UNIT I ISDN – STANDARDS AND SERVICES

Switching networks

- Long distance transmission are done over a network of switched nodes. Nodes not concerned with content of data.
- End devices are stations:

Computer, terminal, phone,etc.

- A collection of nodes and connection is a network.
- Data routed being by network node by node.

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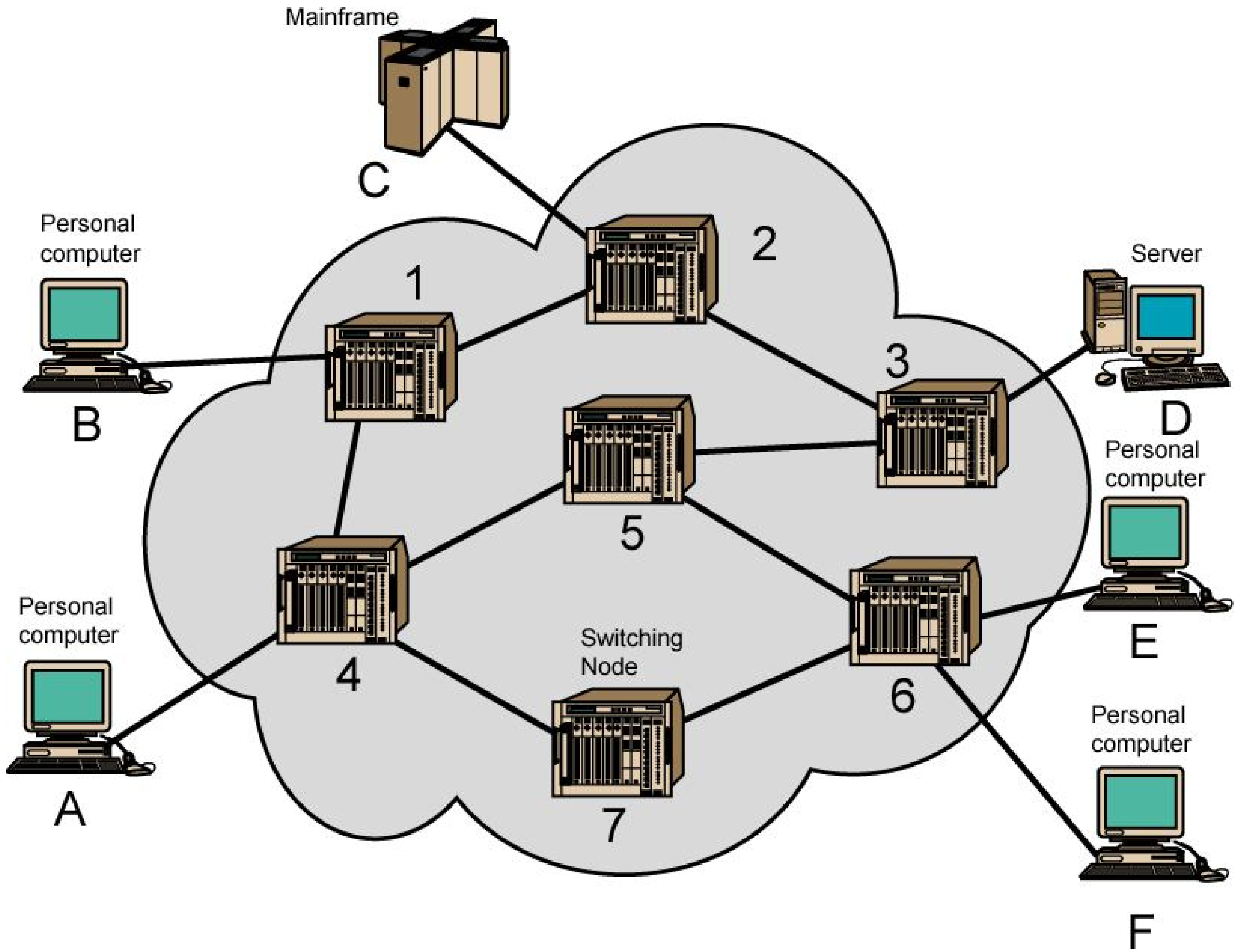
Nodes:

- Nodes may connect to other nodes only, or to stations and other nodes
- Node to node links usually multiplexed
- Network is usually partially connected
  - Some redundant connections are desirable for reliability
- Two different switching technologies
  - Circuit switching
  - Packet switching

Simple switched network



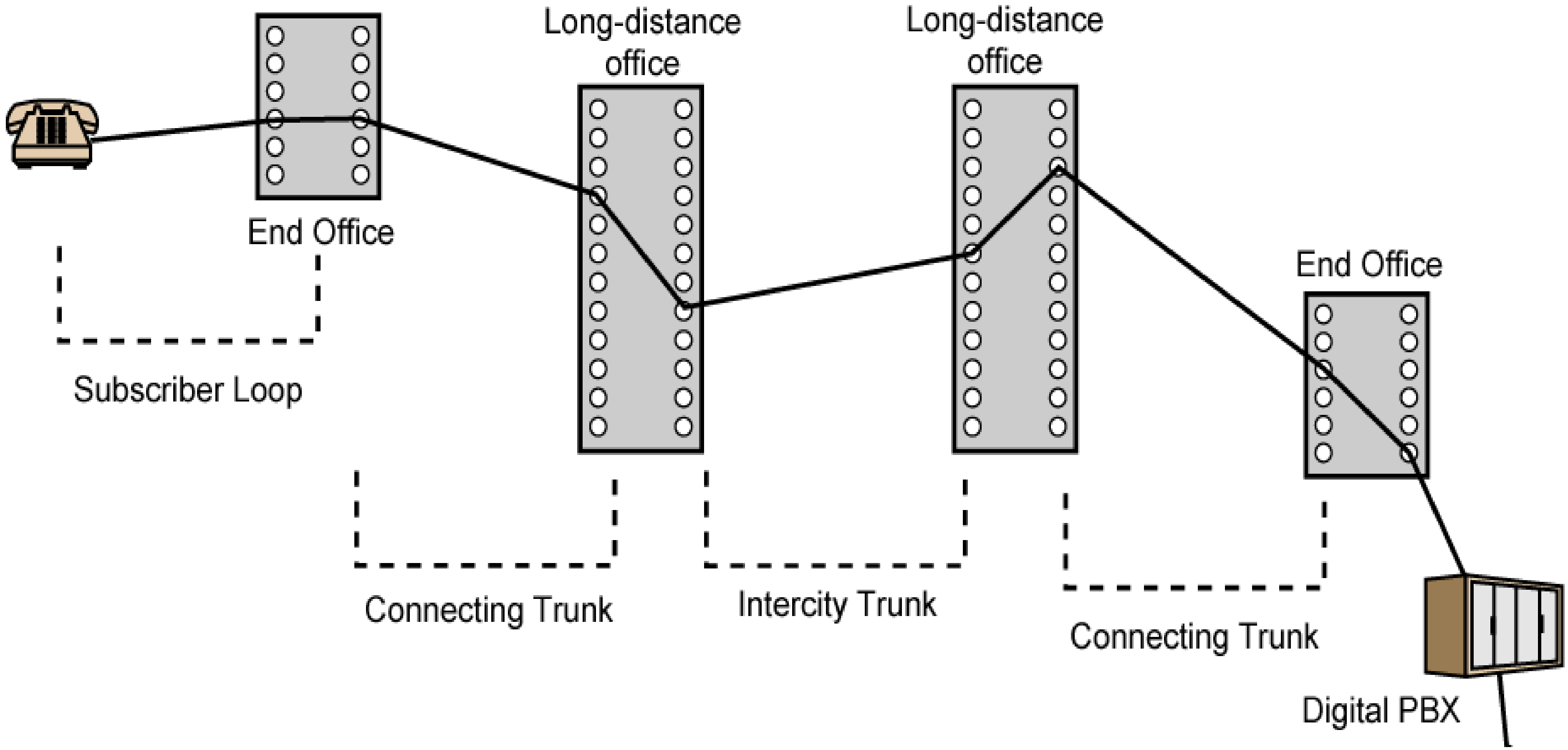
Circuit switching

- Dedicated communication path between two stations
- Three phases
  - Establish
  - Transfer
  - Disconnect
- Must have switching capacity and channel capacity to establish connection`
- Must have intelligence to work out routing

Circuit Switching Concepts

- Digital Switch
  - Provide transparent signal path between devices
- Network Interface
- Control Unit
  - Establish connections
    - Generally on demand
    - Handle and acknowledge requests
    - Determine if destination is free
    - construct path
  - Maintain connection
  - Disconnect

Circuit switched network



Telecomms Components

- Subscriber
  - Devices attached to network
- Subscriber line
  - Local Loop
  - Subscriber loop
  - Connection to network
  - Few km up to few tens of km
- Exchange
  - Switching centers
  - End office - supports subscribers

Packet Switching Principles

Packet switching designed for voice

- Resources dedicated to a particular call
- Much of the time a data connection is idle
- Data rate is fixed
- Both ends must operate at the same rate

- Data transmitted in small packets

  Typically 1000 octets

  - Longer messages split into series of packets
  - Each packet contains a portion of user data plus some control info
- Control info Routing (addressing) info Packets are received, stored briefly (buffered) and past on to the next node
- Store and forward

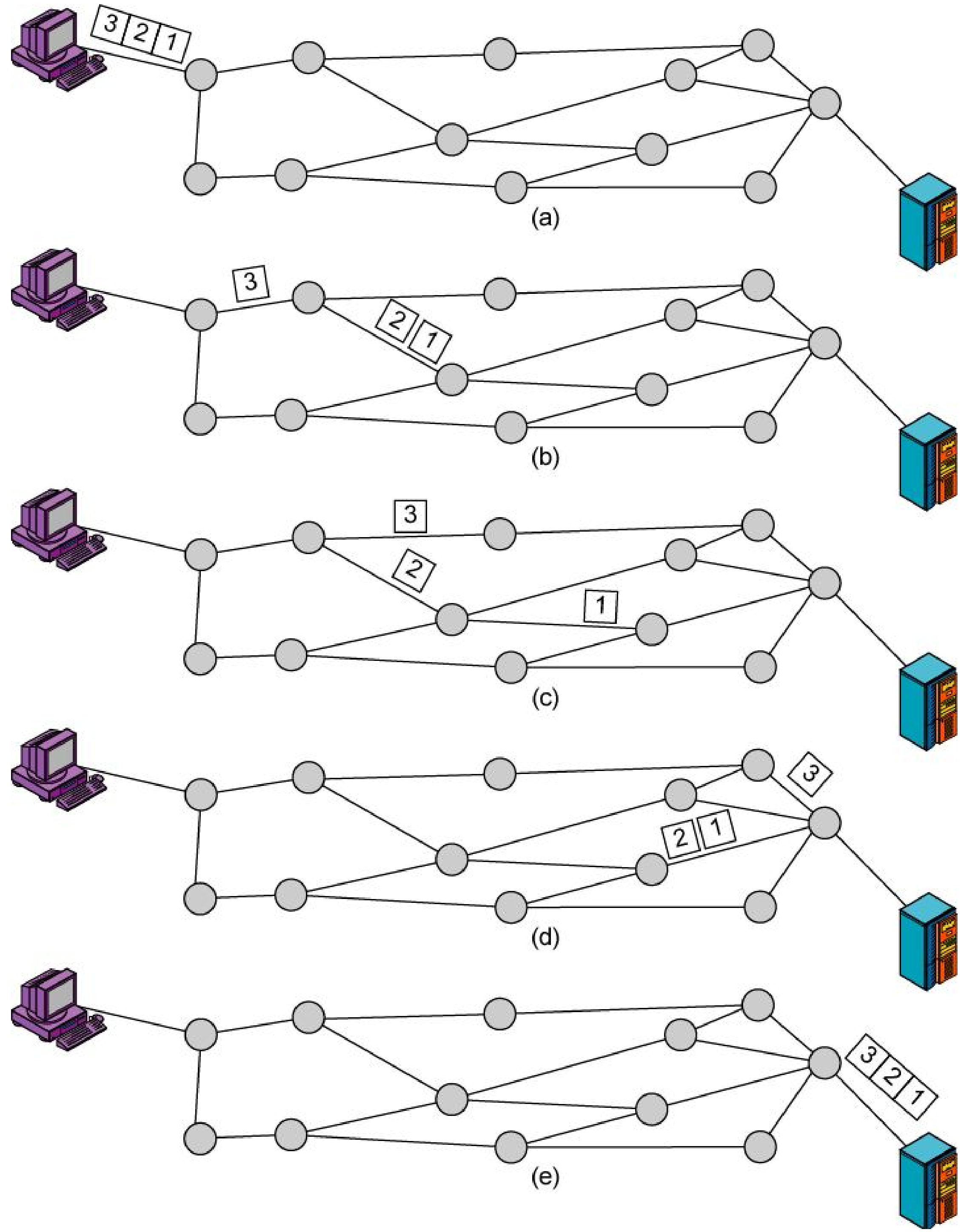
Switching Techniques:

- Station breaks long message into packets
- Packets sent one at a time to the network
- Packets handled in two ways
    - Datagram
    - Virtual circuit

Datagram:

- Each packet treated independently
- Packets can take any practical route
- Packets may arrive out of order
- Packets may go missing
- Up to receiver to re-order packets and recover from missing packets

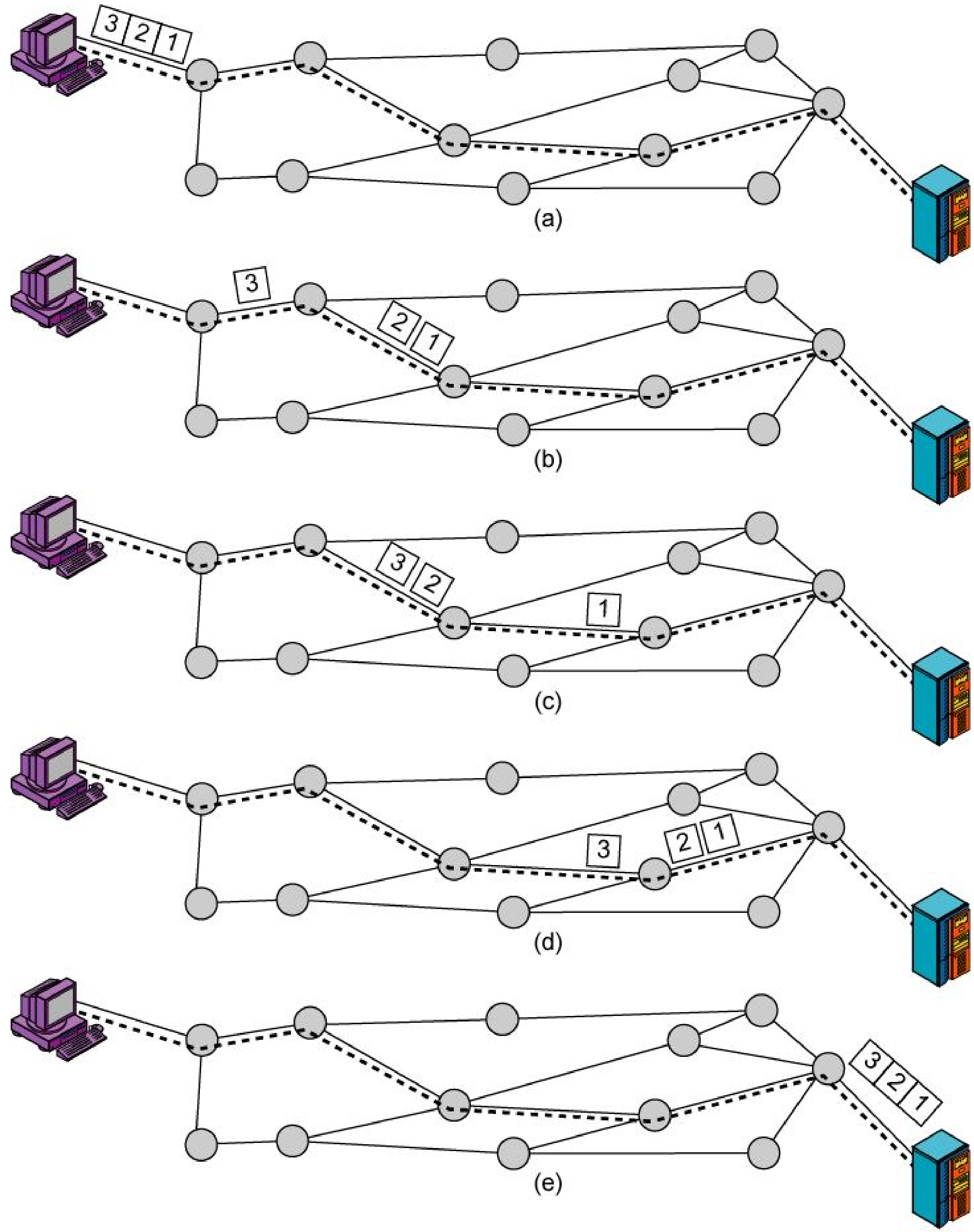
Datagram approach



Virtual Circuit:

- Preplanned route established before any packets sent
- Call request and call accept packets establish connection (handshake)
- Each packet contains a virtual circuit identifier instead of destination address
- No routing decisions required for each packet
- Clear request to drop circuit
- Not a dedicated path

Virtual circuit Diagram



Virtual circuit Vs Datagram:

Virtual circuits

- Network can provide sequencing and error control
- Packets are forwarded more quickly
  - No routing decisions to make
- Less reliable
  - Loss of a node looses all circuits through that node

Datagram

- No call setup phase
  - Better if few packets
- More flexible
  - Routing can be used to avoid congested parts of the network

Circuit Vs Packet switching:

Performance

- Propagation delay
- Transmission time
- Node delay

The importance of switching in communication

- The cost of switching is high

Definition: Transfer input sample points to the correct output ports at the correct time

Terminology :

- Switching
- Digital switching (sample points amplitudes are 0's and 1's)
- PABX
- Circuit
- Circuit switching
- Packet switching

Integrated Services Digital Network

- Public networks are used for a variety of services
  - Public Switched Telephone Network
  - Private Lines (leased)
  - Packet Switched Data Networks
  - Circuit Switched Data networks

ISDN

- Users have a variety of equipment to connect to public networks
  - Telephones
  - Private Branch Exchanges
  - Computer Terminals or PCs
  - Mainframe Computers
- A variety of physical interfaces and access procedures are required for connection

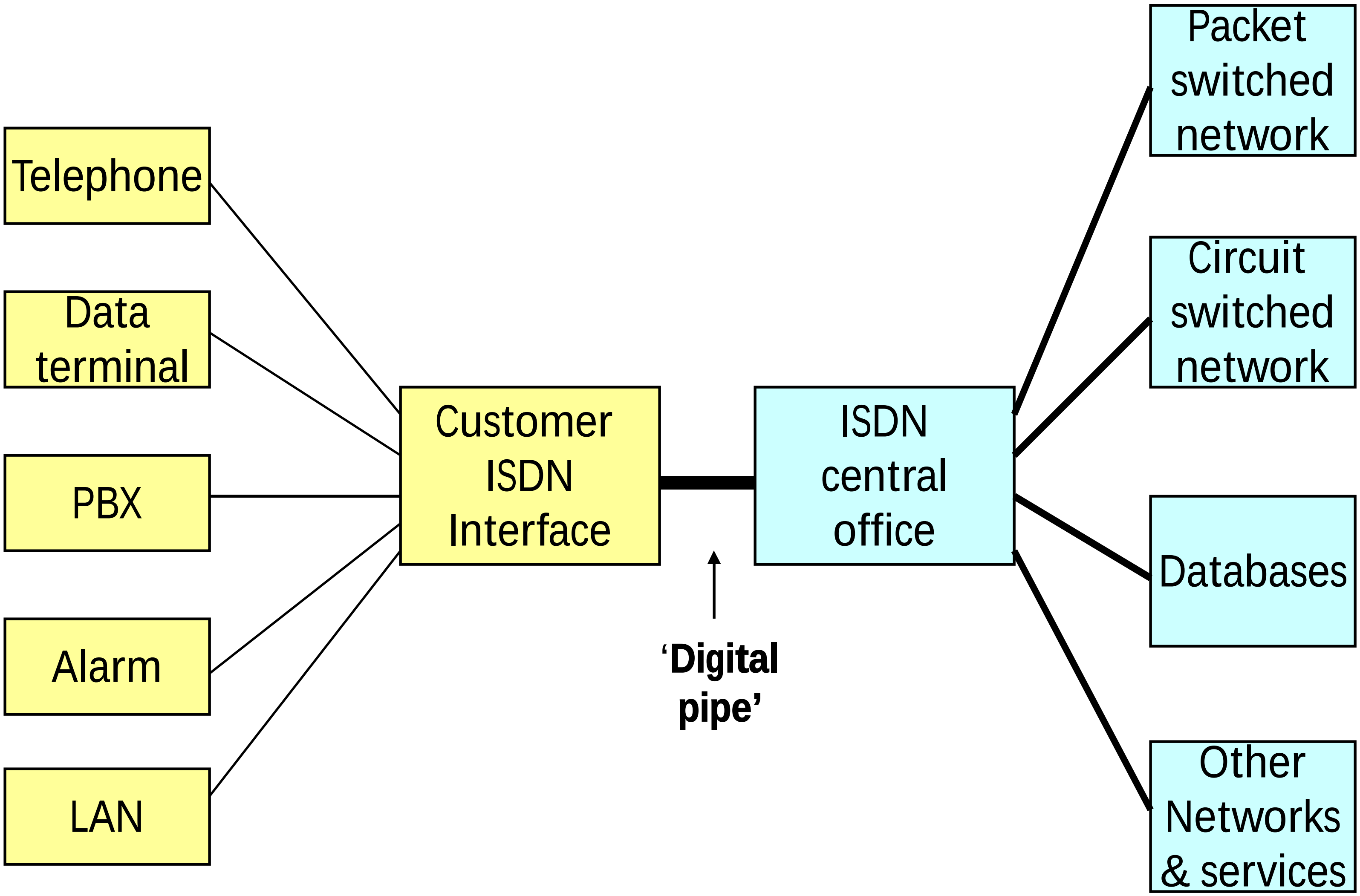
ISDN

- The telephone network has evolved into a digital one with digital exchanges and links
- The signalling system has become a digital message-oriented common channel signalling system (SS#7)
- The term ‘Integrated Digital Network’ is used to describe these developments

ISDN

- The Public Switched Telephone network is still analogue from the subscriber to the local exchange
- The need has arisen to extend the digital network out to subscribers and to provide a single standardised interface to all different users of public networks
- ISDN fulfils that need

Integrated Services Digital Network



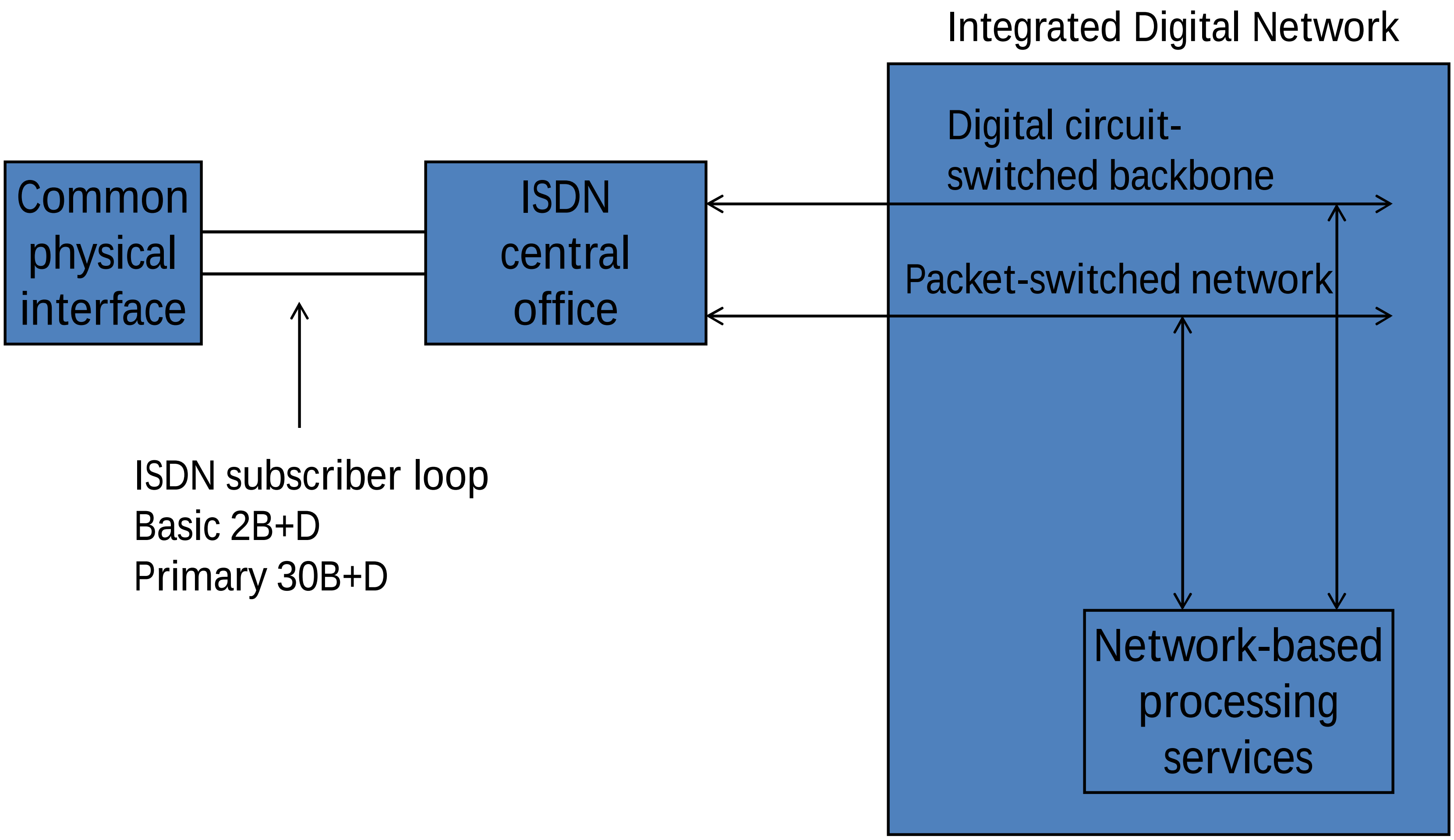
ISDN

- In Practice there are multiple networks providing the service nationally
- The user however, sees a single network

Benefits to Subscribers

- Single access line for all services
- Ability to tailor service purchased to suit needs
- Competition among equipment vendors due to standards
- Availability of competitive service providers

Architecture



ISDN Standards

- Contained in the I-series recommendations
- Issued by CCITT (now ITU-T)
- Six main groupings I.100 to I.600 series
- I.100 series - General Concepts
- I.200 series - Service Capabilities
- I.300 series - Network Aspects
- I.400 series - User-Network Interfaces
- I.500 series - Internetwork Interfaces
- I.600 series - Maintenance Principles

ISDN Channels

- The Digital pipe is made up of channels - one of three types
- B channel, D channel or H channel
- Channels are grouped and offered as a package to users

B Channel

- B channel-64 kbps
- B is basic user channel
  - can carry digital data or PCM-encoded voice
  - or mixture of lower rate traffic.

B Channel

- Four kinds of connection possible
- Circuit-switched
- Packet-switched - X.25
- Frame mode - frame relay (LAPF)
- Semipermanent - equivalent to a leased line

D Channel

- D Channel - 16 or 64 kbps
- Carries signalling information to control circuit-switched calls on B channels
- Can also be used for packet switching or low-speed telemetry

H Channel

- Carry user information at higher bit rates 384kbps or 1536kbps or 1920kbps
- Can be used as a high-speed trunk
- Can also be subdivided as per user’s own TDM scheme
- Uses include high speed data, fast facsimile, video, high-quality audio

ISDN Channels and their Applications

B Channel (64 kbps)	**D Channel (16/64 kbps)**	**H Channel (384/1536 kbps)**
Digital voice	Signalling (using SS#7)	High-speed trunk
High-speed data (e.g. packet and circuit switched data)	Low- speed data, (e.g. packet, terminal, videotex)	Very high speed data
Other (e.g. fax, slow video)	Other (e.g. telemetry)	Other (e.g. fast fax. Video)

ISDN Channel Groupings

- Basic Access -
  - ⌫ two 64 kbps B channels
  - ⌫ plus one 16kbps D channel
- B channels can be used for voice and data
- simultaneous calls to separate destinations supported
- D channel used for signalling and also for data using X.25

ISDN Basic Access

- Intended for small business and residential use
- A single physical interface is provided
- Data rate is 144kbps plus 48kbps overhead bits totalling 192 kbps
- Most existing subscriber loops can support basic access

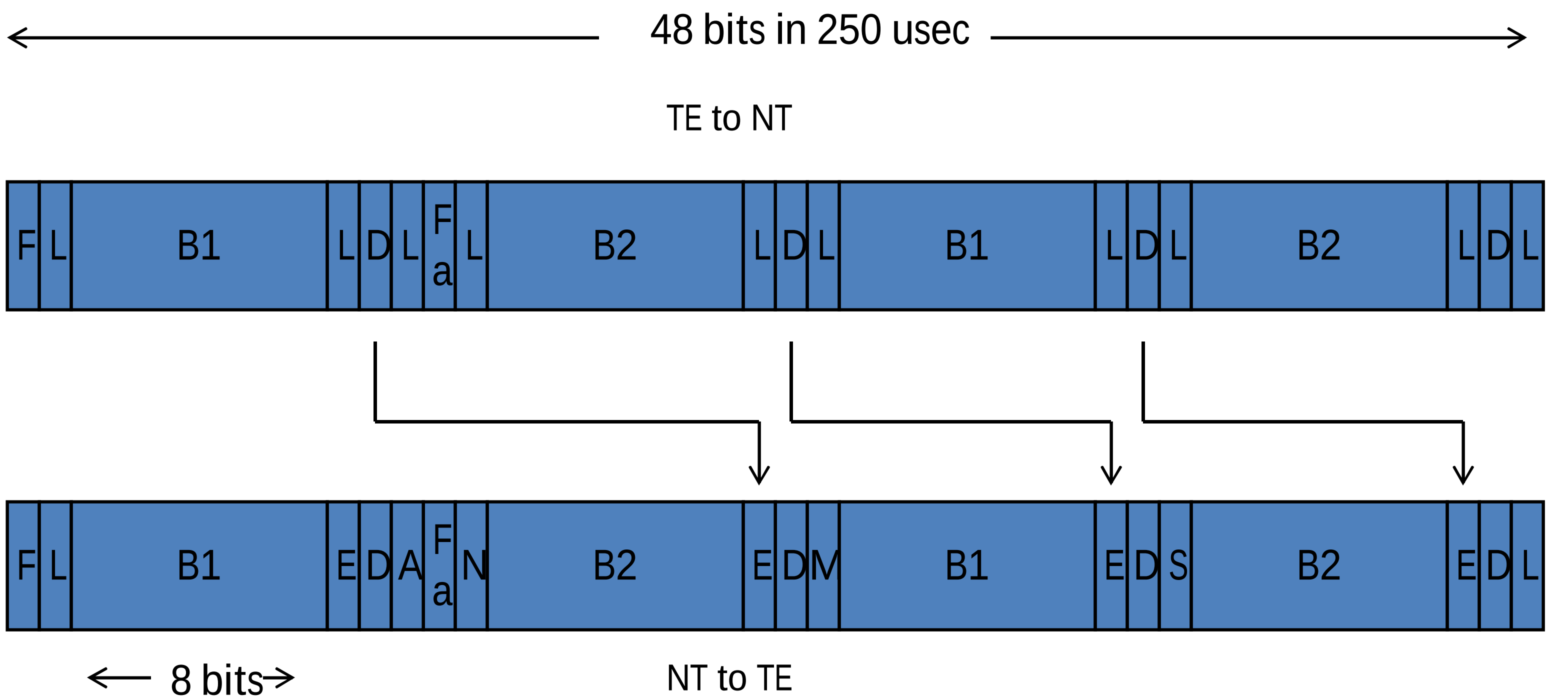
ISDN Primary Access

- Intended for users with greater capacity requirements
- Example would be a digital PBX
- Two standards exist
  - 1.544 Mbps American
  - 2.048 Mbps European

ISDN Primary Access

- Typically it is structured as 30 B channels plus one 64kbps D channel (Europe)
- Can also be structured as H channels
  - 5H0 +D for a 2.048 Mbps interface
  - or 1H12 +D

ISDN Frame Structure Basic Rate Access



F= Framing bit
L = dc balancing bit
E = D-echo channel bit
A = Activation bit

Fa = Auxiliary Framing bit
N = opposite of Fa
M = multiframing bit
B1 = B channel bits

B2 = B channel bits
D = D channel bits
S = Spare bits

ISDN Contention Resolution

- Several TE’s can share a single line
- How is contention resolved?
- B-channel Traffic
  - No contention as each channel dedicated to particular TE
- D - Channel used for data and control so requires a contention resolution mechanism

D Channel Contention

- Incoming Traffic
  - LAPD protocol resolves contention
- Outgoing Traffic
  - Multiple devices share D channel
  - Contention resolution algorithm required

D Channel Contention

- Idle TEs sends binary 1s on D channel
- This means no signal (pseudoternery)
- NT echos received binary value back as echo bit
- When NT wishes to send on D channel, it listens to echo bits
- If it hears a string of 1’s equal in length to a threshold value Xi, it may transmit
- Otherwise it must wait

D Channel Contention

- If two TE's start transmitting simultaneously a collision occurs
- This is detected by each TE by monitoring E bits
- If E bits are identical to D bits sent then no collision
- If discrepency detected TE stops and listens

D Channel Contention

- Priority mechanisms based on threshold values
  - Control information has priority over user data
  - When TE has sent data its priority is lowered until other terminals transmit

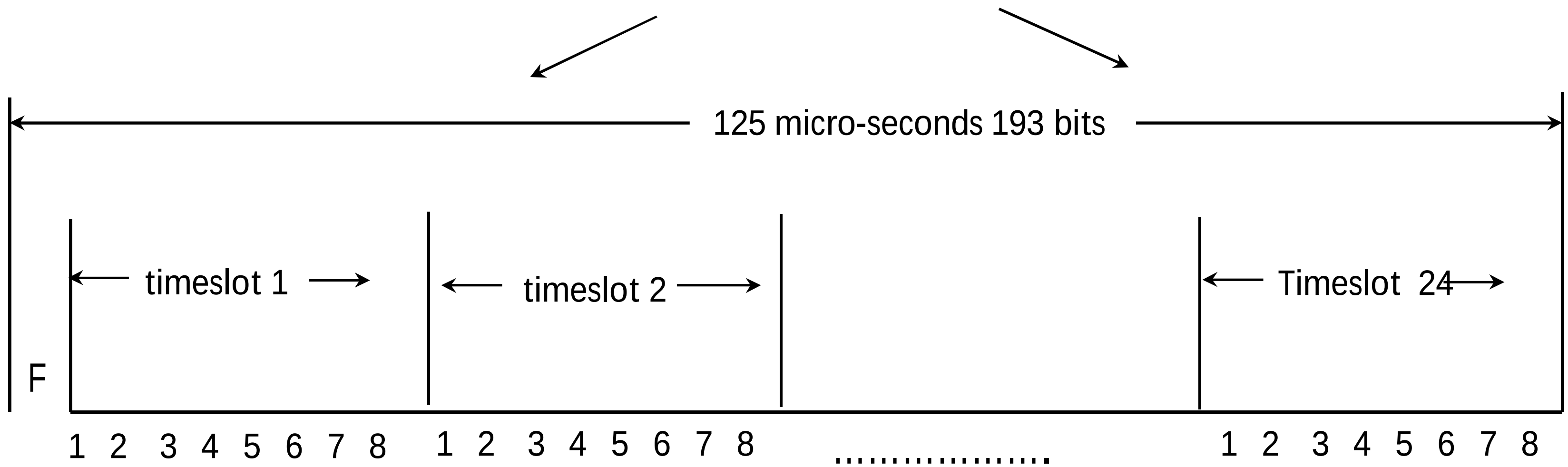
D Channel Priorities

- Control Information
  - Normal Priority X1 =8
  - Lower Priority X1 =9
- User Data
  - Normal Priority X2 =10
  - Lower Priority X2 =11

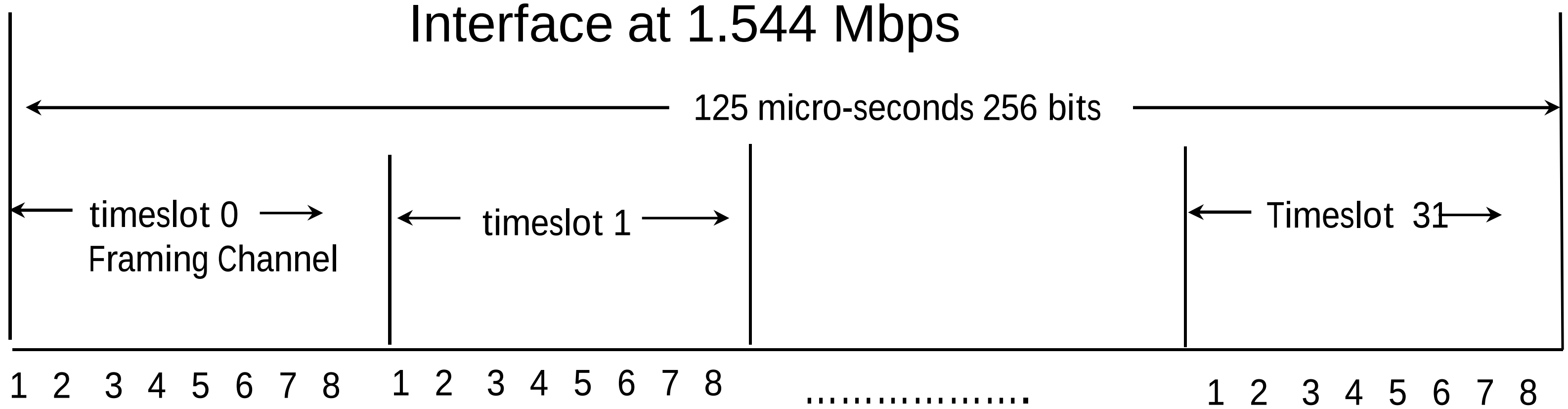
ISDN Primary Interface

- Multiple channels multiplexed on single medium
- Only point to point configuration is allowed
- Typically supports a digital PBX and provides a synchronous TDM facility

ISDN Primary Access Frame Formats



Interface at 1.544 Mbps

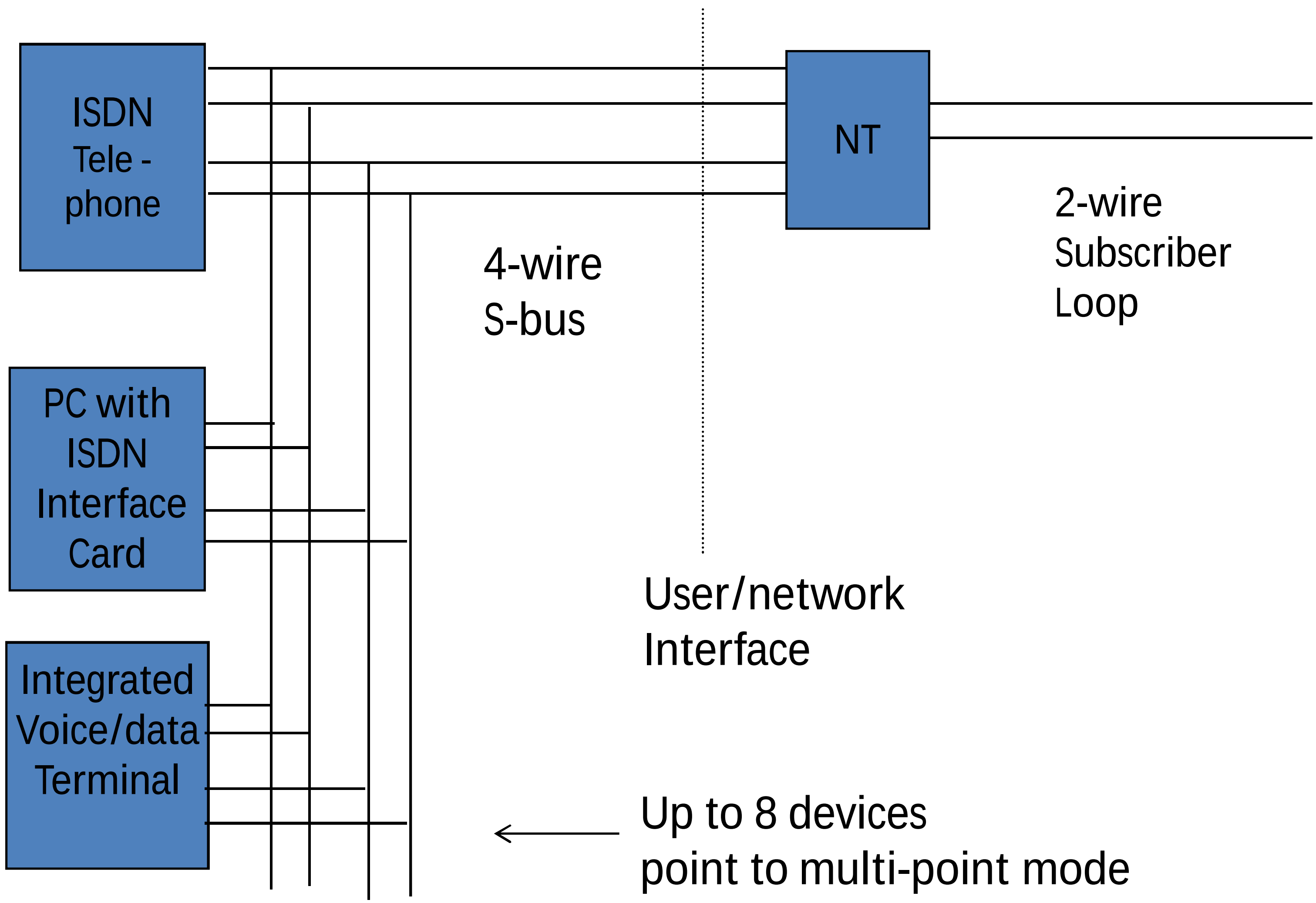


Interface at 2.048Mbps

User Access

- Defined using two concepts
  - Functional groupings of equipment
  - Reference points to separate functional groupings

Typical User Access Layout



ISDN Protocol Architecture

Application	End-end user signalling				
Presentation					
Session					
Transport					
Network	I.451/Q.931 call control	X.25 packet level	for further study		X.25 packet level
Datalink	LAPD (Q921)			Frame Relay	LAPB
Physical	I.430 basic interface + I.431 primary interface				

ISDN Data Link Layer

- Link Access Protocol for the D channel (LAPD) defined for ISDN
- Three applications are supported
  - Control Signalling
  - Packet Switching
  - Telemetry

Network Layer Above LAPD

- Control Signalling
  - Call Control Protocol (I.451 / Q.931)
    - Establishes, maintains and terminates connections on B channels
    - Possibility of user - user control signalling above this layer

B-Channel

- Uses
  - Circuit Switching
  - Semi-permanent circuits
  - Packet switching

B-Channel

- Circuit Switching
  - Circuit is set up on B-channel on demand
  - D-channel call control protocol is used
  - Transparent full-duplex digital data path established between users
  - Layers 2 to 7 are not visible to ISDN or specified

B-Channel

- Semipermanent circuit can be set up by prior agreement between users and network operator
- Can be for indefinite time or at specified times during day or week
- As with circuit switched connection, full duplex digital data path is established
- Layers 2 to 7 are not visible to ISDN or specified

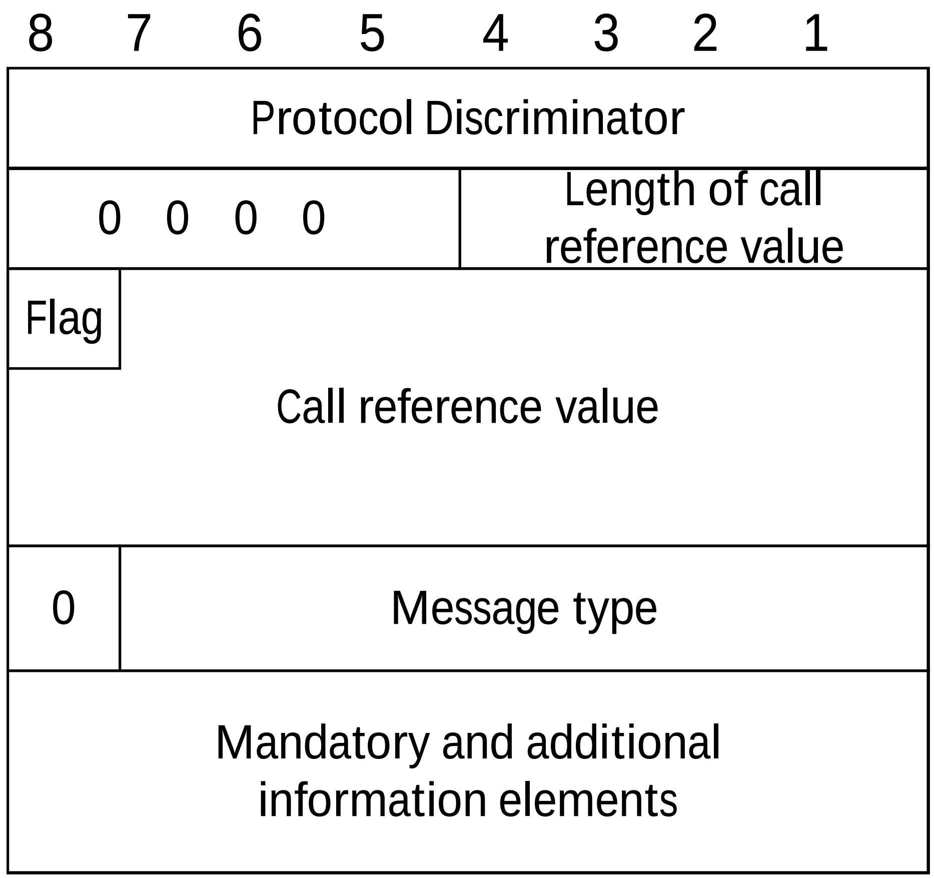
B-Channel Packet Switching

- Circuit-switched connection is established between user and packet-switched node using D-channel call control protocol
- The packet switching node can be integrated into ISDN or be a separate network
- User then employs X.25 layers 2 and 3 to establish virtual circuit to other user
- Frame relay can also be used instead of X.25

D-Channel Packet Switching

- Integrated X.25 service can be accessed by D-Channel in addition to B-Channel
- ISDN provides a semi-permanent connection to a packet switching node within ISDN
- The X.25 level 3 protocol is used for the packet layer
- LAPD is used for the link layer

I.451 Formats



General message format

LAPD

- Provides two types of service
  - Unacknowledged information transfer
    - No guarantee of delivery
    - Frames with error are discarded
  - Acknowledged information transfer
    - Similar to HDLC
    - Flow and error control
    - Logical connection established prior to data transfer
    - Also called multiple-frame operation

LAPD Format

			Length in octets
Flag			1
Service access point identifier	C/R	0	1
Terminal endpoint identifier			1
Control			1or 2
Information			0 to 128 or 0 to 260
Frame Check Sequence			2
Flag			1

ISDN Physical Interface

- There are no separate control circuits
- Transmit and receive circuits carry data and control signals
- Pseudoternery coding scheme is used for basic access signals
  - Voltage level is + or - 750 mV
  - Data rate is 192 kbps
- HDB3 code is used for 2.048 Mbps access
- B8ZS code is used for 1.544 Mbps access

ISDN INTERFACE PLUG PINOUT

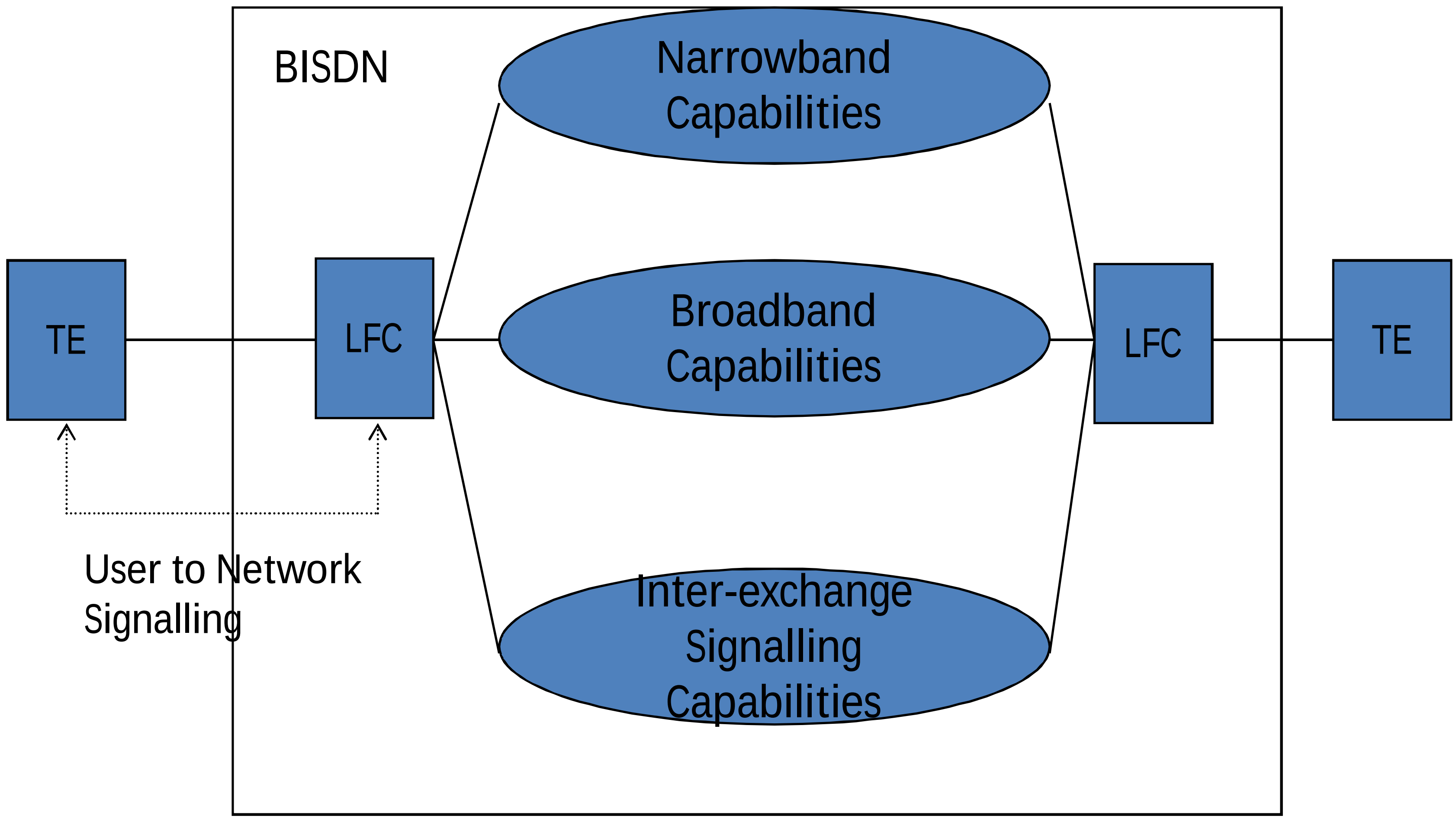
PIN	TERMINAL EQUIPMENT	NETWORK TERMINATING EQUIPMENT
1	Power Source 3	Power Sink 3
2	Power Source 3	Power Sink 3
3	Transmit	Receive
4	Receive	Transmit
5	Receive	Transmit
6	Transmit	Receive
7	Power Sink 2	Power Source 2
8	Power Sink 2	Power Source 2

•

Broadband ISDN

- Recommendations to support video services as well as normal ISDN services
- Provides user with additional data rates
  - 155.52 Mbps full-duplex
  - 155.52 Mbps / 622.08 Mbps
  - 622.08 Mbps full-duplex
- Exploits optical fibre transmission technology
- Very high performance switches

B-ISDN Architecture

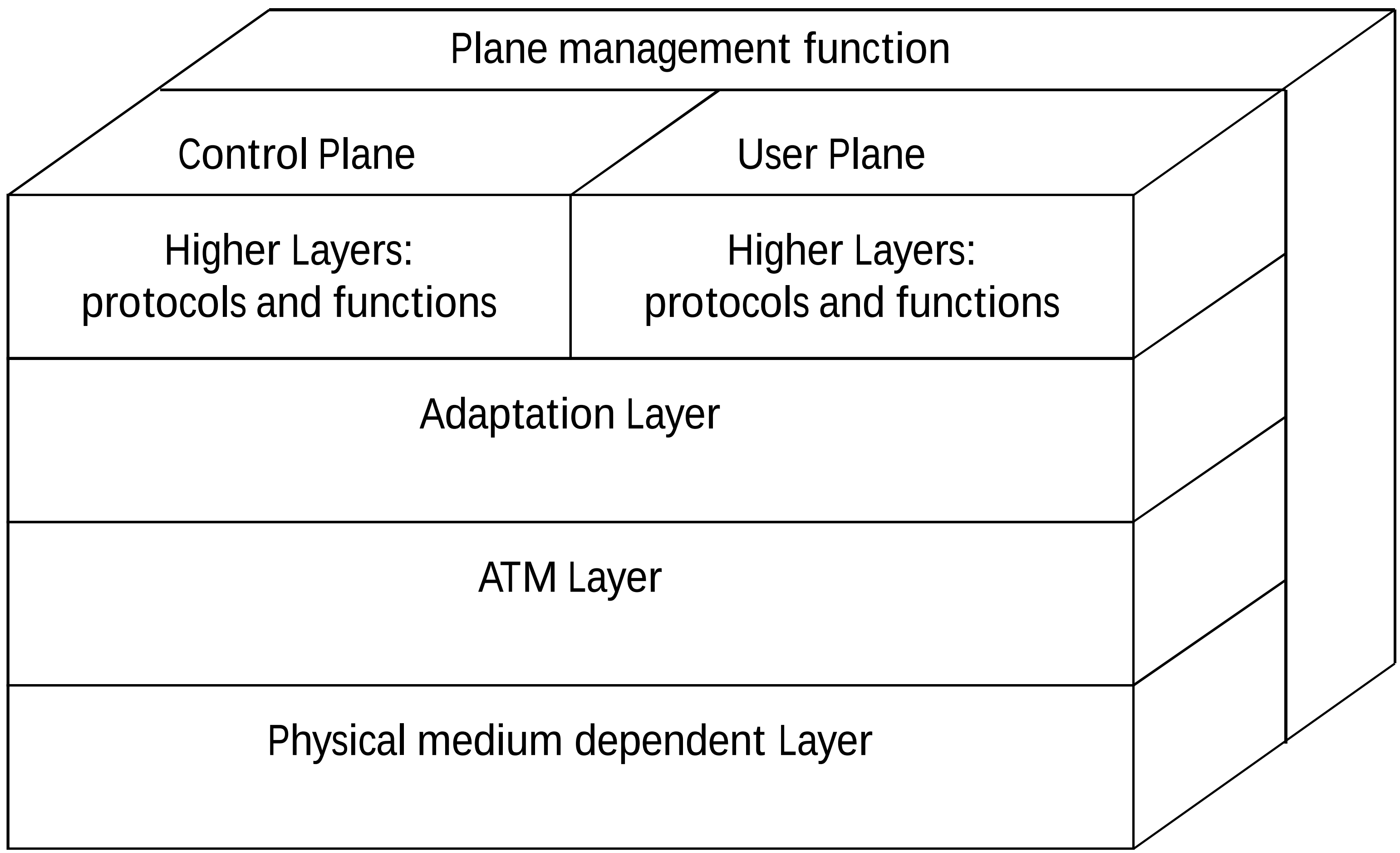


TE = Terminal equipment
LFC = Local function capabilities

B-ISDN

- ATM is specified for Information transfer across the user-network interface
- Fixed size 53 octet packet with a 5 octet header
- Implies that internal switching will be packet-based

BISDN Protocol Structure



UNIT II - ISDN PROTOCOL ARCHITECTURE AND SIGNALING

ISDN and the OSI Reference Model

- The ISDN Physical Layer
- The ISDN Data Link Layer
- The ISDN Network Layer

ISDN Protocols

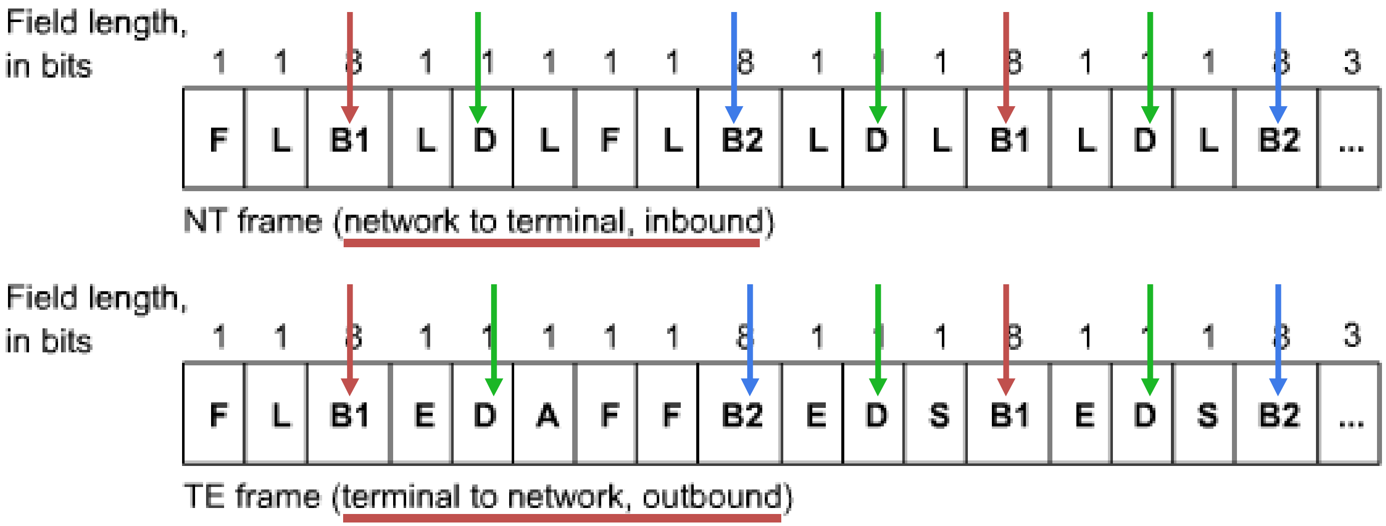
- E-series protocols—Telephone network standards for ISDN.
- I-series protocols—Specify ISDN concepts and interfaces.
- Q-series protocols—Standards for ISDN switching and signaling.
- Operate at the physical, data link, and network layers of the OSI reference model

ISDN Protocol Operating OSI Layers 1 Through 3

- Physical layer ISDN protocols
  - BRI (ITU-T I.430) / PRI (ITU-T I.431)
    - Defines two ISDN physical layer frame formats
      - Inbound (local exchange to ISDN customer)
      - Outbound (ISDN customer to local exchange)

- Data link layer ISDN protocols
  - LAPD signaling protocol (ITU-T Q.920 for BRI and Q.921 for PRI) for transmitting control and signaling information over the D channel
    - LAPD frame format similar to ISO HDLC frame format
- Network layer ISDN protocols
  - ITU-T I.930 and ITU-T Q.931 defines switching and signaling methods using the D channel

ISDN Physical Layer



A = Activation bit
B1 = B1 channel bits
B2 = B2 channel bits
D = D channel (4 bits x 4000 frames/sec = 16 kbps) bit
E = Echo of previous D bit
F = Framing bit
L = Loading balance bit
S = Spare bit

ISDN physical-layer frame formats are 48 bits long, of which 36 bits represent data

D Channel

- When a TCP connection is established, there is an exchange of information called the connection setup.
  - This information is exchanged over the path on which the data will eventually be transmitted.
  - Both the control information and the data share the same pathway.
  - This is called **in-band signaling**.
- **ISDN** however, uses a separate channel for control information, the **D channel**.

- The D channel carries signaling messages, such as call <u>setup and teardown, to control calls on B channels</u>.
- Traffic over the D channel employs the Link Access Procedure on the D Channel (LAPD) protocol.
- LAPD is a data link layer protocol based on HDLC.

SS7 PROTOCOLS

ISO-OSI Layers

Basic SS7 Layers

Message Transfer: *Part 1*

Message Transfer: *Part 2*

Message Transfer: *Part 3*

SCCP

TCAP

ISUP

TUP

ISO-OSI LAYERS

Application	**Interfaces directly with application programs**
Presentation	**Provides code conversion and data reformatting.**
Session	**Co-ordinates interaction between end-to-end application processes.**
Transport	**Provides end-to-end data integrity and reliable delivery of data.**
Network	**Switches and routes data to the destination node: *comm. sub-network*.**
Data Link	**Transfers units of data point-to-point.**
Physical	**Transmits and receives on the communication medium**

Basic Layers

Transaction Capability Control Part

Signaling Connection Control Part

Integrated Services Digital Network User Part

Telephone User Part

Message Transfer Part (3): ***Network Layer***

Message Transfer Part (2): ***Data Link Layer***

Message Transfer Part (1): ***Physical Layer***

MESSAGE TRANSFER: *PART 1*

Basic Function	**Physical Layer: It deals with hardware and electrical configuration**
	Associated with interface cards and multiplexers
Support	**Software providers should understand its function for higher layers**
Communication	**Bi-directional links of the same bit rate: *Symmetric Links***

MESSAGE TRANSFER: *PART 2*

Function	**First to handle received messages**
	Last to handle transmitted messages
	Ensures integrity of messages
	Acknowledges "good" messages.
	Discards "bad" messages and requests copies of them.
	Tests links before allowing their use.
	Places links in service.
	Gives sequence numbers to messages
Interface	**Reports information to MTP3**

MESSAGE TRANSFER: *PART 3*

Routing	**Message discrimination.**
	Message distribution.
	Message routing: *Signaling message handling*.
Management	**Traffic & link management.**
	Congestion management
	Signaling network management

SIGNALING CONNECTION CONTROL PART

Basic Services	**Connectionless service:** ***datagram*****.**
	Connection service: ***virtual circuit*****.**
	Subsystem management: ***databases*****.**
Special Routing	**Addressing capabilities:** ***Allow locating database information; and invoking features at a switch.***
	Global Title Translation (GTT): ***800 / Calling card number / MIN***
TCAP	**Transport Layer for TCAP**

TRANSACTION CAPABILITIES APPLICATION PART

Basic Services	**Operations, Maintenance & Administration**
	User Designed *Applications*
	GSM *(Global System Mobile)* MAP *(Mobility Application Part)*
Data Exchange	**Data between applications over SCCP connection-less services.**
	SSPs-SCPs queries and responses
	Obtain data from databases: e.g. 800
	Mobile Switches-Databases: *user and equipment identification, roaming,..*

ISDN User Part: ISUP

Function: *Call Connection* *(Management)*	**In PSTN:** *Messaging for setting-up and tearing-down of circuits*
	In Wireless Networks: *Establishing connections through PSTN*
	In Telephone Networks: *Messages follow the path of voice circuits*
Types of Services	**Basic:** *Setting-up and Tearing-down calls*
	Supplementary: *Passing messages needed to maintain and modify calls*
Procedures	*Signaling Procedure Control / Circuit Supervision Control / Call Processing Control*

Telephone User Part: TUP

Function	Supporting basic call set-up and tear-down
	Only for analog circuits
ISUP v. TUP	ISUP is used instead of TUP for Call Management

SS7 Services: Current (1/2)

Service	Explanation
Portability of Local Number	Numbers no longer associated with exchanges (geography). They can be kept fixed.
	Number translation using databases.
	Routing to real address
800 & 900 Numbers	Unified area code
	Translation & Routing (as above)

SS7 Services: *Current (2/2)*

Service	Explanation
Congestion Avoidance	**Automatic re-routing in case of congestion or failure:** ***switch or link***
	Congestion / Failure ***management***
Remote Maintenance	**Network monitoring**
	Failure detection and correction ***management*****:** ***for most cases***
Others	**Intelligence: e.g.** ***diversion of calls***
Higher "Reliability", but More "Cost"	

SS7 Services: *Current (1/2)*

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SS7 Services: *Current (2/2)*

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<tr><td rowspan="2">Congestion Avoidance</td><td>Automatic re-routing in case of congestion or failure: switch or link</td></tr>
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<tr><td>Others</td><td>Intelligence: e.g. diversion of calls</td></tr>
<tr><td colspan="2">Higher “Reliability”, but More “Cost”</td></tr>
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Using ISDN for IP Data Networks

- Characteristics
  - Speed
  - Fast call setup
  - Bandwidth on Demand

Using ISDN for IP Data Networks

- Modes of Usage
  - Dial Up (LAN or host)
  - Bandwidth on Demand
  - Backup lines
  - Permanent connections

Dial Up

- Providers need:
  - subscribe for PRI connections or multiple BRI connections
  - ISDN Access Server

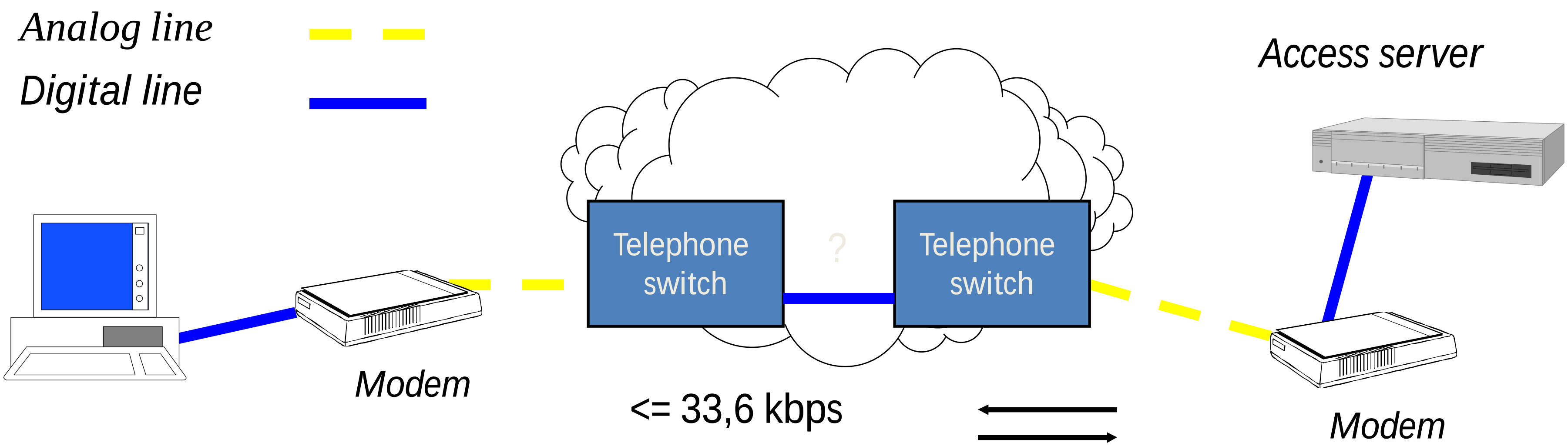
ISDN Access Servers

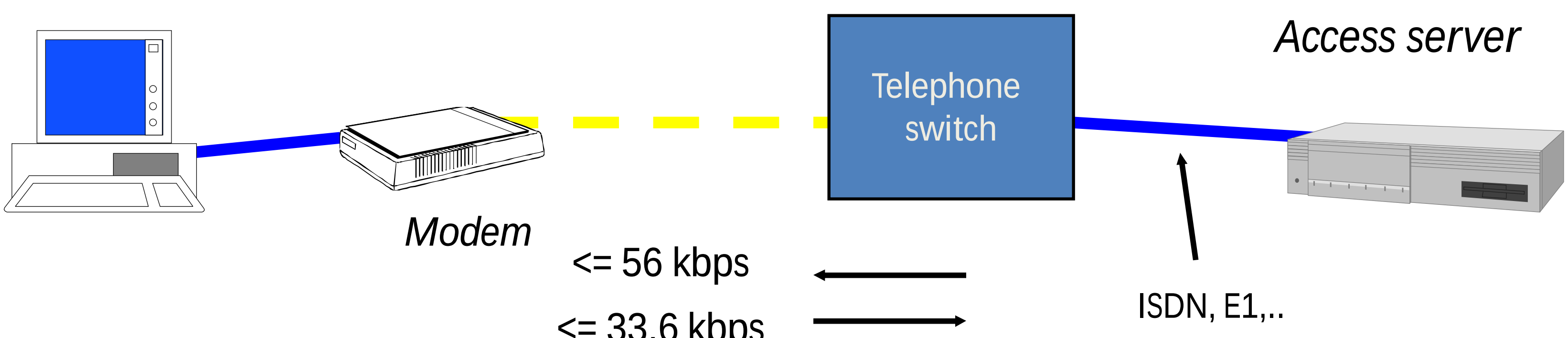
- Digital modems (accepting analog and ISDN calls)
  - software busy-out feature
- 56 kbit/s technologies
- Rate adaption (V.110, V.120,..)
- Compression (Stac,..)
- Synchronous PPP (with CHAP/PAP authentication)

ISDN Access Servers 2

- PPP Multilink
- BACP
- Controlling the number of B-channels per user
- D-channel based callback
- CLIP - Caller Line Identification Presentation

56 k Technology





56 k Prerequisites

- Only one analogue/digital conversion
  - less noise and faster digital lines
- Digital Access Server
- Same technology in Access Server and in dial-up modem
  - K56Flex from Lucent Technologies and Rocwell
  - X2 from U.S. Robotics, Texas Instruments and Cirrus Logic

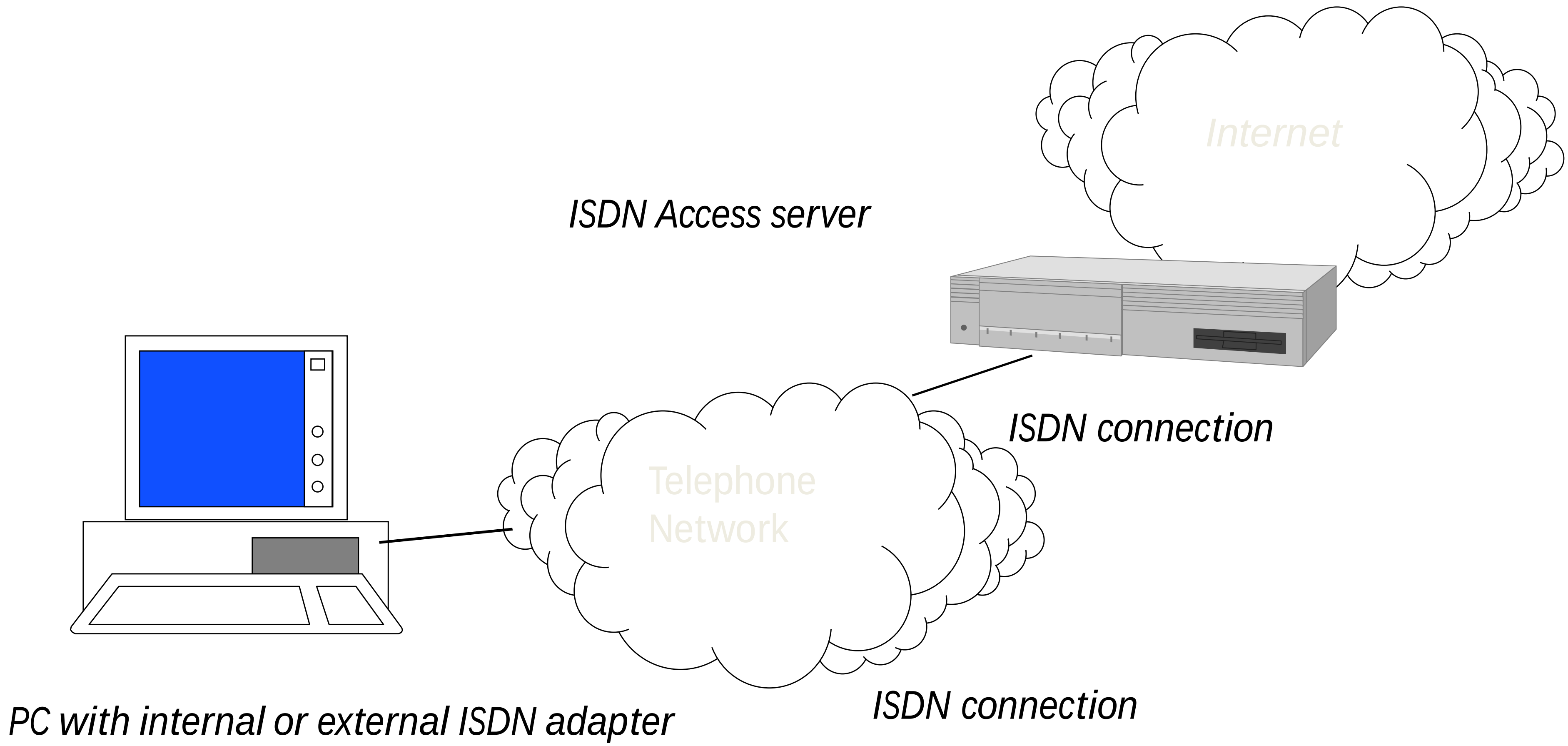
56 k Considerations

- 56 k not reached in reality
  - 43 kbps practical maximum
- Cost for upgrading equipment to ITU standard

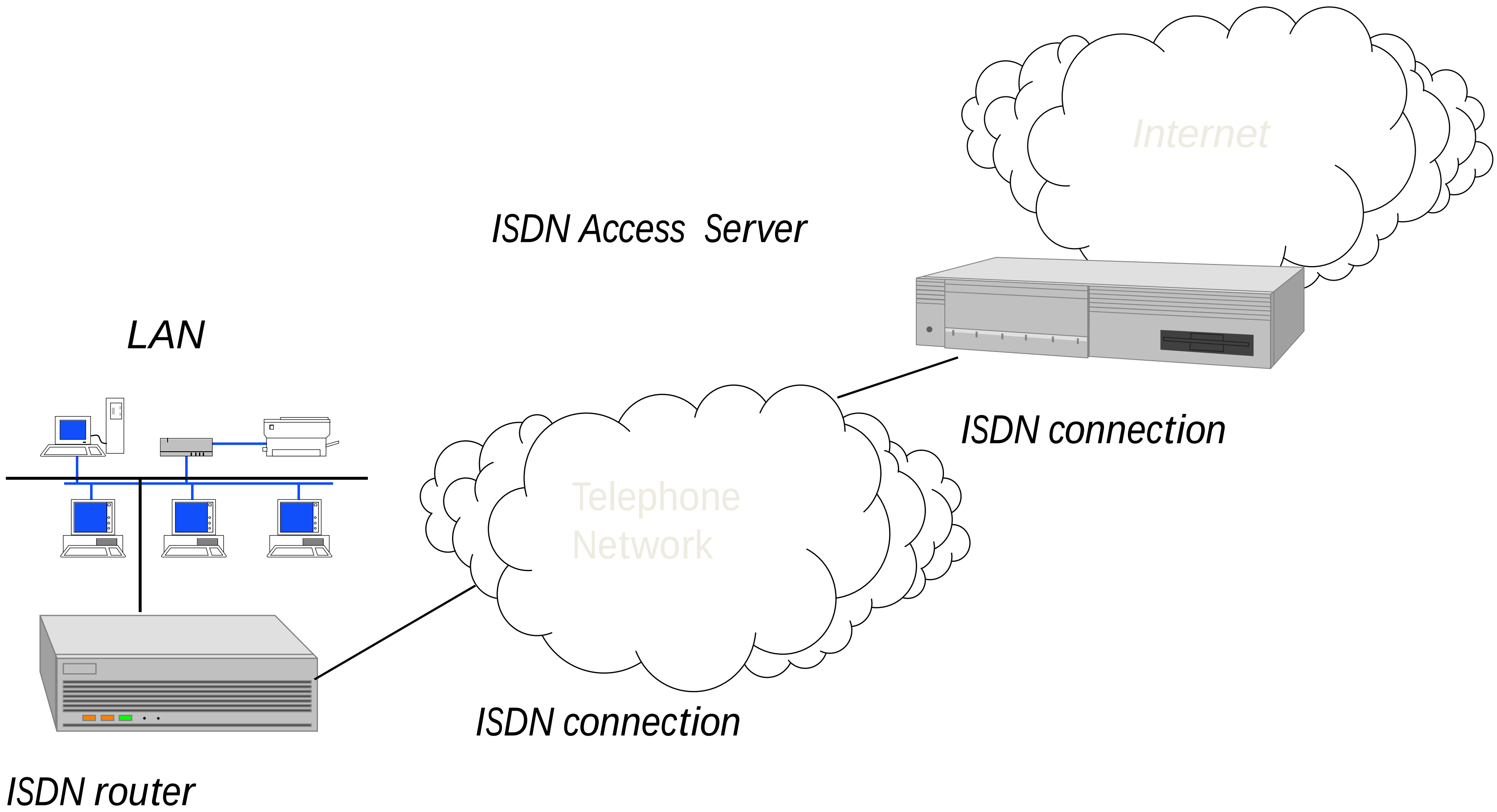
Dial Up

- Users need for host connections:
  - subscribe for BRI connection
  - ISDN Adapter
- Users need for LAN connections
  - subscribe for PRI or BRI connection
  - ISDN router (commercial, PC version with ISDN Adapter,..)

Dial Up - Private



Dial Up - LAN



Internet
ISDN Access Server
LAN
ISDN connection
Telephone
Network
ISDN connection
ISDN router

ISDN Adapters

- Internal/external
- Active/passive (for internal)
- Integrated NT
- Plug for telephone line
- Integrated modem
- Synchronous PPP (with CHAP/PAP authentication)

ISDN Adapters 2

- PPP Multilink
- Rate adaption (V.110, V.120,..)
- CAPI
- Compression (Stac,…)

ISDN Routers

- Integrated NT
- Plug for telephone line
- Integrated modem
- Synchronous PPP (with CHAP/PAP authentication)
- PPP Multilink
- Compression (Stac,…)
- Tarrif management

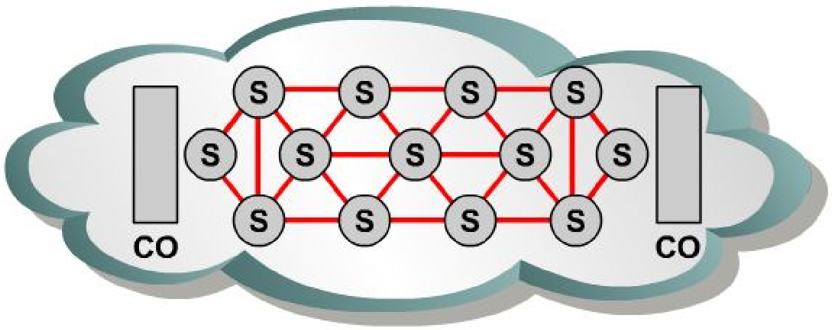
Bandwidth on Demand

- Router to router connections
- ISDN call setup when leased line overloaded

Backup lines

- Router to router connections
- ISDN call setup when leased line fails

ISDN switch types



Many providers and switch types

Services vary by regions and countries

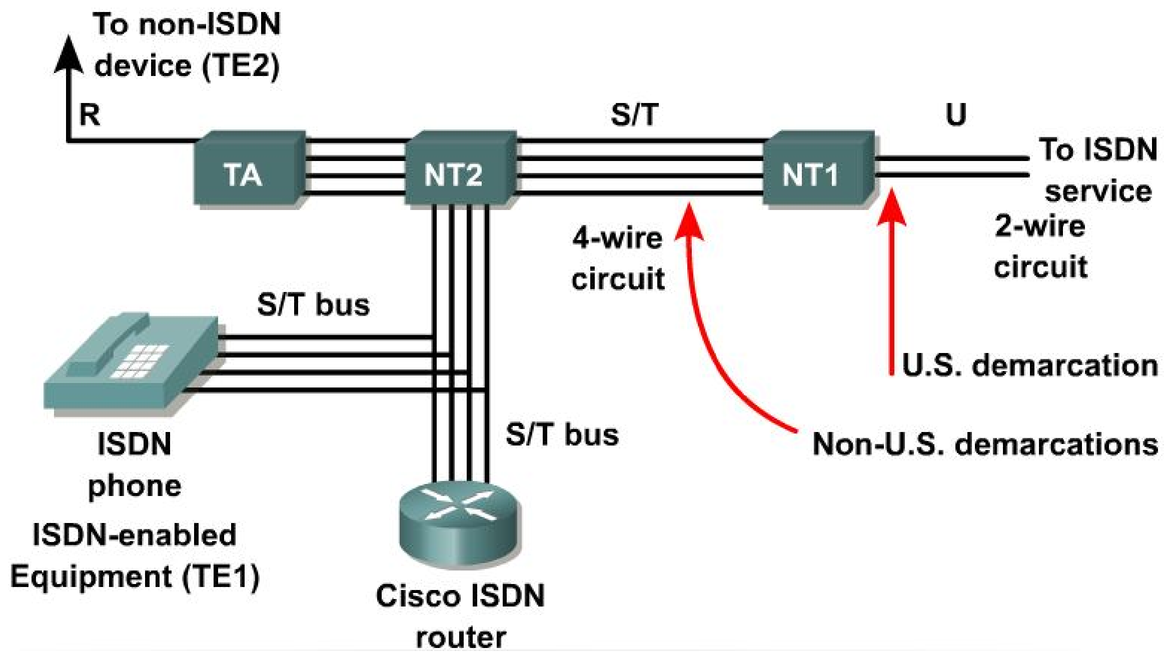
- Routers must be configured to identify the type of switch with which they will communicate.
- Available ISDN switch types vary, depending in part on the country in which the switch is being used.

As a consequence of various implementations of Q.931, the D channel signaling protocol used on ISDN switches varies from vendor to vendor.

<u>Before the router can be connected to an ISDN service, it must be configured for the switch type used at the CO.</u>

This information must be specified during router configuration.

ISDN Interfaces



- To connect devices that perform specific functions, the interface between the two devices needs to be well defined.
- R – References the connection between a non-ISDN compatible device Terminal Equipment type 2 (TE2) and a Terminal Adapter (TA), for example an RS-232 serial interface.

S – References the points that connect into the customer switching device Network Termination type 2 (NT2) and enables calls between the various types of customer premises equipment.

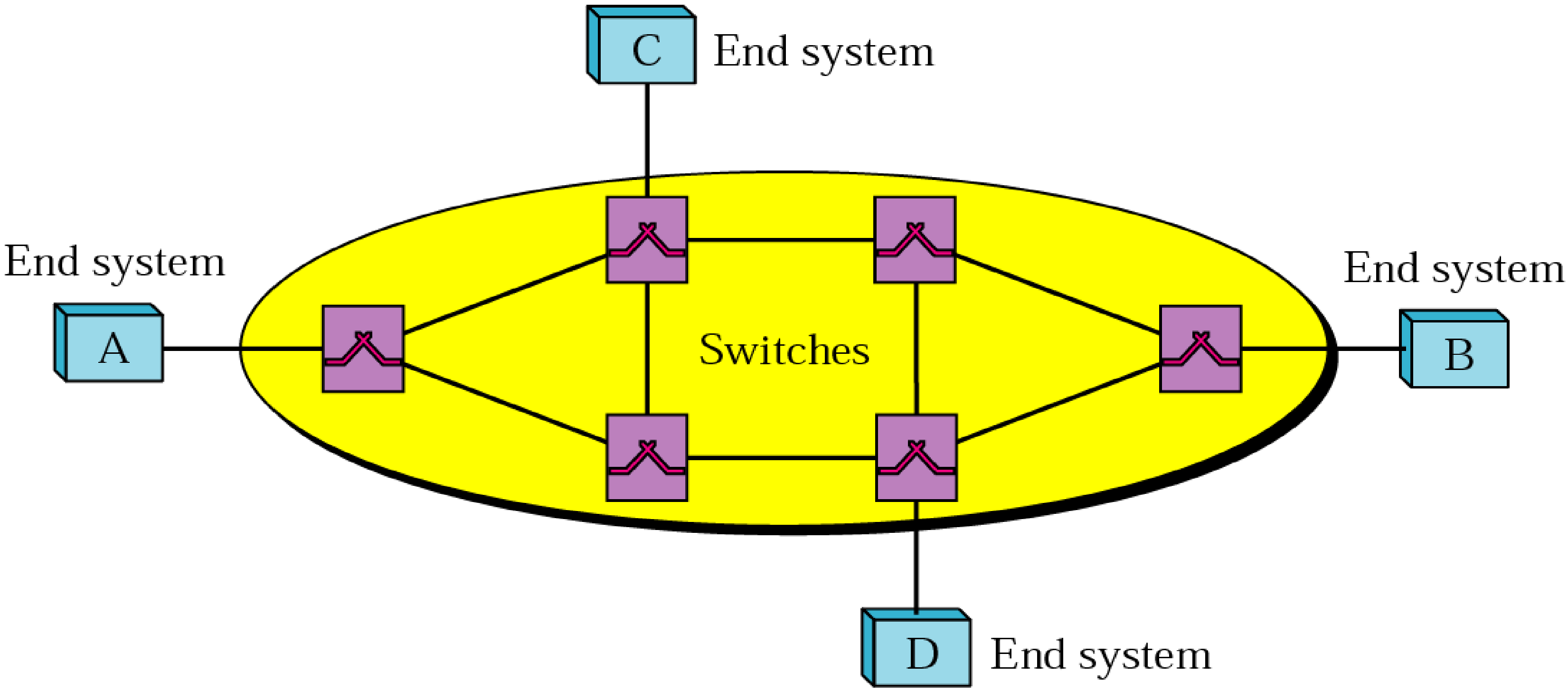
T – Electrically identical to the S interface, it references the outbound connection from the NT2 to the ISDN network or Network Termination type 1 (NT1).

U – References the connection between the NT1 and the ISDN network owned by the telephone company

UNIT III - BROAD BAND ISDN

Frame relay

Frame Relay operates only at the physical and data link layers.



Frame Relay does not provide flow or error control; they must be provided by the upper-layer protocols.

DLCI(Data-link Connection Identifier)

A **'local identifier'** between the **DTE** and the **DCE**, it identifies the logical connection that is multiplexed into the physical channel.

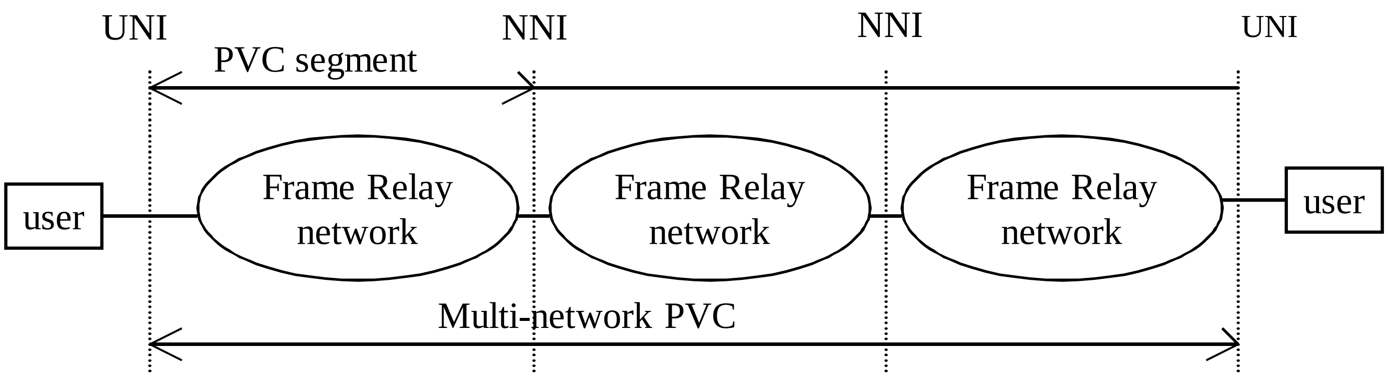
In the basic Frame Relay specification, DLCIs are **'locally significant'**.

In the LMI extended specification, DLCIs are **'globally significant'** (DLCIs specify individual end devices).

The *FR Switch* **maps** the **DLCIs** between each pair of routers to create a **PVC**.

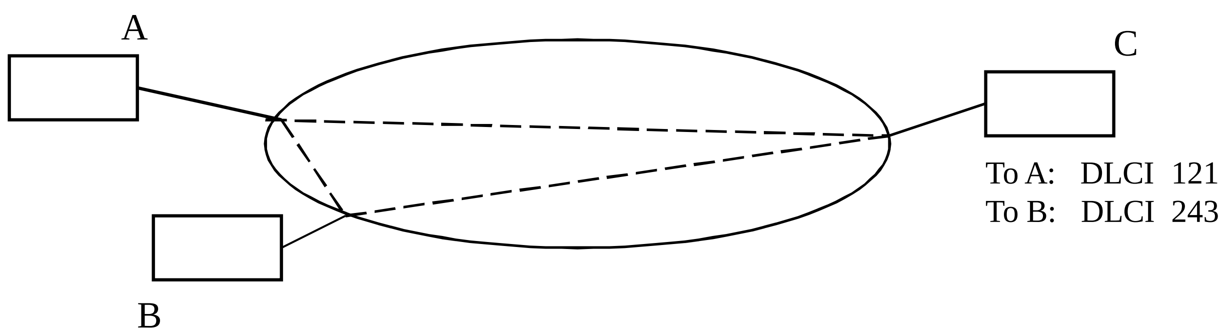
Frame Relay-Interface types

- UNI: User-|Network Interface
- NNI: Network-Network Interface



Frame Relay-Local addressing

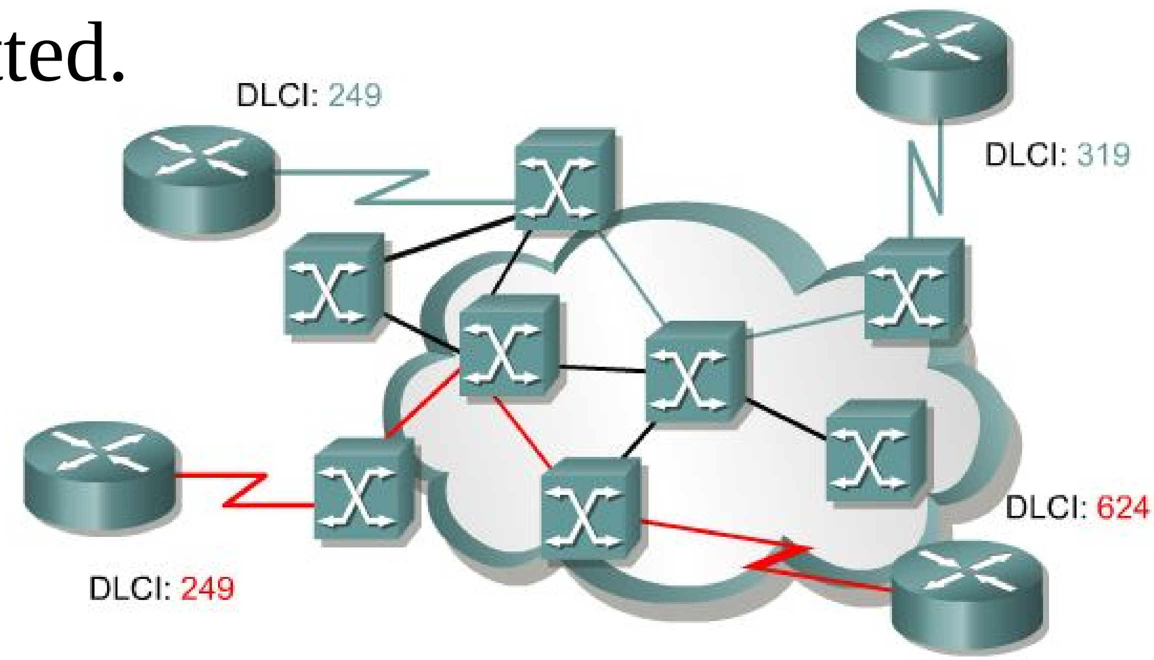
- DLCI (Data Link Connection Identifier) - identification of a virtual circuit
- DLCI - of local (for a given port) meaning
- there can be max. 976 VCs on an interface user-network



- DLCI values: 0 - LMI channel, 1-15 - reserved, 16-991 - available for VCs, 992-1007 - layer 2 management of FR service, 1008-1022 - reserved, 1023 - in channel layer management

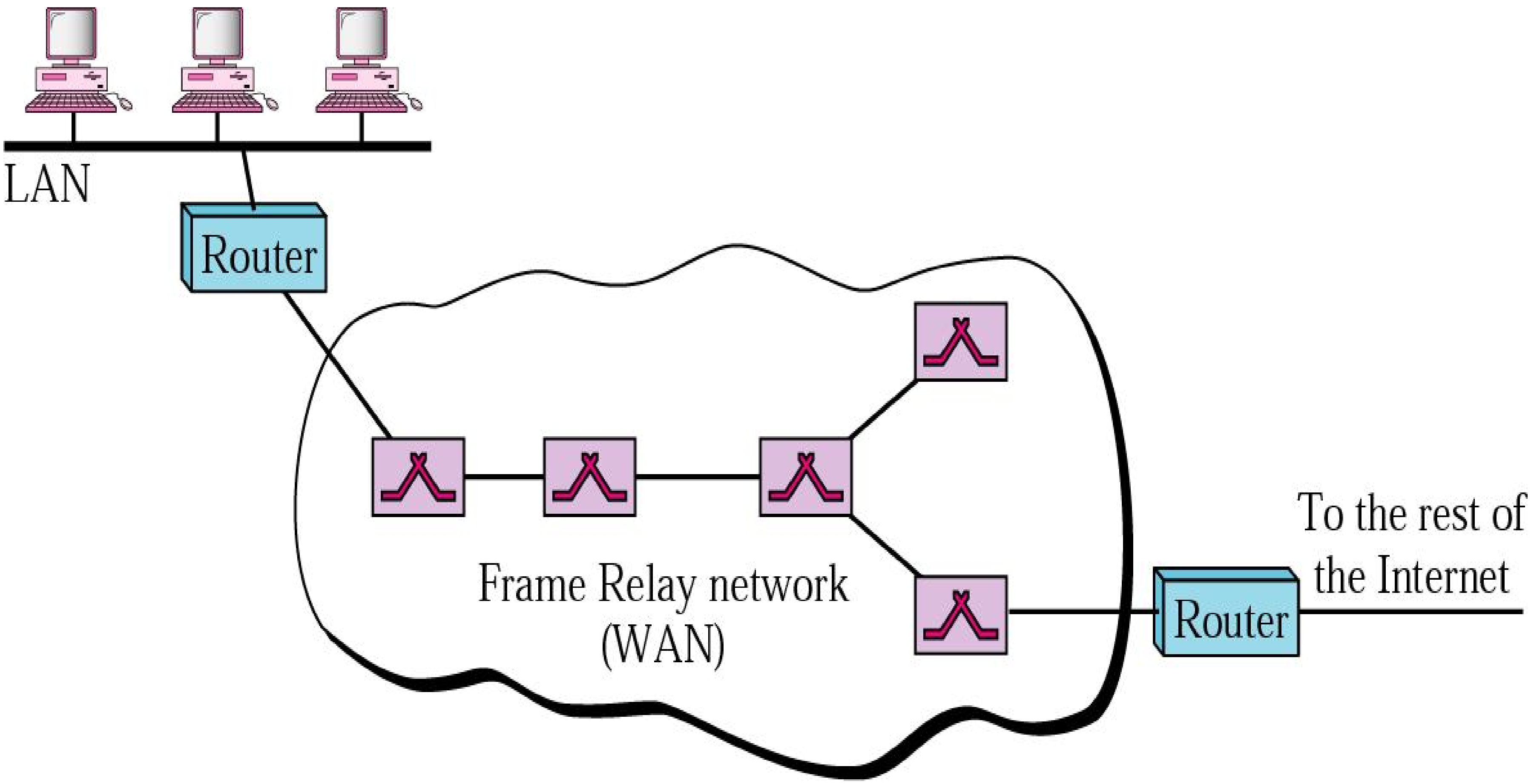
Local Significance of DLCIs

The data-link connection identifier (DLCI) is stored in the Address field of every frame transmitted.



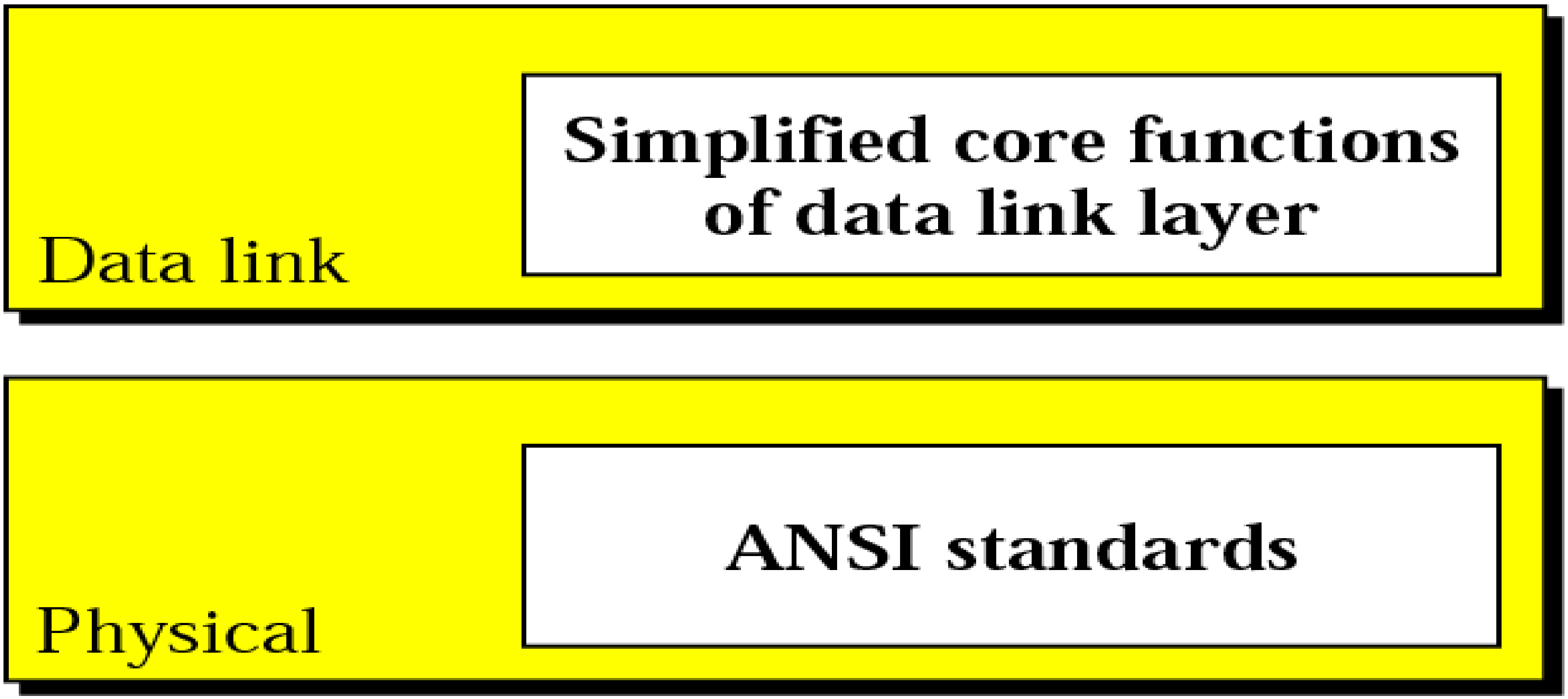
DLCIs have local significance only - the same number on a different link indicates a different VC, and has a different DLCI on each end.

Frame Relay network



VCIs in Frame Relay are called DLCIs.

Frame Relay layers



Frame Relay frame

C/R: Command/response

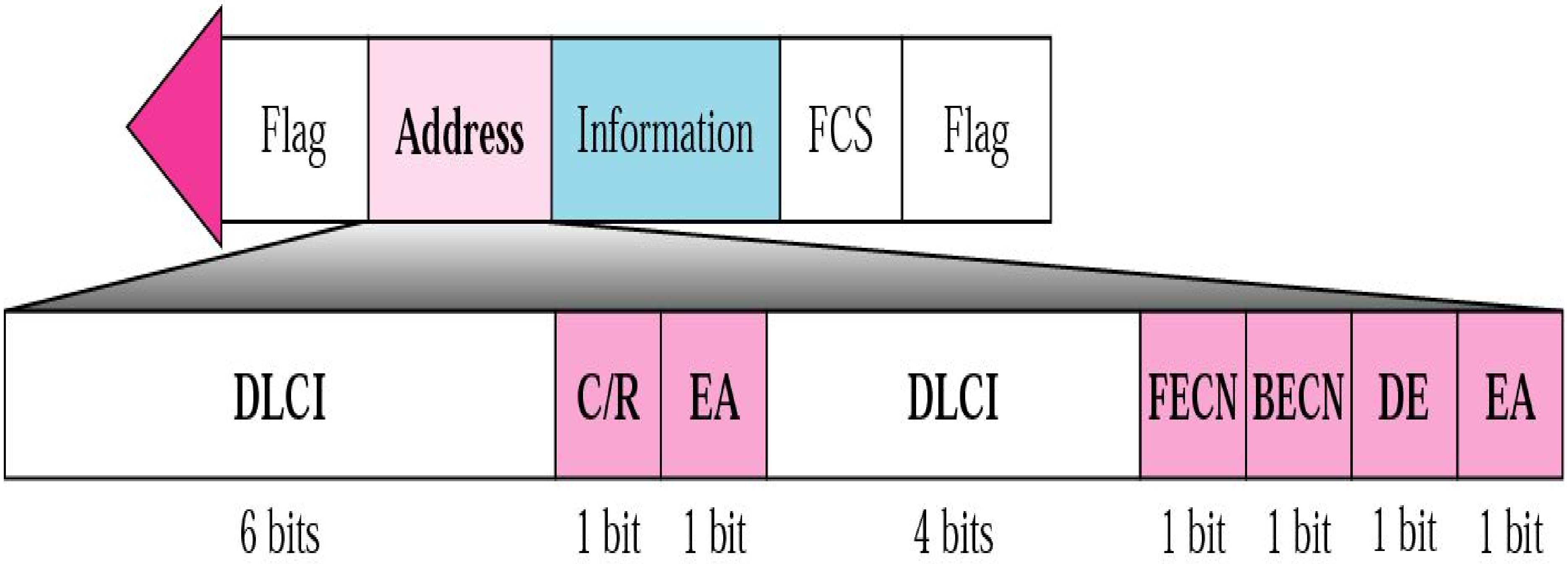
EA: Extended address

FECN: Forward explicit congestion notification

BECN: Backward explicit congestion notification

DE: Discard eligibility

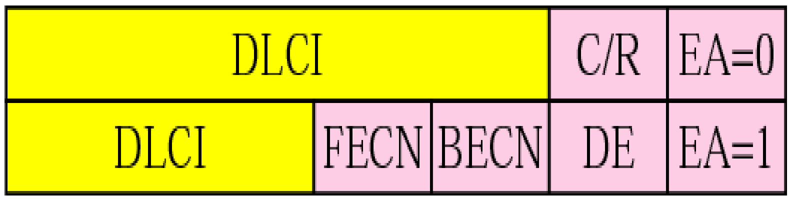
DLCI: Data link connection identifier



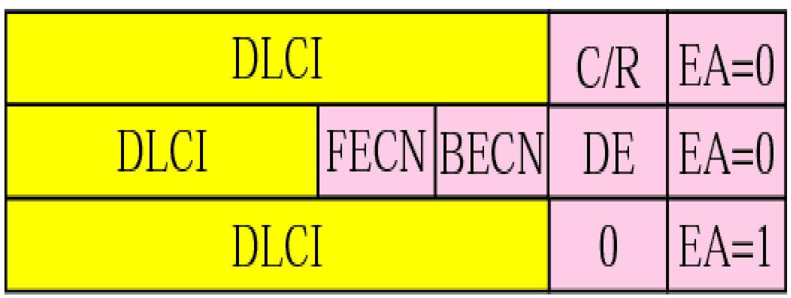
Frame Relay-Global addressing

- Extension proposed by “Group of Four”
- Each end user access device FRAD is assigned a unique DLCI number - a global address Transmission to a given user goes over VC identified by a unique DLCI
- Current DLCI format limits number of devices to less than 1000
- Another addition to the standard - extended DLCI addresses

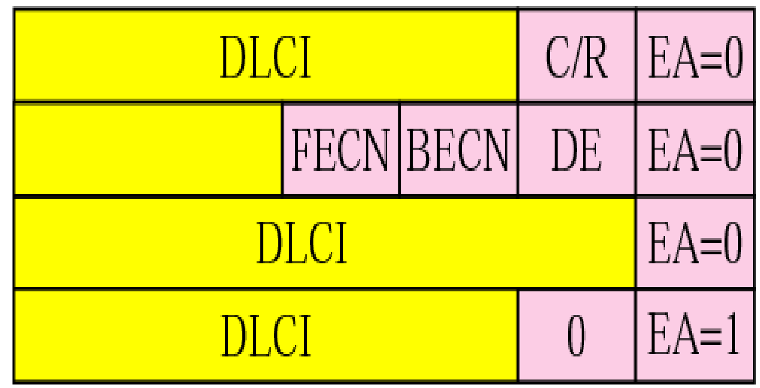
Three address formats



a. Two-byte address (10-bit DLCI)



b. Three-byte address (16-bit DLCI)



c. Four-byte address (23-bit DLCI)

LAPF Frame – Address Field

Although normally 2 bytes, Frame Relay permits up to 4 in the address field.
The last byte is indicated by setting its least significant bit to 1.
The extra bytes permit DLCIs of 16 or 23 bits.

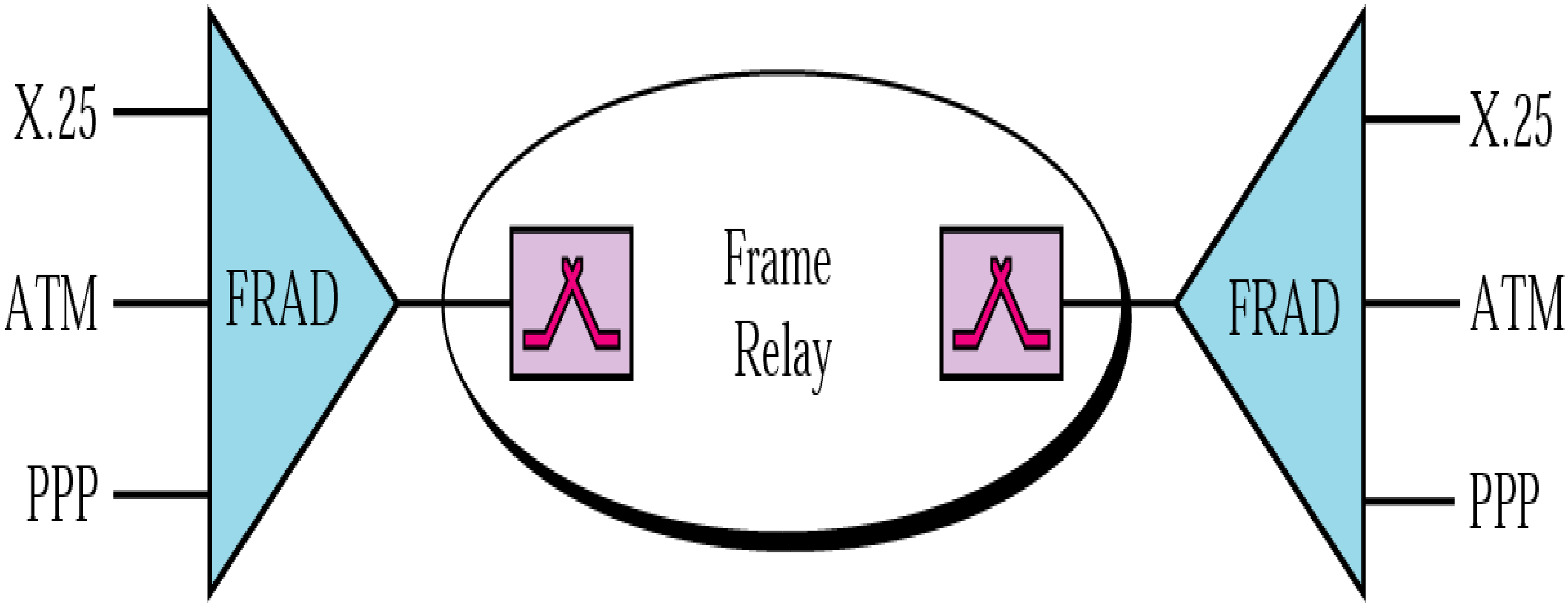
6-bits

	7	4	3	2	1	0
Byte 0	DLCI high bits				C/R	0
Byte 1	DLCI low		F	B	DE	1

4-bits

The C/R bit is not used by Frame Relay, but switches are required to pass it unchanged, so it may be used by the FRAD or Router.

FRAD



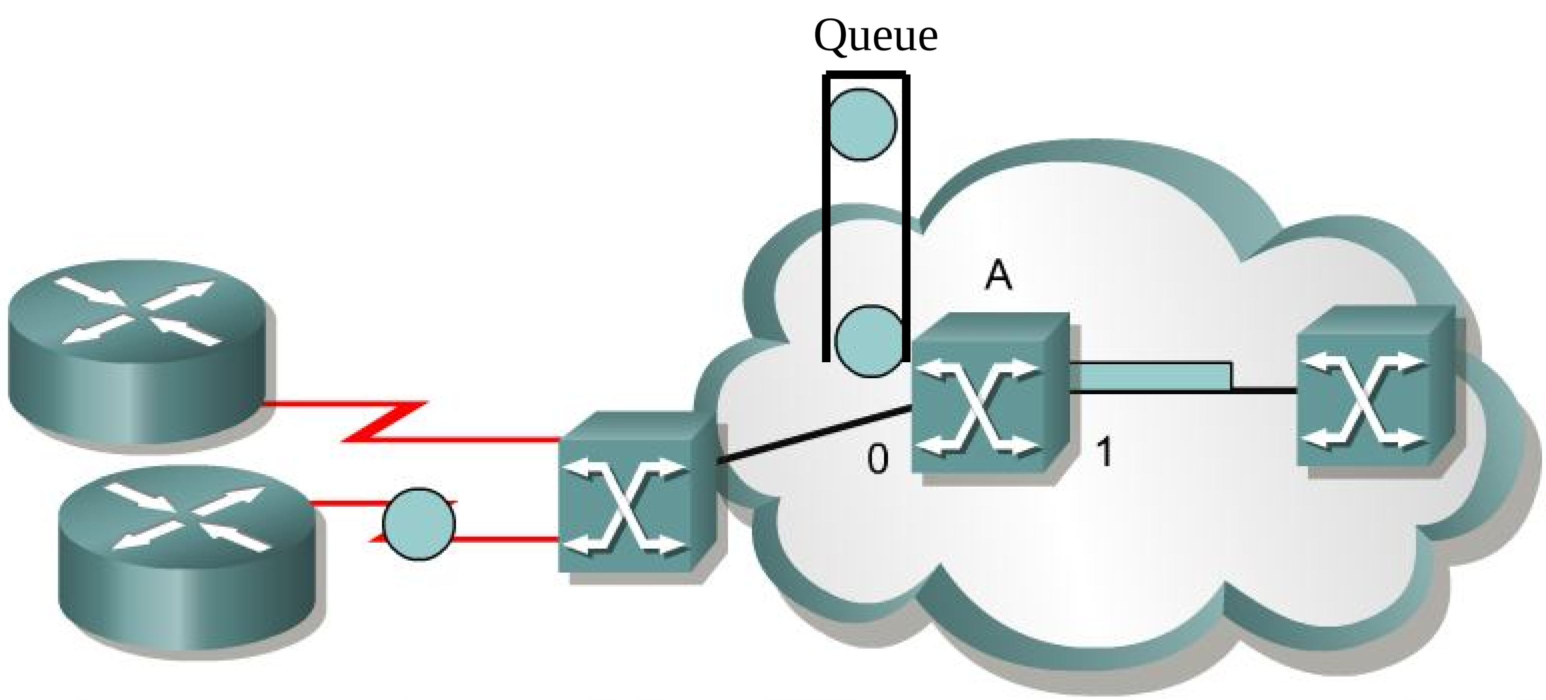
Frame Relay
Flow and congestion control

- There is no explicit flow control in FR; the network informs a user about congestion
- Congestion: FR frames are discarded from overflowed buffers of switching devices
- Congestion information:
  - FECN - Forward Explicit Congestion Notification
  - BECN - Backward Explicit Congestion Notification

FRAD

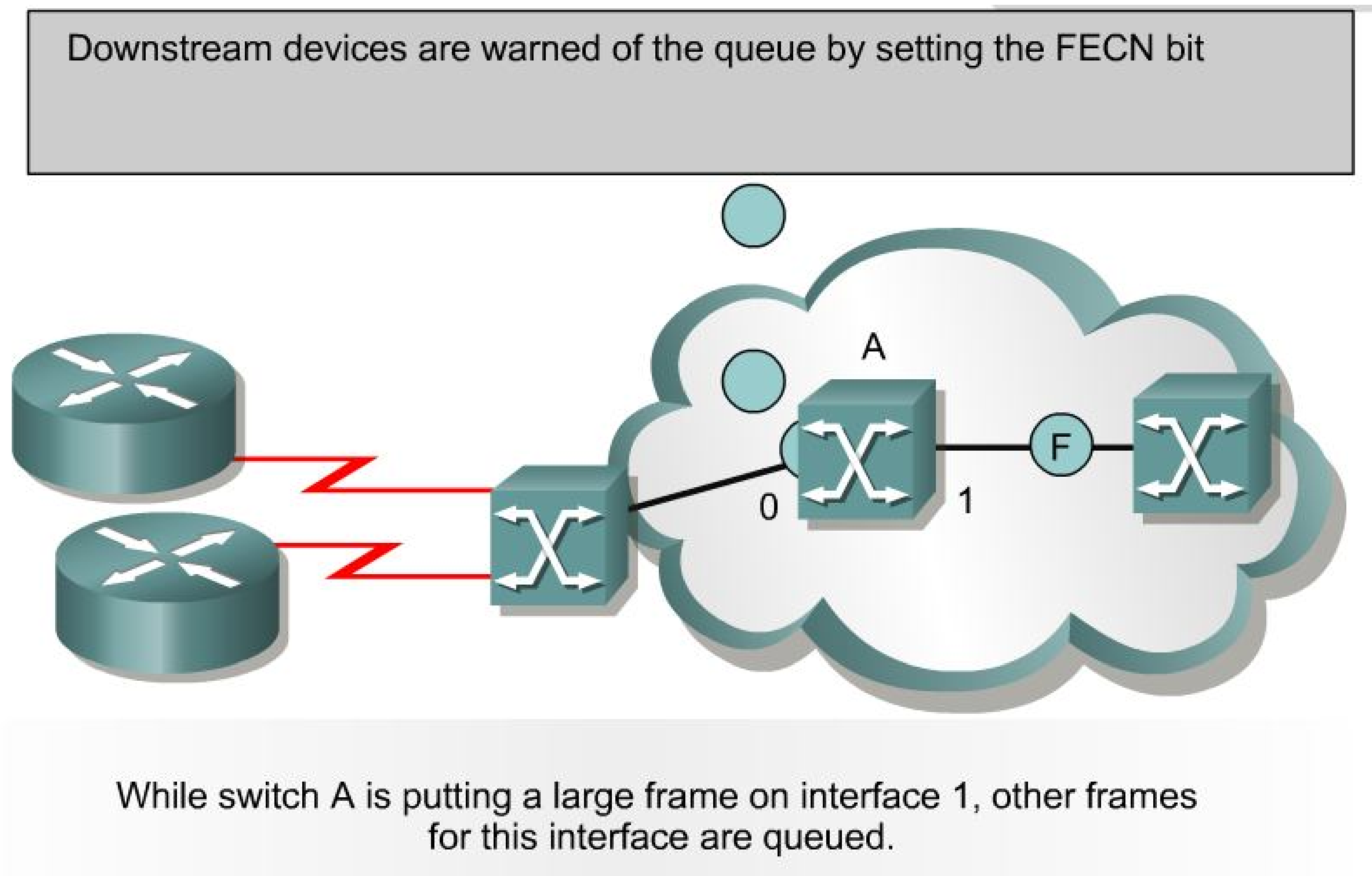
FRAD

Frame Relay Concepts



While switch A is putting a large frame on interface 1, other frames for this interface are queued.

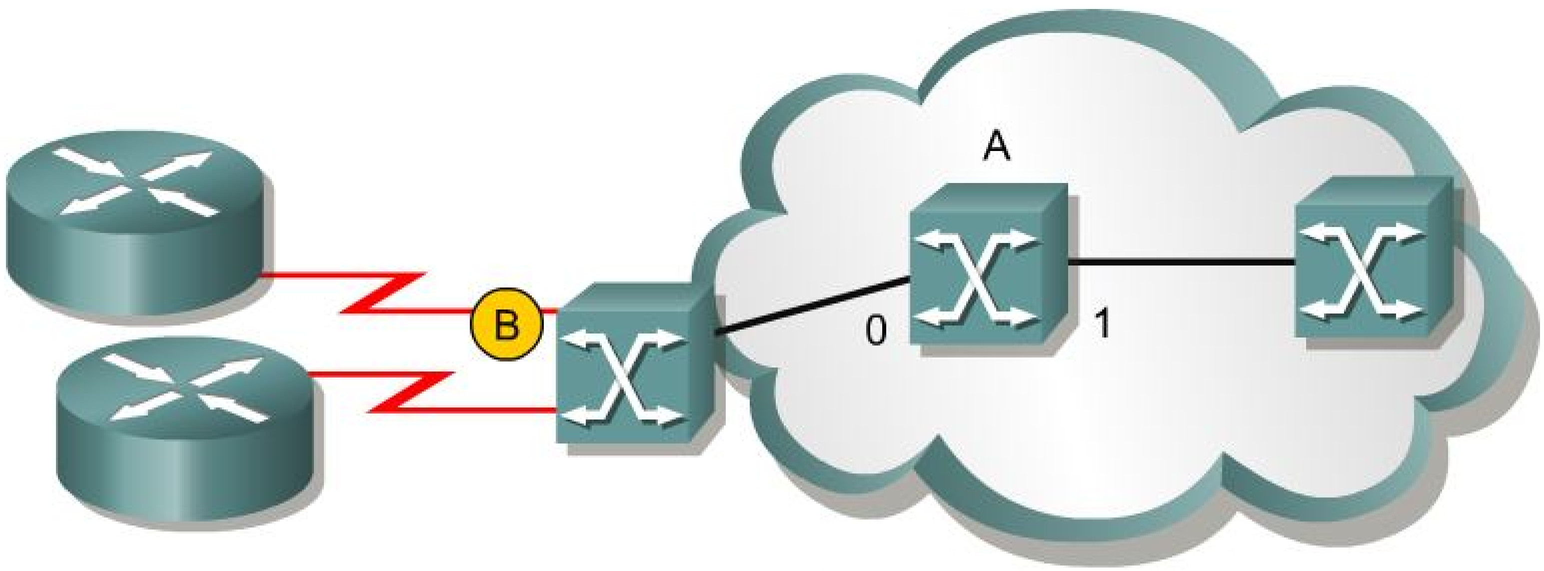
Frame Relay Concepts



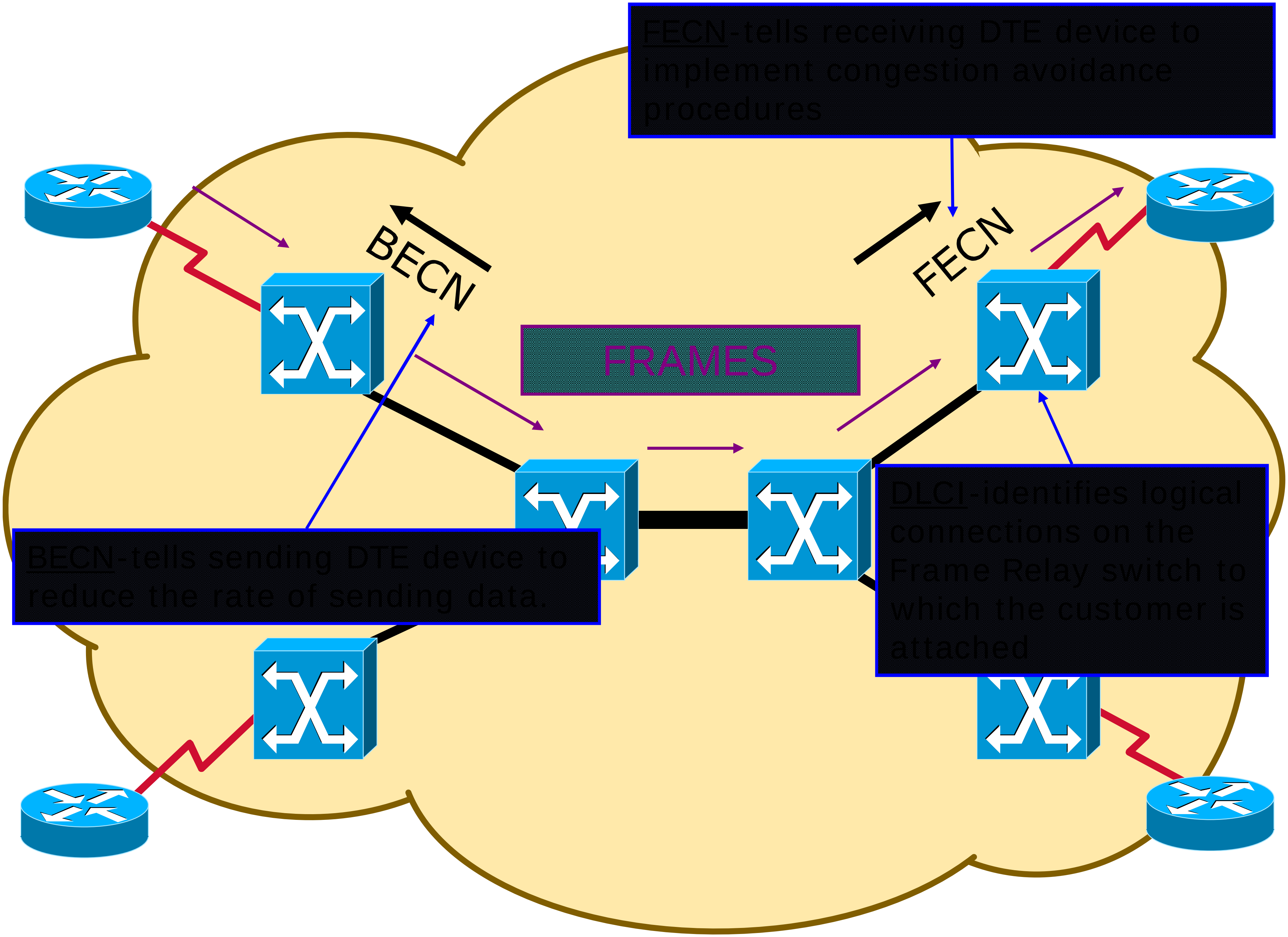
Frame Relay Concepts

Downstream devices are warned of the queue by setting the FECN bit

Upstream devices are warned of the queue by setting the BECN bit- even though they may not have contributed to the congestion

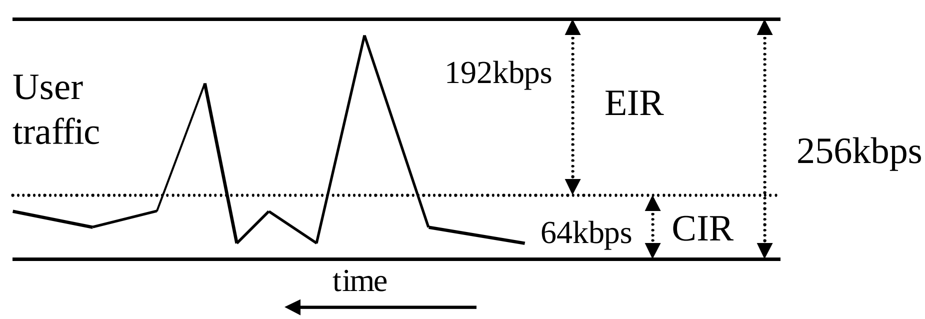


While switch A is putting a large frame on interface 1, other frames for this interface are queued.


[redacted]
BECN
FECN
FRAMES
[redacted]
[redacted]

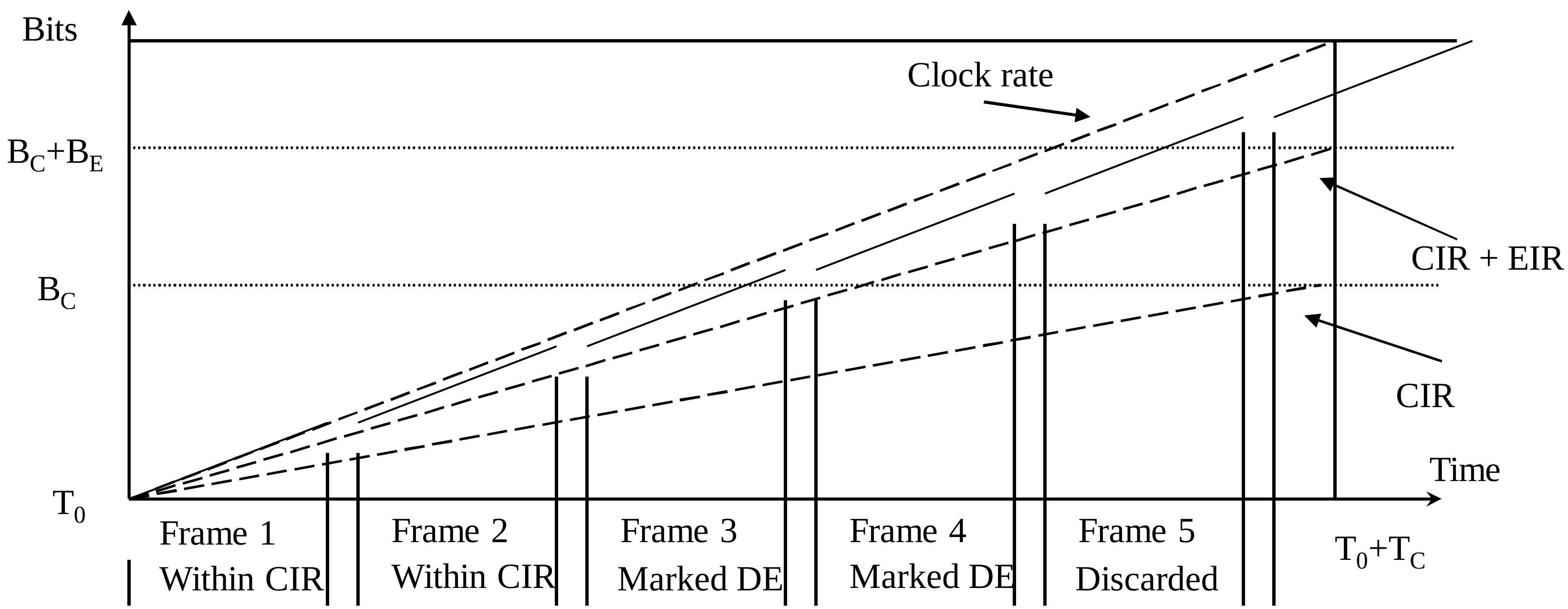
Frame Relay
Parameters of a UNI interface

- Physical speed - just clock rate
- Guaranteed bandwidth parameters
  - CIR: Committed Information Rate
  - B_C: Committed Burst Size
- Extended bandwidth parameters
  - EIR: Extended Information Rate
  - B_E: Extended Burst Size
- T_C: Measurement Interval



Frame Relay
CIR and EIR - how does it work

- $B_C = T_C * CIR$
- $B_E = T_C * EIR$



Data Link Control Identifier

- The 10-bit DLCI associates the frame with its virtual circuit
- It is of local significance only - a frame will not generally be delivered with the same DLCI with which it started
- Some DLCI's are reserved

VC Identifiers	VC Types
0	LMI (ANSI, ITU)
1..15	Reserved for future use
992..1007	CLLM
1008..1022	Reserved for future use (ANSI, ITU)
1019..1022	Multicasting (Cisco)
1023	LMI (Cisco)

Frame Relay
Local Management Interface - LMI

- LMI - a signaling protocol used on an interface: end user - network (UNI)
- Implementation optional (everybody implements it...)
- Usage:
  - notification about: creation, deletion, existence of PVCs on a given port
  - notification about status and availability of PVCs

Local Management Interface (LMI)

- Three types of LMIs are supported by Cisco routers:

  Cisco — The original LMI extensions

  Ansi — Corresponding to the ANSI standard T1.617 Annex D

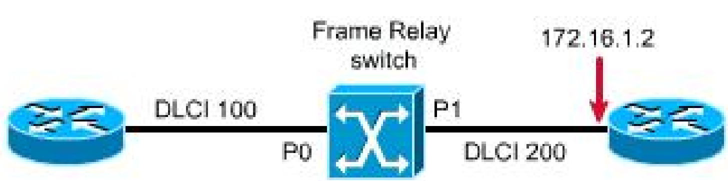
  q933a — Corresponding to the ITU standard Q933 Annex A

Frame Relay Map

- The term map means to “map” or bind a Layer 2 address to a Layer 3 address.
  - An ARP table maps MACs to IPs in a LAN
  - In ISDN, we use the **dailer-map** command to map SPIDs to IP addresses
- In Frame Relay, we need to map the data link layer’s DLCI to the IP address
  - We use the **frame-relay map** command

Frame Relay Map

- The Frame Relay switch builds a table of incoming/outgoing ports and DLCIs.
- The router builds a Frame Relay Map through Inverse ARP requests of the switch during the LMI exchange process.
- The Frame Relay Map is used by the router for next-hop address resolution.

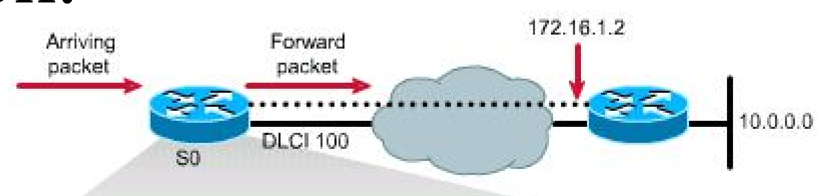


Frame Relay map

Address of next router	DLCI
172.16.1.2	100

P0 switching table

IN_Port	IN_DLCI	OUT_Port	OUT_DLCI
P0	100	P1	200



Routing table

Network	Address of next router	Interface
10.0.0.0	172.16.1.2	S0

Main memory

Frame Relay map

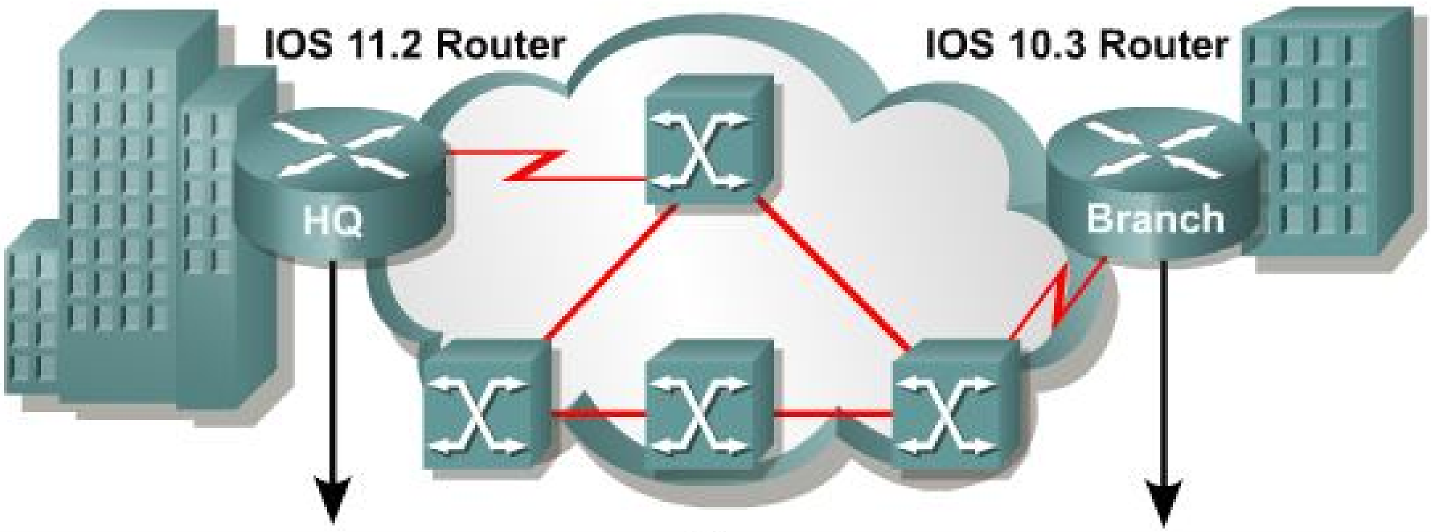
Address of next router	DLCI
172.16.1.2	100

Physical interface

Frame Relay-IARP

- FRADs know DLCIs of available PVCs (through LMI), but don't know IP addresses of other ends
- IP addresses for given DLCIs are obtained automatically; mapping IP-DLCI is generated - dynamic mapping
- IARP can be switched of; static maps have to be generated by FRAD user

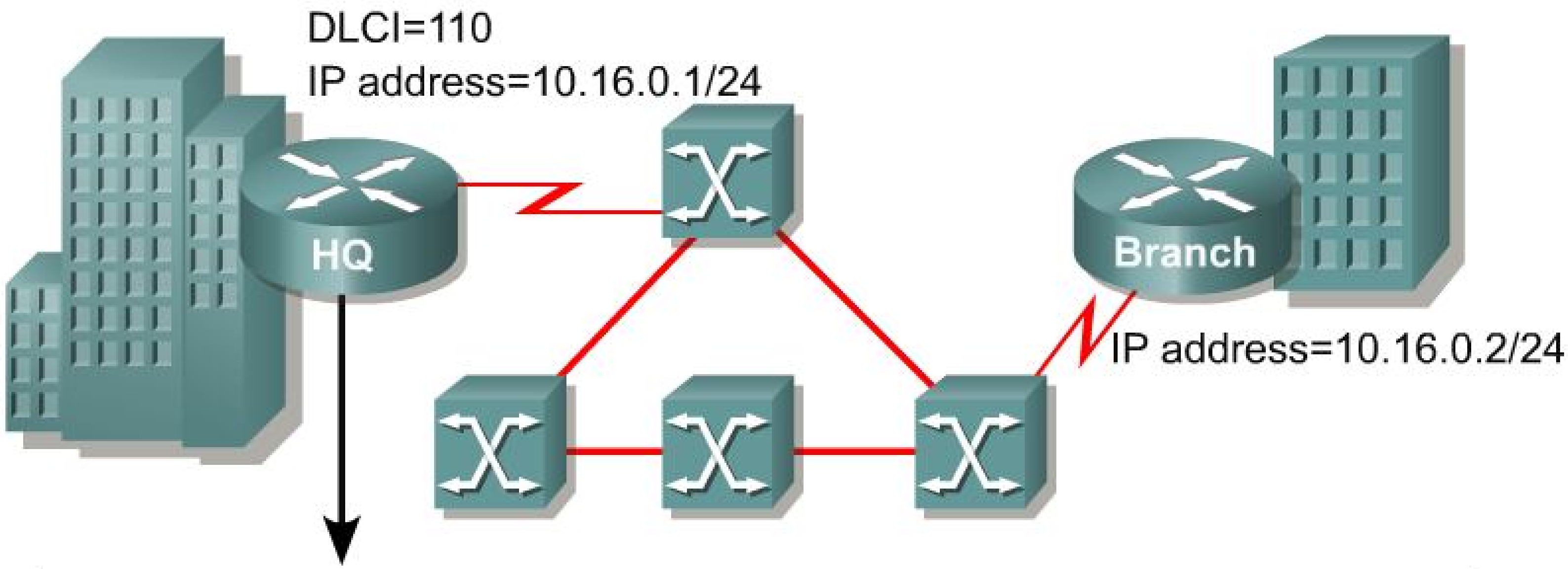
Configuring Basic Frame Relay




```
interface Serial0/1
  ip address 10.16.0.1 255.255.255.0
  encapsulation frame-relay
  bandwidth 64
```

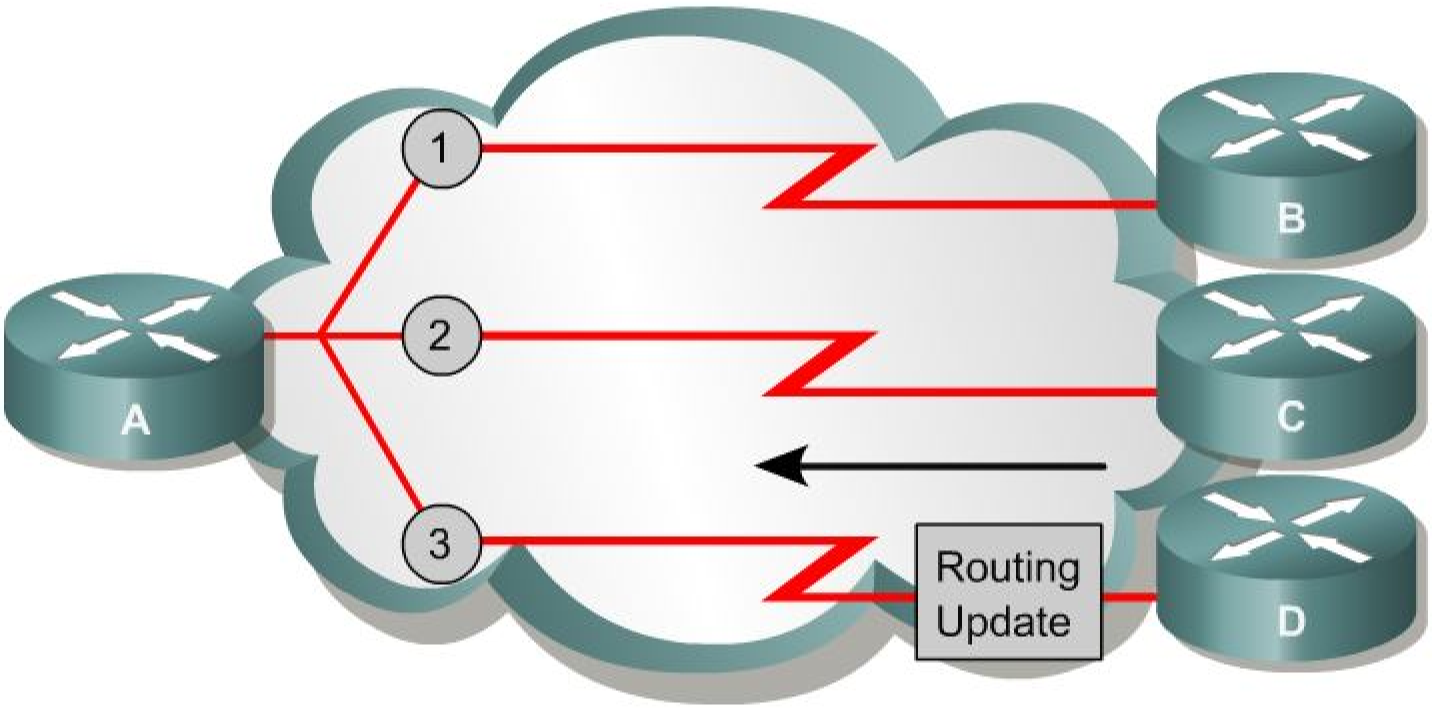
```
interface Serial0/1
  ip address 10.16.0.2 255.255.255.0
  encapsulation frame-relay
  bandwidth 64
  frame-relay lmi-type ansi
```

Configuring a Static Frame Relay Map




```
interface Serial 0/1
  ip address 10.16.0.1 255.255.255.0
  encapsulation frame-relay
  bandwidth 64
  frame-relay map ip 10.16.0.2 110 broadcast
```

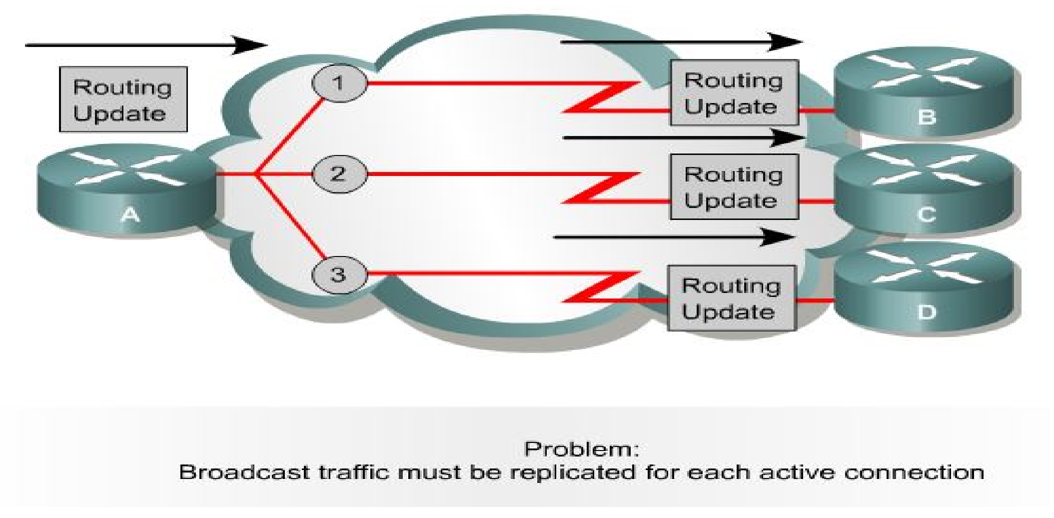
Reachability Issues with Routing Updates in NBMA



Problem:
Update received on physical interface is not retransmitted out that same interface - split horizon

Reachability Issues with Routing Updates in NBMA

By default, a Frame Relay network provides nonbroadcast multiaccess (NBMA) connectivity between remote sites. An NBMA environment is treated like other multiaccess media environments, where all the routers are on the same subnet.



Frame Relay Subinterfaces

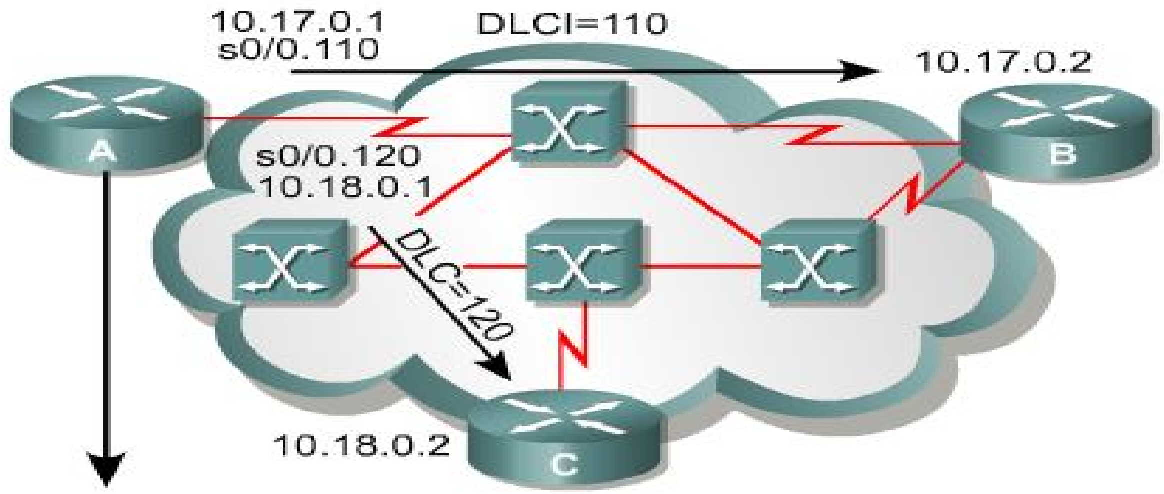
Point-to-Point

- Subinterfaces act as leased line
- Each point-to-point subinterface requires its own subnet
- Applicable to hub and spoke topologies

Multipoint

- Subinterfaces act as NBMA network so they do not resolve the split horizon issue
- Can save address space because uses single subnet
- Applicable to partial-mesh and full-mesh topology

Configuring Point-to-Point Subinterfaces




```
interface Serial0/0
  no ip address
  encapsulation frame-relay
  !
  interface Serial0/0.110 point-to-point
   ip address 10.17.0.1 255.255.255.0
   bandwidth 64
   frame-relay interface-dlci 110
  !
  interface Serial0/0.120 point-to-point
   ip address 10.18.0.1 255.255.255.0
   bandwidth 64
   frame-relay interface-dci 120
  !
```

Verifying Frame Relay

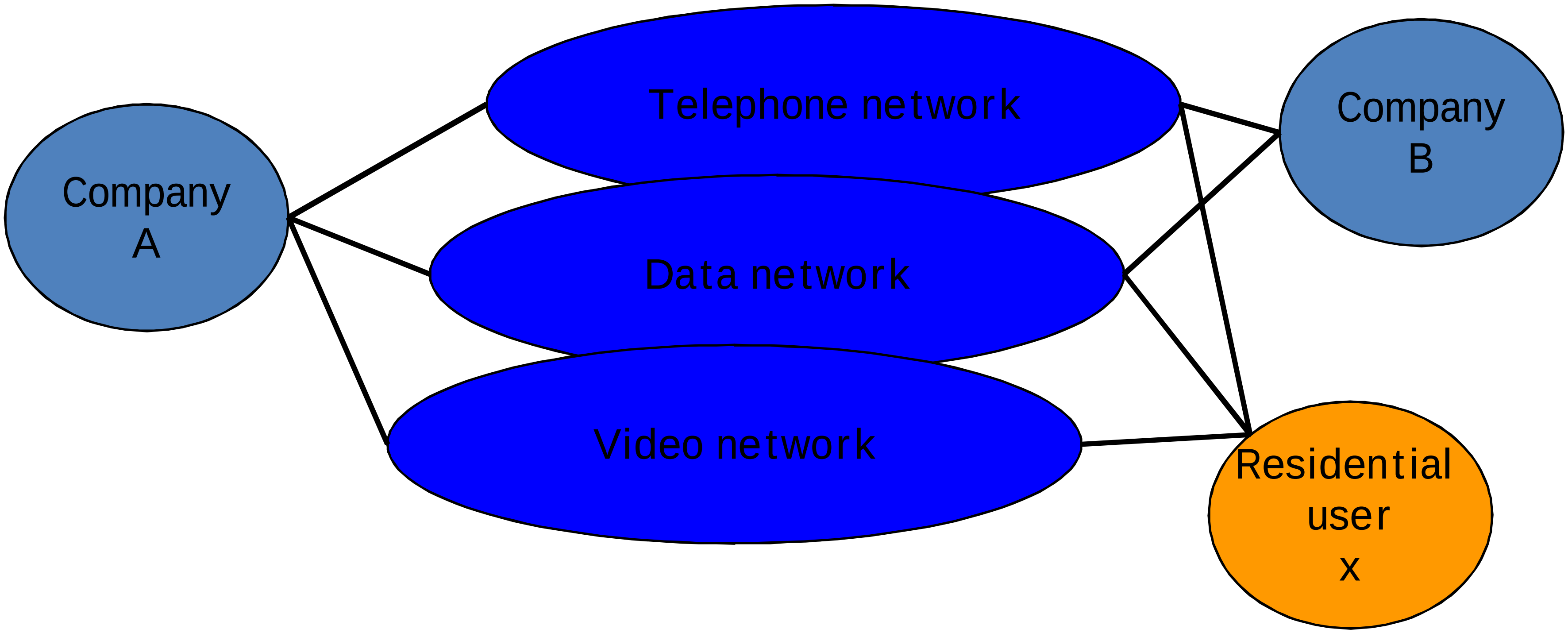
- The show interfaces command displays information regarding the encapsulation and Layer 1 and Layer 2 status. It also displays information about the following:
  - The LMI type
  - The LMI DLCI
  - The Frame Relay data terminal equipment/data circuit-terminating equipment (DTE/DCE) type

ATM

Broadband Integrated Services Networks

- In the mid-1980s, the ITU-T (formerly CCITT) initiated a standardization effort to merge voice, video and data on a single network
- The goal was to replace all existing networks (telephony networks, Cable TV network, data networks) with a single network infrastructure. The effort was called **B-ISDN (Broadband Integrated Services Digital Networks)**

Traditional Network Infrastructure

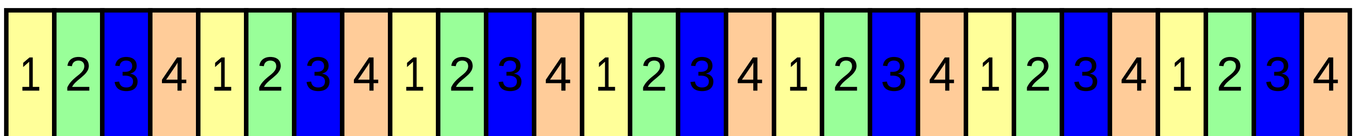


Why “asynchronous”?

Synchronous transfer mode (= Time division multiplexing)

– Each source gets period assignment of bandwidth

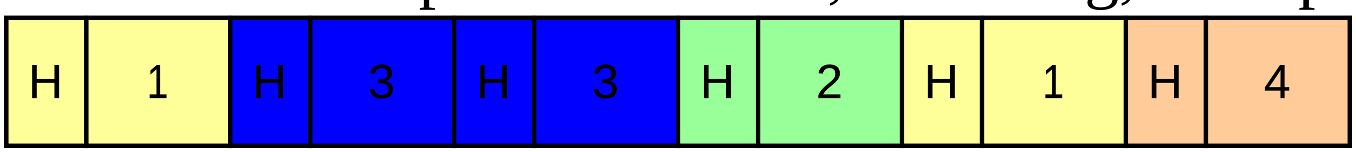
- good: fixed delays, no overhead
- bad: poor utilization for bursty sources



Asynchronous transfer mode (= Statistical multiplexing)

– Sources packetize data. Packets are sent only if there is data

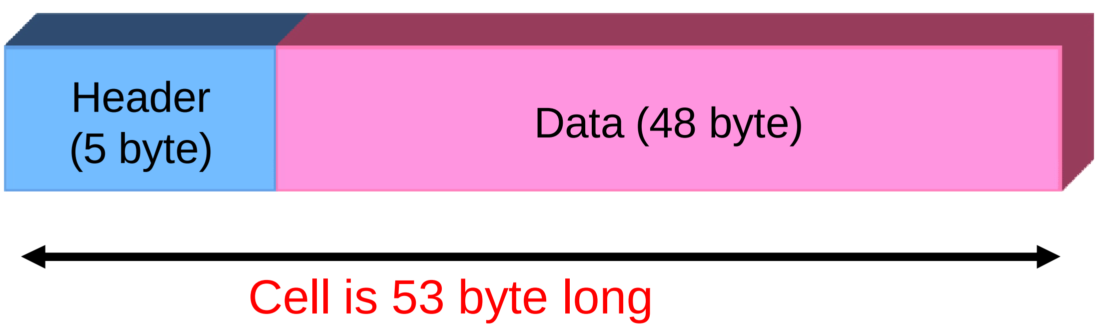
- good: no bandwidth use when source is idle
- bad: packet headers, buffering, multiplexing delay



ATM's Key Concepts

- **ATM uses Virtual-Circuit Packet Switching**
  - ATM can reserve capacity for a virtual circuit. This is useful for voice and video, which require a minimum level of service
  - Overhead for setting up a connection is expensive if data transmission is short (e.g., web browsing)

- **ATM packets are small and have a fixed sized**
  - Packets in ATM are called ***cells***
  - Small packets are good for voice and video transmissions



53 Byte Cells

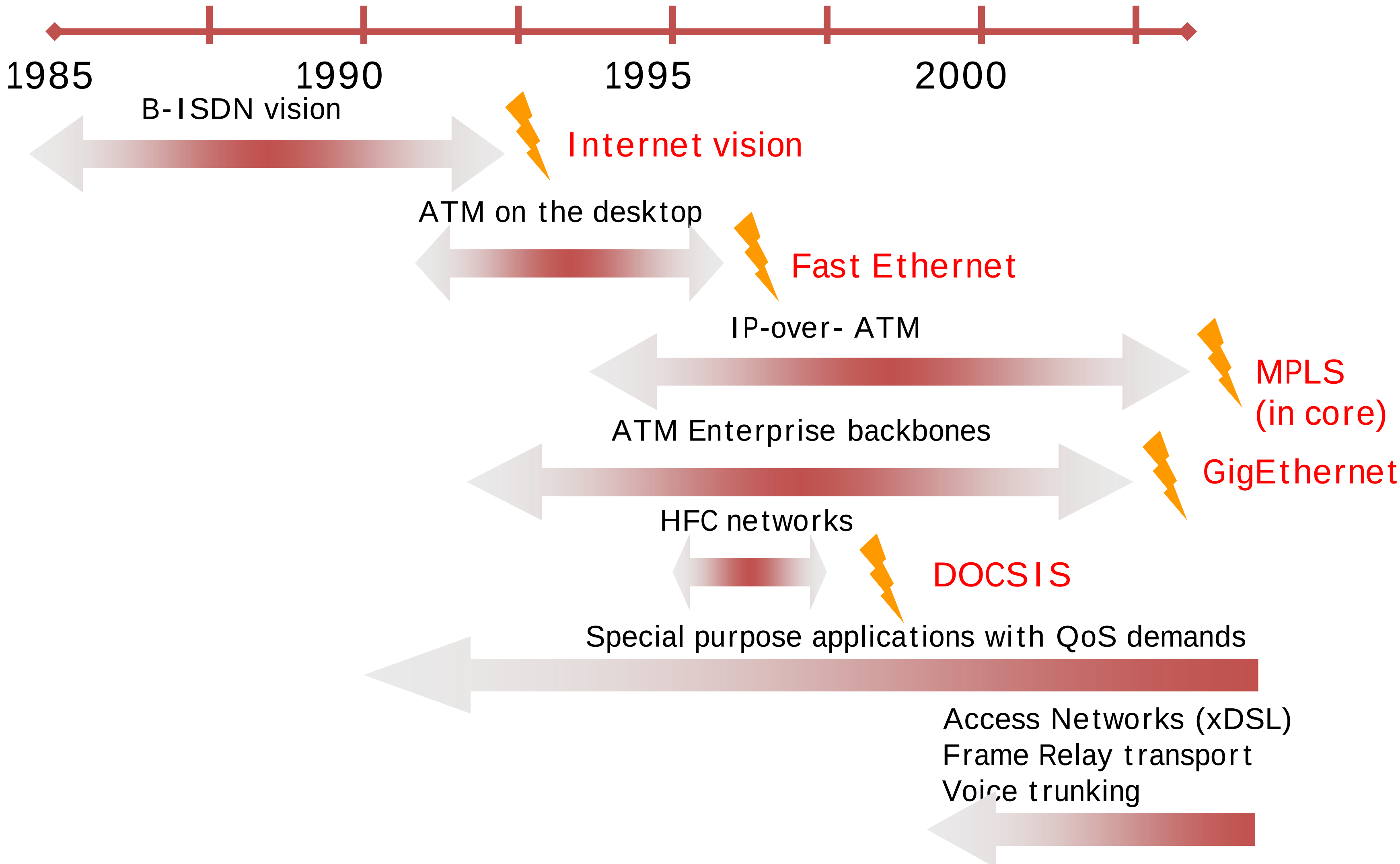
- **Why 53 Bytes?**
  A 48 byte payload was the result of a compromise between a 32 byte payload and a 64 byte payload
- **Advantages**
  - Low packetization delay for continuous bit rate applications (video, audio)
  - Processing at switches is easier
- **Disadvantages**
  - High overhead (5 Bytes per 48)
  - Poor utilization at lower line rates links

ATM Standardization

- Until 1991, standardization occurred within CCITT (now: ITU-T) in a series of recommendations in the I series.
- In 1991, ATM Forum was formed as an industry consortium
    - ATM Forum starts to prepare specifications to accelerate the definition of ATM.
    - Specifications are passed to ITU-T for approval
    - Since 1993, ATM Forum drives the standardization process

- IETF publishes Request for Comments (RFCs) that relate to IP/ATM issues

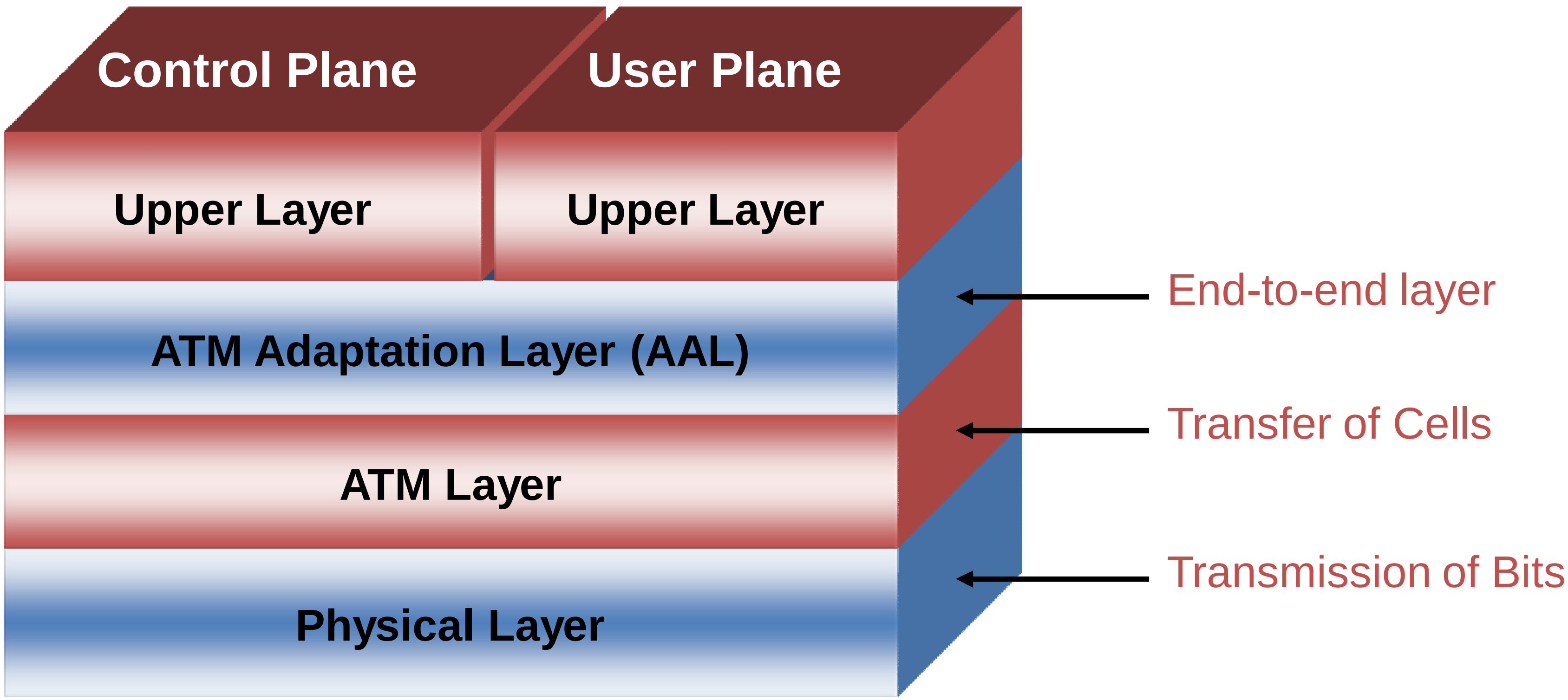
Uses of ATM


1985
1990
1995
2000
B-ISDN vision
Internet vision
ATM on the desktop
Fast Ethernet
IP-over- ATM
MPLS
(in core)
ATM Enterprise backbones
GigEthernet
HFC networks
DOCSIS
Special purpose applications with QoS demands
Access Networks (xDSL)
Frame Relay transport
Voice trunking

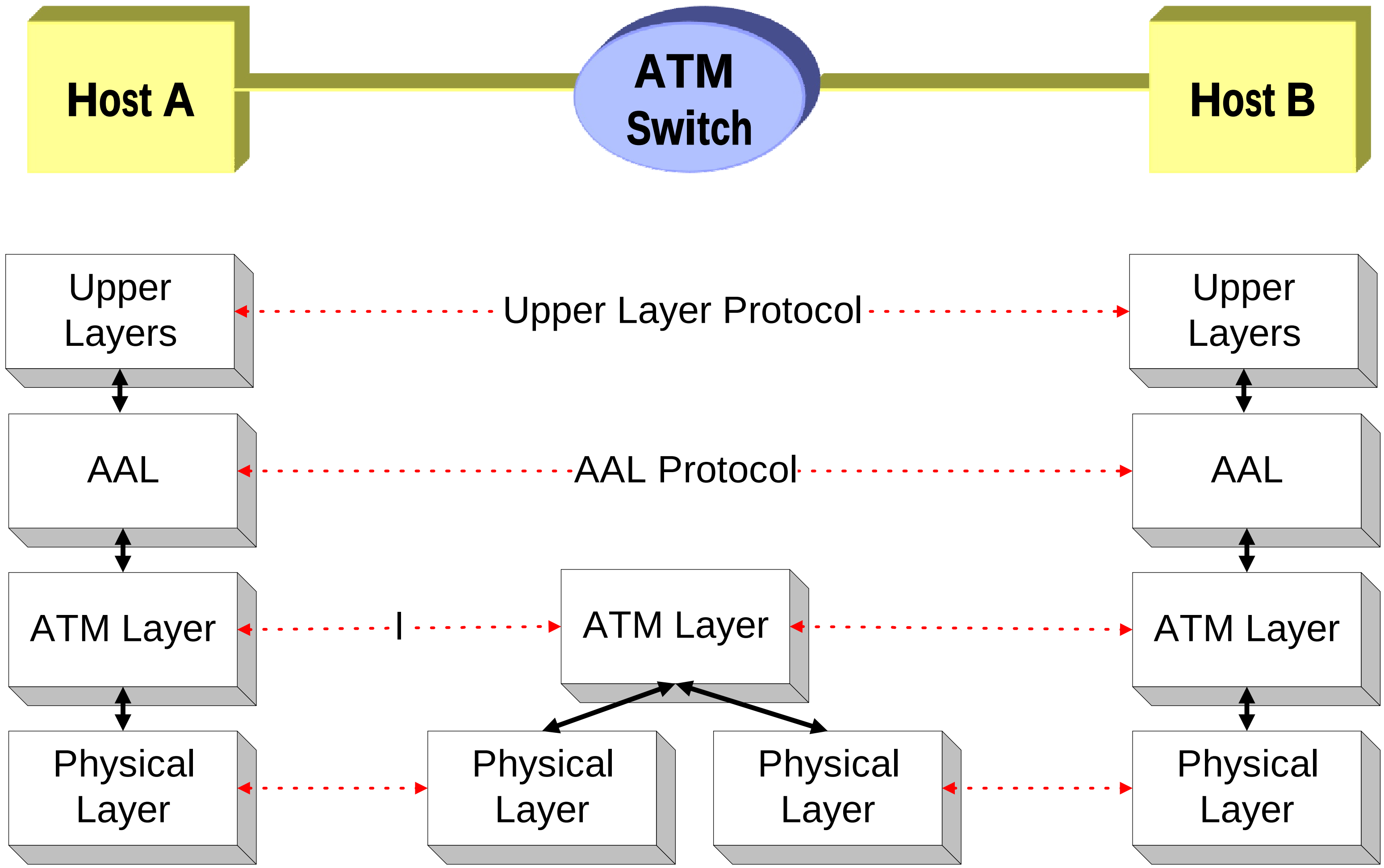
ATM Architecture Overview

The ATM Reference Model

- ATM technology has its own protocol architecture



Layers of ATM



ATM Layer

- The ATM Layer is responsible for the transport of 53 byte cells across an ATM network

- Multiplex logical channels within a physical channel

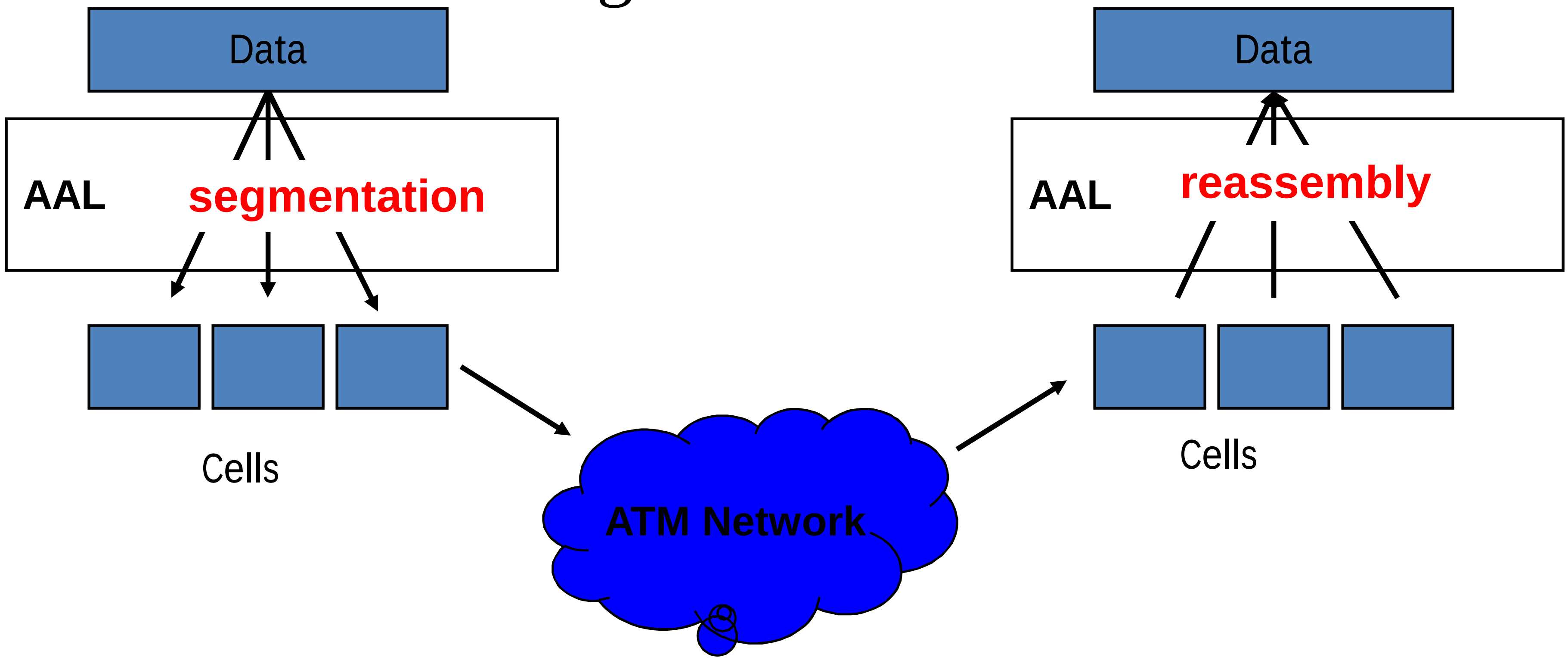
ATM Layer

The ATM Layer can provide a variety of services for cells from an ATM virtual connection:

- **Constant Bit Rate (CBR)**
  - guarantees a fixed capacity, similar to circuit switching
  - guarantees a maximum delay for cells
- **Variable Bit Rate (VBR)**
  - guarantees an average throughput and maximum delay
- **Available Bit Rate (ABR)**
  - guarantees ‘fairness” with respect to other traffic
- **Unspecified Bit Rate (UBR)**
  - service is on a “best effort” basis
- **Guarantees Frame Rate (GFR)**
  - Throughput guarantee for multiple cell frames

ATM Adaptation Layer (AAL)

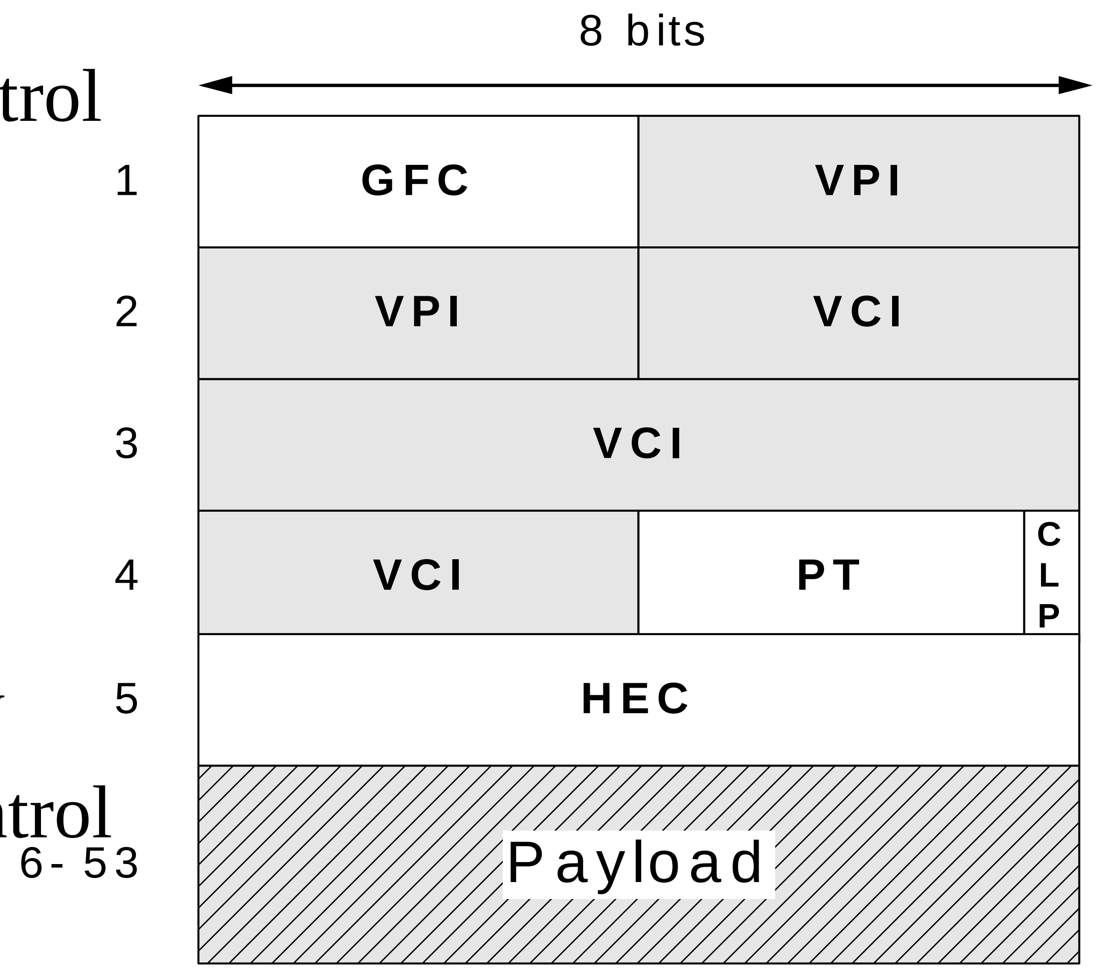
- AAL encapsulates user-level data
- Performs segmentation and reassembly of user-level messages



ATM Cells

ATM Cells

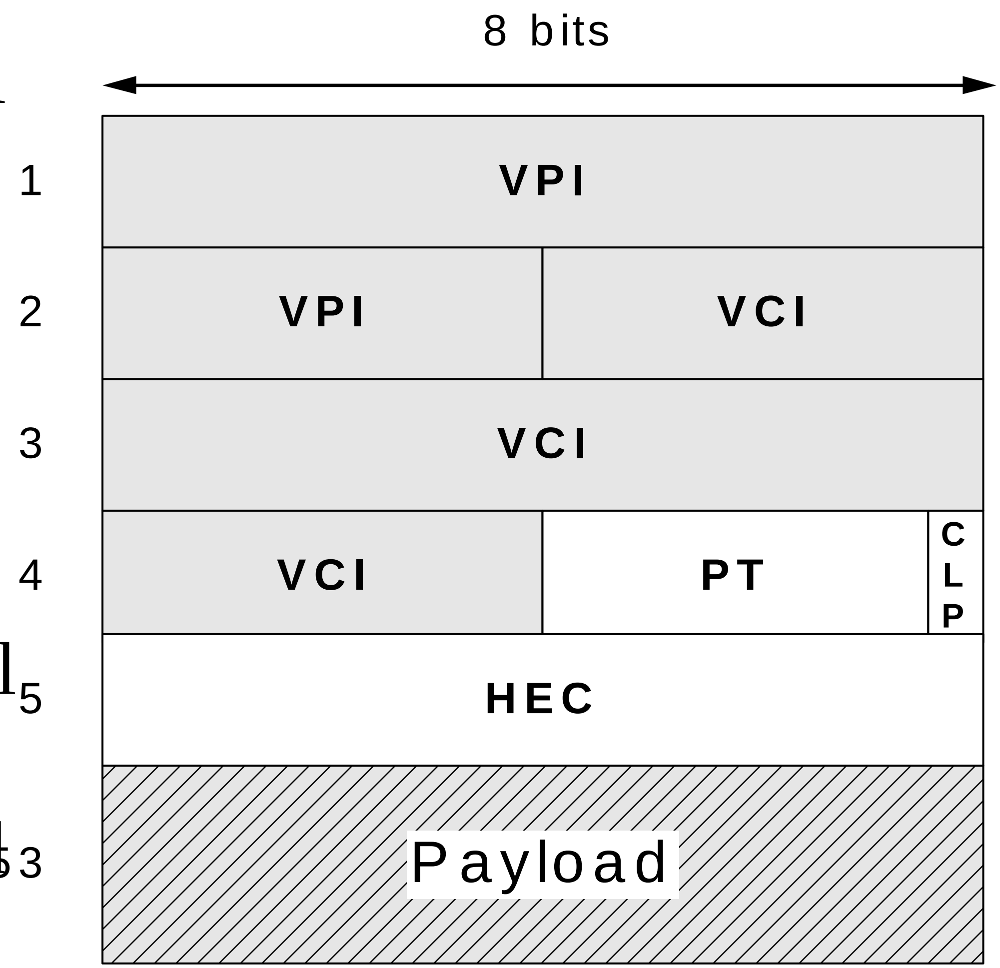
- 4-bit Generic flow control
- 8/12 bit Virtual Path Identifier
- 16 bit Virtual Channel Identifier
- 3 bit Payload Type
- 1 bit Cell Loss Priority
- 8 bit Header Error Control
- 48 byte payload
- GFC field only in UNI cells



UNI Cell

ATM Cells

- 4-bit Generic flow control
- 8/12 bit Virtual Path Identifier
- 16 bit Virtual Channel Identifier
- 3 bit Payload Type
- 1 bit Cell Loss Priority
- 8 bit Header Error Control
- 48 byte payload
- At NNI: GFC byte is used for additional VPI

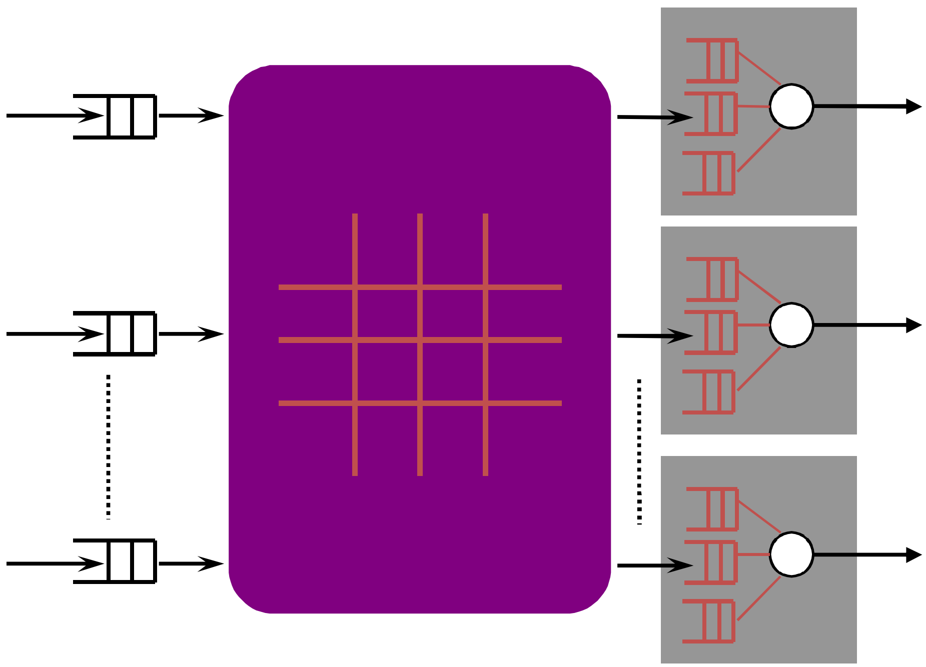


NNI Cell

ATM Connections

A Packet Switch

Packet



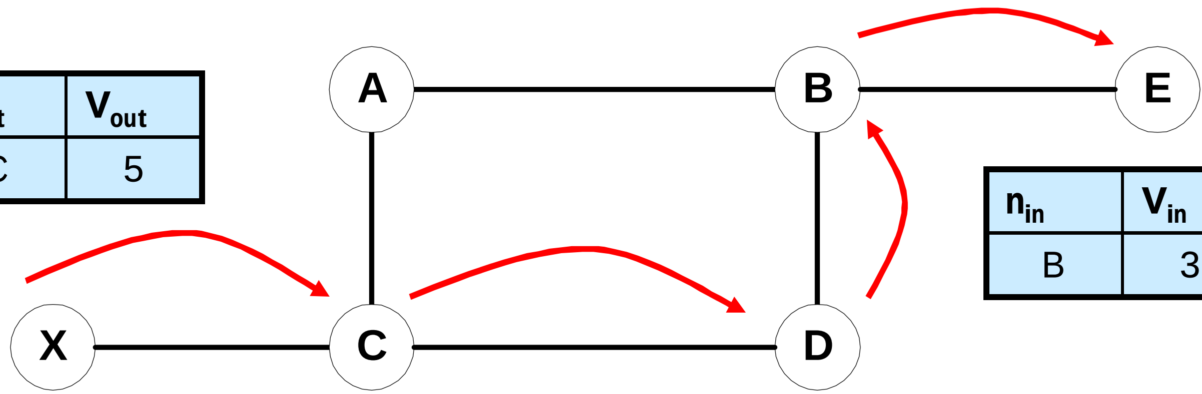
Packet switch

Forwarding with VCs

Part 1: VC setup from X to E

n_{in}	V_{in}	n_{out}	V_{out}
D	5	E	3

n_{in}	V_{in}	n_{out}	V_{out}
-	-	C	5



n_{in}	V_{in}	n_{out}	V_{out}
B	3	-	-

n_{in}	V_{in}	n_{out}	V_{out}
X	5	D	3

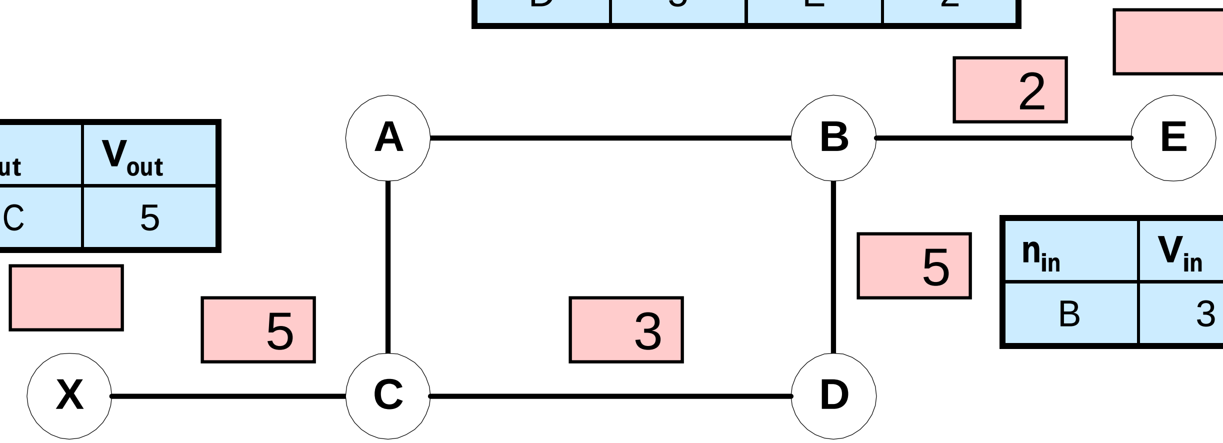
n_{in}	V_{in}	n_{out}	V_{out}
C	3	B	5

Forwarding with VCs

Part 2: Forwarding the packet

n_{in}	V_{in}	n_{out}	V_{out}
-	-	C	5

n_{in}	V_{in}	n_{out}	V_{out}
D	5	E	2

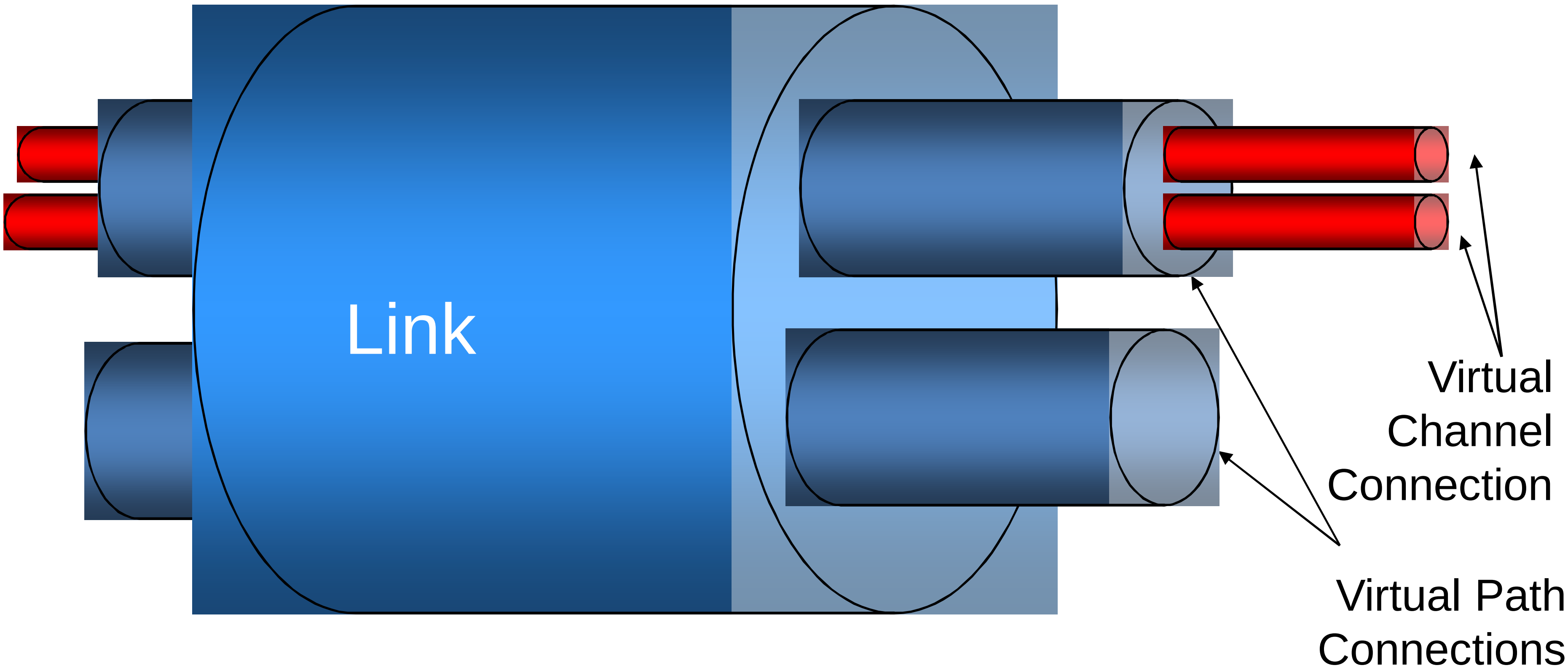


n_{in}	V_{in}	n_{out}	V_{out}
B	3	-	-

n_{in}	V_{in}	n_{out}	V_{out}
X	5	D	3

n_{in}	V_{in}	n_{out}	V_{out}
C	3	B	5

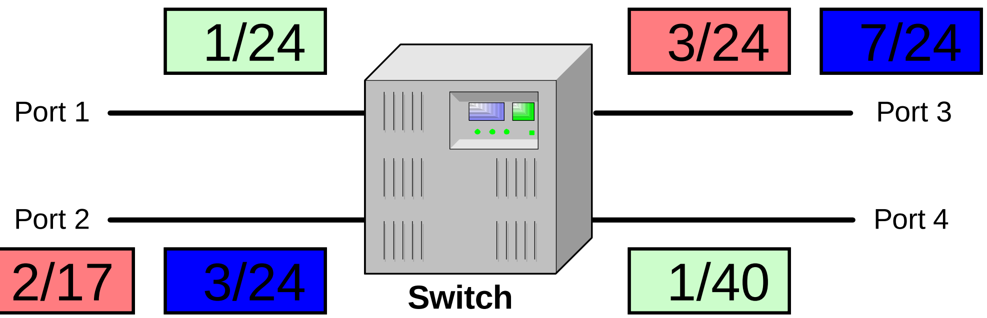
Virtual Paths and Virtual Circuits



VPI identifies virtual path (8 or 12 bits)

VCI identifies virtual channel in a virtual path (16 bits)

VPI/VCI assignment at ATM switches



Routing Table of switch v

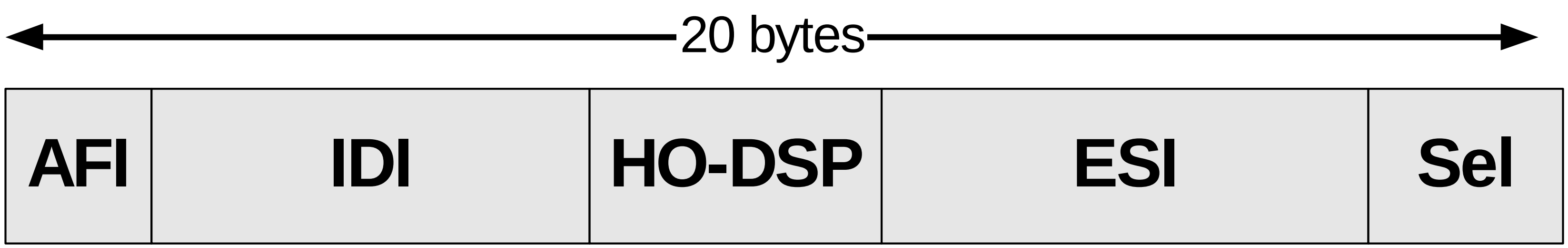
port	VPI/ VCI	to	VPI/ VCI
2	3/24	3	7/24
1	1/24	4	1/40
2	2/17	3	3/24

Addressing and Signaling

ATM Endsystem Addresses (AESA)

- All ATM addresses are 20 bytes long
- Source and destination address are supplied when setting up a connection
- ATM endpoints use the NSAP (Network Service Access Point) format from ISO OSI
- Three different types of addresses
    - **NSAP encoding for E.164:** ISDN telephone numbers (e.g., 001-434-9822200)
    - DCC format: for public networks
    - ICD format: for private networks

ATM Endsystem Addresses (AESA)



AFI (1 byte): Authority and Format Identifier
Tells which addressing scheme to use

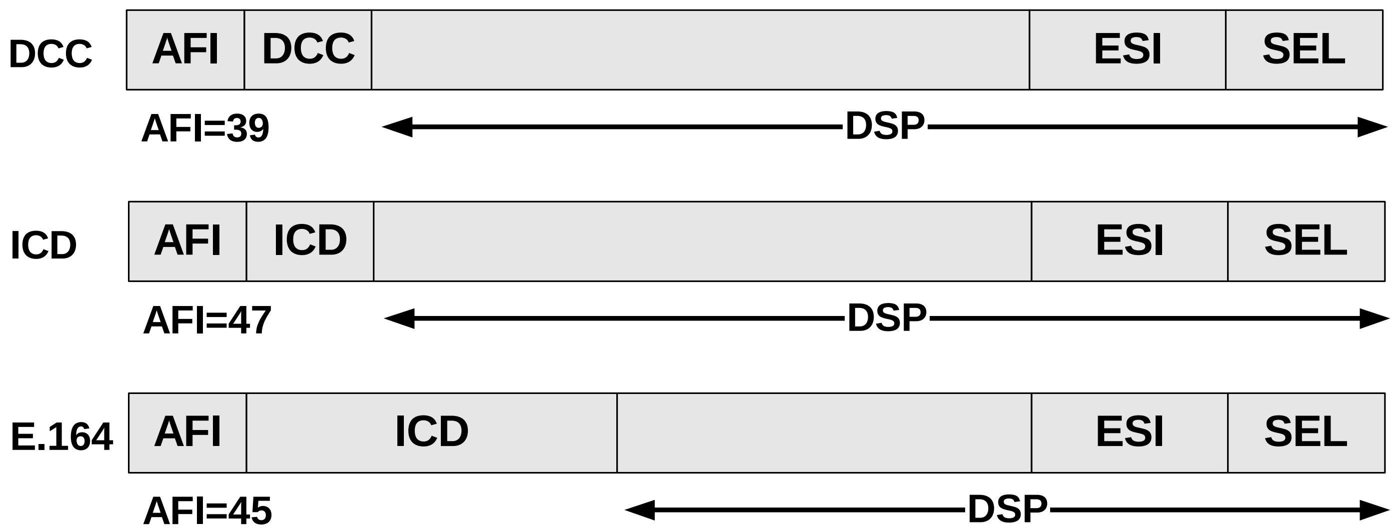
IDI (2-8 bytes): Initial Domain Identifier
Identifies a domain within scope of addressing authority

HO-DSP (4-10 bytes): High-order bits of domain specific part
similar to network prefix of IP address

ESI (6 bytes): Endsystem identifier
similar to host number of IP address

SEL (1 byte): Selector
for endsystem use only

Formats of an ATM address



AFI: Authority and Format Identifier

DCC: Data Country Code

ICD: International Code Designator

E.164: ISDN (telephone)

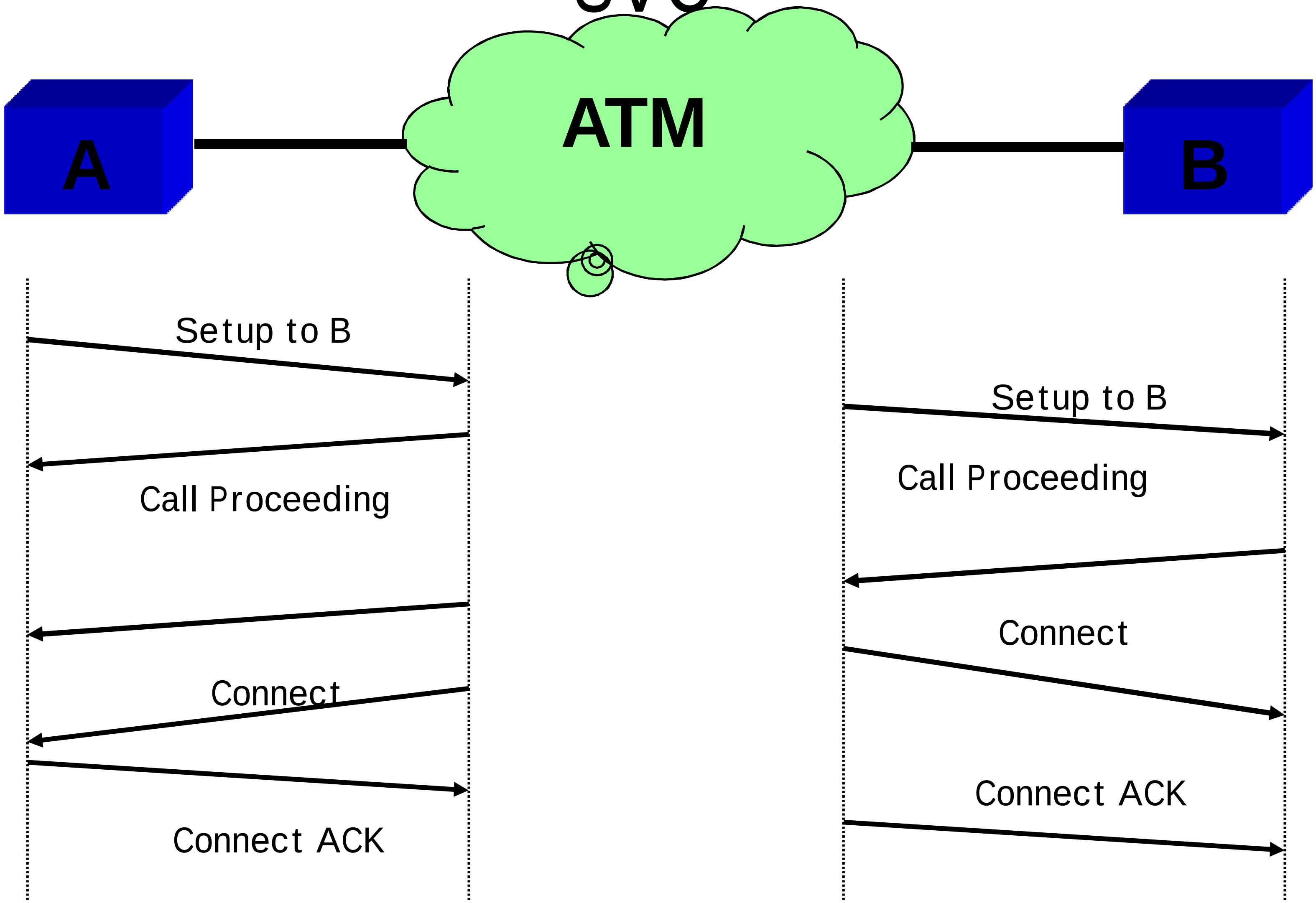
IDI: Initial Domain Identifier

DSP: Domain Specific Part

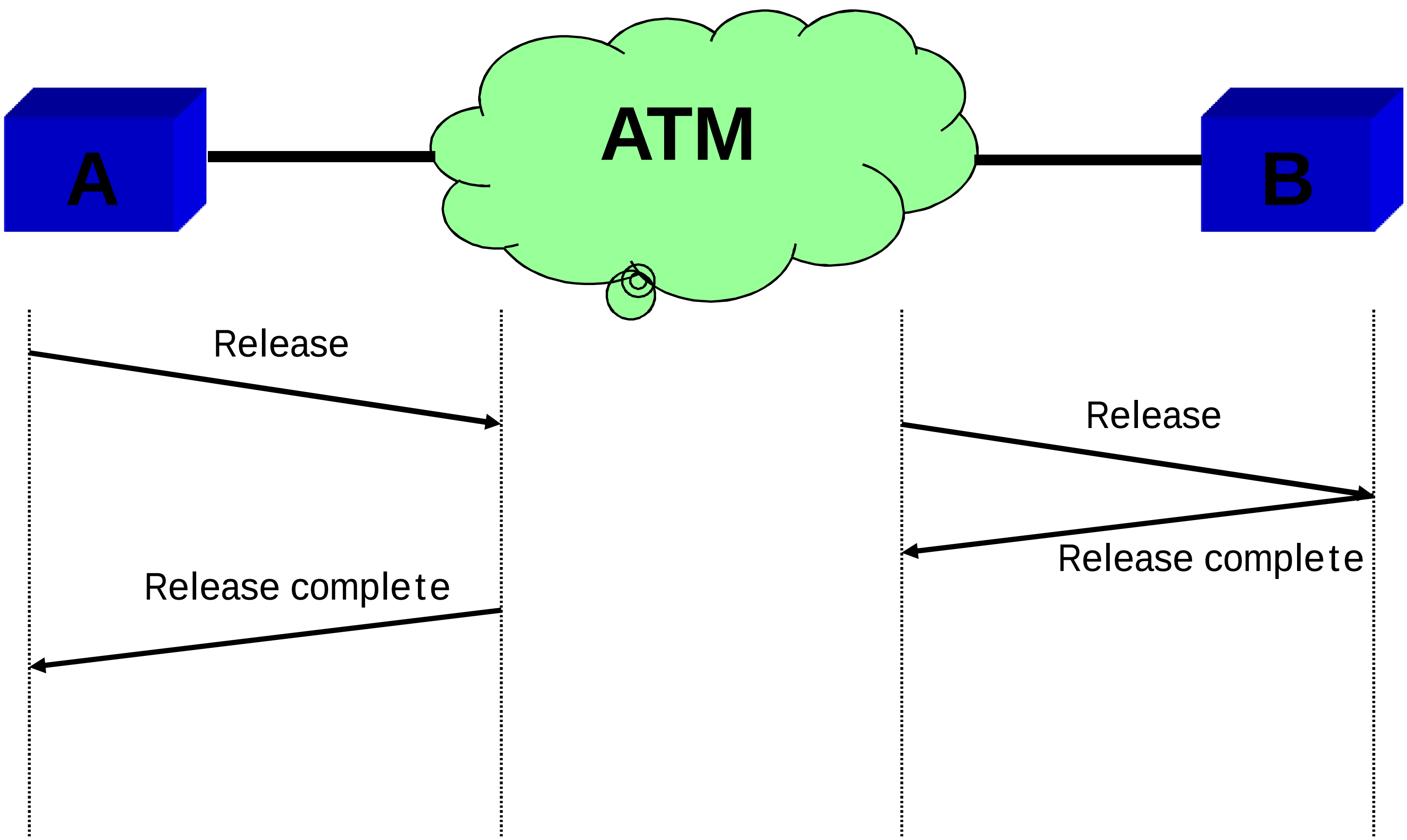
ESI: Endsystem identifier

SEL: Selector

Basic Signaling Exchange: Setup of a SVC



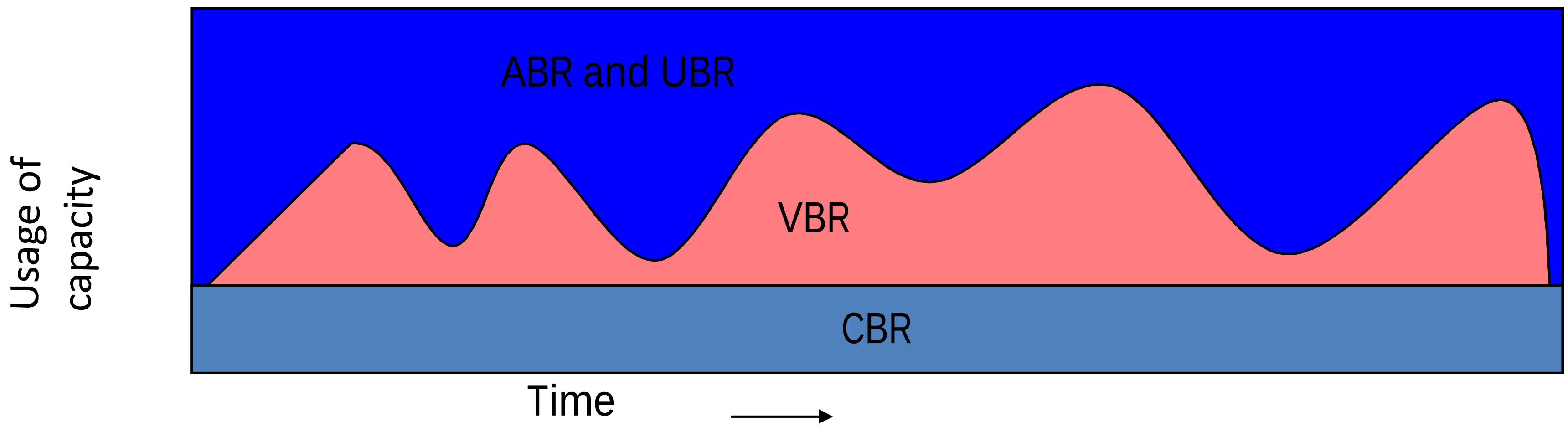
Basic Signaling Exchange: Tear down



ATM Layer Services

ATM Services at the ATM Layer

The following ATM services have been defined:
Constant Bit Rate (CBR)
Real-time Variable Bit Rate (rt-VBR)
Non-real-time Variable Bit Rate (nrt-VBR)
Available Bit Rate (ABR)
Unspecified Bit Rate (UBR)
Guaranteed Frame Rate (GFR)



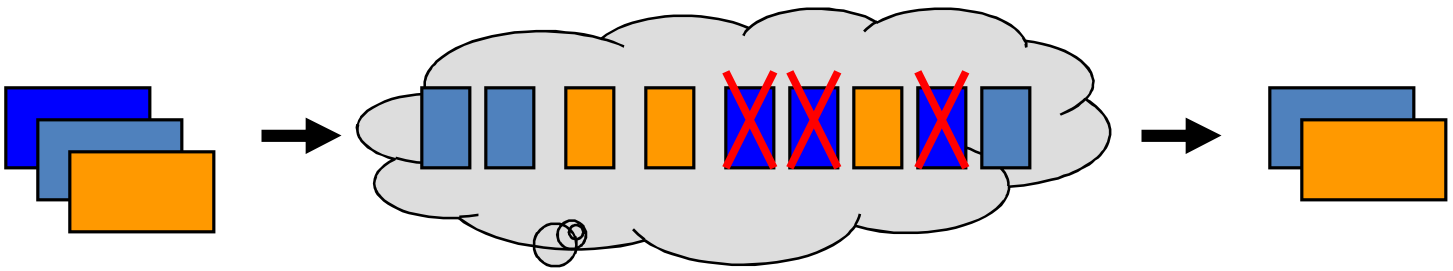
ATM Network Services

	Traffic Parameters		QoS Parameters		
Service	Bandwidth	Burst Size	Loss	Delay	Jitter
CBR	PCR		CLR	maxCTD	CDV
rt-VBR	PCR, SCR	MBS	CLR	maxCTD	CDV
nrt-VBR	PCR, SCR	MBS	CLR		
ABR	PCR, MCR		low		
UBR	PCR*				
GFR	PCR,MCR, MBS,MFS		low		

- CDVT characterizes an interface and is not connection specific
- PCR in UBR is not subject to CAC or UPC

Guaranteed Frame Rate (UBR)

- For non-real-time applications which guarantee a minimum rate guarantee
- Recognizes AAL5 boundaries
  - Frame consists of multiple cells
  - If a cell is dropped, remaining cells from that frame will be dropped as well



- Minimum rate (MCR) is guaranteed by network, the rest (up to PCR) is delivered on a best effort basis.
- Adaptation Layer: AAL5

UNIT IV NETWORK TRAFFIC MANAGEMENT

ATM Traffic and congestion control

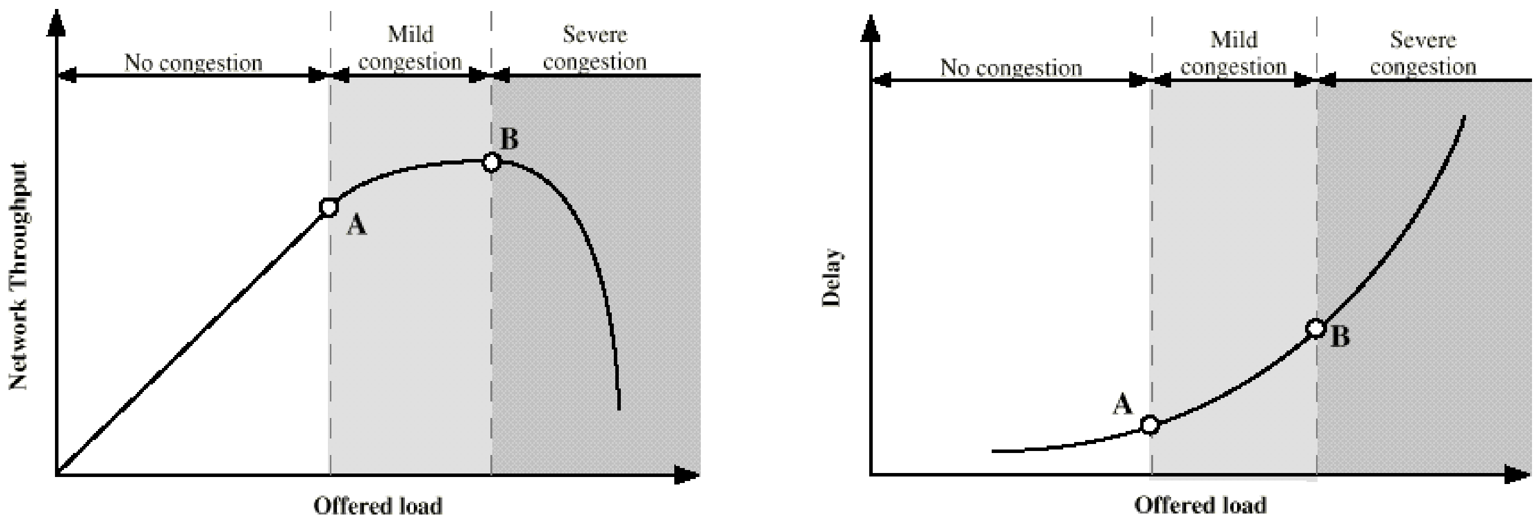
Why Traffic Management?

- The ATM technology is intended to support a wide variety of services and applications such as voice, video, and data
- ATM promises to support all these different requirements with a common network
- Within such a network all connections may impact on each other
- ATM must manage traffic fairly and provide effective allocation of network resources for these different applications
- It is the task of ATM traffic control to:
  - protect the network and the end-systems from congestion in order to provide specified and guaranteed levels of Quality of Service (QoS)
  - use available network resources efficiently

Network Congestion

- Network congestion is a state when the network cannot meet the negotiated network performance objectives for established connections or for new connection requests
- Network congestion can be caused by:
  - Unpredictable statistical fluctuation of traffic flows
  - Fault conditions within the network
- ATM layer traffic control is a set of actions taken by the network to avoid network congestion
- Traffic control takes measures to adapt to unpredictable fluctuations in traffic flows and other problems within the network.
- ATM layer congestion control refers to the set of actions taken by the network to minimize the intensity, spread, and duration of congestion

Effects of Network Congestion



(a) Throughput (b) Delay

Source: Stallings: Data and Computer Communications p316

Traffic Parameters

- Traffic parameters describe traffic characteristics of a connection
- For a given connection, traffic parameters are grouped into a source traffic descriptor
- Traffic parameters specified in ATM Forum UNI
  - Peak Cell Rate (PCR)
    - An upper bound on the rate that traffic can be submit on a connection
    - Measured in cells/second
  - Sustainable Cell Rate (SCR)
    - An upper bound on the average cell rate of a burst traffic of an ATM connection
    - Measured in cells/second

Traffic Parameters (concluded)

- Maximum Burst Size (MBS)
  - The maximum number of cells that can be sent at the peak cell rate
- Minimum Cell Rate (MCR)
  - The minimum number of cells that the user considers acceptable

ATM Service Categories

- ATM carries a wide range of heterogeneous traffic mix
- To ensure network resources are fairly allocated for each traffic type, ATM services are divided into different service categories
- Each ATM service category represents a class of ATM connections that have homogeneous characteristics in terms of traffic pattern, QoS requirements, and possible use of control mechanisms, making it suitable for a given type of resource allocation
- The ATM Forum specifies the following five categories of services:
  - CBR: Constant Bit Rate
  - rt-VBR: Real-Time Variable Bit Rate
  - nrt-VBR: Non-Real-Time Variable Bit Rate
  - UBR: Unspecified Bit Rate

ATM Service Categories (continued)

- All service categories apply to both VCCs and VPCs.
- ATM services are characterized by the traffic parameters:
- Constant Bit Rate (CBR)
  - Requires a fixed amount of bandwidth continuously available during the connection lifetime
  - The amount of bandwidth is characterized by a Peak Cell Rate (PCR) value

ATM Service Categories (continued)

- Non-Real-Time Varible Bit Rate (nrt-VBR)
  - Intended for non-real-time applications
  - Source transmits bursty traffic
  - Characterized by a PCR, SCR, and MBS
  - Requires low Cell Loss Ratio (CLR)
  - May support statistical multiplexing of connections
  - No delay bounds are associated with this service category
  - Application Example: Critical response time transaction processing such as airline reservations.

ATM Service Categories (continued)

- Unspecified Bit Rate (UBR)
  - Intended for non-real-time, bursty applications
  - Does not specify traffic related service guarantees
  - No commitment is made about cell transfer delay
  - No commitment is made as to cell loss ratio experienced by cells on the connection
  - Best effort service
  - Application example: E-mail, LAN traffic, and TCP/IP traffic
- Available Bit Rate (ABR)
  - Intended for bursty traffic whose bandwidth range is known roughly`End system specifies maximum required bandwidth (PCR) and minimum usable bandwidth (MCR)

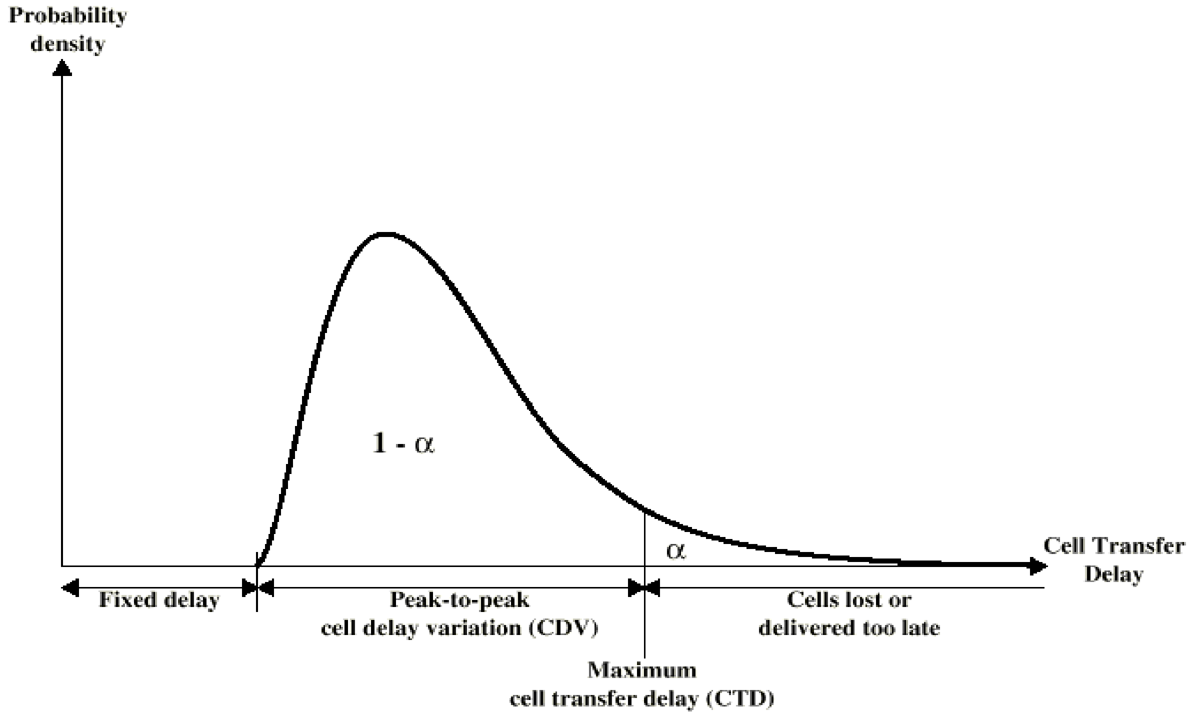
Quality of Service (QoS)

- QoS is a set of user-perceivable performance parameters that characterize the traffic over an ATM connection
- Defined on an end-to-end basis
- User requests a QoS class for an ATM connection
- The requested QoS class is a part of the traffic contract
- The network commits to meet the requested QoS as long as the user complies with the traffic contract
- ATM Forum QoS Classes

Quality of Service (QoS) Parameters

- QoS parameters describe the level of service for each connection
- ATM Forum specified six QoS parameters
- Through the use of network signaling to establish an ATM connection, three of these may be negotiated between the end-system and the network
  - Peak-to-peak Cell Delay Variation (peak-to-peak CDV)
  - Maximum Cell Transfer Delay (maxCTD)
  - Cell Loss Ratio (CLR)

Quality of Service (QoS) Parameters (continued)



Cell Transfer Delay Probability Density Model

Quality of Service (QoS) Parameters (concluded)

- Higher values of cell loss is dominated by the effects of queuing strategy and buffer sizes
- Delay, delay variation, and cell loss are impacted by buffer size and buffering strategy
- The error rate is determined by fiber transmission characteristics

Traffic Contract

- Agreement between user and network across UNI regarding:
  - The QoS that a network is expected to provide
  - The Connection Traffic Descriptor, which includes
    - Source Traffic Descriptor
    - Cell Delay Variation Tolerance (CDVT)
    - Conformance Definition
  - Source Traffic Descriptor
    - Defines the characteristics of ATM traffic coming into the network
    - Includes several negotiable traffic parameters: PCR, SCR, MBS, and Burst Tolerance (BT)
    - Specifies flow for CLP = 0 and/or CLP = 0 + 1
  - Cell Delay Variation Tolerance (CDVT)

Traffic Contract (concluded)

- A separate traffic contract for each Virtual Path Connection (VPC) or Virtual Channel Connection (VCC)
- Negotiated at connection time
  - Signaling message for SVC
  - Circuit provision for PVC

Traffic Control Functions

- Connection Admission Control (CAC)
- Usage Parameter Control (UPC)
- Selective cell discarding
- Traffic Shaping
- Explicit Forward Congestion Indication (EFCI)
- Cell Loss Priority Control
- Network Resource Management (NRM)
- Frame discard
- ABR Flow Control
- Others

Selective Cell Discard and EFCI

- Selective Cell discard
  - A congested network may selectively discard cells which meet either or both the following conditions:
    - Cells which belong to a non-compliant ATM connection
    - Cells which have CLP = 1
  - This is to protect the CLP = 0 flow as much as possible
- Explicit Forward congestion Indication (EFCI)
  - A network element in an impending congested state or a congested state may set an EFCI in the cell header
  - This indication may be examined by the destination end-system
  - The end-system may adaptively lower the cell rate of the connection

Traffic Shaping

- A mechanism that alters the traffic characteristics of a cell stream on a connection to achieve better network efficiency or to ensure conformance to the traffic parameters in the traffic contract
- Traffic shaping examples:
  - Peak cell rate reduction
  - Burst length limiting
  - Spacing cells in time to reduce CDV
  - Cell scheduling policy

Packet Discarding

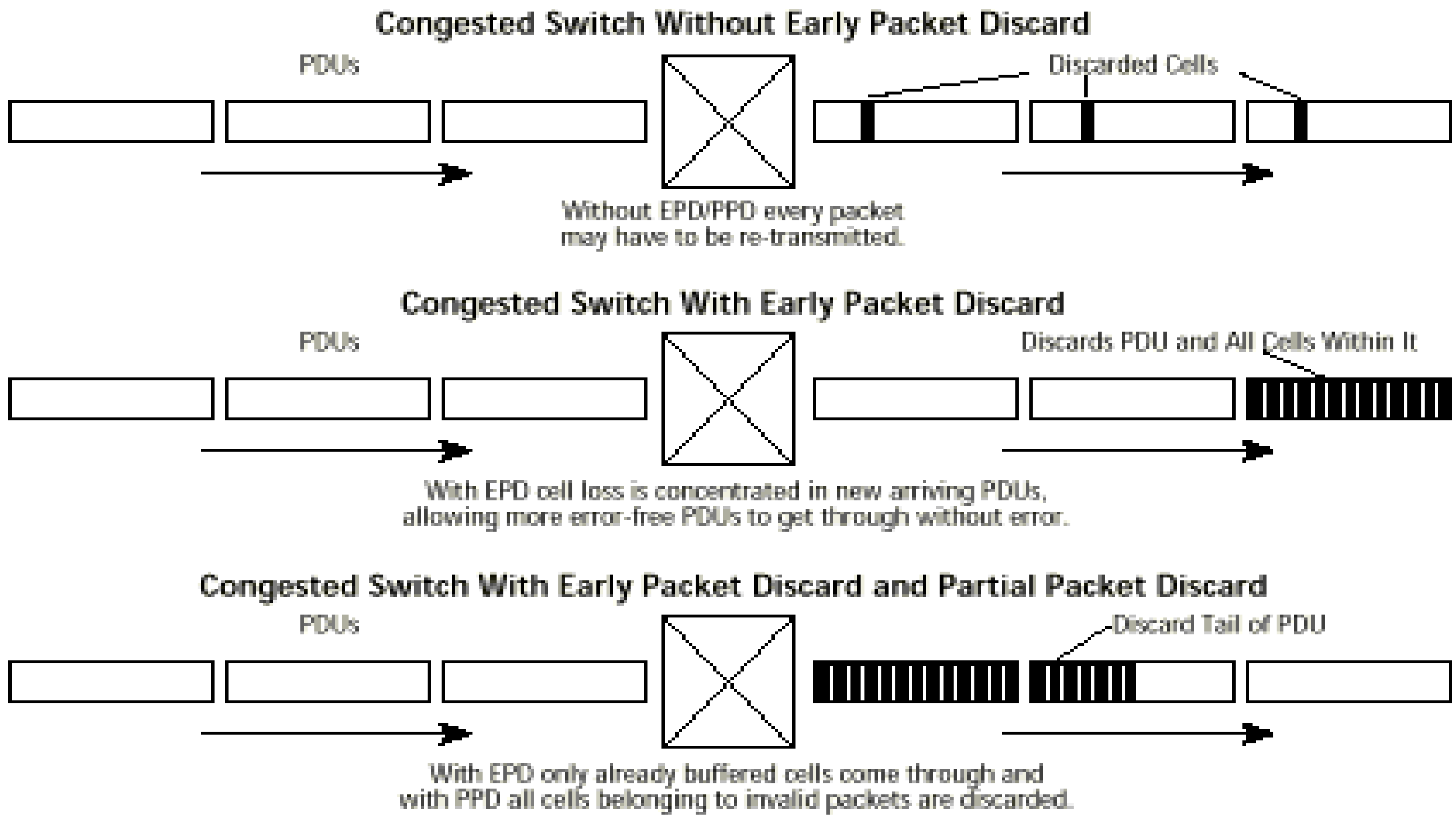
- The ATM Adaptation Layer (AAL) segments higher layer packets into small fixed-size cells for transporting over the ATM network
- A cell discarded by a switch causes the loss of the entire packet and eventually requires end-to-end error recovery through packet retransmission
- A small congestion problem could potentially escalate to a more serious one
- To prevent congestion escalation, Early Packet Discard (EPD) and Partial Packet Discard (PPD) can be used to discard cells on a packet basis
- EPD and PPD are applied for ABR and UBR traffic of AAL-5 connections

Packet Discarding (continued)

- The remaining buffer space can then be used for cells belonging to packets that already have entered the queue
- EPD maximizes the chances for already queued packets to leave the queue successfully

- PPD
  - If EPD does not remove congestion and cells arriving at a queue have to be discarded because of buffer overflow PPD is applied
  - PPD discards all subsequent cells associated with the same packet rather than just a few cells within the packet during buffer overflow

Packet Discarding (concluded)



Source: Newbridge White Paper

- Traffic Management Roles:
  - Maximize efficiency
  - Minimize data loss
  - Control traffic during times of heavy utilization
- Control is based on:
  - Connection Admission Control (CAC)
  - Call Routing
  - Network Resource Allocation

Traffic management capabilities:

Requirements	ATM	TCP/IP
QoS Signaling	Sig 4.0	RSVP or IP Precedence
QoS Routing	PNNI 1.0	None
Explicit Rate Flow Control	TM 4.0	None

ATM Forum Traffic Management

Traffic Management – functions to prevent and control congestion across ATM networks and provide the QoS required.

Congestion – fluctuation in traffic flow and faults within the network

Traffic Management

- Traffic Control
- Congestion Control

Traffic Management forms:

Signaling Phase:

- Connection Admission Control
- PNNI’s Generic CAC (GCAC)

After Connection Setup

- Usage Parameter Control
- Priority Control
- Traffic Shaping
- Network Resource Management
- Frame Discard

QoS related issues

- Constant vs. variable bit rate
- Degree of burstiness
- Suitability for statistical multiplexing
- Real-time delay constraints
- Delay tolerance for non real-time applications
- Degree of interactiveness
- Loss tolerance
- Priority requirements
- Ability to use free bandwidth
- Coding
- Fairness

ATM Forum service categories:

- Constant Bit Rate (CBR)
- Real-time and non-real-time Variable Bit Rate (rt-VBR nrt-VBR)
- Unspecified Bit Rate (UBR)
- Available Bit Rate (ABR)

QoS Parameters:

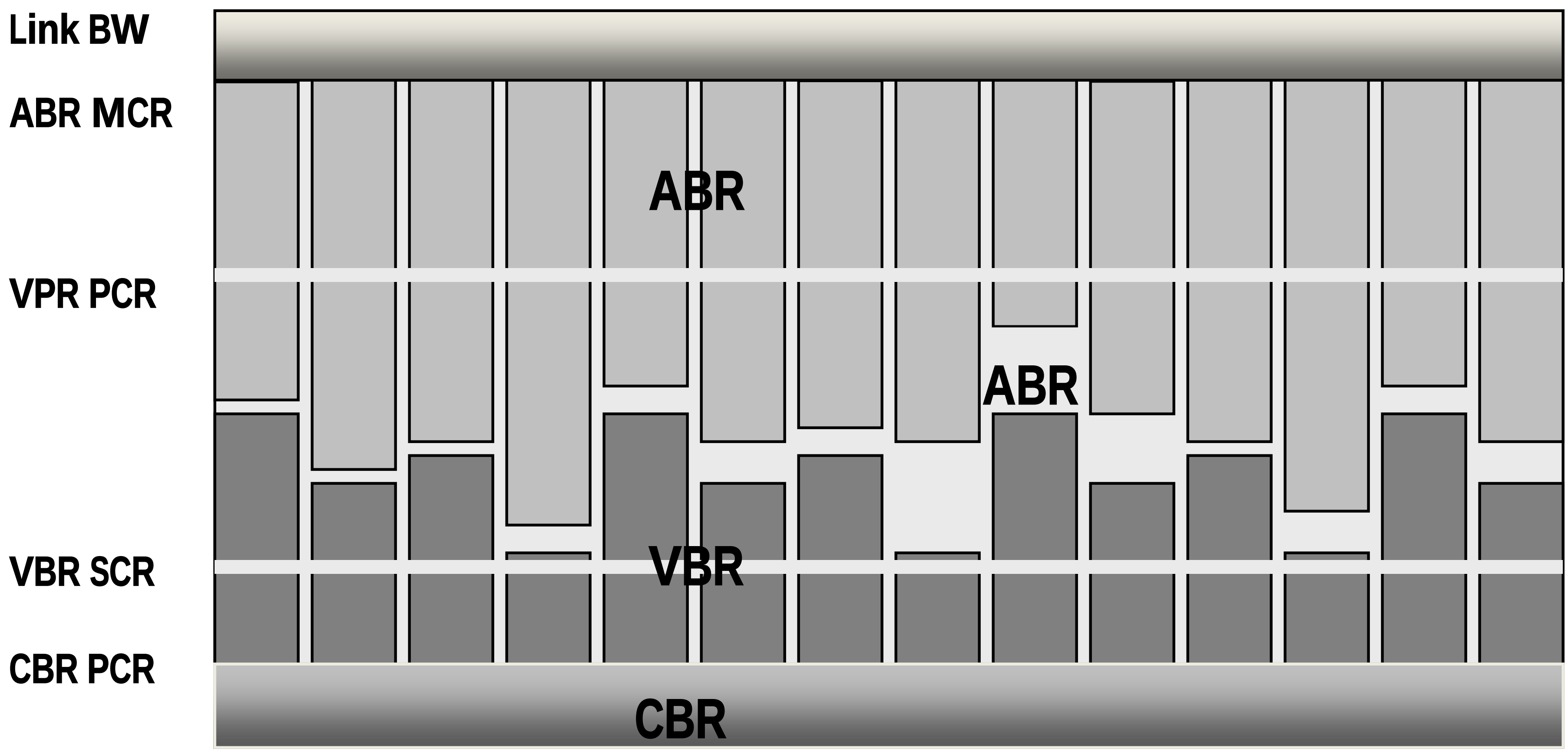
- Peak-to-peak Cell Delay Variation (ppCDV)
- Maximum Cell Transfer Delay(Max CTD)
- Mean Cell Transfer Delay (Mean CTD)
- Cell Loss Ratio (CLR)

Source Traffic Descriptors

- Peak Cell Rate (PCR)
- Sustainable Cell Rate (SCR)
- Maximum Burst Rate (MBR)
- Minimum Cell Rate (MCR)

- Guaranteed Services (CBR,rt-VBR,nrt-VBR)
  - Admission control
  - Bandwidth reservation
  - UPC and policing
  - Scheduling (CBR)
  - Minimizing buffer size (CBR, rt-VBT)
- Best Effort Services (UBR,ABR)
  - Buffer management
  - Discard techniques
  - Feedback
  - Slow start

ATM trunk loading by service category



Constant Bit Rate

- Real-time applications which contain audio and video information
- Constant bandwidth requirement
- Low delay tolerance and acceptable CLR

Real Time Variable Bit Rate

- Real-time applications which are bursty in nature
- No pre-reserved bandwidth
- Predetermined SCR and MBR

Non-Real-Time Variable Bit Rate

- Less stringent requirement for CDV and CTD
- Suitable for data services

Unspecified Bit Rate

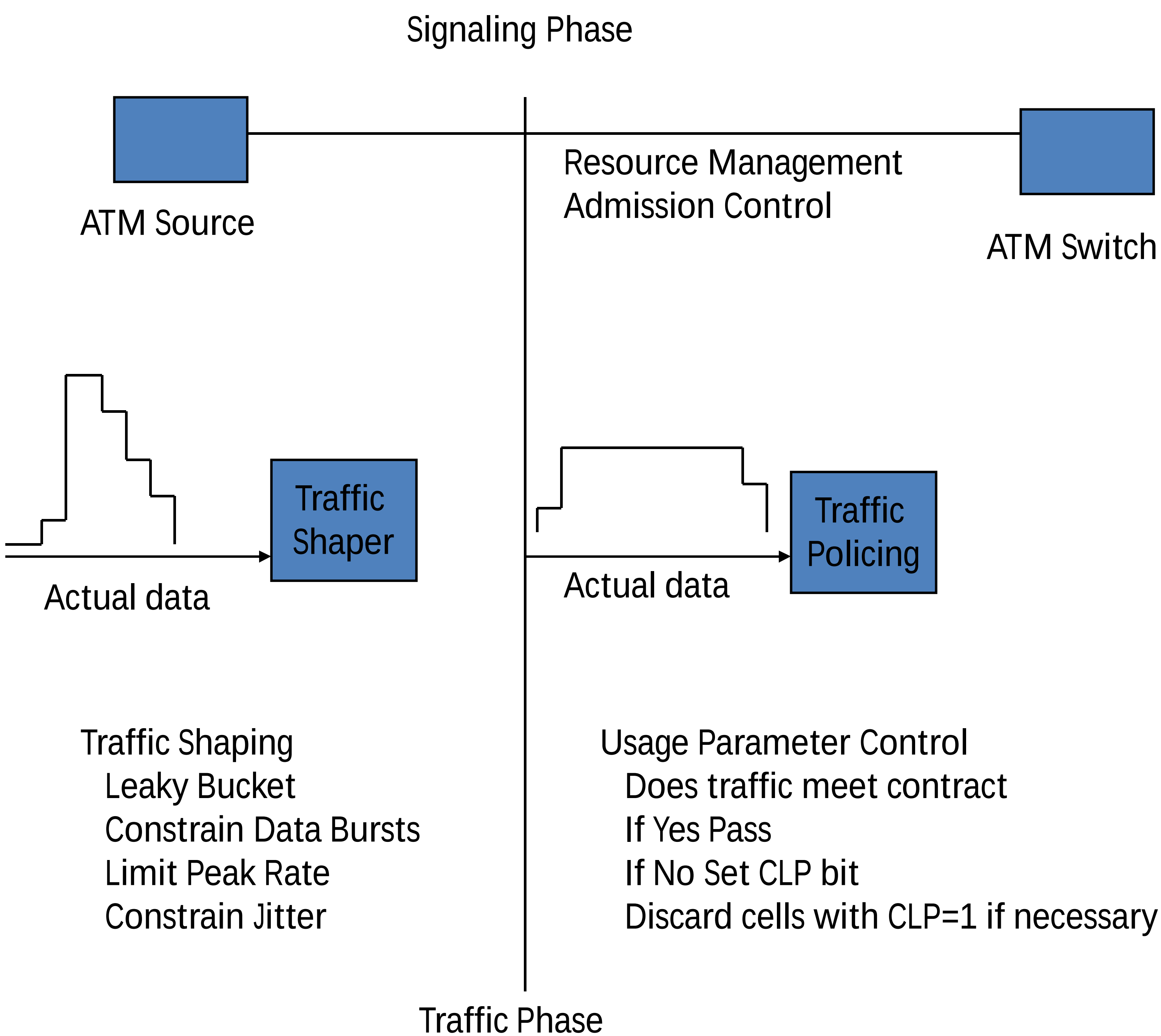
- Non-real-time applications with no guarantee of bounded delay
- End system applications must handle cell loss and delay (best effort service)
- Specifies only PCR and CDVT

Available Bit Rate:

- Sources which may vary in transmission rate but need service guarantees
- Require low cell loss but allow for some delay
- Can specify a minimal bandwidth

Traffic and Congestion Control Functions

- Network Resource Management
- Connection Admission Control
- Usage Parameter Control
- Selective Cell or Packet discarding
- Traffic Shaping and Scheduling
- Explicit Forward Congestion Indication
- VP Resource Management
- The ABR Mechnism


Signaling Phase
ATM Source
Resource Management
Admission Control
ATM Switch
Traffic
Shaper
Actual data
Traffic
Policing
Actual data
Traffic Shaping
Leaky Bucket
Constrain Data Bursts
Limit Peak Rate
Constrain Jitter
Usage Parameter Control
Does traffic meet contract
If Yes Pass
If No Set CLP bit
Discard cells with CLP=1 if necessary
Traffic Phase

Preventive Congestion Control

- Leaky Bucket Algorithm – congestion control at the entry of an ATM network
- EFCI – feedback-based flow control
- EPD and TPD – selective cell discarding

Reactive Congestion Control

- Information propagates from ATM switches to ATM sources
- Credit based or rate based
- Rate based – uses bits in ATM header to inform the source about the networks condition
- Credit based – a form of windowing mechanism

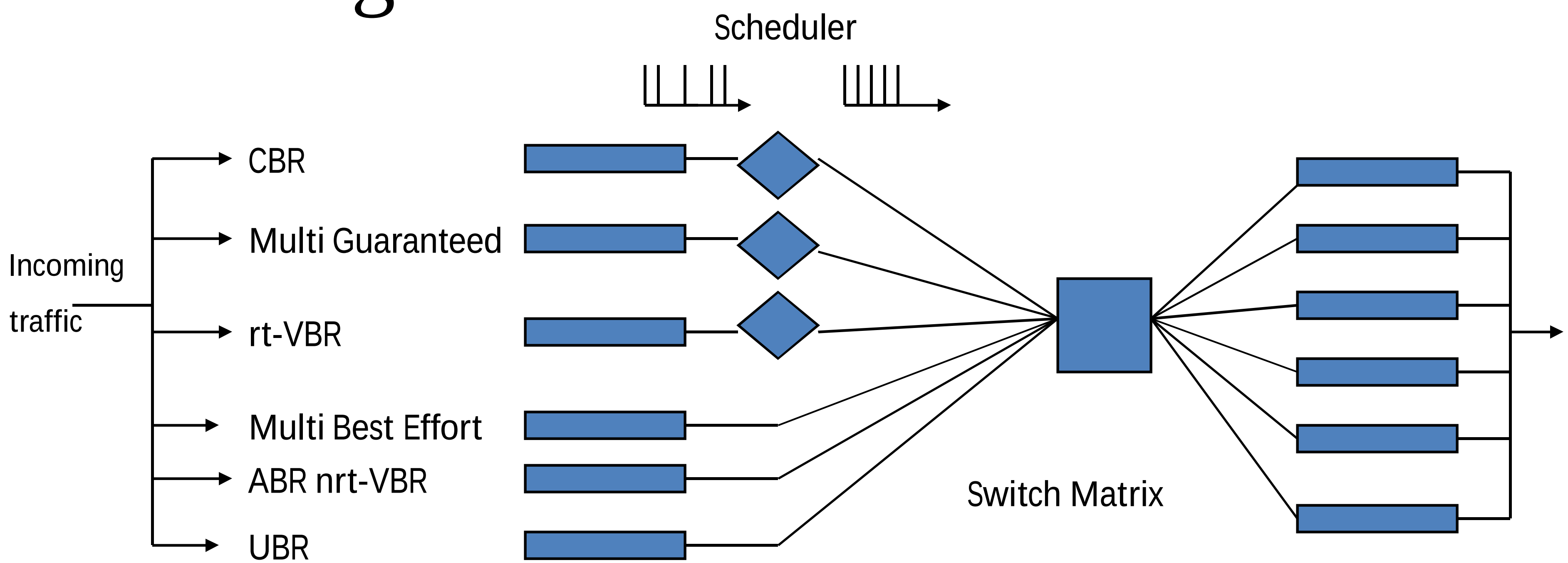
ABR Service:

- The source must adapt to network availability and limit it’s output in order to receive an acceptable QoS
- The source must specify a PCR and MCR
- The network will divide the available network resources among ABR connections

ABR: protocol operations

- At setup the source specifies a number of parameters: PCR,MCR, Initial Cell rate, Rate Increase Factor, Rate Decrease Factor, Transfer Buffer Exposure, Fixed Round Trip Time.
- The source sends RM cells in order to regulate it’s transmission rate

Switch Buffering and Traffic Management



Congestion: Effects

- Congestion is undesirable because it can cause:

  Increased delay, due to queueing within the network

  Packet loss, due to buffer overflow

  Reduced throughput, due to packet loss and retransmission
- Analogy: “rush hour” traffic

Congestion: Causes

- The basic cause of congestion is that the <u>input traffic demands exceed the capacity of the network</u>
- In typical packet switching networks, this can occur quite easily when:

  - output links are slower than inputs
  - multiple traffic sources competing for same output link at the same time

Motivation

- The congestion control problem is even more acute in high speed networks
- Faster link speeds mean that congestion can happen faster than before

  e.g., 64 kilobyte buffer

    @ 64 kbps: 8.2 seconds

    @ 10 Mbps: 52 milliseconds

    @ 1 Gbps: 0.52 milliseconds

Reactive versus Preventive

- There are two fundamental approaches to congestion control: reactive approaches and preventive approaches
- Reactive: feedback-based
  - attempt to detect congestion, or the onset of congestion, and take action to resolve the problem before things get worse
- Preventive: reservation-based
  - prevent congestion from ever happening in the first place, by reserving resources

Reactive versus Preventive (Cont'd)

- Most of the Internet approaches are reactive schemes
  - TCP Slow Start
  - Random-Early-Detection (RED) Gateways
  - Source Quench
- The large d x b product means that many of these approaches are <u>not</u> applicable to high speed networks
- Most ATM congestion control strategies are preventive, reservation-based

Congestion Control in ATM

- When people discuss congestion control in the context of high speed ATM networks, they usually distinguish between call-level controls and cell-level controls

Call-Level Control

- An example of the call-level approach to congestion control is call admission control (to be discussed later this semester)
- Tries to prevent congestion by not allowing new calls or connections into the network unless the network has sufficient capacity to support them

Call-Level Control (Cont’d)

- At time of call setup (connection establishment) you request the resources that you need for the duration of the call (e.g., bandwidth, buffers)
- If available, your call proceeds
- If not, your call is blocked
- E.g., telephone network, busy signal

Call-Level Control (Cont'd)

- Tradeoff: aggressive vs conservative
- Want to accept enough calls to have reasonably high network utilization, but don't want to accept so many calls that you have a high probability of network congestion (which might compromise the QOS requirements that you are trying to meet)

Cell-Level Control

- Also called <u>input rate control</u>
- Control the input rate of traffic sources to prevent, reduce, or control the level of congestion
- Many possible mechanisms:

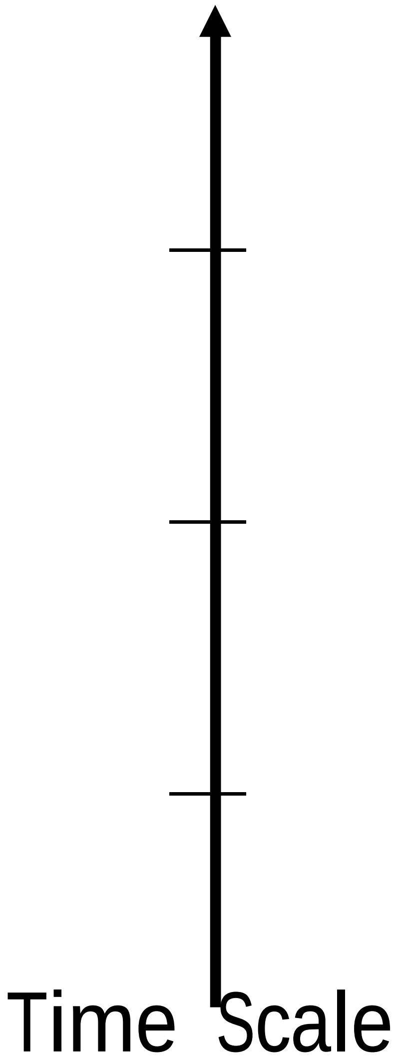
  Traffic shaping, traffic policing, UPC

  Leaky bucket (token bucket)

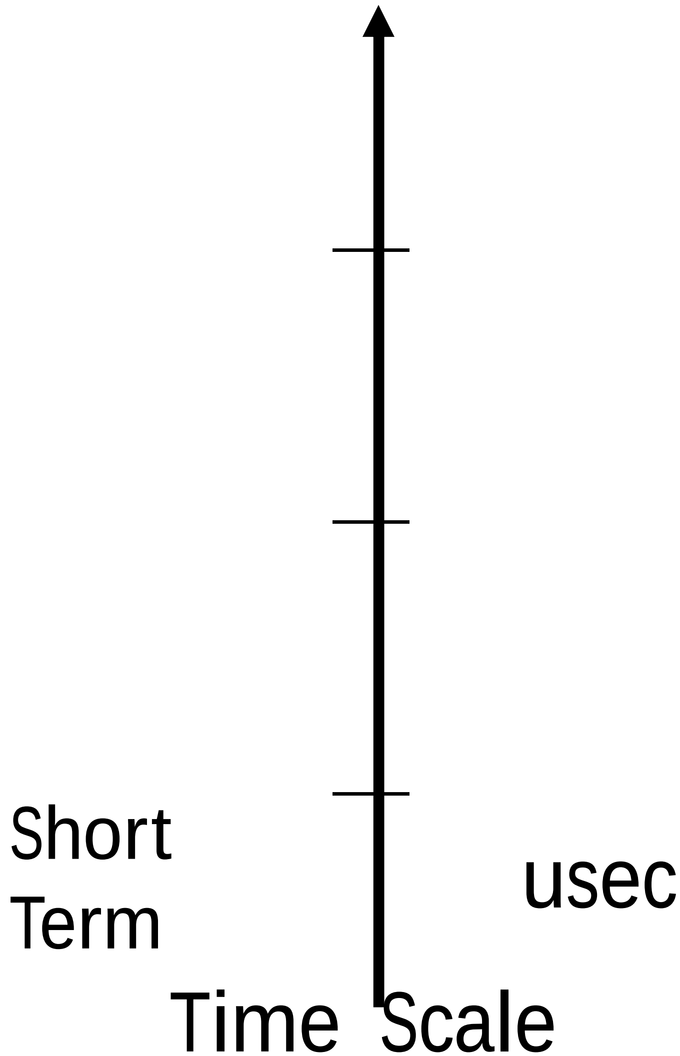
  Cell tagging (colouring), cell discarding

  Cell scheduling disciplines

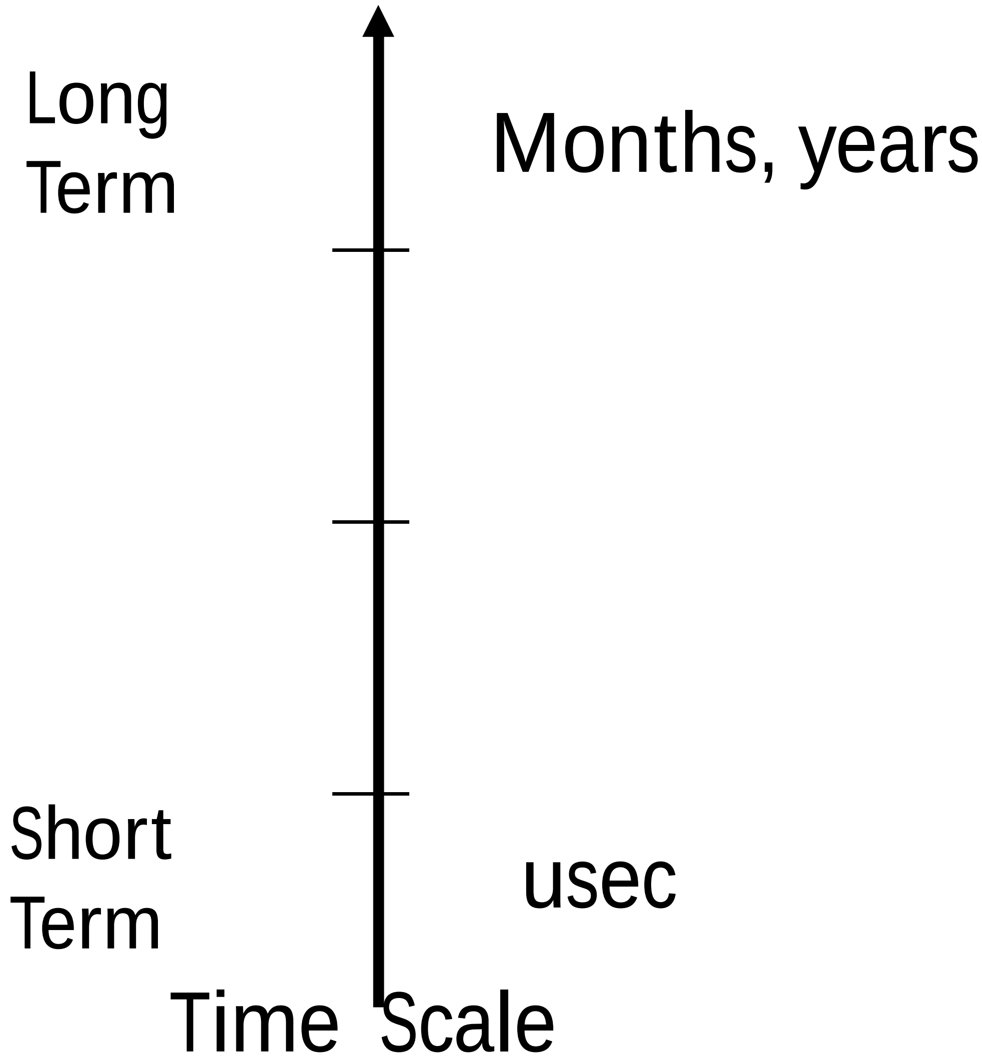
ATM Traffic Control Schemes



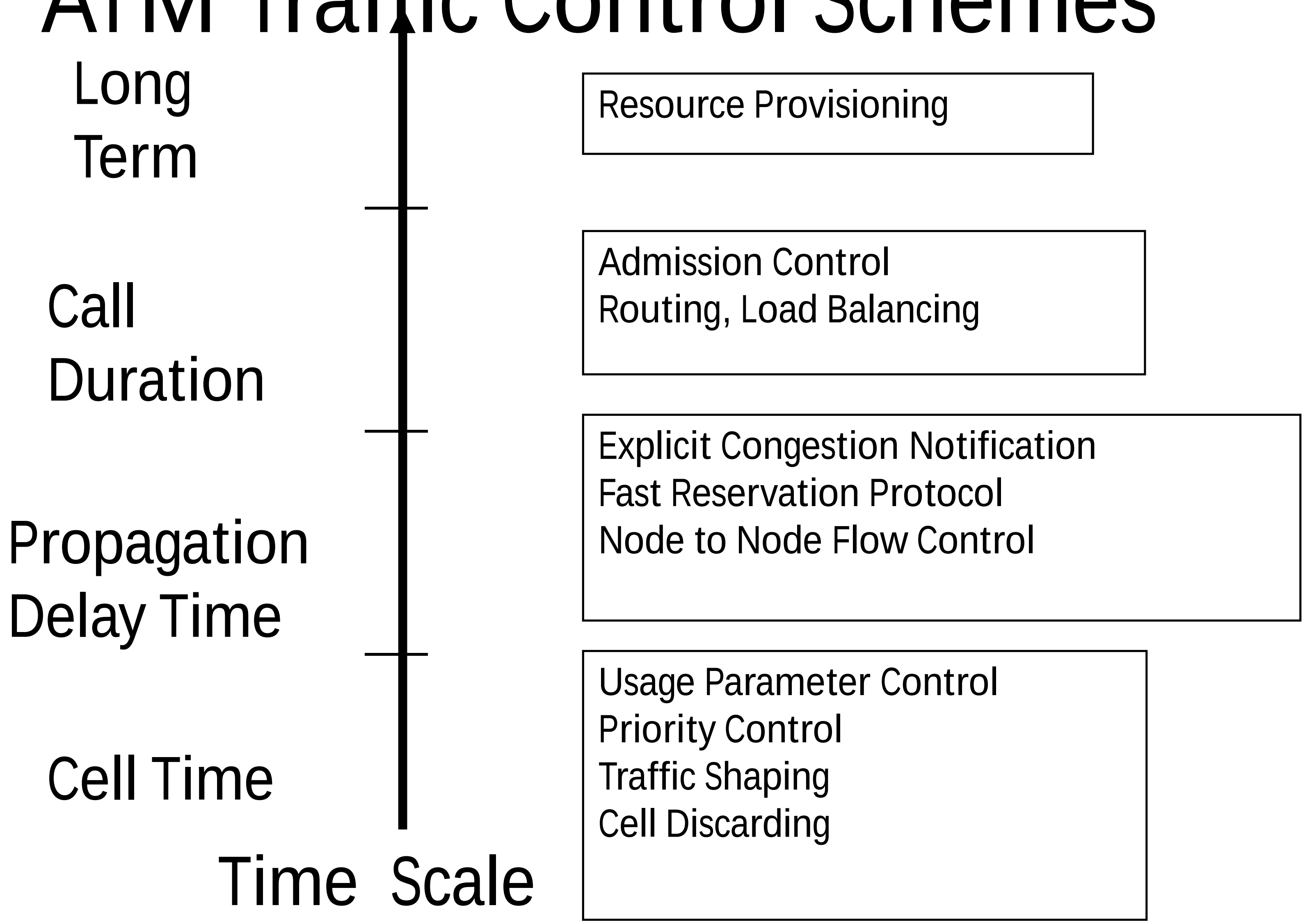
ATM Traffic Control Schemes



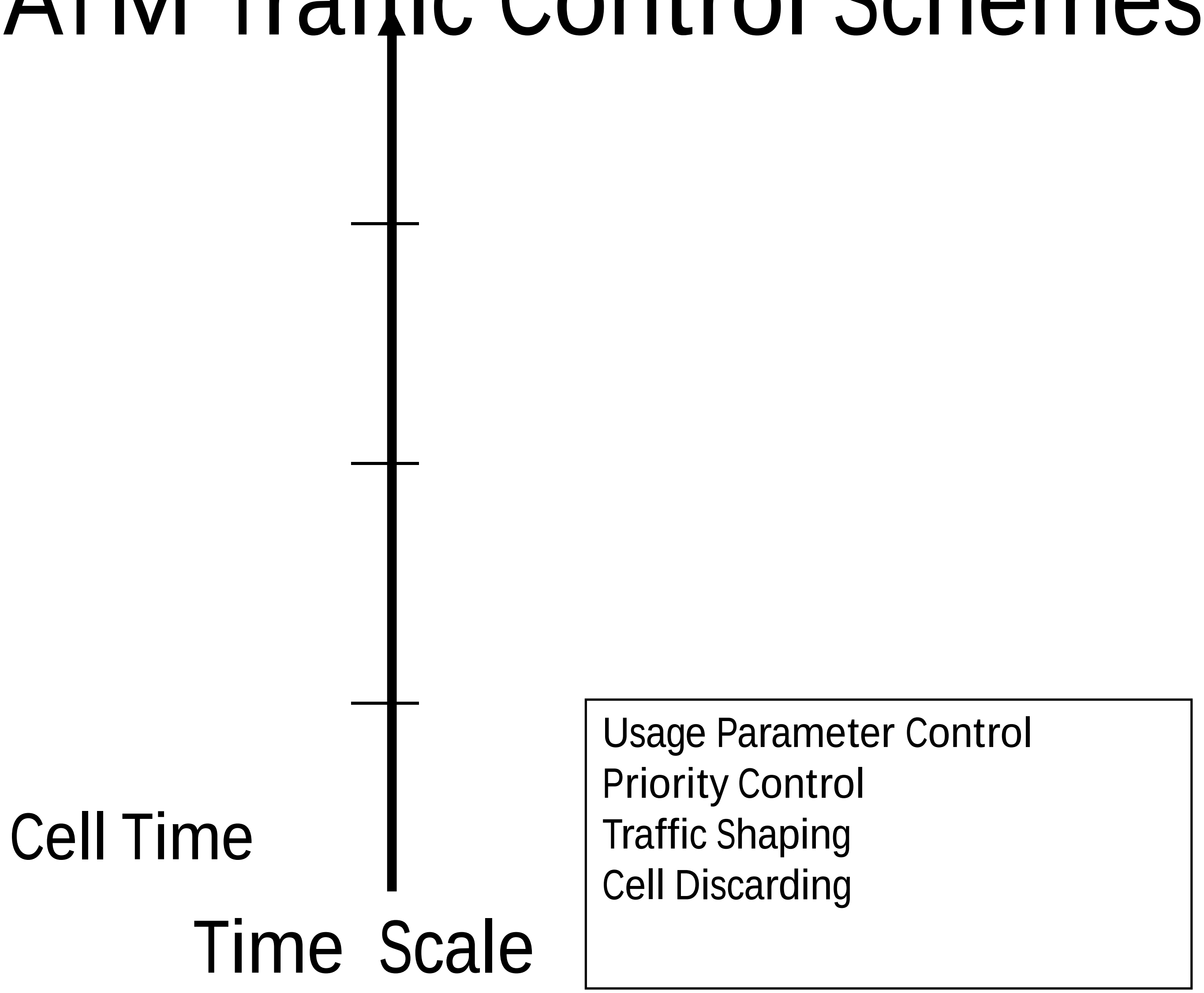
ATM Traffic Control Schemes



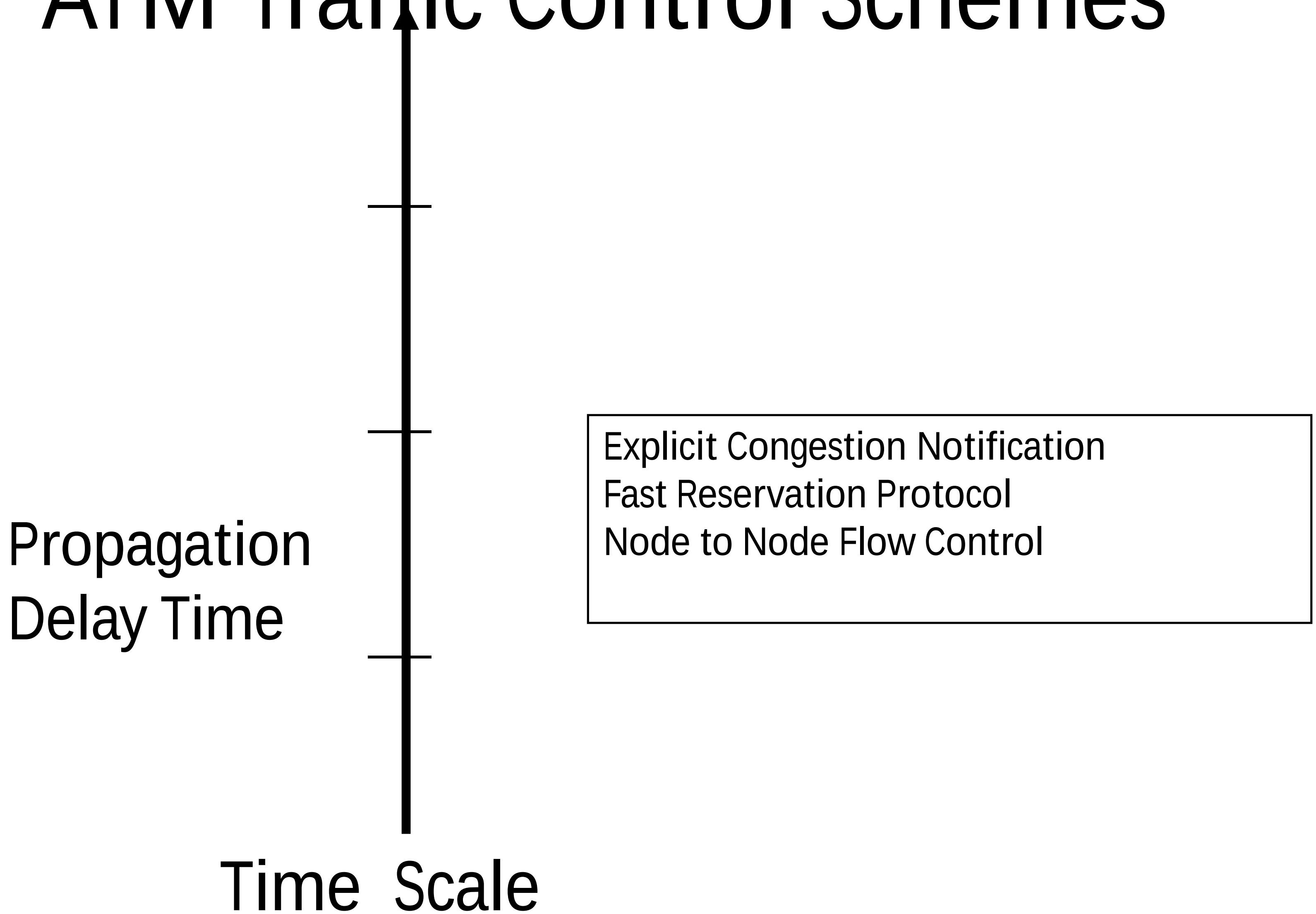
ATM Traffic Control Schemes



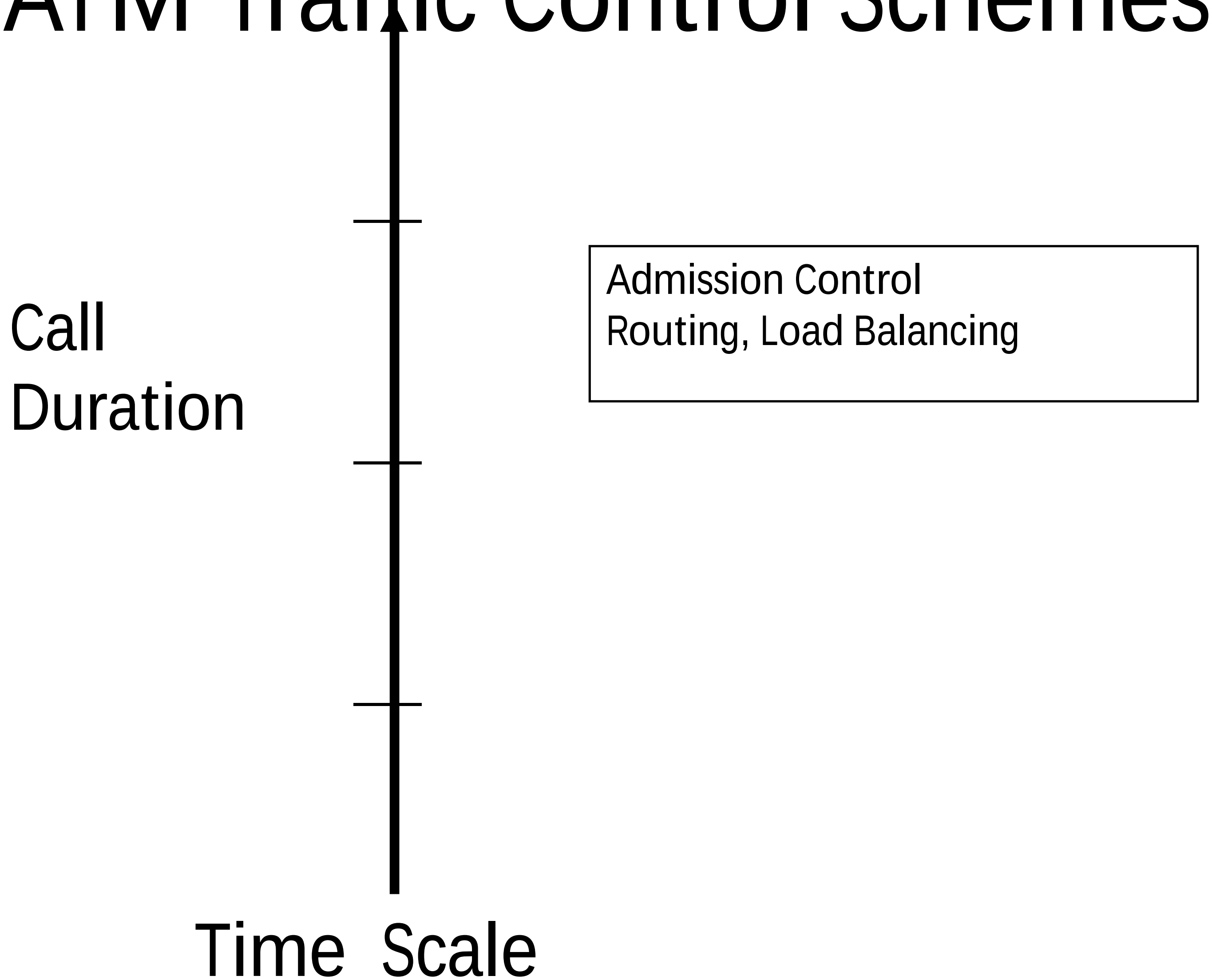
ATM Traffic Control Schemes



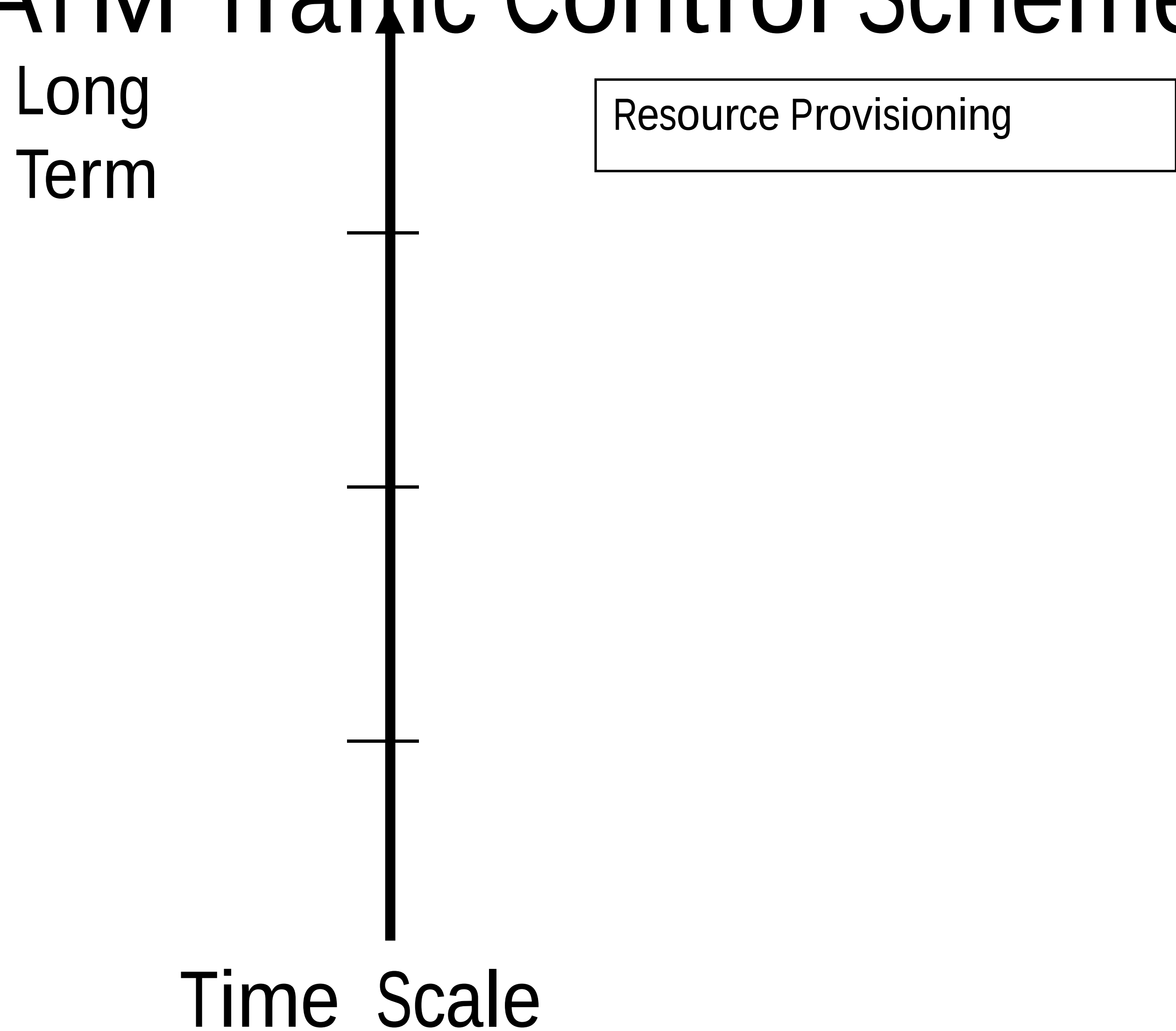
ATM Traffic Control Schemes



ATM Traffic Control Schemes



ATM Traffic Control Schemes



ATM Traffic Control Schemes

Time Scale	
Long Term	Resource Provisioning
Call Duration	Admission Control Routing, Load Balancing
Propagation Delay Time	Explicit Congestion Notification Fast Reservation Protocol Node to Node Flow Control
Cell Time	Usage Parameter Control Priority Control Traffic Shaping Cell Discarding

ATM Traffic Control Schemes

- Preventive controls:

  Resource provisioning

  Connection admission control

  Call routing and load balancing

  Usage parameter control

  Priority control

  Traffic shaping

  Fast reservation protocol

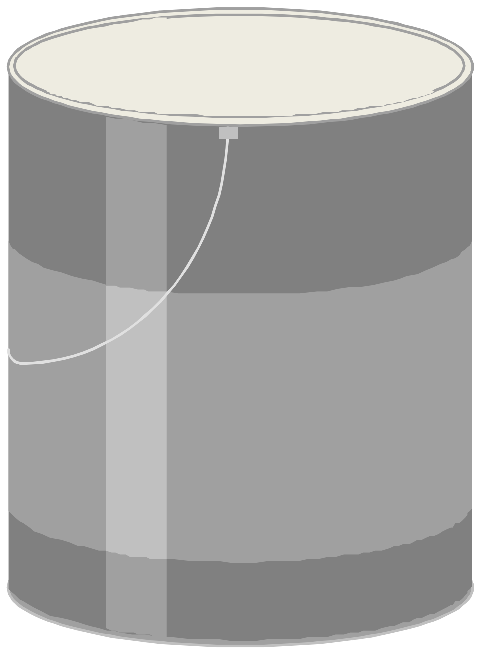
Leaky Bucket

- One of the cell-level control mechanisms that has been proposed is the leaky bucket (a.k.a. token bucket)
- Has been proposed as a traffic policing mechanism for Usage Parameter Control (UPC), to check conformance of a source to its traffic descriptor
- Can also be used as a traffic shaper

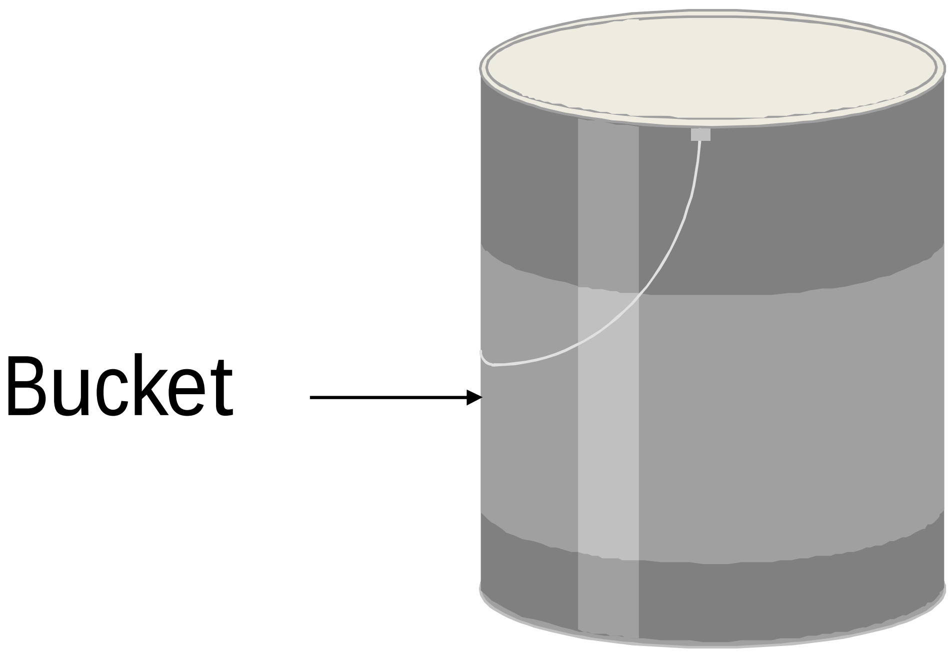
Leaky Bucket (Cont'd)

- Think of a bucket (pail) with a small hole in the bottom
- You fill the bucket with water
- Water drips out the bottom at a nice constant rate: drip, drip, drip...

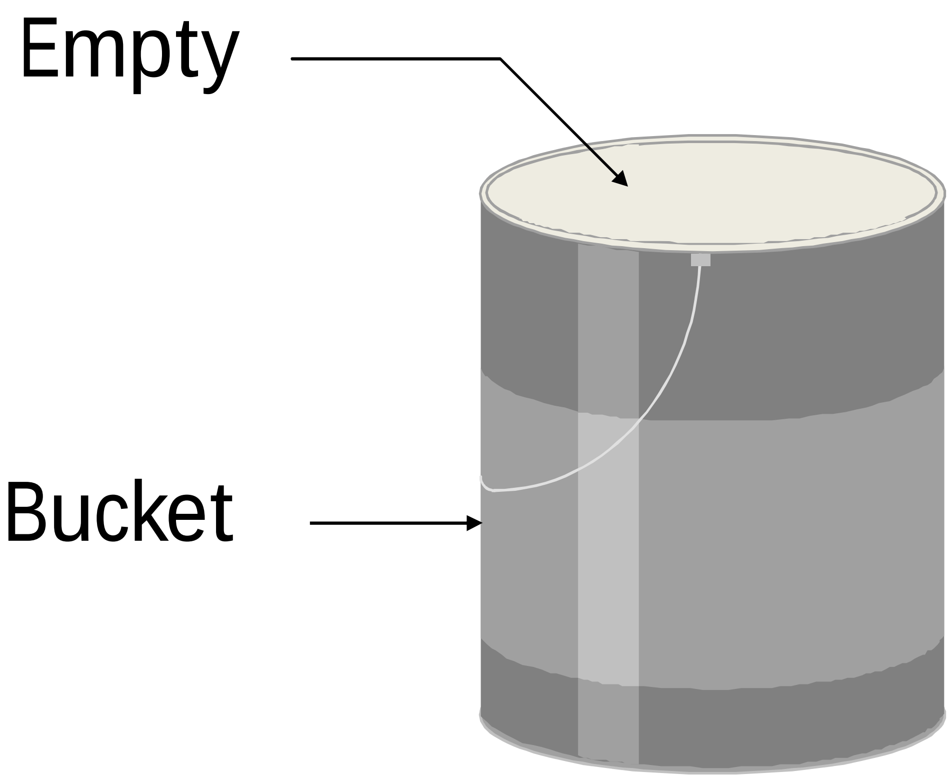
Leaky Bucket (Cont’d)



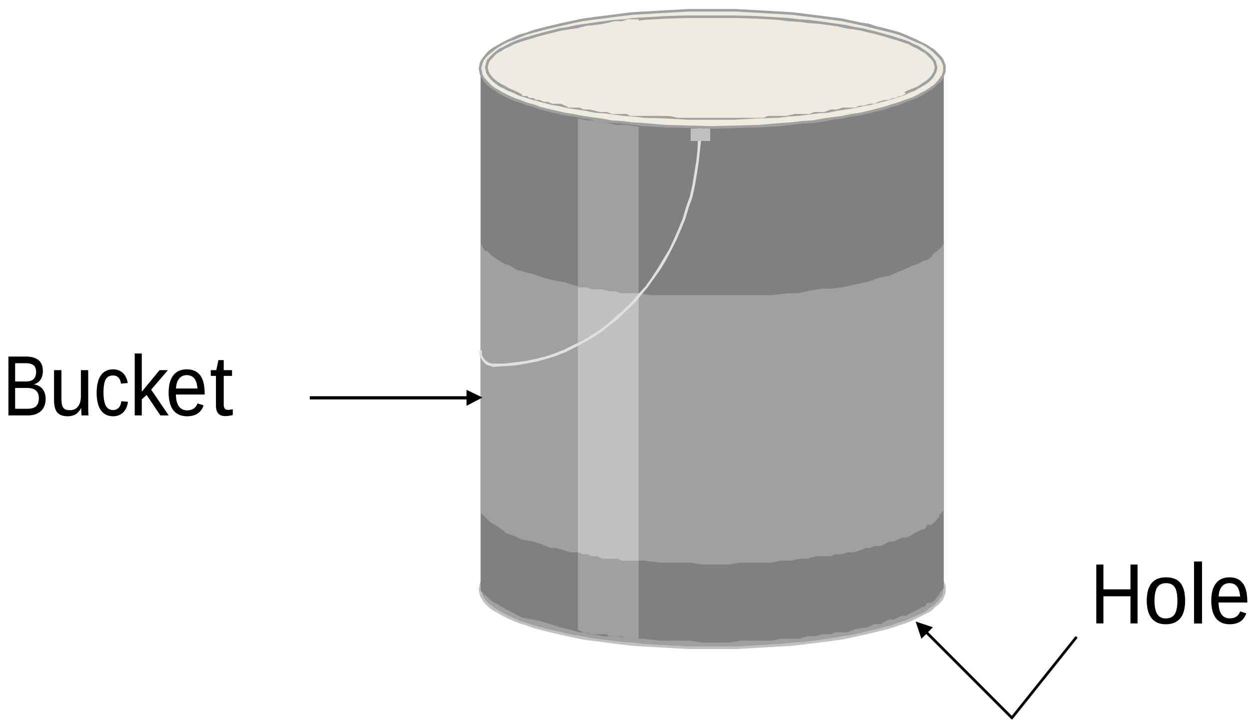
Leaky Bucket (Cont'd)



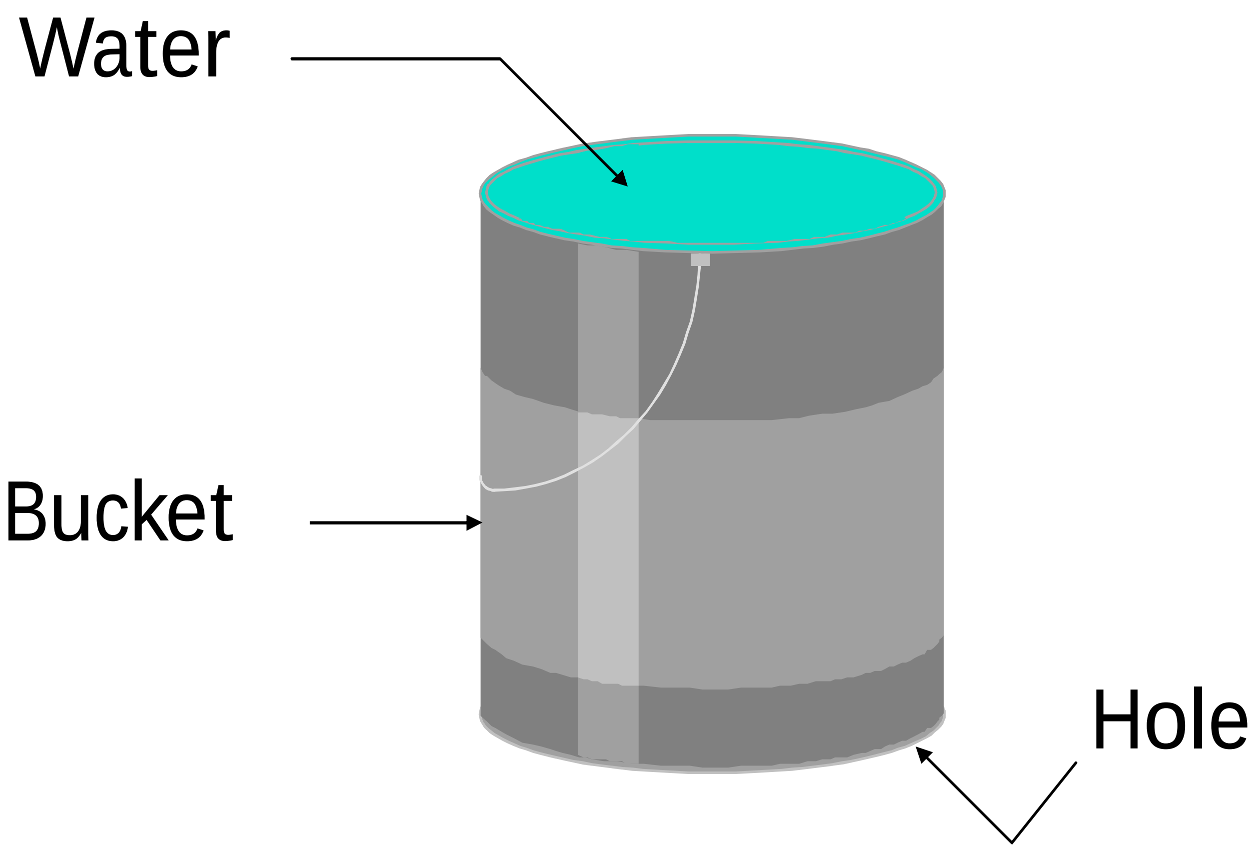
Leaky Bucket (Cont’d)



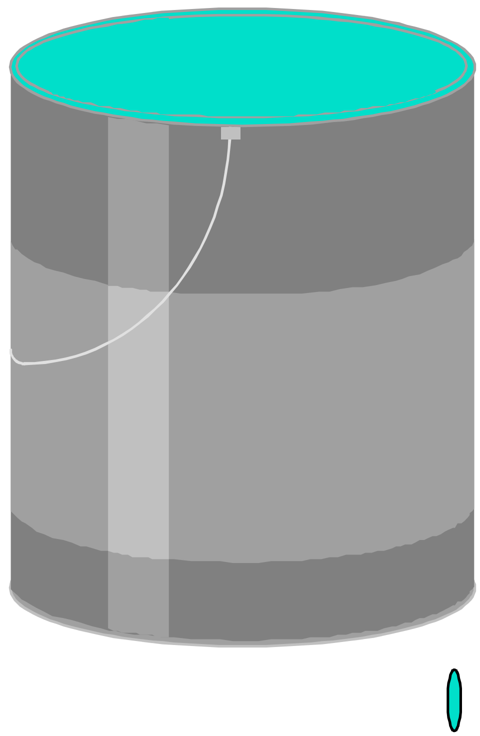
Leaky Bucket (Cont'd)



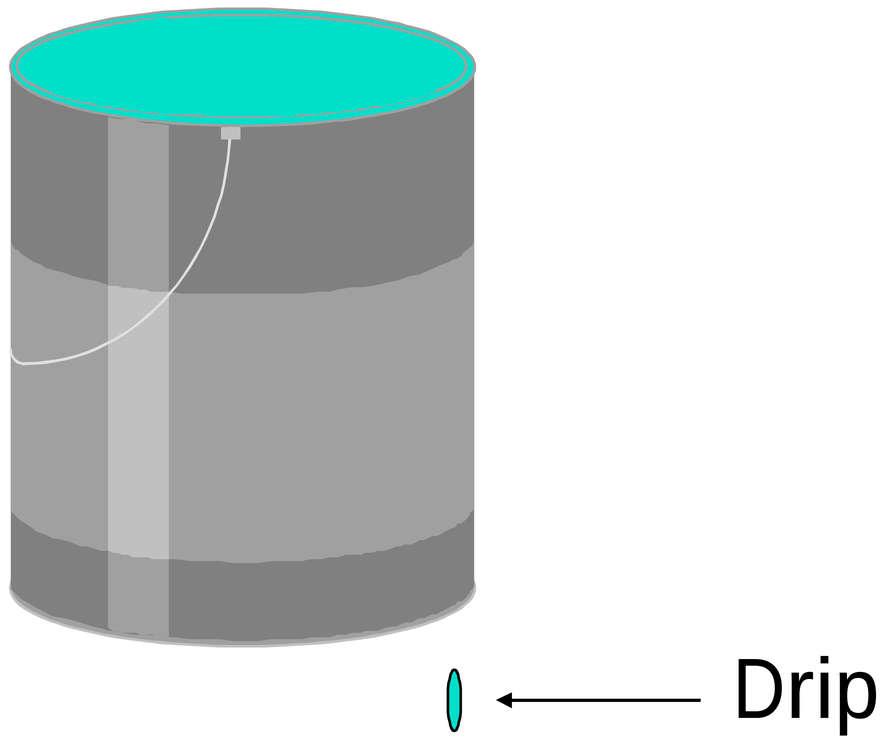
Leaky Bucket (Cont'd)



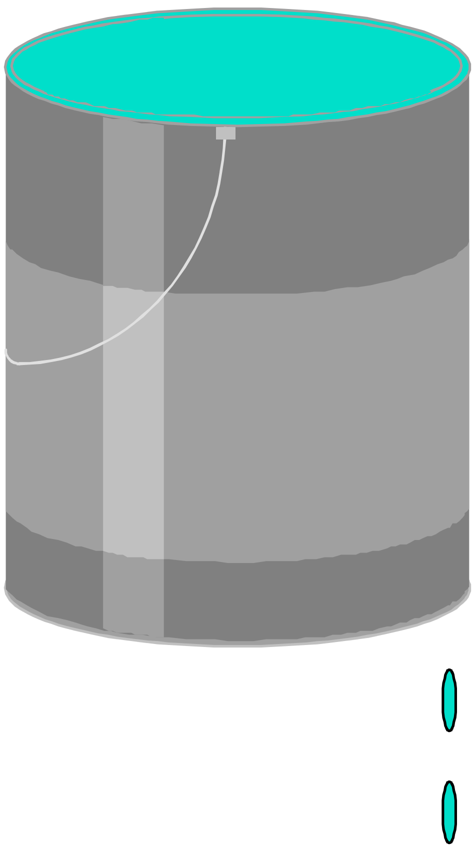
Leaky Bucket (Cont'd)



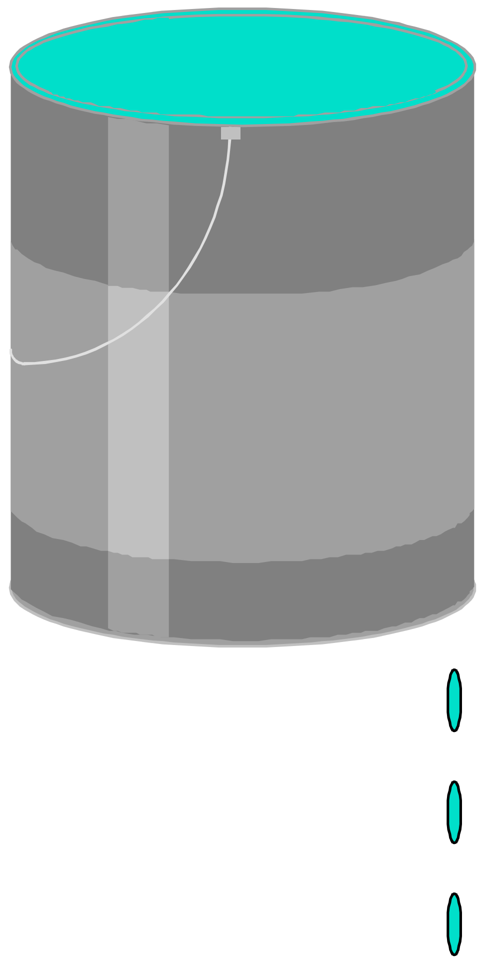
Leaky Bucket (Cont'd)



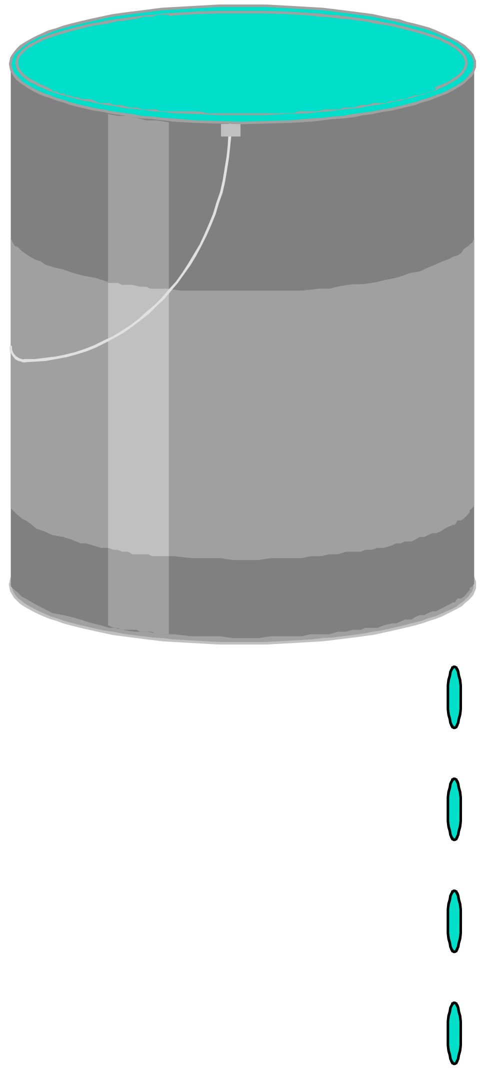
Leaky Bucket (Cont'd)



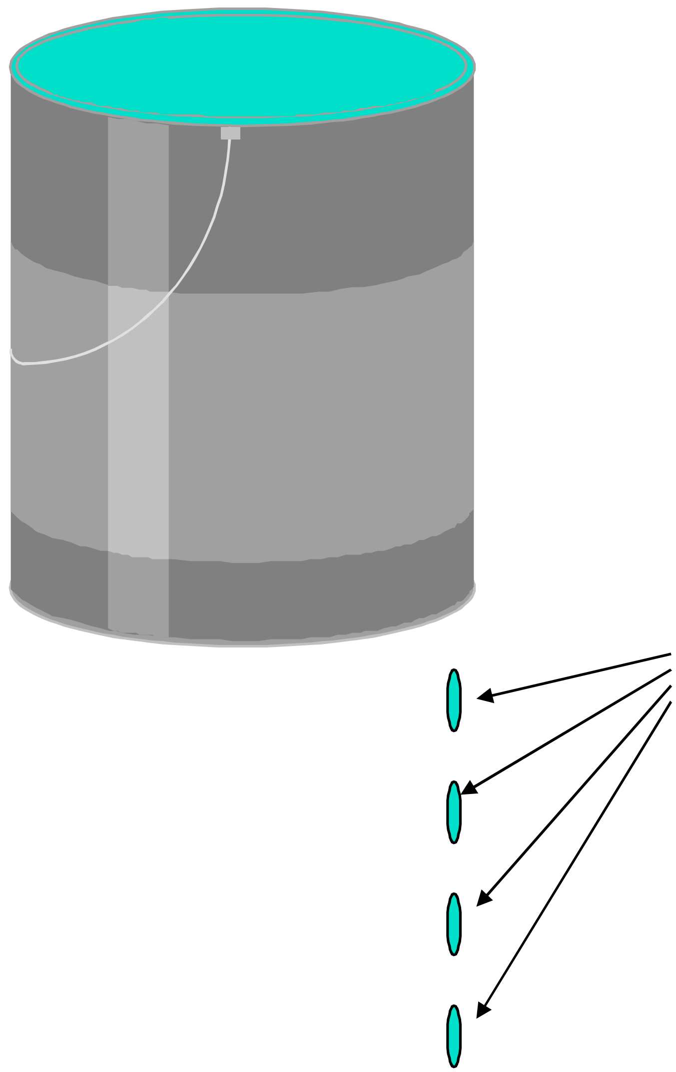
Leaky Bucket (Cont'd)



Leaky Bucket (Cont'd)



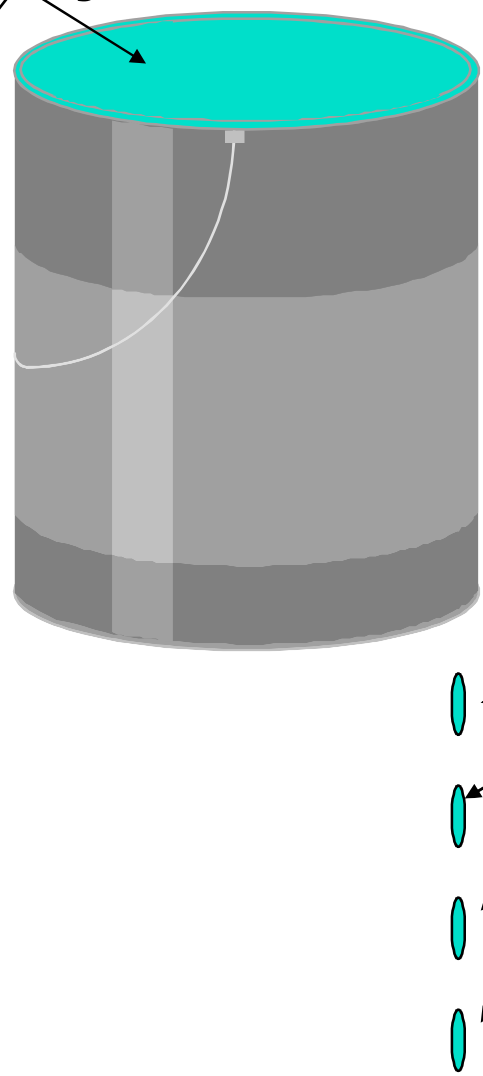
Leaky Bucket (Cont'd)



Constant
rate stream of
drips, all nicely
spaced, periodic

Leaky Bucket (Cont'd)

Storage area
for drips
waiting to go

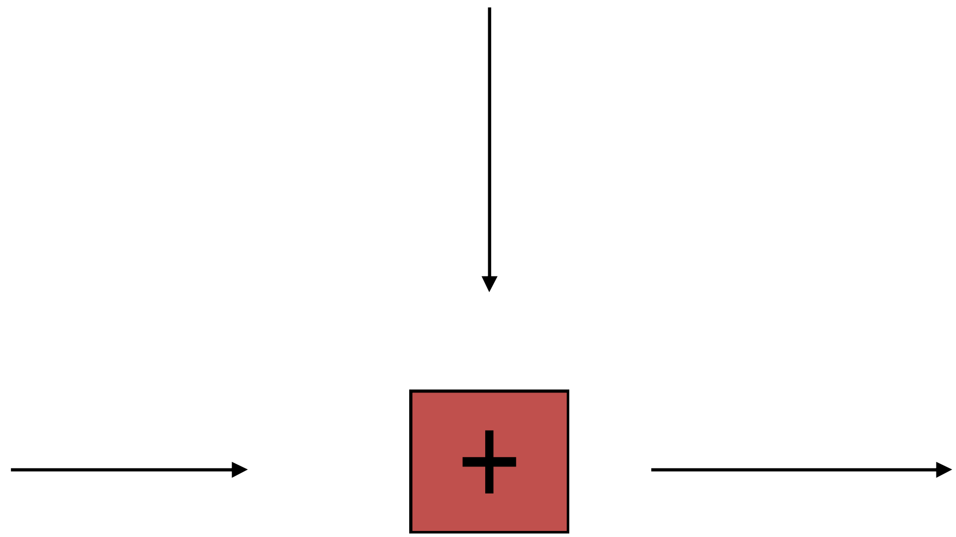


Constant
rate stream of
drips, all nicely
spaced, periodic

Leaky Bucket (Cont'd)

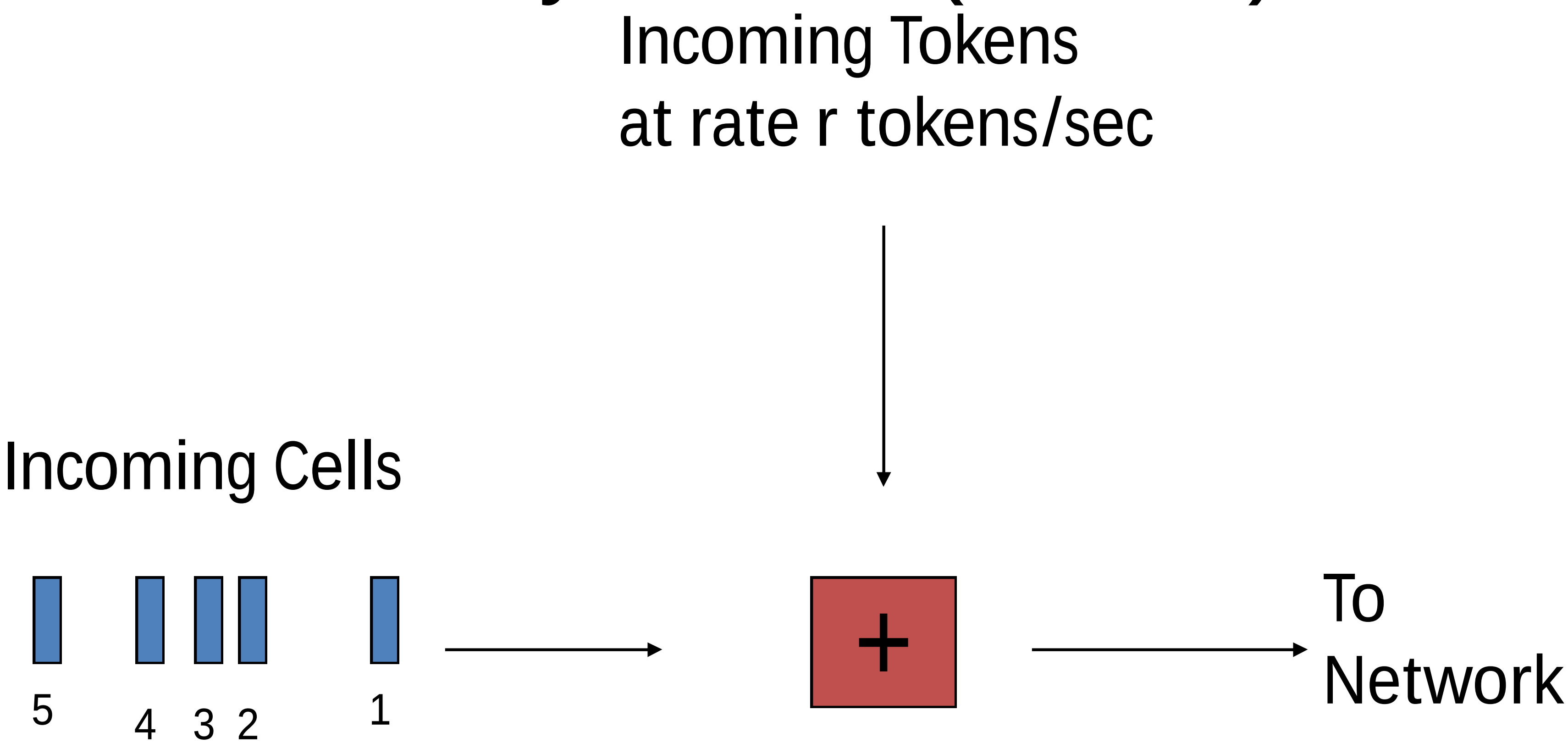
Incoming Tokens
at rate r tokens/sec

Incoming Cells
(generated by
traffic source
with rate X)

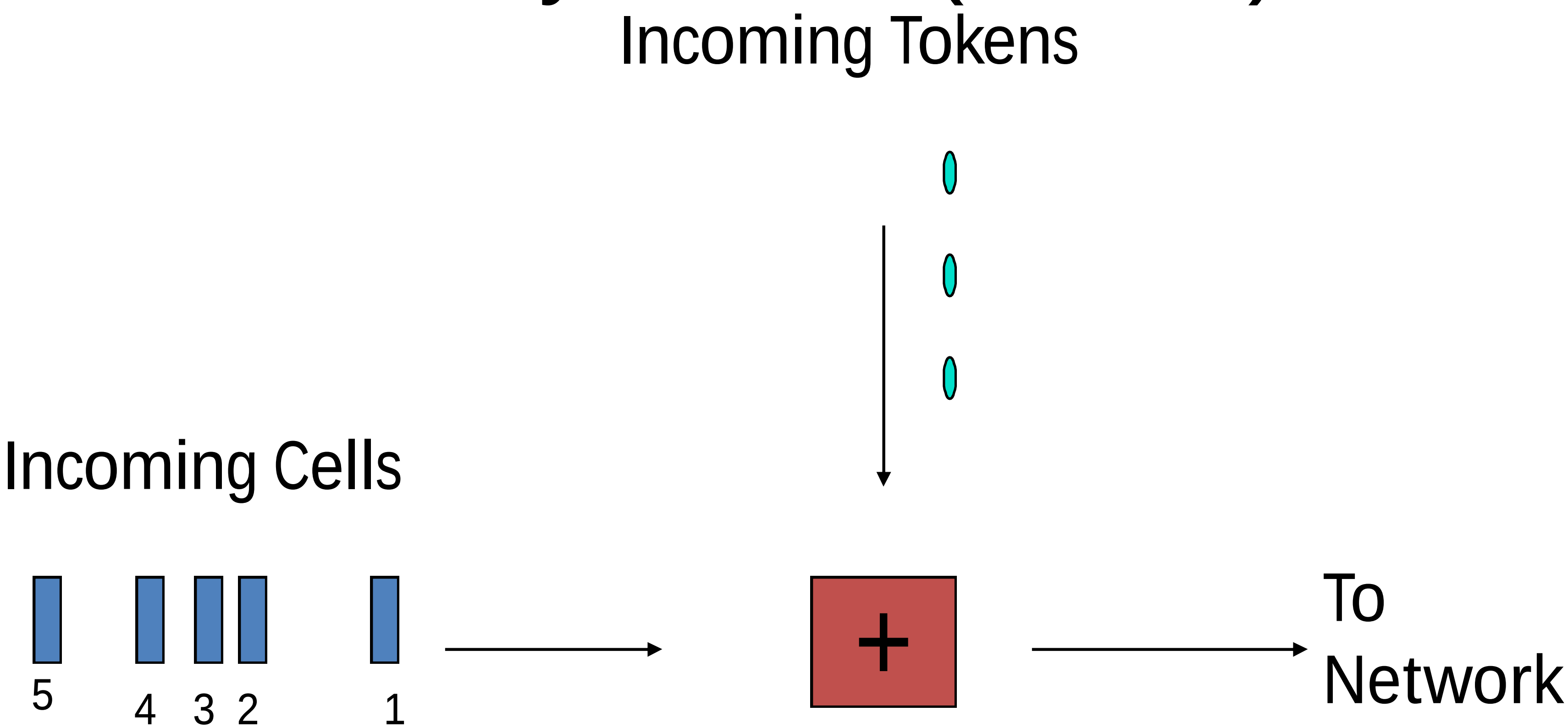


To
Network

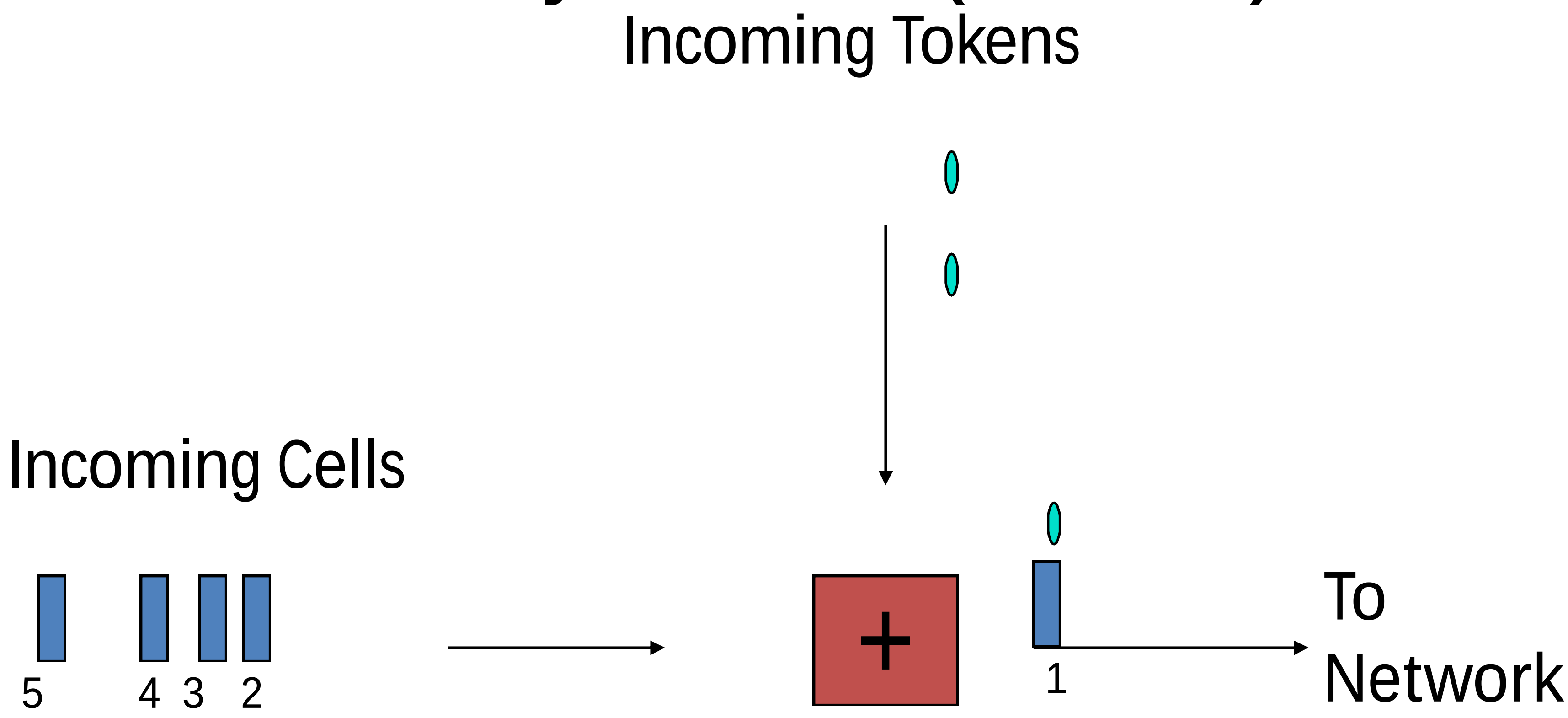
Leaky Bucket (Cont'd)



Leaky Bucket (Cont'd)



Leaky Bucket (Cont’d)



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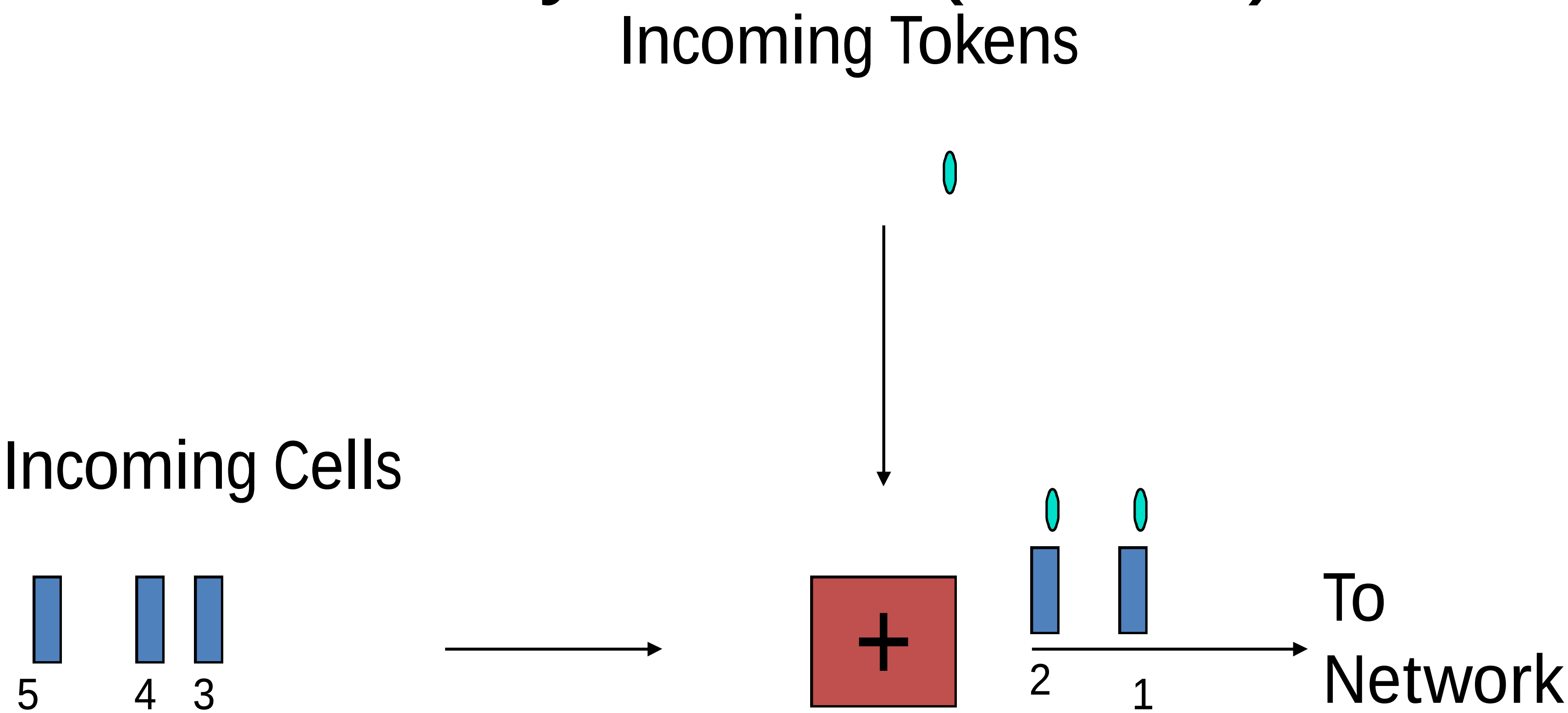
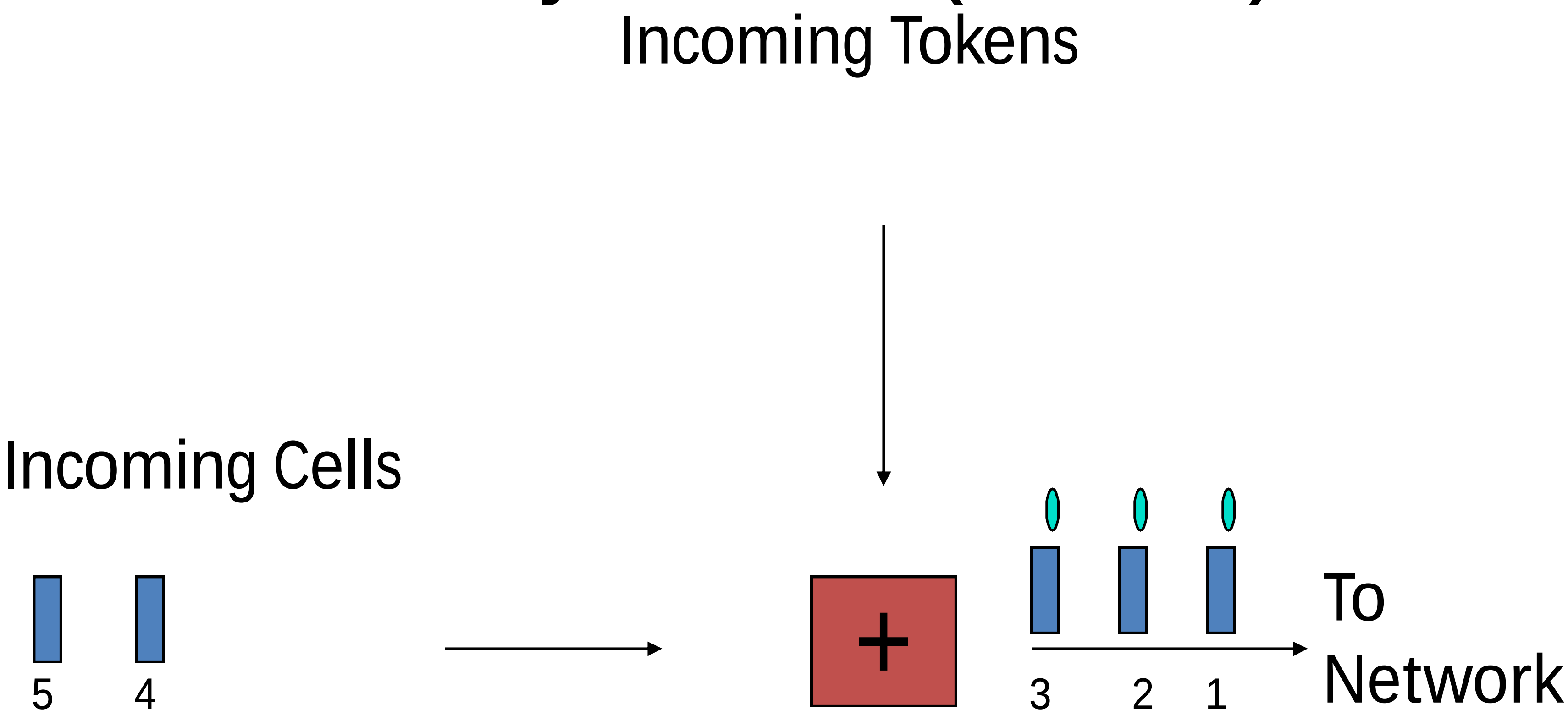
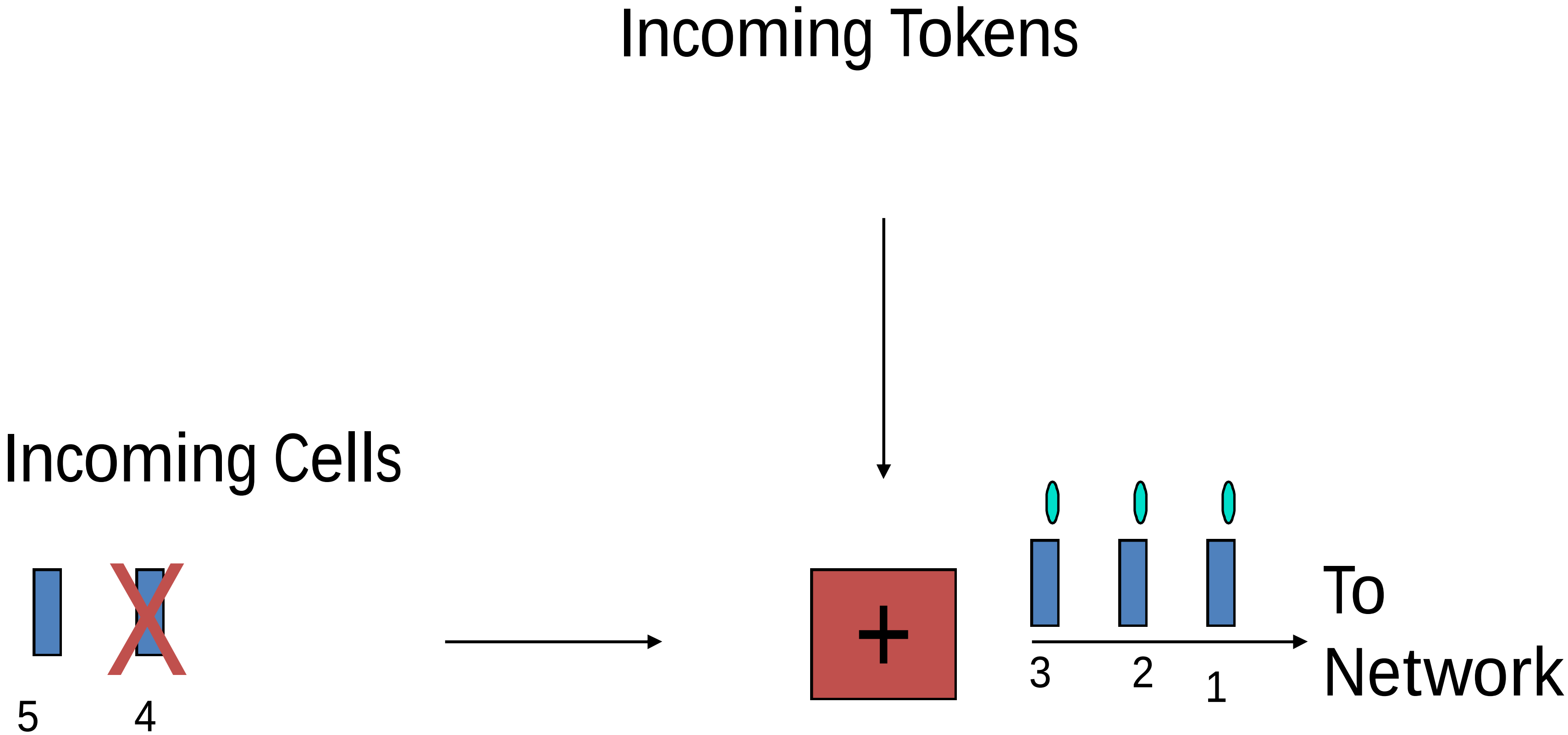


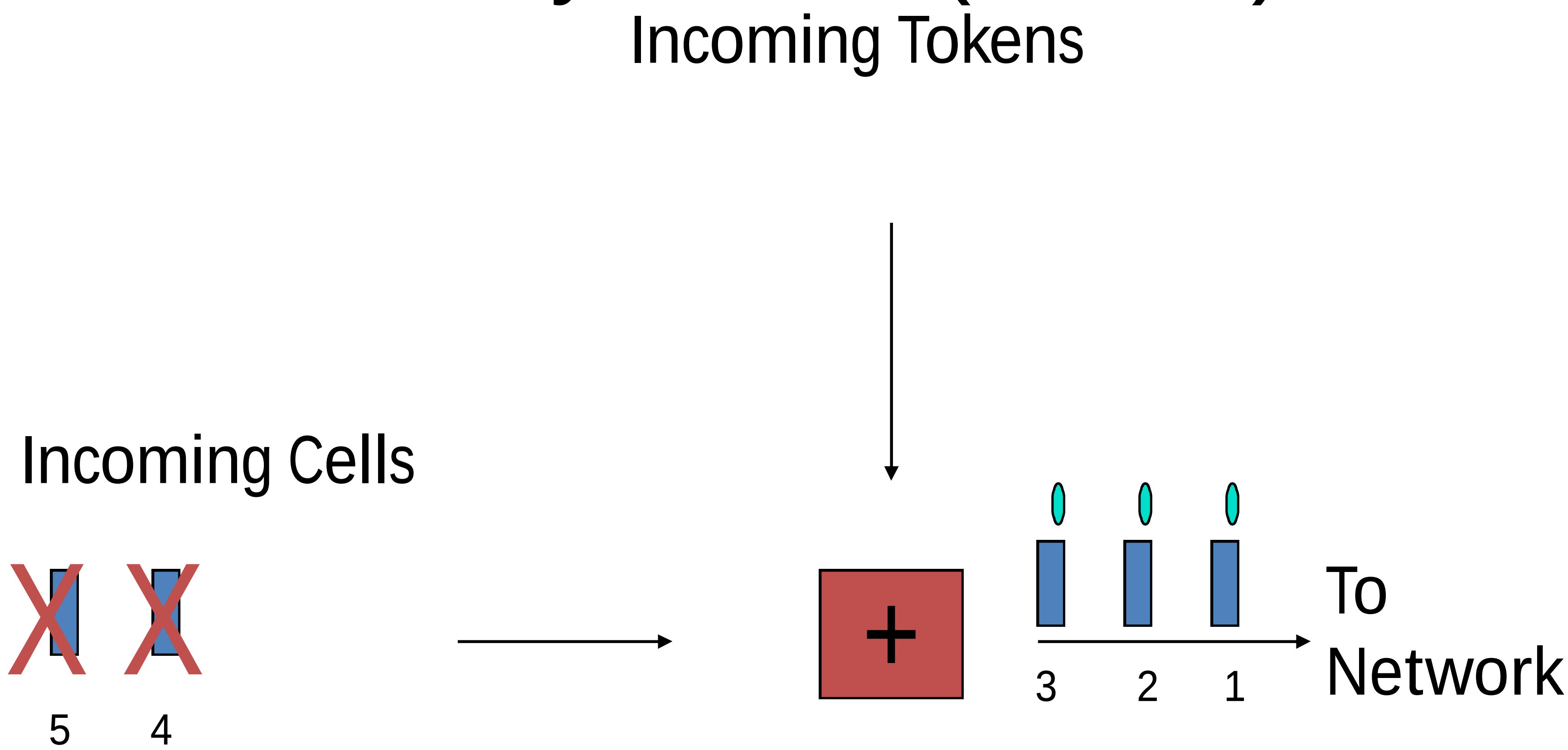
Leaky Bucket (Cont’d)



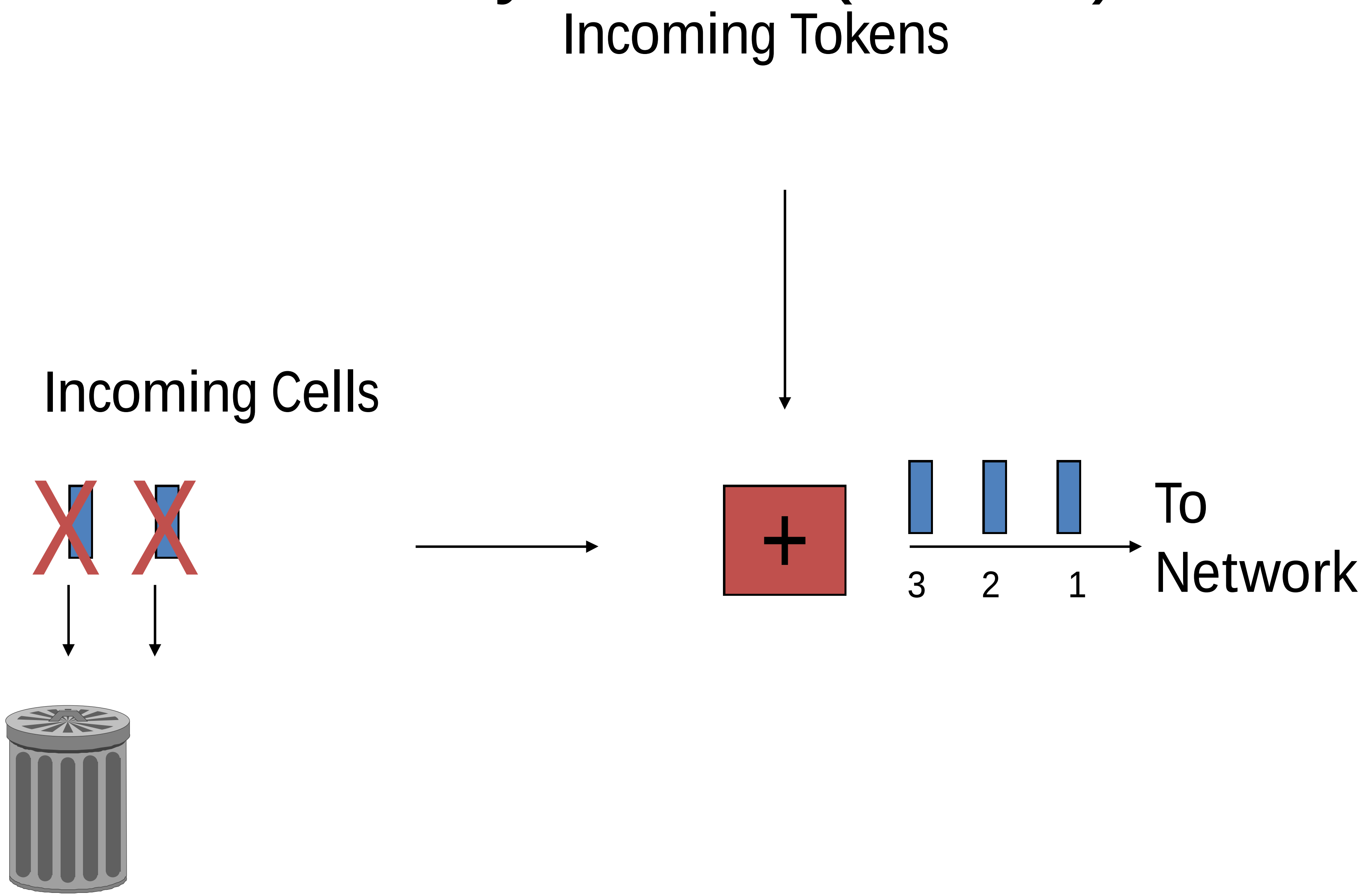
Leaky Bucket (Cont'd)



Leaky Bucket (Cont'd)



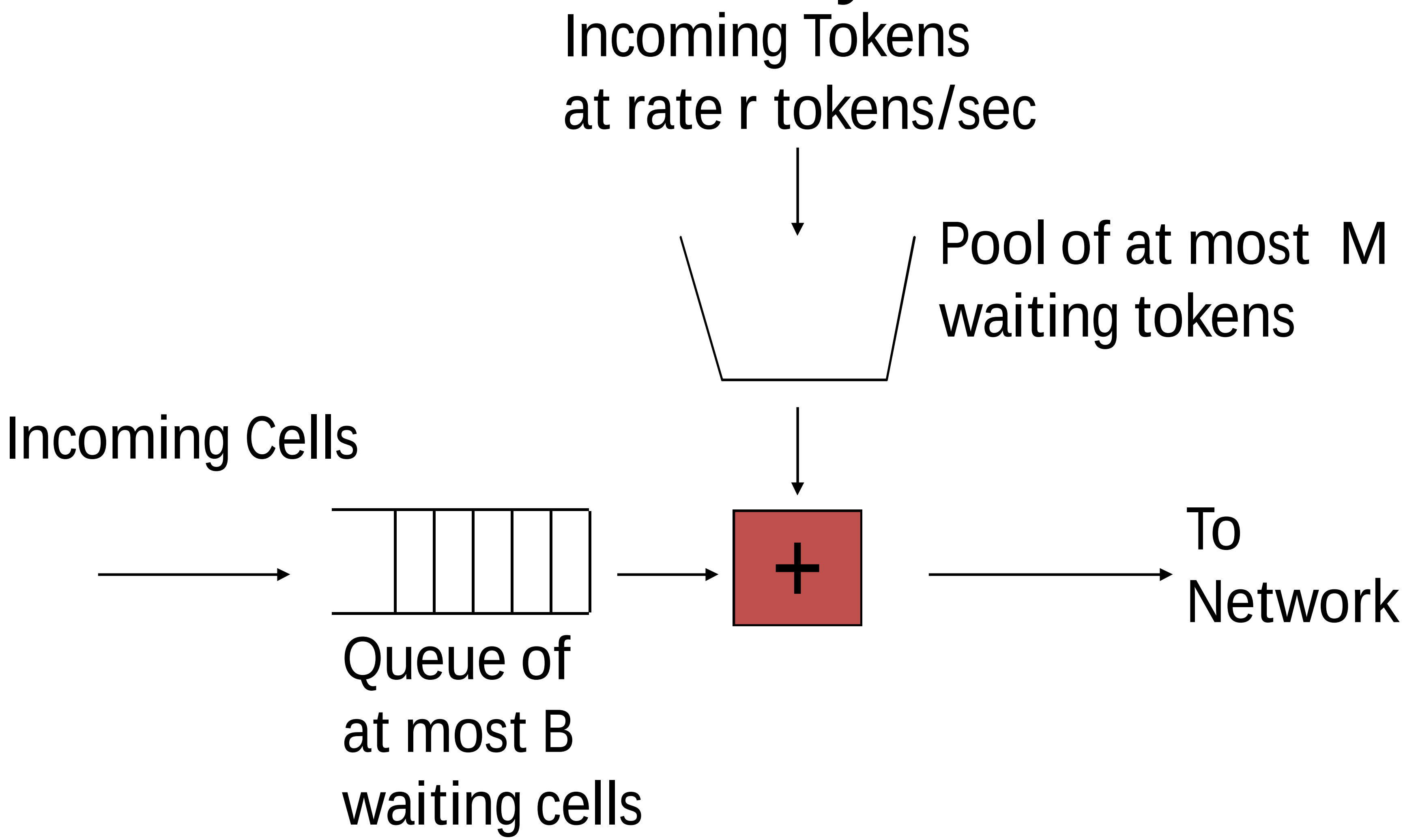
Leaky Bucket (Cont'd)



<u>Buffered</u> Leaky Bucket

- Arriving cells that find a token waiting can proceed directly into the network
- Arriving cells that find no token ready must <u>wait in queue </u>for a token
- Cells that arrive to a full queue are lost
- Tokens that arrive to a full token pool are simply discarded

Buffered Leaky Bucket



Buffered Leaky Bucket (Cont'd)

- Incoming cell rate: X
- Token rate: r
- If X > r, then cells wait in buffer until tokens are available

  Output traffic is r cells/sec, nicely paced
- If X < r, then tokens always ready

  Output traffic is X (< r)
- Use for traffic shaping or UPC

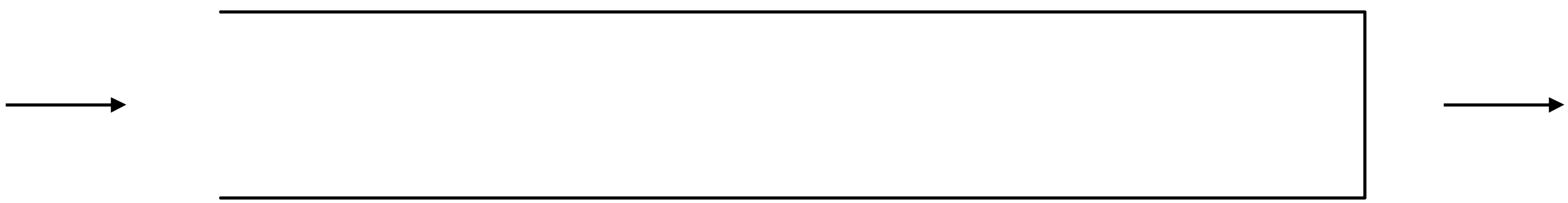
Selective Cell Discard (SCD)

- A cell-level control mechanism in ATM switches called selective cell discard can be implemented quite easily using a CLP threshold on each queue/buffer
- Below the threshold, can accept both green and red cells
- Beyond the threshold, can only accept green cells

Selective Cell Discard (Cont'd)

Buffer in an ATM switch

Selective Cell Discard (Cont'd)

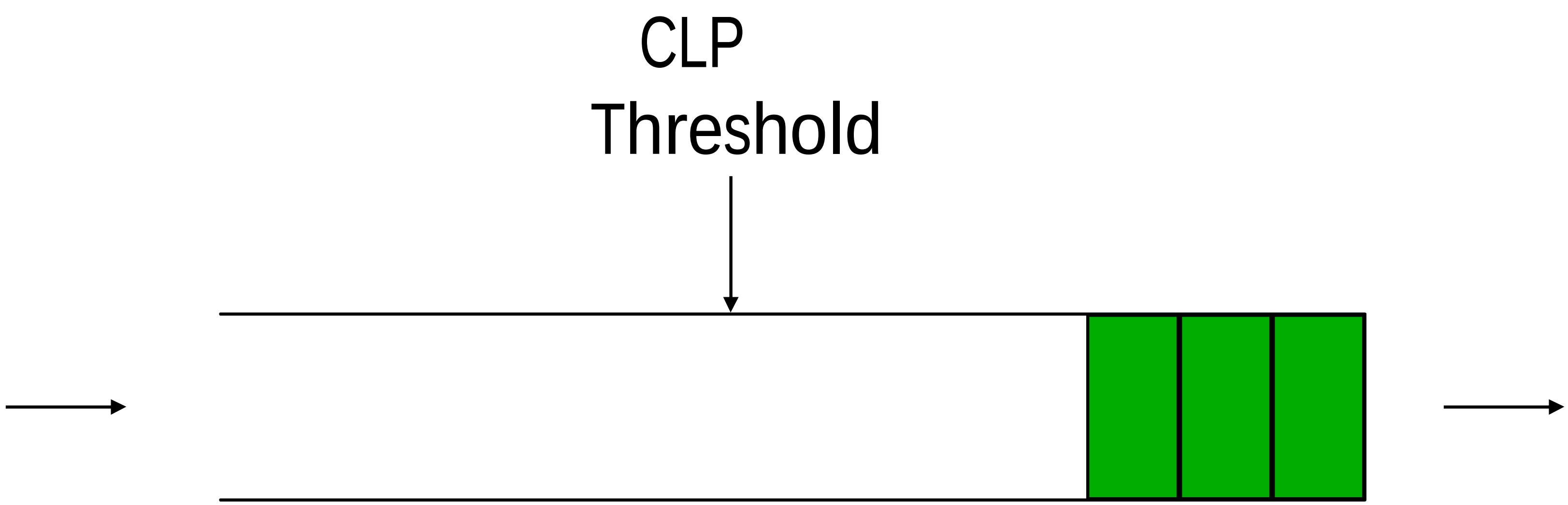


Buffer in an ATM switch

Selective Cell Discard (Cont’d)

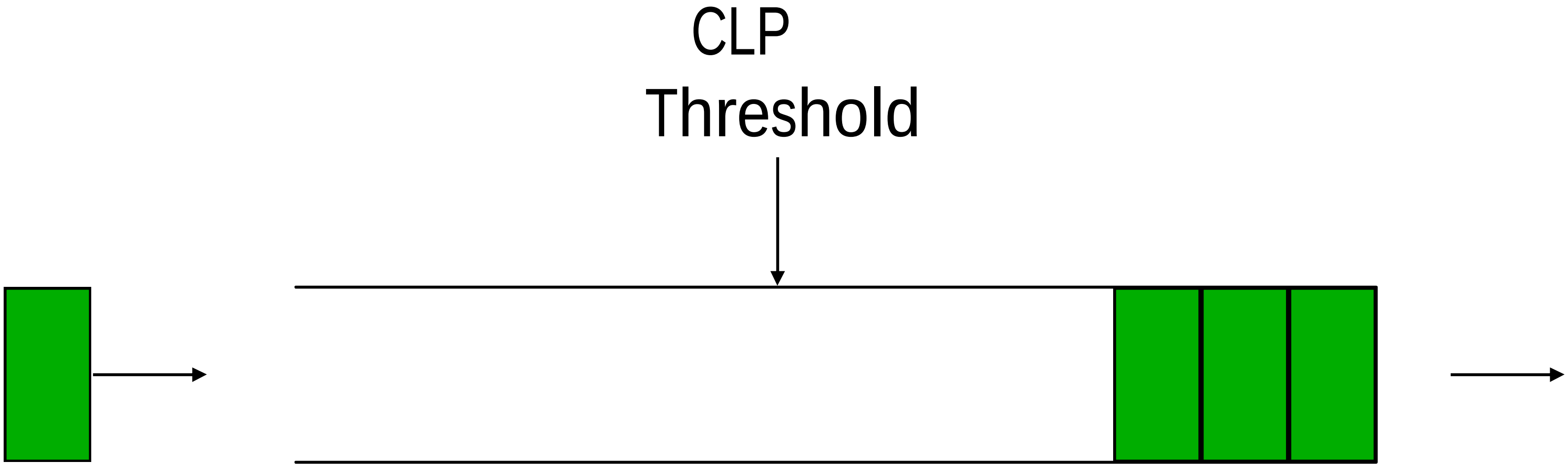
Buffer in an ATM switch

Selective Cell Discard (Cont'd)

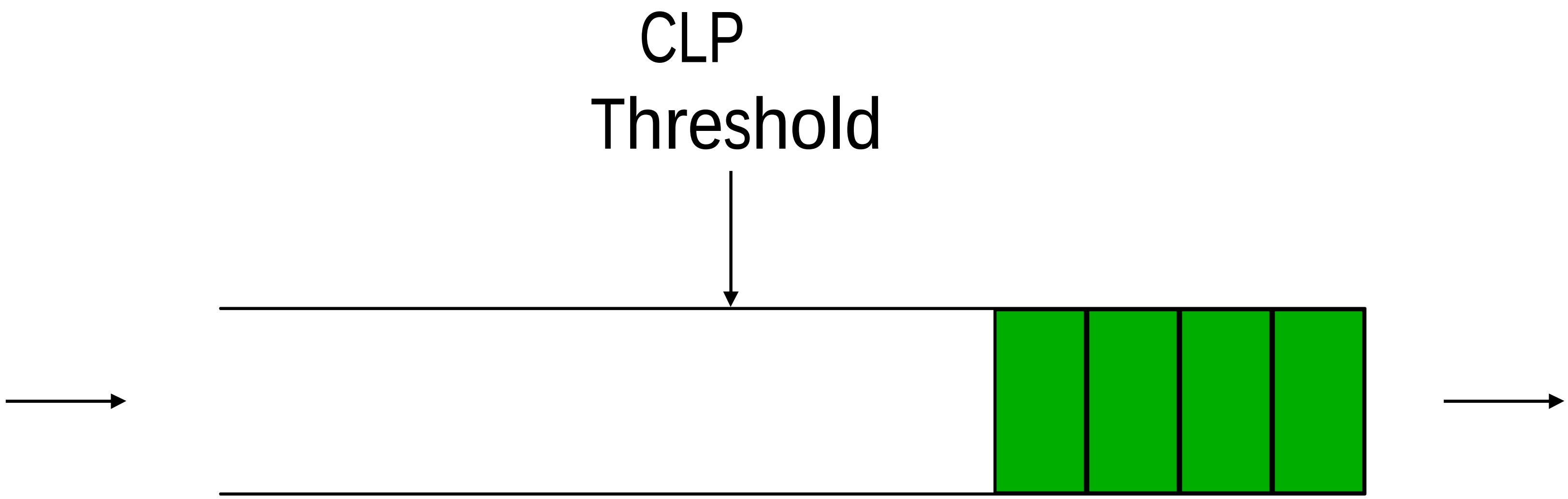


Buffer in an ATM switch

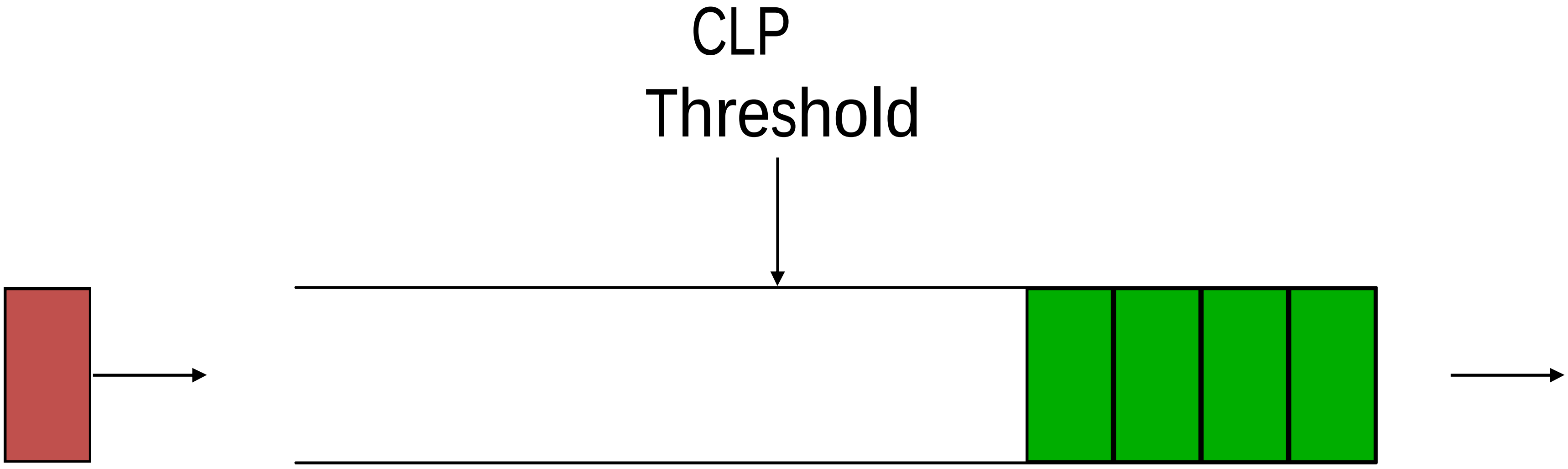
Selective Cell Discard (Cont'd)



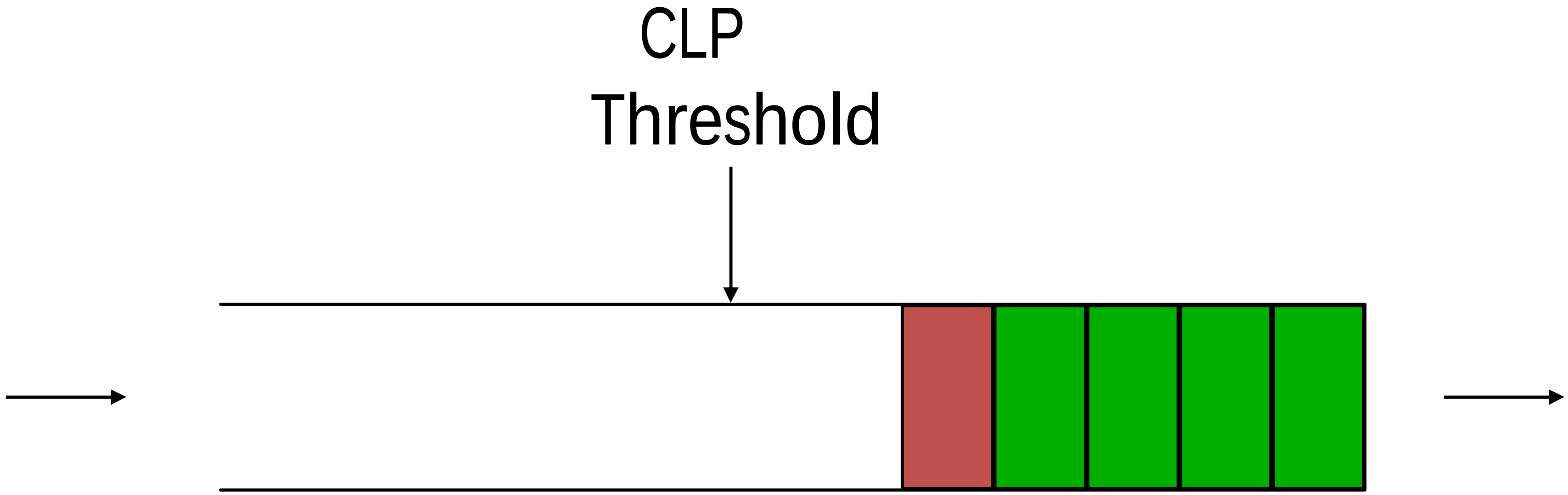
Selective Cell Discard (Cont'd)



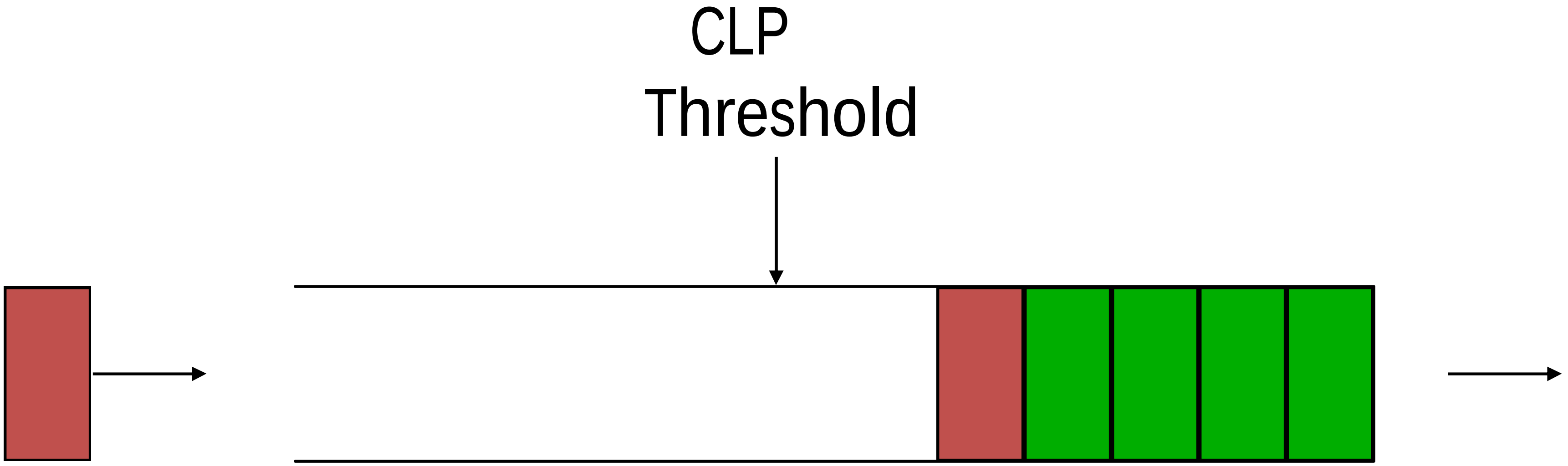
Selective Cell Discard (Cont'd)



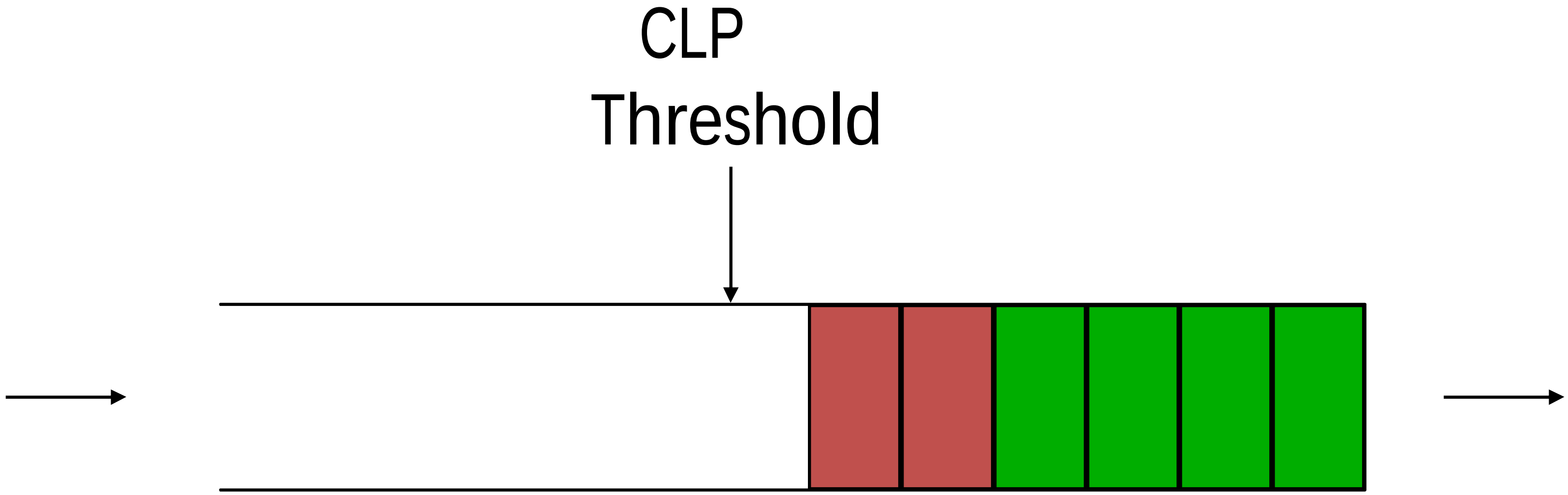
Selective Cell Discard (Cont'd)



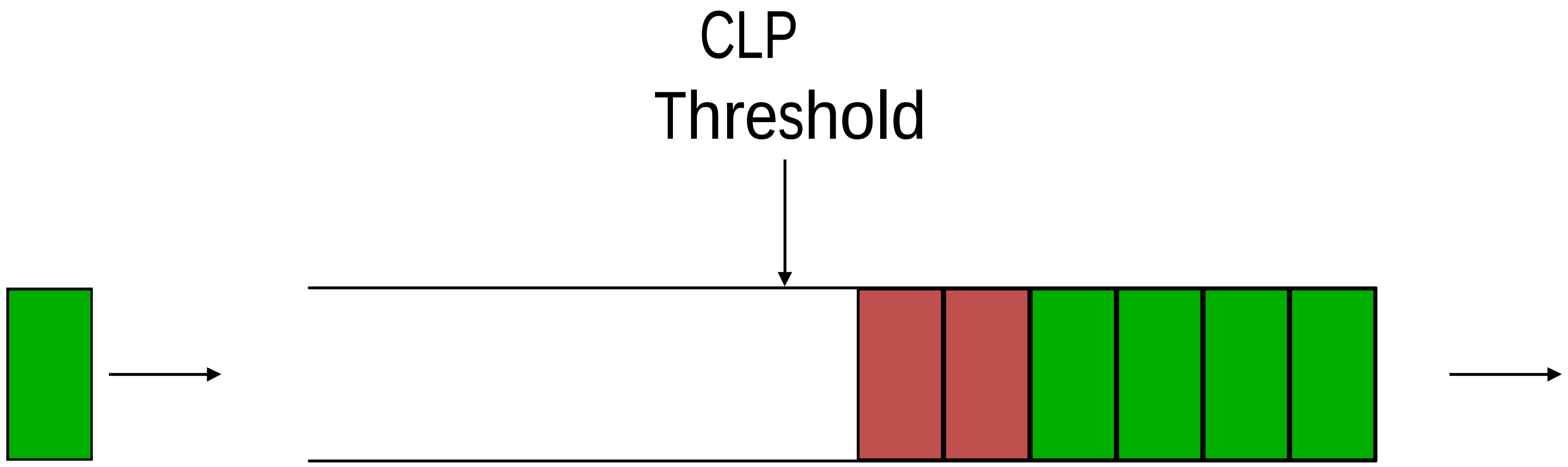
Selective Cell Discard (Cont'd)



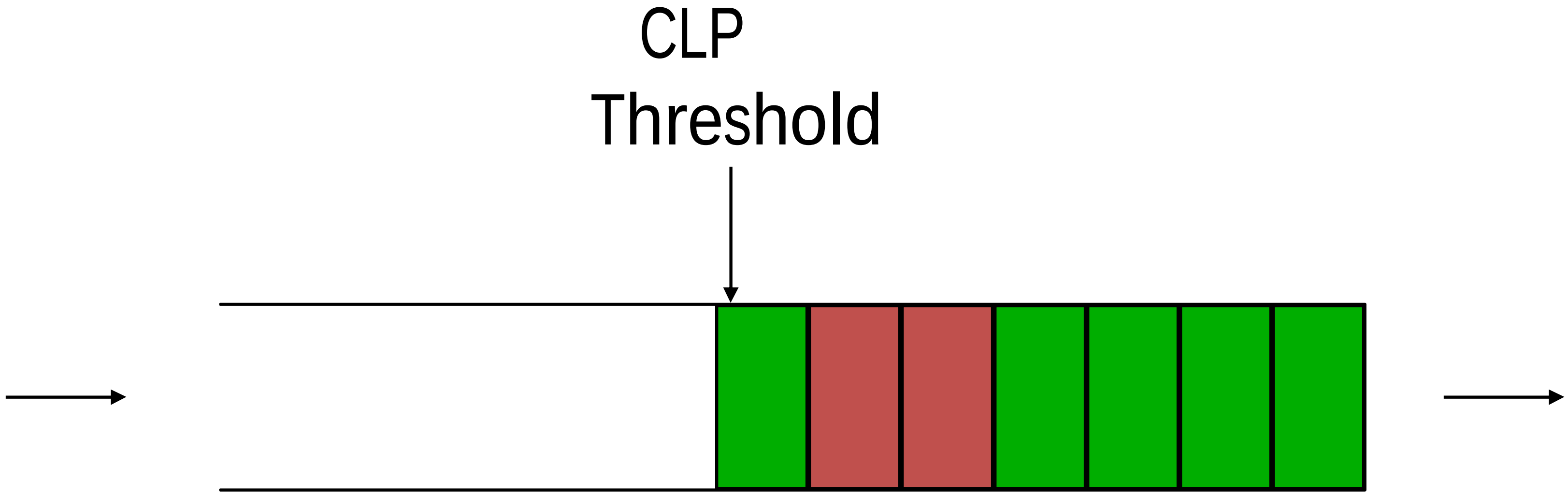
Selective Cell Discard (Cont'd)



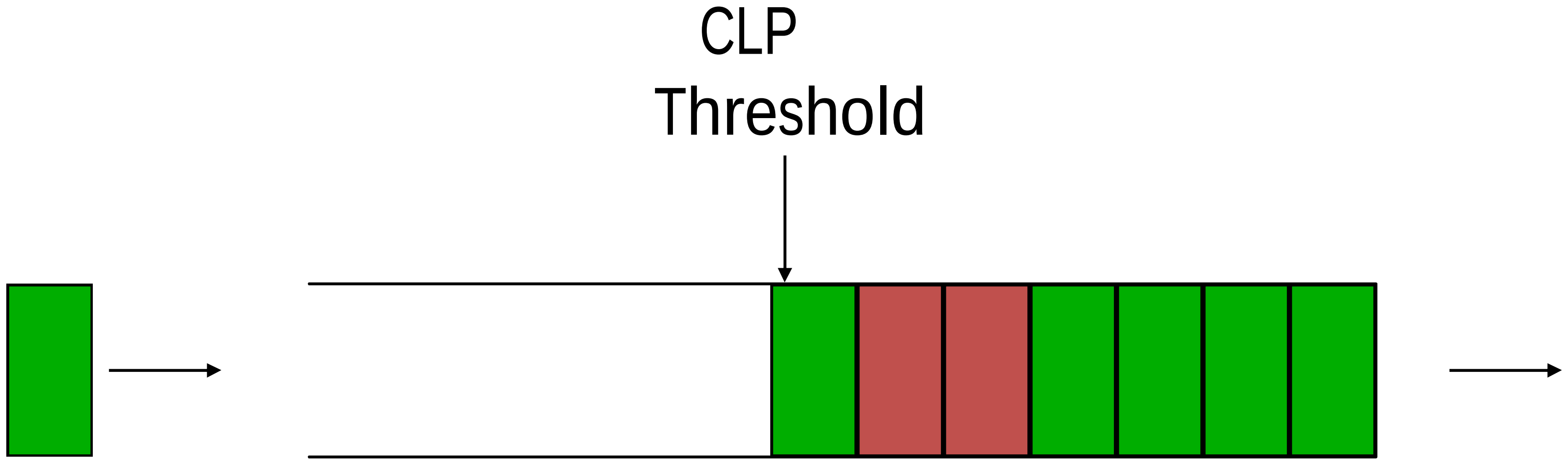
Selective Cell Discard (Cont'd)



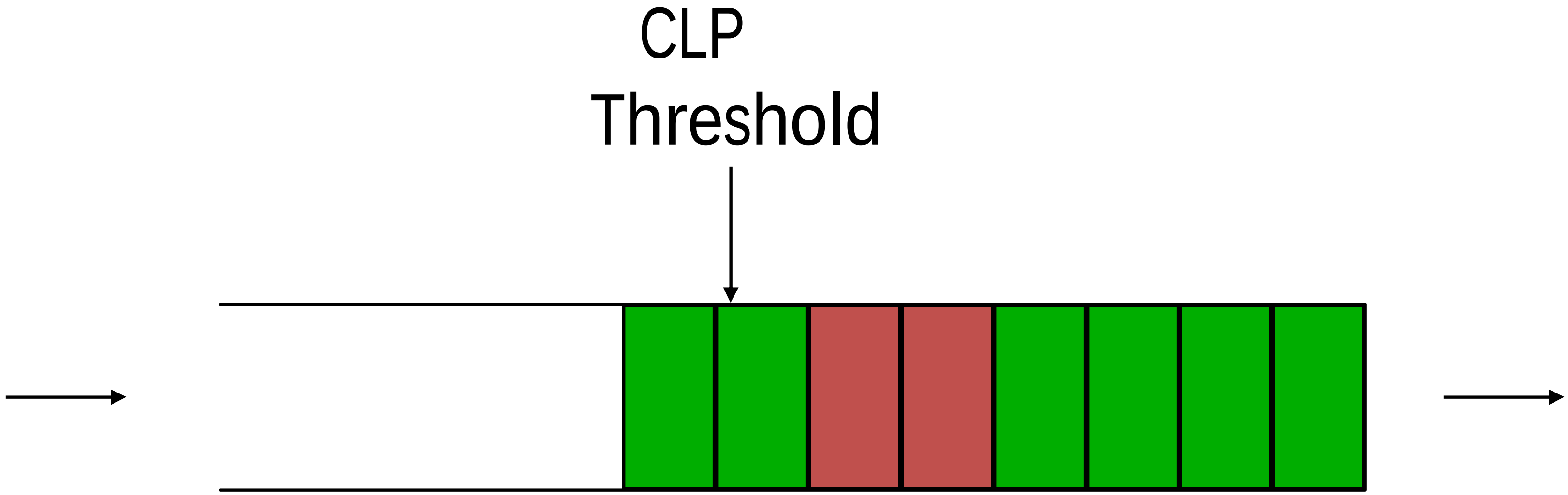
Selective Cell Discard (Cont’d)



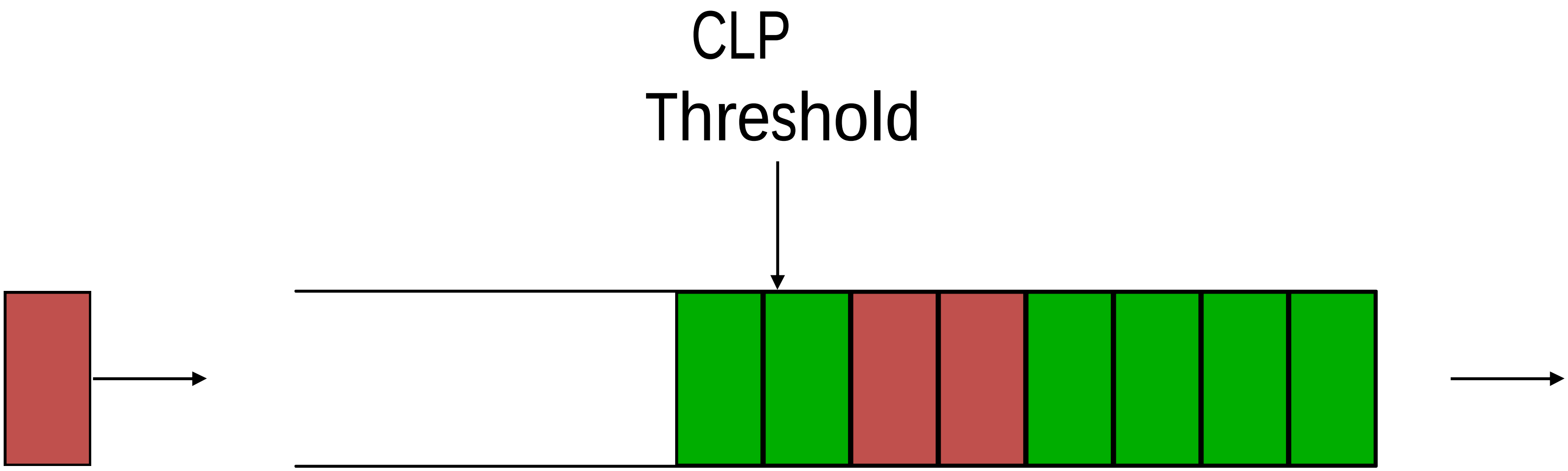
Selective Cell Discard (Cont'd)



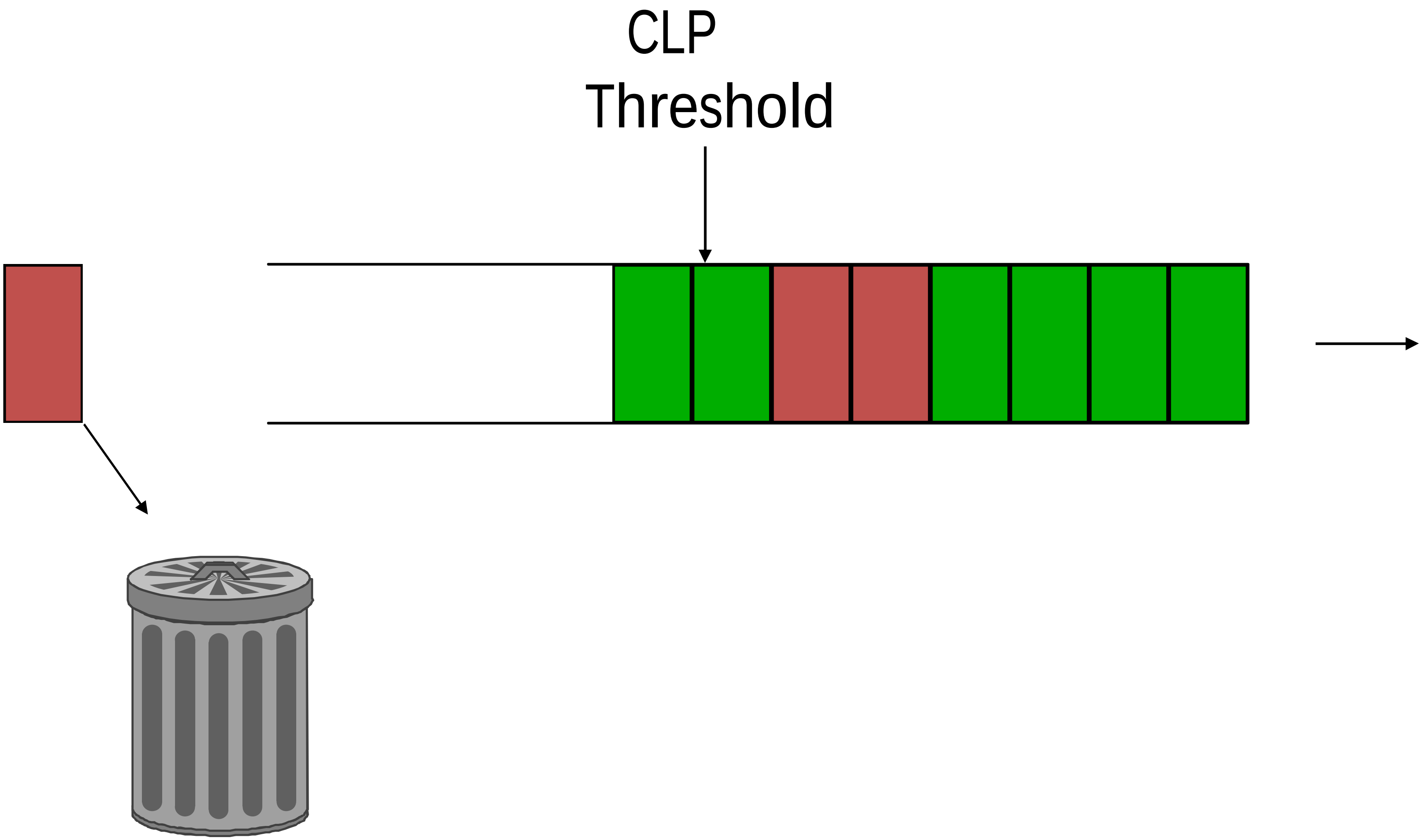
Selective Cell Discard (Cont'd)



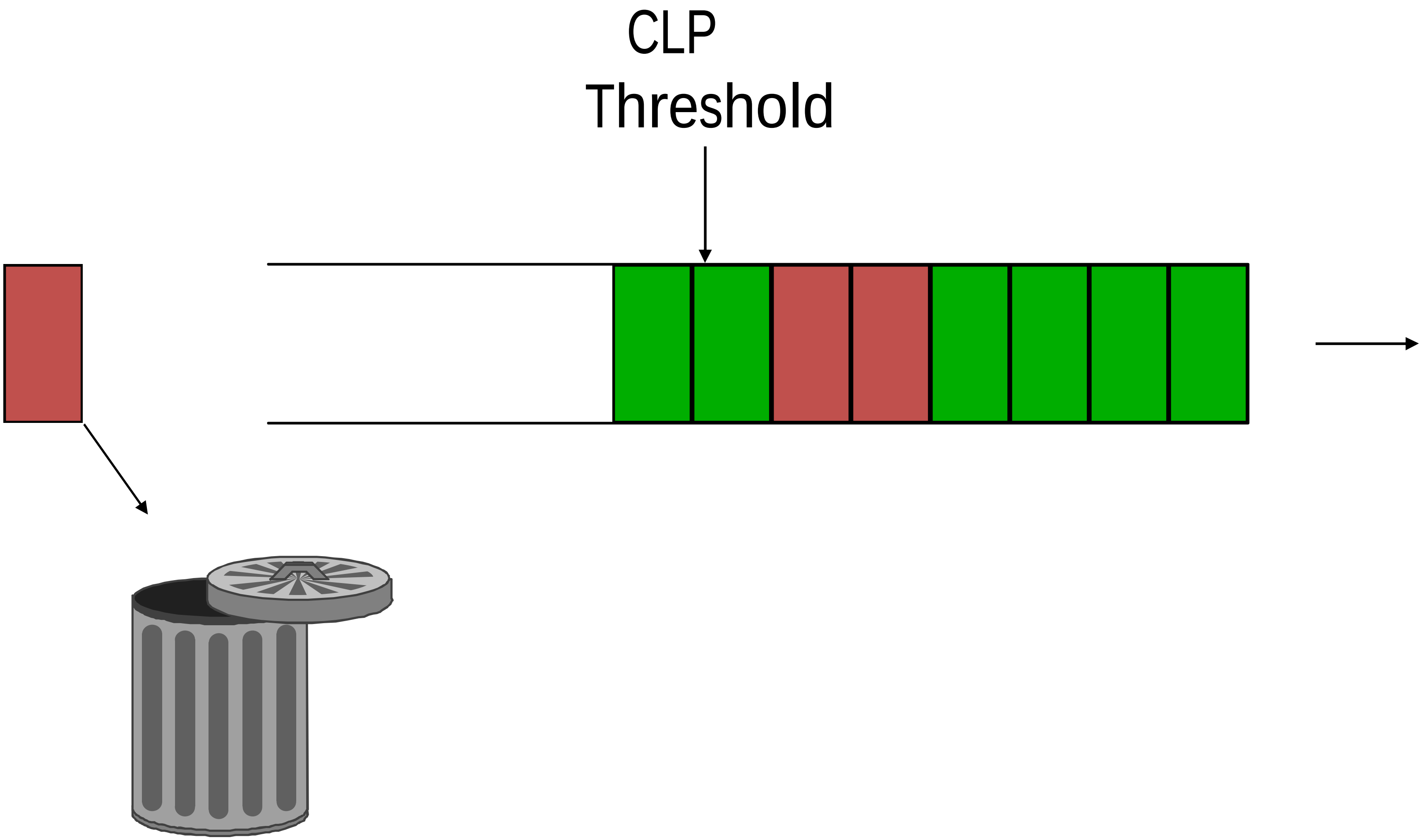
Selective Cell Discard (Cont'd)



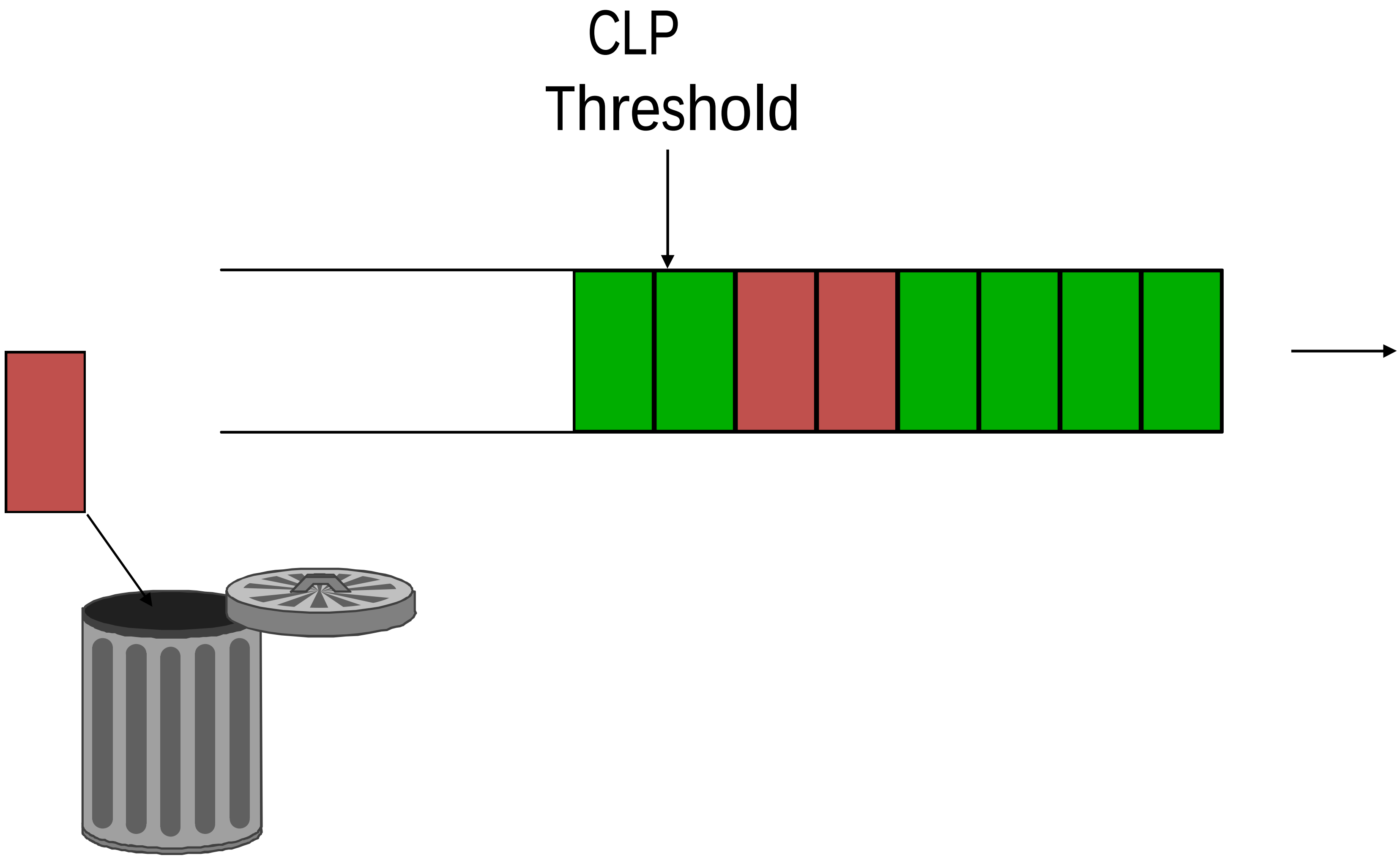
Selective Cell Discard (Cont'd)



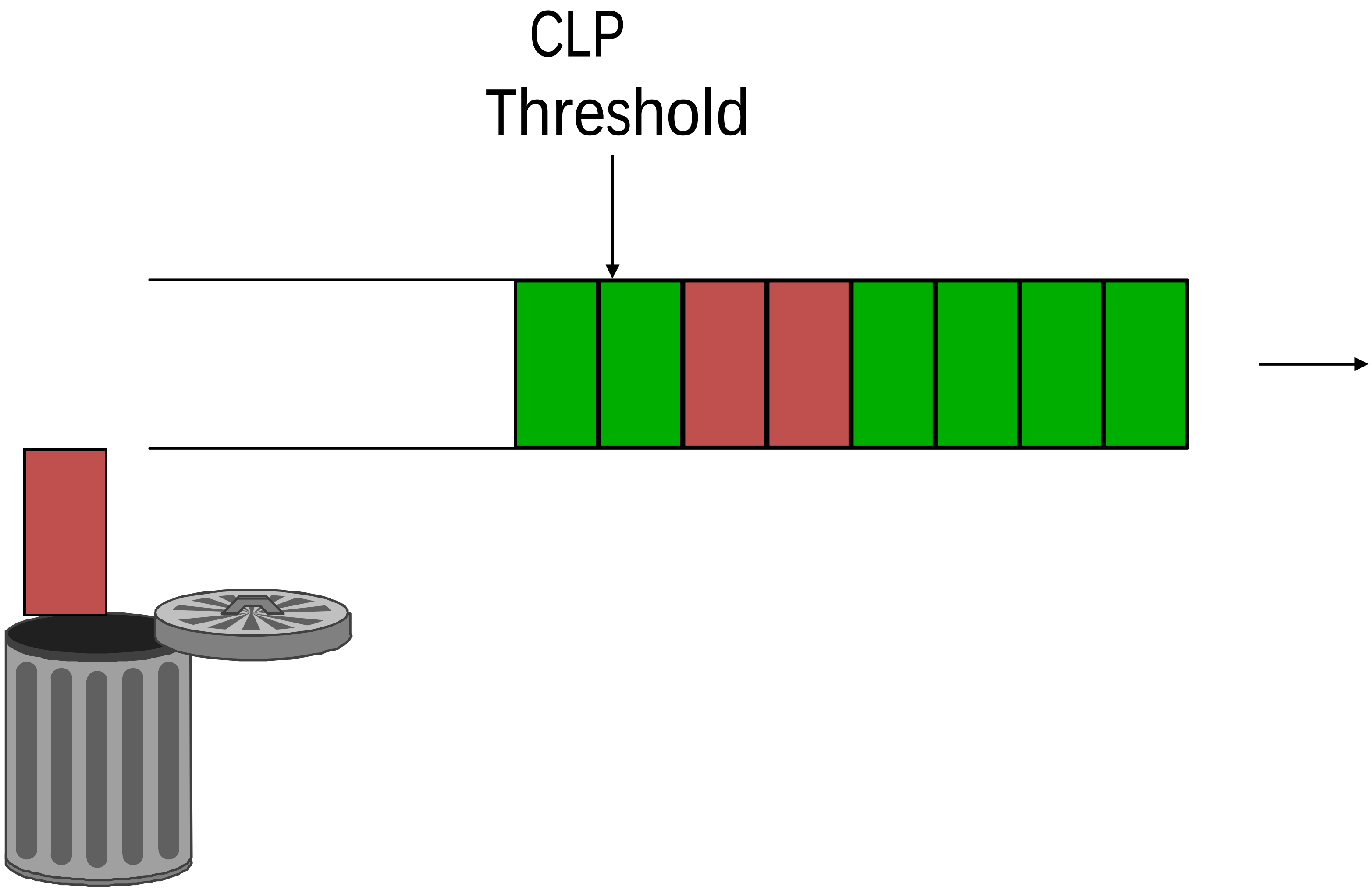
Selective Cell Discard (Cont'd)



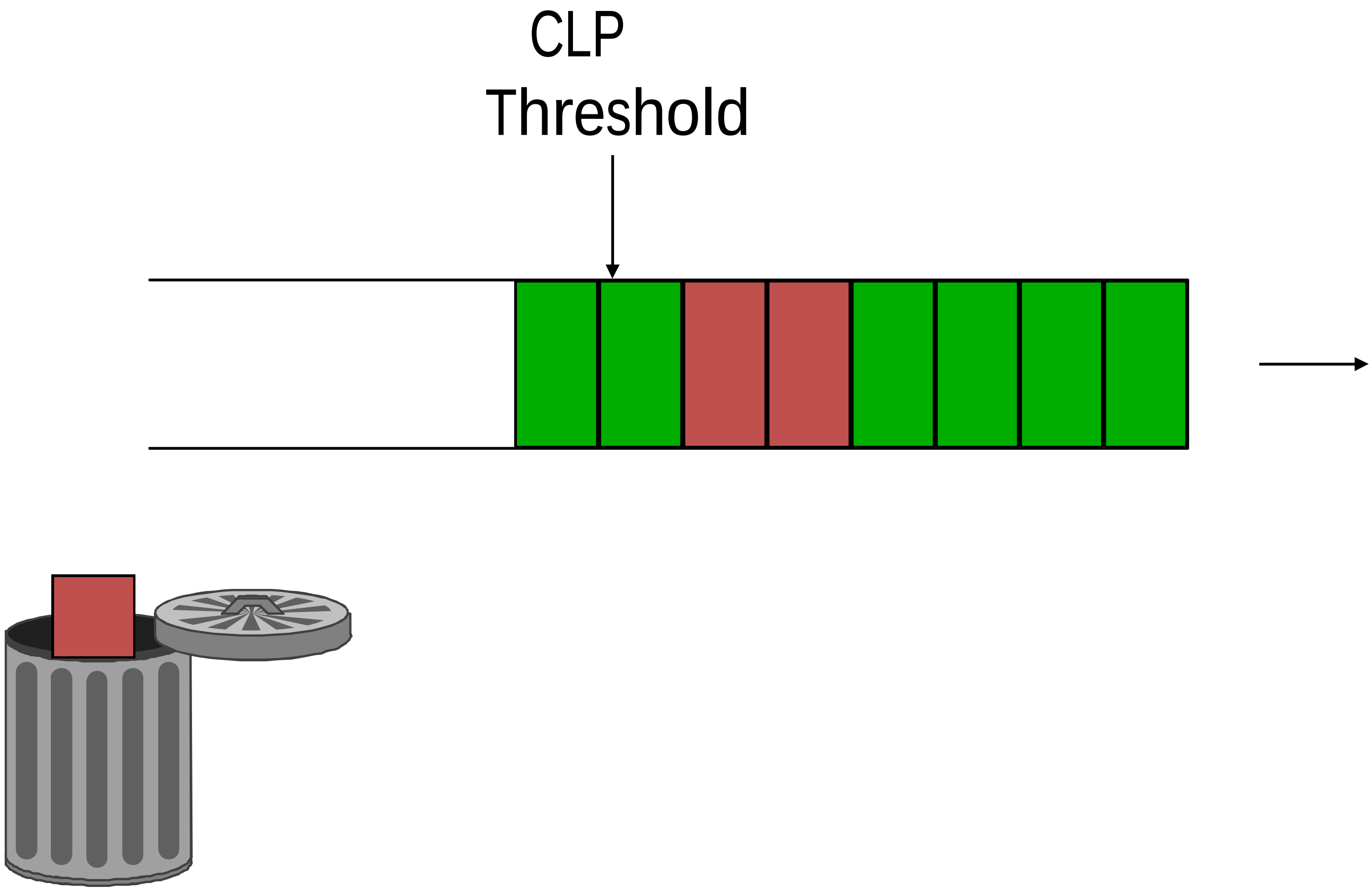
Selective Cell Discard (Cont’d)



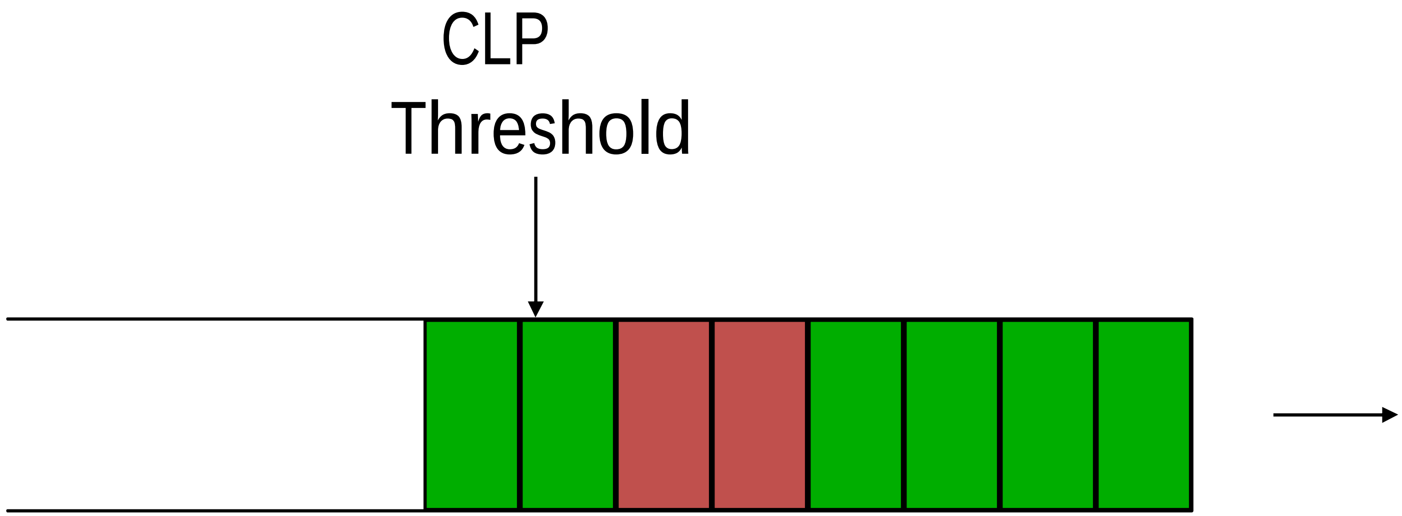
Selective Cell Discard (Cont’d)

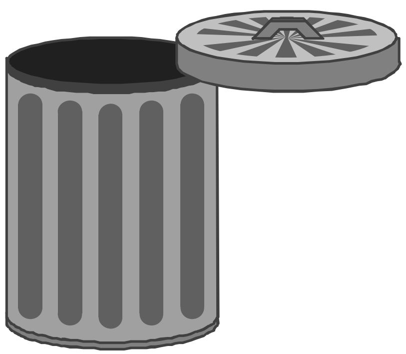


Selective Cell Discard (Cont’d)

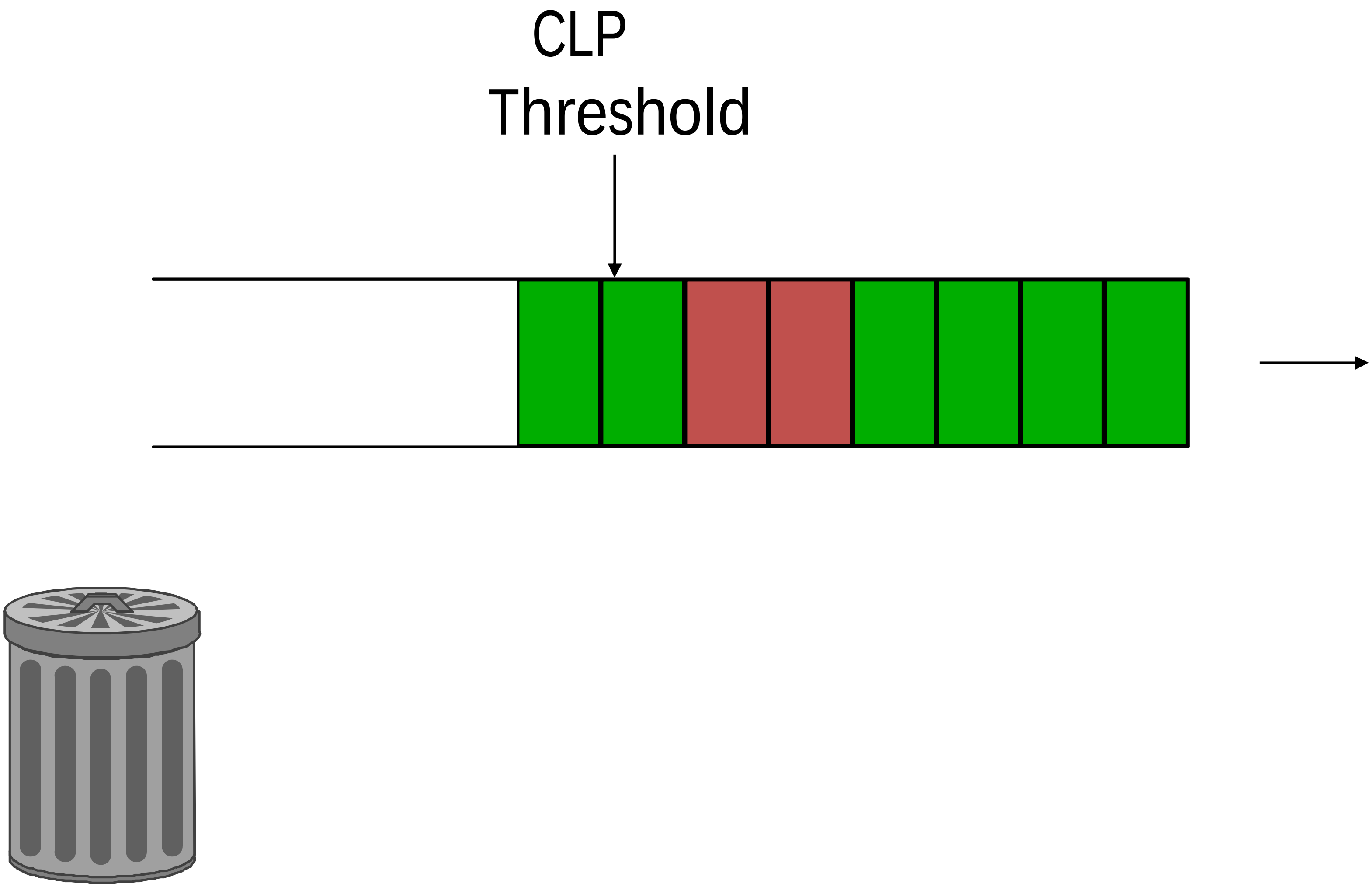


Selective Cell Discard (Cont'd)

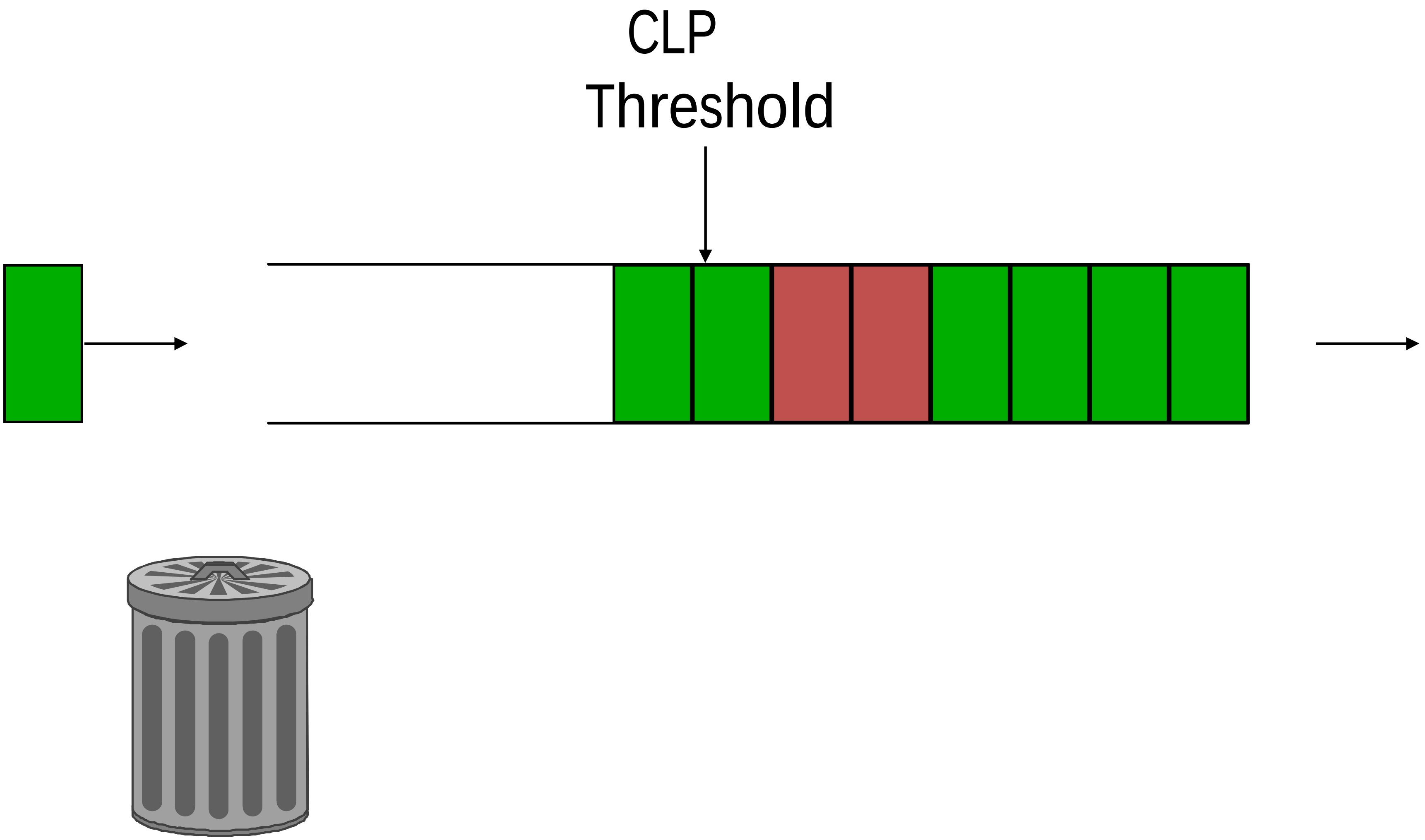




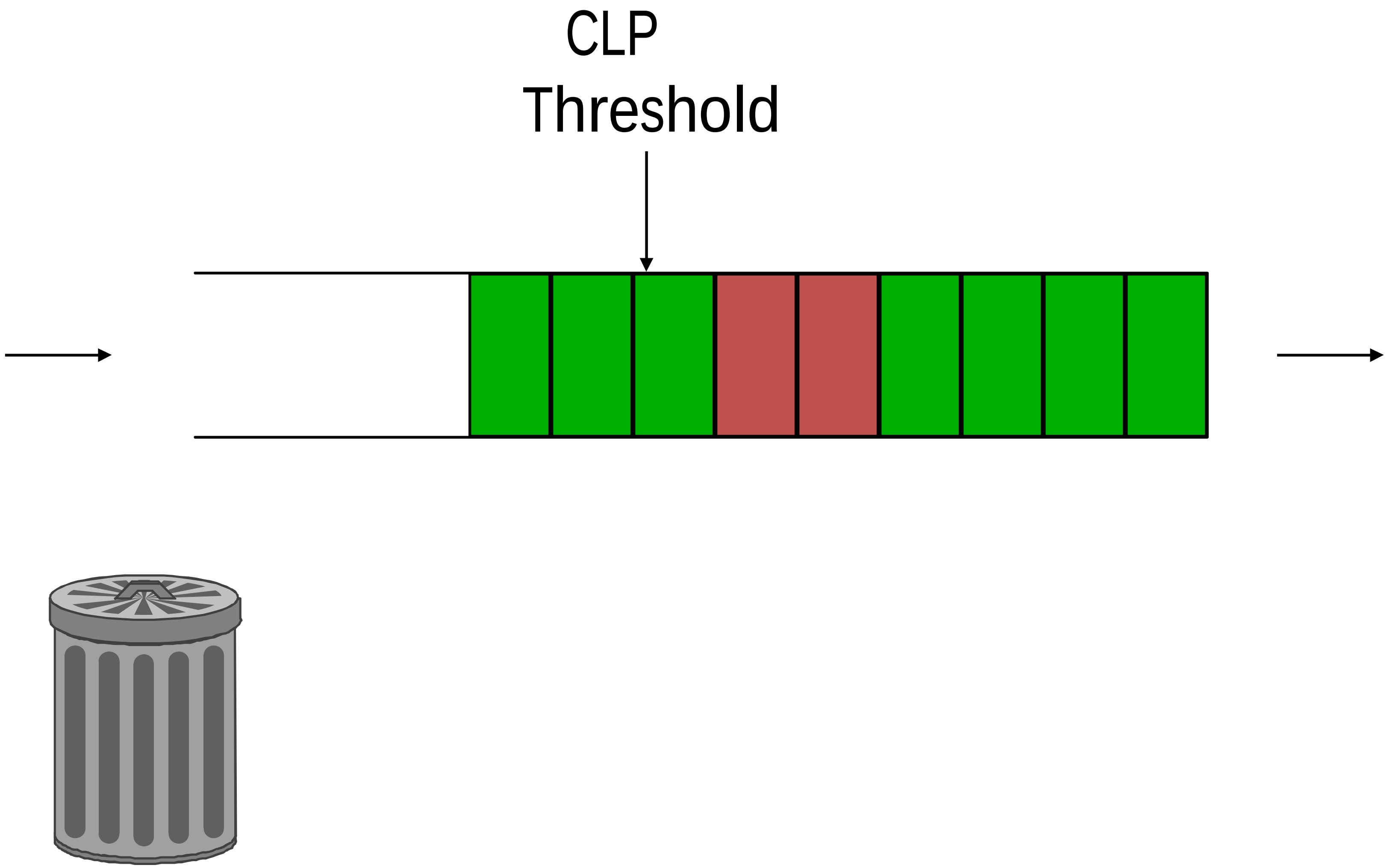
Selective Cell Discard (Cont'd)



Selective Cell Discard (Cont'd)



Selective Cell Discard (Cont'd)



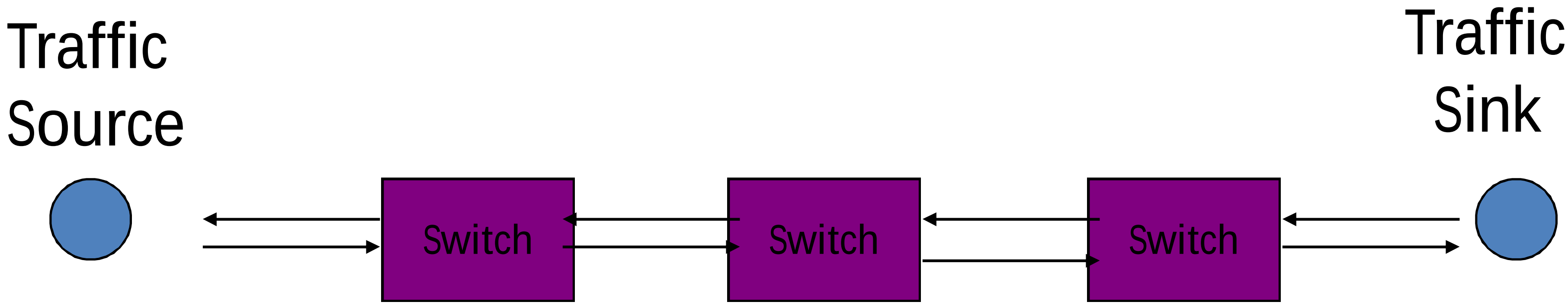
Explicit Congestion Notification

- There are some proposals to use reactive congestion control approaches for end-to-end flow control in ATM
- One of the mechanisms proposed is called Explicit Forward Congestion Notification (EFCN) (or EFCI, for Explicit Forward Congestion Indication)

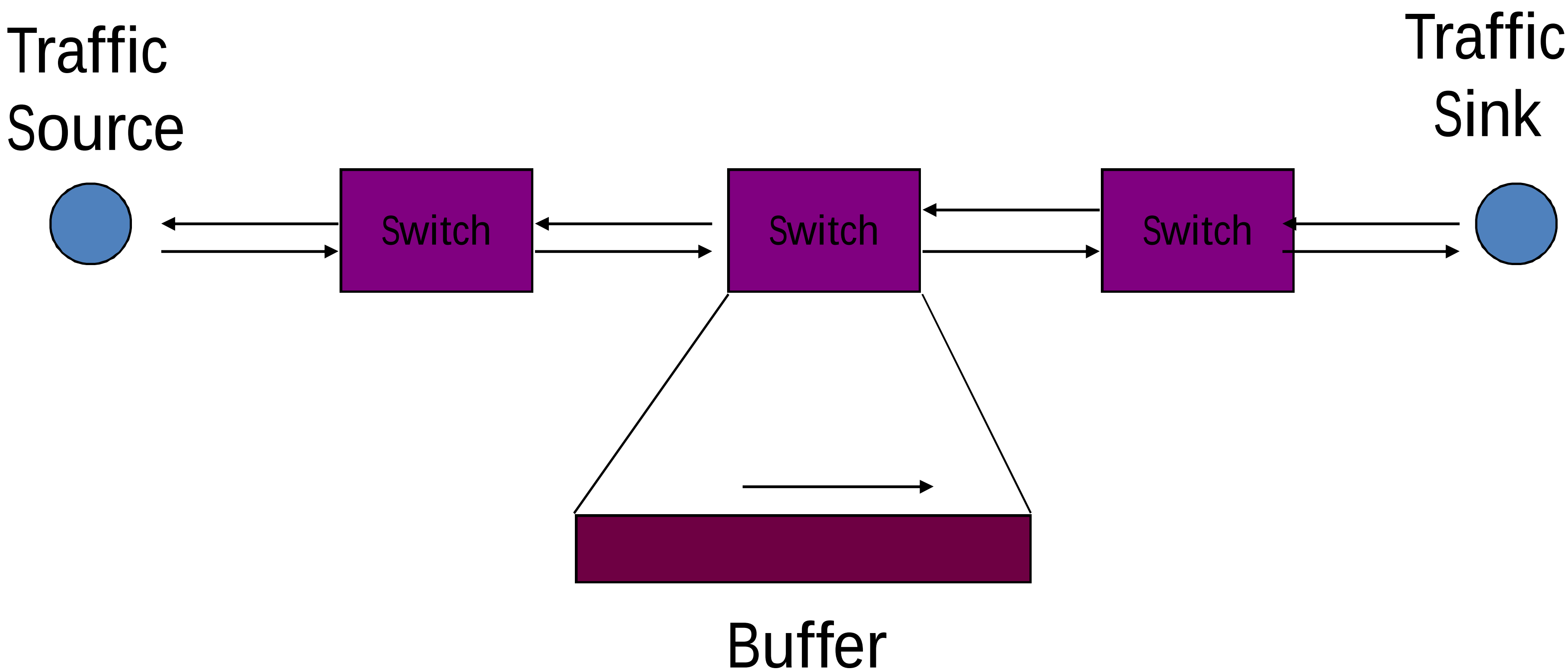
EFCI: Basic Operation

- Switches can detect the onset of congestion (e.g., buffers filling up)
- Switches set a control bit in cell headers to indicate this congestion condition
- Sources react by reducing the volume of traffic that they are sending through that switch
- Suitable for VBR or ABR traffic

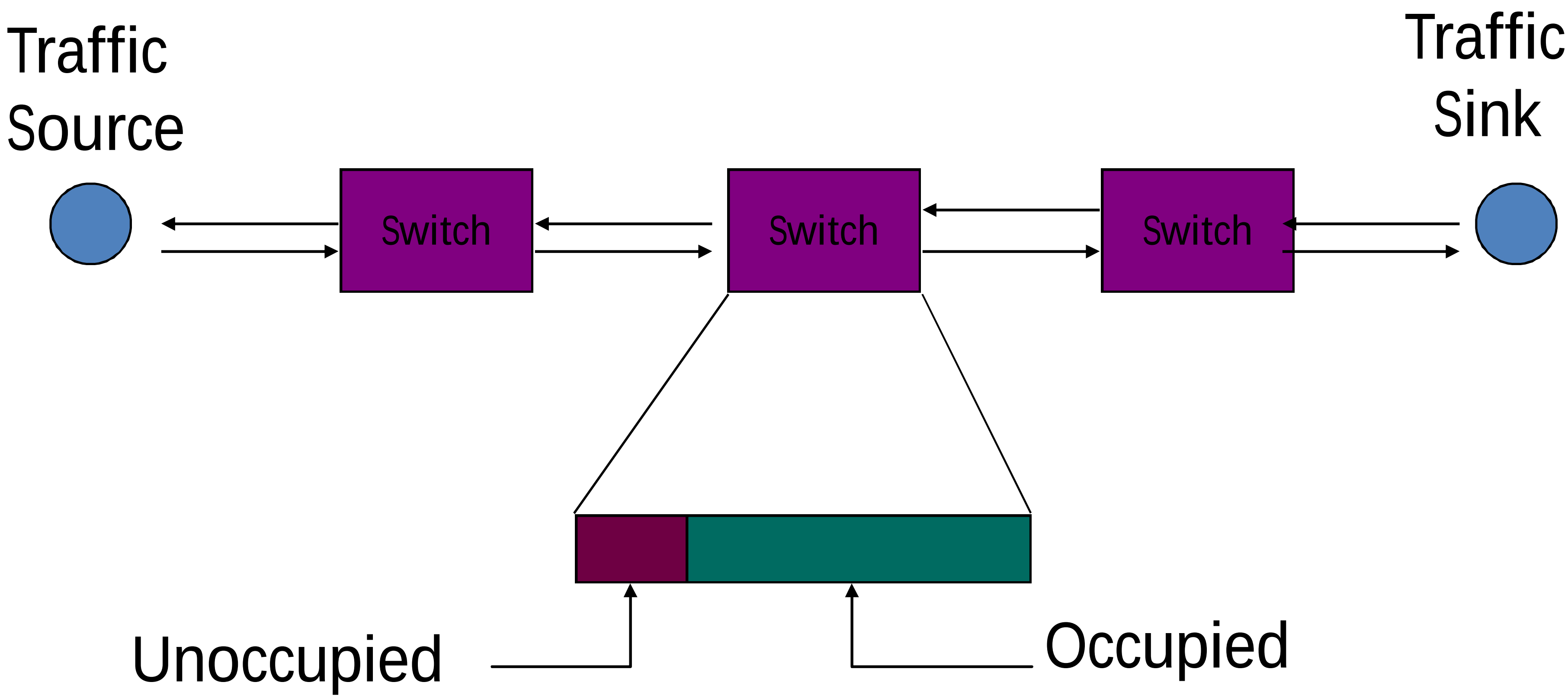
EFCI: Basic Operation (Cont'd)



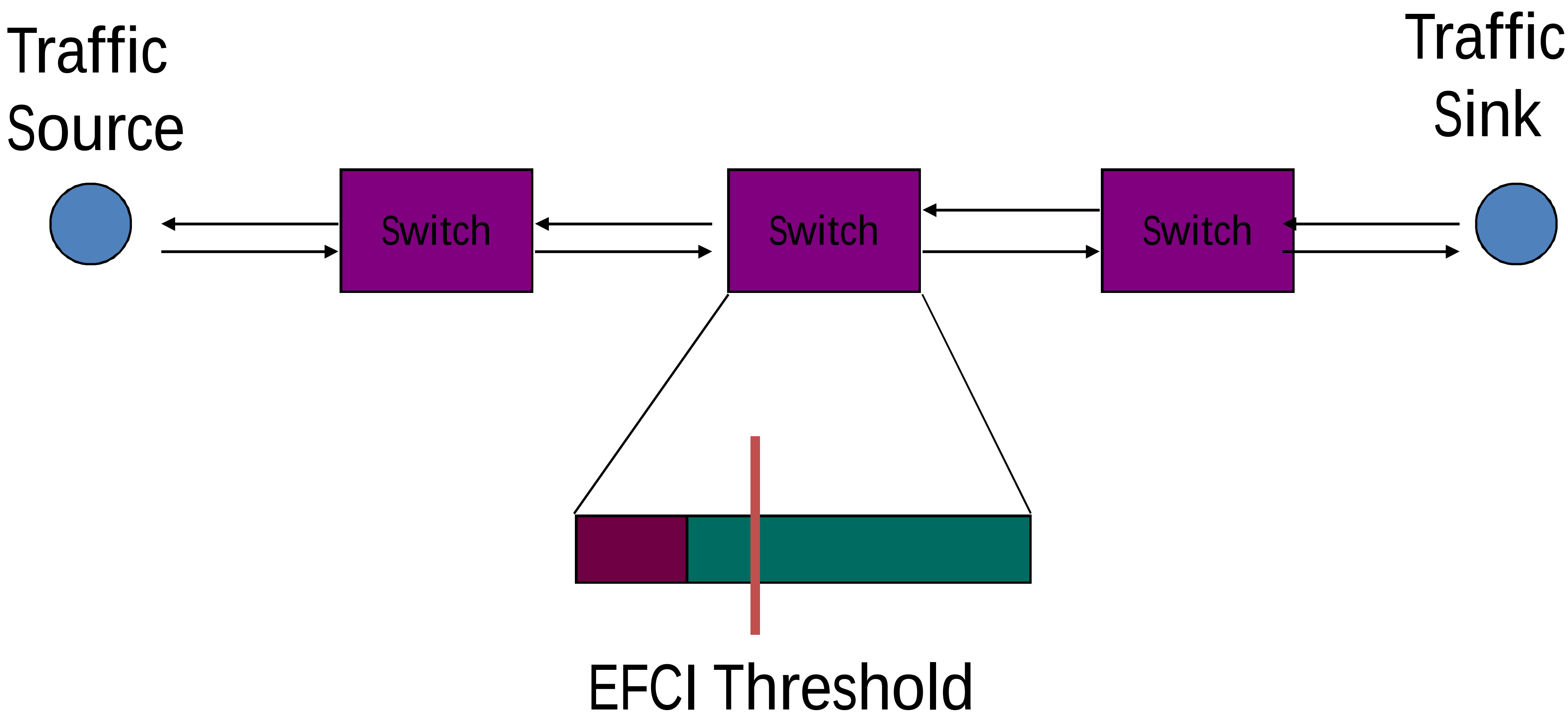
EFCI: Basic Operation (Cont’d)



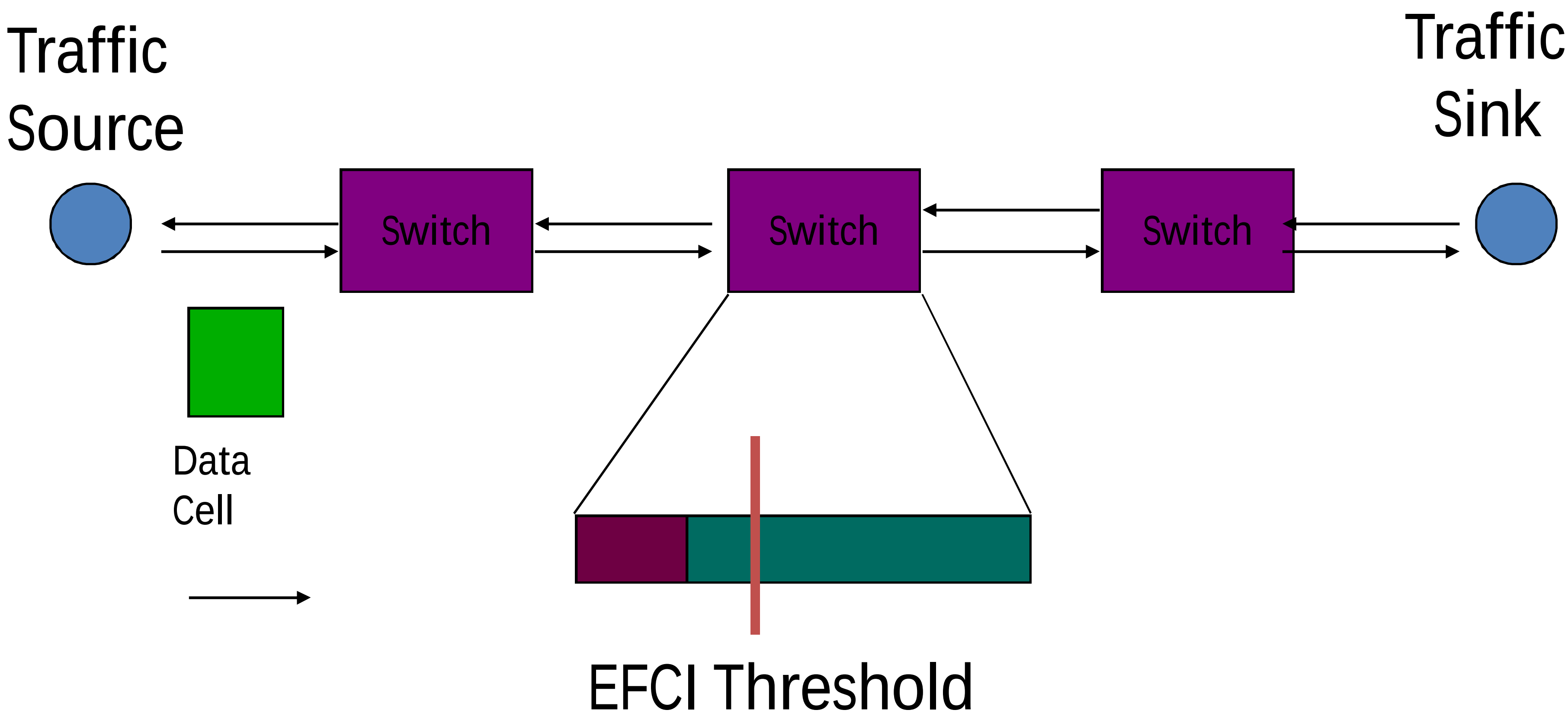
EFCI: Basic Operation (Cont’d)



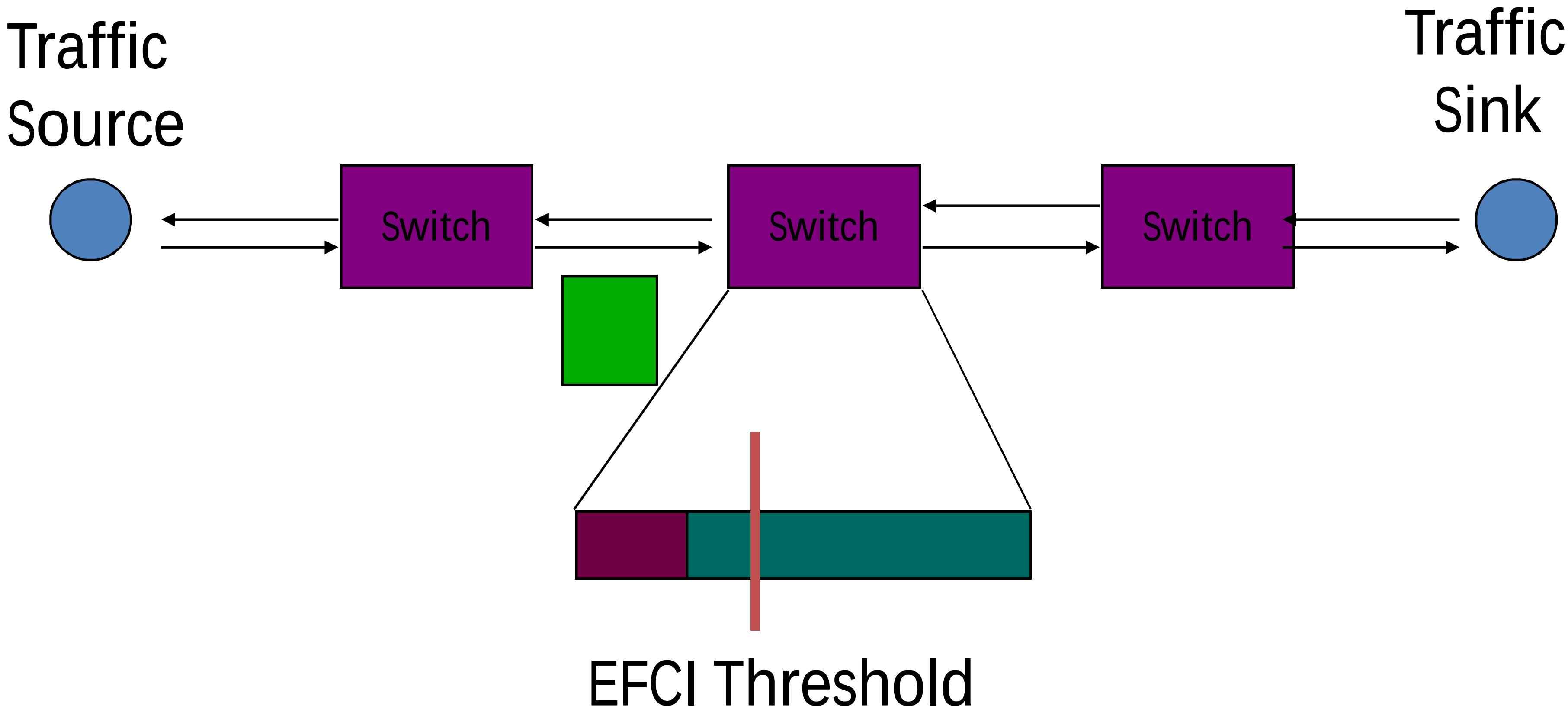
EFCI: Basic Operation (Cont'd)



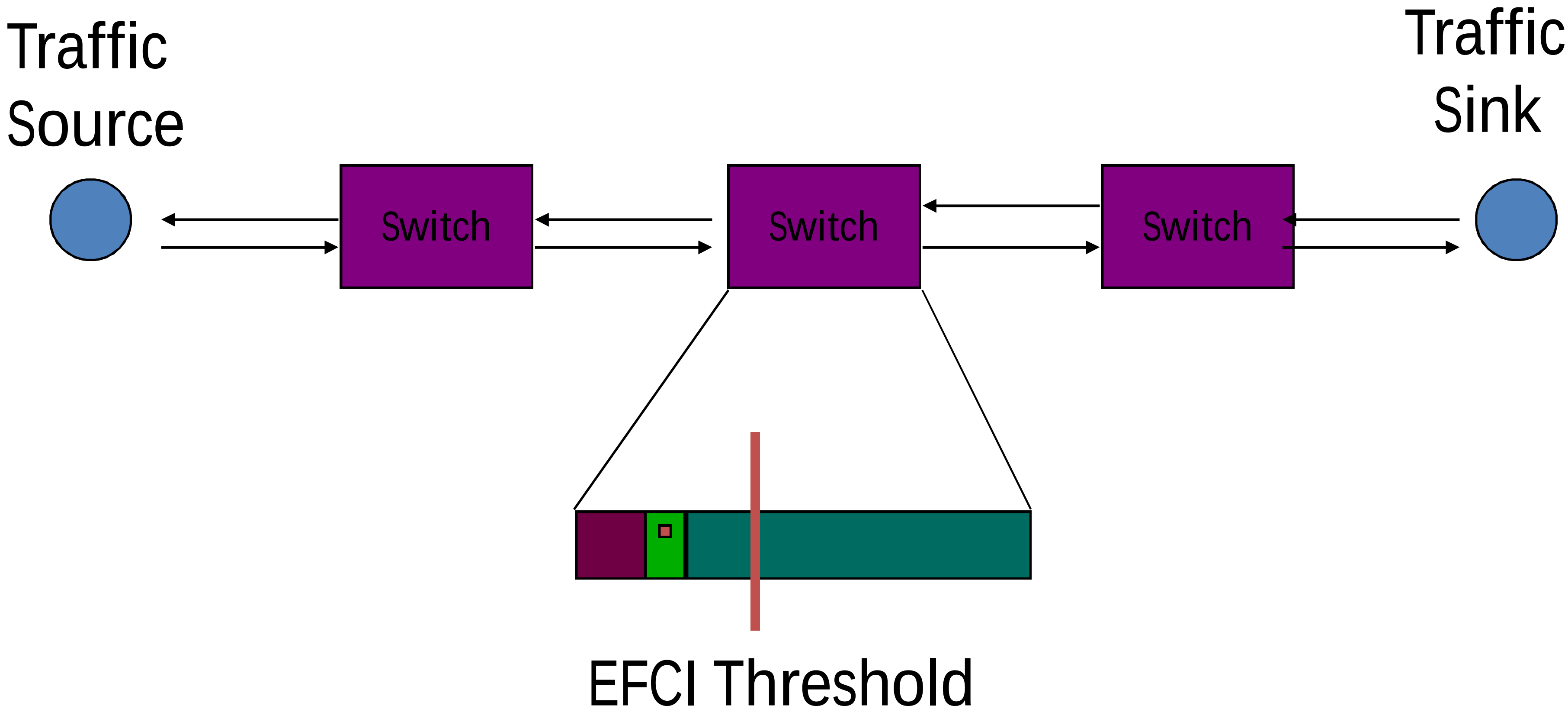
EFCI: Basic Operation (Cont'd)



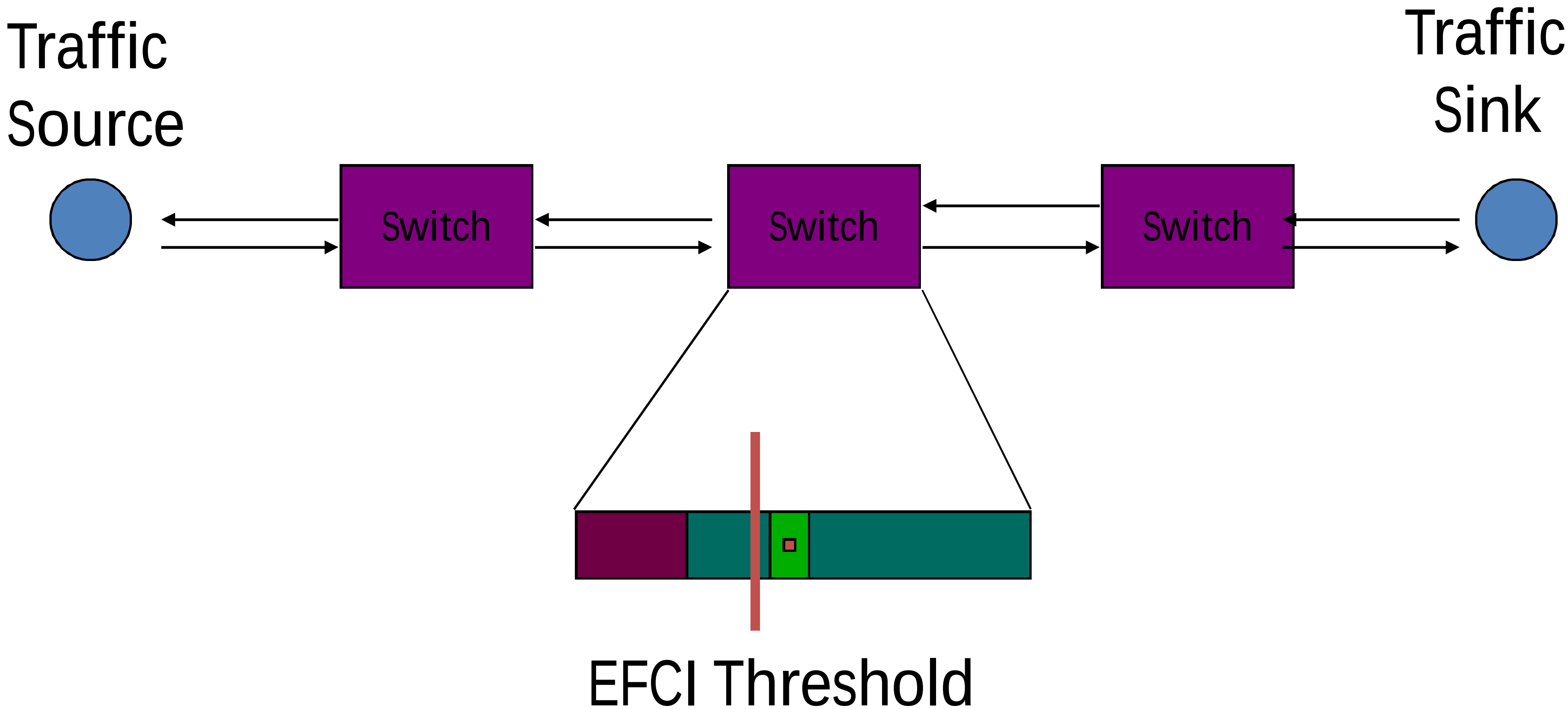
EFCI: Basic Operation (Cont'd)



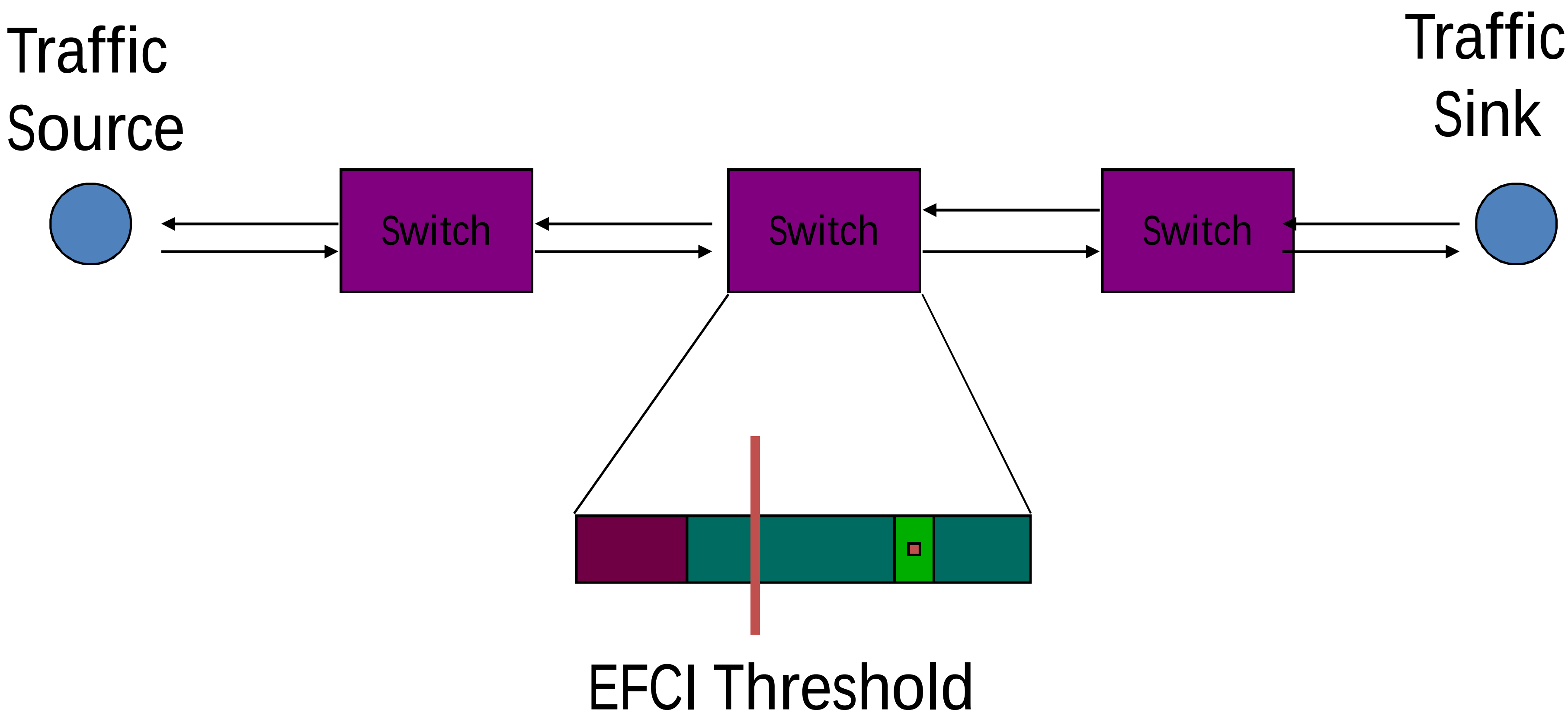
EFCI: Basic Operation (Cont'd)



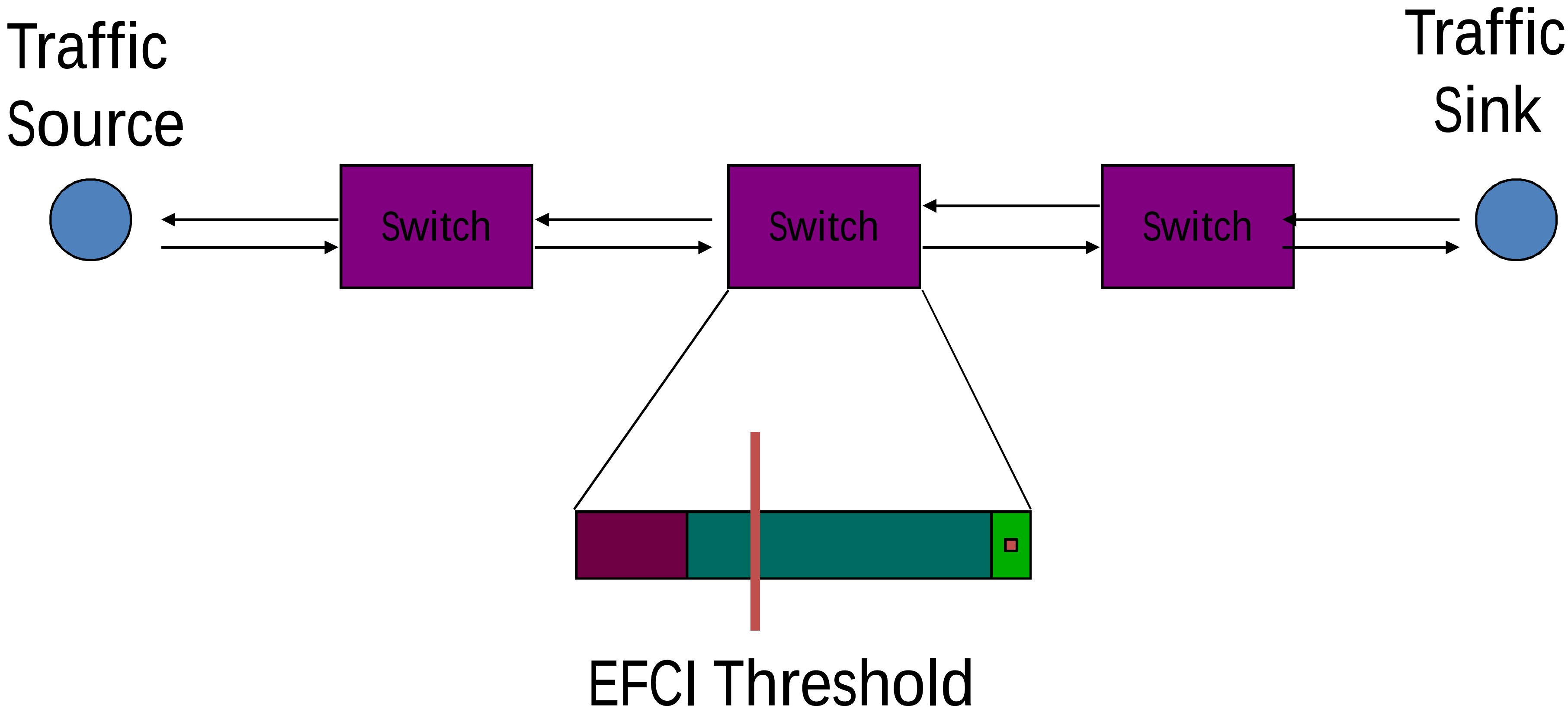
EFCI: Basic Operation (Cont’d)



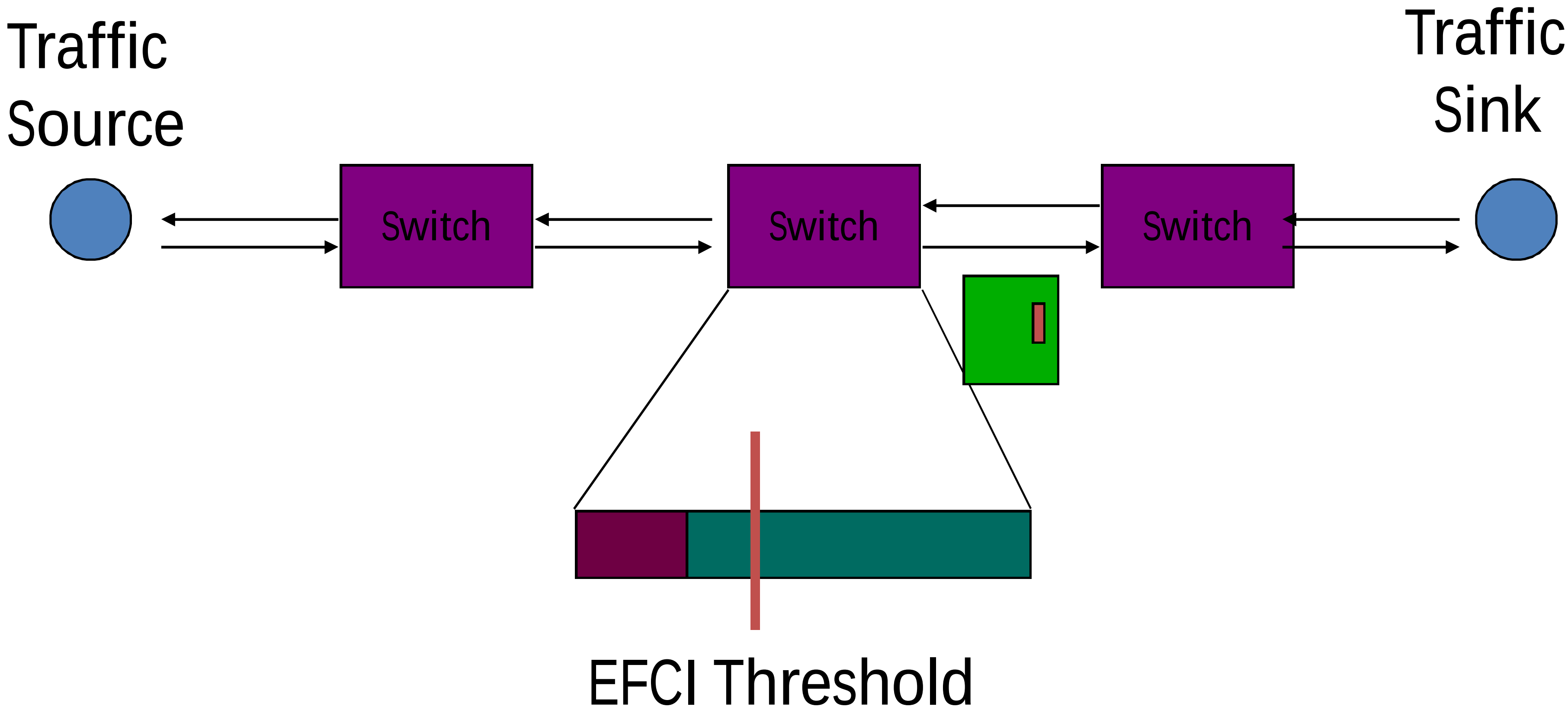
EFCI: Basic Operation (Cont'd)



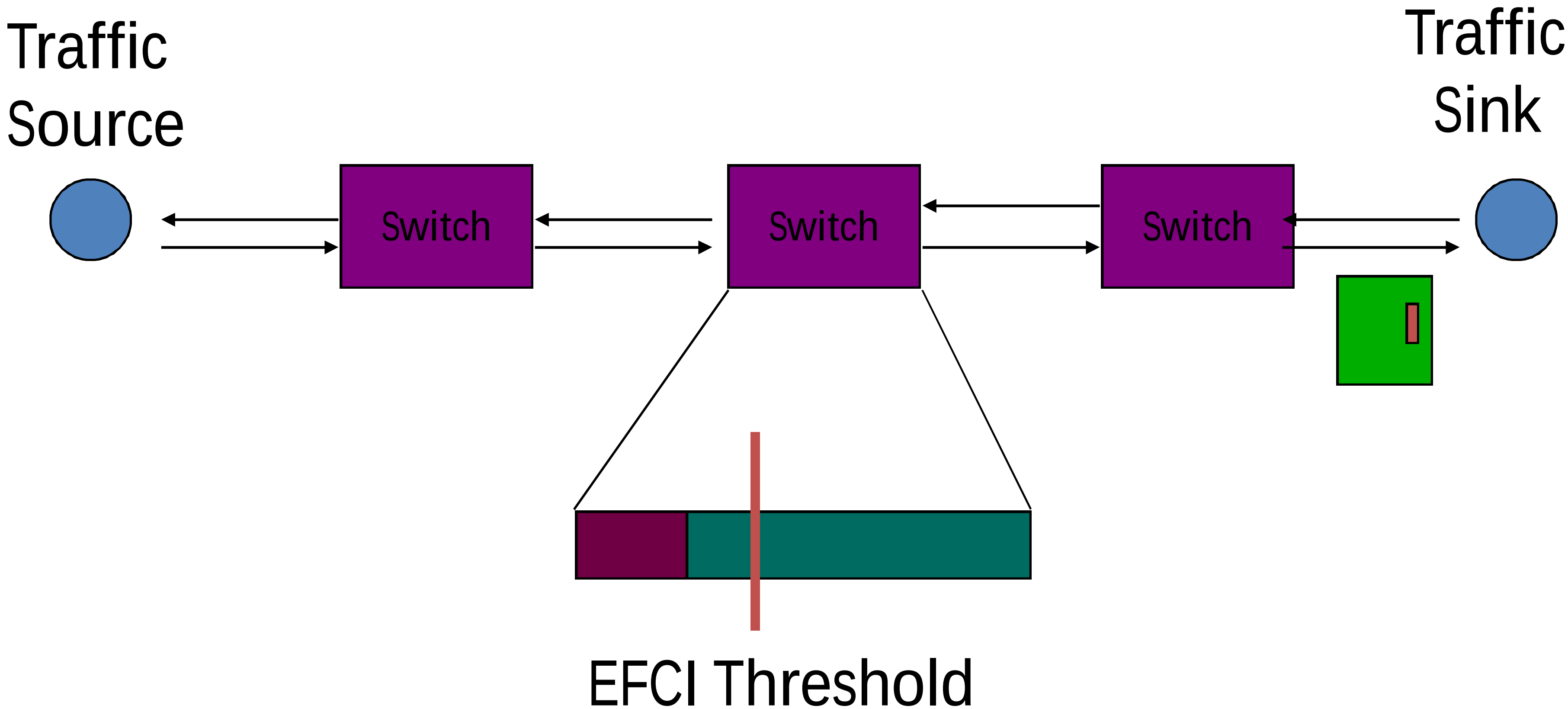
EFCI: Basic Operation (Cont'd)



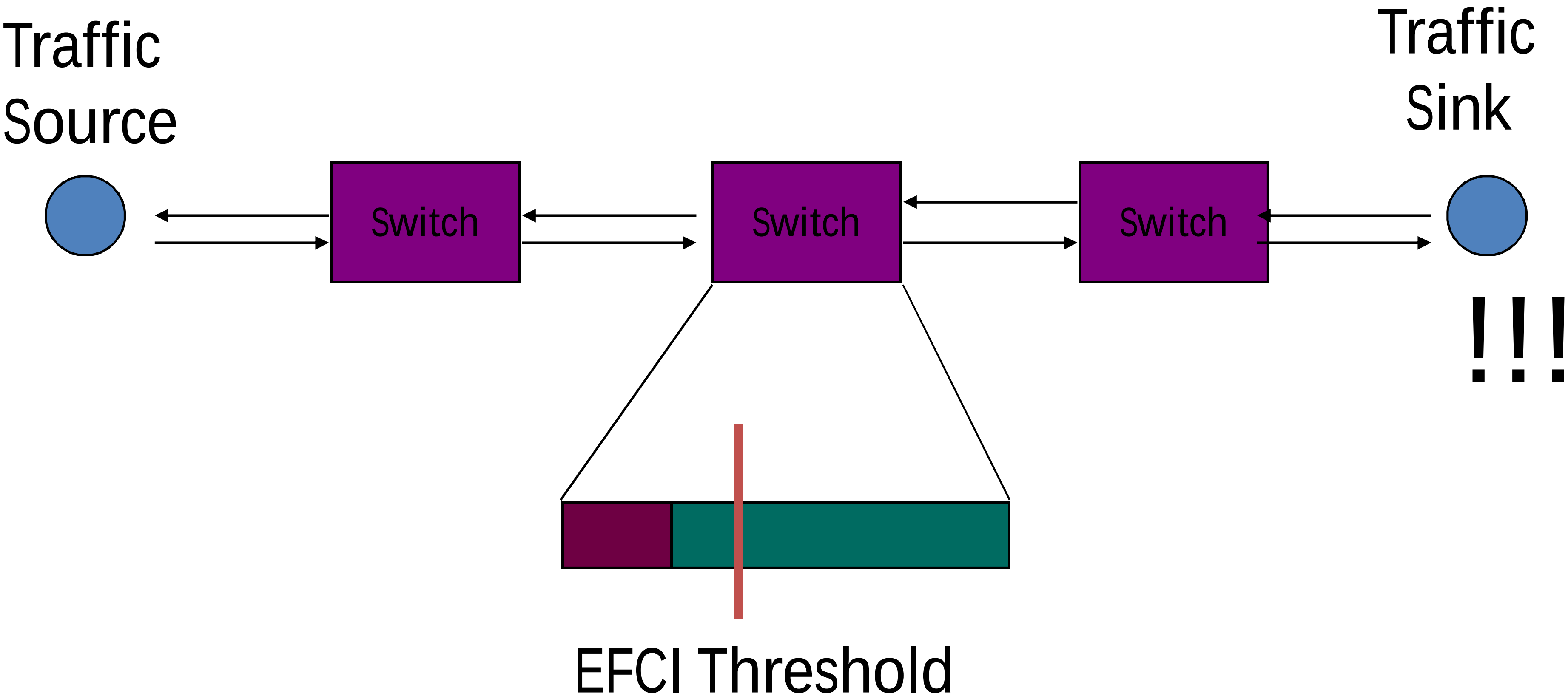
EFCI: Basic Operation (Cont'd)



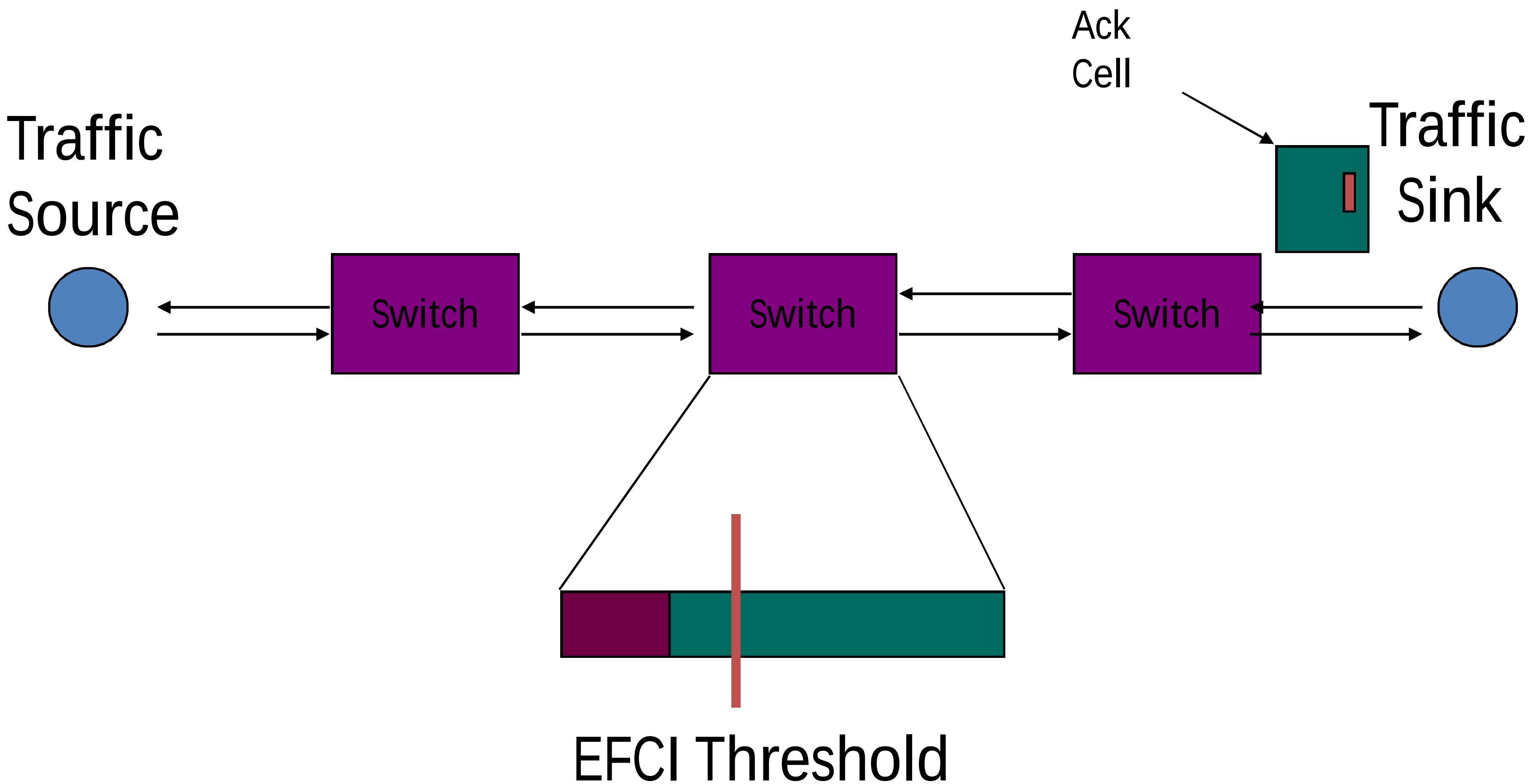
EFCI: Basic Operation (Cont’d)



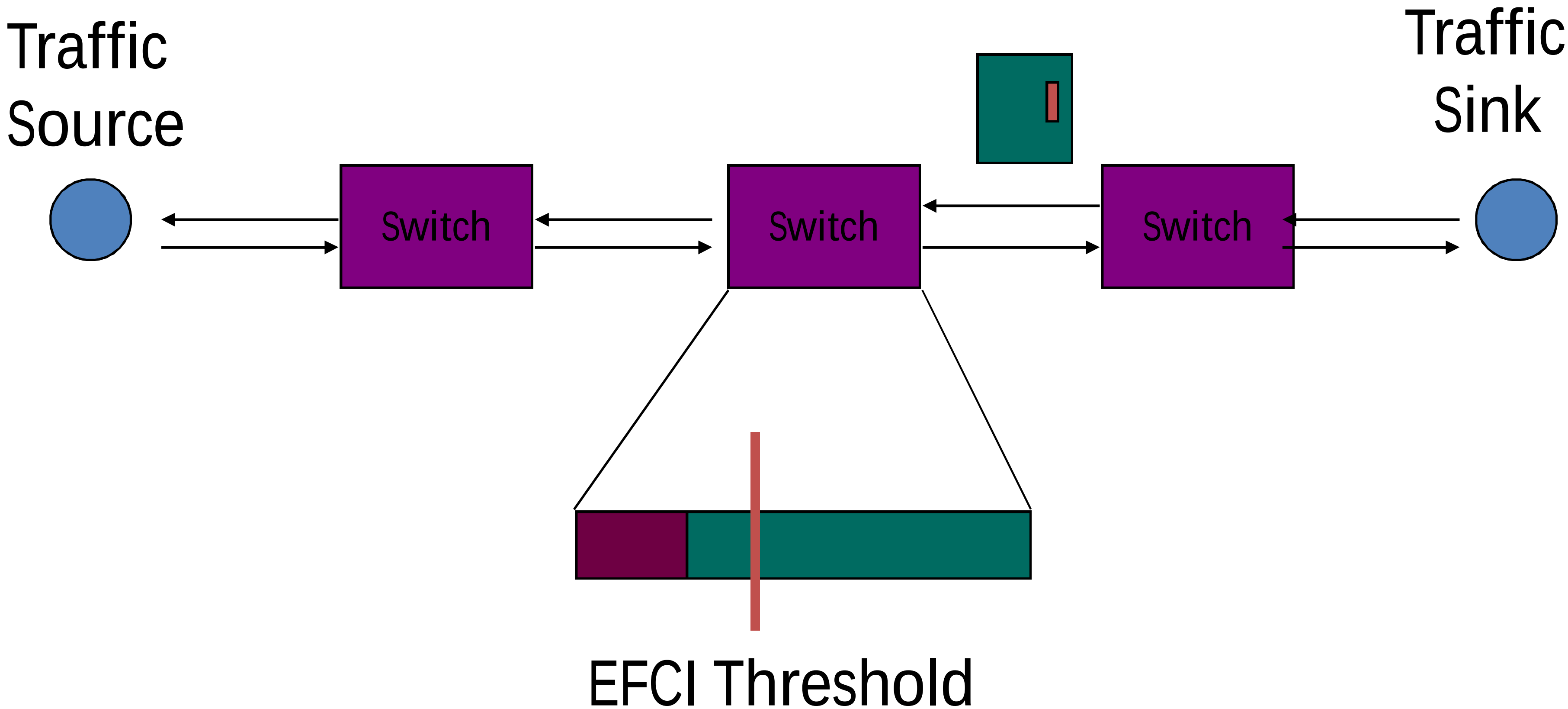
EFCI: Basic Operation (Cont'd)



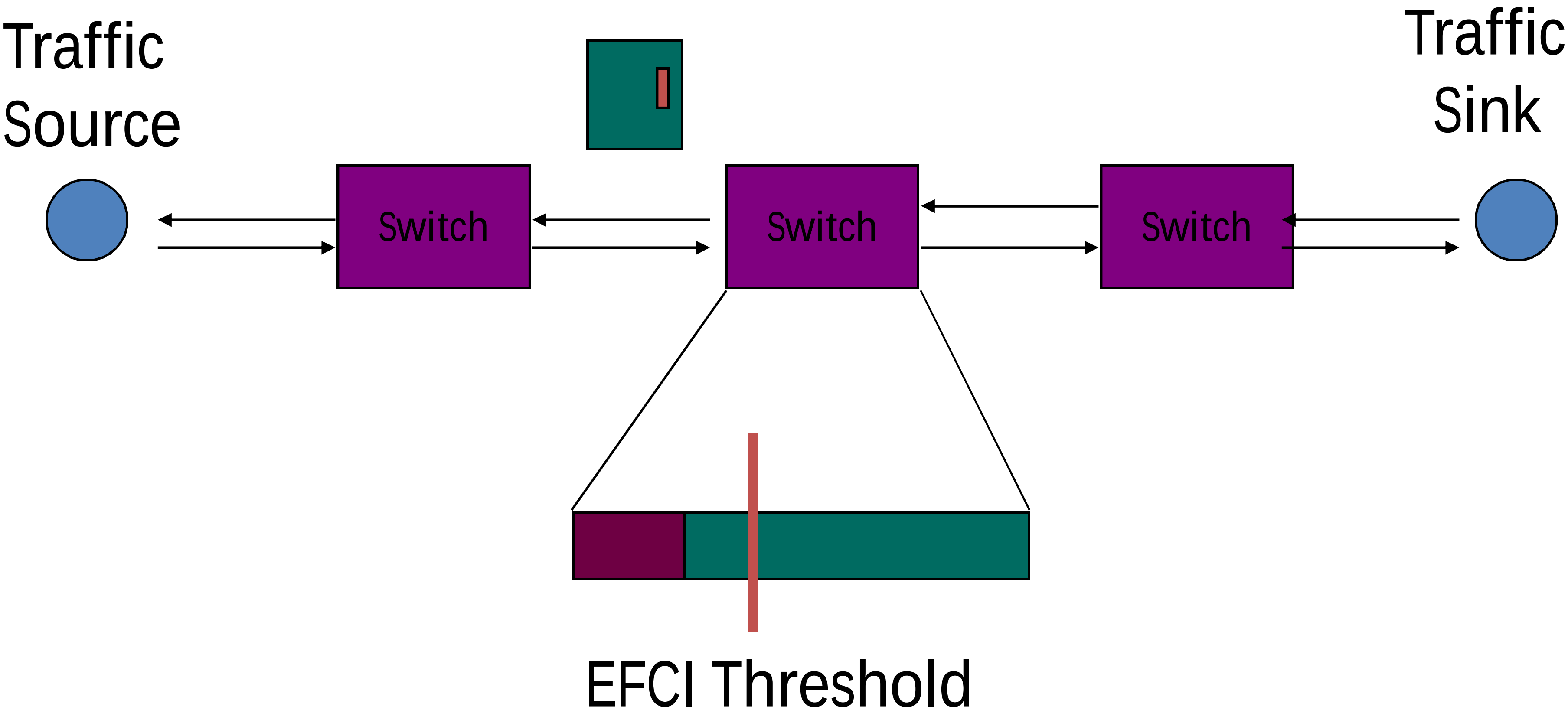
EFCI: Basic Operation (Cont'd)



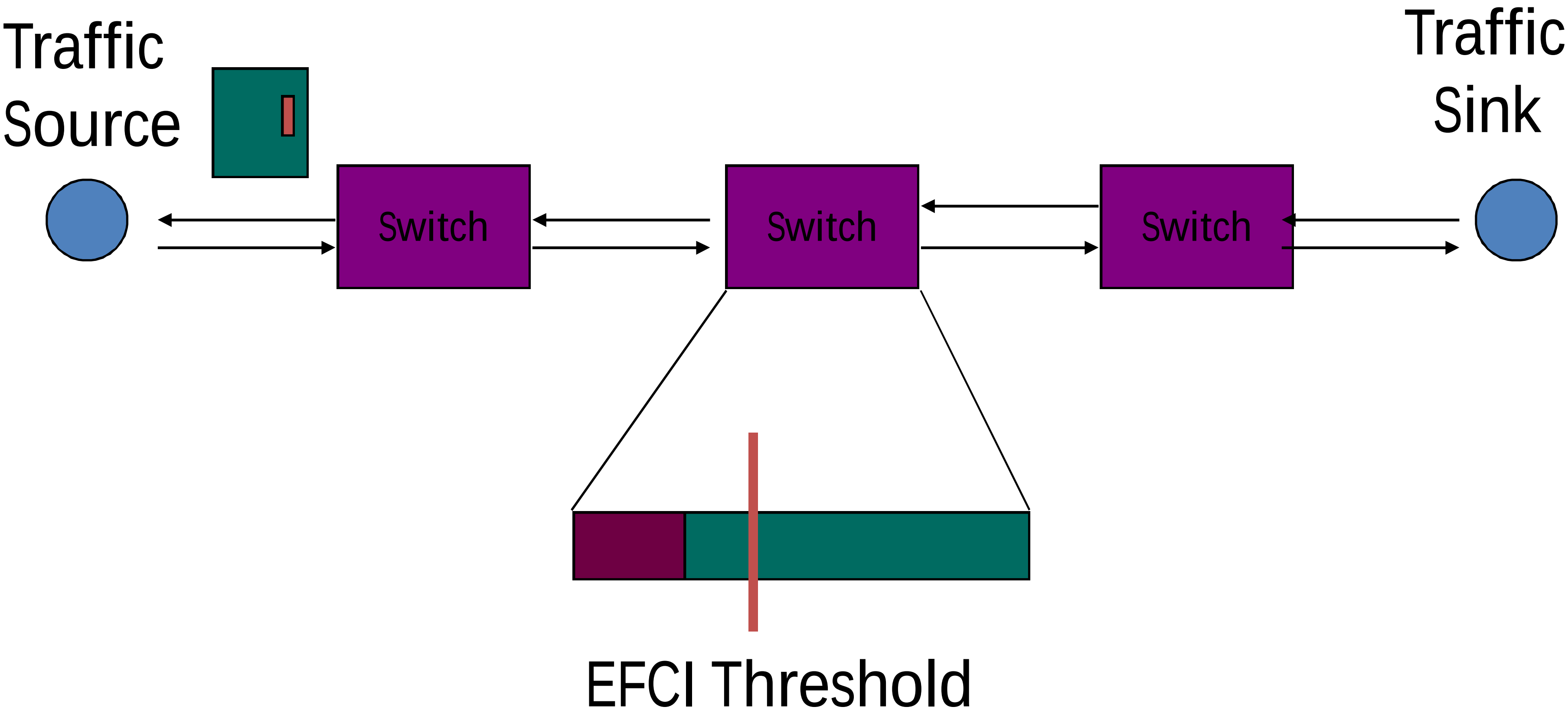
EFCI: Basic Operation (Cont'd)



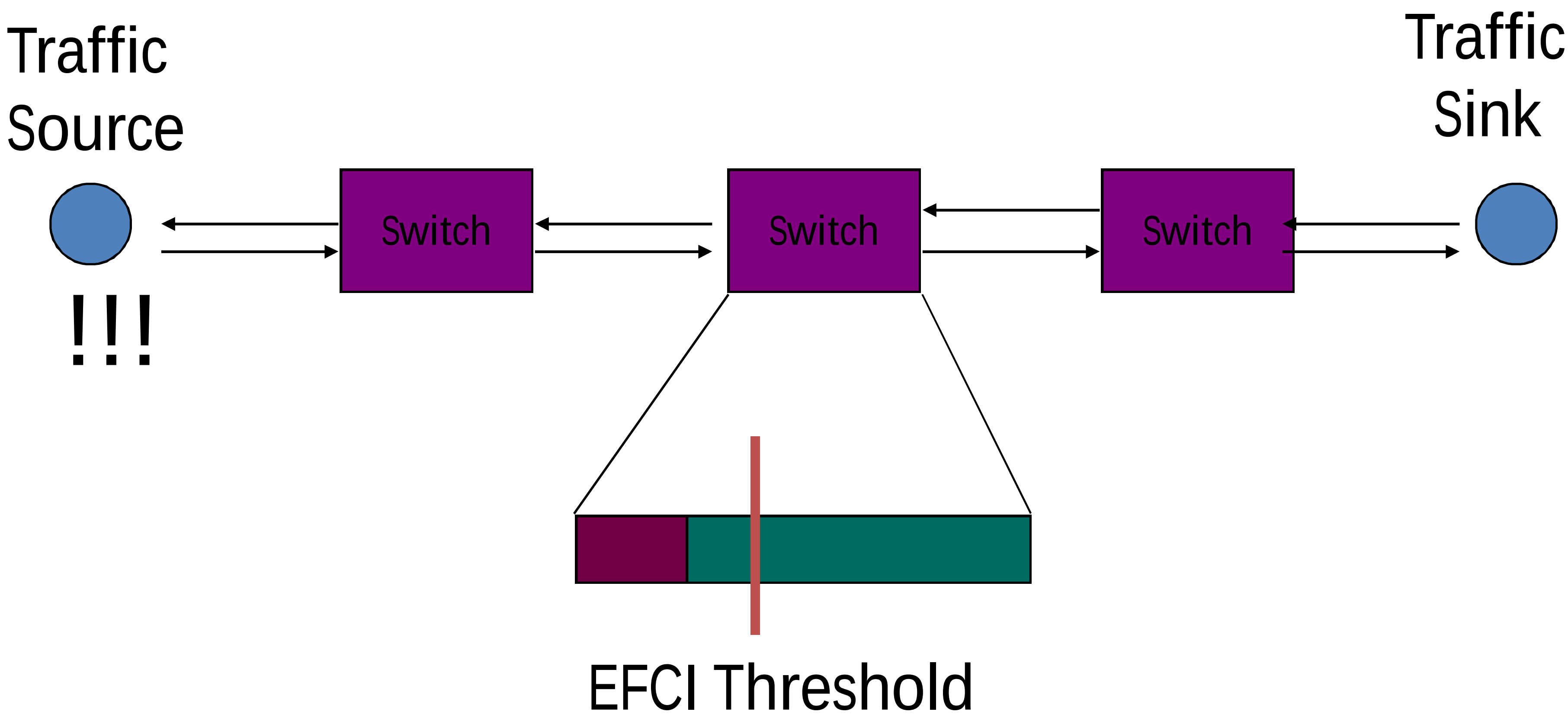
EFCI: Basic Operation (Cont'd)



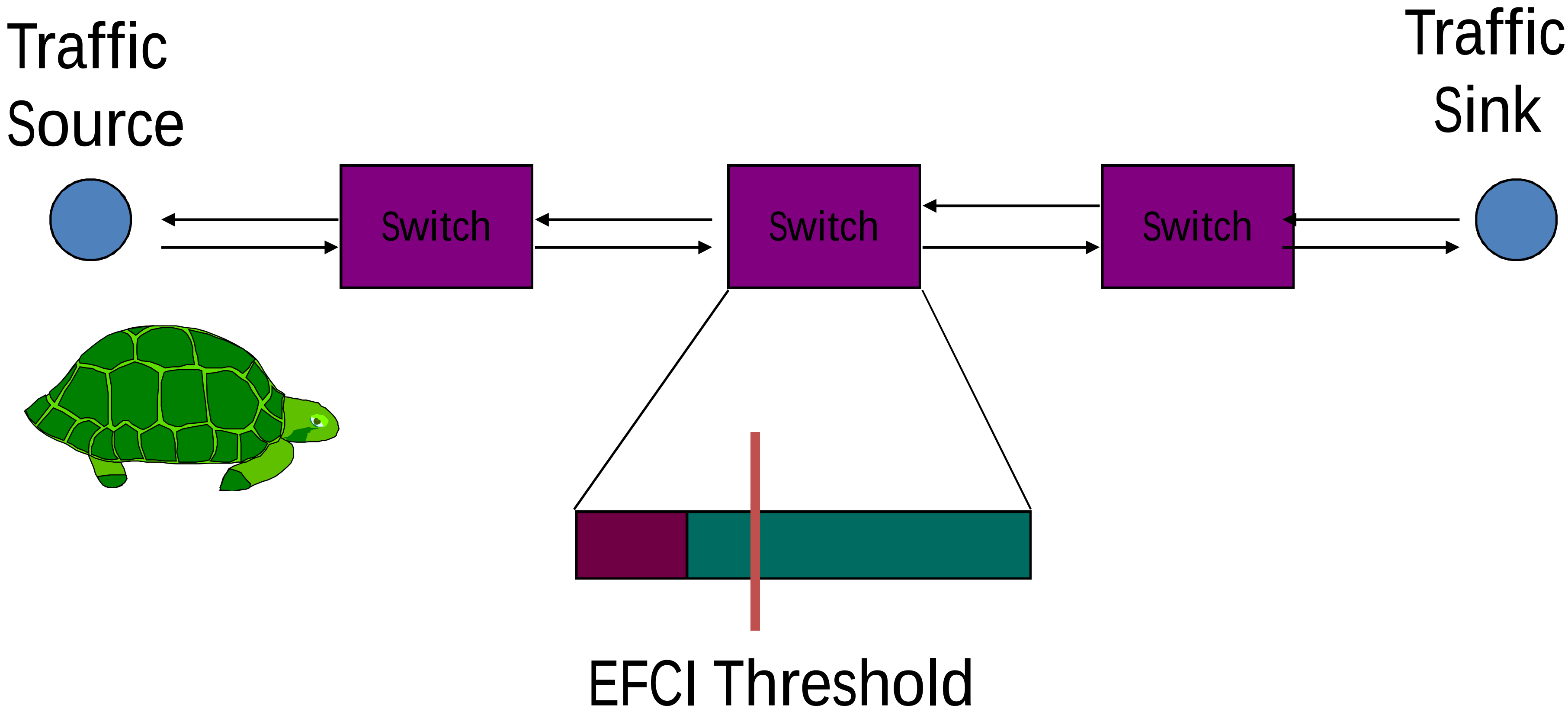
EFCI: Basic Operation (Cont'd)



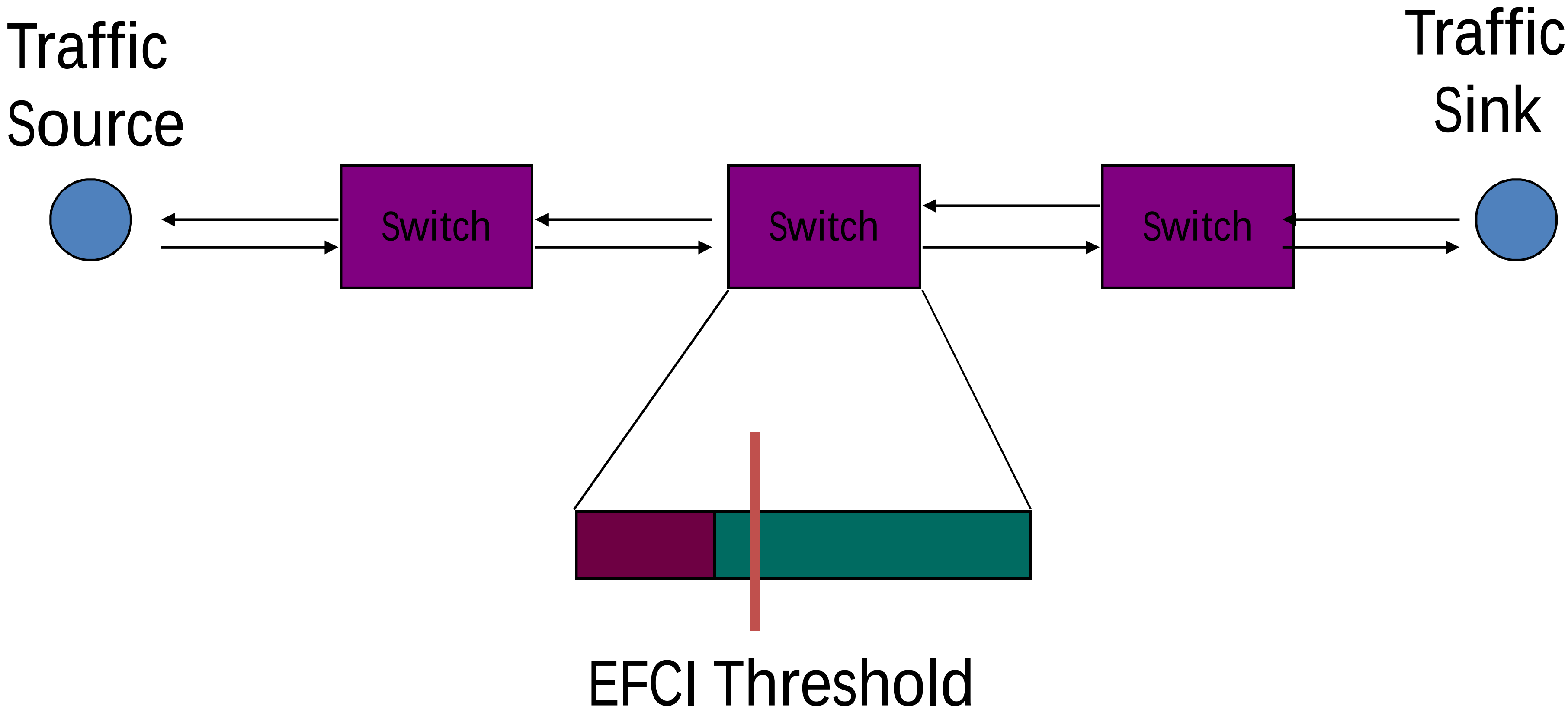
EFCI: Basic Operation (Cont'd)



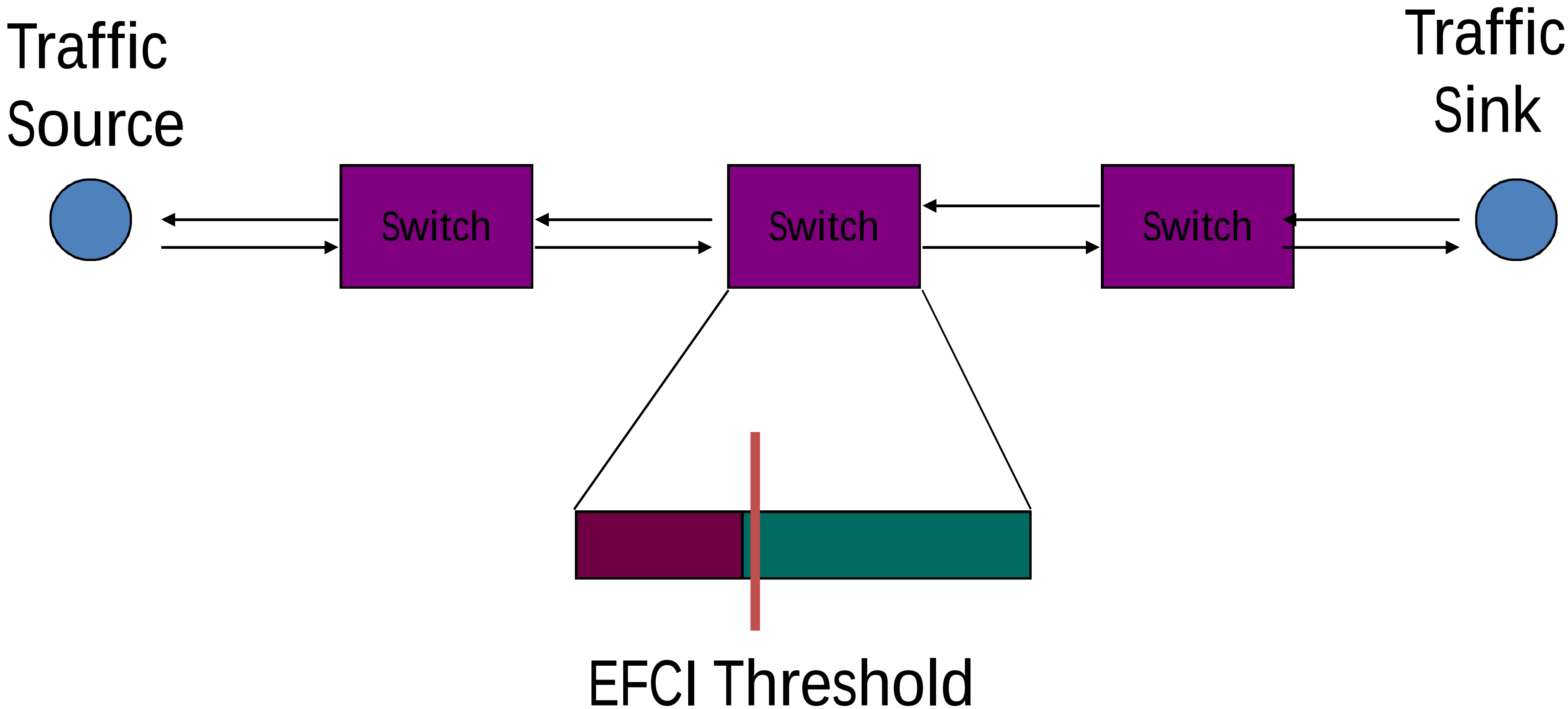
EFCI: Basic Operation (Cont'd)



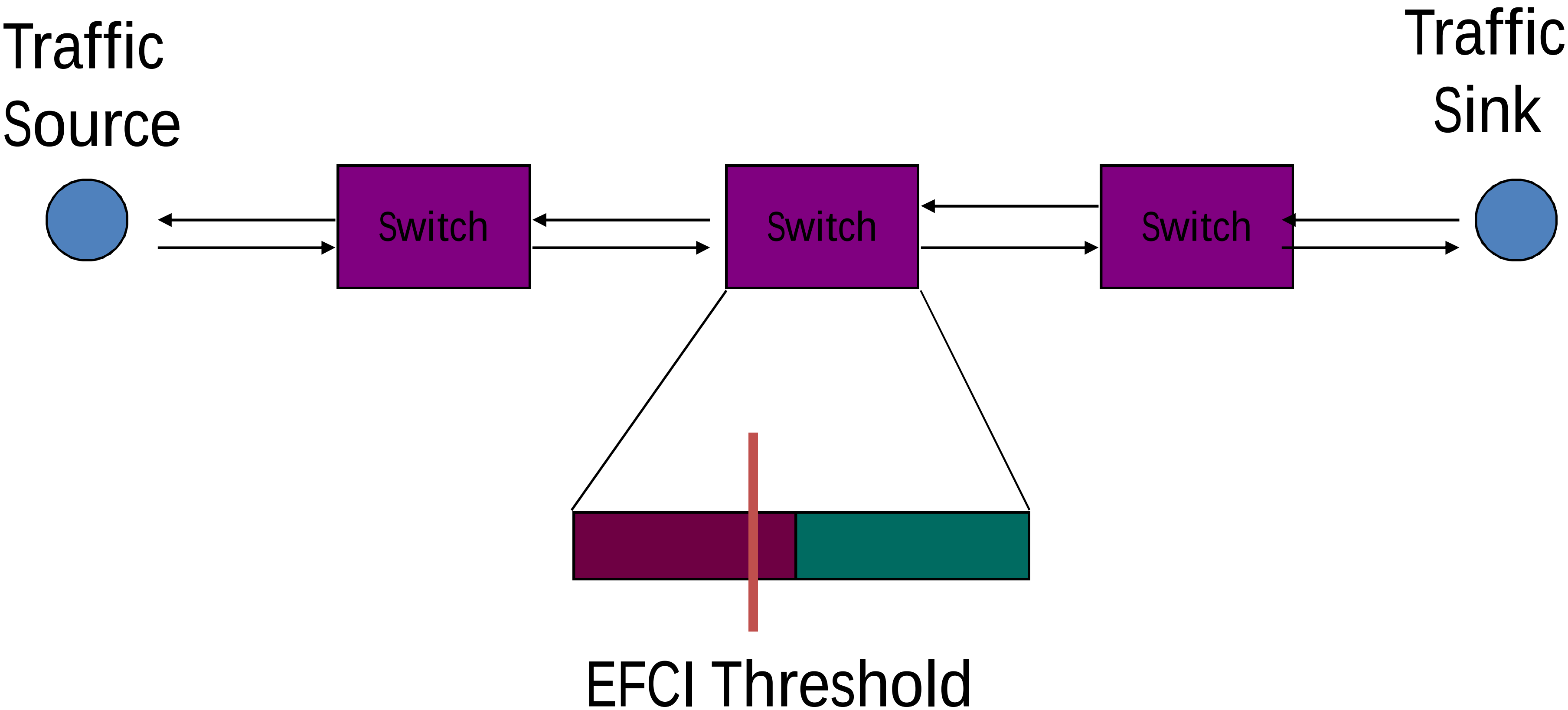
EFCI: Basic Operation (Cont'd)



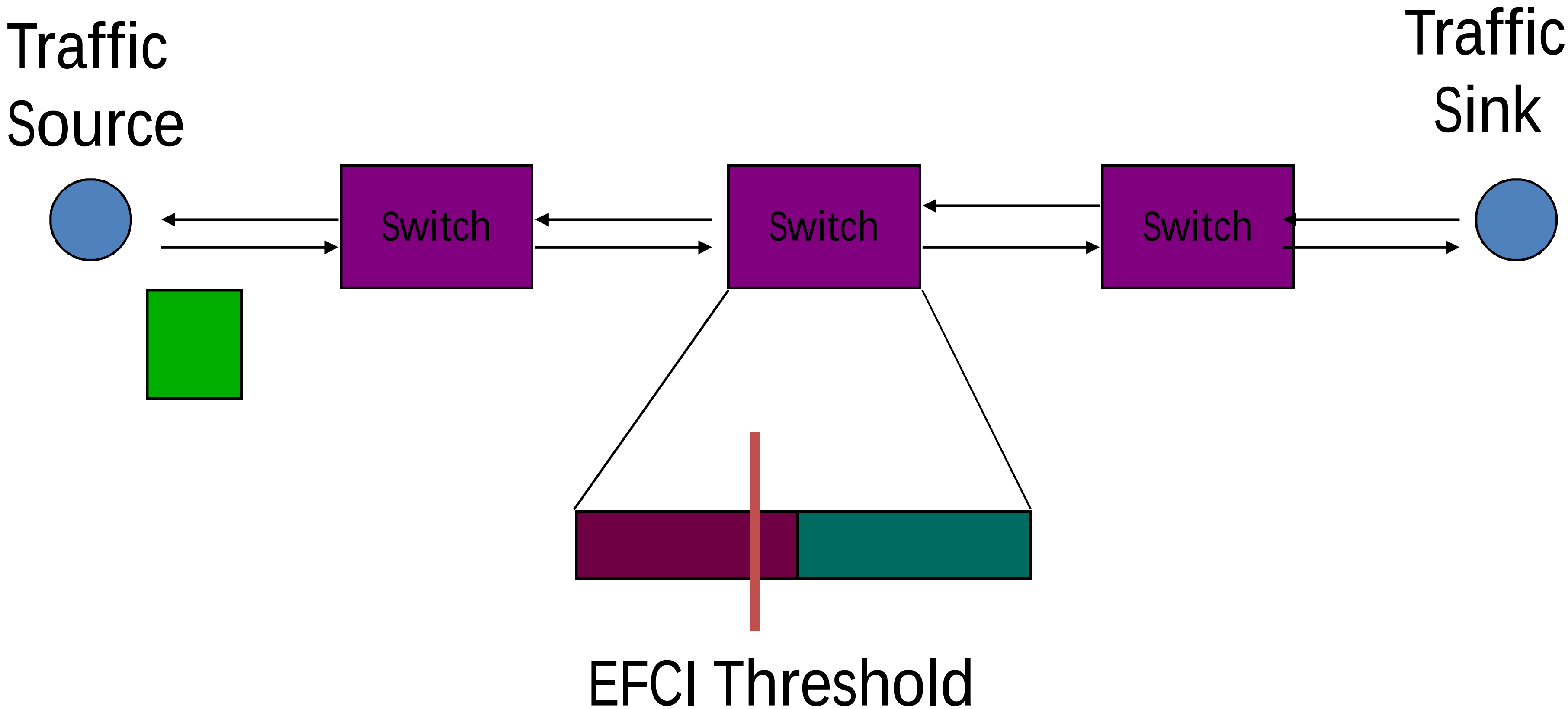
EFCI: Basic Operation (Cont'd)



EFCI: Basic Operation (Cont'd)



EFCI: Basic Operation (Cont'd)



UNIT V -NETWORK PERFORMANCE MODELING AND ESTIMATION

Queuing Analysis

- Elements of Waiting Line Analysis
- The Single-Server Waiting Line System
- Undefined and Constant Service Times
- Finite Queue Length
- Finite Calling Problem
- The Multiple-Server Waiting Line
- Additional Types of Queuing Systems

Queuing Analysis Overview

- Significant amount of time spent in waiting lines by people, products, etc.
- Providing quick service is an important aspect of quality customer service.
- The basis of waiting line analysis is the trade-off between the cost of improving service and the costs associated with making customers wait.
- Queuing analysis is a probabilistic form of analysis.
- The results are referred to as operating characteristics.
- Results are used by managers of queuing operations to

Queuing Analysis
Elements of Waiting Line Analysis

• Waiting lines form because people or things arrive at a service faster than they can be served.

• Most operations have sufficient server capacity to handle customers in the long run..

• Customers however, do not arrive at a constant rate nor are they served in an equal amount of time.

• Waiting lines are continually increasing and decreasing in length.and approach an average rate of customer arrivals and an average service time, in the long run.

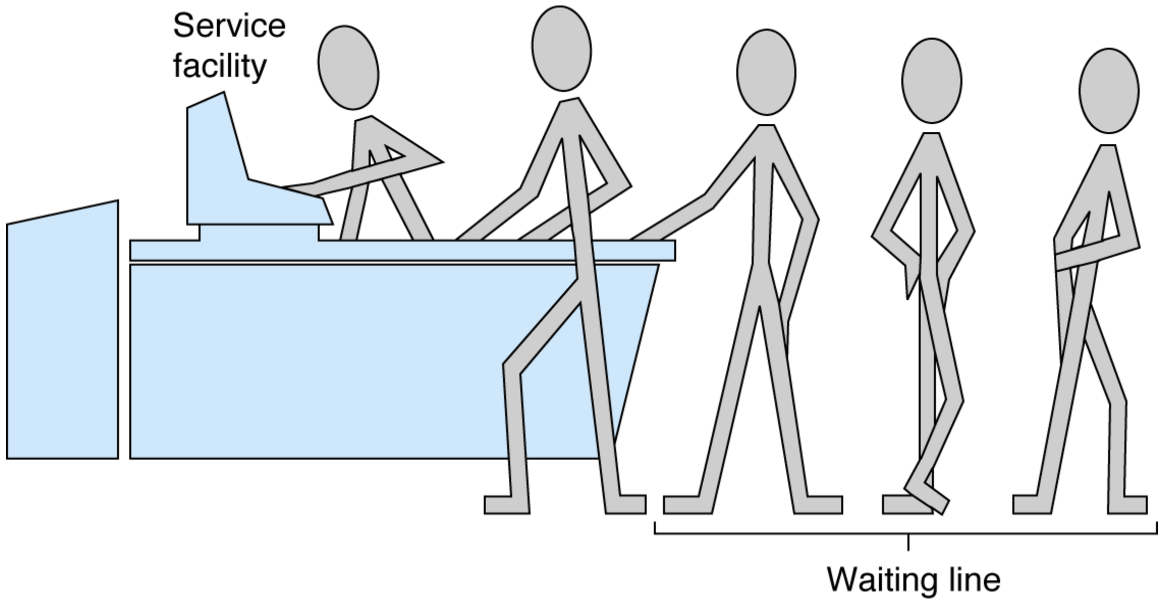
• Decisions concerning the management of waiting lines are based on these averages for customer arrivals and service times.

• They are used in formulas to compute operating characteristics of the system which in turn form the basis of decision making.

Queuing Analysis
The Single-Server Waiting Line System

- Components of a waiting line system include *arrivals* (customers), *servers*, (cash register/operator), customers in line form a *waiting line.*

The Fast Shop Market queuing system



Factors to consider in analysis:

1. The queue discipline.
2. The nature of the calling population
3. The arrival rate
4. The service rate.

The Single-Server Waiting Line System

- The *queue discipline:*

  The order in which waiting customers are served.

- The *calling population:*

  The source of customers (infinite or finite).

- *The arrival rate:*

  The frequency at which customers arrive at a waiting line according to a probability distribution (frequently described by a Poisson distribution).

- The *service rate:*

  The average number of customers that can be served during a time period (often described by the negative exponential distribution).

The Single-Server Waiting Line System-
The Single-Server Model

- Assumptions of the basic single-server model:

    1. An infinite calling population

    2. A first-come, first-served queue discipline

    3. Poisson arrival rate

    4. Exponential service times

- Symbology:

    λ = the arrival rate (average number of arrivals per time period)

    μ = the service rate (average number served per time period)

- Customers must be served faster than they arrive ($\lambda < \mu$) or an infinitely large queue will build up.

The Single-Server Waiting Line System
Basic Single-Server Queuing Formulas

Probability that no customers are in the queuing system: $P_o = \left(1 - \frac{\lambda}{\mu}\right)$

Probability that n customers are in the system: $P_n = \left(\frac{\lambda}{\mu}\right)^n \cdot P_o = \left(\frac{\lambda}{\mu}\right)^n \left(1 - \frac{\lambda}{\mu}\right)$

Average number of customers in system: $L = \frac{\lambda}{\mu - \lambda}$ and waiting line: $L_q = \frac{\lambda^2}{\mu(\mu - \lambda)}$

Average time customer spends waiting and being served: $W = \frac{1}{\mu - \lambda} = \frac{L}{\lambda}$

Average time customer spends waiting in the queue: $W_q = \frac{\lambda}{\mu(\mu - \lambda)}$

Probability that server is busy (utilization factor): $U = \frac{\lambda}{\mu}$

Probability that server is idle: $I = 1 - U = 1 - \frac{\lambda}{\mu}$

The Single-Server Waiting Line System Steady-State Operating Characteristics

Because of steady -state nature of operating characteristics:

- Utilization factor, U, must be less than one: $U<1$,or $\lambda / \mu < 1$ and $\lambda < \mu$.

- The ratio of the arrival rate to the service rate must be less than one

or, the service rate must be greater than the arrival rate. The server must be able to serve customers faster than the arrival rate in the long run, or waiting line will grow to infinite size.

The Single-Server Waiting Line System
Effect of Operating Characteristics on Managerial Decisions
(1 of 3)

- Manager wishes to test several alternatives for reducing customer waiting time:

  1. Addition of another employee to pack up purchases

  2. Addition of another checkout counter.

- Alternative 1: Addition of an employee (raises service rate from $\mu = 30$ to $\mu = 40$ customers per hour)

  Cost $150 per week, avoids loss of $75 per week for each minute of reduced customer waiting time.

  System operating characteristics with new parameters:

  $P_o = .40$ probability of no customers in the system

  $L = 1.5$ customers on the average in the queuing system

  $L_q = 0.90$ customer on the average in the waiting line

  $W = 0.063$ hour (3.75 minutes) average time in the system per customer

  $W_q = 0.038$ hour (2.25 minutes) average time in the waiting line per customer

  $U = .60$ probability that server is busy and customer must wait, .40 probability server available

  Average customer waiting time reduxed from 8 to 2.25 minutes worth $431.25 per week.

  Net savings = $431.25 - 150 = $281.25 per week.

The Single-Server Waiting Line System
Effect of Operating Characteristics on Managerial Decisions
(2 of 3)

- Alternative 2: Addition of a new checkout counter ($6,000 plus $200 per week for additional cashier)

λ =24/2 = 12 customers per hour per checkout counter.

μ = 30 customers per hour at each counter

System operating cartelistic with new parameters:

P_o = .60 probability of no customers in the system

L = 0.67 customer in the queuing system

L_q = 0.27 customer in the waiting line

W = 0.055 hour (3.33 minutes) per customer in the system

W_q = 0.022 hour (1.33 minutes) per customer in the waiting line

U = .40 probability that a customer must wait

I = .60 probability that server is idle and customer can be served.

Savings from reduced waiting time worth $500 per week - $200 = $300 net savings per week.

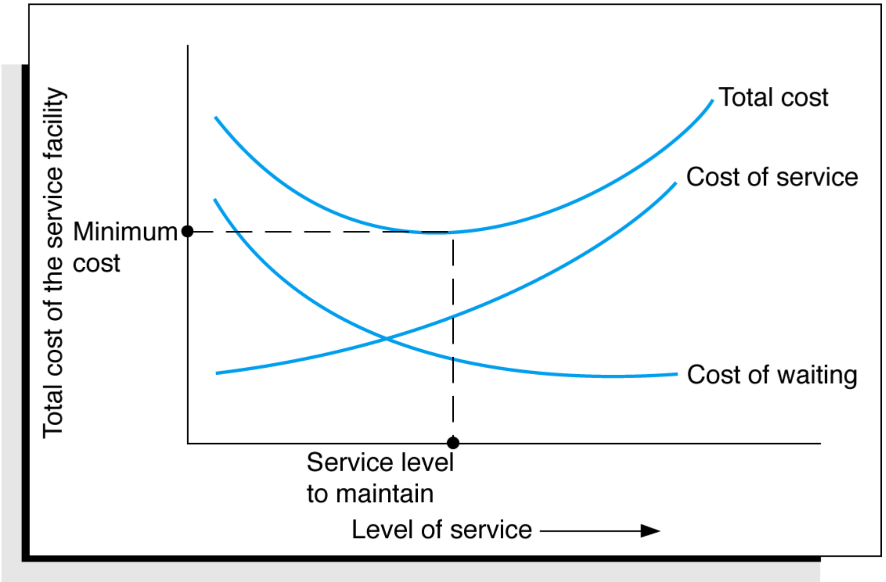
After $6,000 recovered, alternative 2 would provide $300 -281.25 = $18.75 more savings per week.

The Single-Server Waiting Line System
Effect of Operating Characteristics on Managerial Decisions (3 of 3)

Operating Characteristics	Present System	Alternative I	Alternative II
L	4.00 customers	1.50 customers	0.67 customer
L_q	3.20 customers	0.90 customer	0.27 customer
W	10.00 min	3.75 min	3.33 min
W_q	8.00 min	2.25 min	1.33 min
U	.80	.60	.40

Operating Characteristics for Each Alternative System

Cost trade-offs for service levels



The Single-Server Waiting Line System
Computer Solution of Single-Server Model with QM for Windows

Cost analysis
- (•) No costs
- ( ) Use Costs

Time unit (arrival, service rate): hours

Instruction
There are more results available in additional windows. These may be opened by using the WINDOW option in the Main Menu.

Waiting Lines Results

Fast Shop Market Example Solution

Parameter	Value	Parameter	Value	Minutes	Seconds
M/M/1 (exponential service		Average server utilization	0.8		
Arrival rate(lambda)	24.	Average number in the queue(Lq)	3.2		
Service rate(mu)	30.	Average number in the system(Ls)	4.		
Number of servers	1.	Average time in the queue(Wq)	0.1333	8.	480.
		Average time in the system(Ws)	0.1667	10.	600.

Finite Queue Length

- In a finite queue, the length of the queue is limited.

- Operating characteristics, where M is the maximum number in the system:

$$P0 = \frac{1 - \lambda / \mu}{1 - (\lambda / \mu)^{M+1}}$$

$$Pn = (P0)\left(\frac{\lambda}{\mu}\right)^{n} \text{ for n} \leq \text{M}$$

$$L = \frac{\lambda / \mu}{1 - \lambda / \mu} - \frac{(M+1)(\lambda / \mu)^{M+1}}{1 - (\lambda / \mu)^{M+1}}$$

$$Lq = L - \frac{\lambda(1 - PM)}{\mu}$$

$$W = \frac{L}{\lambda(1 - PM)}$$

$$Wq = W - \frac{1}{\mu}$$

Finite Queue Length Example (1of 2)

- Metro Quick Lube single bay service; space for one vehicle in service and three waiting for service; mean time between arrivals of customers is 3 minutes; mean service time is 2 minutes; both inter-arrival times and service times are exponentially distributed; maximum number of vehicles in the system equals 4.

- Operating characteristics for $\lambda = 20$, $\mu = 30$, $M = 4$:

$$P_o = \frac{1-\lambda/\mu}{1-(\lambda/\mu)^{M+1}} = \frac{1-20/30}{1-(20/30)^5} = .38 \text{ probability of no cars in the system}$$

$$P_M = (P_0)\left(\frac{\lambda}{\mu}\right)^{n=M} = (.38)\left(\frac{20}{30}\right)^4 = .076 \text{ probability that system is full and customer must drive on}$$

Finite Queue Length Example (2 of 2)

- Average queue lengths and waiting times:

$$L = \frac{\lambda/\mu}{1-\lambda/\mu} - \frac{(M+1)(\lambda/\mu)^{M+1}}{1-(\lambda/\mu)^{M+1}}$$

$$L = \frac{20/30}{1-20/30} - \frac{(5)(20/30)^5}{1-(20/30)^5} = 1.24 \text{ cars in the system}$$

$$L_q = L - \frac{\lambda(1-P_M)}{\mu} = 1.24 - \frac{20(1-.076)}{30} = 0.62 \text{ cars waiting}$$

$$W = \frac{L}{\lambda(1-P_M)} = \frac{1.24}{20(1-.076)} = 0.067 \text{ hours or } 4.03 \text{ minutes waiting in the system}$$

$$W_q = W - \frac{1}{\mu} = 0.067 - \frac{1}{30} = 0.033 \text{ hour or } 2.03 \text{ minutes waiting in line}$$

Finite Calling Population

- In a finite calling population there is a limited number of potential customers that can call on the system.

- Operating characteristics for system with Poisson arrival and exponential service times:

$$P_o = \frac{1}{\sum_{n=0}^{N} \frac{N!}{(N-n)!}\left(\frac{\lambda}{\mu}\right)^n} \text{ where N = population size, and n = 1, 2,...N}$$

$$P_n = \frac{N!}{(N-n)!}\left(\frac{\lambda}{\mu}\right)^n P_o$$

$$L_q = N - \left(\frac{\lambda - \mu}{\lambda}\right)(1 - P_o)$$

$$L = L_q + (1 - P_0)$$

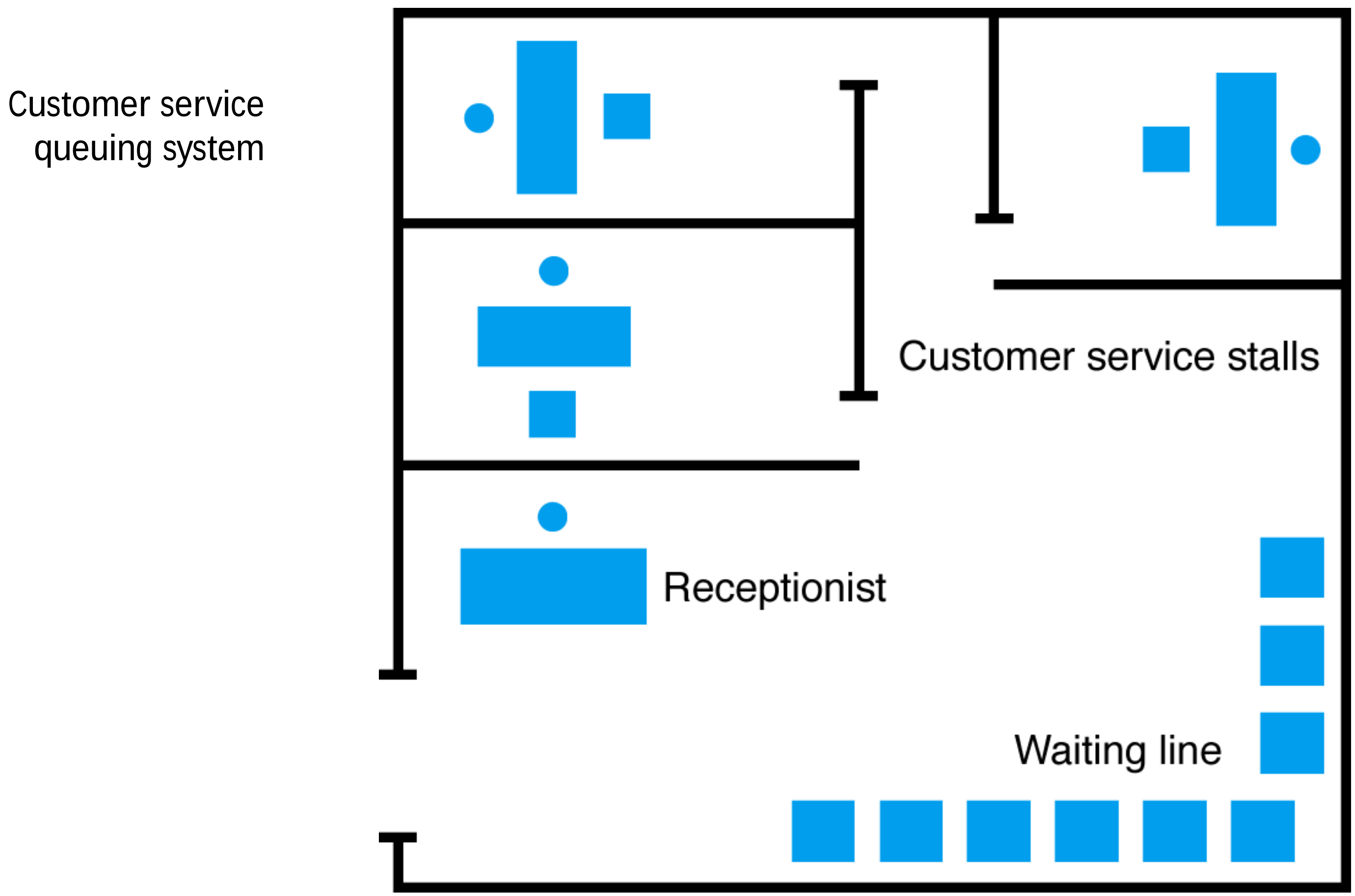
$$W_q = \frac{L_q}{(N - L)\lambda}$$

$$W = W_q + \frac{1}{\mu}$$

The Multiple-Server Waiting Line

- In multiple-server models, two or more independent servers in parallel serve a single waiting line.

- Biggs Department Store service department; first-come, first-served basis.



The Multiple-Server Waiting Line
Queuing Formulas
(1 of 2)

-Assumptions:

First-come first-served queue discipline

Poisson arrivals, exponential service times

Infinite calling population.

- Parameter definitions:

λ = arrival rate (average number of arrivals per time period)

μ = the service rate (average number served per time period) per server (channel)

c = number of servers

c μ = mean effective service rate for the system (must exceed arrival rate)

The Multiple-Server Waiting Line Queuing Formulas (2 of 2)

$$Po = \frac{1}{\left[\sum_{n=0}^{n=c-1} \frac{1}{n!}\left(\frac{\lambda}{\mu}\right)^n\right] + \frac{1}{c!}\left(\frac{\lambda}{\mu}\right)^c \left(\frac{c\mu}{c\mu-\lambda}\right)} = \text{probability no customers in system}$$

$$Pn = \frac{1}{c!c^{n-c}}\left(\frac{\lambda}{\mu}\right)^n Po \text{ for n > c;} \quad Pn = \frac{1}{n}\left(\frac{\lambda}{\mu}\right)^n Po \text{ for n < c} = \text{probability of n customers in system}$$

$$L = \frac{\lambda\mu(\lambda/\mu)^c}{(c-1)!(c\mu-\lambda)^2} Po + \frac{\lambda}{\mu} \mu = \text{average number of customers in the system}$$

$$W = \frac{L}{\lambda} = \text{average time customer spends in the system}$$

$$Lq = L - \frac{\lambda}{\mu} = \text{average number of customers in the queue}$$

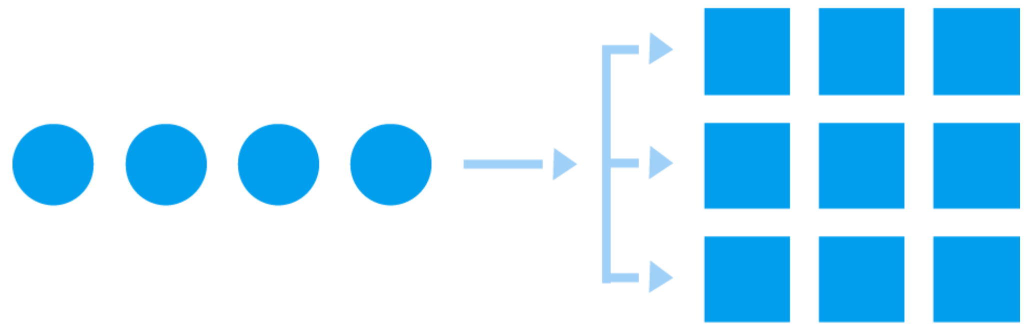
$$Wq = W - \frac{1}{\mu} = \frac{Lq}{\lambda} = \text{average time customer is in the queue}$$

$$Pw = \frac{1}{c!}\left(\frac{\lambda}{\mu}\right)^c \frac{c\mu}{c\mu-\lambda} Po = \text{probability customer must wait for service}$$

Additional Types of Queuing Systems

Single queues with single and multiple servers in sequence

Single queue with single servers in sequence



Single queue with multiple servers in sequence

Other items contributing to queuing systems:

- Systems in which customers *balk* from entering system, or leave the line (*renege*
- Servers who provide service in other than first-come, first-served manner
- Service times that are not exponentially distributed or are undefined or constant
- Arrival rates that are not Poisson distributed.
- *Jockeying*, i.e., moving between queues.

Queuing analysis-Queuing System Concepts

Arrival Rate, Occupancy, Time in the System

- Queuing system
  - Data network where packets arrive, wait in various queues, receive service at various points, and exit after some time
- Arrival rate
  - Long-term number of arrivals per unit time
- Occupancy
  - Number of packets in the system (averaged over a long time)
- Time in the system (delay)
  - Time from packet entry to exit (averaged over many packets)

Stability and Steady-State

- A single queue system is stable if

  packet arrival rate < system transmission capacity

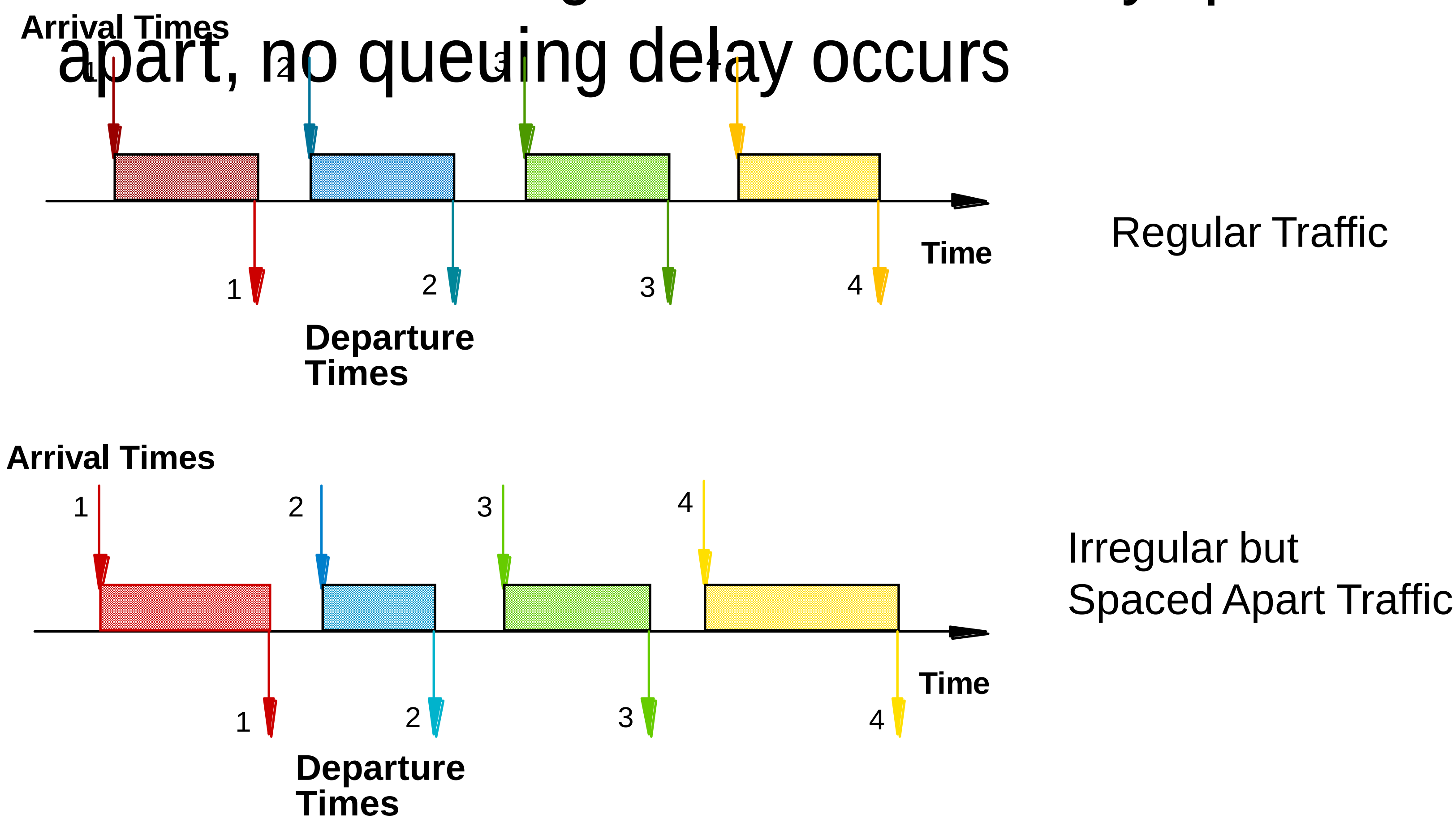
- For a single queue, the ratio

  packet arrival rate / system transmission capacity

  is called the utilization factor
  - Describes the loading of a queue
- In an unstable system packets accumulate in various queues and/or get dropped
- For unstable systems with large buffers some packet delays become very large
  - Flow/admission control may be used to limit the packet arrival rate
  - Prioritization of flows keeps delays bounded for the important traffic

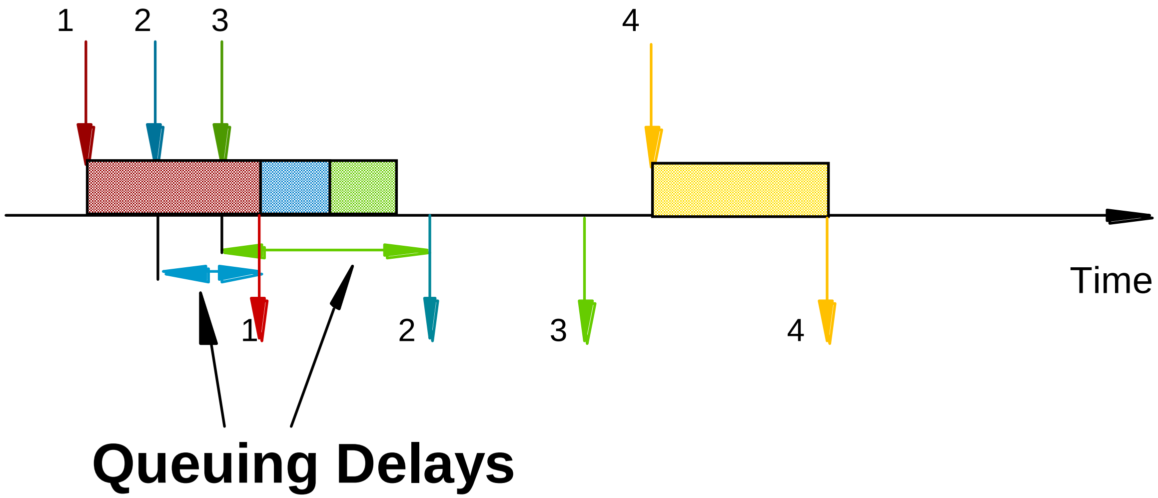
Delay is Caused by Packet Interference

- If arrivals are regular or sufficiently spaced apart, no queuing delay occurs



Burstiness Causes Interference

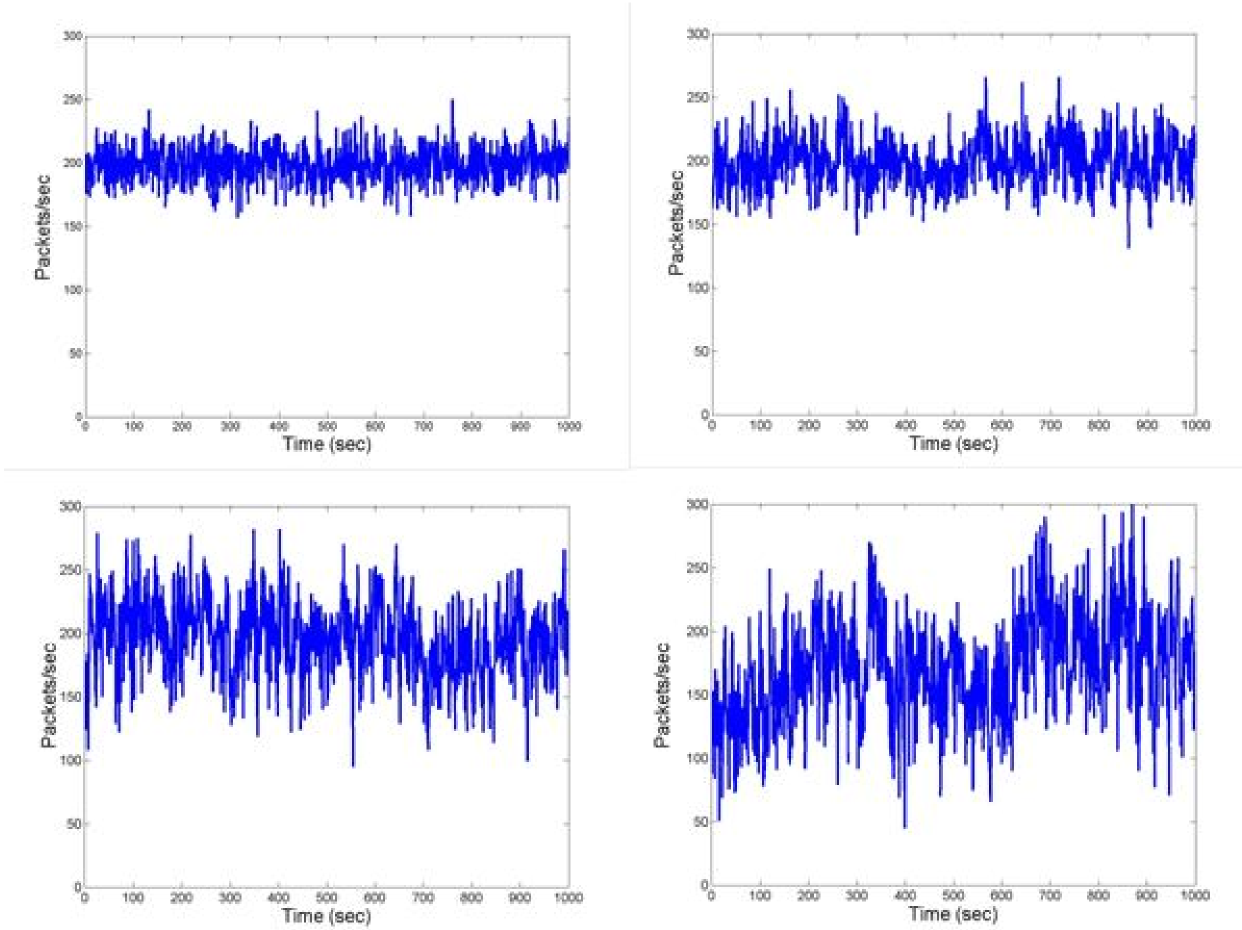
- Note that the departures are less bursty



Bursty Traffic

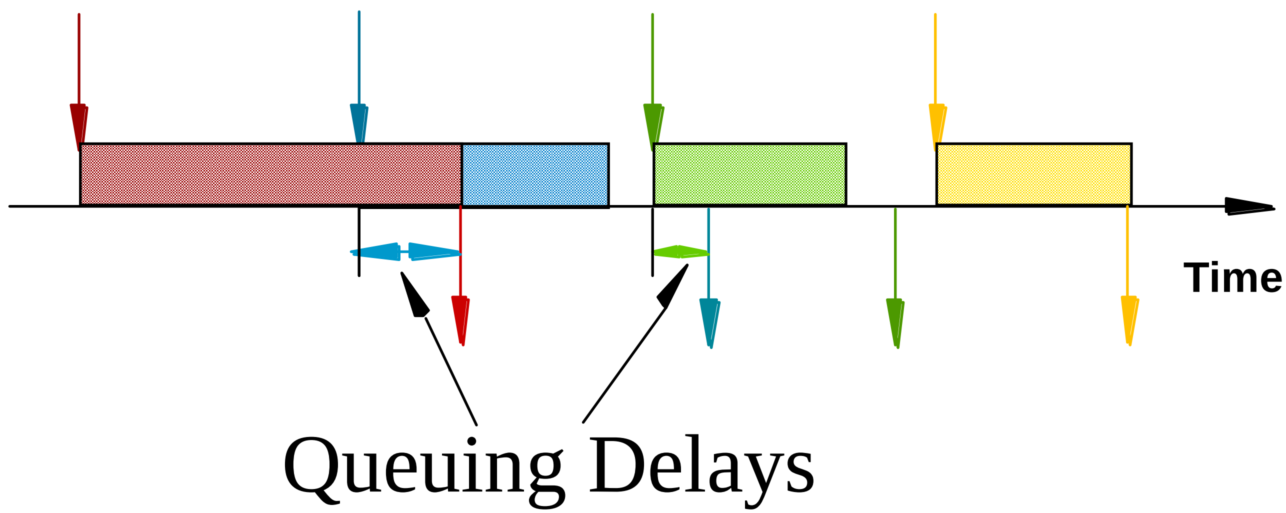
Burstiness Example

Different Burstiness Levels at Same Packet Rate



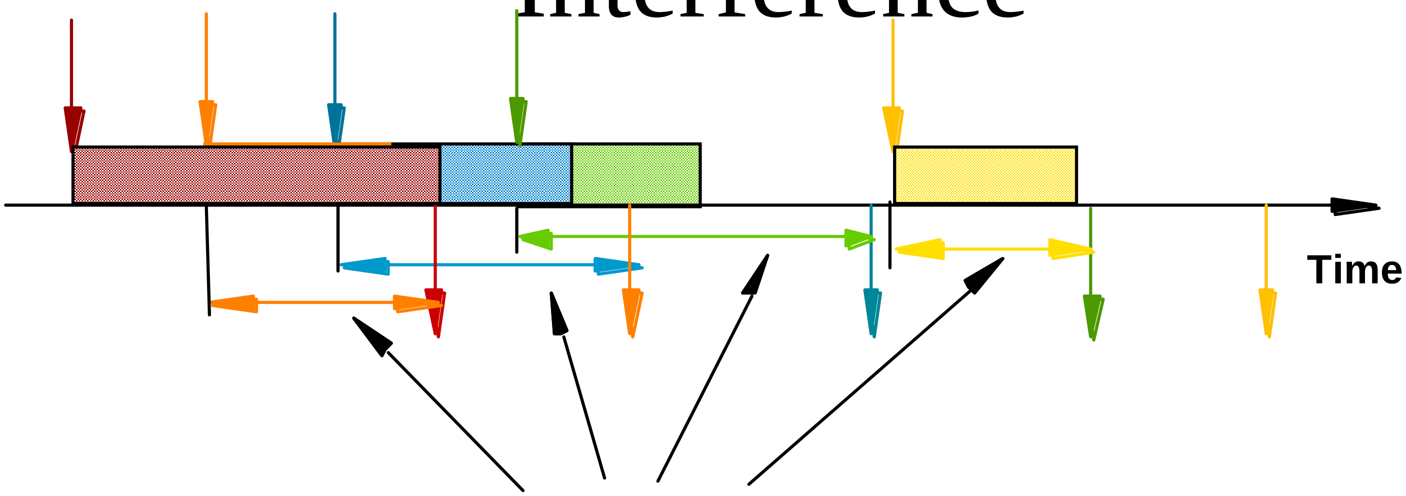
Source: Fei Xue and S. J. Ben Yoo, UCDavis, "**On the Generation and Shaping Self-similar Traffic in Optical Packet-switched Networks", OPNETWORK 2002**

Packet Length Variation Causes Interference



Regular arrivals, irregular packet lengths

High Utilization Exacerbates Interference



Queuing Delays

As the work arrival rate:

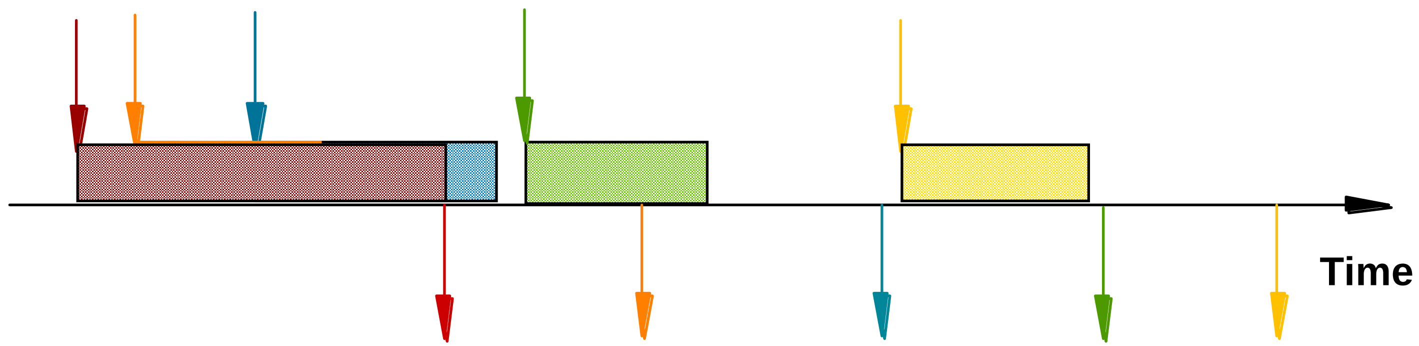
(packet arrival rate * packet length)

increases, the opportunity for interference increases

Bottlenecks

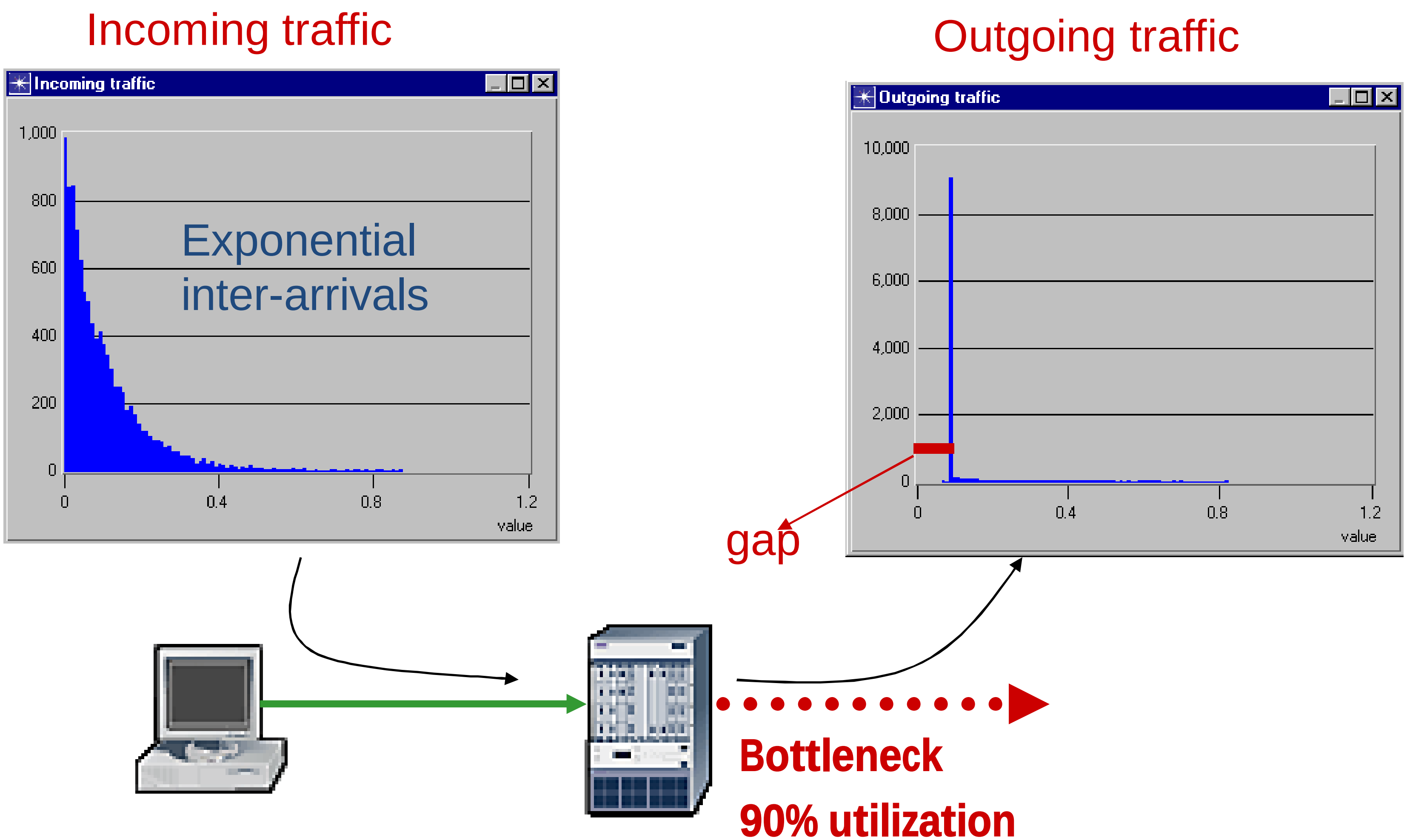
- Types of bottlenecks
  - At access points (flow control, prioritization, QoS enforcement needed)
  - At points within the network core
  - Isolated (can be analyzed in isolation)
  - Interrelated (network or chain analysis needed)
- Bottlenecks result from overloads caused by:
  - High load sessions, or
  - Convergence of sufficient number of moderate load sessions at the same queue

Bottlenecks Cause Shaping

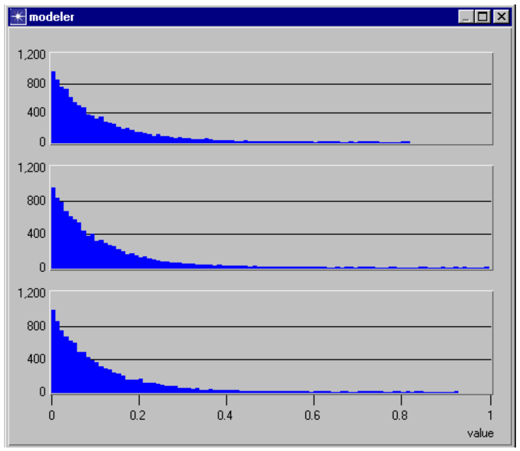


- The departure traffic from a bottleneck is more regular than the arrival traffic
- The inter-departure time between two packets is at least as large as the transmission time of the 2nd packet

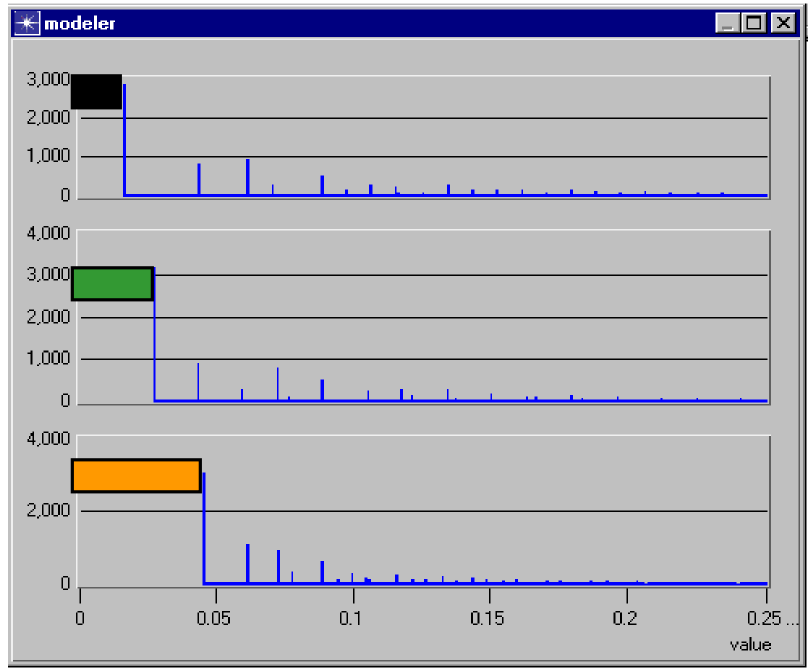
Bottlenecks Cause Shaping

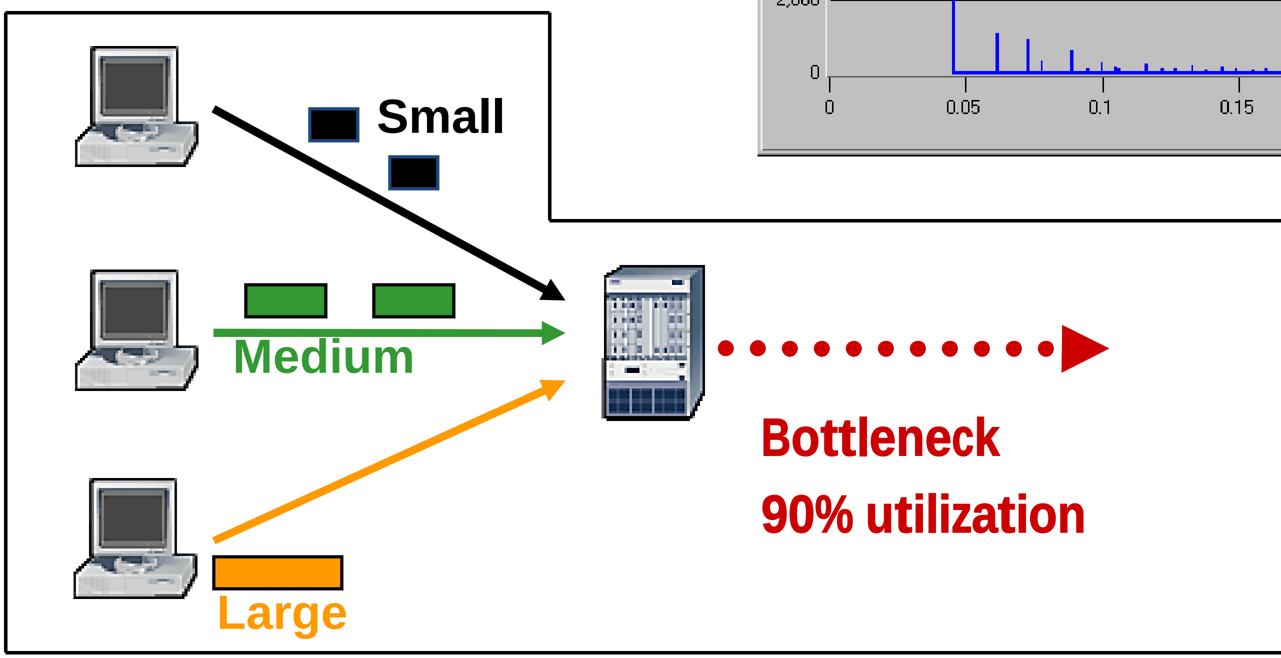


Incoming traffic

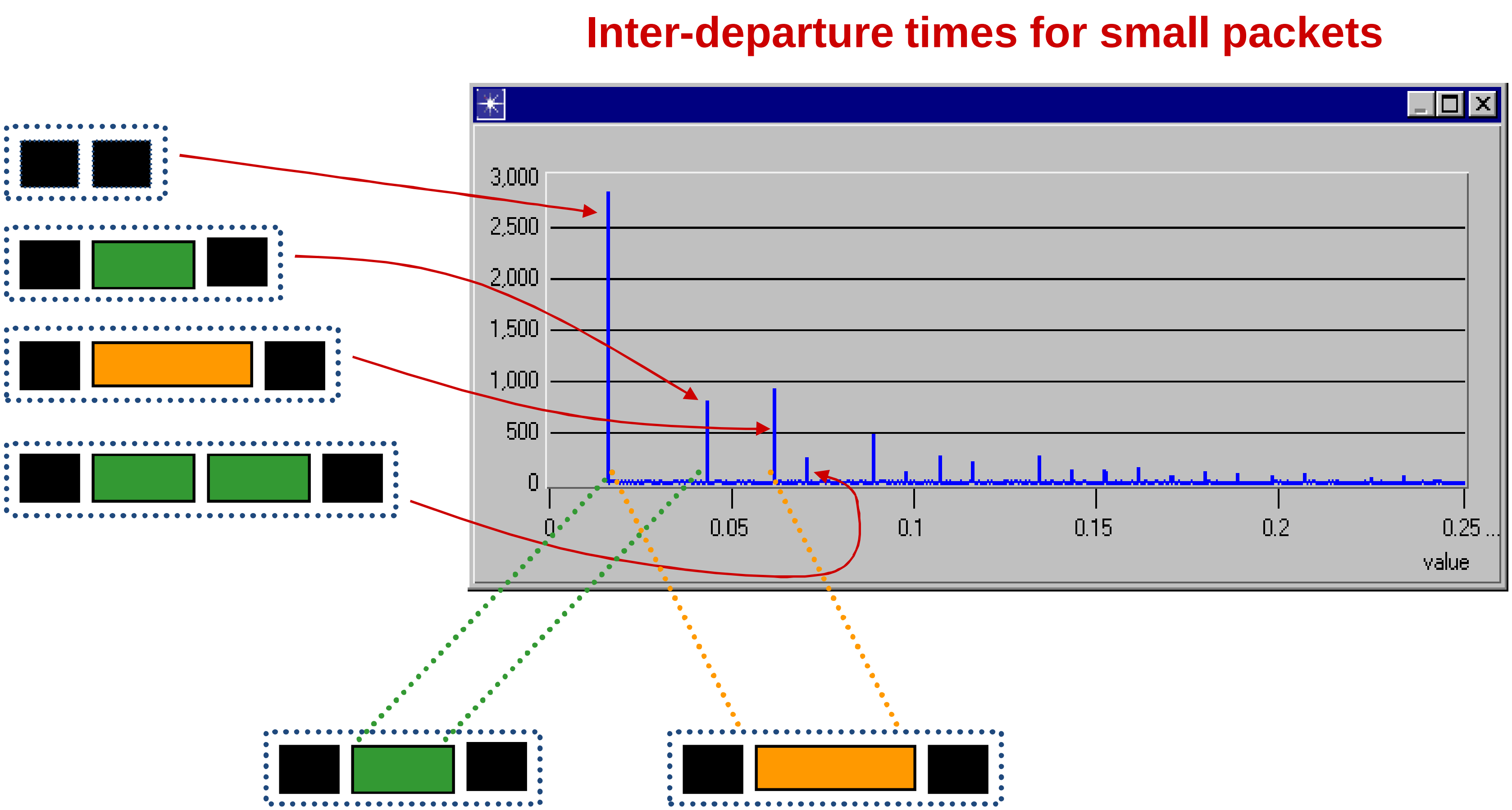


Outgoing traffic



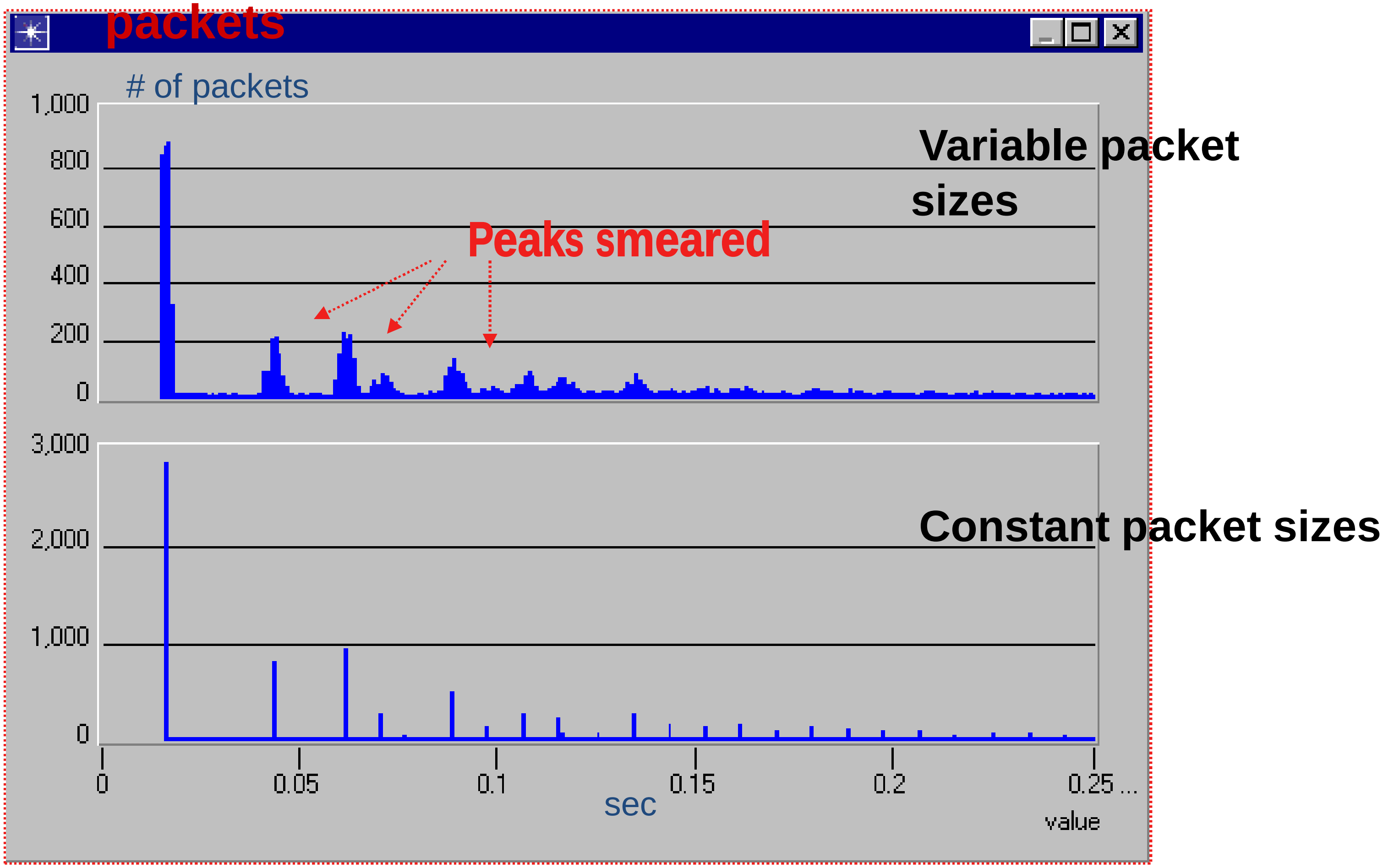


Packet Trains



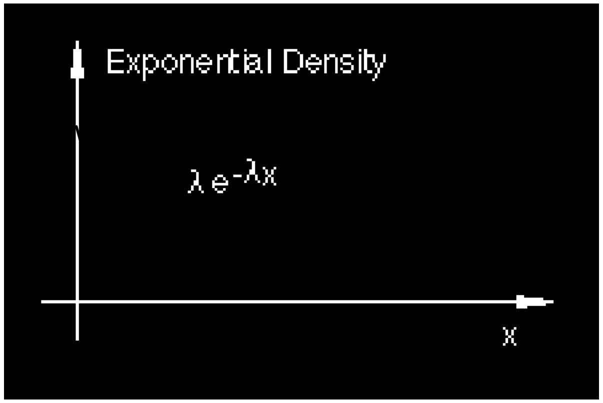
Variable packet sizes

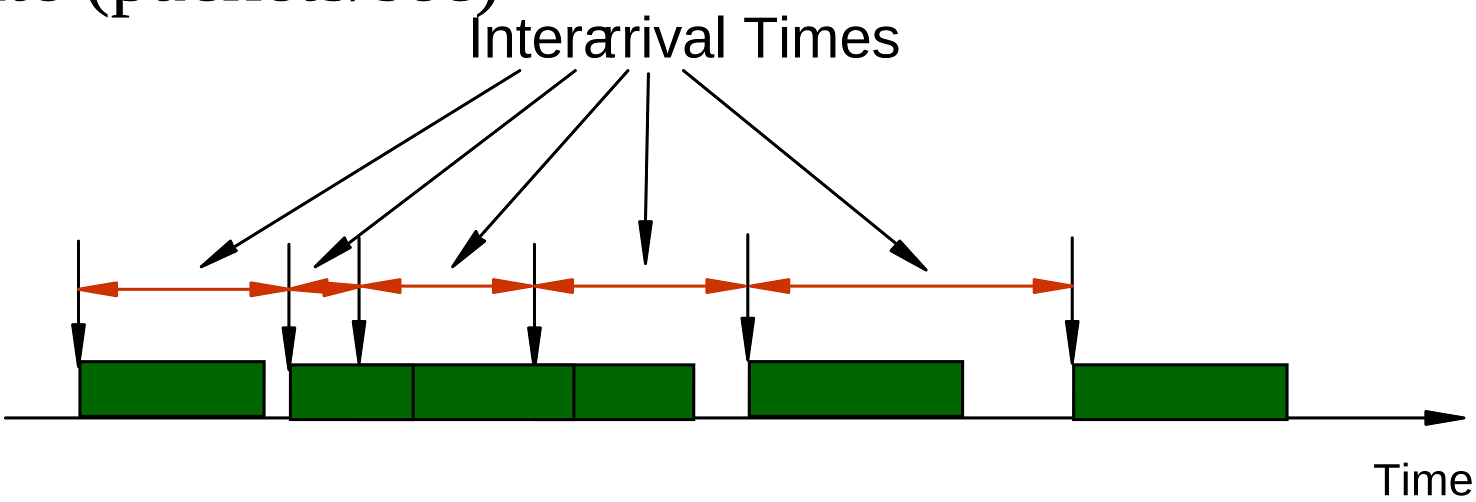
Histogram of inter-departure times for small packets



Poisson Process with Rate l

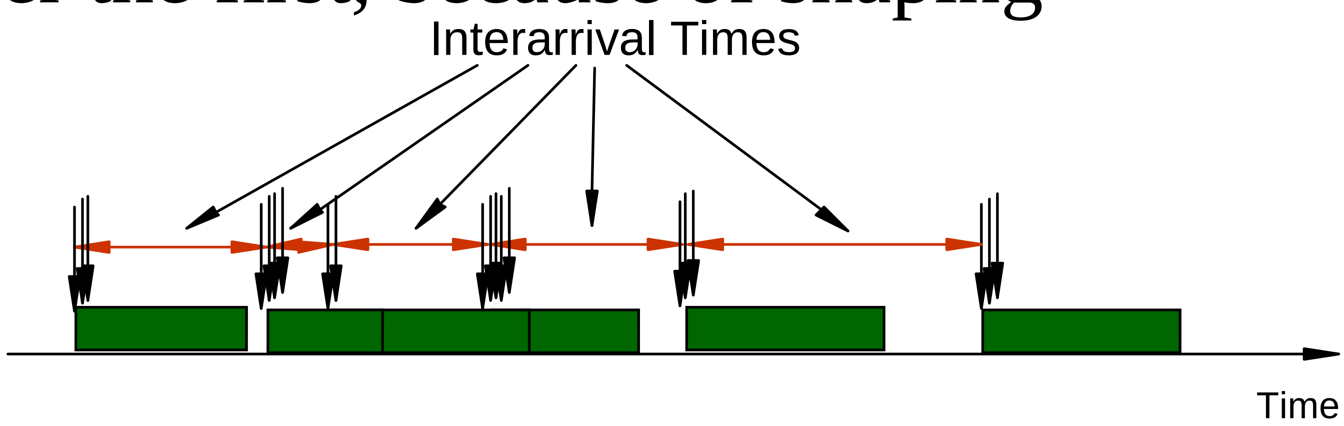
- Interarrival times are independent and exponentially distributed
- Models well the accumulated traffic of many independent sources
- The average interarrival time is 1/ l□ (secs/packet), so l is the arrival rate (packets/sec)



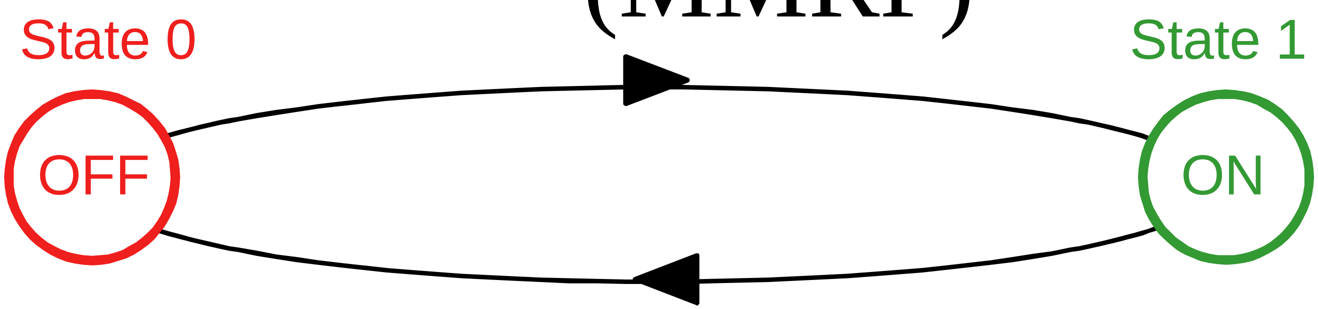


Batch Arrivals

- Some sources transmit in packet bursts
- May be better modeled by a batch arrival process (e.g., bursts of packets arriving according to a Poisson process)
- The case for a batch model is weaker at queues after the first, because of shaping



Markov Modulated Rate Process (MMRP)



Stay in each state an exponentially distributed time,
Transmit according to different model (e.g., Poisson, deterministic, etc) at each state

- Extension: Models with more than two states

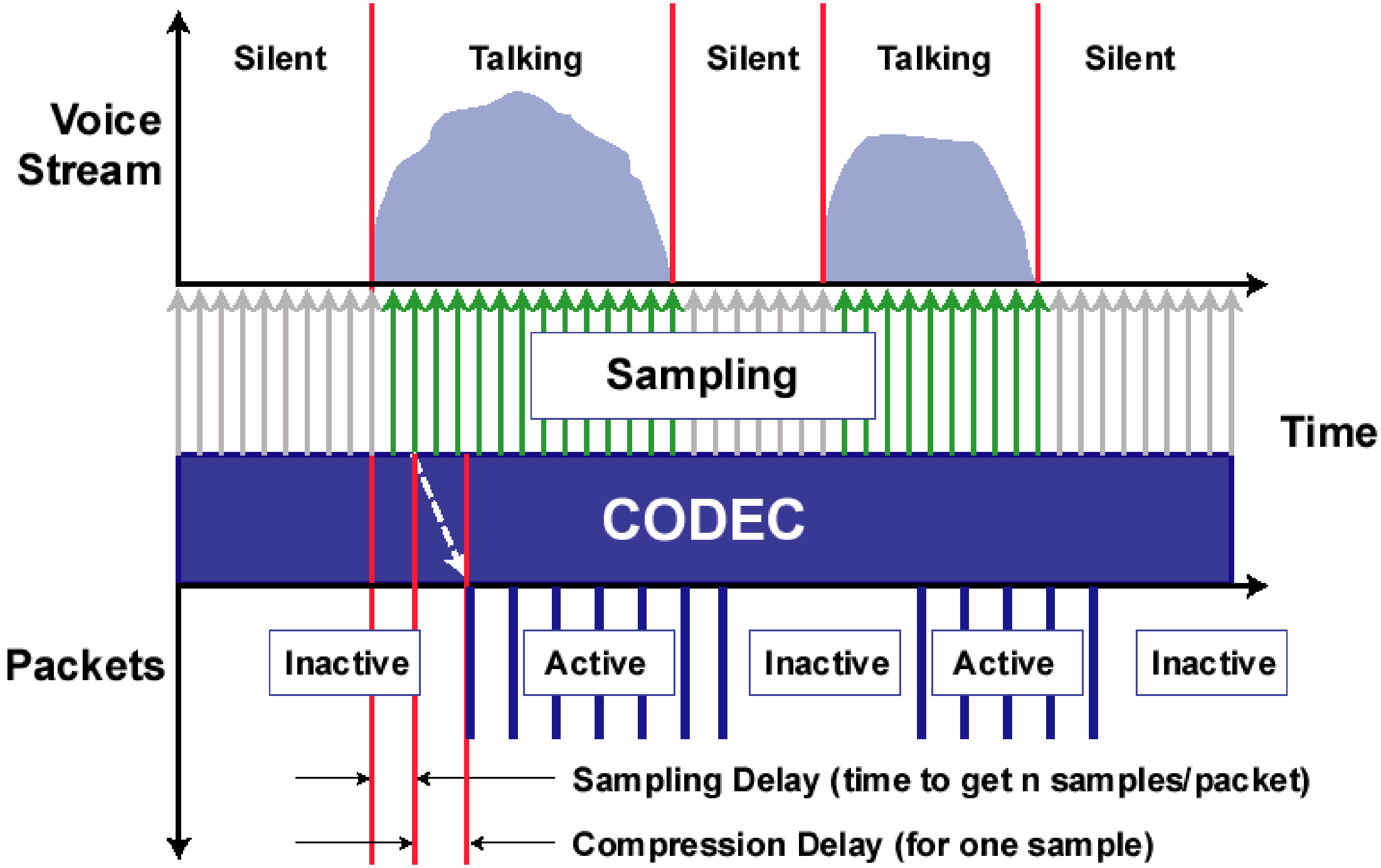
Source Types

- Voice sources
- Video sources
- File transfers
- Web traffic
- Interactive traffic
- Different application types have different QoS requirements, e.g., delay, jitter, loss, throughput, etc.

Source Type Properties

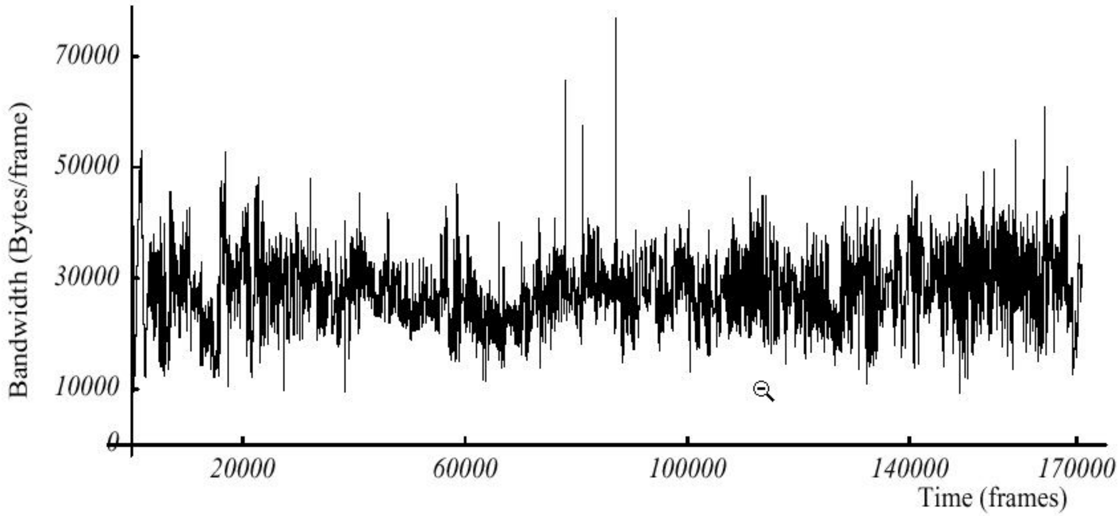
	Characteristics	QoS Requirements	Model
Voice	* Alternating talk-spurts and silence intervals. * Talk-spurts produce constant packet-rate traffic	**Delay < ~150 ms** Jitter < ~30 ms Packet loss < ~1%	* Two-state (on-off) Markov Modulated Rate Process (MMRP) * Exponentially distributed time at each state
Video	* Highly bursty traffic (when encoded) * Long range dependencies	Delay < ~ 400 ms **Jitter < ~ 30 ms** Packet loss < ~1%	K-state (on-off) Markov Modulated Rate Process (MMRP)
Interactive *FTP* *telnet* *web*	* Poisson type * Sometimes batch-arrivals, or bursty, or sometimes on-off	Zero or near-zero packet loss Delay may be important	Poisson, Poisson with batch arrivals, Two-state MMRP

Typical Voice Source Behavior



MPEG1 Video Source Model

- The MPEG1 MMRP model can be extremely bursty, and has “long range dependency” behavior due to the deterministic frame sequence



Device Queuing Mechanisms

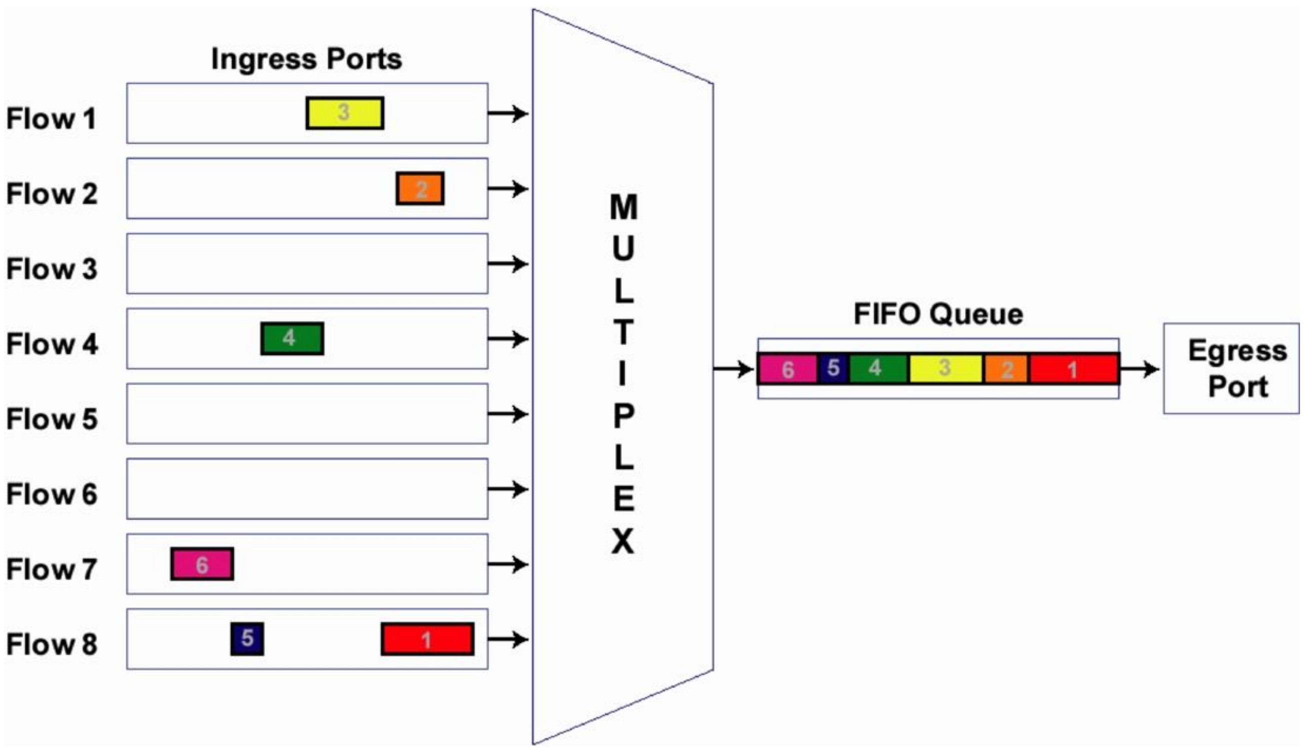
- Common queue examples for IP routers
  - FIFO: First In First Out
  - PQ: Priority Queuing
  - WFQ: Weighted Fair Queuing
  - Combinations of the above
- Service types from a queuing theory standpoint
  - Single server (one queue - one transmission line)
  - Multiple server (one queue - several transmission lines)
  - Priority server (several queues with hard priorities - one transmission line)
  - Shared server (several queues with soft priorities - one transmission line)

Single Server FIFO

- Single transmission line serving packets on a FIFO (First-In-First-Out) basis
- Each packet must wait for all packets found in the system to complete transmission, before starting transmission
  - Departure Time = Arrival Time + Workload Found in the System +Transmission time
- Packets arriving to a full buffer are dropped

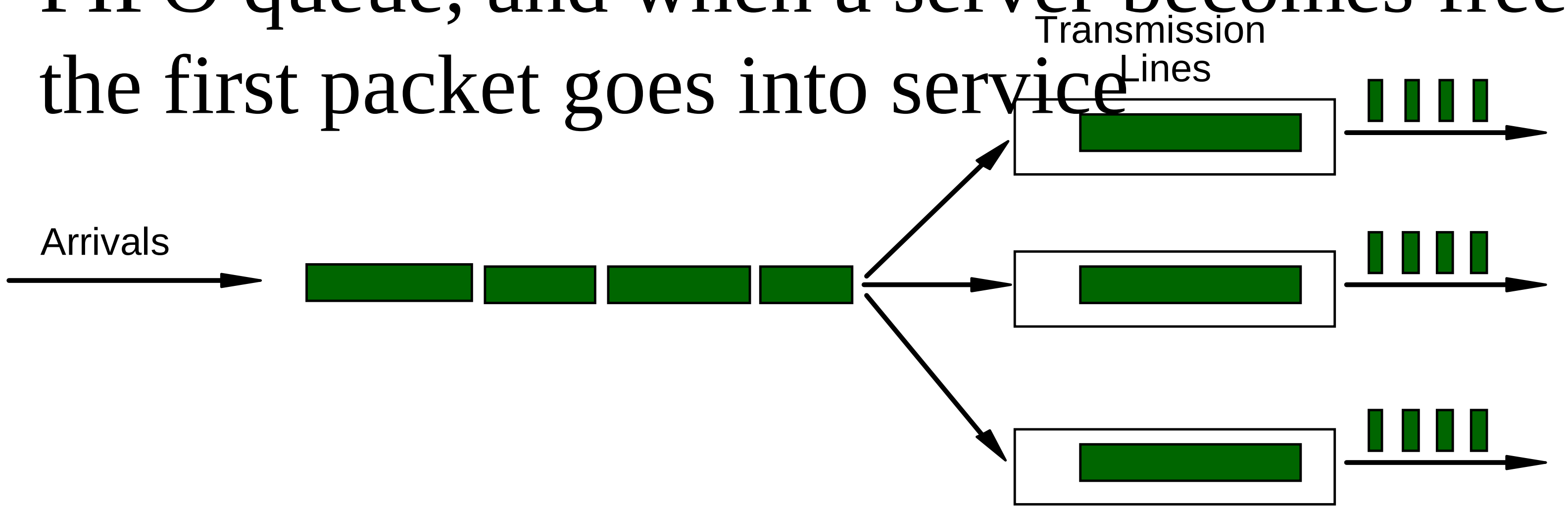
FIFO Queue

- Packets are placed on outbound link to egress device in FIFO order
  - Device (router, switch) multiplexes different flows arriving on various ingress ports onto an output buffer forming a FIFO queue



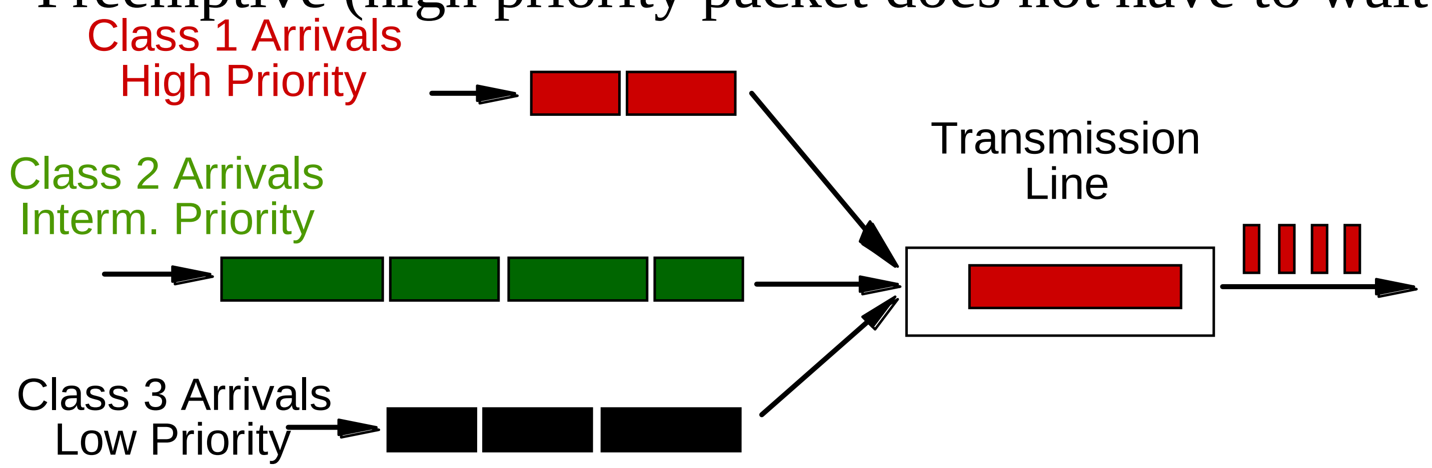
Multiple Servers

- Multiple packets are transmitted simultaneously on multiple lines/servers
- Head of the line service: packets wait in a FIFO queue, and when a server becomes free, the first packet goes into service



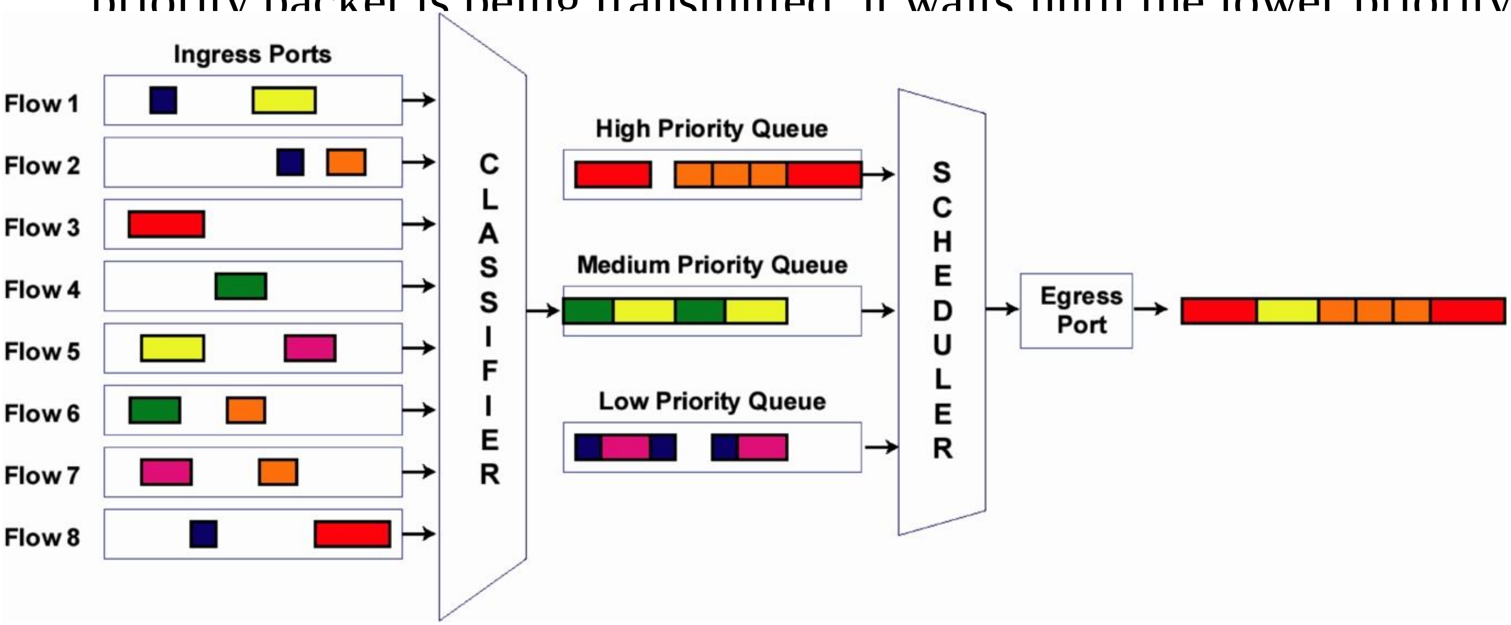
Priority Servers

- Packets form priority classes (each may have several flows)
- There is a separate FIFO queue for each priority class
- Packets of lower priority start transmission only if no higher priority packet is waiting
- Priority types:
  - Non-preemptive (high priority packet must wait for a lower priority packet found under transmission upon arrival)
  - Preemptive (high priority packet does not have to wait …)



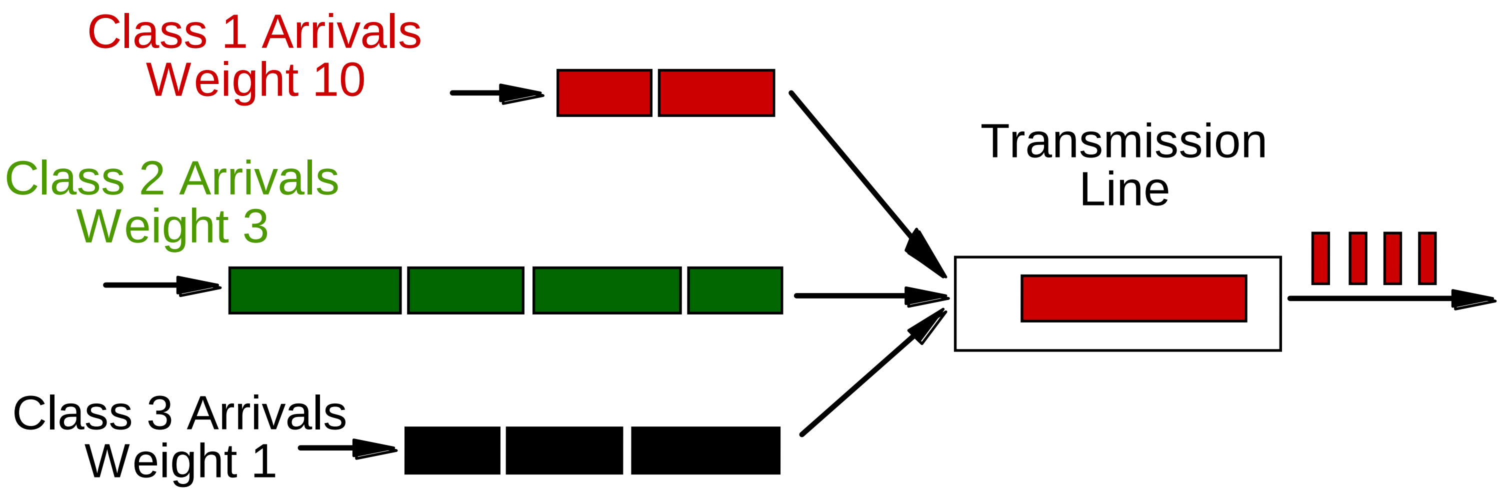
Priority Queuing

- Packets are classified into separate queues
  - E.g., based on source/destination IP address, source/destination TCP port, etc.
- All packets in a higher priority queue are served before a lower priority queue is served
  - Typically in routers, if a higher priority packet arrives while a lower priority packet is being transmitted, it waits until the lower priority



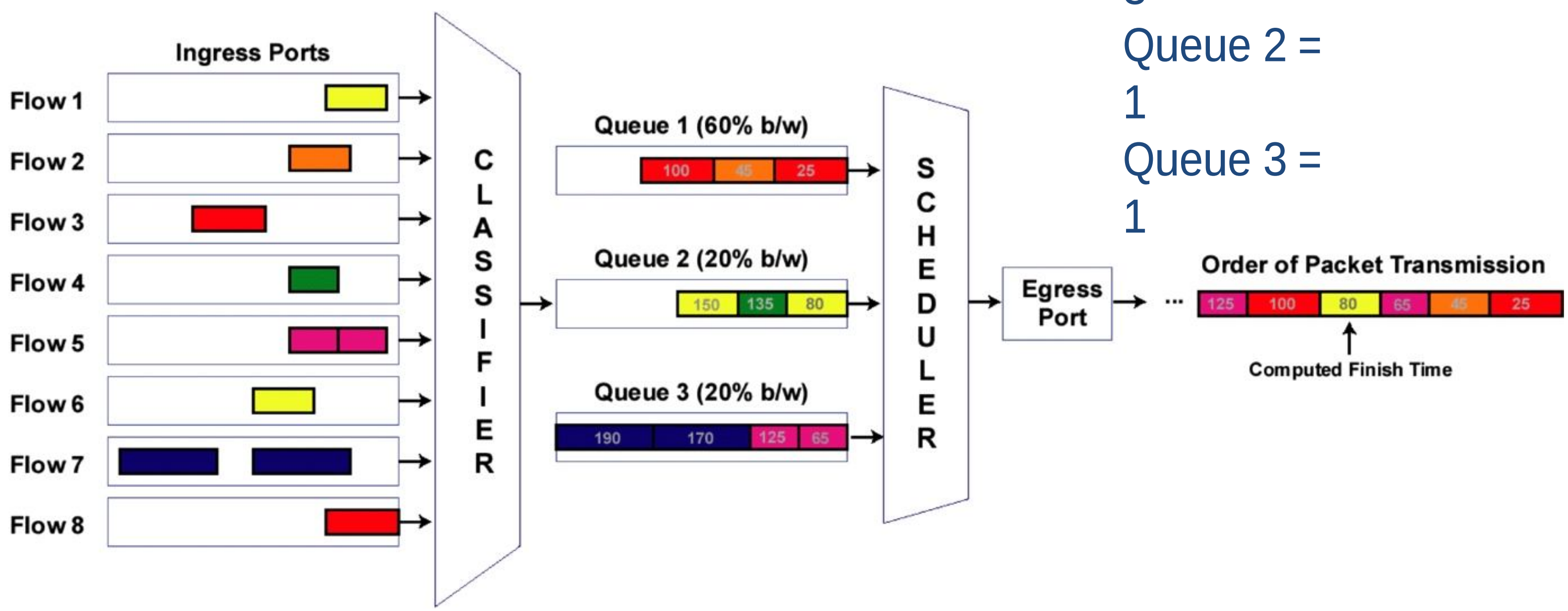
Shared Servers

- Again we have multiple classes/queues, but they are served with a “soft” priority scheme
- Round-robin
- Weighted fair queuing



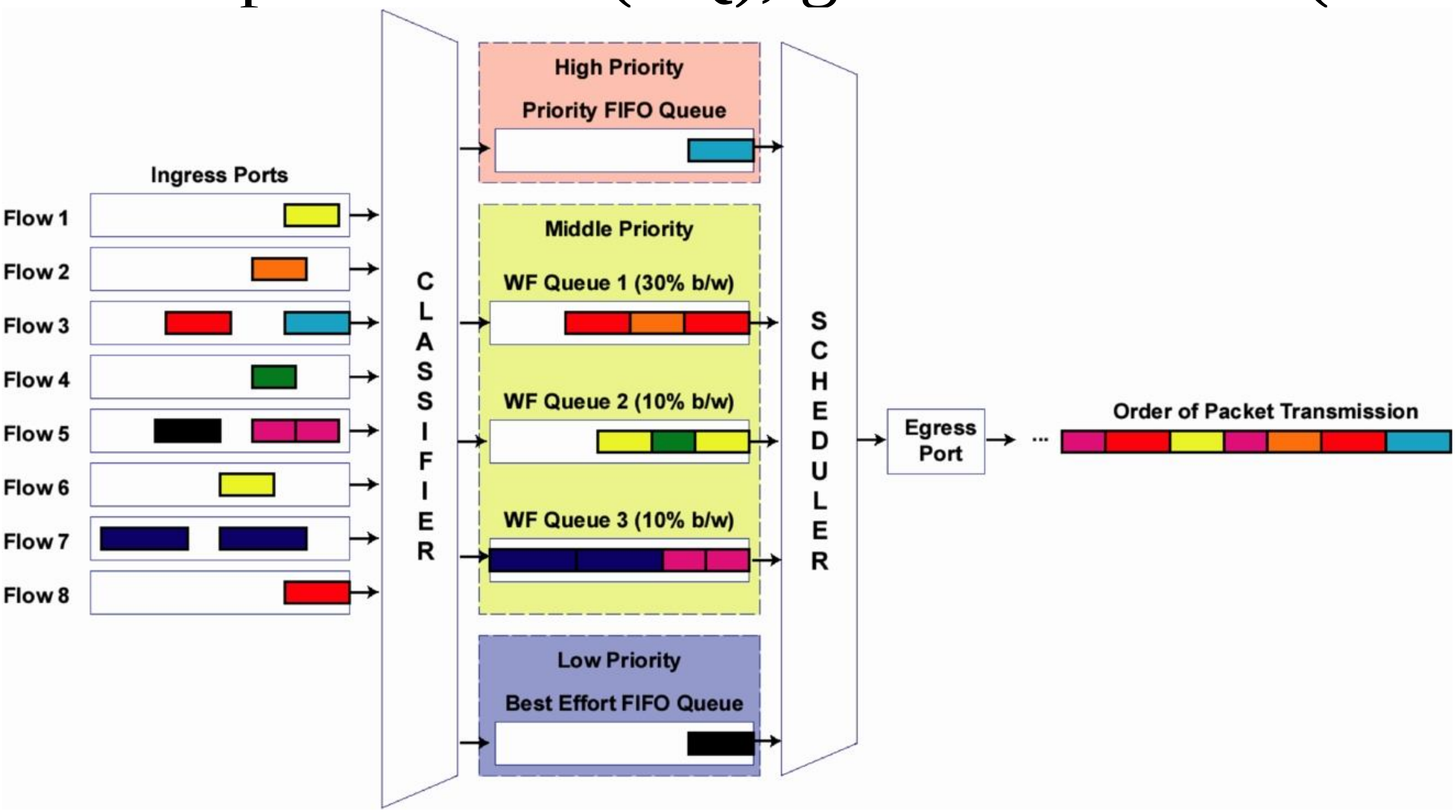
Weighted Fair Queuing Illustration

Weights:
Queue 1 = 3
Queue 2 = 1
Queue 3 = 1

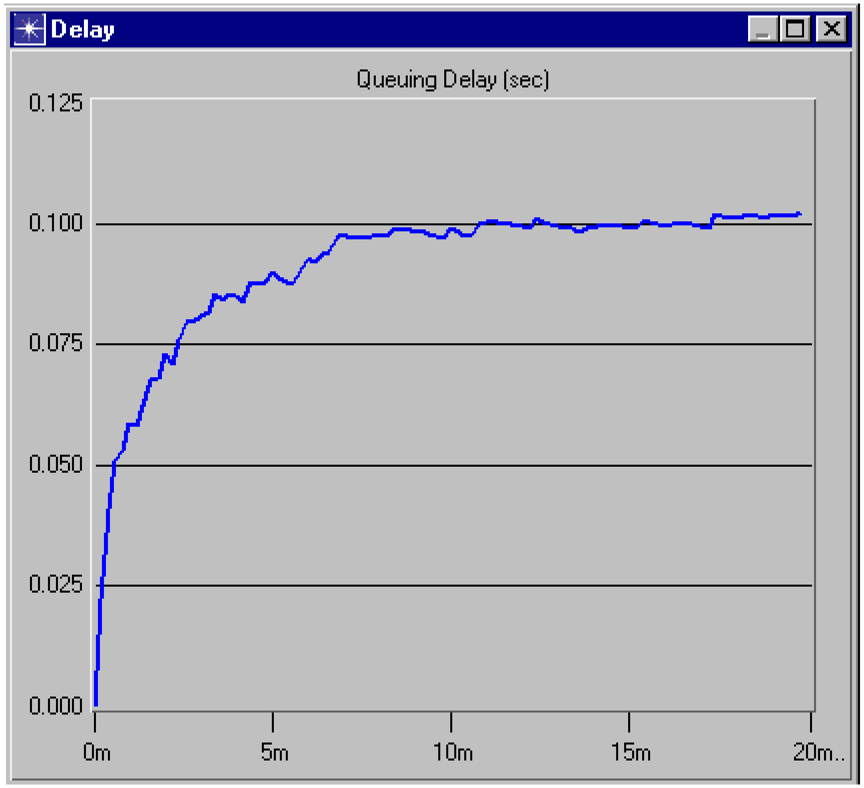


Combination of Several Queuing Schemes

- Example – voice (PQ), guaranteed b/w (WFQ),



Demo: FIFO Queuing Delay



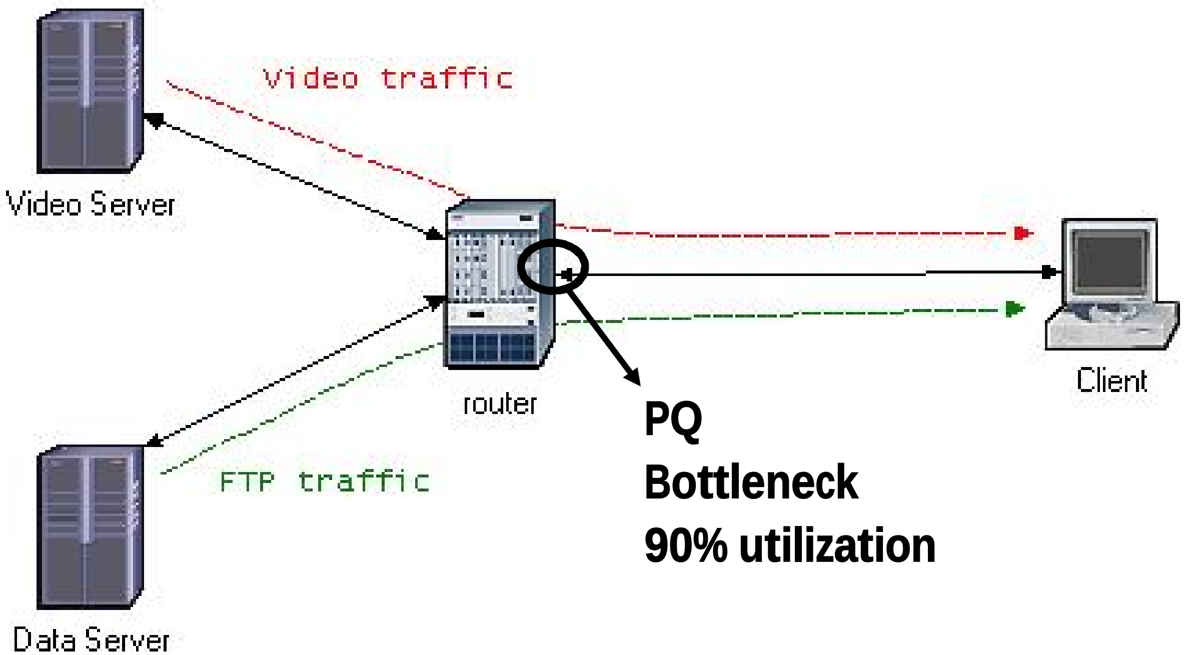
Applications have different requirements

- **Video**
  - » **delay, jitter**
- **FTP**
  - » **packet loss**

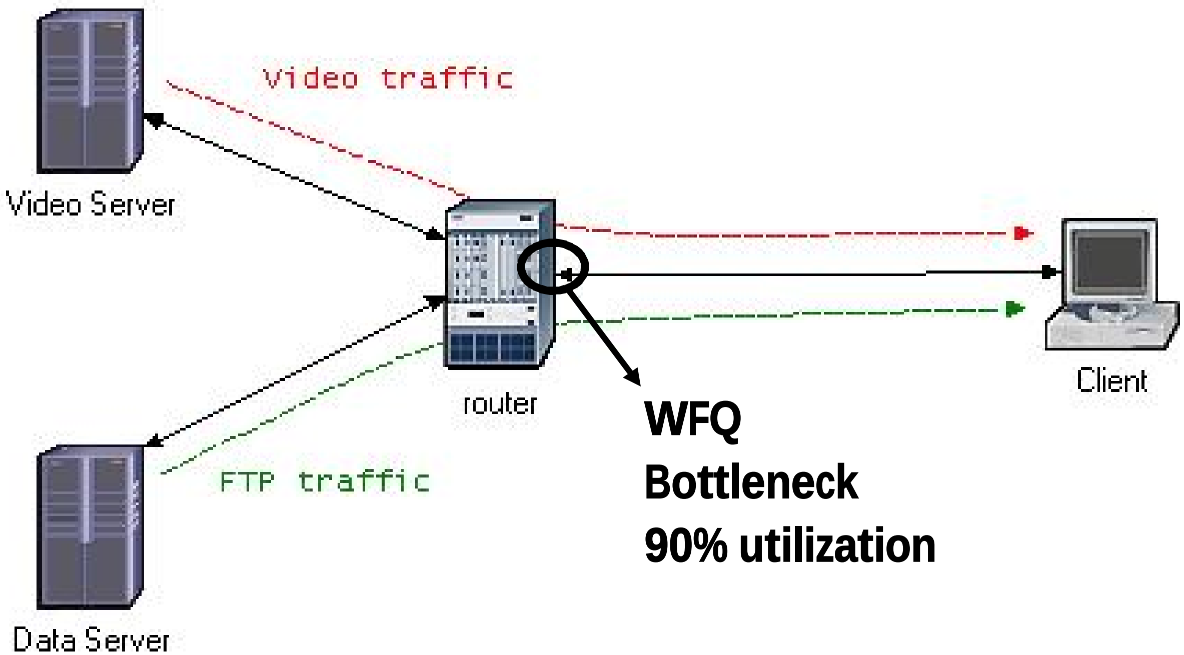
Control beyond "best effort" needed

- **Priority Queuing (PQ)**
- **Weighted Fair Queuing (WFQ)**

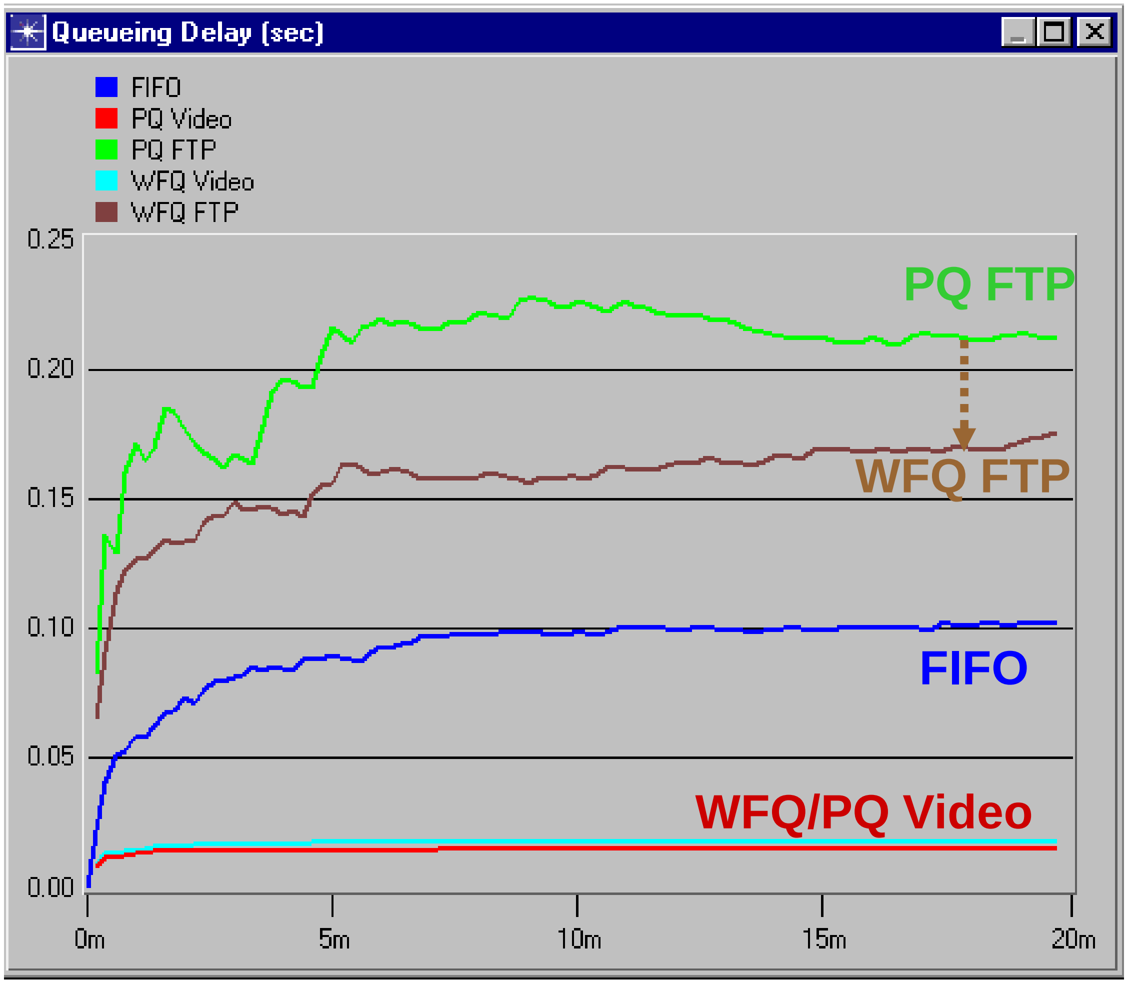
Demo: Priority Queuing (PQ)



Demo: Weighted Fair Queuing (WFQ)



Demo: WFQ Queuing Delays



Queuing: Take Away Points

- Choice of queuing mechanism can have a profound effect on performance
- To achieve desired service differentiation, appropriate queuing mechanisms can be used
- Complex queuing mechanisms may require simulation techniques to analyze behavior
- Improper configuration (e.g., queuing mechanism selection or weights) may impact performance of low priority traffic

Delay Calculation

- Let

  Q = Average time spent waiting in queue

  T = Average packet delay (transmission plus queuing)
- Note that T = 1/m + Q
- Also by Little's law

  $N = l\,T$ and $N_q = l\,Q$

where

  N_q = Average number waiting in queue
- These quantities can be calculated with formulas derived by Markov chain analysis (see references)

M/M/m, M/M/∞ System

- Same as M/M/1, but it has m (or □) servers
- In M/M/m, the packet at the head of the queue moves to service when a server becomes free
- Qualitative result
  - Delay increases to □ as r = l/mm approaches 1
- There are analytical formulas for the occupancy probabilities and average delay of these systems

Finite Buffer Systems: M/M/m/k

- The M/M/m/k system
  - Same as M/M/m, but there is buffer space for at most k packets. Packets arriving at a full buffer are dropped
- Formulas for average delay, steady-state occupancy probabilities, and loss probability
- The M/M/m/m system is used widely to size telephone or circuit switching systems

M/G/1 System

- Same as M/M/1 but the packet transmission time distribution is general, with given mean 1/m and variance s^2
- Utilization factor □ = l /m
- Pollaczek-Kinchine formula for

  Average time in queue = $l(s^2 + 1/m^2)/2(1-$ □$)$

  Average delay = $1/m + l(s^2 + 1/m^2)/2(1-$ □$)$
- The formulas for the steady-state occupancy probabilities are more complicated
- Insight: As s^2 increases, delay increases

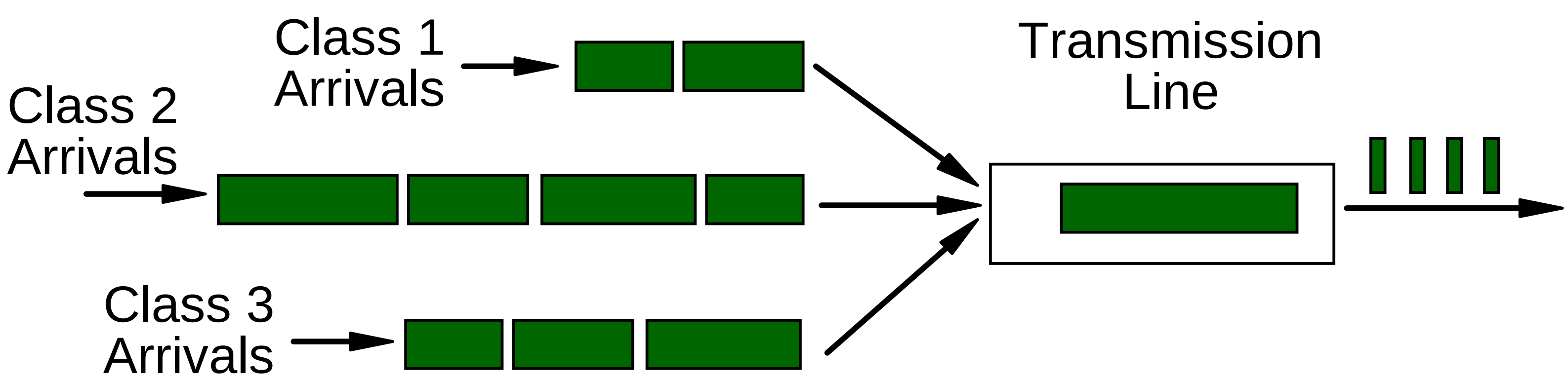
G/G/1 System

- Same as M/G/1 but now the packet interarrival time distribution is also general, with mean □ and variance □^{2}
- We still assume FIFO and independent interarrival times and packet transmission times
- Heavy traffic approximation:

  Average time in queue ~ l(s^2 + □^{2})/2(1- □)
- Becomes increasingly accurate as □□□

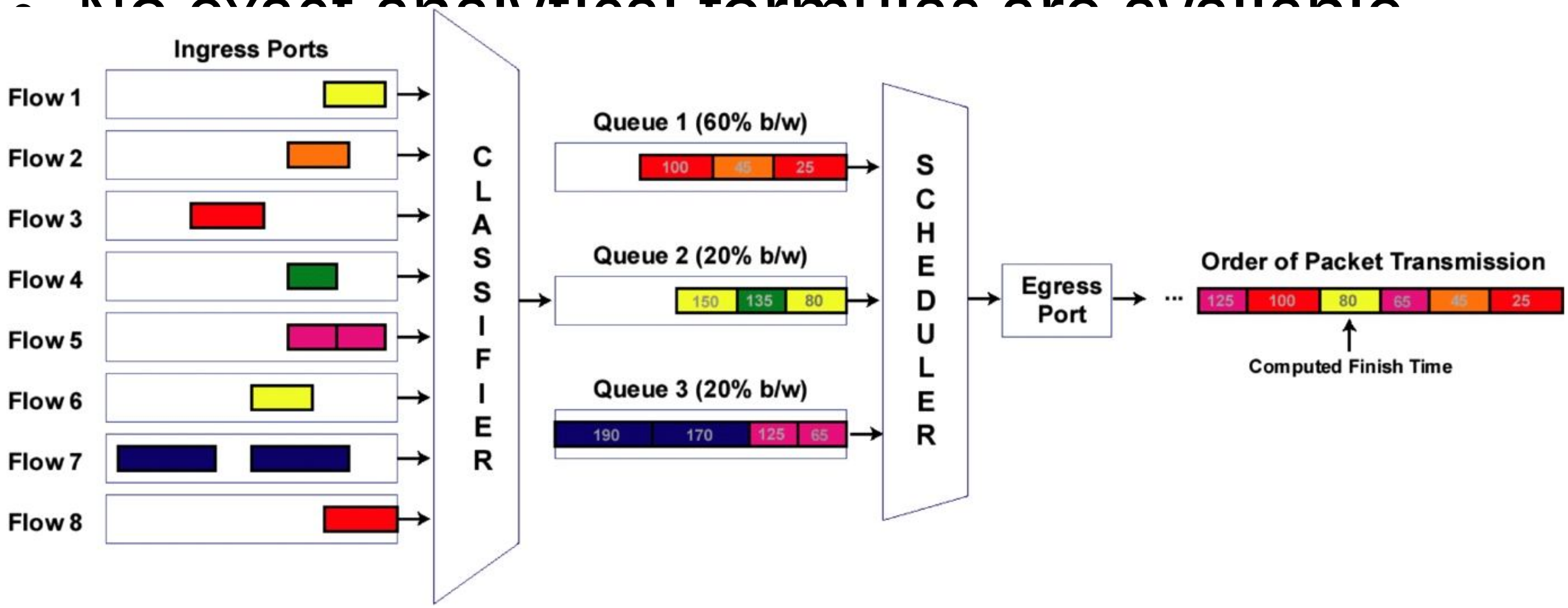
Cyclic Service Systems

- Multiple flows, each with its own queue
- Fair system: Each flow gets access to the transmission line in turn
- Several possible assumptions about how many packets each flow can transmit when it gets access



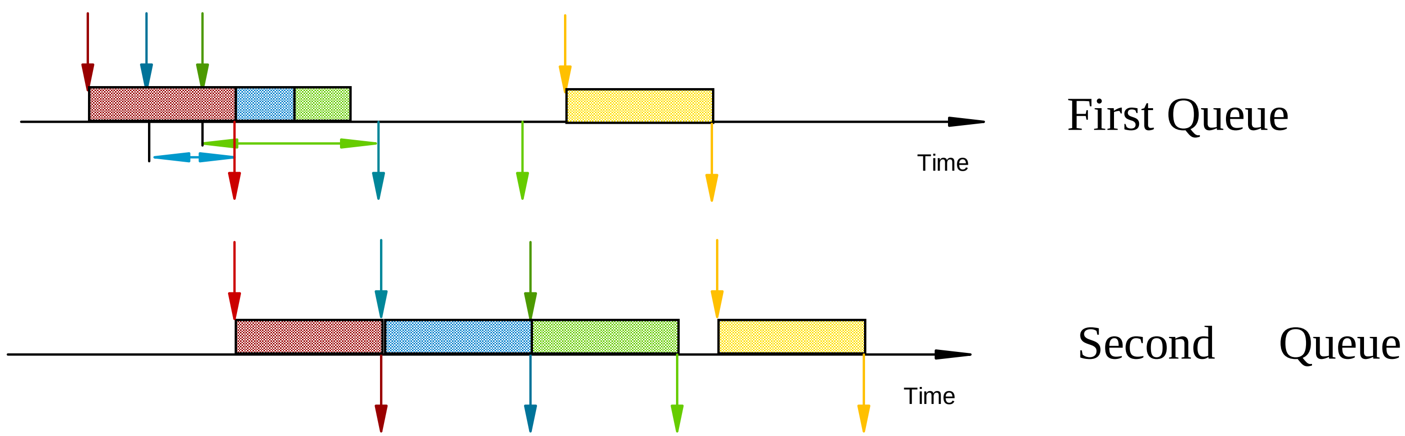
Weighted Fair Queuing

- A combination of priority and cyclic service
- No exact analytical formulas are available

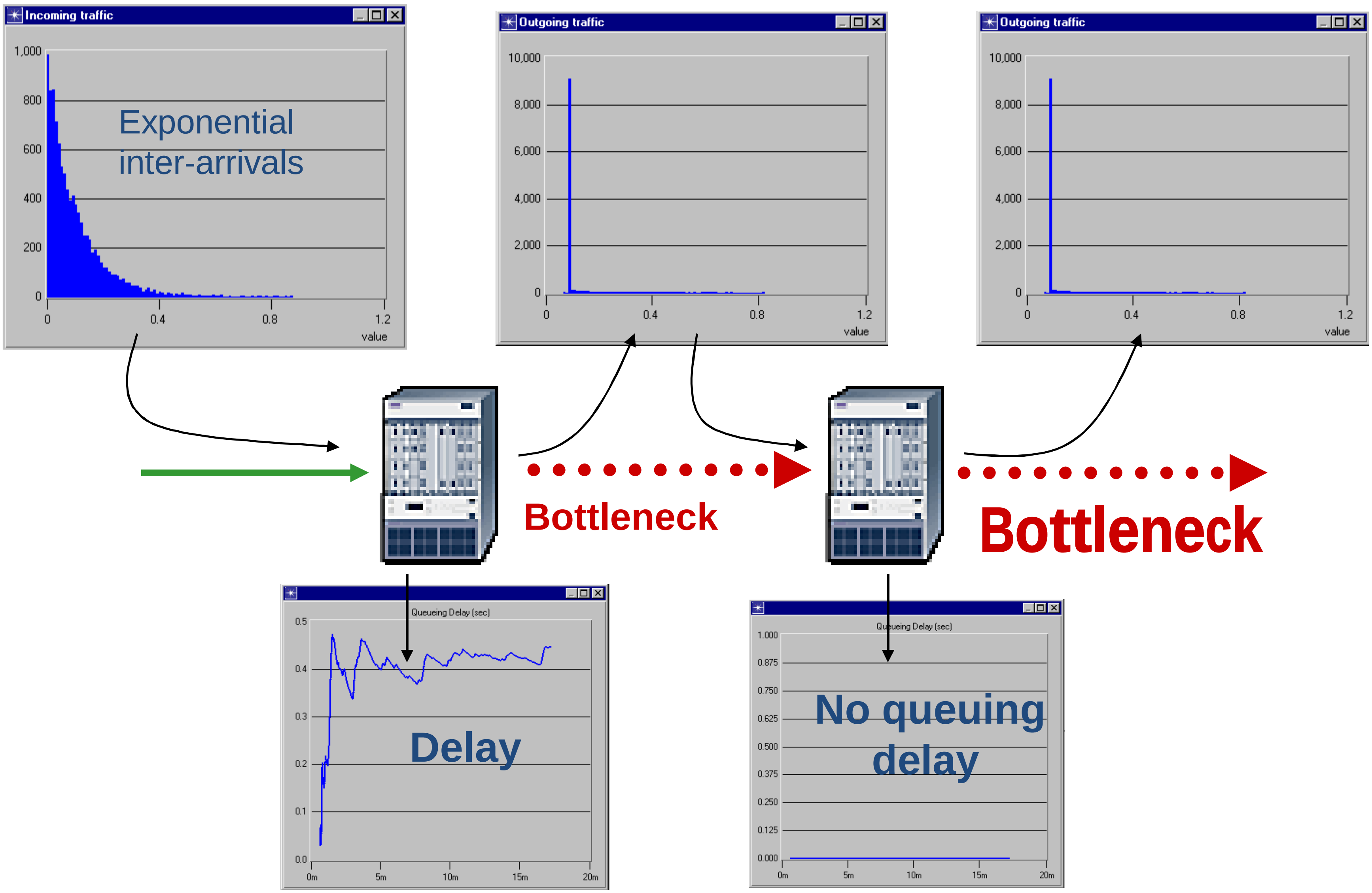


Two Queues in Series

- First queue shapes the traffic into second queue
- Arrival times and packet lengths are correlated
- M/M/1 and M/G/1 formulas yield significant error for second queue

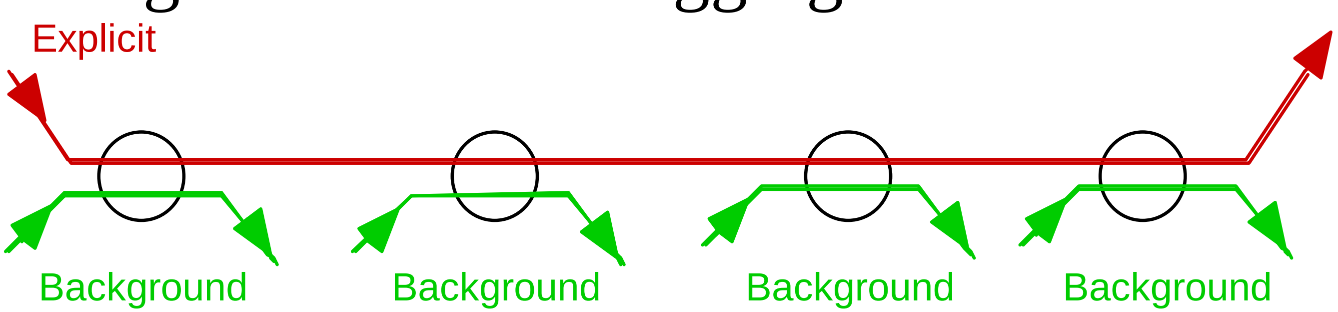


Two bottlenecks in series



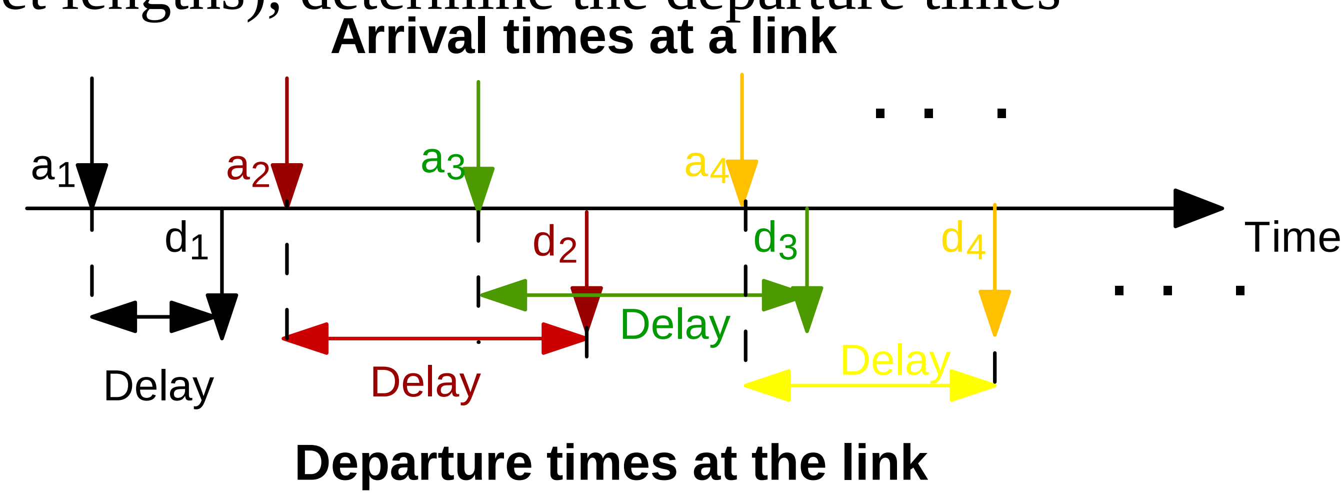
Basic Concepts of Hybrid Simulation

- Aims to combine the best of analytical results and simulation
- Achieve significant gain in simulation speed with little loss of accuracy
- Divides the traffic through a node into **explicit** and **background**
  - Explicit traffic is simulated accurately
  - Background traffic is aggregated



Explicit Traffic

- Modeled in detail, including the effects of various protocols
- Each packet's arrival and departure times are recorded (together with other data of interest, e.g., loss, etc.) along each link that it traverses
- Departure times at a link are the arrival times at the next link (plus propagation delay)
- Objective: At each link, given the arrival times (and the packet lengths), determine the departure times



Aggregated Traffic

- Simplified modeling
  - We don’t keep track of individual packets, only workload counts (number of packets or bytes)
  - We “generate” workload counts
    - by probabilistic/analytical modeling, or
    - by simplified simulation
- Aggregated (or background) traffic is local (per link)
- Shaping effects are complex to incorporate
- Some dependences between explicit and background traffic along a chain of links are complicated and are ignored

Steady-State Queue Length Distribution

- If the interval between two successive explicit packets is very long, we can assume that the queue found by the second packet is in steady state.So, we can obtain w_{k+1} by sampling the steady-state distribution
- Applies to cases where the steady-state distribution can be found or can be reasonably approximated
  - M/M/1 and other M/M/. Queues
  - Some M/G/. systems

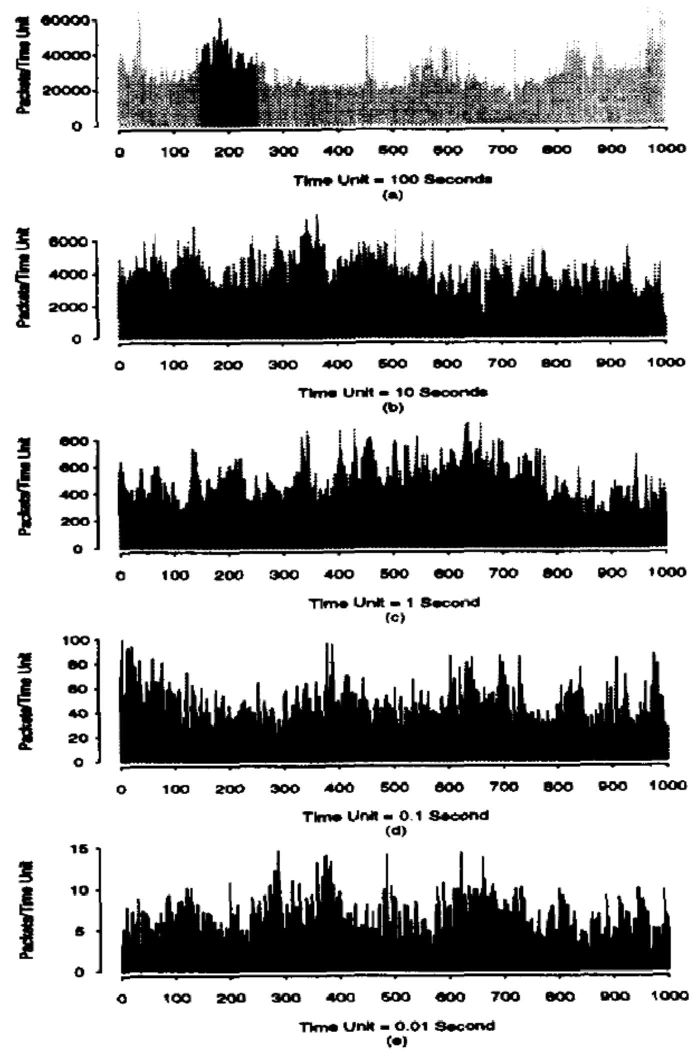
Self-Similarity in Network Traffic

What is Self-Similarity?

- Self-similarity describes the phenomenon where a certain property of an object is preserved with respect to scaling in space and/or time.

- If an object is self-similar, its parts, when magnified, resemble the shape of the whole.

Pictorial View of Self-Similarity



Why is Self-Similarity Important?

- Recently, network packet traffic has been identified as being self-similar.
- Current network traffic modeling using Poisson distributing (etc.) does not take into account the self-similar nature of traffic.
- This leads to inaccurate modeling which, when applied to a huge network like the Internet, can lead to huge financial losses.

Definitions and Properties

- Long-range Dependence
  - covariance decays slowly
- Hurst Parameter
  - Developed by Harold Hurst (1965)
  - H is a measure of “burstiness”
    - also considered a measure of self-similarity
  - $0 < H < 1$
  - H increases as traffic increases

Self-Similar Measures

- Background
  - Let time series: $X = (X_t : t = 0, 1, 2, \ldots.)$ be a covariance stationary stochastic process
  - autocorrelation function: $r(k), k \geq 0$
  - assume $r(k) \sim k^{-\beta} L(t)$, as $k \rightarrow \infty$ where $0 < \beta < 1$
    - $\lim_{t \rightarrow \infty} L(tx) / L(t) = 1$, for all $x > 0$

Measuring Self-Similarity

- time-domain analysis based on R/S statistic
- analysis of the variance of the aggregated processes $X^{(m)}$
- periodogram-based analysis in the frequency domain