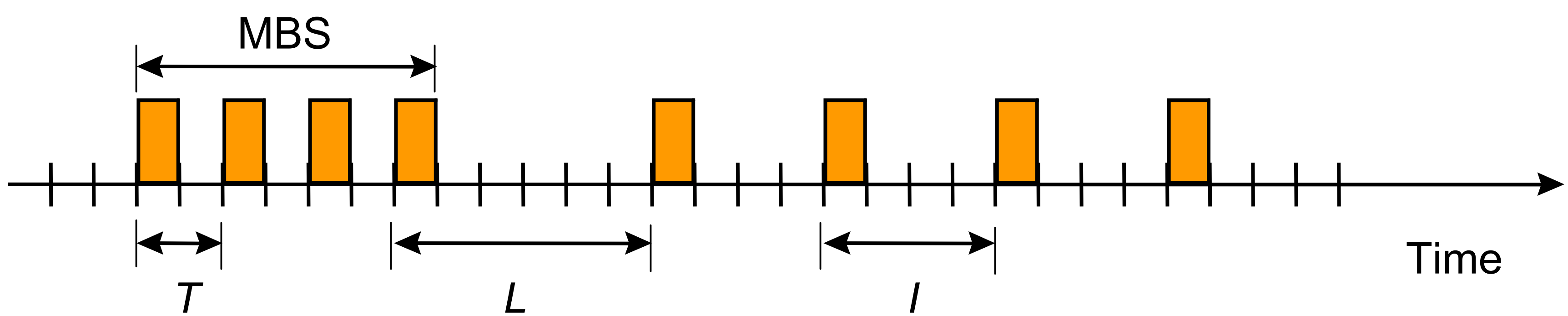



Non-conforming packets not allowed into bucket & hence not included in calculations

# Policing Parameters

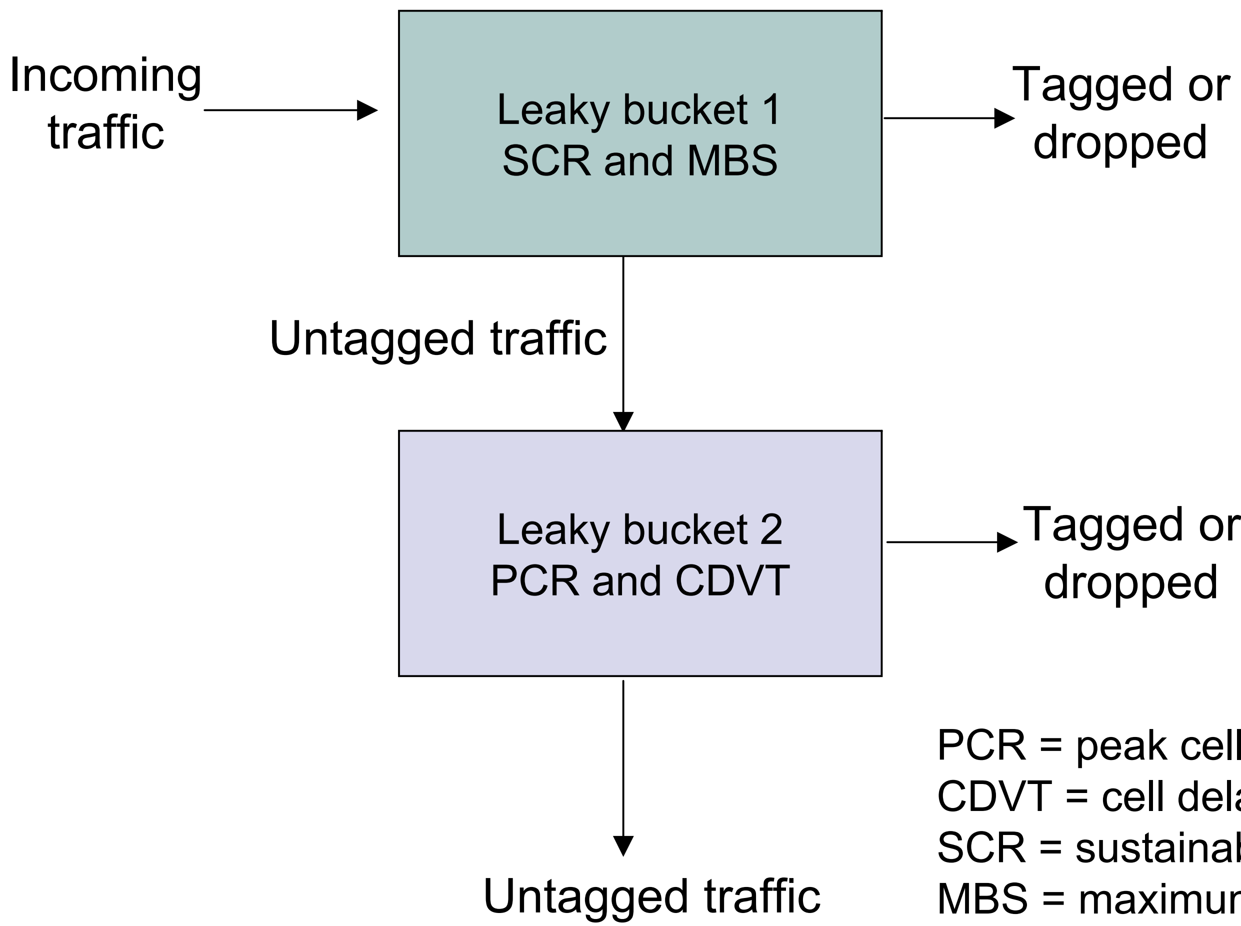
*T* = 1 / peak rate
MBS = maximum burst size
*I* = nominal interarrival time = 1 / sustainable rate

$$MBS = 1 + \left\lfloor \frac{L}{I - T} \right\rfloor$$



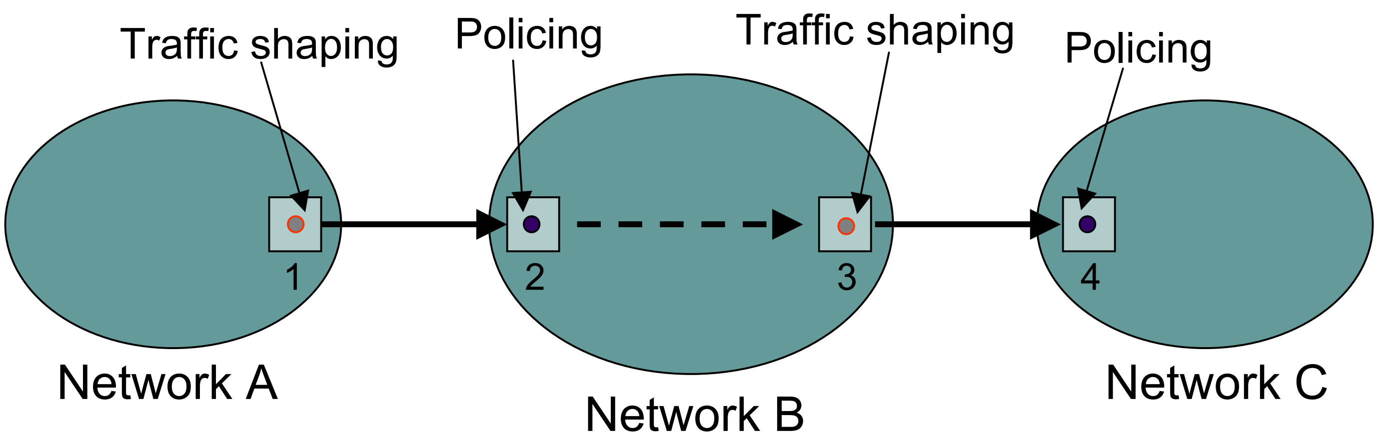
# Dual Leaky Bucket

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



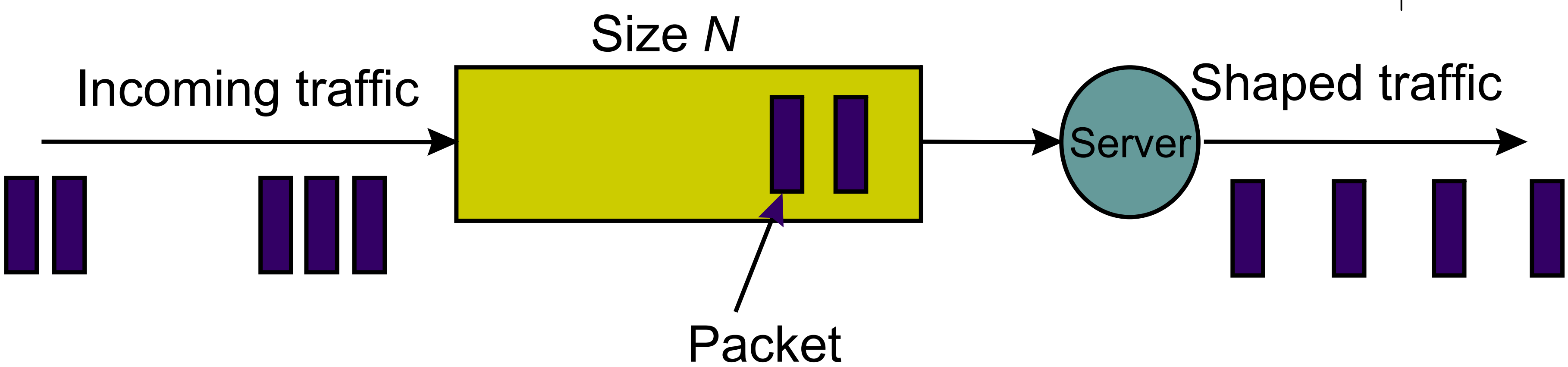

PCR = peak cell rate
CDVT = cell delay variation tolerance
SCR = sustainable cell rate
MBS = maximum burst size

# 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

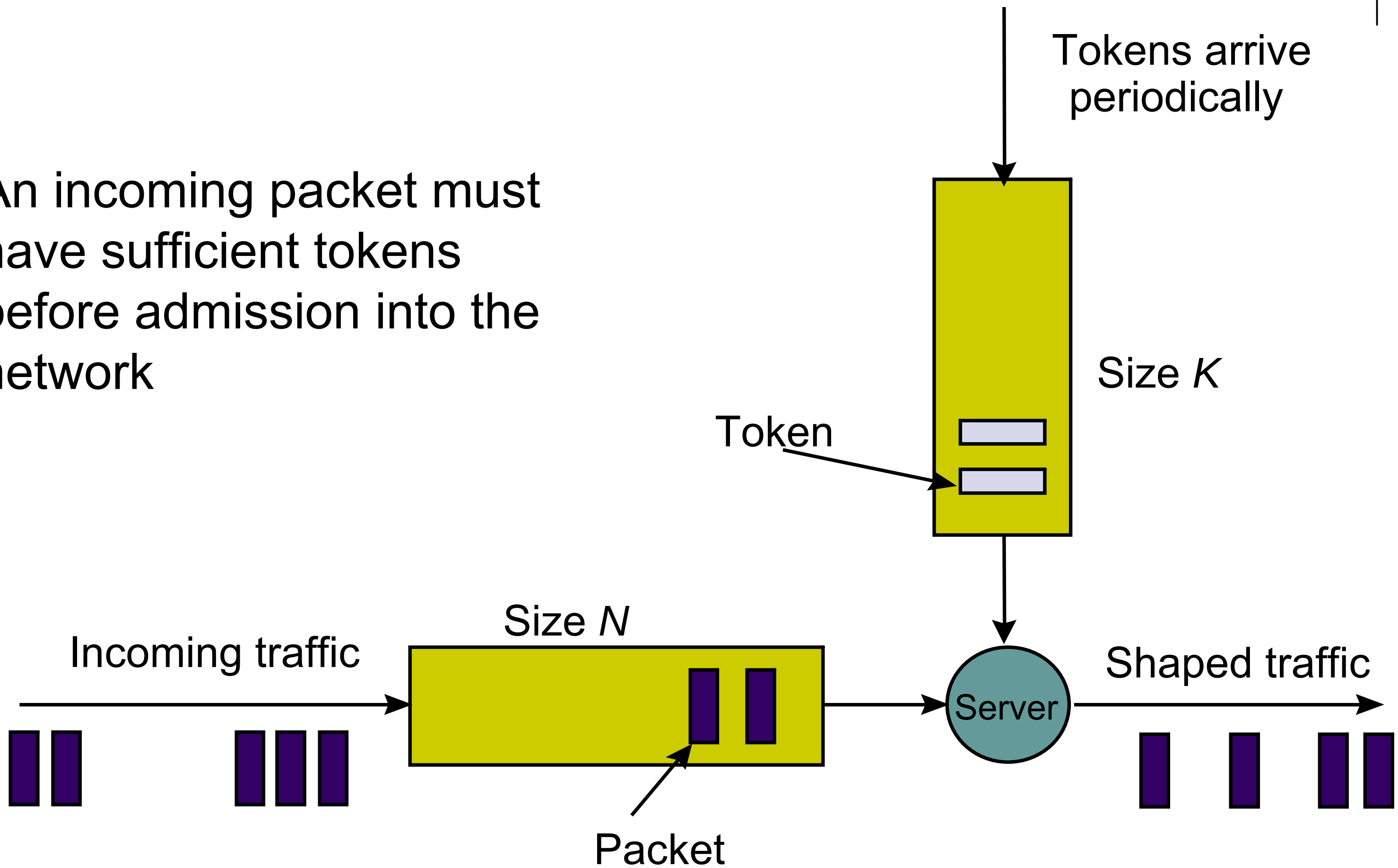
# Leaky Bucket Traffic Shaper




- 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

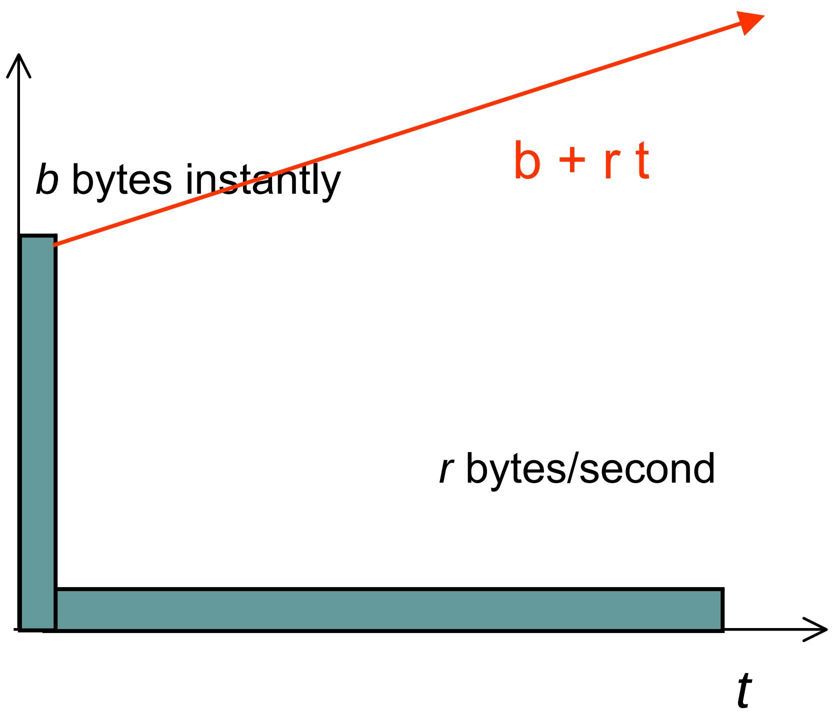
An incoming packet must have sufficient tokens before admission into the network



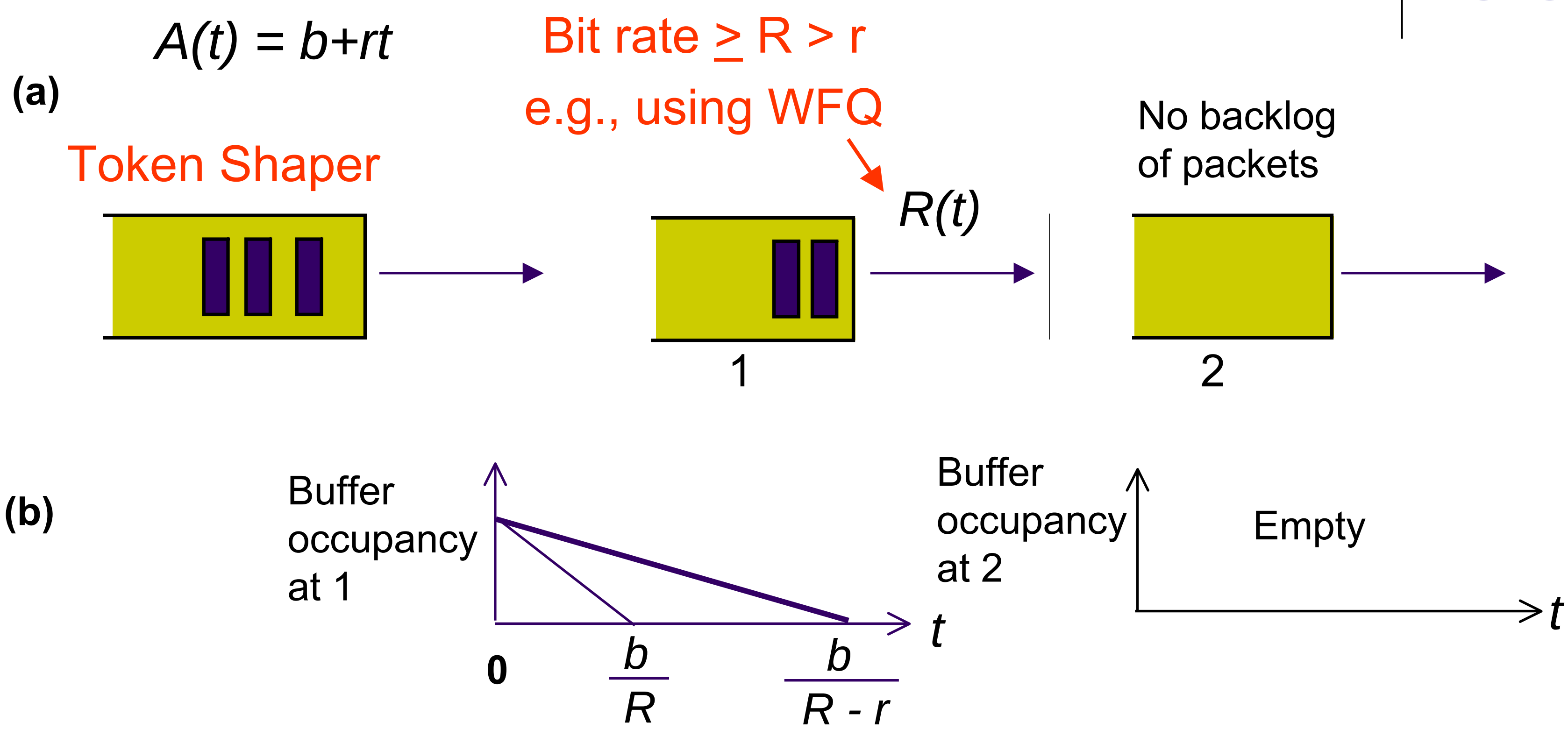

- Token rate regulates transfer of packets
- If sufficient tokens available, packets enter network without delay
- K determines how much burstiness allowed into the network

# Token Bucket Shaping Effect

The token bucket constrains the traffic from a source to be limited to *b* + *r t* bits in an interval of length *t*



# Packet transfer with Delay Guarantees




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

# Delay Bounds with WFQ / PGPS

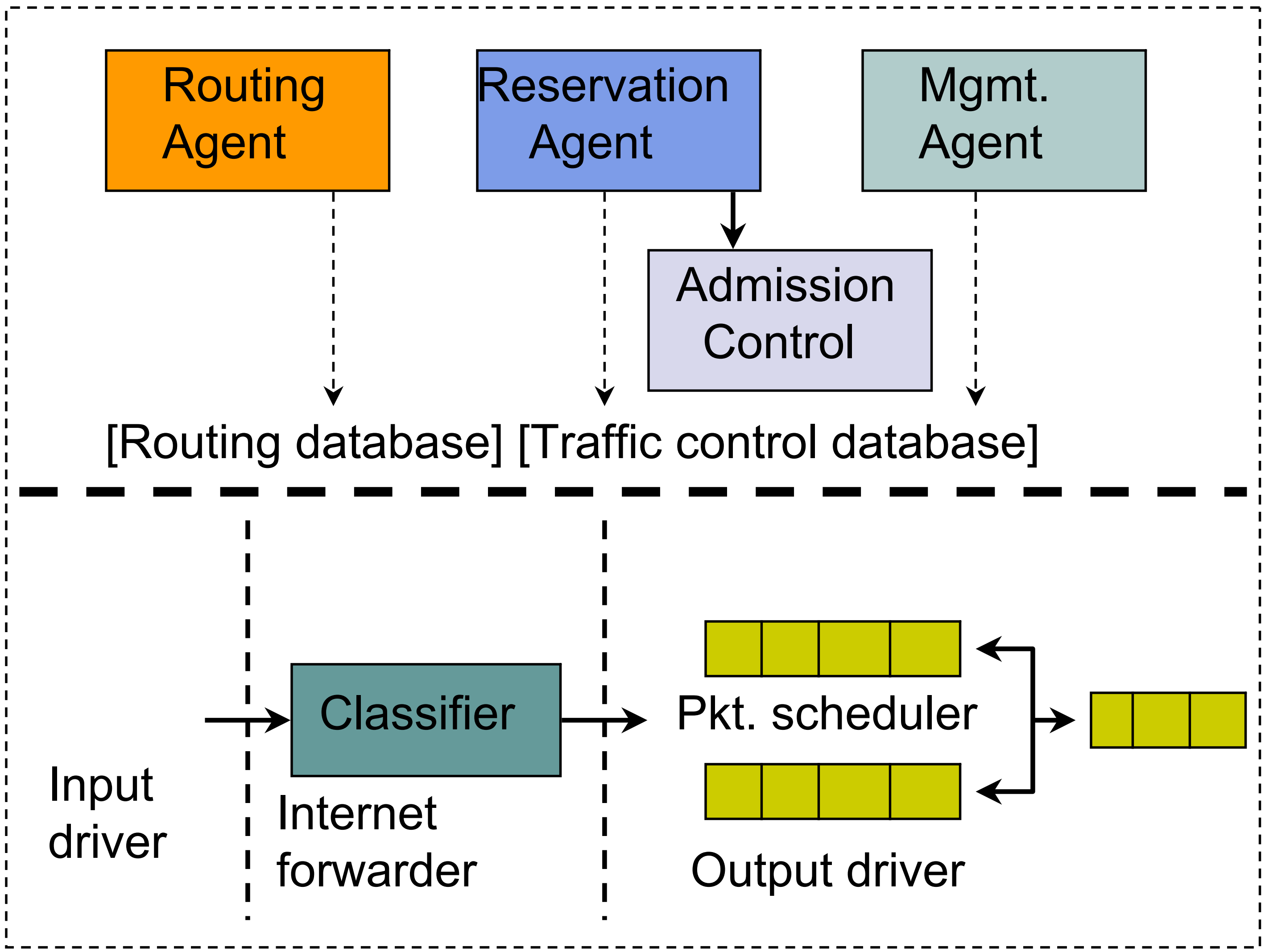
- Assume
  - traffic shaped to parameters b & r
  - schedulers give flow at least rate R>r
  - H hop path
  - m is maximum packet size for the given flow
  - M maximum packet size in the network
  - $R_j$ transmission rate in jth hop
- Maximum end-to-end delay that can be experienced by a packet from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

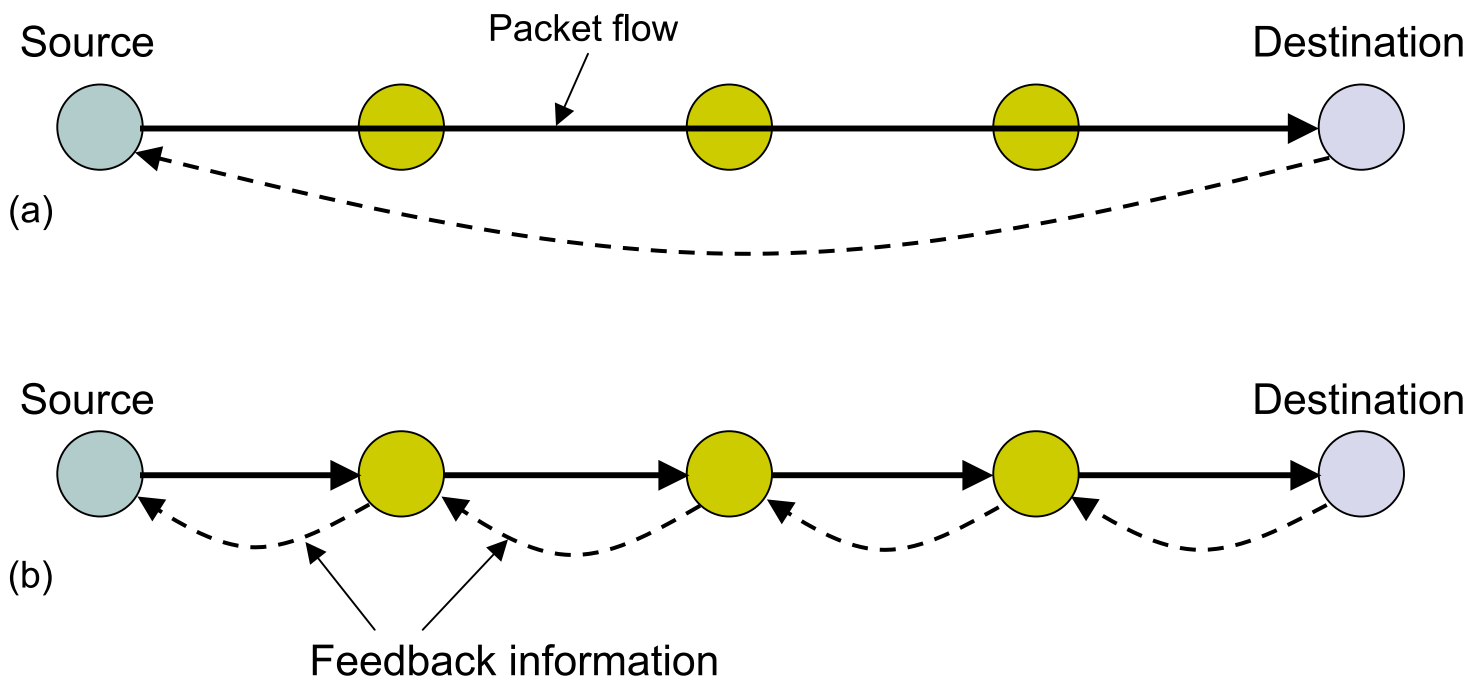
# Current View of Router Function



# Closed-Loop Flow Control

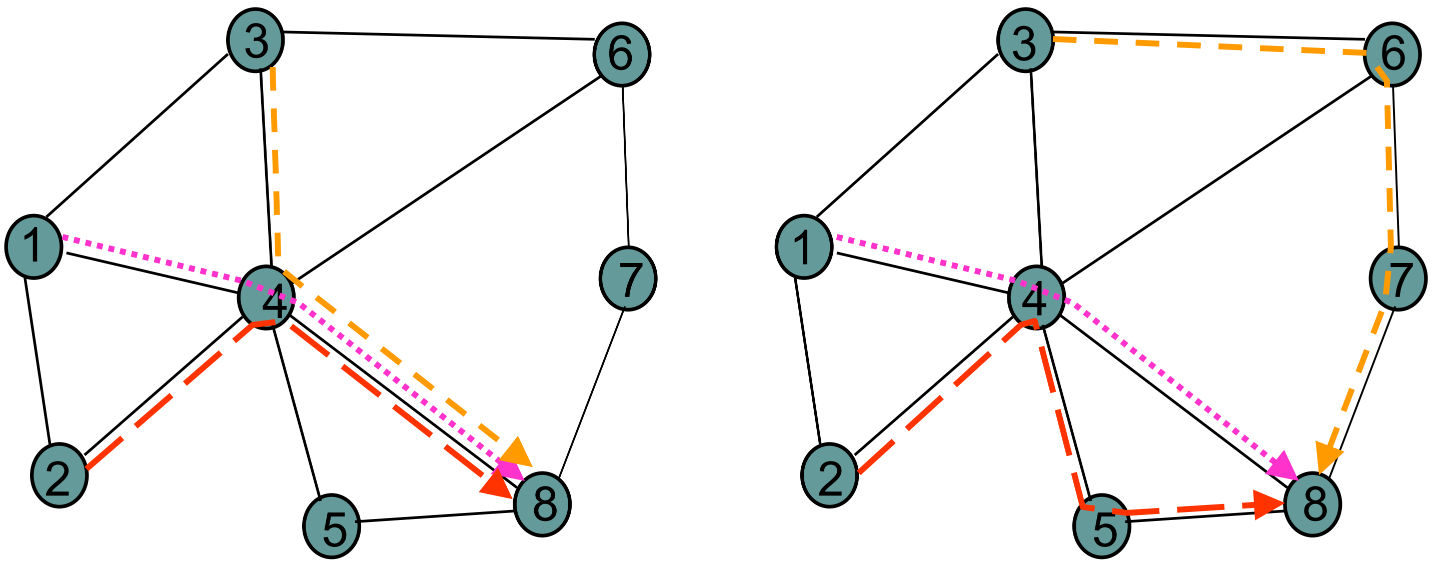
- Congestion control
  - feedback information to regulate flow from sources into network
  - Based on buffer content, link utilization, etc.
  - Examples: TCP at transport layer; congestion control at ATM level
- End-to-end vs. Hop-by-hop
  - Delay in effecting control
- Implicit vs. Explicit Feedback
  - 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




(a) (b)

Shortest path routing
congests link 4 to 8

Better flow allocation
distributes flows
more uniformly