Traffic Management
&
Traffic Engineering

Outline

- Economic principles
- Traffic classes
- Time scales
- Mechanisms
- Some open problems

Traffic classes

- Networks should match offered service to source requirements (corresponds to utility functions)
- **Example:** telnet requires low bandwidth and low delay
  - utility increases with decrease in delay
  - network should provide a low-delay service
  - or, telnet belongs to the low-delay *traffic class*
- Traffic classes encompass both *user requirements* and *network service offerings*
  - *Applications match the traffic to the service offering*
  - *Request resources from the network accordingly*

Traffic classes - details

- A basic division: guaranteed service and best effort
  - like flying with reservation or standby
- **Guaranteed-service (GS)**
  - utility is zero unless app gets a minimum level of service quality
    - ☞ bandwidth, delay, loss
  - *open-loop flow control* with *admission control (reserve resources)*
  - e.g. telephony, remote sensing, interactive multiplayer games
- **Best-effort (BE)**
  - send and pray
  - *closed-loop flow control*
  - e.g. email, net news

GS vs. BE (cont.)

- **Degree of synchrony**
  - time scale at which peer endpoints interact
  - GS are typically *synchronous* or *interactive*
    - interact on the timescale of a round-trip time
    - e.g. telephone conversation or telnet
  - BE are typically *asynchronous* or *non-interactive*
    - interact on longer time scales
    - e.g. e-mail
- **Sensitivity to time and delay**
  - GS apps are *real-time*
    - performance depends on wall clock
  - BE apps are typically indifferent to real time
    - automatically scale back during overload

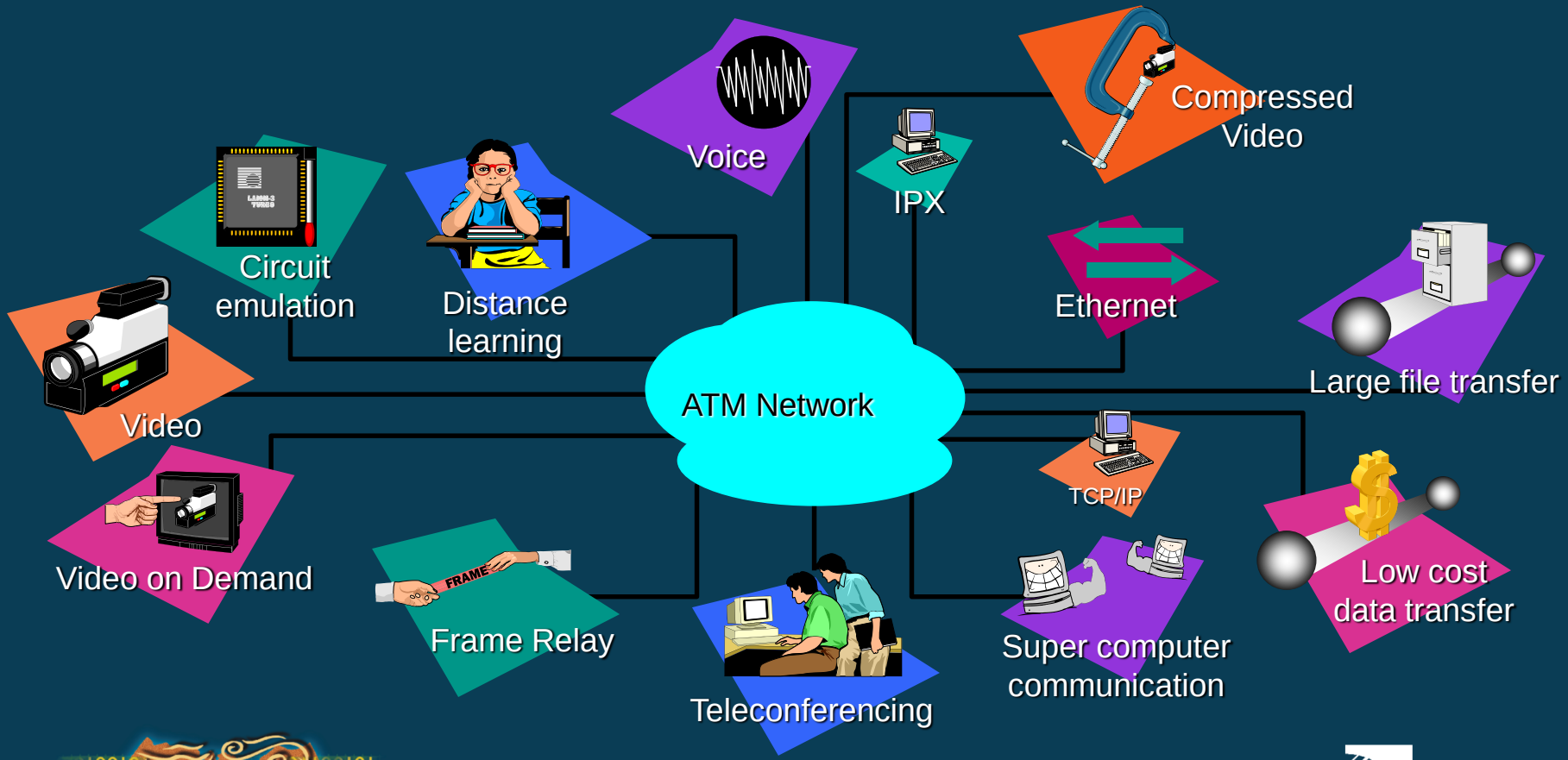
Best Effort (Flow Control)

- **Explicit**
  - Network tells the rate at which the source should send the packets
  - Network elements may compute connection fair-share based on Max-Min allocation (e.g, ABR service in ATM Networks)
  - Or it can be based on 1-bit congestion indicator (e.g., EFCI (Explicit Forward Congestion Indication) in ABR of ATM Networks)
- **Implicit**
  - Packet drop is detected by the source and adjusts the window transmission (e.g., TCP)
- **No flow control**
  - Packets are dropped by the network nodes
  - Sources may not react (e.g, UDP, UBR)
- Problems are caused if these two types are mixed!!

Traffic subclasses (roadmap)

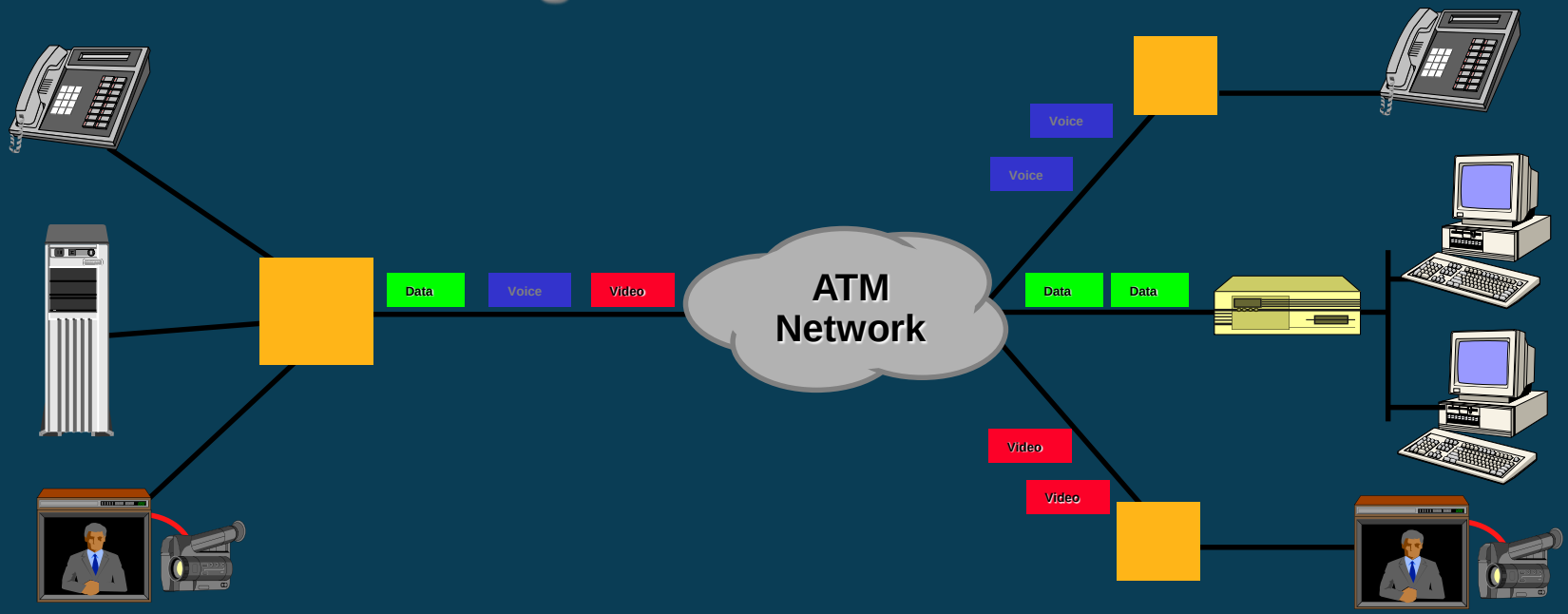
- ATM (Asynchronous Transfer Mode) Forum
  - based on sensitivity to bandwidth
  - GS
    - CBR (Constant Bit Rate)
    - VBR (Variable Bit Rate)
  - BE
    - ABR (Available Bit Rate)
    - UBR (Unspecified Bit Rate)
- IETF (Internet Engineering Task Force) (ietf.org)
  - based on ToS (Type-of-Service)
- IETF based on RSVP (Resource Reservation Protocol)
  - based on sensitivity to delay
  - GS
    - Intolerant, tolerant
  - BE
    - interactive burst, interactive bulk, asynchronous bulk
- IETF based in DiffServ (Differentiated Services)
  - PHB (Per-Hop Behavior)
  - EF, 4 AFs and BE

ATM Applications and Network Objectives



ATM Vision

The Ultimate Integrated Services Network



- ATM network moves cells (fixed length packets) with low delay and low delay variation at high speeds
- Devices at ends translate (e.g., segment and reassemble) between cells and original traffic

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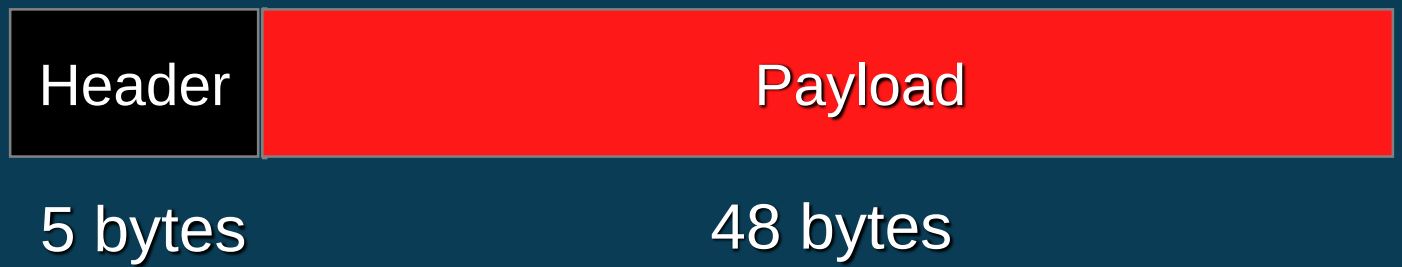
ATM Cell (simplified)



- Header contains information to allow cell to be forwarded to its destination

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ATM Applications and Network Objectives

- All traffic carried via the same network elements (potentially multi-vendor)
- Optimize use of network resources
- Meet stringent QoS requirements specific to each application
- Protects networks and users to achieve network performance objectives

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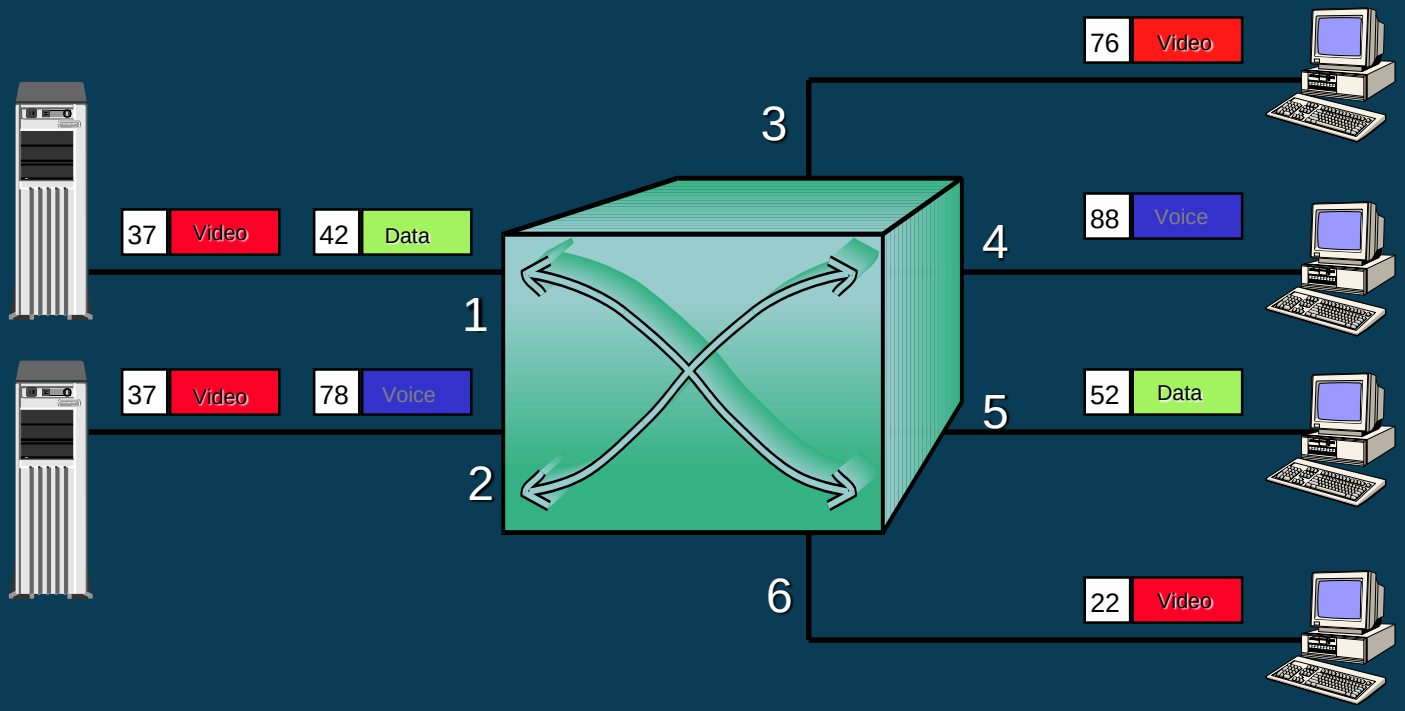
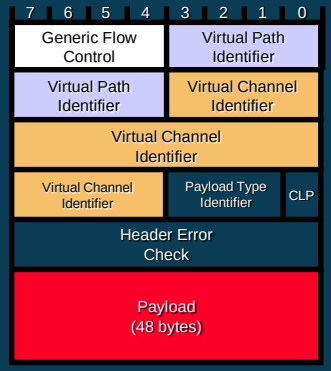
Virtual Connections





Connection Table

	Port	VPI/VCI	Port	VPI/VCI
Video	1	0/37	3	0/76
Data	1	0/42	5	0/52
Video	2	0/37	6	0/22
Voice	2	0/78	4	0/88

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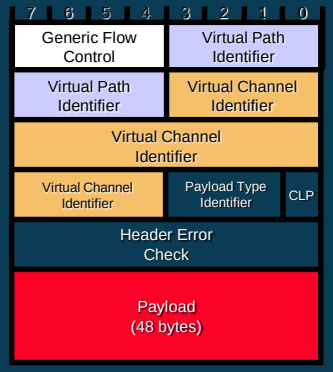
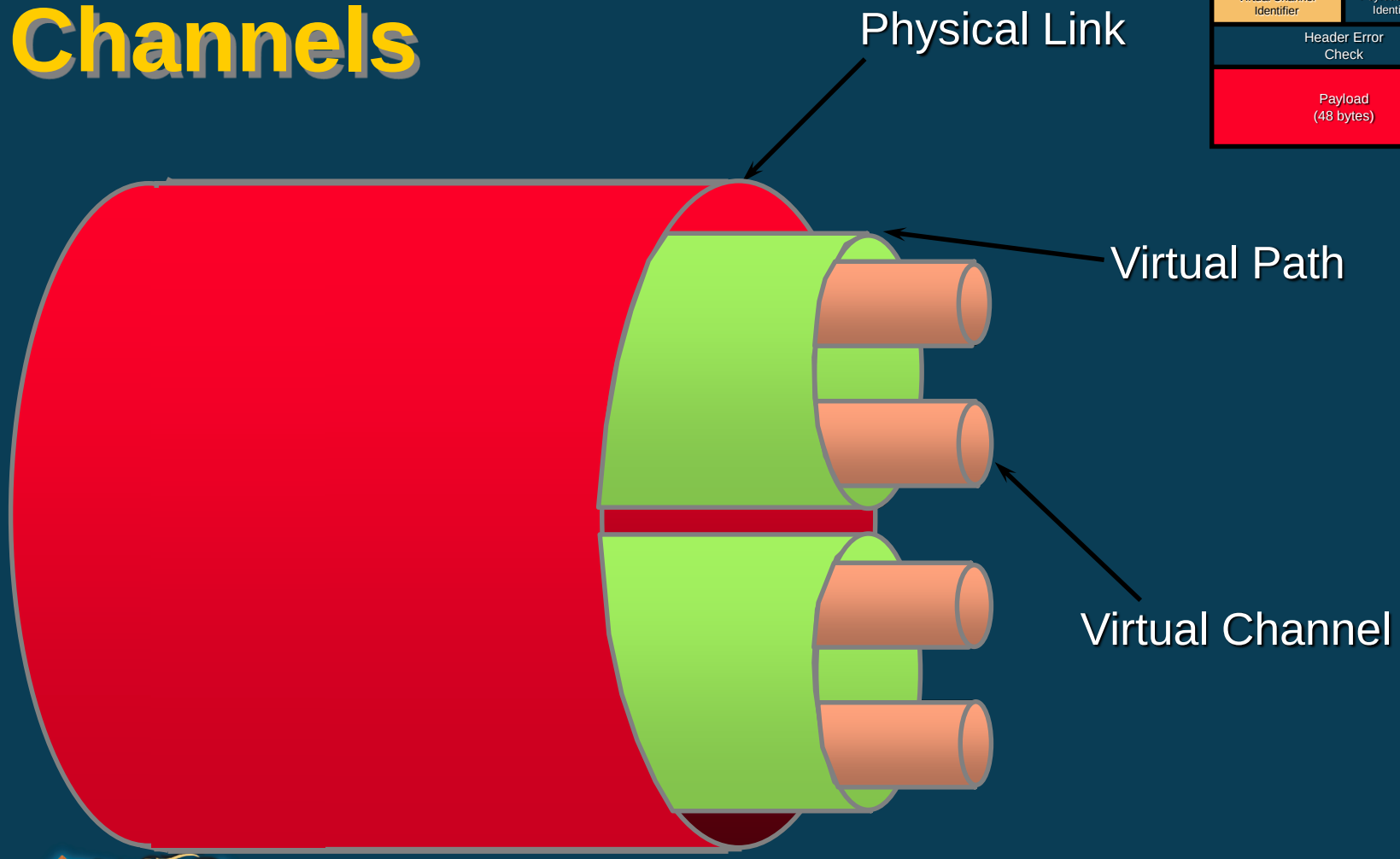
Virtual Paths and Virtual Channels





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ATM Service Architecture
Five Service Categories

		Example
• CBR	Constant Bit Rate	*-voice*
• rt-VBR	Real-Time Variable Bit Rate	*-video*
• nrt-VBR	Non-Real Time Variable Bit Rate	*-frame relay*
• ABR	Available Bit Rate	*-data*
• UBR	Unspecified Bit Rate	*-data*

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ATM Forum Service Categories

Attribute	ATM Layer Services Categories				
	CBR	rt-VBR	nrt-VBR	ABR	UBR
CLR	specified			network specific	unspecified
CTD and CDV	specified		unspecified	unspecified	unspecified
PCR and CDVT [1]	specified			specified	specified
SCR and BT	n/a	specified		n/a	
MCR	n/a			specified	n/a
Feedback	unspecified			specified	unspecified

Notes:

- 1. CVDT is not signalled, it is network specific.

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Traffic Contract
Quality of Service (QoS)

- Rate Guarantees
  - On PCR, SCR, MCR, and ACR
- Delay Guarantees
  - On Cell Transfer Delay - CTD
  - On Cell Delay Variation - CDV
- Loss Guarantees
  - On Cell Loss Ratio - CLR (Lost cells/Total cells)

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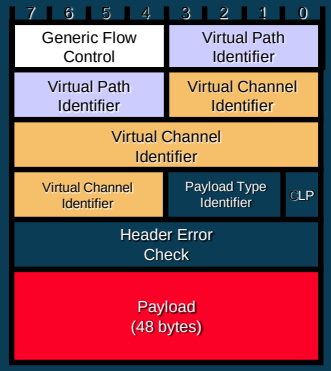
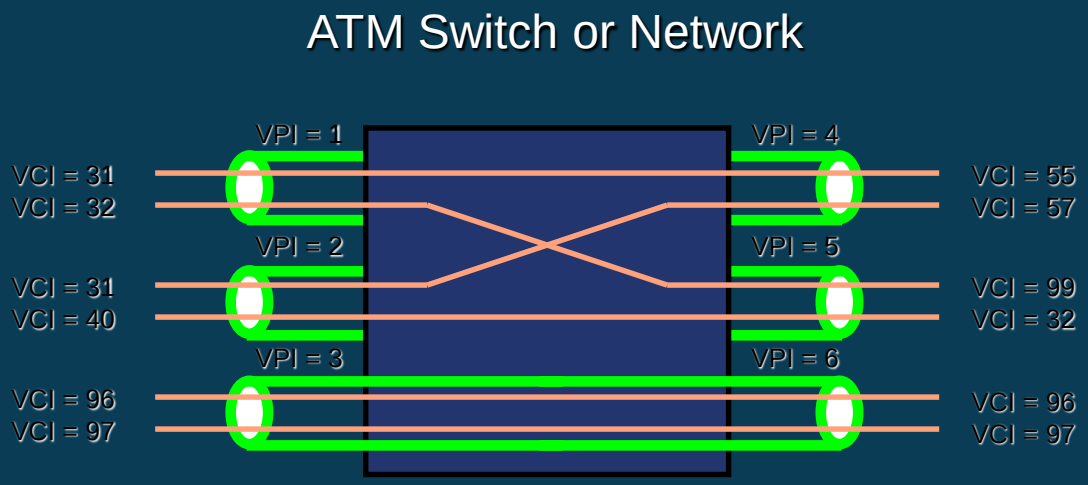
Virtual Paths and Virtual Channels





- Bundles of Virtual Channels are switched via Virtual Paths
- Virtual Path service from a carrier allows reconfiguration of Virtual Channels without service orders to carrier

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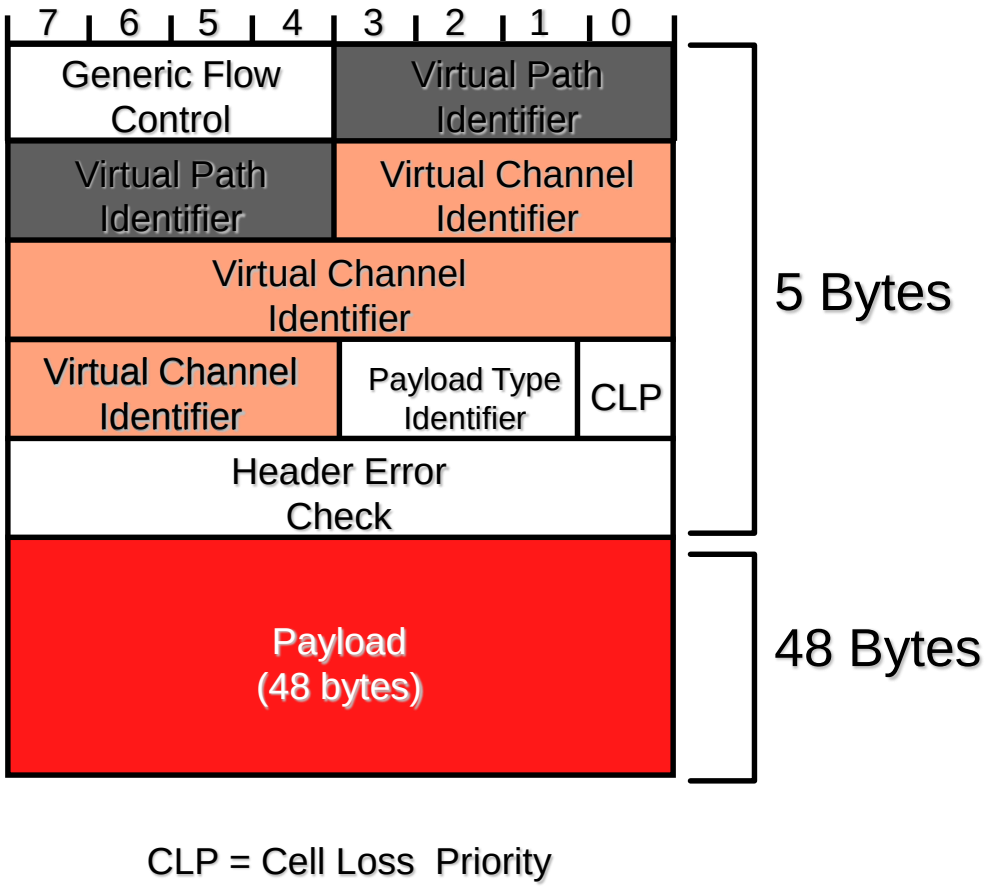
ATM Basics

- Logical or Virtual Connection
- Connection is first established using a signaling protocol
  - Route from the source to the destination is chosen
  - The same route is used for all cells (fixed size packets) of the connection
- No routing decision for every cell (they are switched in the same path)



CLP = Cell Loss Priority

Virtual Circuits in ATM

Virtual Circuit Identifier is represented jointly by:

- Virtual Channel Identifier (VCI)
- Virtual Path Identifier (VPI)

Virtual Channel (VC)

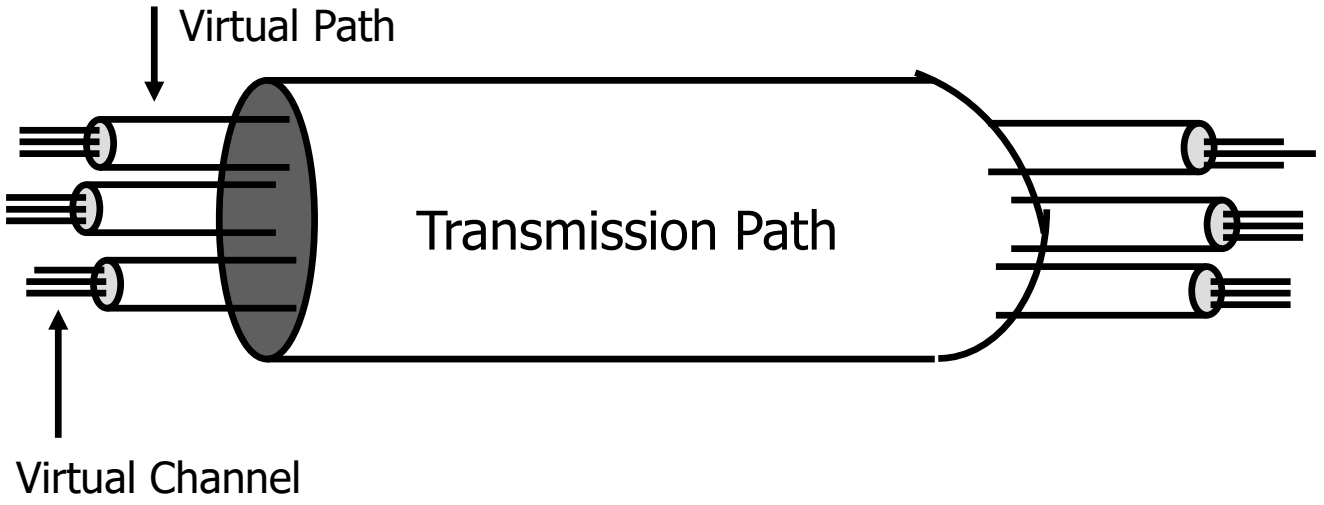
- Path for cell associated with a connection
- Supports transportation of a data stream
- Each VC is assigned a unique VCI on a link

Virtual Channels in ATM

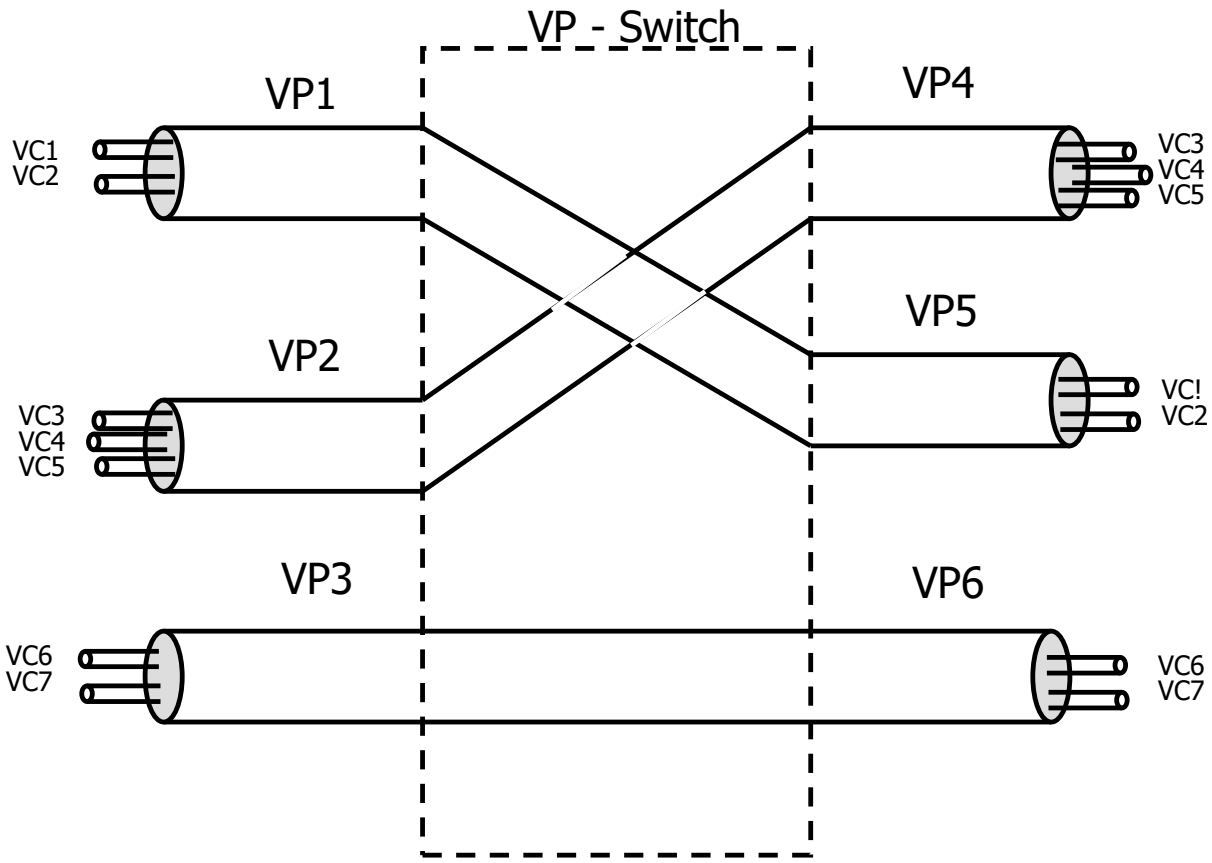
Virtual Path (VP)

- Grouping of virtual channels on a physical link
- Switching can be performed on the path basis:
  - reduced overheads
- Each virtual path is assigned Virtual Path Identifier (VPI)

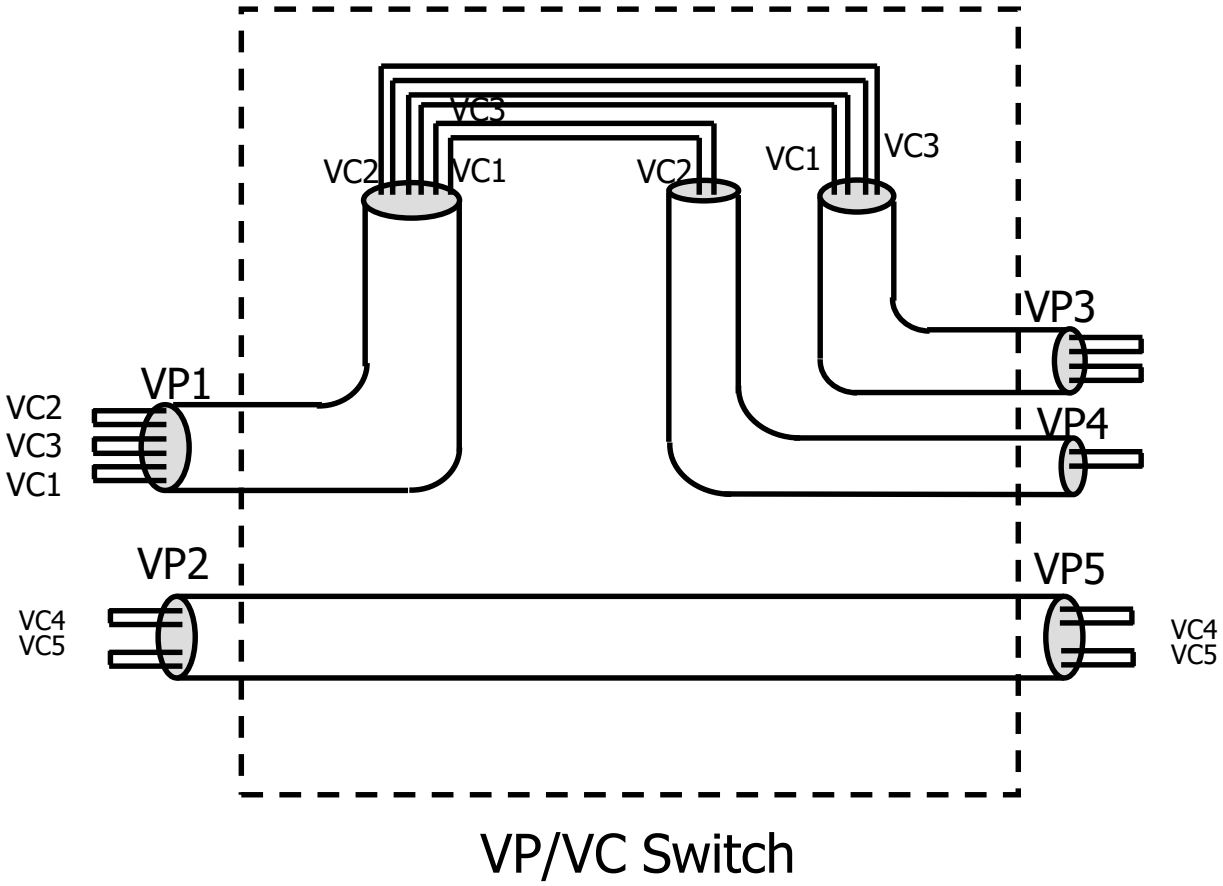
VCs In ATM



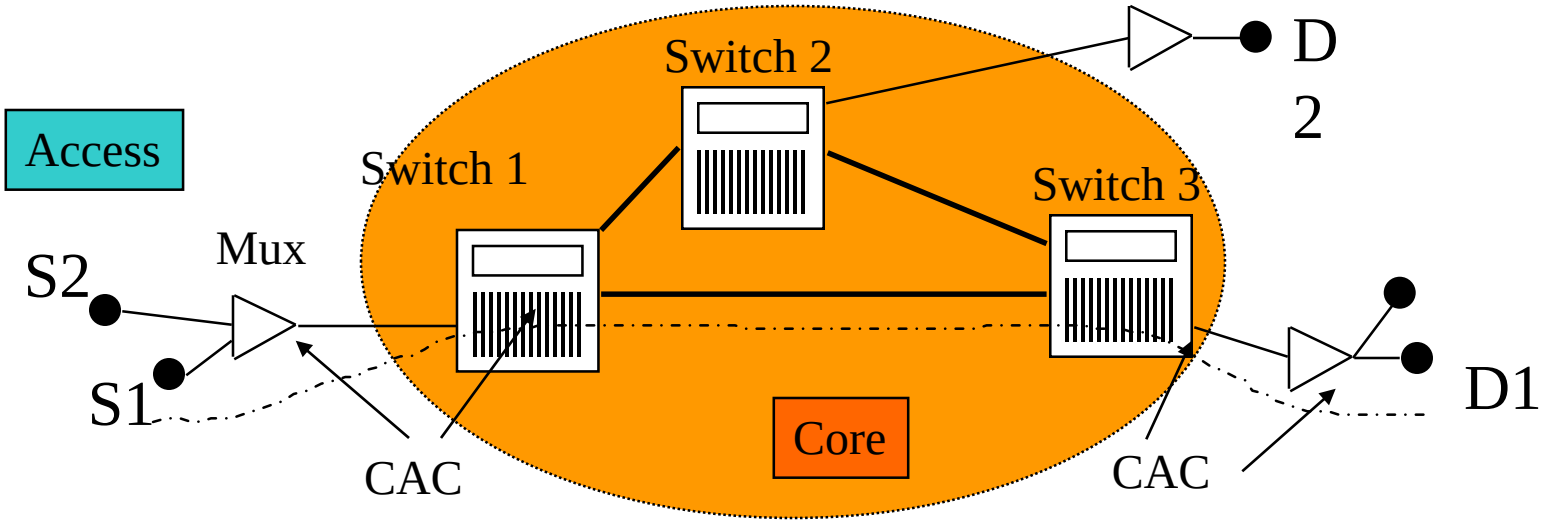
Virtual Path Switch
(VP - Switch)



VP / VC Switch


VC3
VC2
VC1
VC2
VC1
VC3
VP3
VP1
VC2
VC3
VC1
VP4
VP2
VP5
VC4
VC5
VC4
VC5
VP/VC Switch

ATM Network Example



- Each connection has its own traffic descriptors such as PCR, SCR, MBS, CDVT, CLR, MCR
- A Connection Admission Control algorithm (CAC) will check for the resources at queuing points to make a decision on admissibility
- Network efficiency depends upon the CAC

ATM Forum GS subclasses

- Constant Bit Rate (CBR)
  - constant, cell-smooth traffic
  - mean and peak rate are the same
  - e.g. telephone call evenly sampled and uncompressed
  - constant bandwidth, variable quality
- Variable Bit Rate (VBR)
  - long term average with occasional bursts
  - try to minimize delay
  - can tolerate loss and higher delays than CBR
  - e.g. compressed video or audio with constant quality, variable bandwidth

ATM Forum BE subclasses

- Available Bit Rate (ABR)
  - users get whatever is available
  - zero loss if network signals (in RM cells) are obeyed
  - no guarantee on delay or bandwidth
- Unspecified Bit Rate (UBR)
  - like ABR, but no feedback
  - no guarantee on loss
  - presumably cheaper
- Guaranteed Frame Rate (GFR)
  - like UBR/ABR, expressed in terms of frame rate

ATM Attributes

- How do we describe a flow (connection) of ATM Service?
  - Service Category
  - Traffic Parameters or descriptors
  - QoS parameters
  - Congestion (for ABR)
  - Other (for UBR)
  - Cell Loss Priority (CLP=0 or CLP=0+1)
- Connections are signaled with various parameters
- A Connection Admission Control (CAC) procedure checks for resources in the network
- If connection is accepted, a “traffic contract” is awarded to the user (Service Level Agreement)

Traffic Descriptors or Parameters

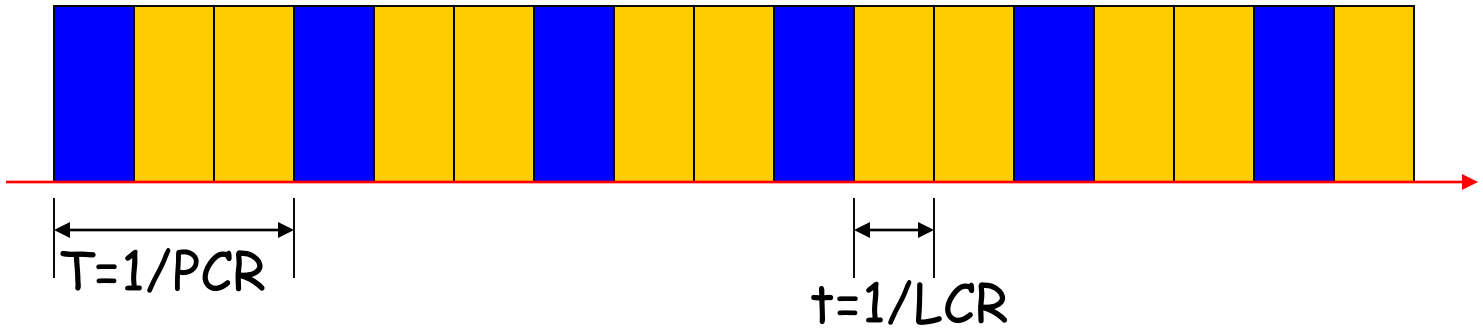
- Connection Traffic Descriptor
  - *Source Traffic Descriptor*: PCR, SCR, MBS, MCR, MFS
  - *Cell Delay Variation Tolerance (τ):* upper bound on amount of cell delay that is introduced by the network interface and the UNI (due to interleaving, physical layer overhead, multiplexing, etc.)
  - *Conformance Definition:* unambiguous specification of conforming cells of a connection at the User-Network-Interface UNI (a policing function is used to check for conformance such as Generic Cell Rate Algorithm (GCRA))

Traffic Parameters (Source Traffic Descriptor)

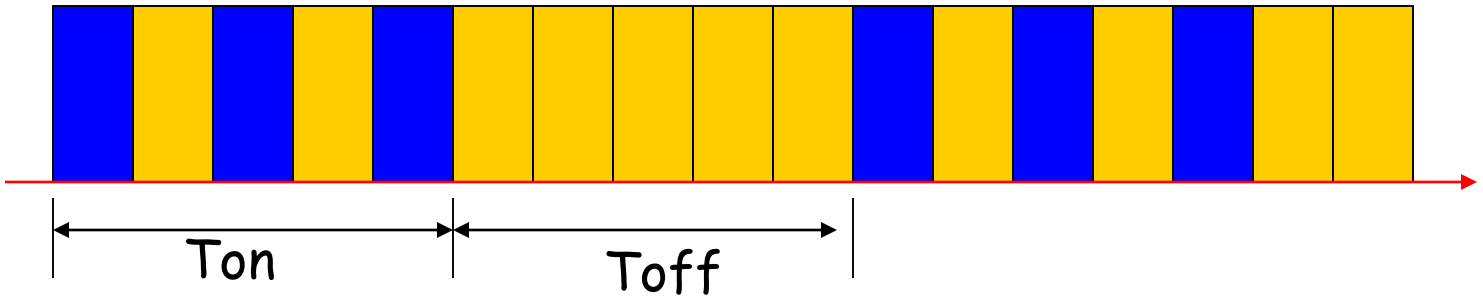
- *Peak Cell Rate (PCR):* upper bound on traffic submitted by source (PCR = 1/T, where T = minimum cell spacing)
- *Sustainable Cell Rate (SCR):* upper bound on "average rate" of traffic submitted by source (over a larger T)
- *Maximum Burst Size (MBS):* maximum number of cells sent continuously *at Peak Cell Rate (PCR)*
- *Minimum Cell Rate (MCR):* used with ABR, and GFR minimum cell rate requested, access to unused capacity up to PCR (elastic capacity = PCR-MCR)
- *Maximum Frame Size (MFS):* maximum size of a frame in cells available for GFR service

Cell Rates

- Peak Cell Rate (PCR), Line Cell Rate (LCR)

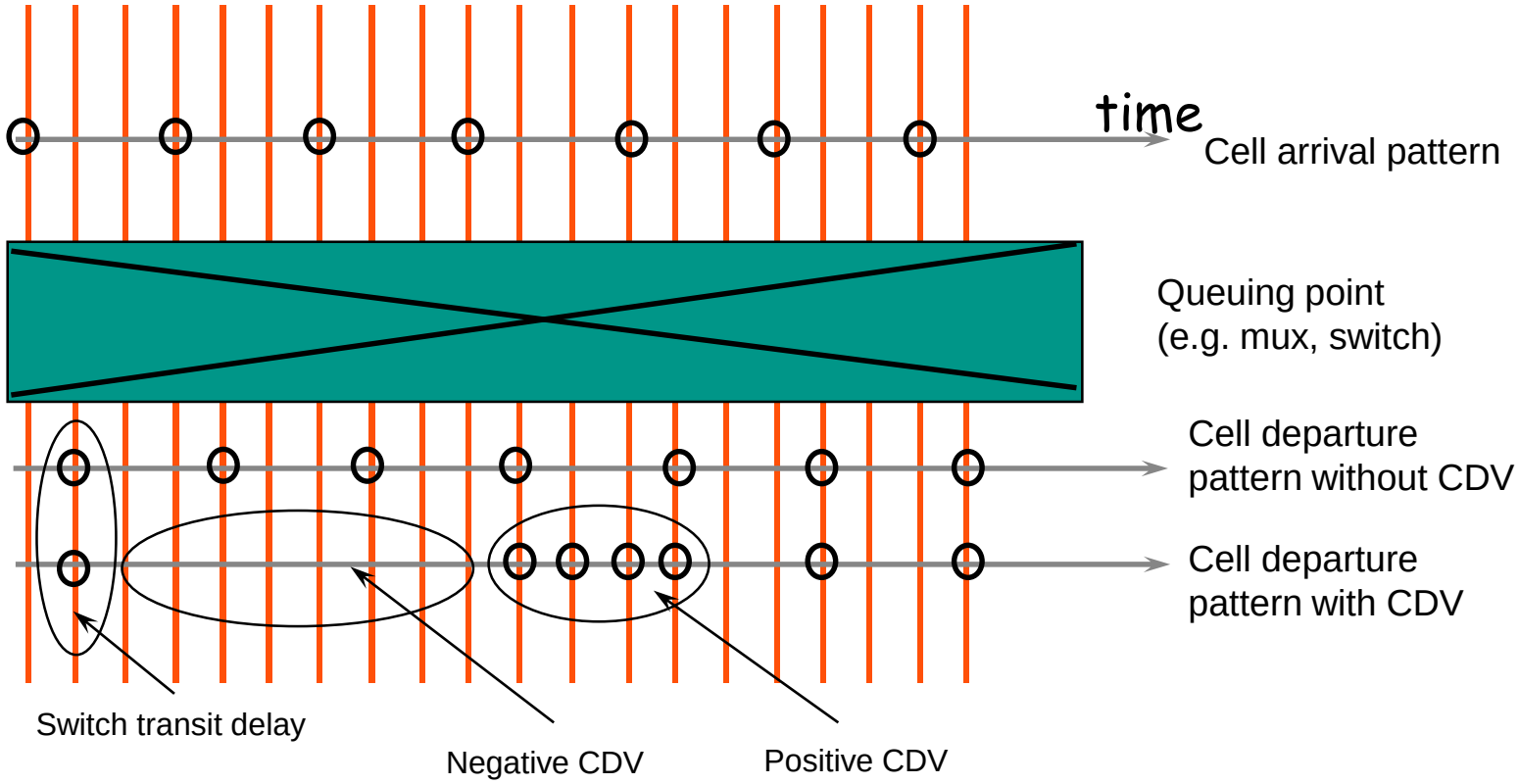


- Sustained Cell Rate (SCR) = PCR*(Ton/Ton+Toff)

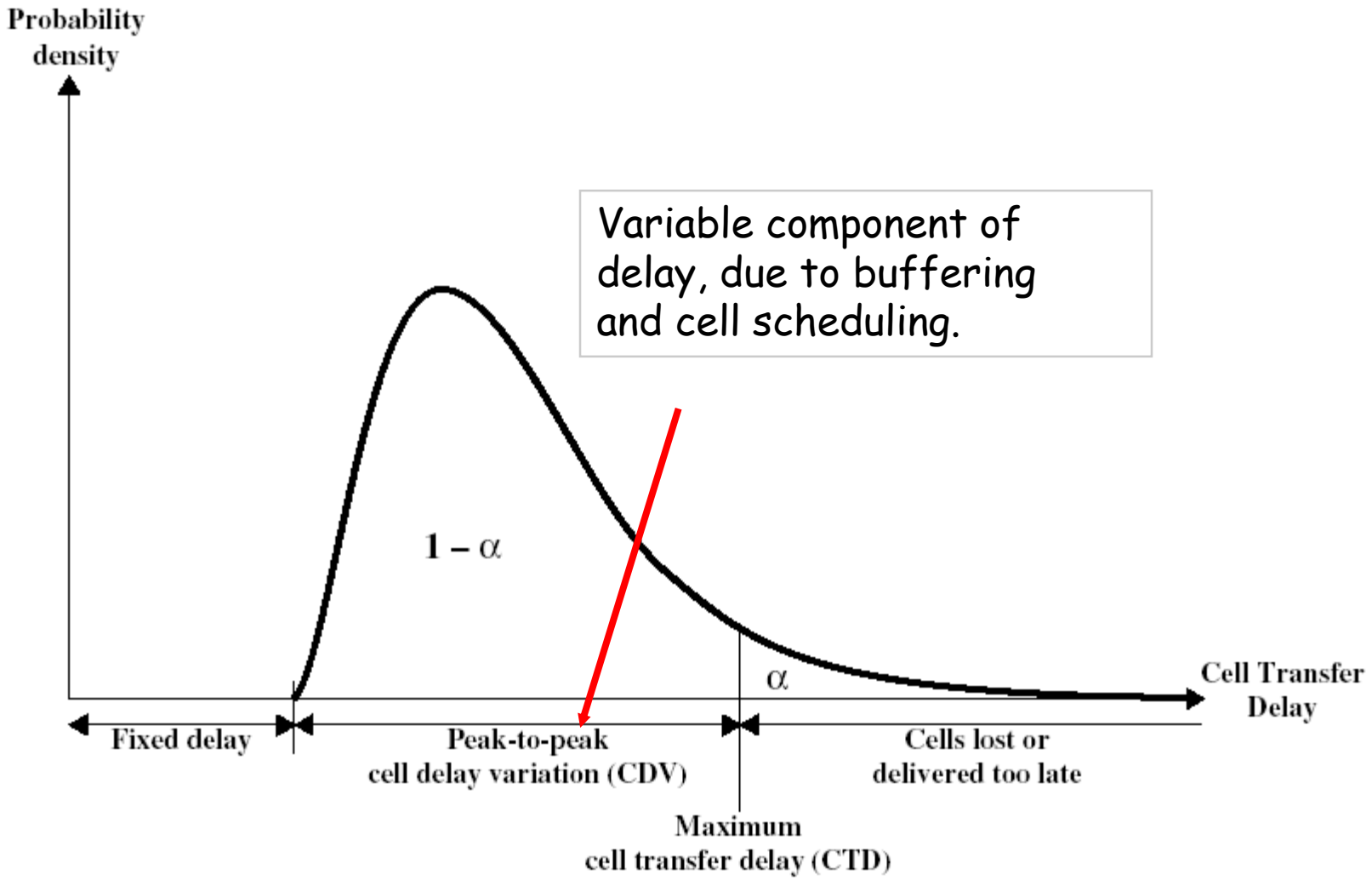


Quality of Service

- Cell Transfer Delay (CTD)
- Cell Delay Variation (CDV)



Cell Transfer Delay Probability Density



QoS Parameters

- *Peak-to-peak cell delay variation (CDV):* acceptable delay variation at destination. The peak-to-peak CDV is the (1 - α) quantile of the CTD minus the fixed CTD that could be experienced by any delivered cell on a connection during the entire connection holding time.
- *Maximum Cell Transfer Delay (maxCTD):* maximum time between transmission of first bit of a cell at the source UNI to receipt of its last bit at the destination UNI
- *Cell Loss Ratio:* ratio of lost cells to total transmitted cells on a connection = *Lost Cells/Total Transmitted Cells*

Other Attributes

- Congestion Control
  - defined only for ABR service category
  - uses network feedback controls
  - ABR flow control mechanism (more later)
- Other Attributes (introduced July 2000)
  - Behavior class selector (BCS):
    - for IP differentiated services (DiffServ)
    - provides for different levels of service among UBR connections
    - implementation dependent, no guidance in specs
  - Minimum desired cell rate (MDCR):
    - UBR application minimum capacity objective

Attributes of Each Service Category

	ATM Layer Service Category					
Attribute	**CBR**	**rt-VBR**	**nrt-VBR**	**UBR**	**ABR**	**GFR**
Traffic Parameters[4]						
PCR, CDVT[5]	Specified			Specified[2]	Specified[3]	Specified
SCR, MBS, CDVT[5]	N/A	Specified		N/A		
MCR	N/A				Specified	N/A
MCR, MBS, MFS, CDVT[5]	N/A					Specified
QoS Parameters						
Peak-to-peak CDV	Specified		Unspecified			
Max CTD	Specified		Unspecified			
CLR	Specified			Unspecified	See note 1	See note 6
Congestion Control						
Feedback	Unspecified				Specified	Unspecified
Other Attributes						
BCS	Unspecified			Optional	Unspecified	
MDCR[7]	N/A			Optional	N/A	

Service Paradigm

- Quantitative Commitments
  - Sets explicit values
  - Ensures service quality through resource allocation and traffic policing
- Qualitative Commitments
  - Relative measure and no explicit guarantees
  - Some unspecified level of quality through “network engineering”

Quantitative Commitments

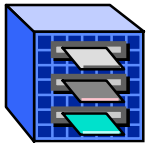
- Generally connection oriented transport
- Network nodes maintain *per-flow state info*
- QoS (or GOS) requirements of each connection is explicitly *specified* and *signaled*
- Network *enforces* traffic regulation (policing, shaping) if necessary and *allocates* resources for each connection
- Examples: *Voice networks (POTS), ATM, FR*
- Expensive and under-utilized

Qualitative Commitments

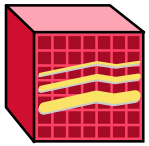
- Generally connection less transport
- no *per-flow state info* is maintained due to *flow aggregation*
- QoS requirements are not explicitly specified
- Network may not enforce traffic regulation
- May allocate resources for logical groups (such as VPN)
- Examples: *IP, LANs*
- Cheap and over-utilized

QoS Building Blocks

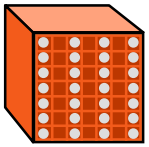
- **Backbone supporting QoS: speed and scale**



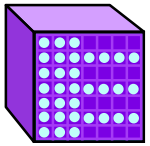
- **Packet / Service classification (sorting)**



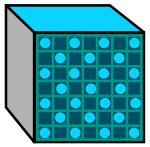
- **Bandwidth management and admission control**



- **Queue management**



- **Congestion management**



- **Granular measurements**

Functions Needed

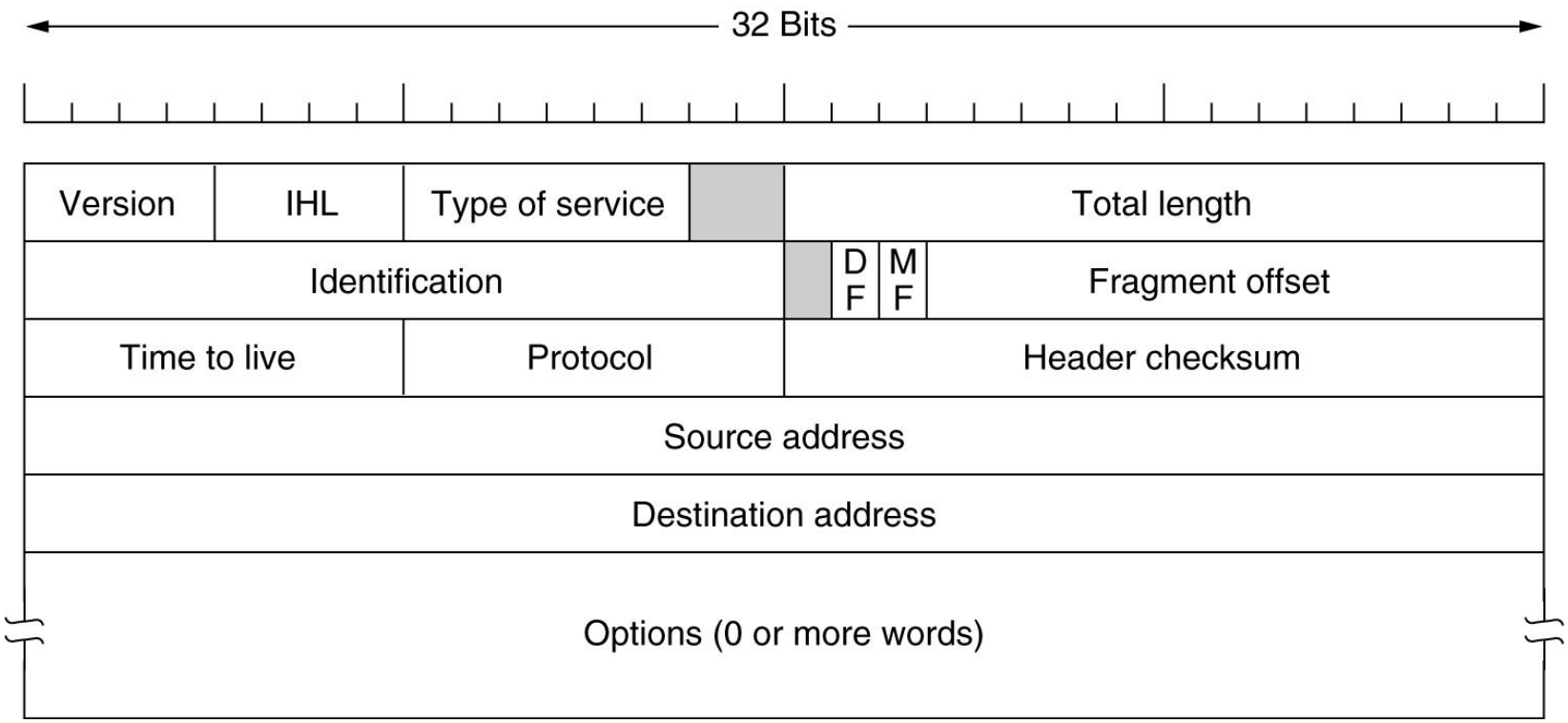
- *Admission control* - some way to limit usage relative to resources.
- *Packet scheduling* - some way to treat different packets differently.
- *Classifier mechanism* - some way to sort packets into different treatment groups.
- *Policies and rules* for allocating resources.

IETF (Internet Engineering Task Force)

- Internet currently provides only single class of “best-effort” service.
  - No admission control and no assurances about delivery
- Existing applications are *elastic.*
  - Tolerate delays and losses
  - Can adapt to congestion
- Future “real-time” applications may be inelastic.
- Should we modify these applications to be more adaptive or should we modify the Internet to support inelastic behavior?

IETF ToS (1-byte Type-of-Service)

- Bits 0-2: Precedence.
- Bit 3: 0 = Normal Delay, 1 = Low Delay.
- Bits 4: 0 = Normal Throughput, 1 = High Throughput.
- Bits 5: 0 = Normal Relibility, 1 = High Relibility.
- Bit 6-7: Reserved for Future Use



IETF int-serv (Integrated Services)

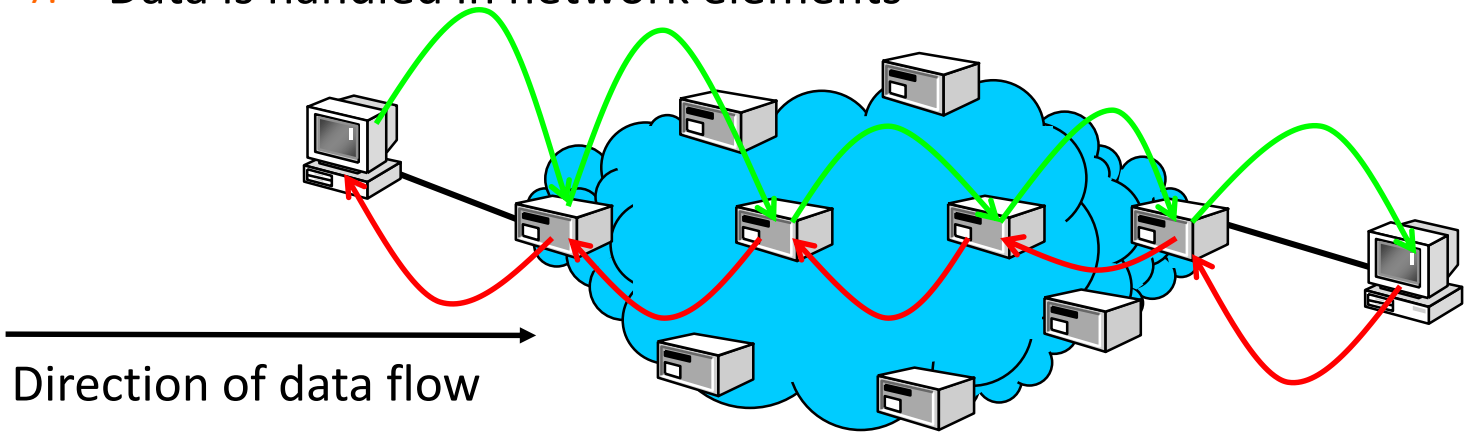
- Focus on per-flow QoS.
  - Support specific applications such as video streaming.
  - Based on mathematical guarantees.
- Many concerns:
  - Complexity
  - Scalability
  - Business model
  - Charging
- Uses RSVP (Resource-Reservation Protocol)
  - To signal QoS requirements

IETF int-serv (Integrated Services)

- Guaranteed service
  - Targets hard real-time applications.
  - User specifies traffic characteristics and a service requirement.
  - Requires admission control at each of the routers.
  - Can mathematically guarantee bandwidth, delay, and jitter.
- Controlled load.
  - Targets applications that can adapt to network conditions within a certain performance window.
  - User specifies traffic characteristics and bandwidth.
  - Requires admission control at each of the routers.
  - Guarantee not as strong as with the guaranteed service.
    - e.g., measurement-based admission control.
- Best effort

RSVP

1. Sender sends PATH message to network
2. PATH leads data through the network
3. Routers install per-flow state
4. Receiver responds with RESV
5. RESV follows PATH trail back towards sender
6. Routers accept resource request (commit resources to flow) or reject resource request
7. Data is handled in network elements



IETF GS subclasses

- Tolerant GS
  - nominal mean delay, but can tolerate “occasional” variation
  - not specified what this means exactly
  - uses *controlled-load* service
  - even at “high loads”, admission control assures a source that its service “does not suffer”
  - it really is this imprecise!
- Intolerant GS
  - need a worst case delay bound
  - equivalent to CBR+VBR in ATM Forum model

IETF BE subclasses

- Interactive burst
  - bounded asynchronous service, where bound is qualitative, but pretty tight
    - e.g. paging, messaging, email
- Interactive bulk
  - bulk, but a human is waiting for the result
  - e.g. FTP
- Asynchronous bulk
  - junk traffic
  - e.g netnews

IETF Diff-Serv (Differentiated Services)

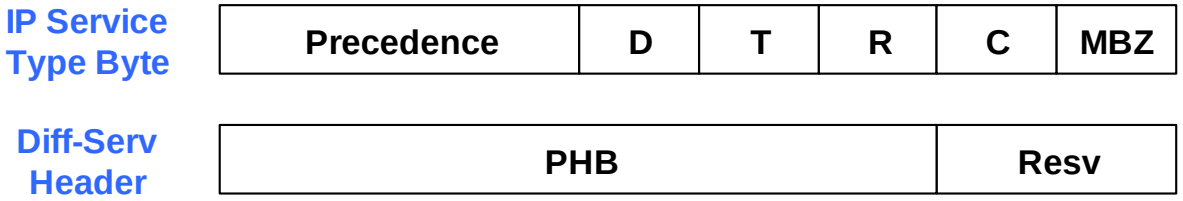
- Intended to address the following difficulties with Intserv and RSVP;
- **Scalability**: maintaining states by routers in high speed networks is difficult due to the very large number of flows
- **Flexible Service Models**: Intserv has only two classes, want to provide more qualitative service classes; want to provide ‘relative’ service distinction (Platinum, Gold, Silver, …)
- **Simpler signaling**: (than RSVP) many applications and users may only want to specify a more qualitative notion of service

Diffserv PHB (Per-Hop-Behavior)

- Packet is marked in the Type of Service (TOS) in IPv4, and Traffic Class in IPv6.
- 6 bits used for Differentiated Service Code Point (DSCP) and determine PHB that the packet will receive.
  - EF, 4 classes of AF, each with 3 drop priorities (AF11, AF12, AF13, AF21, AF22, AF23, AF31, AF32, AF33, AF41, AF42, AF43)and Best-Effort (BE)
- 2 bits are currently unused.

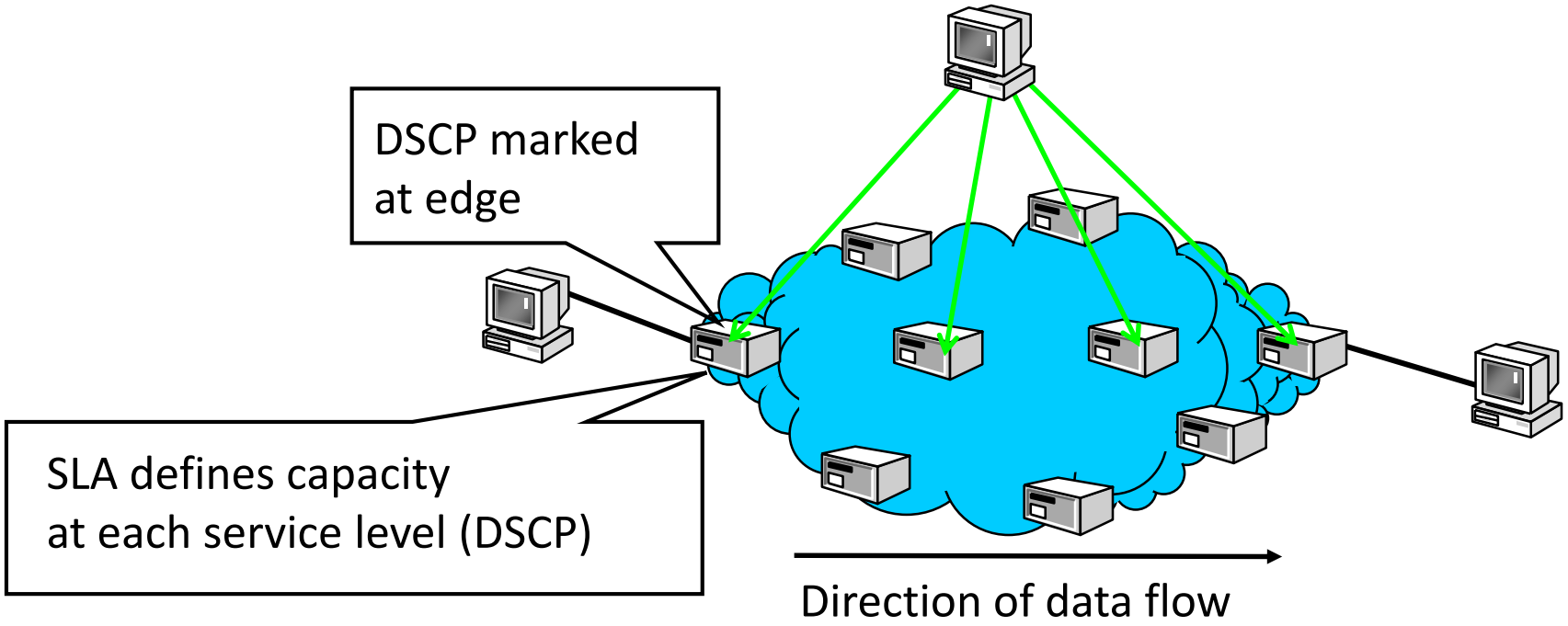
PHB: *Class Selector*

- Derived from IP Precedence values
- 6 bit diff-serv code point (DSCP) determines per-hop behavior of packet treatment
  - Expedited Forwarding (EF): low loss and latency
  - Assured Forwarding (AF): 4 classes, 3 drop precedence
  - Best Effort (BE): classical IP
- No absolute guarantees

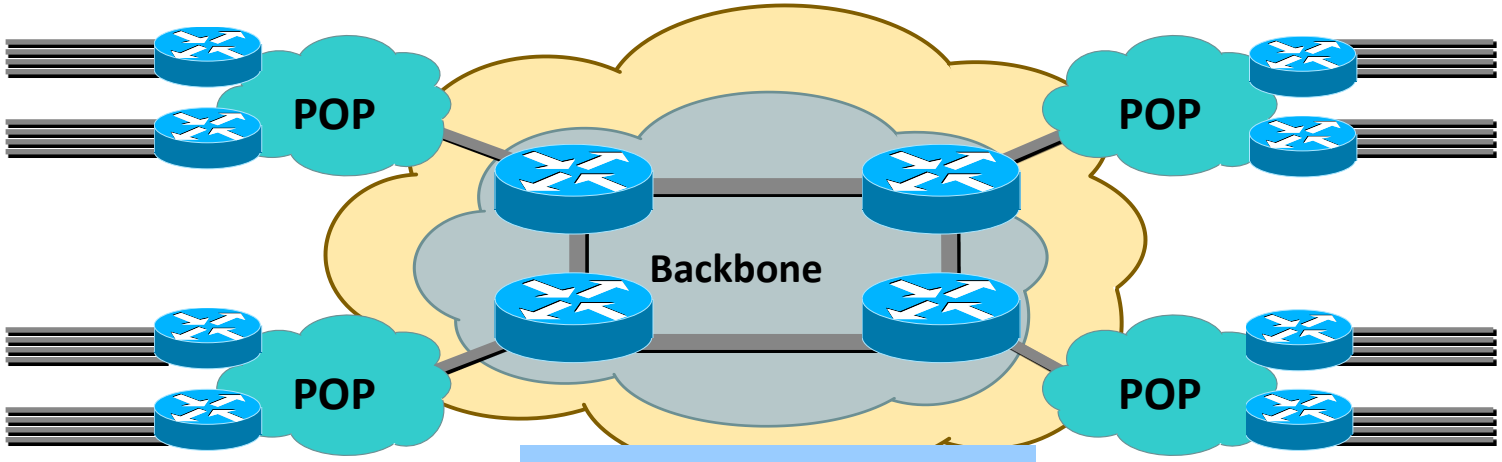


DiffServ

1. Routers configured for certain PHBs (Per Hop Behavior)
2. Resources are allocated to PHBs
3. Edge routers are configured to mark DSCP (requests PHB) based on classification information
4. Traffic arriving at edge router marked with DSCP
5. Traffic in core routers go to PHB requested by DSCP



Diff-Serv Network Architecture



Scalable Solutions Require Cooperative Edge and Backbone Functions

Edge Functions

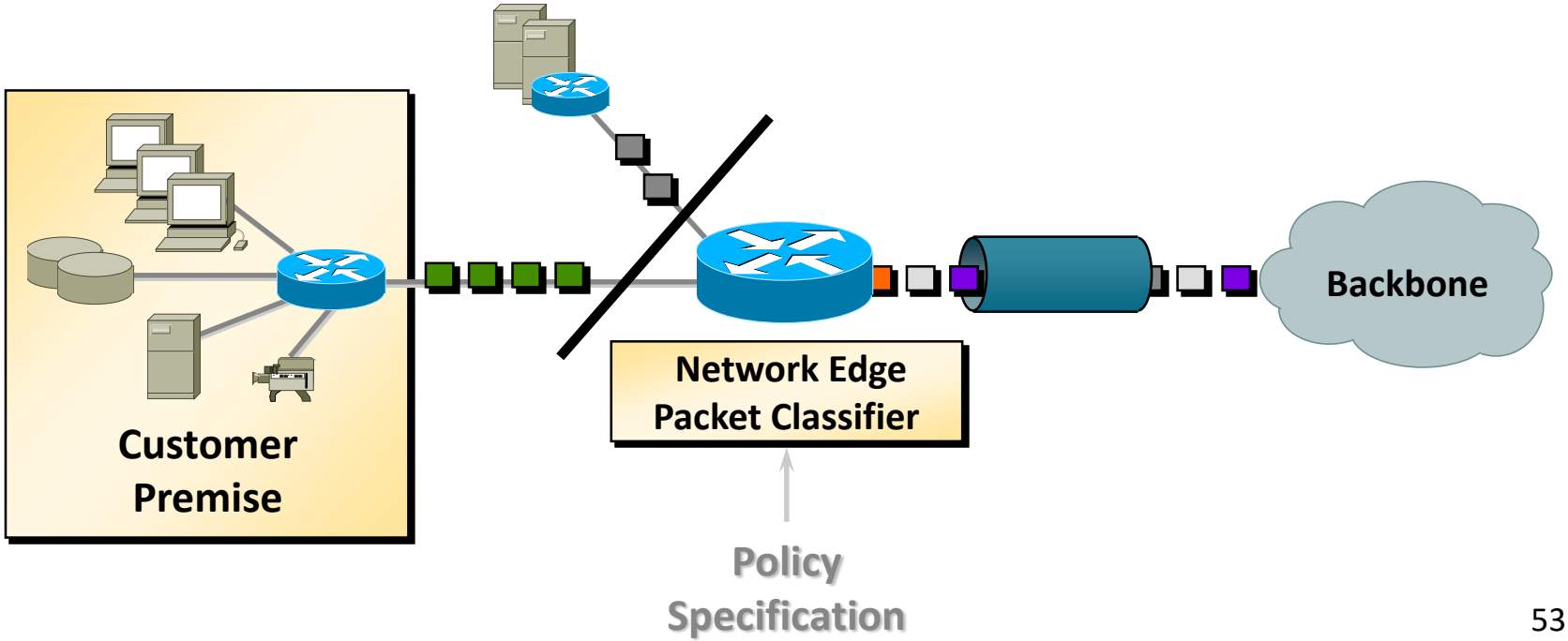
- Packet classification
- Bandwidth management
- L3 metering
- Security filtering
- Access aggregation

Backbone Functions

- High-speed switching and transport
- QoS enforcement
- QoS interworking

Packet Classification

- **Up to six traffic classes via ToS precedence bits**
- **Classification by physical port, IP address, application, IP protocol, etc.**
- **Network or external assignment**



Multi-field Packet Classification

	L3-DA	L3-SA	.....	L4-PROT	
	Field 1	Field 2	...	Field k	Action
Rule 1	5.3.40.0/21	2.13.8.11/32	...	UDP	A_1
Rule 2	5.168.3.0/24	152.133.0.0/16	...	TCP	A_2
...	...	...	...	...	...
Rule N	5.168.0.0/16	152.0.0.0/8	...	ANY	A_N

Example: packet (5.168.3.32, 152.133.171.71, …, TCP)

Packet Classification: Find the action associated with the highest priority rule matching an incoming packet header.

Courtesy Nick McKeown@Stanford

Formal Problem Definition

Given a classifier *C* with *N* rules, R_j, $1 \leq j \leq N$, where R_j consists of three entities:

1) A regular expression $R_j[i]$, $1 \leq i \leq d$, on each of the *d* header fields,
2) A number, $pri(R_j)$, indicating the priority of the rule in the classifier, and
3) An action, referred to as $action(R_j)$.

For an incoming packet P with the header considered as a *d-tuple* of points $(P_1, P_2, \ldots, P_d)$, the *d-dimensional packet classification problem is to* find the rule R_m with the highest priority among all the rules Rj matching the *d-tuple;* i.e., $pri(R_m) > pri(R_j)$, $\forall\ j \neq m$, $1 \leq j \leq N$, such that P_i matches $R_j[i]$, $1 \leq i \leq d$. We call rule R_m the *best matching rule* for packet P.

Courtesy Nick McKeown@Stanford

Routing Lookup: Instance of 1D Classification

- One-dimension (destination address)
- Forwarding table ≡ classifier
- Routing table entry ≡ rule
- Outgoing interface ≡ action
- Prefix-length ≡ priority

Courtesy Nick McKeown@Stanford

Example 4D Classifier

Rule	L3-DA	L3-SA	L4-DP	L4-PROT	Action
R1	152.163.190.69/255.255.255.255	152.163.80.11/255.255.255.255	*	*	Deny
R2	152.168.3/255.255.255	152.163.200.157/255.255.255.255	eq www	udp	Deny
R3	152.168.3/255.255.255	152.163.200.157/255.255.255.255	range 20-21	udp	Permit
R4	152.168.3/255.255.255	152.163.200.157/255.255.255.255	eq www	tcp	Deny
R5	*	*	*	*	Deny

Courtesy Nick McKeown@Stanford

Example Classification Results

Pkt Hdr	L3-DA	L3-SA	L4-DP	L4-PROT	Rule, Action
P1	152.163.190.69	152.163.80.11	www	tcp	R1, Deny
P2	152.168.3.21	152.163.200.157	www	udp	R2, Deny

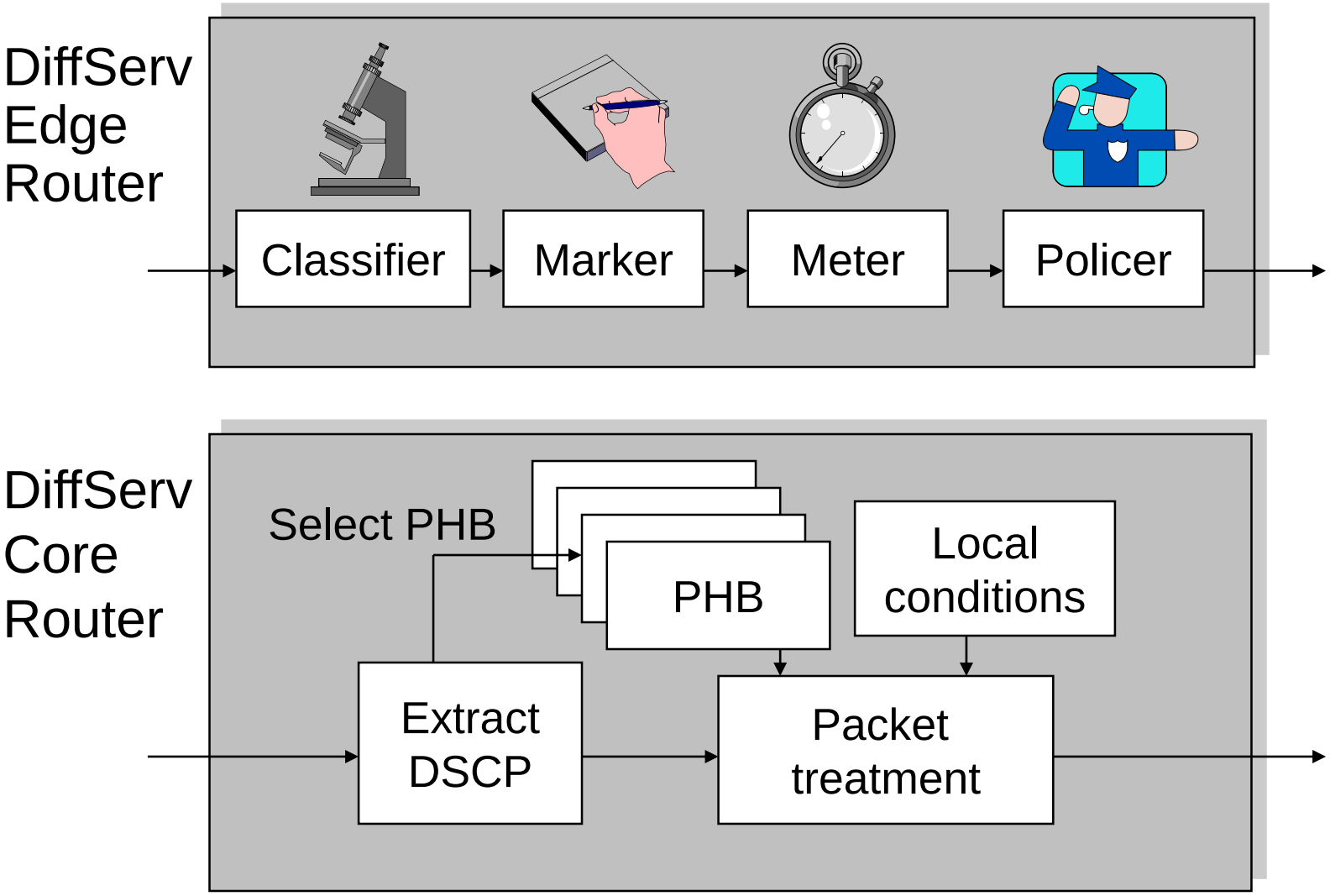
Courtesy Nick McKeown@Stanford

Classification algorithms

- Types
  - Linear search
  - Associative search
  - Trie-based techniques
  - Crossproducting
  - Heuristic algorithms
- Algorithms So far
  - Good for two fields, but do not scale to more than two fields, OR
  - Good for very small classifiers (< 50 rules) only, OR
  - Have non-deterministic classification time, OR
  - Either too slow or consume too much storage

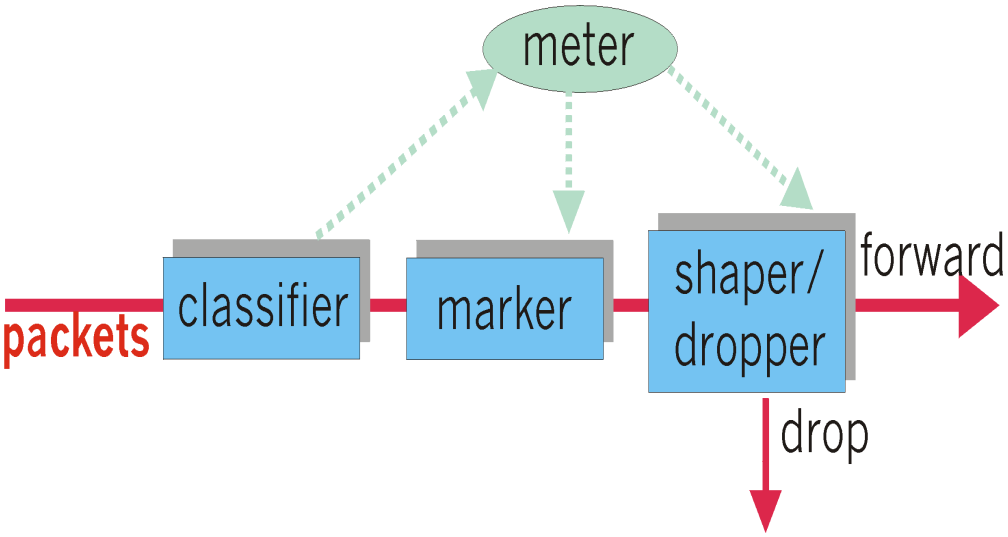
Another Project Item

DiffServ Routers



Edge Router/Host Functions

- **Classification**: marks packets according to classification rules to be specified.
- **Metering:** checks whether the traffic falls within the negotiated profile.
- **Marking**: marks traffic that falls within profile.
- **Conditioning**: delays and then forwards, discards, or remarks other traffic.



Core Functions

- **Forwarding**: according to “Per-Hop-Behavior” or PHB specified for the particular packet class; such PHB is strictly based on class marking (no other header fields can be used to influence PHB).

- BIG ADVANTAGE:

  No state info to be maintained by routers!

Forwarding (PHB)

- PHB results in a different observable (measurable) forwarding performance behavior.
- PHB does not specify what mechanisms to use to ensure required PHB performance behavior.
- Examples:
  - Class A gets x% of outgoing link bandwidth over time intervals of a specified length.
  - Class A packets leave first before packets from class B.

Forwarding (PHB)

- **Expedited Forwarding (EF):**
  - Guarantees a certain minimum rate for the EF traffic.
  - Implies isolation: guarantee for the EF traffic should not be influenced by the other traffic classes.
  - Admitted based on peak rate.
  - Non-conformant traffic is dropped or shaped.
  - Possible service: providing a virtual wire.

Forwarding (PHB)

- **Assured Forwarding (AF)**:
  - AF defines 4 classes with some bandwidth and buffers allocated to them.
  - The intent is that it will be used to implement services that differ relative to each other (e.g., gold, silver,…).
  - Within each class, there are three drop priorities, which affect which packets will get dropped first if there is congestion.
  - Lots of studies on how these classes and drop priorities interact with TCP flow control.
  - Non-conformant traffic is remarked.

Example of EF: A Virtual Leased Line Service

- Service offers users a dedicated traffic pipe.
  - Guaranteed bandwidth between two points.
  - Very low latency and jitter since there should be no queuing delay (*peak rate allocation*).
- Admission control makes sure that all links in the network core have sufficient EF bandwidth.
  - Simple case: sum of all virtual link bandwidth is less than the capacity of the slowest link.
- Traffic enforcement for EF traffic limits how much EF traffic enters the network.

Differentiated Services Issues

- The key to making Diffserv work is bandwidth management in the network core.
  - Simple for simple services such as the virtual pipe, but it is much more challenging for complex service level agreements.
  - Notion of a “bandwidth broker” that manages the core network bandwidth.
- Definition of end-to-end services for paths that cross networks with different forwarding behaviors
  - Some packets will be handled differently in different routers.
  - Some routers are not DiffServ capable.
- Per-Domain Behavior (PDB)

Some points to ponder

- The only thing out there is CBR and asynchronous bulk!
- There are application requirements. There are also organizational requirements (link sharing)
- Users needs QoS for other things too!
  - billing
  - privacy and security
  - reliability and availability

Outline

- Economic principles
- Traffic classes
- Time scales
- Mechanisms
- Some open problems

Time scales

- Some actions are taken once per call
  - tell network about traffic characterization and request resources
  - in ATM networks, finding a path from source to destination
- Other actions are taken during the call, every few round trip times
  - feedback flow control
- Still others are taken very rapidly,during the data transfer
  - scheduling
  - policing and regulation
- Traffic management mechanisms must deal with a range of traffic classes at a range of time scales

Summary of mechanisms at each time scale

- Less than one round-trip-time (cell or packet level)
  - Scheduling and buffer management
  - Regulation and policing
  - Policy routing (datagram networks)
- One or more round-trip-times (burst-level)
  - Feedback flow control
  - Retransmission
  - Renegotiation

Summary (cont.)

- Session (call-level)
  - Signaling
  - Admission control
  - Service pricing
  - Routing (connection-oriented networks)
- Day
  - Peak load pricing
- Weeks or months
  - Capacity planning