

Traffic Engineering (TE) & Multiprotocol Label Switching (MPLS)

Redes de Comunicações II

**Licenciatura em
Engenharia de Computadores e Informática
DETI-UA**

Traffic Engineering (TE)

- Network Engineering

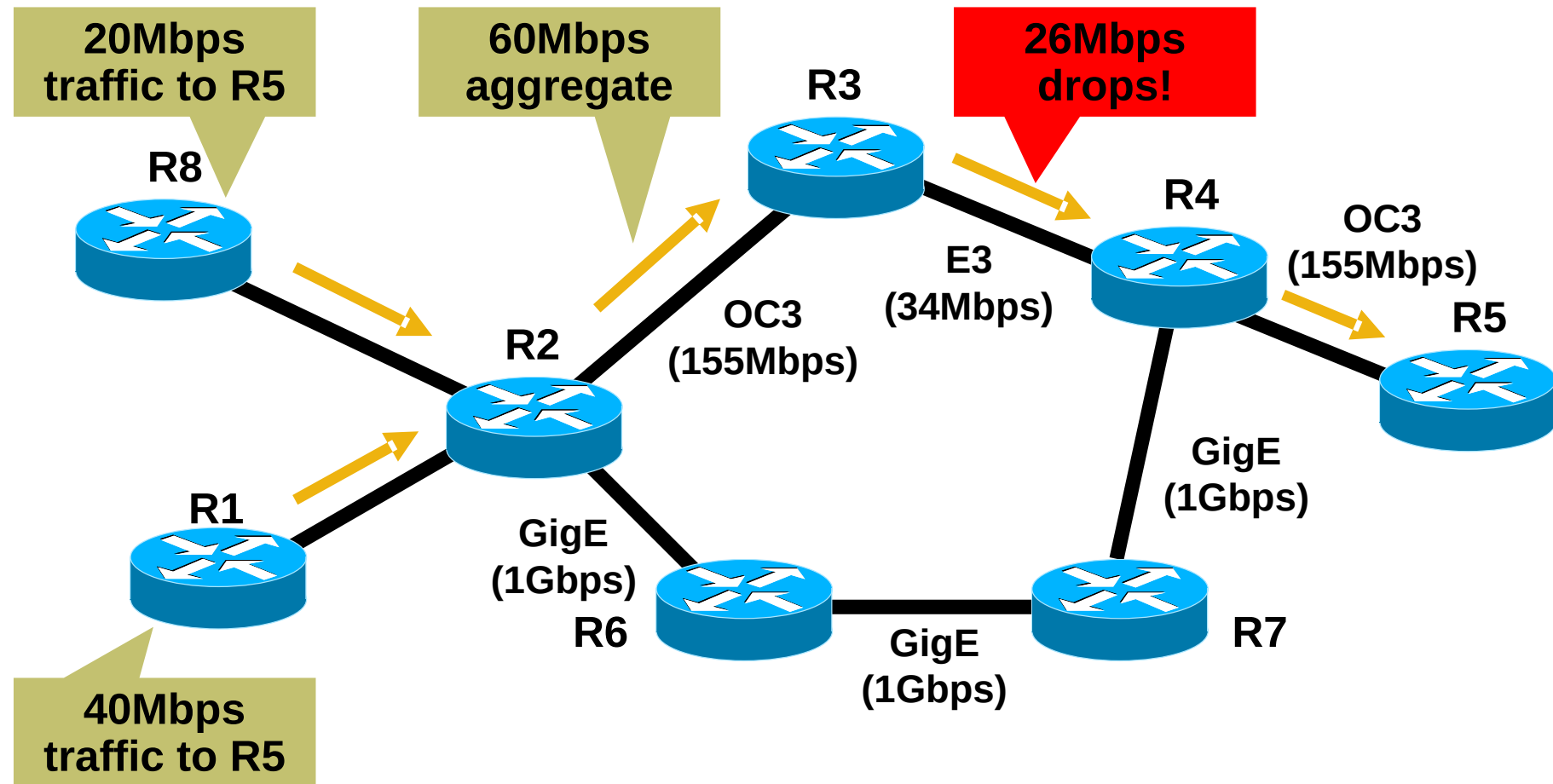
- ♦ Build your network to carry your predicted traffic!
- ♦ Traffic patterns are impossible to predict!
- ♦ Routing is based on the destination and does not allow to take the maximum possible advantage of the network resources.
- ♦ IP source routing (using options field of IP header) is not usable in practice due to security reasons.

- Traffic Engineering

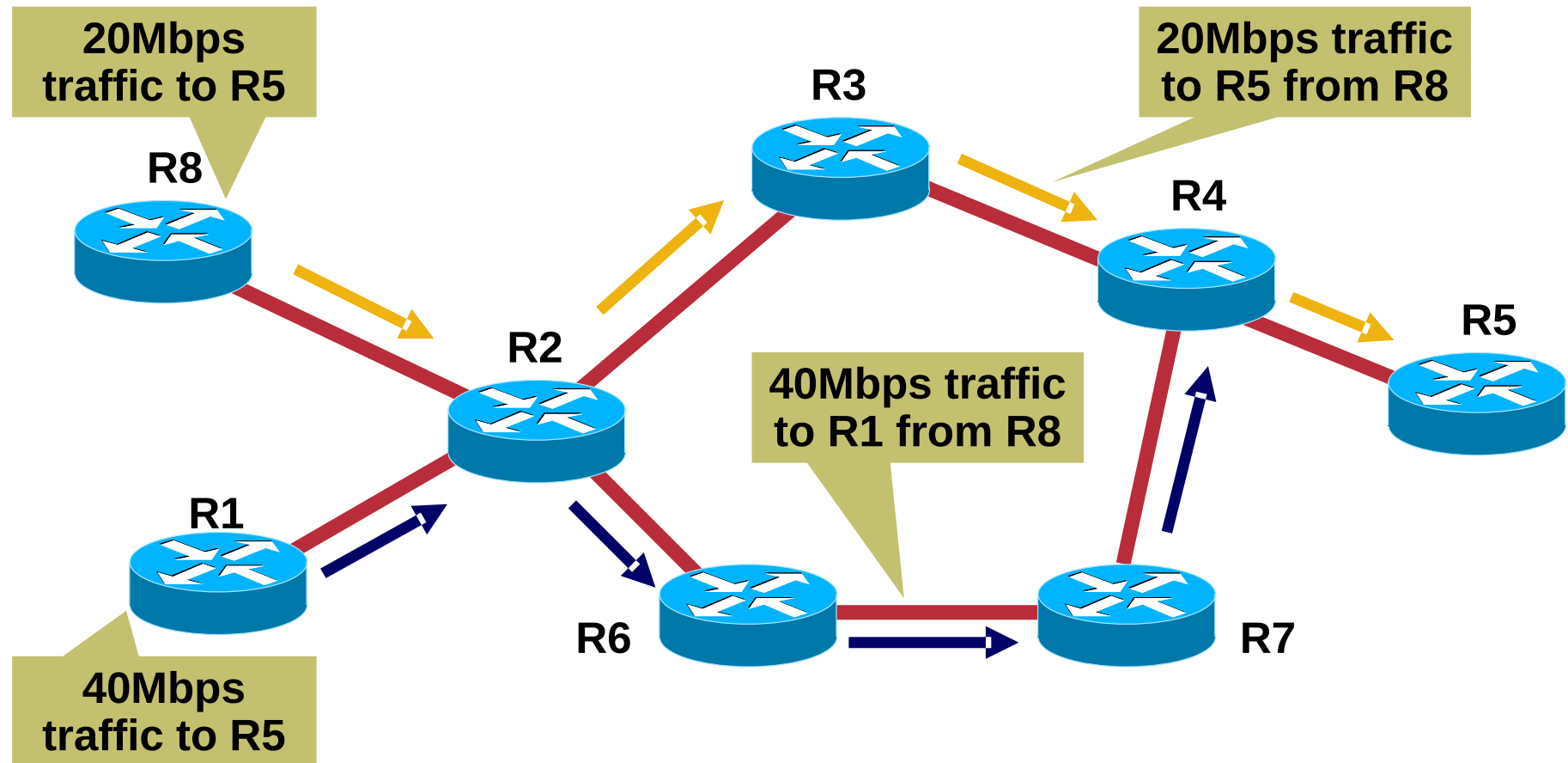
- ♦ Manipulate your traffic path to fit your network!
 - Can be done with routing protocol costs (difficult deployment), or MPLS.
 - With RIP or OSPF or ANY OTHER IGP it is not possible to condition multiple traffic flows.
- ♦ Increase efficiency of bandwidth resources.
 - Prevent over-utilized (congested) links whilst other links are under-utilized.
- ♦ Ensure the most desirable/appropriate path for some/all traffic.
 - Override the shortest path selected by the routing protocols.



Shortest Path and Congestion



A TE Solution



Tunnels are **UNI-DIRECTIONAL**



Normal path: R8 > R2 > R3 > R4 > R5

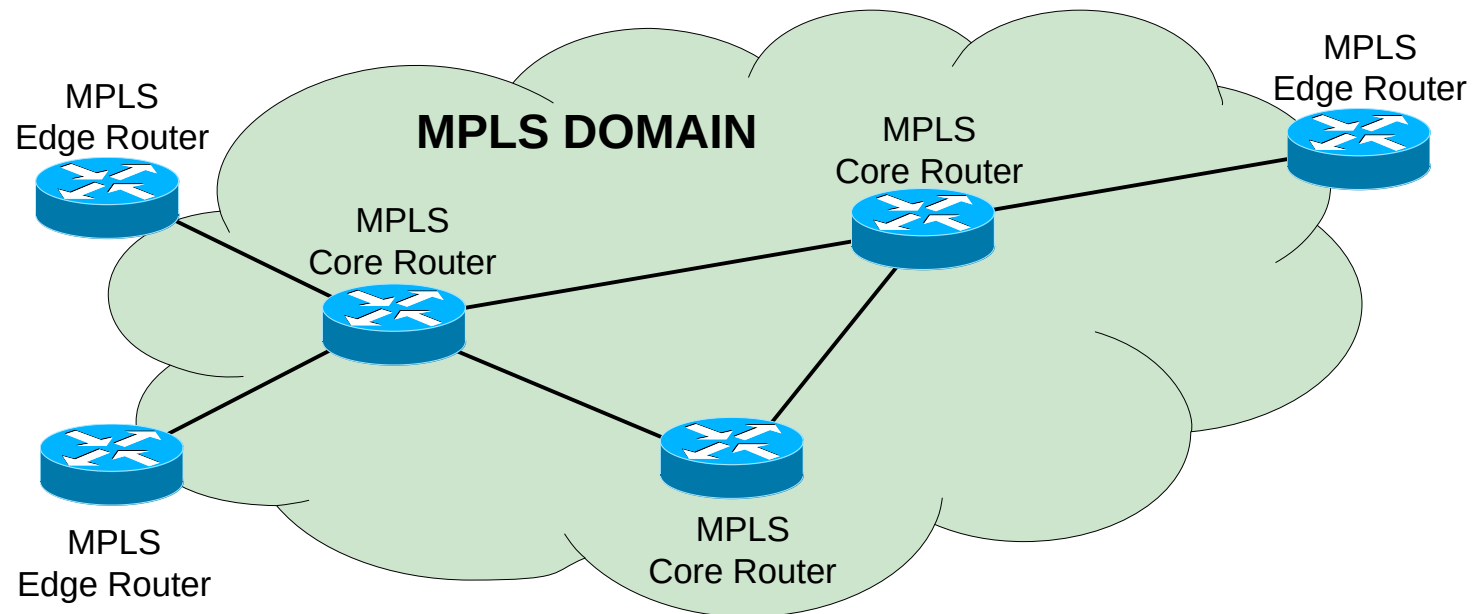


Tunnel path: R1 > R2 > R6 > R7 > R4



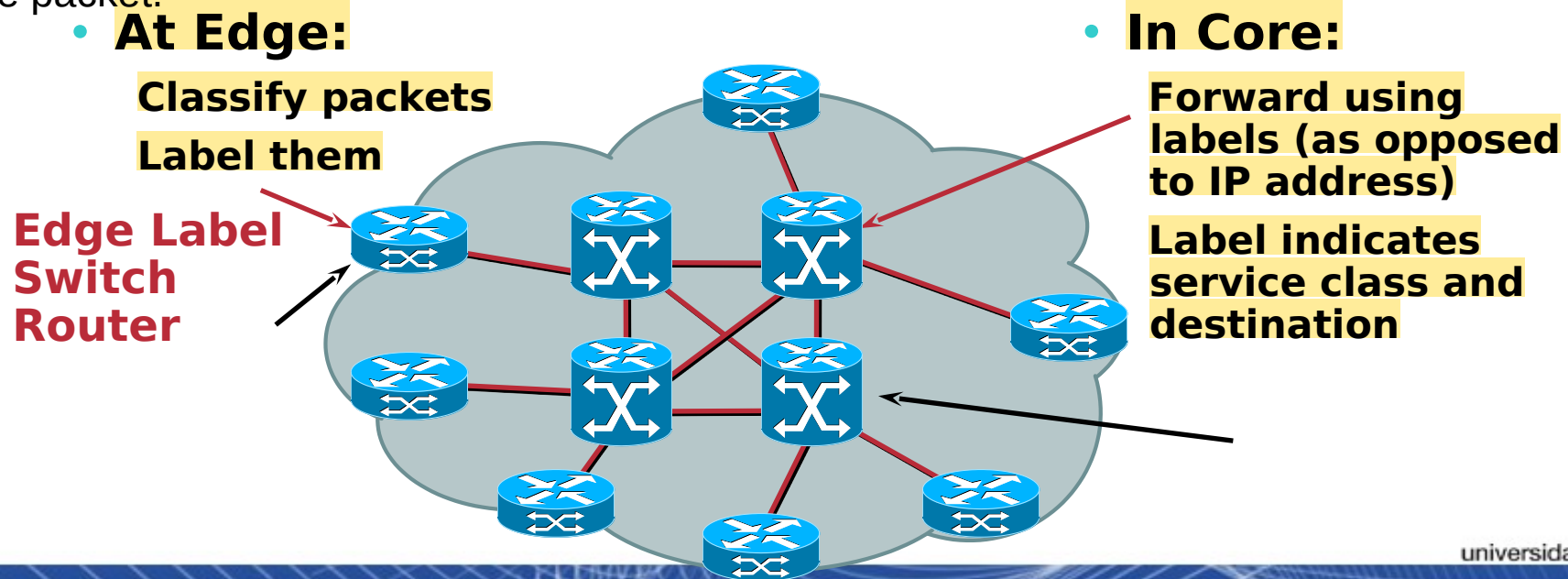
Multiprotocol Label Switching (MPLS)

- Packets are labeled at the source with the label of the first hop.
- As a packet travels from one router to the next, each router makes an independent forwarding decision for that packet based on a label.
- Advantages
 - Simplification of the packet routing process on routers.
 - Traffic engineering capability.
 - Simplification of the network management (a single protocol layer).

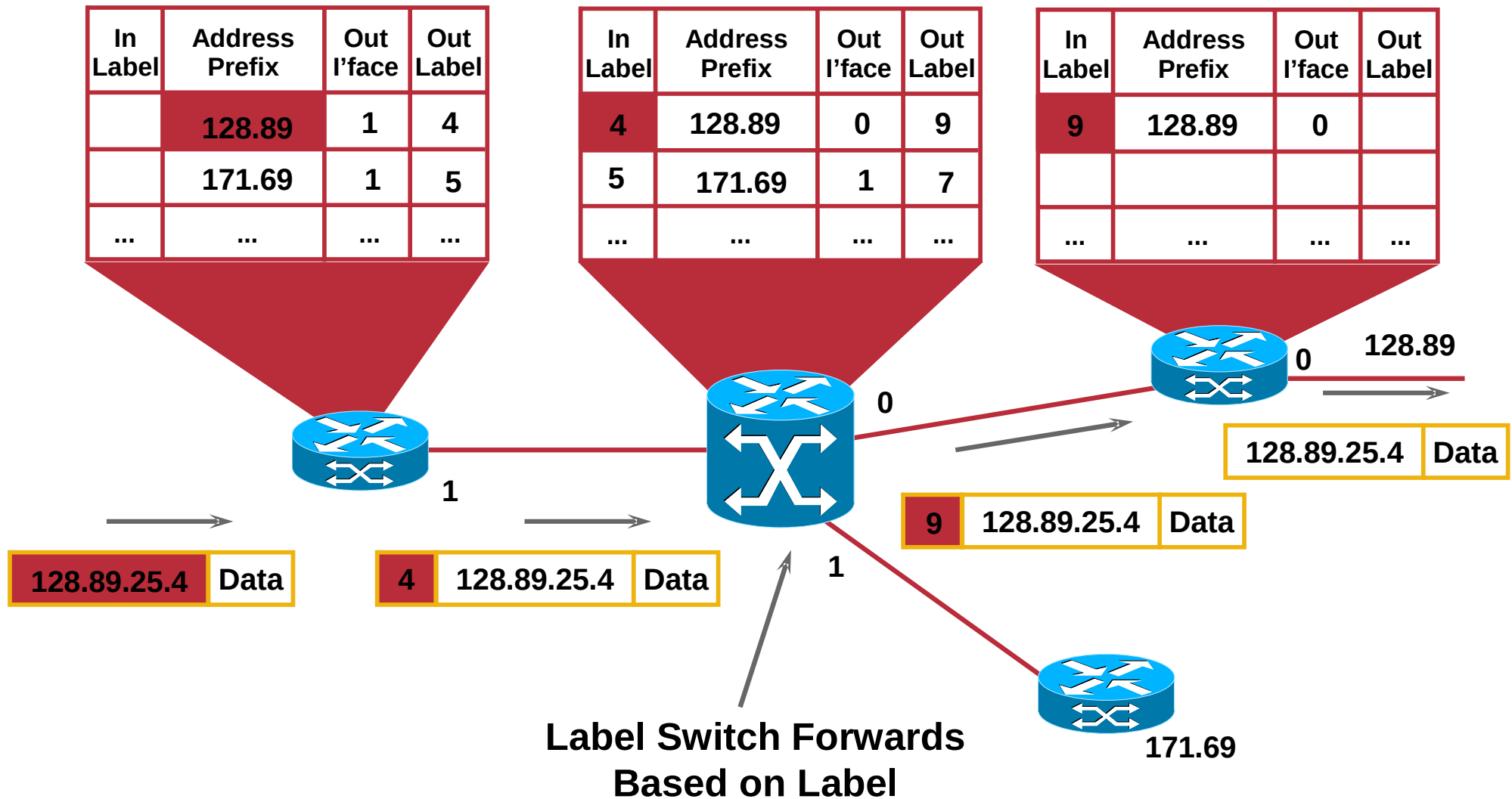


MPLS Fundamentals

- Based on the label-swapping and forwarding paradigm.
- As a packet enters an MPLS network, it is assigned a label based on its **Forwarding Equivalence Class (FEC)** as determined at the edge of the MPLS network.
- FECs are groups of packets forwarded over the same **Label Switched Path (LSP)** by **Label Switching Routers (LSR)**.
- Need a mechanism that will create and distribute labels to establish LSP paths.
- Separated into two planes:
 - Control Plane - Responsible for maintaining correct label tables among Label Switching Routers.
 - Forwarding Plane - Uses label carried by packet and label table maintained by LSR to forward the packet.

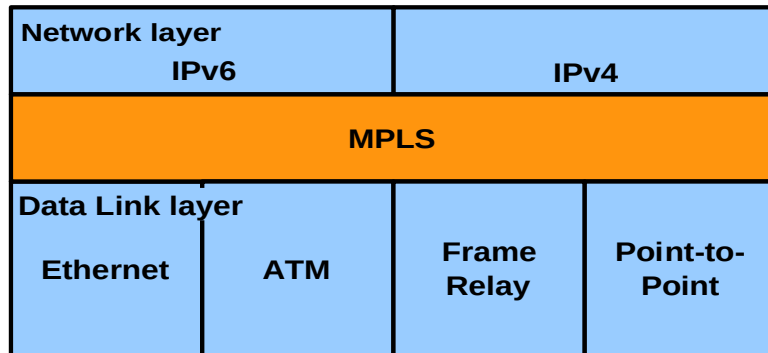


MPLS Switching



MPLS Labels

- On some Data Link (level 2) technologies, label is given by the appropriate fields of their header.
 - ♦ ATM technology : VPI (Virtual Path ID) and VCI (Virtual Channel ID) fields.
 - ♦ Frame Relay technology: DLCI (Data Link Connection Identifier) field.
- On other Data Link technologies (Point-to-Point, Ethernet), the label is inserted between layer 2 and layer 3 headers.
- Label is a 20-bit field that carries the actual value of the Label.
- TTL field is IP independent – Similar purpose.

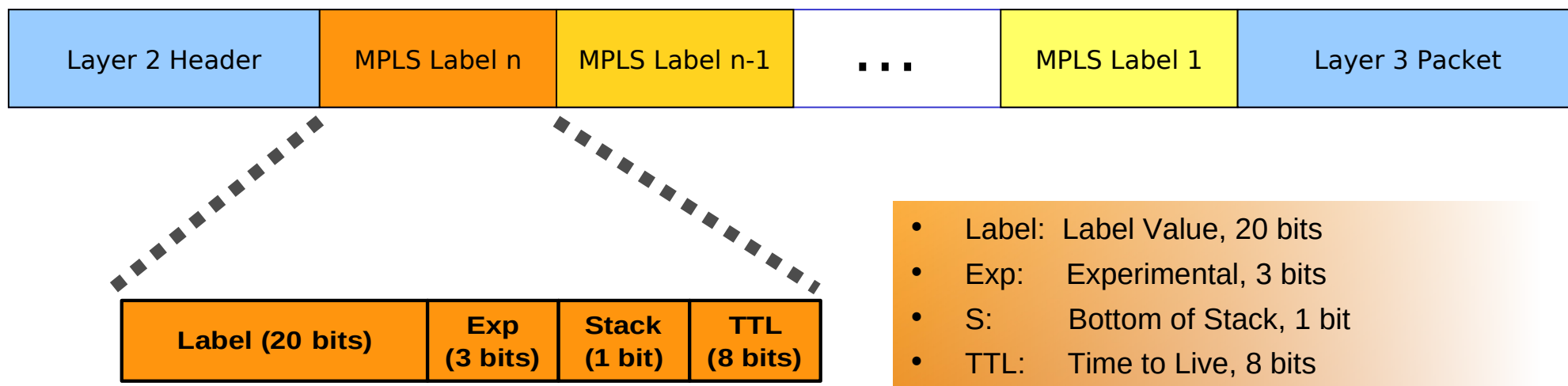


- Label: Label Value, 20 bits
- Exp: Experimental, 3 bits
- S: Bottom of Stack, 1 bit
- TTL: Time to Live, 8 bits



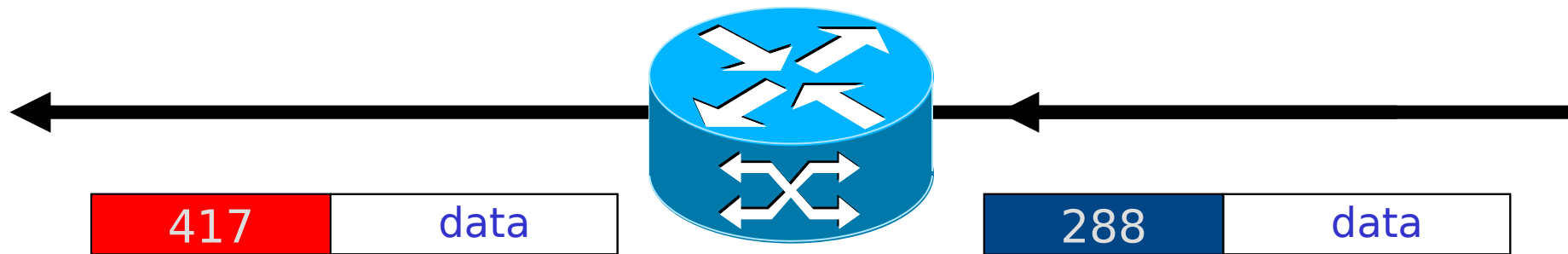
MPLS Label Stacking

RFC 3032: MPLS Label Stack Encoding



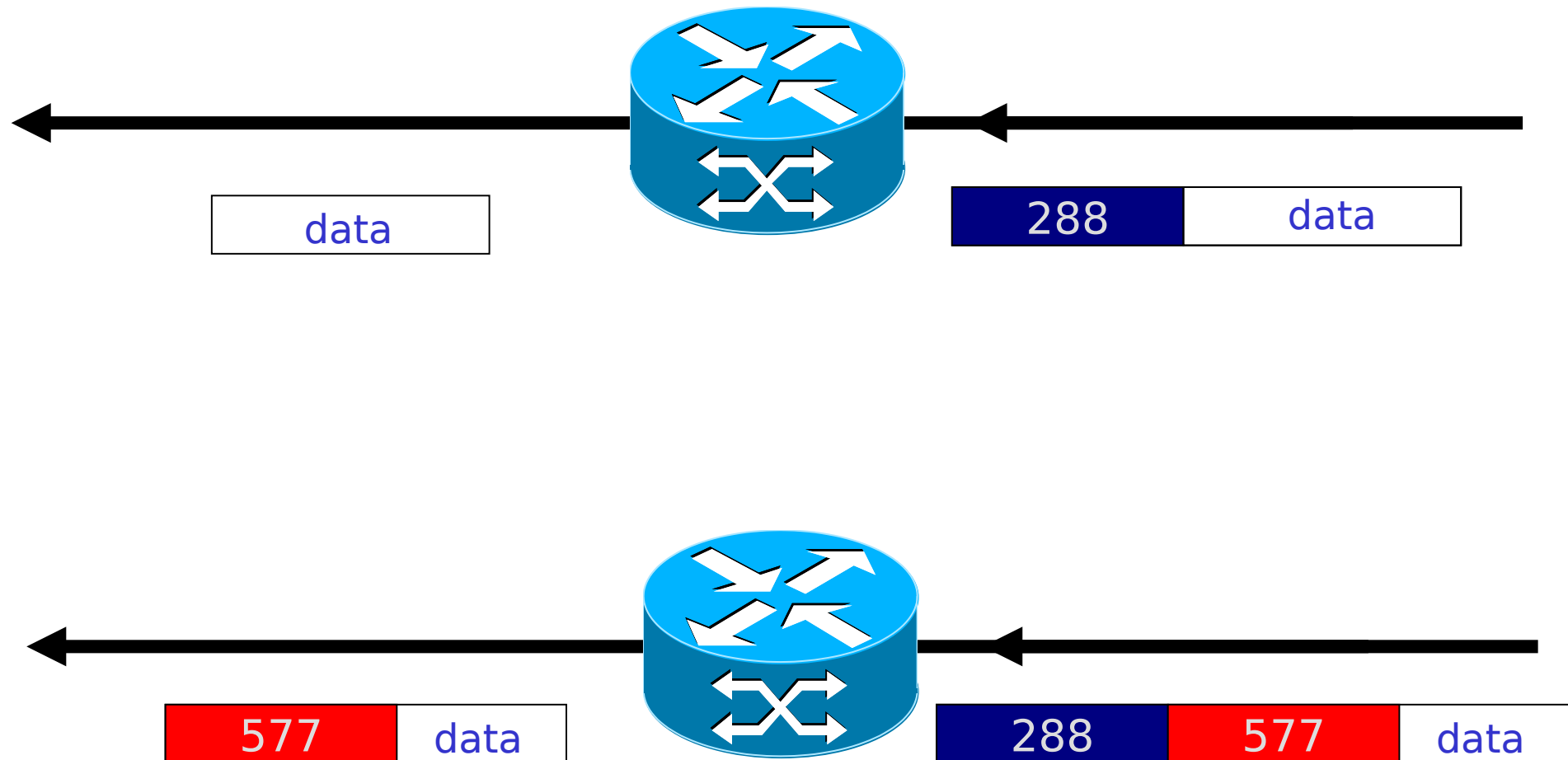
- Labels are arranged in a stack to support multiple services:
 - ♦ Inner labels are used to designate services, FECs, etc.
 - ♦ Outer label is used to switch the packets in MPLS core.
- Bottom of Stack (S) bit is set to one for the last entry in the label stack (i.e., for the bottom of the stack), and zero for all other labels.

Forwarding via Label Swapping

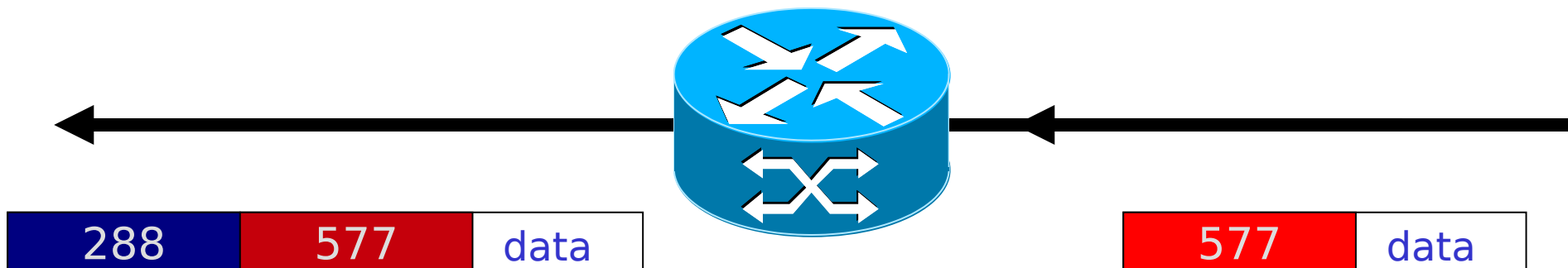
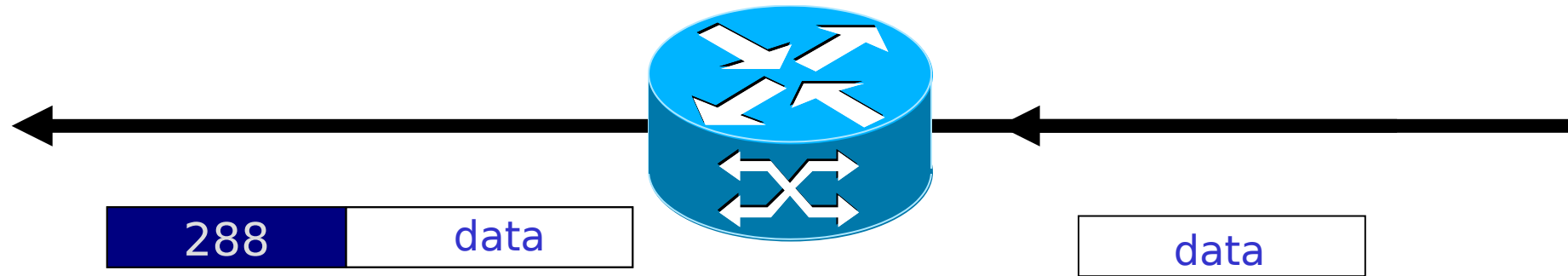


Labels are short, fixed-length values.

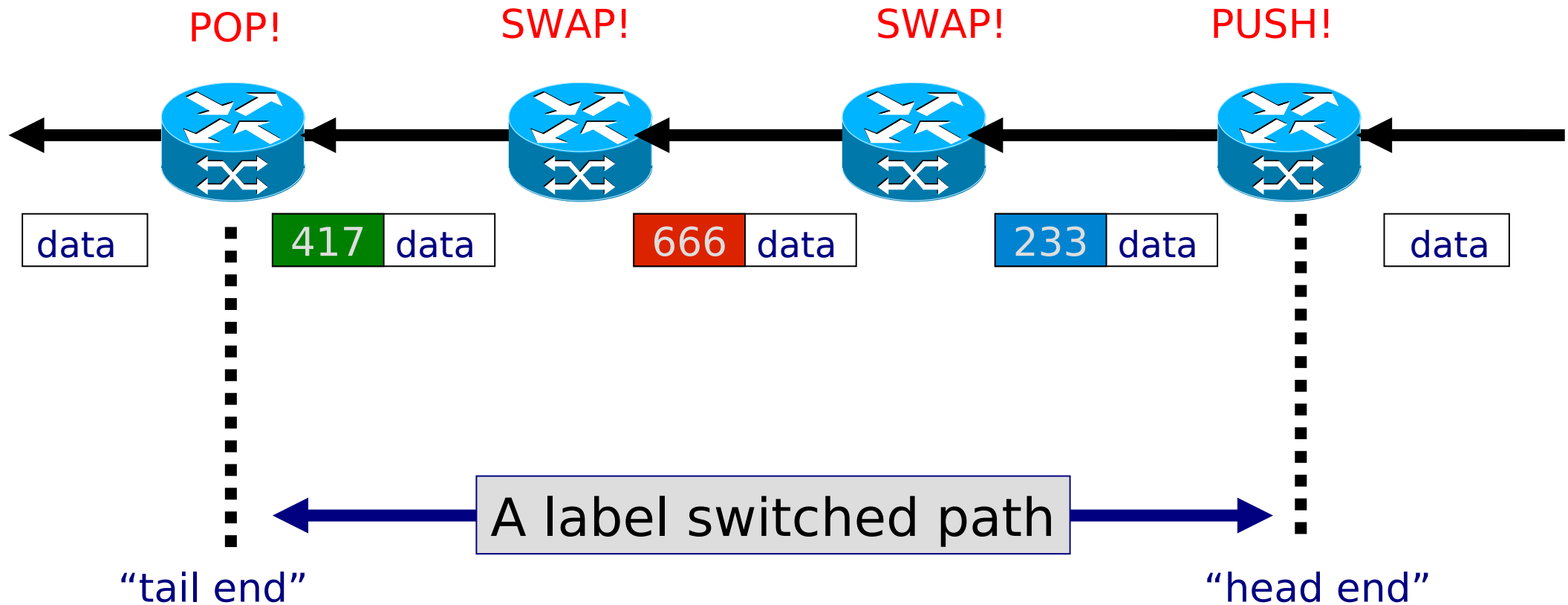
Popping Labels



Pushing Labels

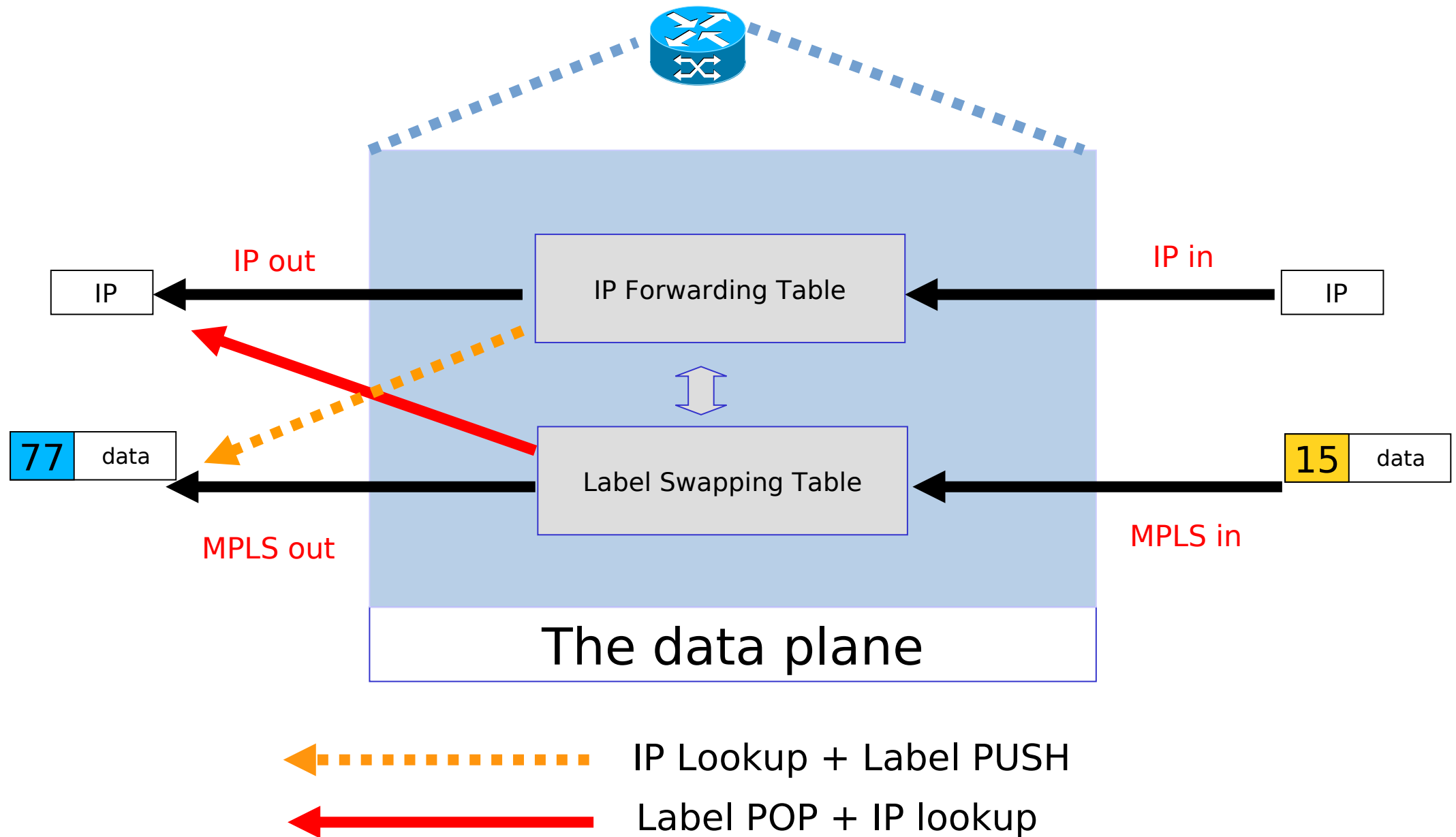


A Label Switched Path (LSP)

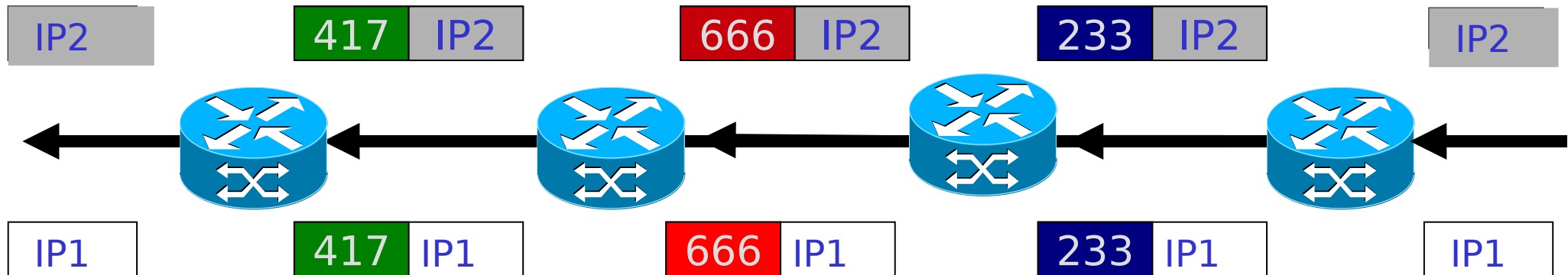


Often called an MPLS tunnel: payload headers are not Inspected inside of an LSP. Payload could be MPLS ...

Label Switched Router



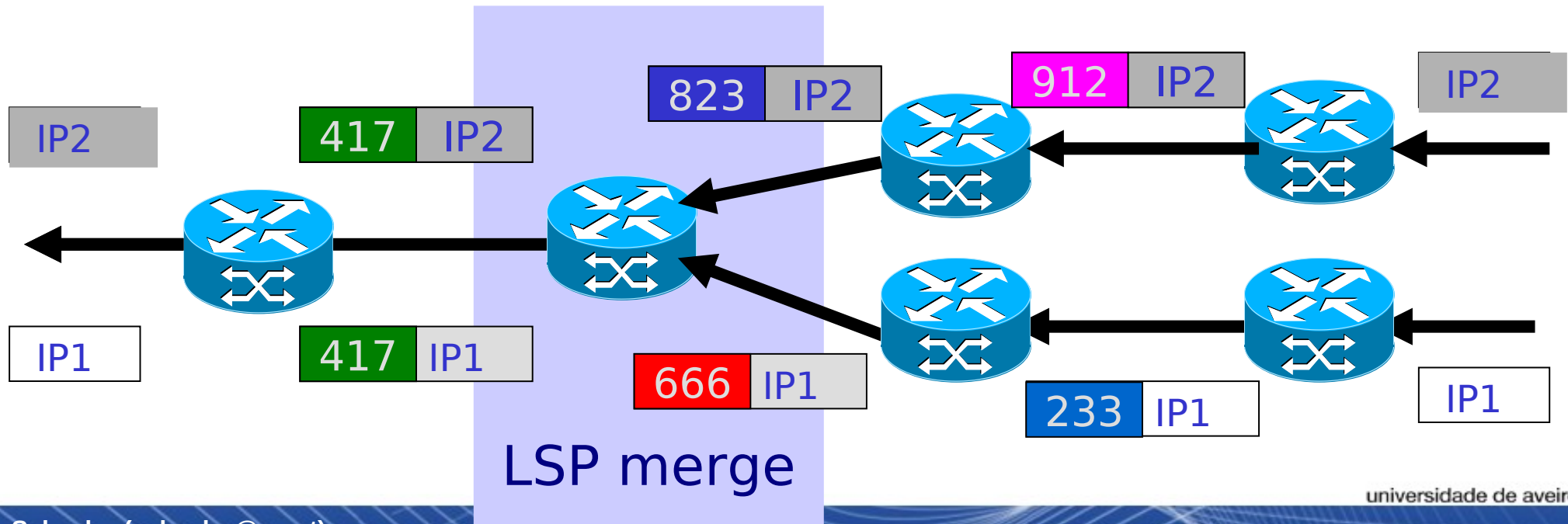
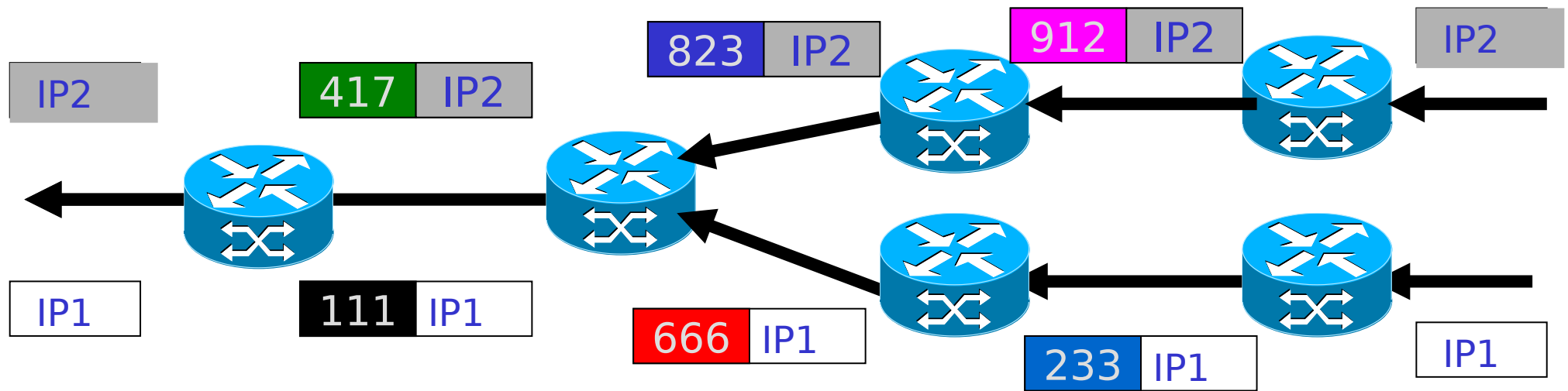
Forwarding Equivalence Class (FEC)



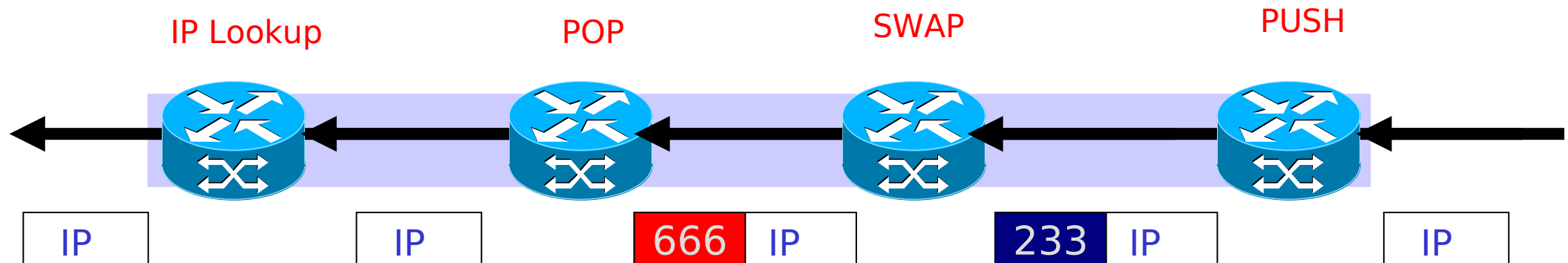
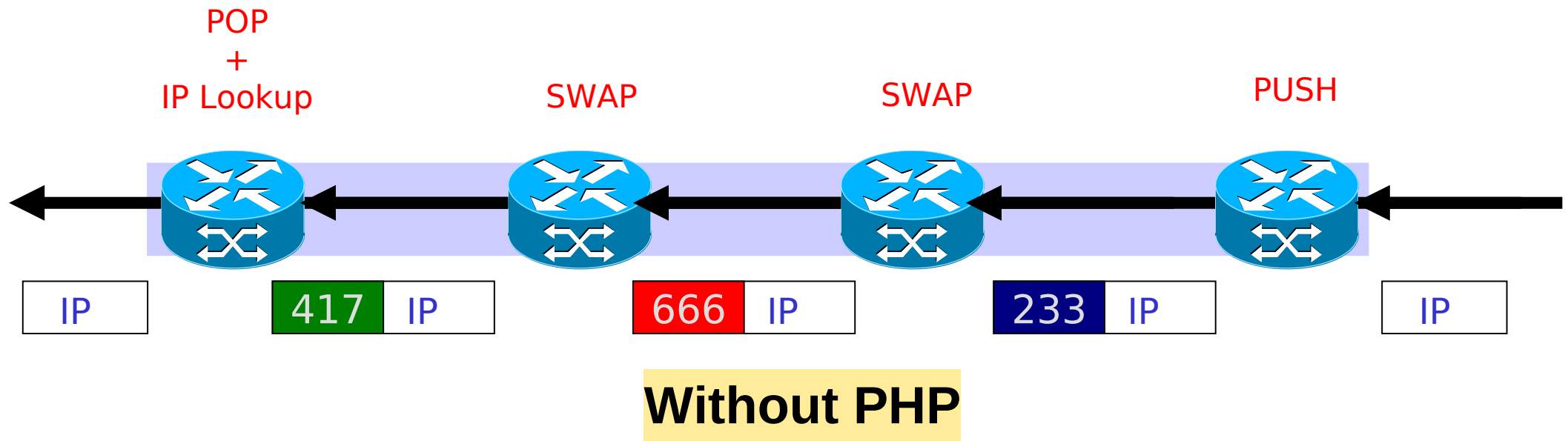
Packets IP1 and IP2 are forwarded in the same way --- they are in the same FEC.

Network layer headers are not inspected inside an MPLS LSP. This means that inside of the tunnel the LSRs do not need full IP forwarding table.

LSP Merge

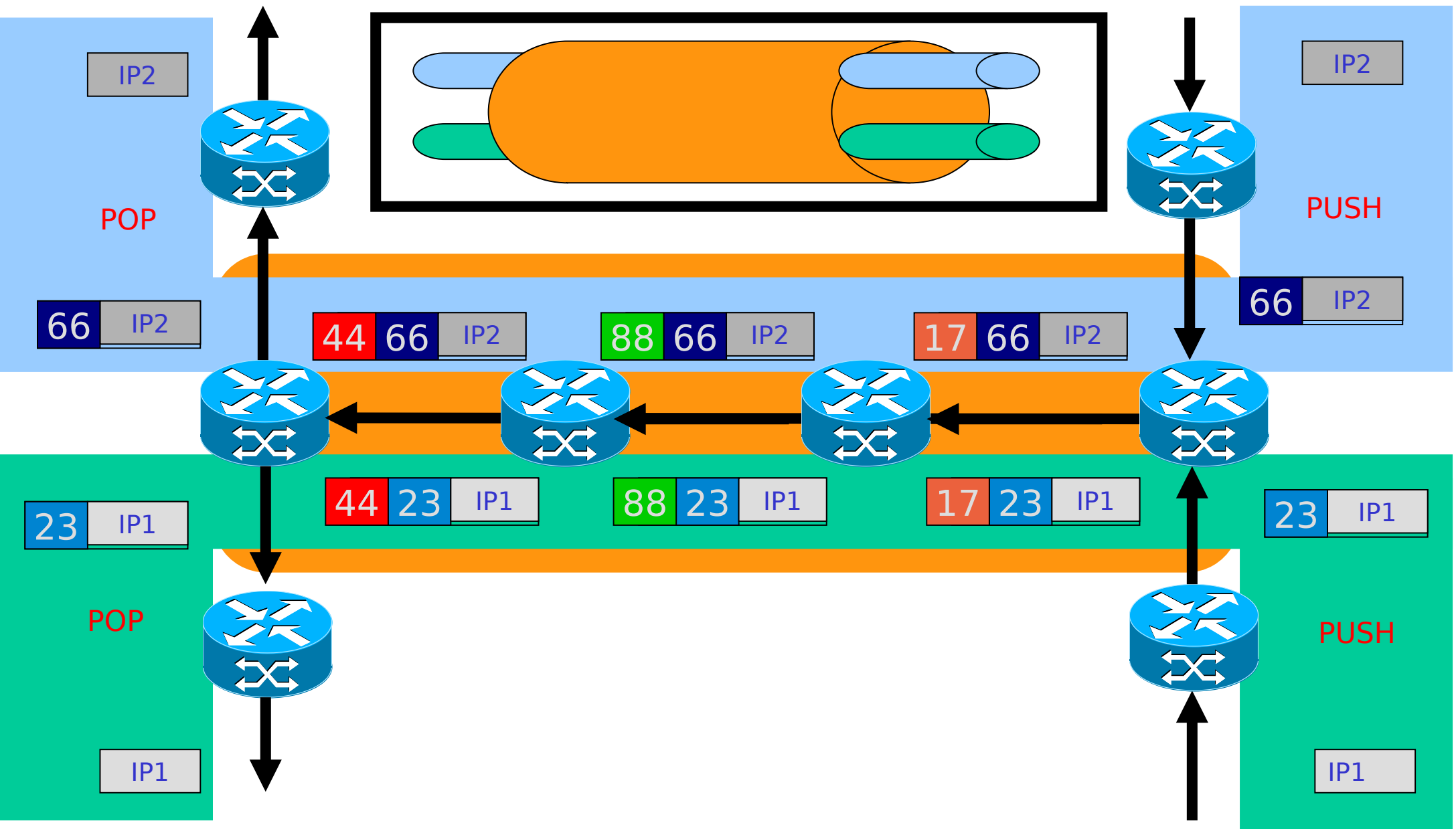


Penultimate Hop Popping (PHP)



With PHP - Reduces Label Edge Router load

LSP Hierarchy via Label Stacking



Label Distribution Protocols

- **Unconstrained routing** *sem restrições*
 - Label Distribution Protocol (LDP).
 - Path is chosen based on IGP shortest path.
- **Constrained routing** *com restrições*
 - Constrained by explicit path definition and/or performance requirements (e.g., available bandwidth).
 - Resource Reservation Protocol with Traffic Engineering (RSVP-TE).
 - Evolution of RSVP to support traffic engineering and label distribution.
 - Constrained based Routing LDP (CR-LDP).
 - Evolution of LDP to support constrained routing.
 - Deprecated!
- **MPLS VPN scope**
 - MP-BGP using address family VPN IPv4 and family specific MP_REACH_NLRI attribute.



Label Distribution Protocol (LDP)

RFC 5036: LDP Specification. (10/2007)

- Dynamic distribution of label binding information.
- LSR discovery.
- Reliable transport with TCP.
- Incremental maintenance of label swapping tables (only deltas are exchanged).
- Designed to be extensible with Type-Length-Value (TLV) coding of messages.
- Modes of behavior that are negotiated during session initialization
 - ◆ Label distribution control (ordered or independent).
 - ◆ Label retention (liberal or conservative).
 - ◆ Label advertisement (unsolicited or on-demand).



LDP Messages

- Discovery messages

- ♦ Announce and maintain the presence of an LSR in a network.
- ♦ **Hello Messages** (UDP) sent to “all-routers” multicast address.
- ♦ Once neighbor is discovered, a LDP session is established over TCP.

- Session messages

- ♦ Establish (**Initialization Message**) and maintain (**KeepAlive Message**) sessions between LDP peers.

- Advertisement messages

- ♦ When a new LDP session is initialized and before sending label information an LSR advertises its interface addresses with one or more **Address Messages**.
- ♦ An LSR withdraw previously advertised interface addresses with **Address Withdraw Messages**.
- ♦ Create, change, and delete label mappings for FECs.
 - **Label Mapping, Label Request, Label Abort Request, Label Withdraw, and Label Release Messages.**

- Notification messages

- ♦ Provide advisory information and to signal error information.

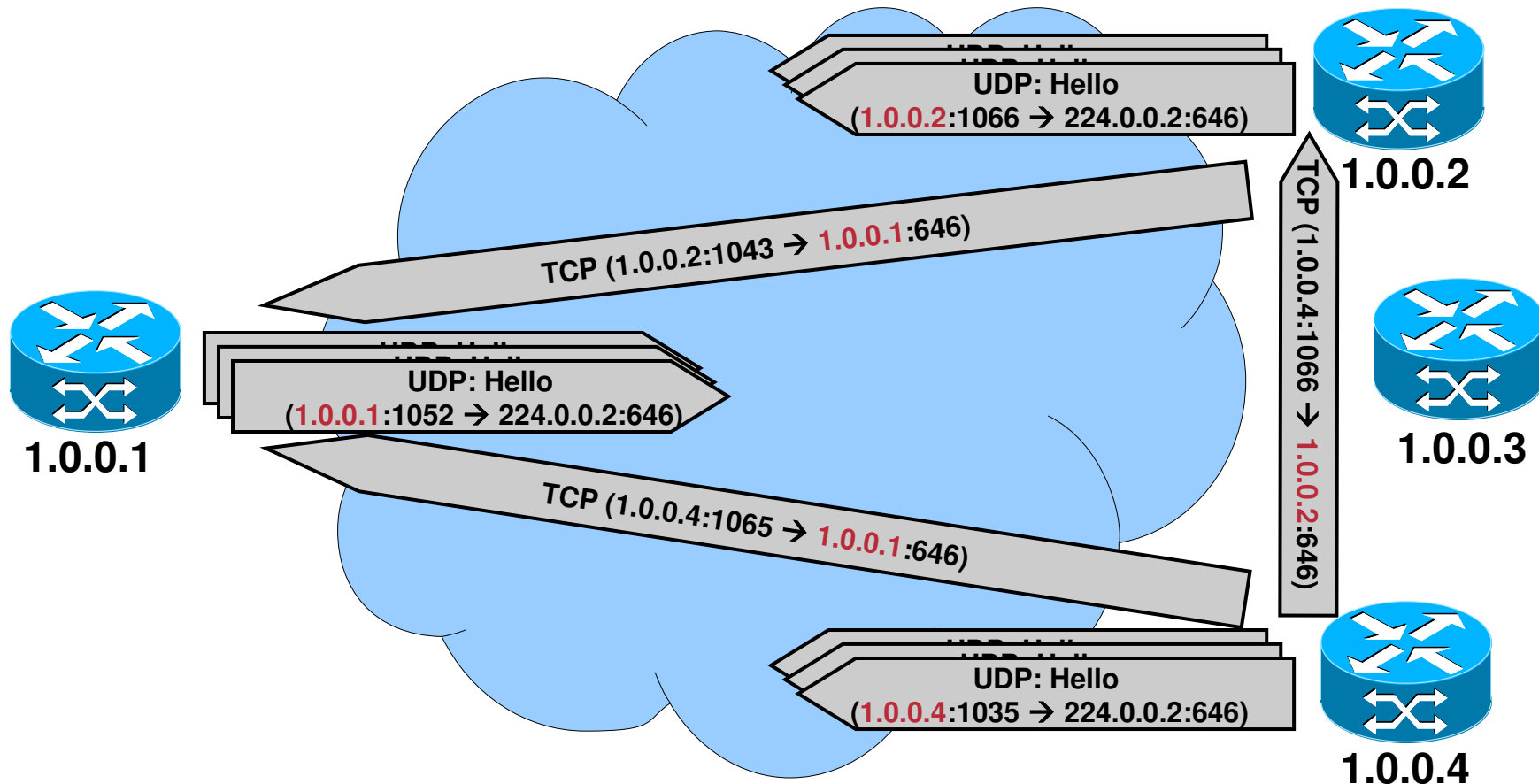


LDP Session Establishment

- Hello messages (UDP) are periodically sent on all interfaces enabled for MPLS to a “all-routers” multicast address (224.0.0.2).
- If there is another router on that interface it will respond by trying to establish a LDP/TCP session with the source of the hello messages.
- Both TCP and UDP messages use well-known LDP port number 646.

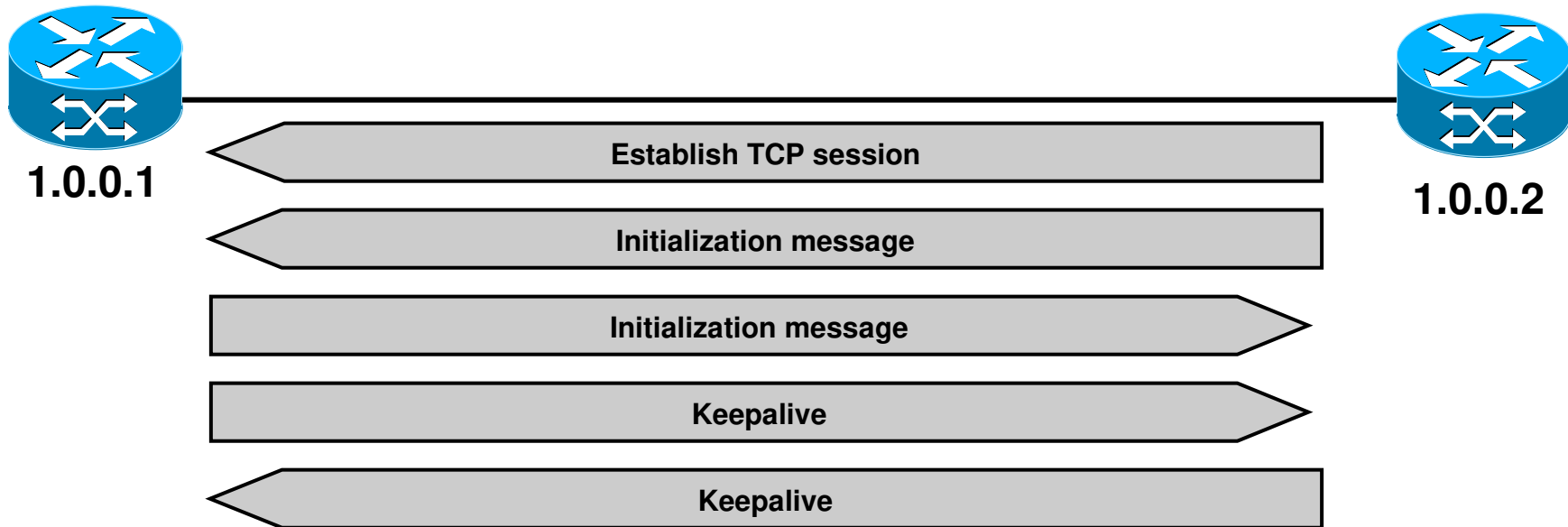


LDP Neighbor Discovery



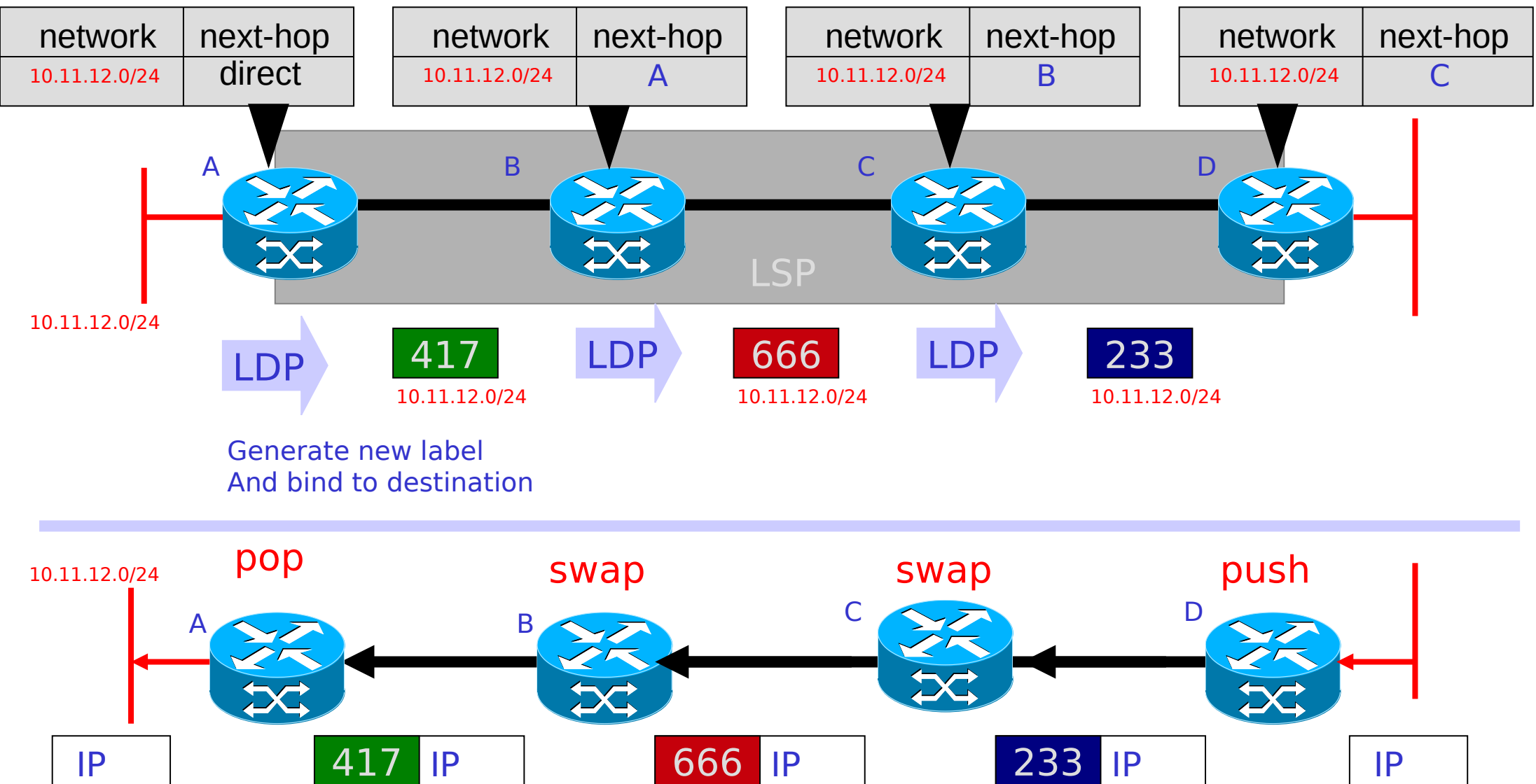
- LDP Session is started by the router with higher IP address.

LDP Session Negotiation



- Peers first exchange initialization messages.
- The session is ready to exchange label mappings after receiving the first keepalive.
 - ◆ Keepalives are resent periodically to maintain the LDP/TCP session active.

LDP and Hop-by-Hop routing



Constraint Based Routing

Basic components

1. Specify path constraints
2. Extend topology database to include resource and constraint information
3. Find paths that do not violate constraints and optimize some metric
4. Signal to reserve resources along path
5. Set up LSP along path (with explicit route)
6. Map ingress traffic to the appropriate LSPs

Note: (3) could be offline,
or online (perhaps an extension to OSPF)

Problem here: OSPF
areas hide information
for scalability. So these
extensions work best only
within an area...

Extend Link State
Protocols (IS-IS, OSPF)

Extend RSVP or LDP
or both!

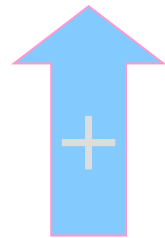
Problem here: what is
the “correct” resource
model for IP services?

Resource Reservation + Label Distribution

Two competing approaches:

Add label distribution and explicit routes to a resource reservation protocol

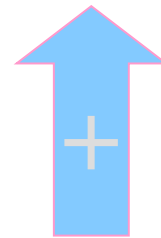
RSVP-TE



RSVP

RSVP-TE:
RFC 3209: RSVP-TE: Extensions to RSVP for LSP Tunnels

CR-LDP



LDP

CR-LDP
RFC 3212: Constraint-Based LSP Setup using LDP

Add explicit routes and resource reservation to a label distribution protocol

As of February 2003, the IETF MPLS working group deprecated CR-LDP and decided to focus purely on RSVP-TE.

RFC 3468: The Multiprotocol Label Switching (MPLS) Working Group decision on MPLS signaling protocols



Resource Reservation Protocol with Traffic Engineering (RSVP-TE)

RFC 3209: RSVP-TE: Extensions to RSVP for LSP Tunnels. (12/2001)

RFC 5151: Resource Reservation Protocol-Traffic Engineering (RSVP-TE) Extensions. (2/2008)

- Evolution of RSVP.
- To map traffic flows onto the physical network topology through label switched paths, requires resource and constraint network information.
 - Provided by Extend Link State Protocols (IS-IS or OSPF with TE extensions).
 - ➔ RFC 3630: Traffic Engineering (TE) Extensions to OSPF Version 2. (9/2003)
 - ➔ RFC 5305: IS-IS Extensions for Traffic Engineering. (10/2008)

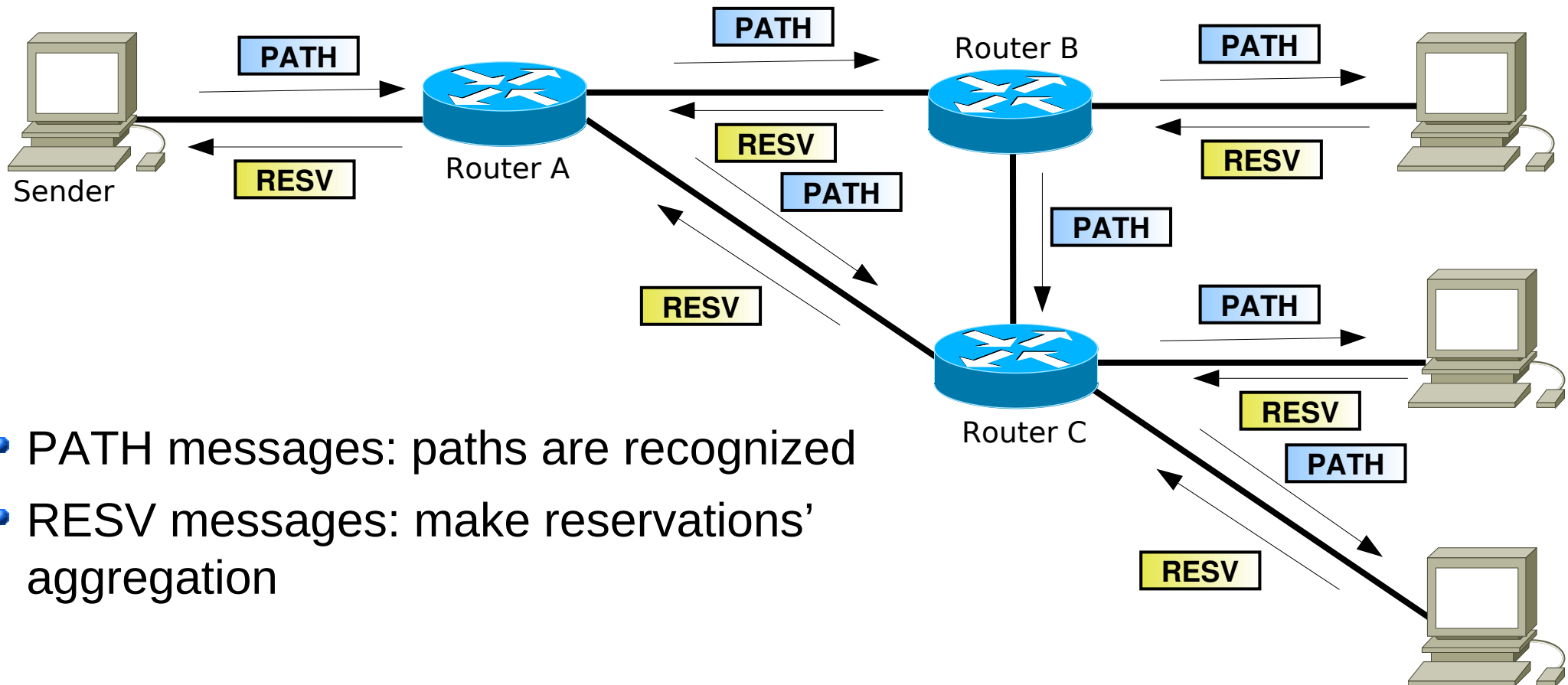


ReSerVation Protocol (RSVP)

- The resource ReSerVation Protocol (RSVP) was developed to communicate resource needs between hosts and network devices (RFC 2205-2215)
- RSVP allows:
 - The source do describe the characteristics of the IP packets flow.
 - Destinations to describe the reservation they want.
 - Routers to know how to process the packets flow in order to fulfill the requested reservation.
- Encapsulated on IP; protocol type = 46 (0x2E)
- Signaling is based on the exchange of PATH and RESV messages.
 - PATH announces the traffic characteristics at the sender.
 - RESV achieves reservations that were initiated by the receivers.
 - If the reservation is not possible, a RESV ERR message is sent.
- The routers reservation states have to be periodically refreshed (soft states).
- RSVP defines a "Session" to be a data flow with a particular destination and transport-layer protocol.
 - RSVP treats each session independently.



RSVP Signaling



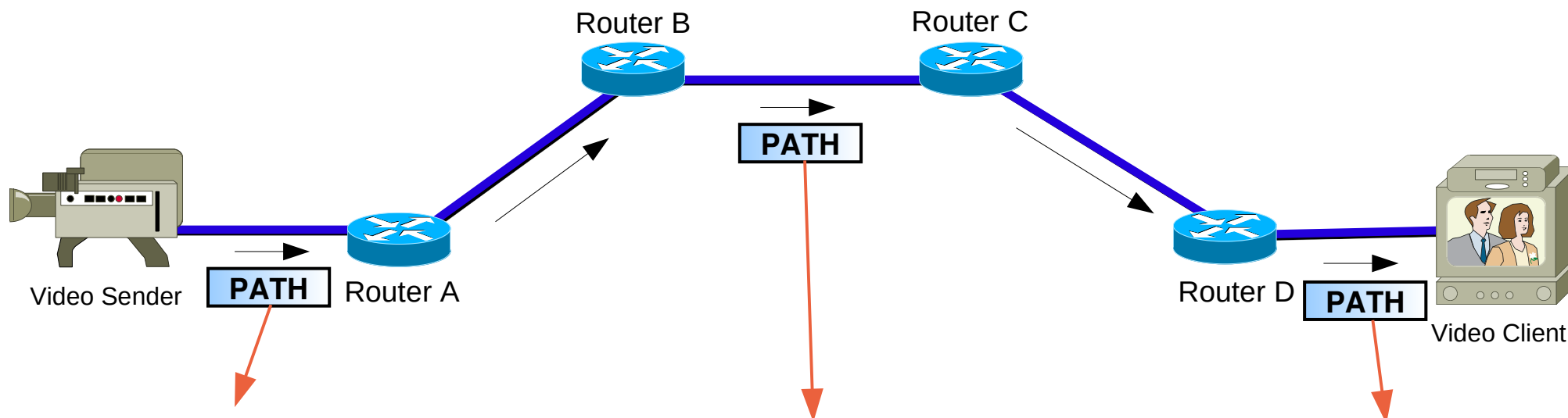
- PATH messages: paths are recognized
- RESV messages: make reservations' aggregation

RSVP messages

- PATH (*Type* = 0x01)
 - ♦ Tspec (“flow traffic specification”): contains the parameters that describe the traffic source based on the “Token Bucket” model
- RESV (*Type* = 0x02)
 - ♦ Tspec: the same that was received on the PATH message
 - ♦ FilterSpec (“*filter specification*”): contains the flow descriptor that enables routers to identify packets belonging to this reservation (source address, destination address, protocol type, source port number, destination port number, any combination of these parameters)
 - ♦ Rspec (“*flow reservation specification*”): contains the parameters describing the reservation that the receiver wants to become supported
 - ➔ Rspec is specified if the receiver wants a service of the “*guaranteed service*” type; when it is not specified, it means that the receiver wants a service of the “*controlled load*” type



RSVP PATH (Example)

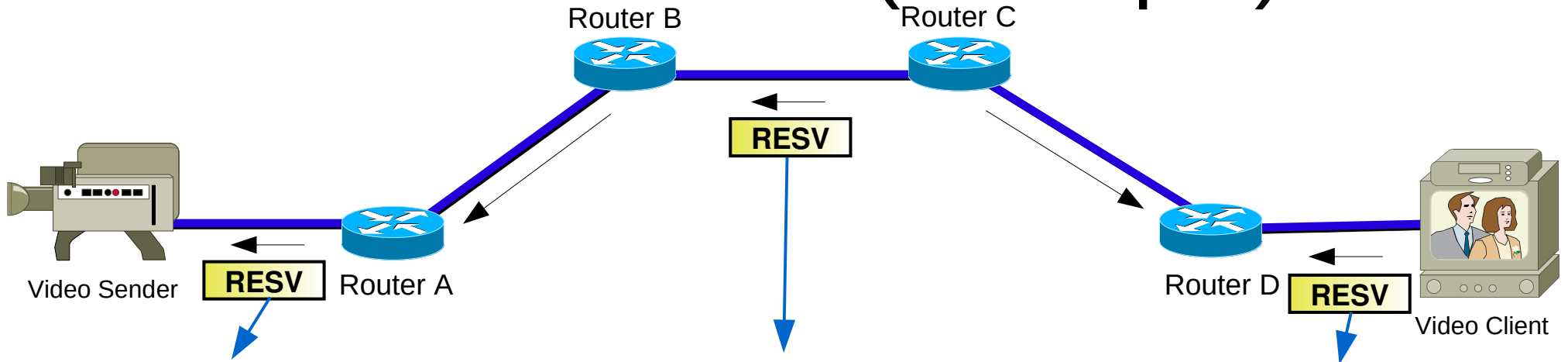


Vs.: 4		iHL: 5		Service		Total Length: 60				
Identification						Flg	Fragment Offset			
Time to Live				Protocol: 46		Header Checksum				
Source Address:						Video Server				
Destination Address:						Video Client				
1		0		Type: 1		Checksum				
Send_TTL				0		Message Length: 40				
SESSION Length.: 12						Class Nº: 1		Class Type: 1		
Destination Address:						Video Client				
Protocol ID				Flags		Destination port				
RSVP_HOP Length. : 12						Class Nº: 3		Class Type: 1		
Last Hop Address:						Video Server				
Logical Interface Handle of the last node (LIH)										
TIME_VALUES Length: 8						Class Nº: 5		Class Type: 1		
Update Period (ms)										

Vs.: 4		iHL: 5		Service		Total Length: 60			
Identification						Flg	Fragment Offset		
Time to Live			Protocol: 46			Header Checksum			
Source Address:						Video Server			
Destination Address:						Video Client			
1	0	Type: 1			Checksum				
Send_TTL			0			Message Length: 40			
SESSION Length: 12						Class Nº: 1		Class Type: 1	
Destination Address:						Video Client			
Protocol ID			Flags			Destination Port			
RSVP_HOP Length: 12						Class Nº: 3		Class Type: 1	
Last Hop Address:						Router B			
Logical Interface Handle of the last node (LIH)									
TIME_VALUES Length: 8						Class Nº: 5		Class Type: 1	
Update Period (ms)									

Vs.: 4		iHL: 5		Service		Total Length: 60			
Identification						Flg	Fragment Offset		
Time to Live			Protocol: 46			Header Checksum			
Source Address:						Video Server			
Destination Address:						Video Client			
1		0		Type: 1		Checksum			
Send_TTL			0			Message Length: 40			
SESSION Length: 12						Class Nº: 1		Class Type: 1	
Destination Address:						Video Client			
Protocol ID			Flags			Destination Port			
RSVP_HOP Length: 12						Class Nº: 3		Class Type: 1	
Last Hop Address:						Router D			
Logical Interface Handle of the last node (LIH)									
TIME_VALUES Length: 8						Class Nº: 5		Class Type: 1	
Update Period (ms)									

RSVP RESV (Example)



Vs.: 4	iHL: 5	Service	Total Length	
Identification			Flg	Fragment Offset
Time to Live		Protocol: 46	Header Checksum	
Source Address: Router A				
Destination Address: Video Server				
1	0	Type: 2	Checksum	
Send_TTL		0	Message Length	
SESSION Length: 12			Class N°: 1	Class Type: 1
Destination Address: Video Client				
Protocol Id		Flags	Destination protocol port	
RSVP_HOP Length: 12			Class N°: 3	Class Type: 1
Address of the last node: Router A				
Logical Interface Handle of the last node (LIH)				
TIME_VALUES Length: 8			Class N°: 5	Class Type: 1
Update period (ms)				
STYLE Object Length : 8			Class N°: 8	Class Type: 1
Flags		Style Option Vector: 0x00000A (FF)		
FLOWSPEC Length			Class N°: 9	Class Type
FLOWSPEC object contents				
FILTER_SPEC Length: 12			Class N°: 10	Class Type: 1
Source Address: Video Server				
Reserved		Reserved	Source protocol port	

Vs.: 4		iHL: 5		Service		Total Length					
Identification						Flg		Fragment Offset			
Time to Live				Protocol: 46		Header Checksum					
Source Address: Router C											
Destination Address: Router B											
1		0		Type: 2			Checksum				
Send_TTL				0			Message Length				
SESSION Length: 12						Class Nº: 1			Class Type: 1		
Destination Address: Video Client											
Protocol Id				Flags			Destination protocol port				
RSVP_HOP Length: 12						Class Nº: 3			Class Type: 1		
Address of the last node: Router C											
Logical Interface Handle of the last node (LIH)											
TIME_VALUES Length: 8						Class Nº: 5			Class Type: 1		
Update period (ms)											
STYLE Object Length : 8						Class Nº: 8			Class Type: 1		
Flags			Style Option Vector: 0x00000A (FF)								
FLOWSPEC Length						Class Nº: 9			Class Type		
FLOWSPEC object contents											
FILTER_SPEC Length: 12						Class Nº: 10			Class Type: 1		
Source Address: Video Server											
Reserved				Reserved			Source protocol port				

Vs.: 4		iHL: 5		Service		Total Length	
Identification				Flg		Fragment Offset	
Time to Live			Protocol: 46		Header Checksum		
Source Address:						Video Client	
Destination Address:						R outer D	
1		0		Type: 2		Checksum	
Send_TTL			0		Message Length		
SESSION Length: 12				Class Nº: 1		Class Type: 1	
Destination Address:						Video Client	
Protocol Id			Flags		Destination protocol port		
RSVP_HOP Length: 12				Class Nº: 3		Class Type: 1	
Address of the last node:						Video Client	
Logical Interface Handle of the last node (LIH)							
TIME_VALUES Length: 8				Class Nº: 5		Class Type: 1	
Update period (ms)							
STYLE Object Length : 8				Class Nº: 8		Class Type: 1	
Flags			Style Option Vector: 0x00000A (FF)				
FLOWSPEC Length				Class Nº: 9		Class Type	
FLOWSPEC object contents							
FILTER_SPEC Length: 12				Class Nº: 10		Class Type: 1	
Source Address: Video Server							
Reserved			Reserved			Source protocol port	



Extensions to RSVP for LSP Tunnels

- The SENDER_TEMPLATE (or FILTER_SPEC) object together with the SESSION object uniquely identifies an LSP tunnel (flow).
- LSP Tunnel related new objects
 - ◆ Explicit Route
 - Carried in PATH and contains a series of variable-length data items called sub-objects.
 - Possible sub-objects: IPv4 prefix, IPv6 prefix, and autonomous system number.
 - ◆ Label Request
 - Carried in PATH requesting a label for a specific tunnel/flow.
 - Request can be without label range, with an ATM label range, or with an Frame Relay label range.
 - ◆ Label
 - Carried in RESV messages and contain a single label for a specific tunnel/flow.
 - ◆ Record Route
 - Carried in PATH and RESV, used to collect detailed path information and useful for loop detection and diagnostics.
 - ◆ Session Attribute
 - Carried in PATH, used to define the type and name of the session/tunnel/flow, also used to define priority values.
- LSP Tunnel related new object types
 - ◆ Session object new types
 - LSP_TUNNEL_IPv4 and LSP_TUNNEL_IPv6
 - ◆ Sender Template object new types
 - LSP_TUNNEL_IPv4 and LSP_TUNNEL_IPv6
 - ◆ Filter Specification object new types
 - LSP_TUNNEL_IPv4 and LSP_TUNNEL_IPv6



RSVP-TE PATH and RESV (example)

Resource ReserVation Protocol (RSVP): PATH Message. SESSION: IPv4-LSP

▷ RSVP Header. PATH Message.

▷ SESSION: IPv4-LSP, Destination 192.2.0.11, Tunnel ID 2, Ext ID c002000a.

▷ HOP: IPv4, 200.10.2.10

▷ TIME VALUES: 30000 ms

▷ EXPLICIT ROUTE: IPv4 200.10.2.2, IPv4 200.2.11.2, IPv4 200.2.11.11,

▷ LABEL REQUEST: Basic: L3PID: IP (0x0800)

▷ SESSION ATTRIBUTE: SetupPrio 7, HoldPrio 7, SE Style, [RA_t2]

▷ SENDER TEMPLATE: IPv4-LSP, Tunnel Source: 192.2.0.10, LSP ID: 8.

▷ SENDER TSPEC: IntServ, Token Bucket, 18750 bytes/sec.

▷ ADSPEC

▽ Resource ReserVation Protocol (RSVP): RESV Message. SESSION: IPv4-LSP

▷ RSVP Header. RESV Message.

▷ SESSION: IPv4-LSP, Destination 192.2.0.11, Tunnel ID 2, Ext ID c002000a.

▷ HOP: IPv4, 200.10.2.2

▷ TIME VALUES: 30000 ms

▷ STYLE: Shared-Explicit (18)

▷ FLOWSPEC: Controlled Load: Token Bucket, 18750 bytes/sec.

▷ FILTERSPEC: IPv4-LSP, Tunnel Source: 192.2.0.10, LSP ID: 8.

▷ LABEL: 19



Traffic Engineering Extensions to OSPF

- RFC 3630: Traffic Engineering (TE) Extensions to OSPF Version 2. (9/2003)
- OSPF Traffic Engineering (TE) extensions are used to advertise TE Link State Advertisements (TE-LSAs) containing information about TE-enabled links.
 - Traffic Engineering LSA is a type 10 Opaque LSAs, which have an area flooding scope.
- TE-LSA contains one of two possible top-level Type Length Values (TLVs)
 - ➔ **Router Address**: specifies a stable IP address of the advertising router that is always reachable if there is any connectivity to it; this is typically implemented as a "loopback address";
 - ➔ **Link**: describes a single link with a set of sub-TLVs (Link type, Link ID, Local interface IP address, Remote interface IP address, Traffic engineering metric, Maximum bandwidth, Maximum reservable bandwidth, Unreserved bandwidth, and Administrative group.
- The information made available by these extensions can be used to build an extended link state database
 - Can be used to:
 - ➔ Monitoring the extended link attributes;
 - ➔ Local constraint-based source routing;
 - ➔ Global traffic engineering.



OSPF-TE Opaque Area Database

- Router Address TLV

```
LS age: 250
Options: (No TOS-capability, DC)
LS Type: Opaque Area Link
Link State ID: 1.0.0.0
Opaque Type: 1
Opaque ID: 0
Advertising Router: 192.2.0.2
LS Seq Number: 80000001
Checksum: 0xDACD
Length: 28
Fragment number : 0

MPLS TE router ID : 192.2.0.2
Number of Links : 0
```

- Link TLV

```
LS age: 246
Options: (No TOS-capability, DC)
LS Type: Opaque Area Link
Link State ID: 1.0.0.2
Opaque Type: 1
Opaque ID: 2
Advertising Router: 192.2.0.2
LS Seq Number: 80000001
Checksum: 0x2FBB
Length: 124
Fragment number : 2

Link connected to Broadcast network
Link ID : 200.1.2.2
Interface Address : 200.1.2.2
Admin Metric : 1
Maximum bandwidth : 12500000
Maximum reservable bandwidth : 64000
Number of Priority : 8
Priority 0 : 64000          Priority 1 : 64000
Priority 2 : 64000          Priority 3 : 64000
Priority 4 : 64000          Priority 5 : 64000
Priority 6 : 64000          Priority 7 : 64000
Affinity Bit : 0x0
IGP Metric : 1
Number of Links : 1
```

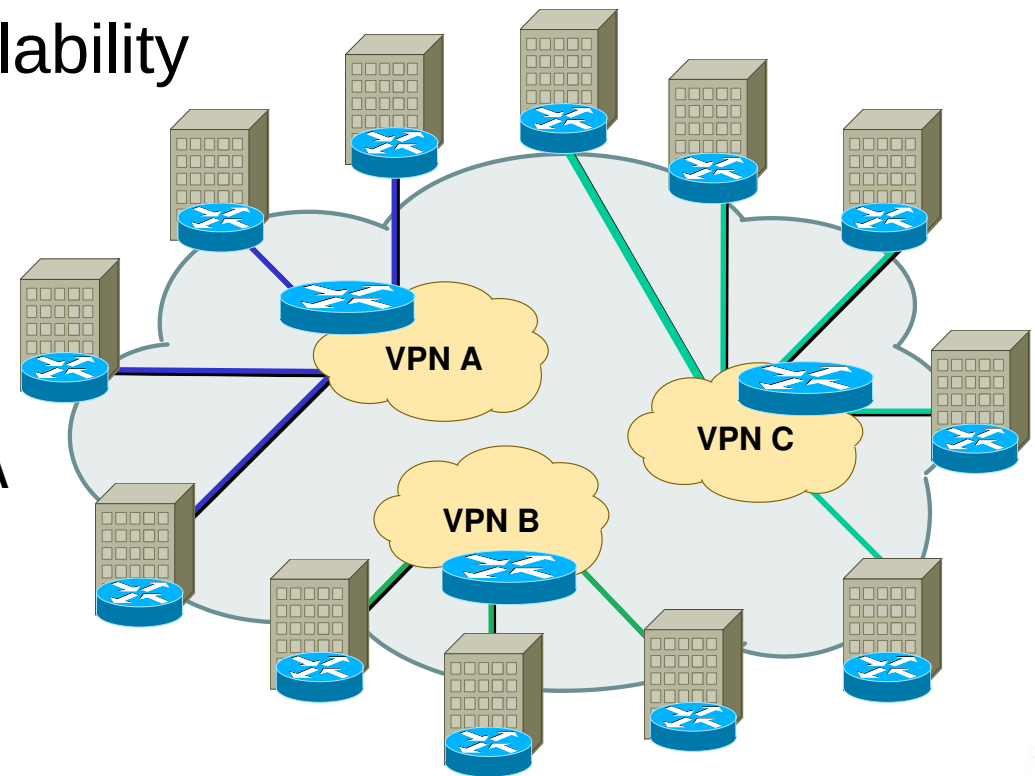
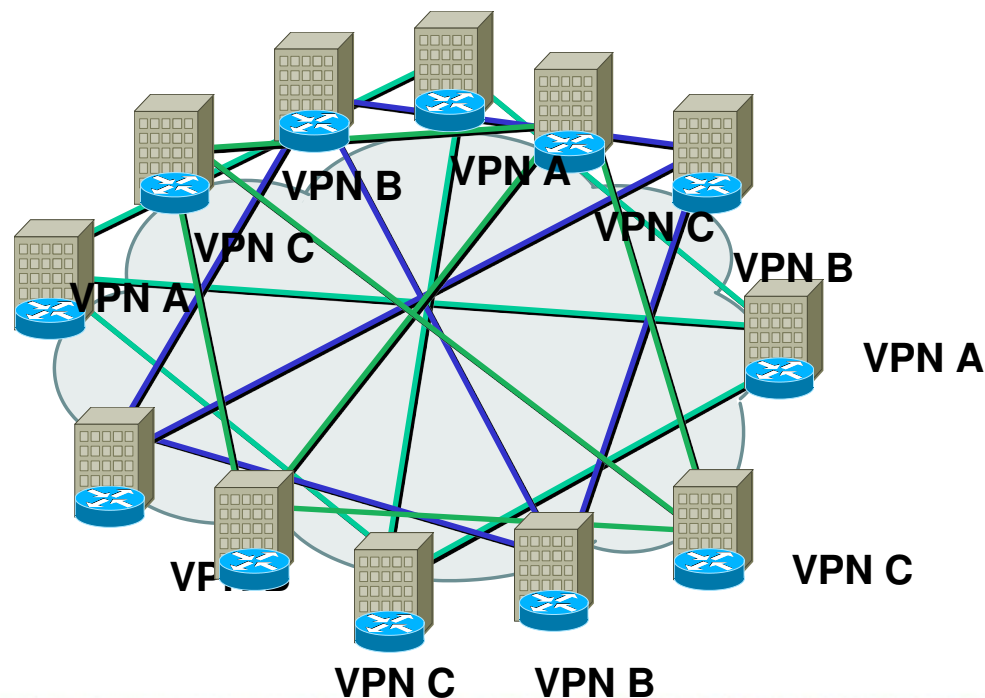


MPLS VPN

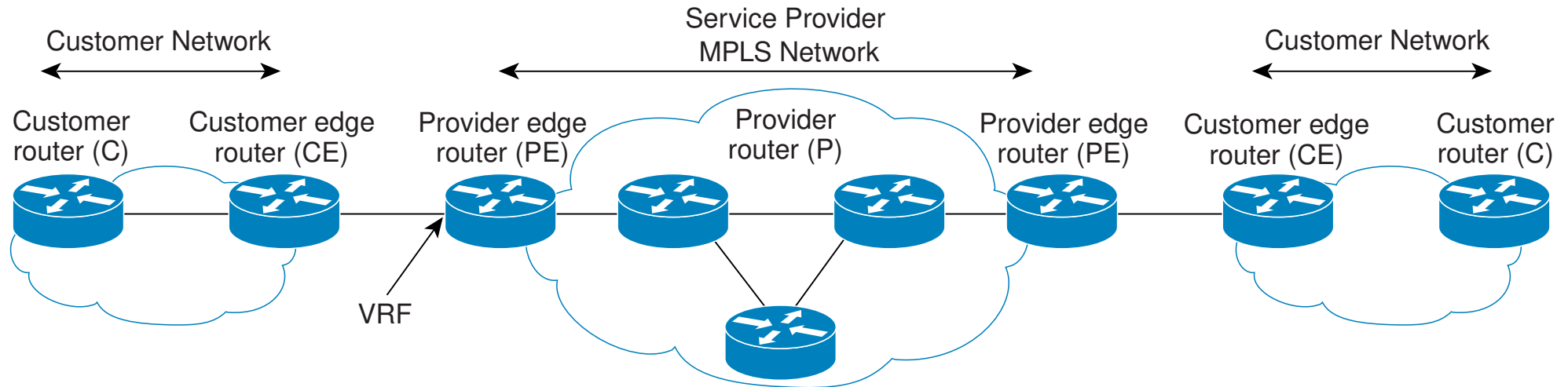


MPLS L3 VPNs using BGP (RFC2547)

- End user perspective
 - Virtual Private IP service.
 - Simple routing – just point default to provider.
 - Full site-site connectivity without the usual drawbacks (routing complexity, scaling, configuration, cost).
- Major benefit for provider – scalability



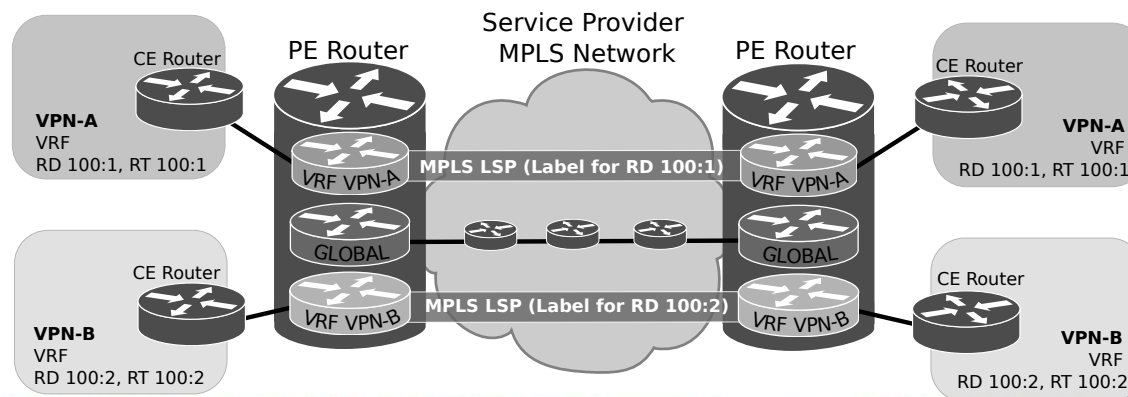
MPLS VPN Terminology



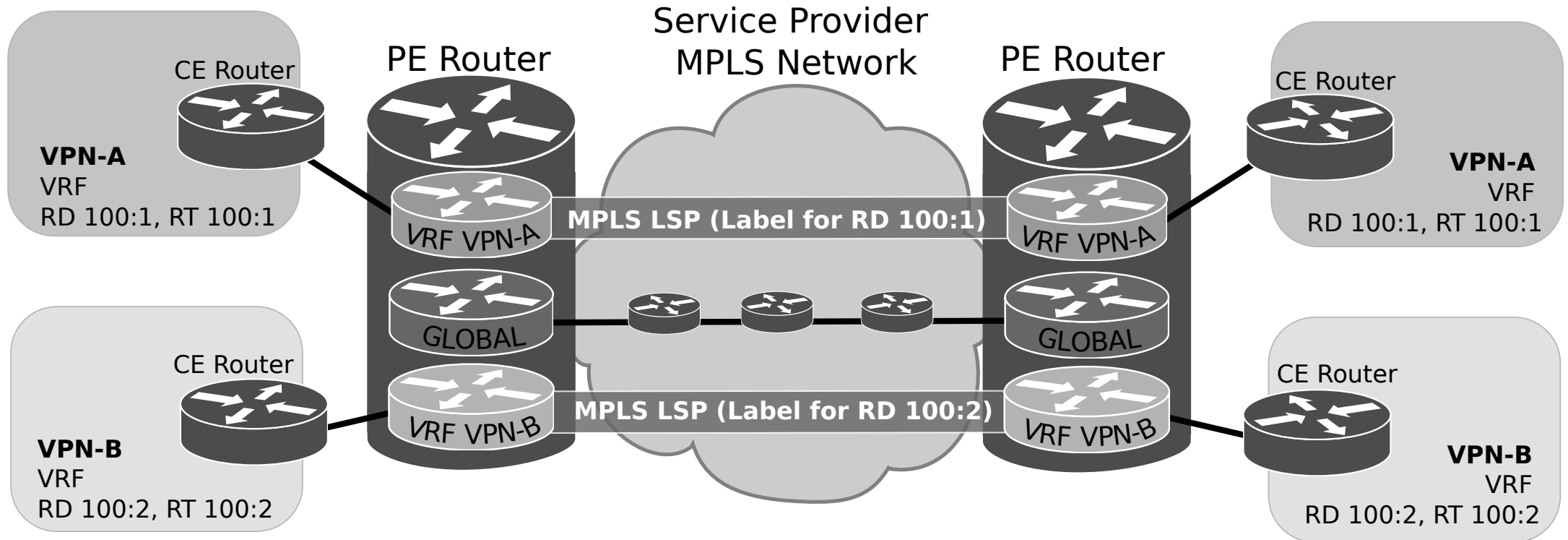
- Customer router (C) is connected only to other customer devices.
- Customer Edge (CE) router peers at Layer 3 to the Provider Edge (PE).
 - ◆ The PE-CE Interface runs either a dynamic routing protocol (eBGP, RIPv2, EIGRP, or OSPF) or has static routing (Static, Connected).
- Provider (P) router, resides in the core of the provider network.
 - ◆ Participates in the control plane for customer prefixes. The P router is also referred to as a Label Switch Router (LSR), in reference to its primary role in the core of the network, performing label switching/swapping of MPLS traffic.
- Provider Edge (PE) router, sits at the edge of the MPLS SP network.
 - ◆ In an MPLS VPN context, separate VRF routing tables are allocated for each user group.
 - ◆ Contains a global routing table for routes in the core SP infrastructure.
 - ◆ The PE is sometimes referred to as a Label Edge Router (LER) or Edge Label Switch Router (ELSR) in reference to its role at the edge of the MPLS cloud, performing label imposition and disposition.

Virtual Routing and Forwarding (VRF)

- Virtual Routing and Forwarding (VRF) instance, is separate from the global routing table that exists on PE routers.
- PE routers maintain separate routing tables:
 - Global routing table
 - ➔ Contains all PE and P routes (perhaps BGP).
 - ➔ Populated by the VPN backbone IGP .
 - VRF table
 - ➔ Routing and forwarding table associated with one or more directly connected sites (CE routers).
 - ➔ VRF is associated with any type of interface, whether logical or physical (e.g. sub/virtual/tunnel) .
 - ➔ Interfaces may share the same VRF if the connected sites share the same routing information.
 - ➔ Routes are injected into the VRF from the CE-PE routing protocols for that VRF and any MP-BGP announcements that match the defined VRF.



MPLS-VPN & VRF



Carrying VPN Routes in BGP

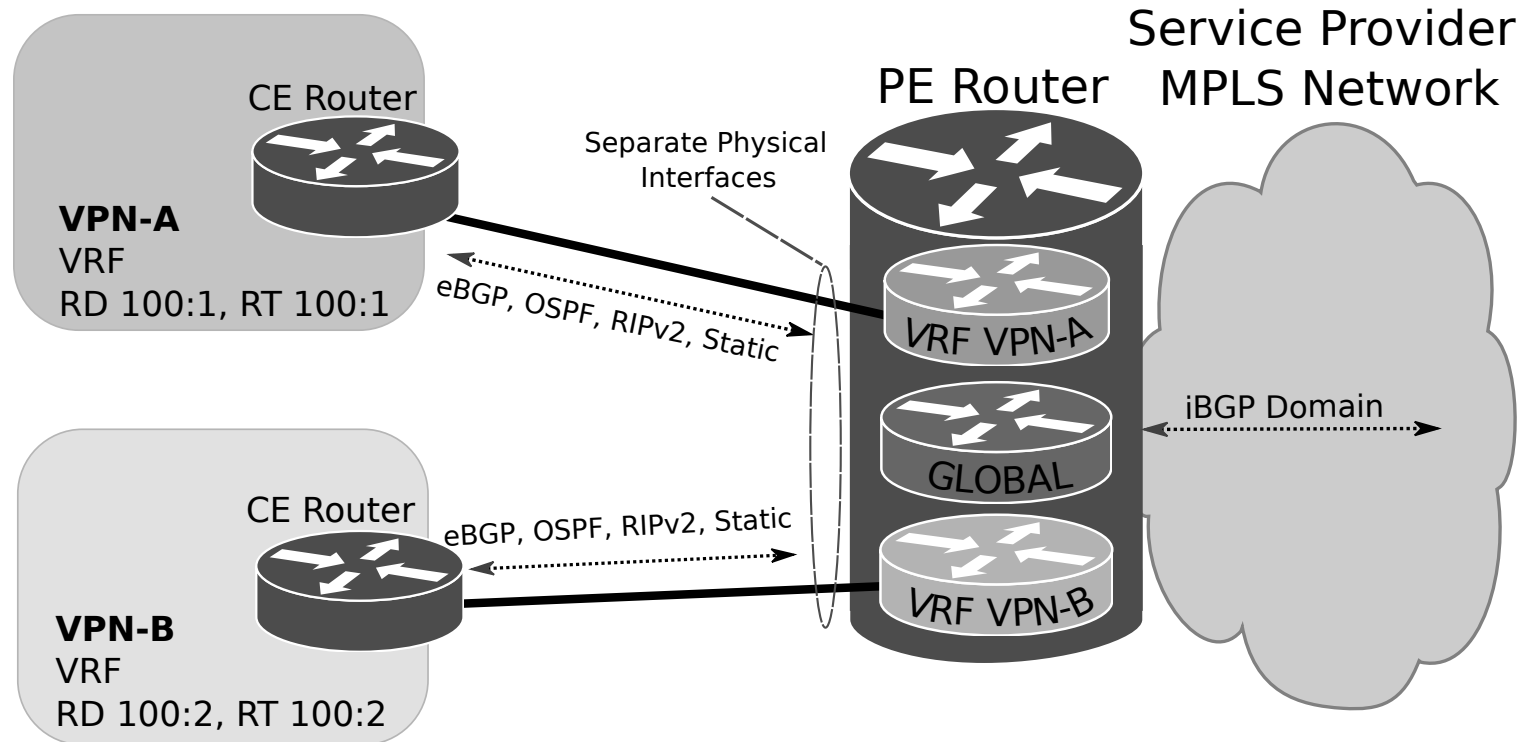
- Need some way to get the VRF routing information off the PE and to other PEs.
- This is done with MP-BGP.
- Additions to MP-BGP to carry MPLS-VPN info:
 - Route Target (RT) sent in EXTENDED_COMMUNITY attribute.
 - MP_REACH_NLRI attribute for Labeled VPN IPv4 (VPNv4) address family,
 - ➔ VPN IPv4 network.
 - ➔ Route Distinguisher (RD).
 - ➔ MPLS Label.

Border Gateway Protocol - UPDATE Message

```
Marker: ffffffffffffffffffffffffffffffffff
Length: 91
Type: UPDATE Message (2)
Withdrawn Routes Length: 0
Total Path Attribute Length: 68
  Path attributes
    Path Attribute - ORIGIN: INCOMPLETE
    Path Attribute - AS_PATH: empty
    Path Attribute - MULTI_EXIT_DISC: 0
    Path Attribute - LOCAL_PREF: 100
    Path Attribute - EXTENDED_COMMUNITIES
      Flags: 0xc0: Optional, Transitive, Complete
      Type Code: EXTENDED_COMMUNITIES (16)
      Length: 8
      Carried extended communities: (1 community)
        Community Transitive Two-Octet AS Route Target: 200:1
    Path Attribute - MP_REACH_NLRI
      Flags: 0x80: Optional, Non-transitive, Complete
      Type Code: MP_REACH_NLRI (14)
      Length: 33
      Address family: IPv4 (1)
      Subsequent address family identifier: Labeled VPN Unicast (128)
      Next hop network address (12 bytes)
        Subnetwork points of attachment: 0
      Network layer reachability information (16 bytes)
        Label Stack=24 (bottom) RD=200:1, IPv4=192.1.1.0/25
```



VRF Route Population



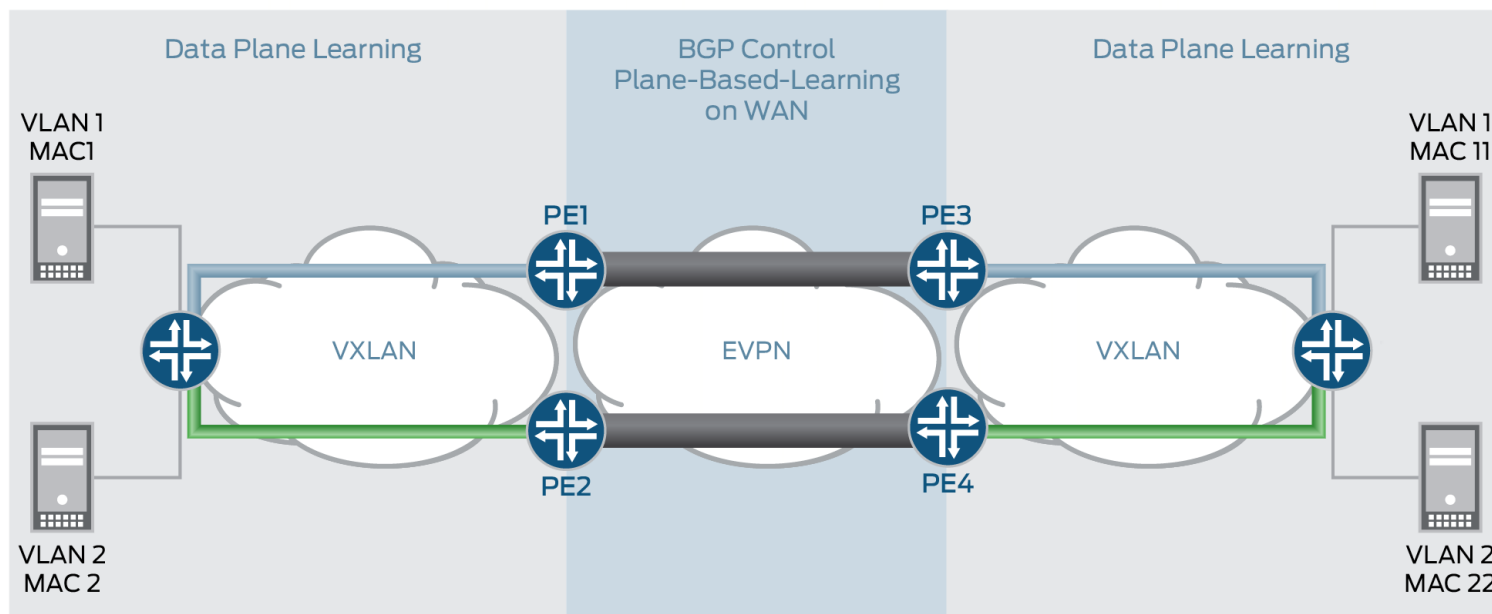
- VRF is populated locally through PE and CE routing protocol exchange.
 - EBGp, OSPF, RIPv2, and Static routing.
 - “Connected” is also supported.
- Separate routing context for each VRF.
 - Routing protocol context (e.g., MP-BGP).
 - Separate process (e.g., OSPF).

MPLS-VPN Packet Forwarding

- Between PE and CE, regular IP packets (currently)
- Within the provider network—label stack
 - ♦ Outer label: “get this packet to the egress PE”
 - ♦ Inner label: “get this packet to the egress CE”
- MPLS nodes forward packets based on TOP label!!!
 - ♦ any subsequent labels are ignored
- Penultimate Hop Popping procedures used one hop prior to egress PE router (shown in example)



VXLAN-EVPN



- Stands for Virtual Extensible LAN (VXLAN) Ethernet Virtual Private Network (EVPN).
- Multi-Site architecture for seamless Layer 2 and Layer 3 extension.
 - ◆ Commonly used in datacenters.
- Constructed based on MP-BGP Layer2 VPN EVPN family.
 - ◆ Is similar to MP-BGP MPLS IP VPN.
- Defines a new type of BGP network layer reachability information (NLRI).
 - ◆ EVPN NLRI
 - ◆ Defines new BGP EVPN routes to implement MAC address learning and advertisement between Layer 2 networks at different sites.