Network Virtualization

Future Internet Communications Technologies

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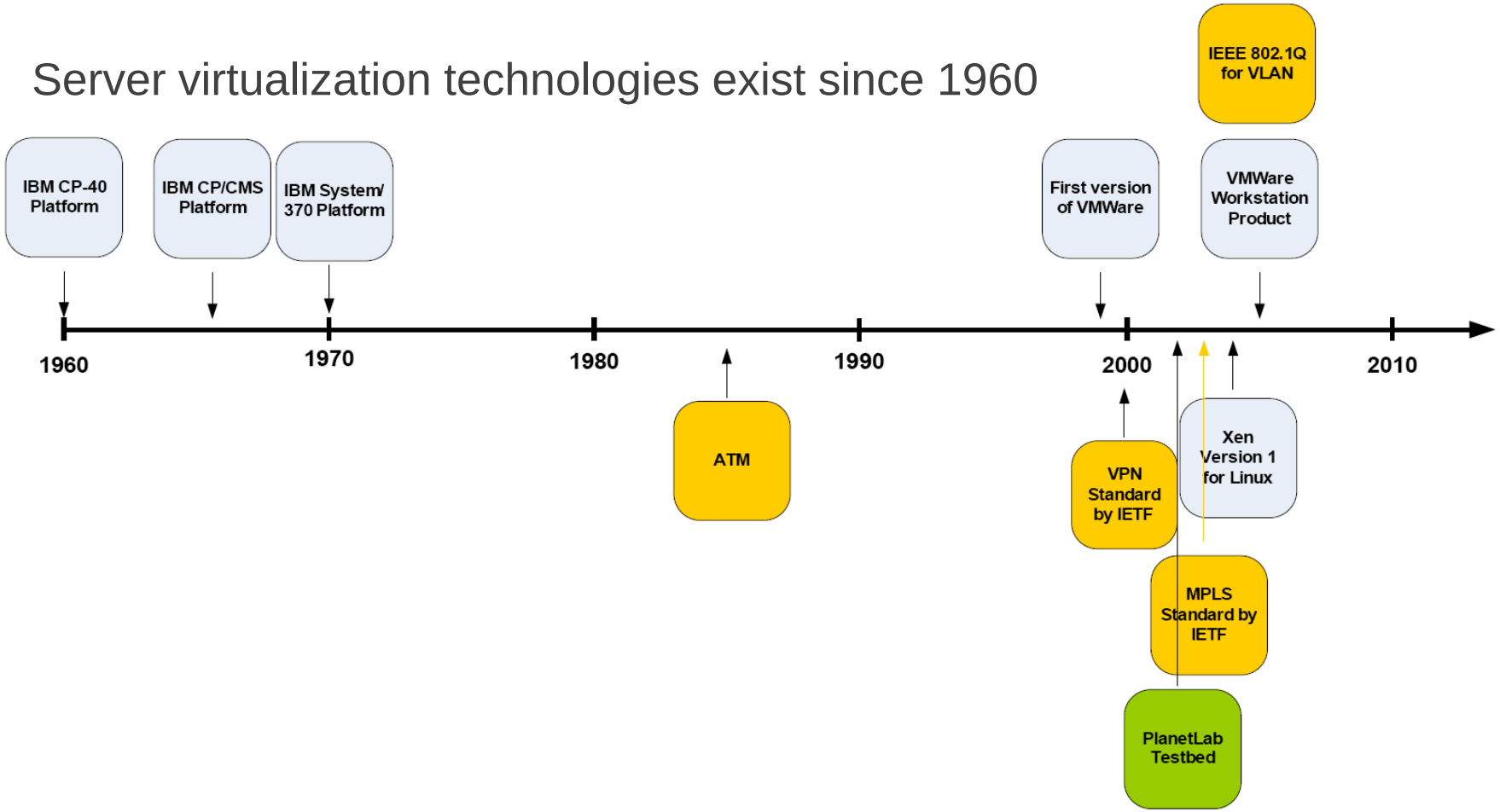
Outline

- Introduction to Network Virtualization
- Network Virtualization Technologies
- Server Virtualization
- Link Virtualization
- Network Interface Virtualization
- Router Virtualization
- Virtual Network Embedding
- Virtual Network Embedding Across Multiple Substrate Networks
- Virtual Link Setup

Introduction to Network Virtualization

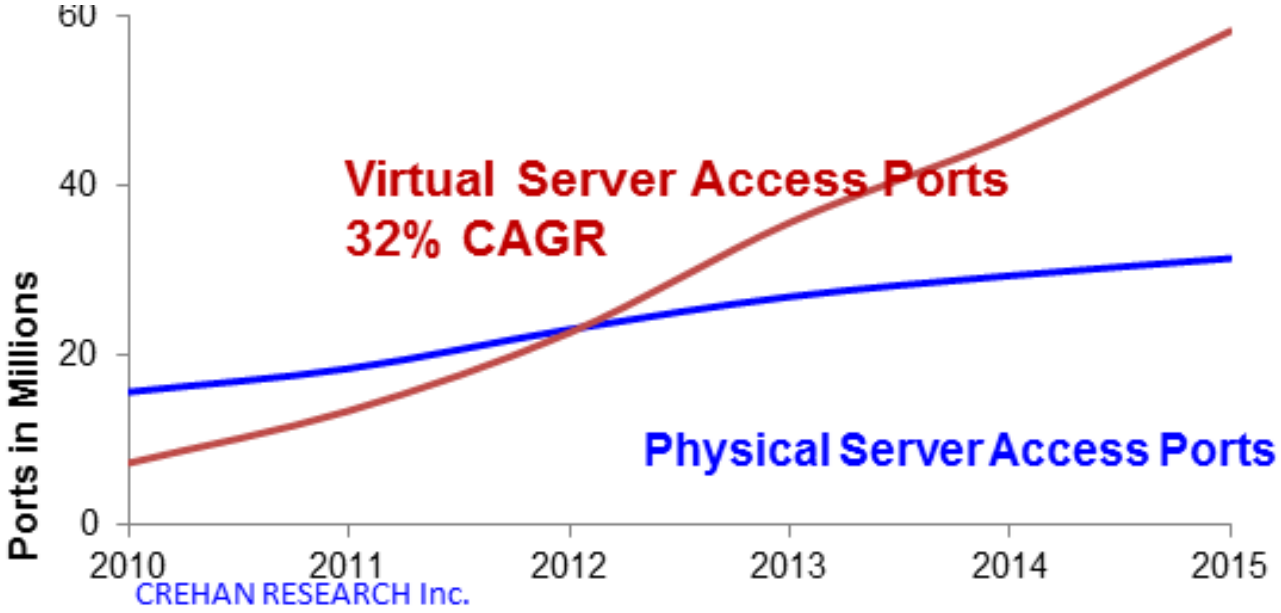
Virtualization

- Virtualization is not a new concept (e.g., virtual memory)
- Server virtualization technologies exist since 1960



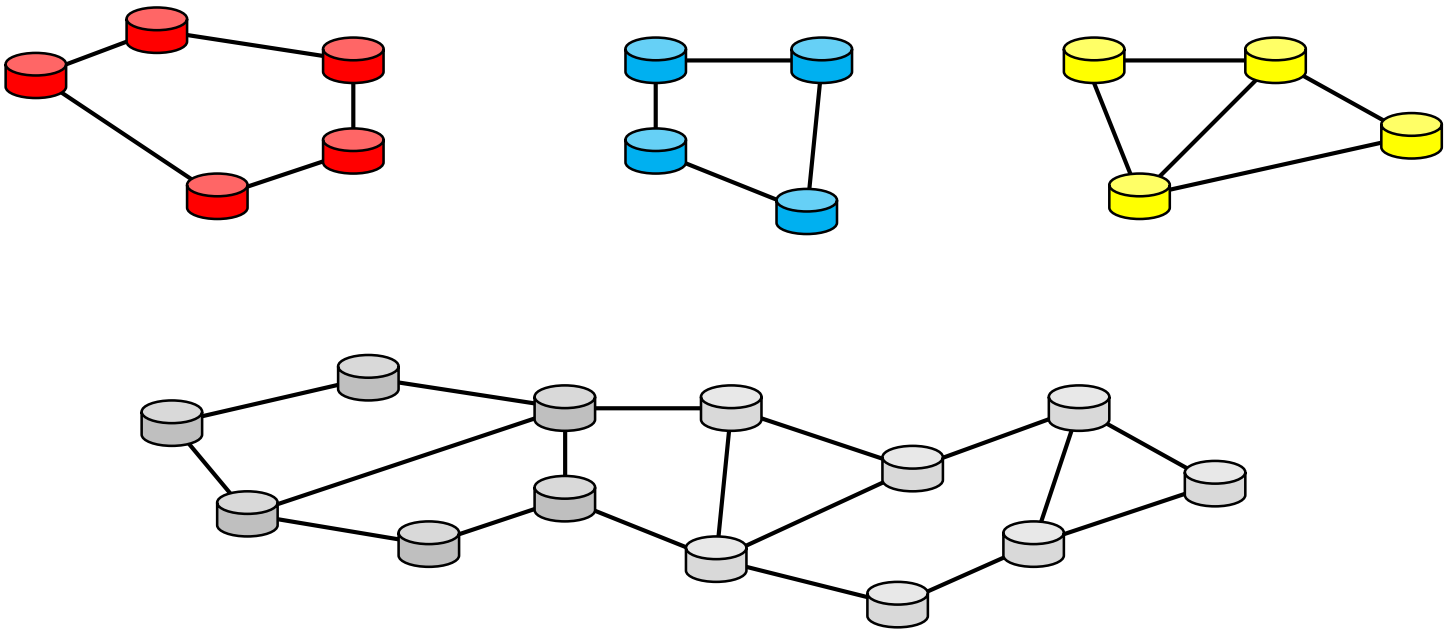
Network Access Virtualization

- The number of virtual access ports increases by 32%



Network Virtualization

- Multiple virtual networks can coexist on top of a shared physical (substrate) network.
- A virtual network is composed of virtual nodes and links.



Network Virtualization Benefits

- Resource sharing (e.g., CPU, bandwidth)
- Independent network management
- Abstraction
- Flexible network management
  - Elasticity
  - Fault tolerance
  - Easier maintenance of physical equipment
- Excellent platform for experimentation
  - Isolating experimental from production traffic
- Innovation in architecture design
  - Concurrent deployment of multiple network architectures

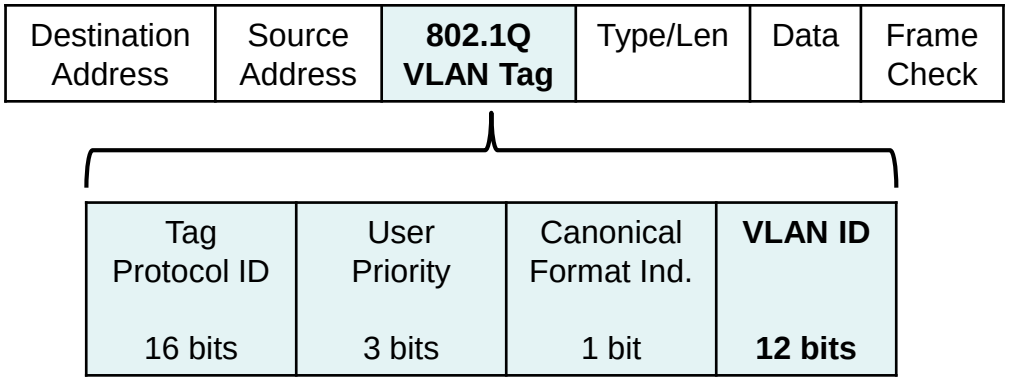
Virtual Networks vs. Overlays

- Virtual networks are conceptually similar to overlays:
  - Virtual networks provide a topology composed of virtual nodes and links on top of one or multiple physical networks
- Overlays:
  - introduce mechanisms above the transport layer to control the routing across the overlay nodes (e.g., multicast)
  - are typically deployed at the network edge
  - do not lead to any fundamental changes in the physical infrastructure
- Virtual networks can provide higher control on routing and packet delivery by utilizing virtual routers with customized protocol stacks and enhanced programmability

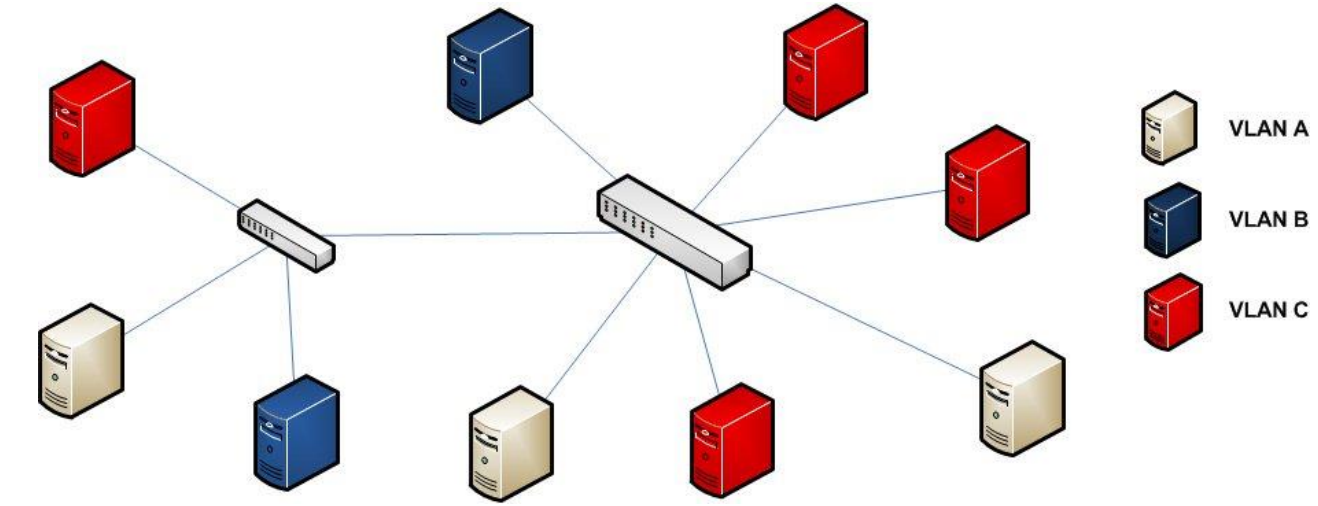
Network Virtualization Technologies

Virtual Local Area Networks (VLANs)

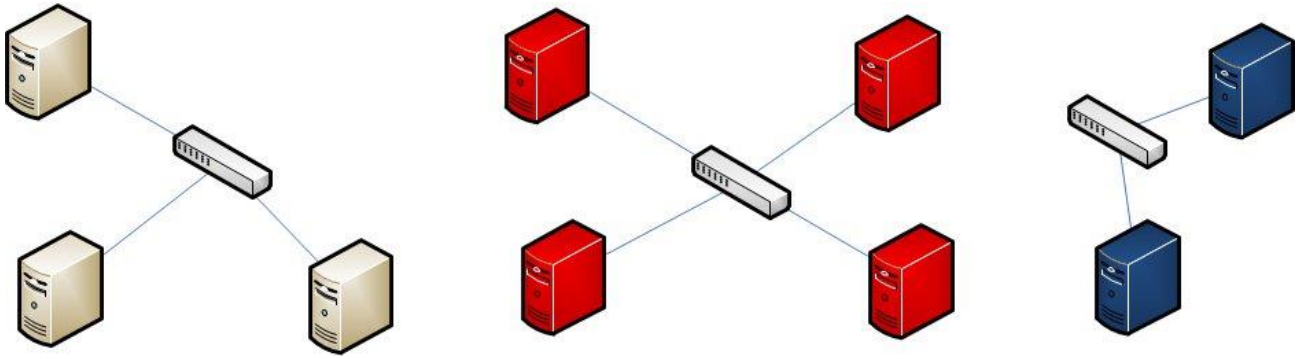
- VLANs isolate groups of hosts into separate broadcast domains using the IEEE 802.1Q standard
  - ✓ Widely available (supported by many switches)
  - ✓ Up to 4096 VLANs
  - ✘ Limited capability for WANs



VLAN Physical and Logical View



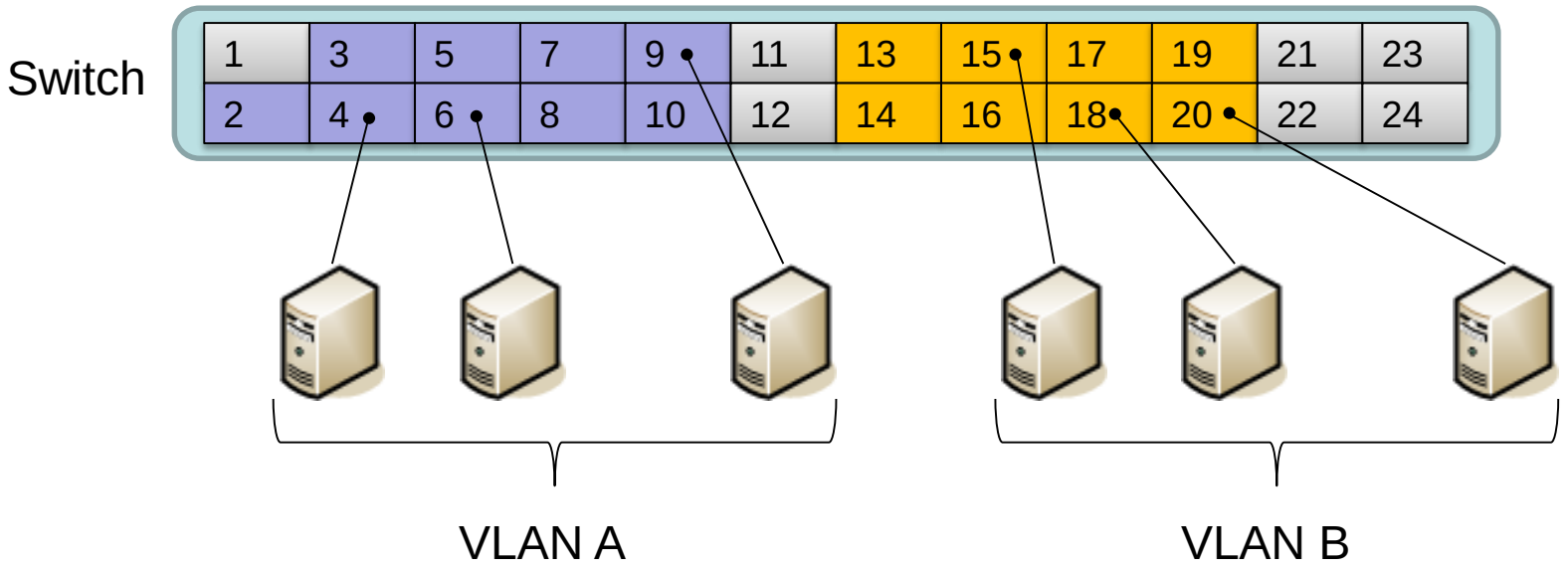
Physical View



Logical View

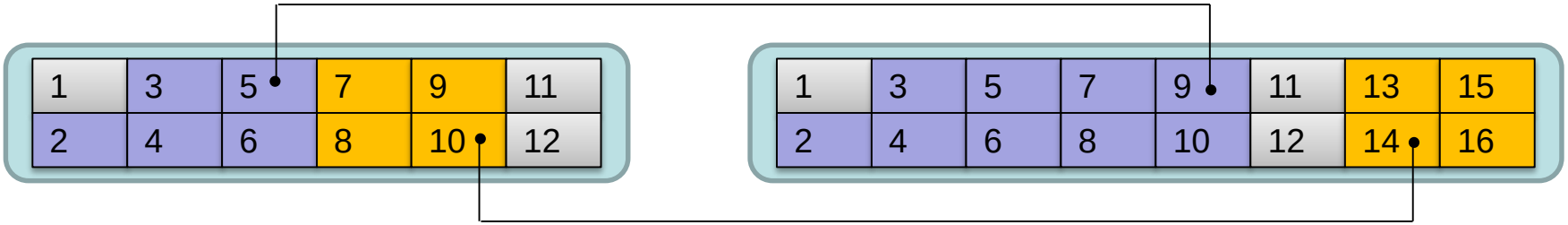
VLAN Configuration

- Switch ports are assigned with VLAN IDs
  - The switch software maintains a table of port-to-VLAN mappings



VLAN Configuration Across Multiple Switches

- Separate connection per VLAN
  - Wastes switch ports
  - Static configuration



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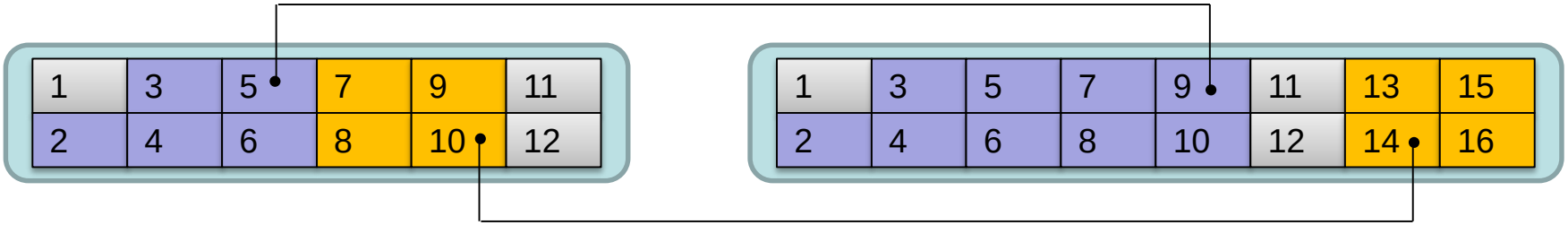
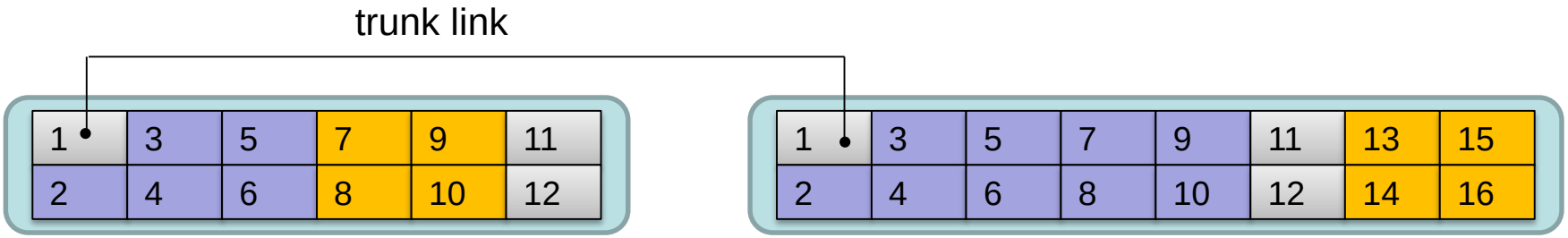


- VLAN trunking
  - All frames (irrespective of VLAN ID) are forwarded over the trunk link



Virtual Private Networks (VPN)

- VPNs comprise a service that provides:
  - remote access to a private network via tunneling
  - secure access via authentication
  - traffic isolation
- VPNs do not offer any benefits or flexibility in terms of management (e.g., independent resource management) as virtual networks do
- VPN setup usually incurs a long delay

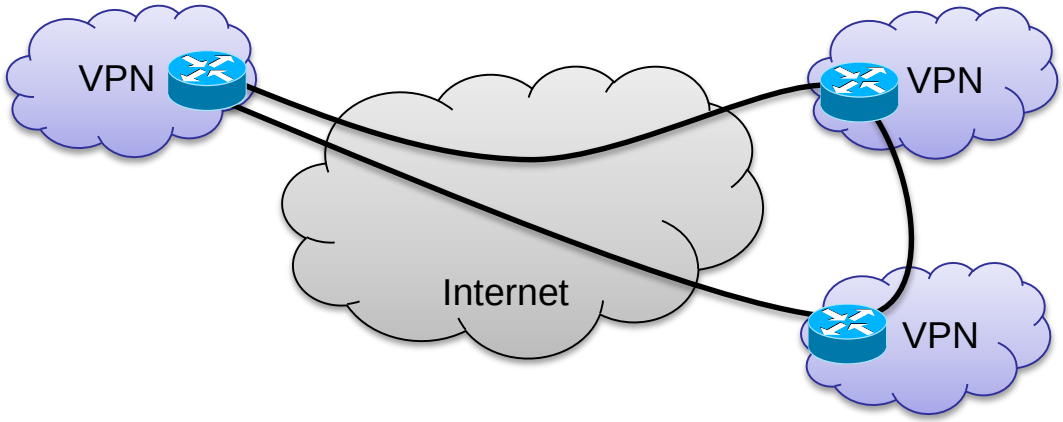
VPN Tunneling

- A tunnel is a method of sending data by encapsulating the data and its protocol information within a different transmission unit

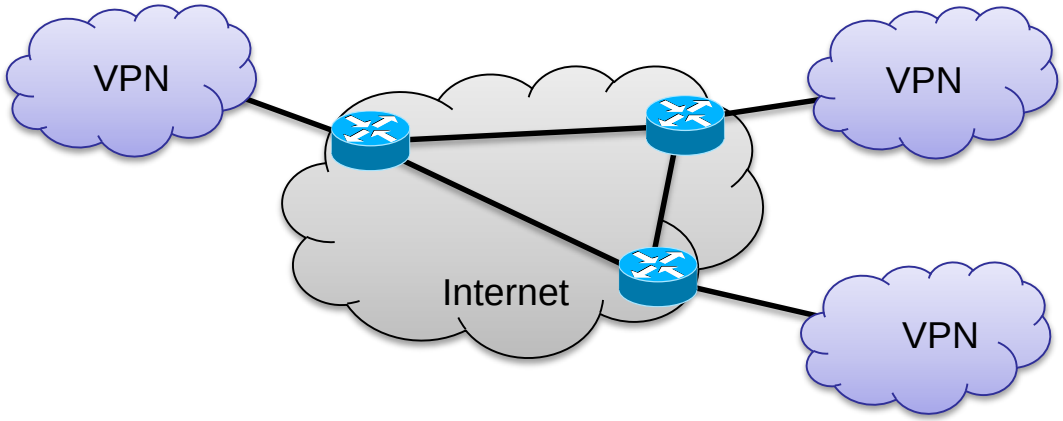
- VPNs encompass various tunneling technologies:
  - Layer 2:
    - Point-to-point:
      - MPLS, L2TP, PPTP, PPP
    - Point-to-multipoint:
      - Virtual Private LANs
  - Layer 3:
    - IP-in-IP
    - Generic Routing Encapsulation (GRE)
    - IPsec

VPN Service Models

- Customer model

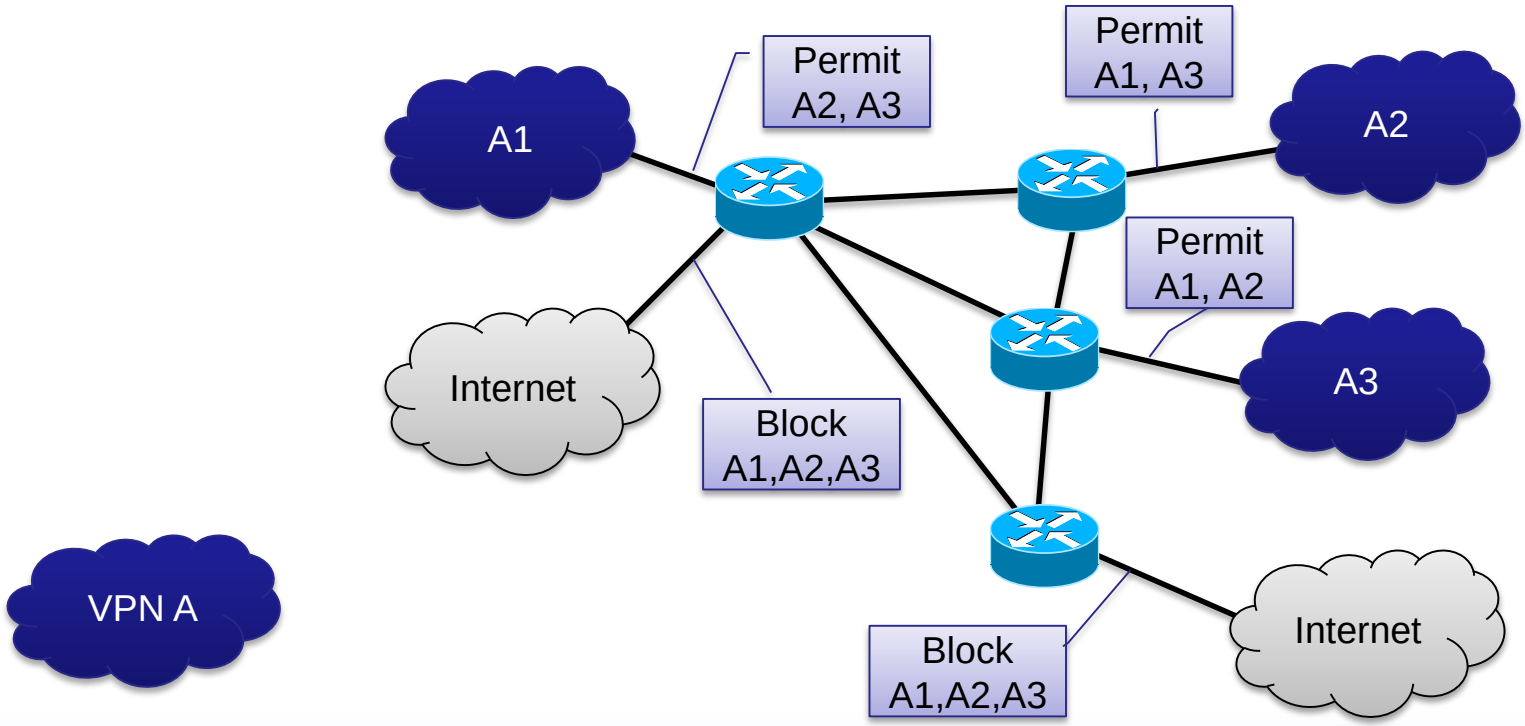


- Provider-provisioned VPN (PPVPN), e.g., BGP/MPLS VPN
  - Logical routers with own:
    - Routing protocol
    - Forwarding table
    - Route filtering



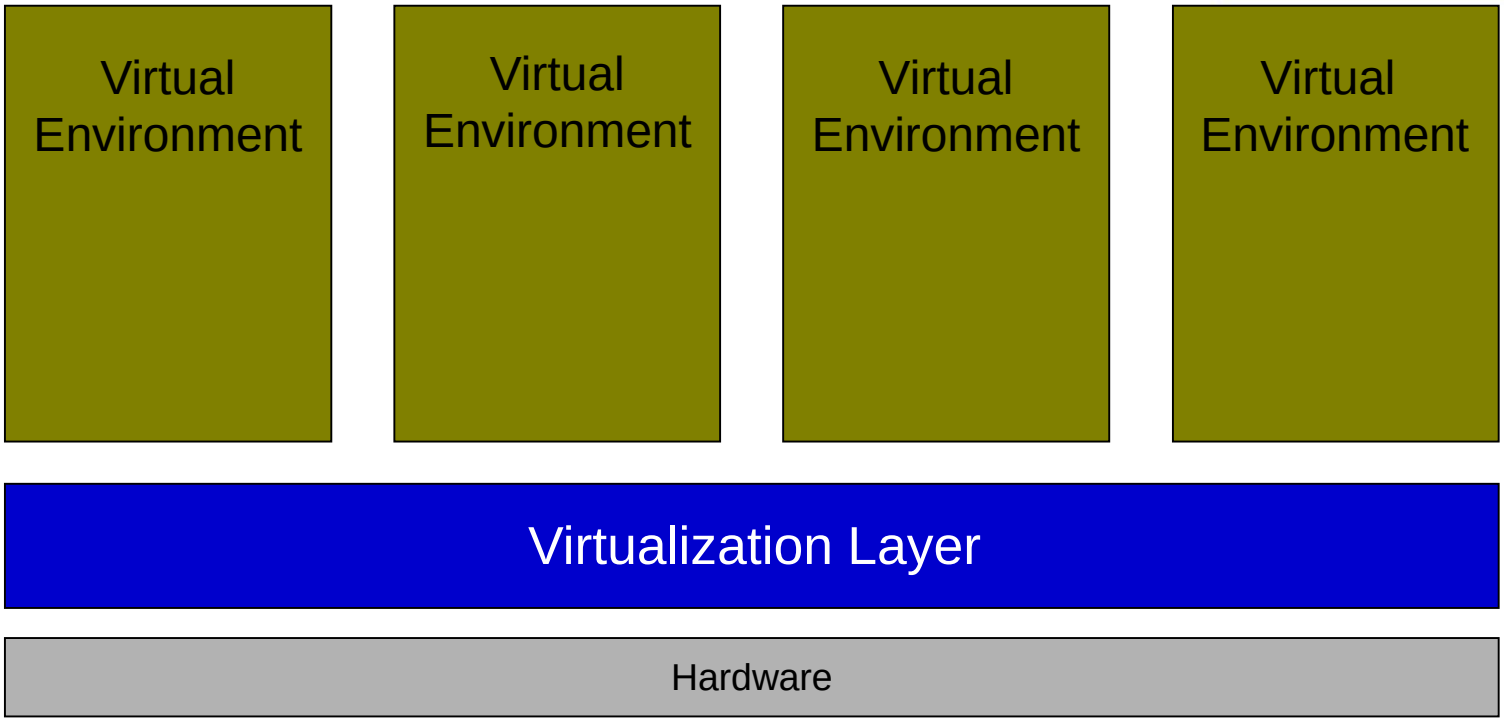
VPN Route Filtering

- Route filtering
  - Controls route propagation so that:
    - networks within a VPN receive route advertisements for other networks in the same VPN
    - networks not in same VPN do not receive these advertisements



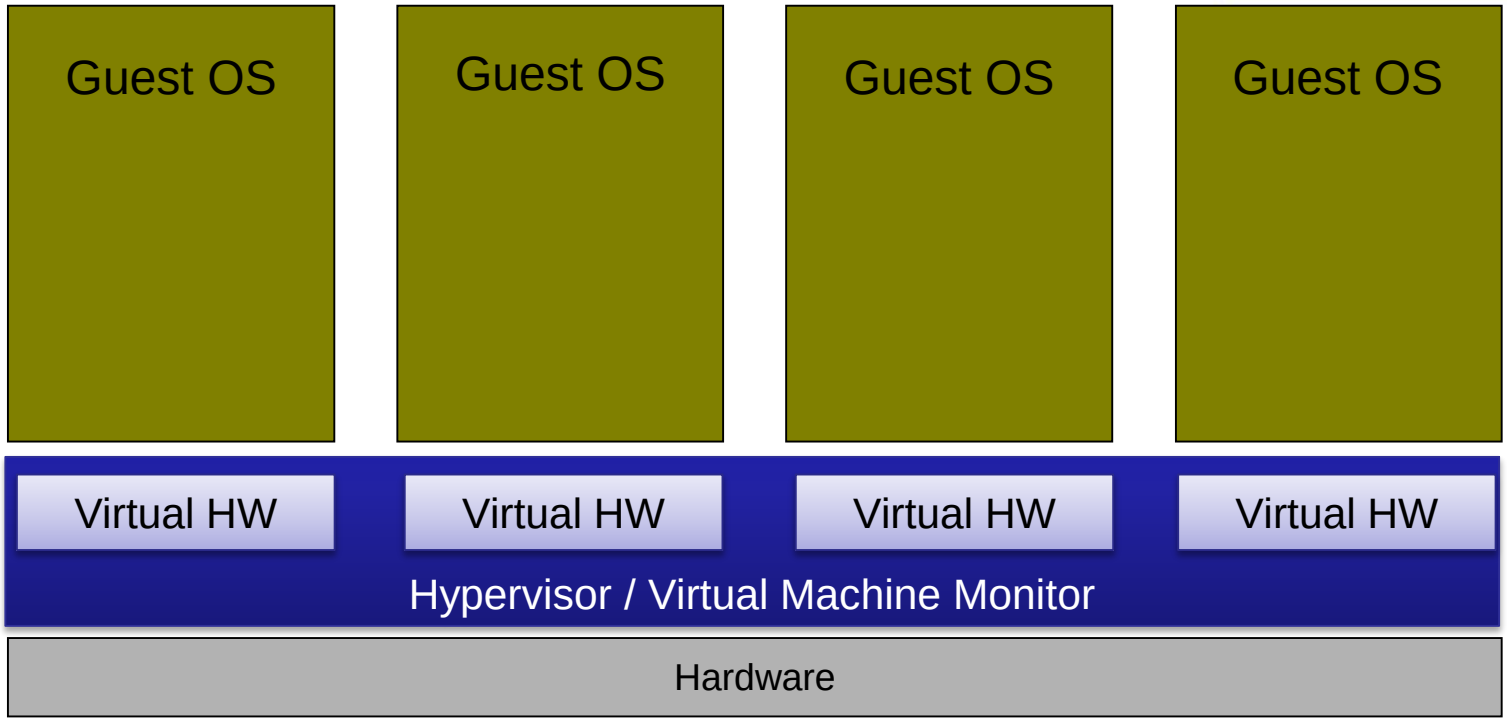
Server Virtualization

Server Virtualization Overview



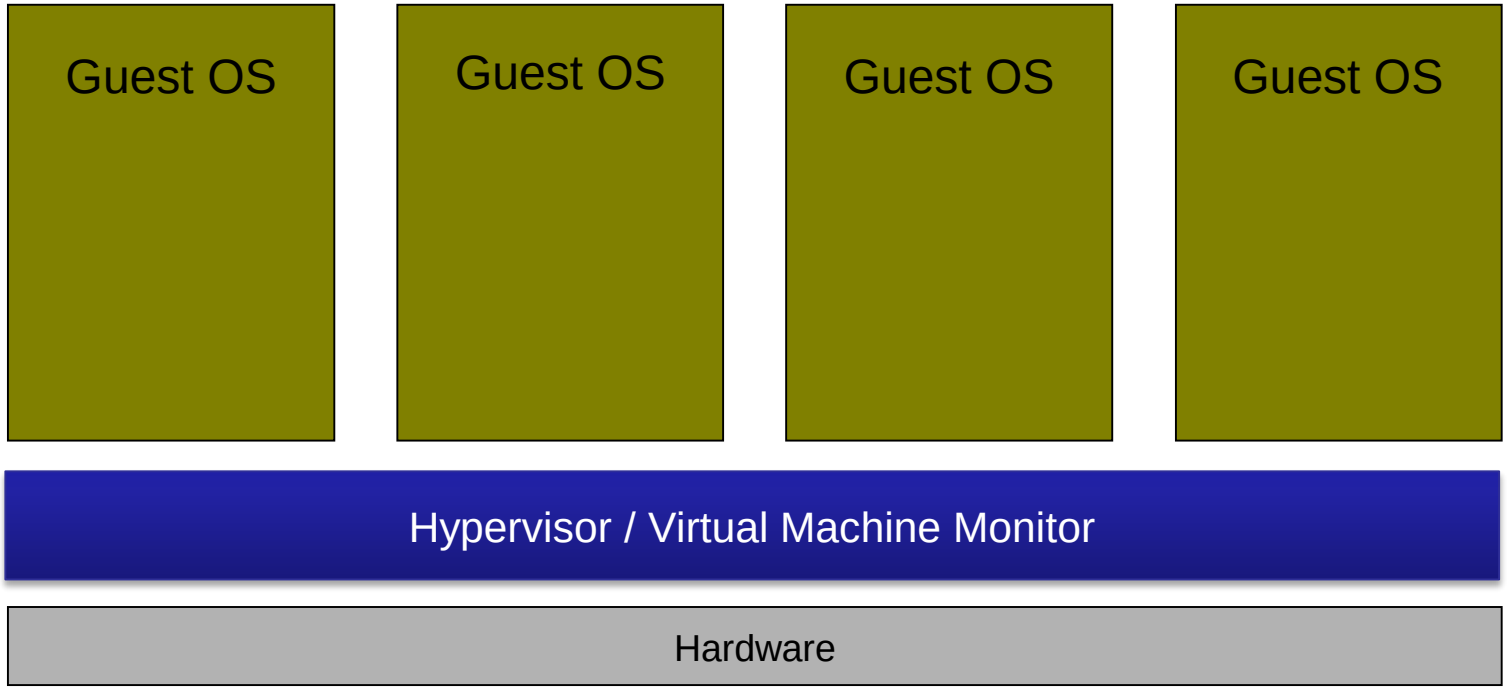
- Server virtualization technologies:
  - aim to provide efficient resource (e.g., CPU, memory) sharing and isolation
  - allow multiple operating systems (OS) to run concurrently on a single host

Full Virtualization



- Full Virtualization (e.g., KVM):
  - provides fully emulated virtual machines (BIOS, devices, memory management) for running multiple OSes
  - allows guest domains to directly execute privileged operations
  - accommodates unmodified guest OSes

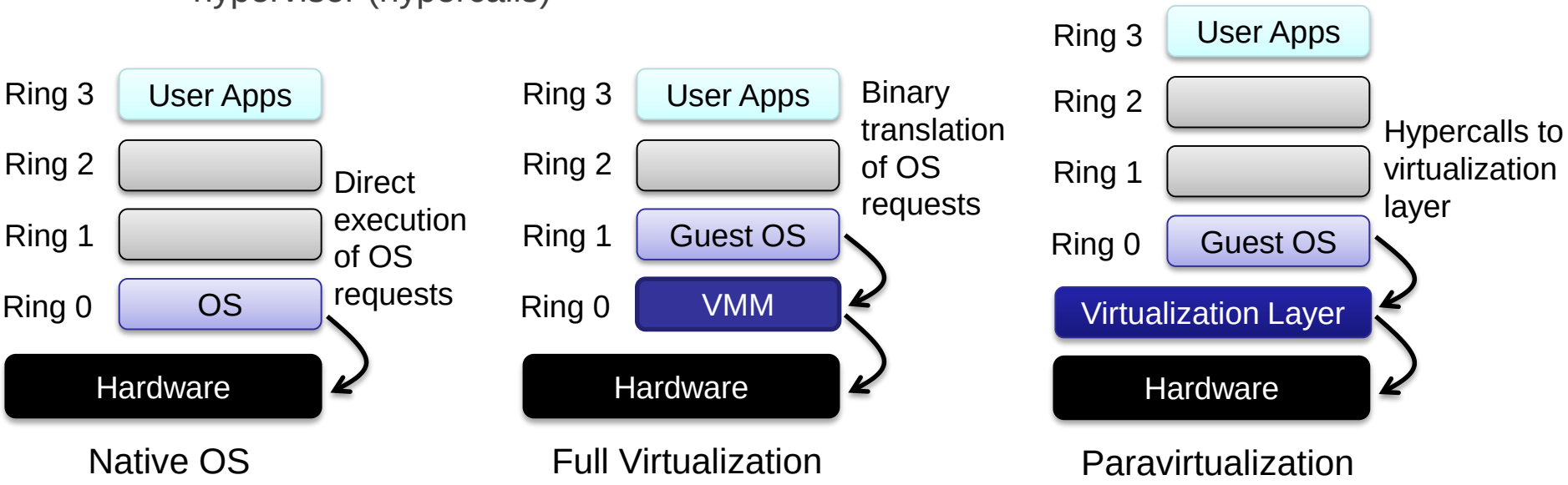
Paravirtualization



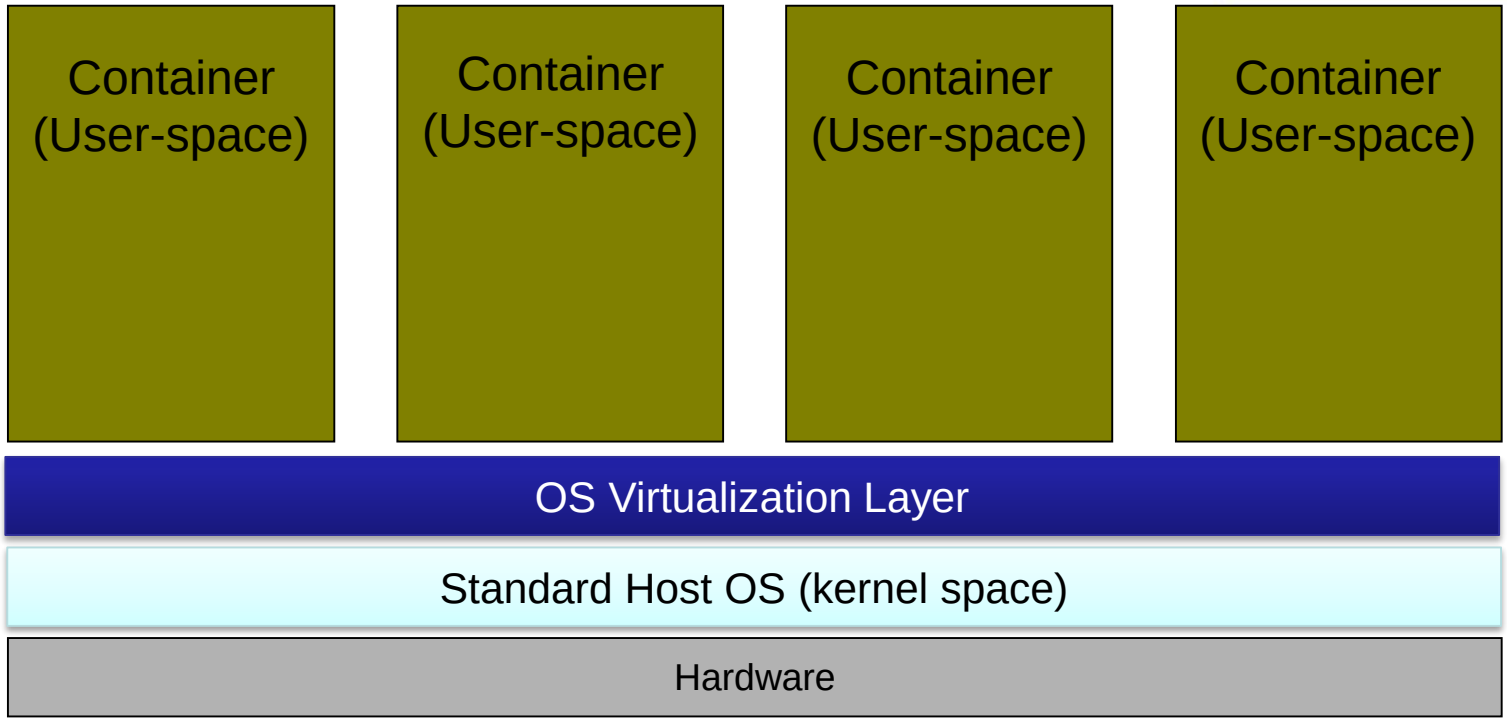
- Paravirtualization (e.g., Xen):
  - provides a hypervisor that runs on top of the hardware
  - does not allow guest domains to directly execute privileged operations (permission is required via hypercalls)
  - requires modified guest OSes

Full Virtualization vs. Paravirtualization

- Protection rings represent hierarchical levels of privilege within the architecture of a computer system
- In full virtualization, VMM provides emulation to handle and modify privileged operations made by unmodified guest OS kernels (as running at Ring 0).
- In paravirtualization, the guest OS kernel is modified to run on the hypervisor
  - Privileged operations that will only run at Ring 0 are replaced with calls to the hypervisor (hypercalls)



OS-based Virtualization

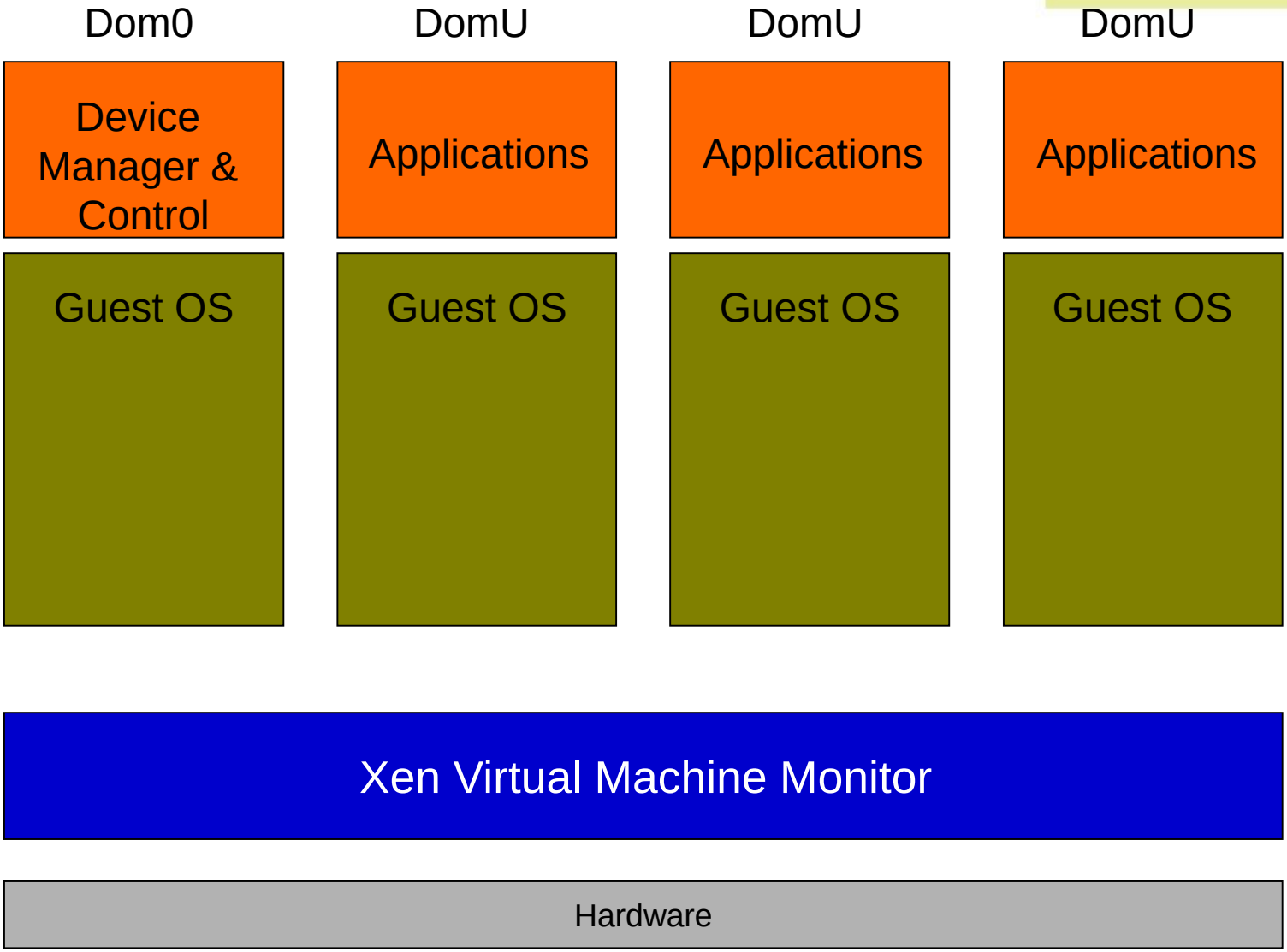


- OS-based virtualization (e.g., OpenVZ, VServer):
  - creates multiple partitions of operating system resources (containers)
  - provides a single kernel instance for all containers

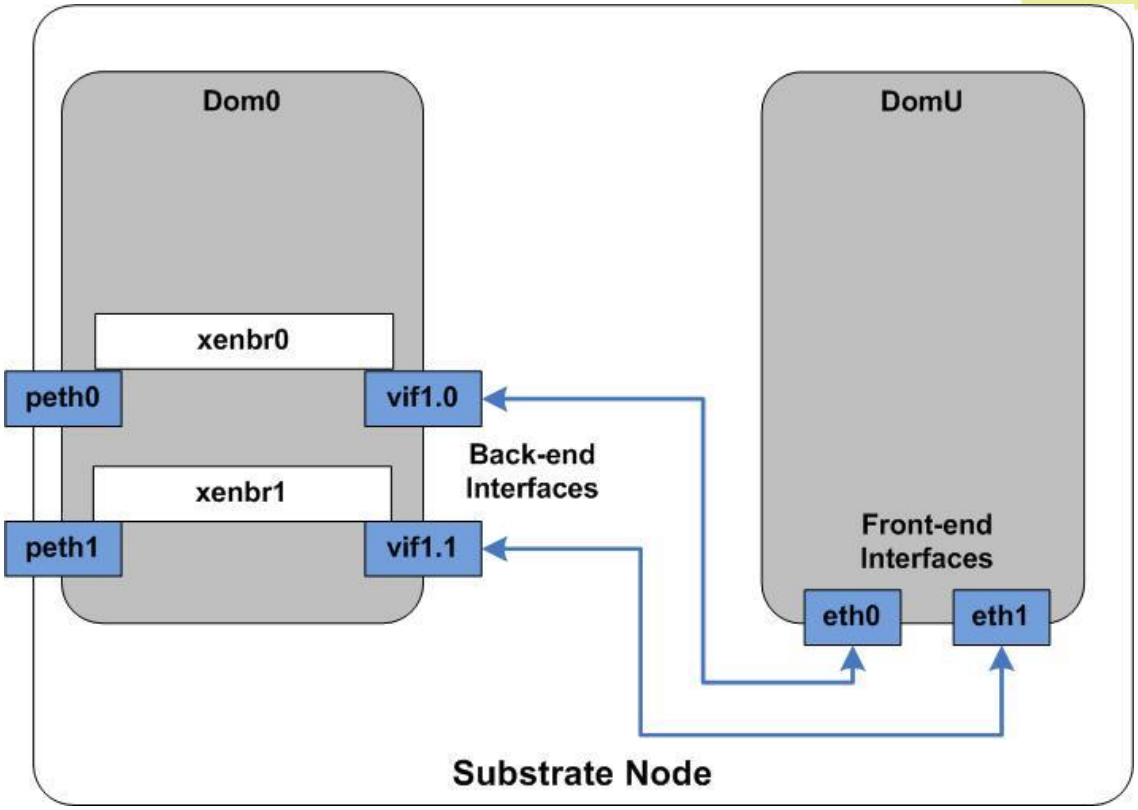
Comparison of Server Virtualization Technologies

- Full Virtualization
  - Maximum isolation
  - Performance penalty
- Paravirtualization (e.g., Xen, Denali)
  - High flexibility (e.g., different guest OSes)
  - Adequate isolation
  - Sub-optimal performance due to overhead
- OS-based virtualization
  - High performance due to small overhead
  - Limited flexibility (single instance of kernel)
  - Lower level of isolation

Xen Overview



Xen Inter-Domain Communication



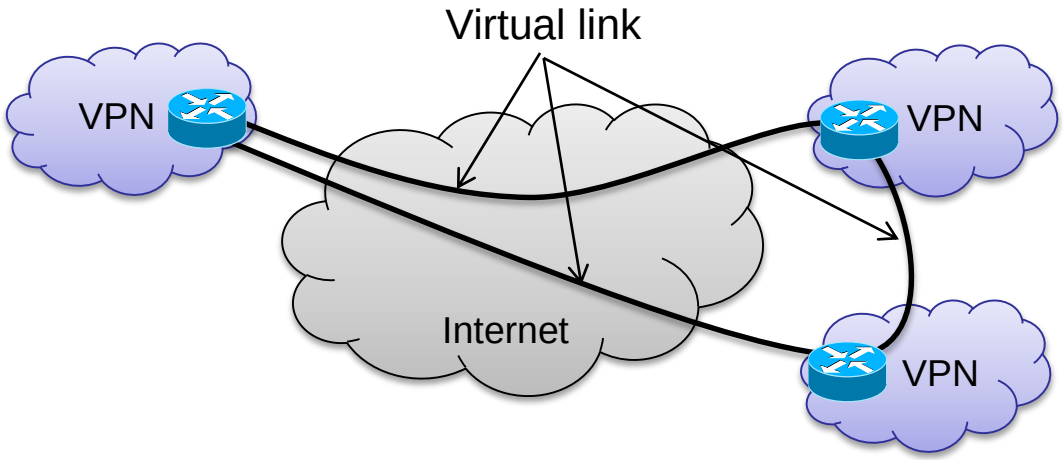
- A NIC driver is split into a front-end and back-end driver
- Xen creates I/O channels to connect front-end with back-end interfaces
- A Linux bridge typically connects a virtual back-end with a physical interface

Link Virtualization

Link Virtualization

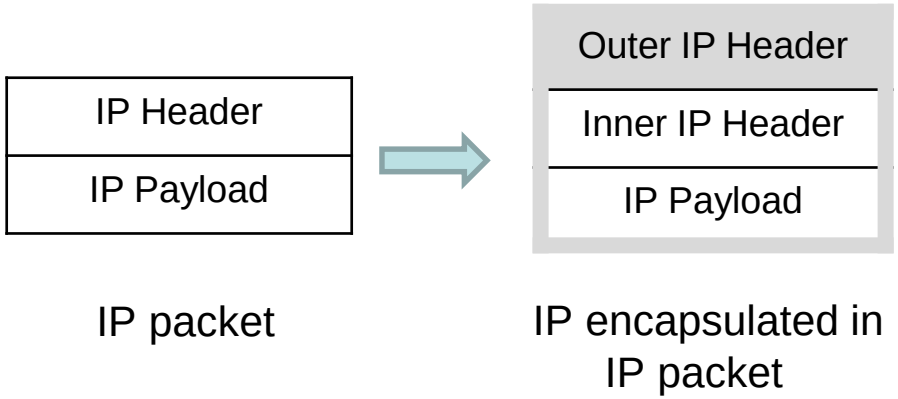
- Virtual links (a.k.a. tunnels) give the appearance of a single link ("pseudo-wire"), although they might span multiple hops

- Various technologies for link virtualization:
  - IP-in-IP
  - Multi-Protocol Label Switching (MPLS)
  - Generic Routing Encapsulation (GRE)
  - Ethernet over IP (EtherIP)

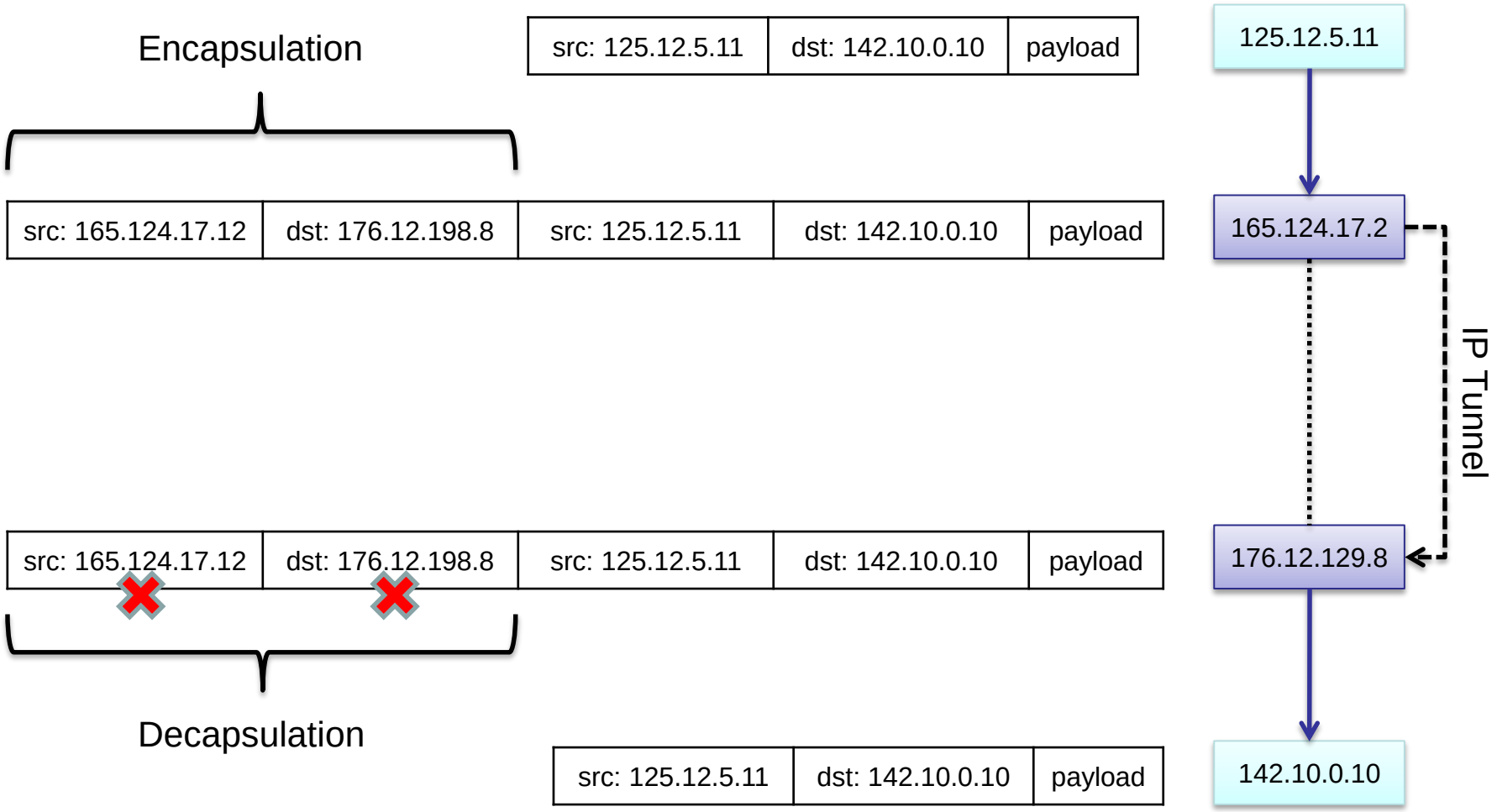


IP-in-IP

- IP-in-IP encapsulates IP packets into other IP packets (v4 or v6)
  - ✓ Widely available
  - ✘ Encapsulation overhead (20 bytes for IPv4)

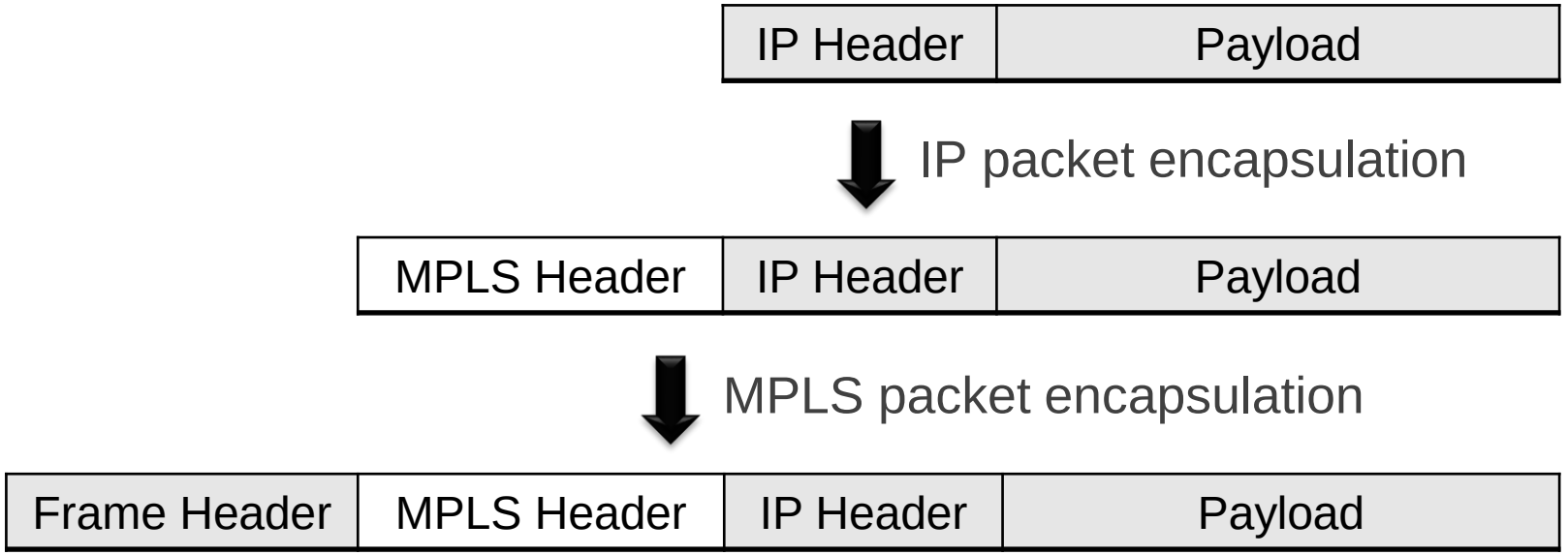


IP-in-IP Example

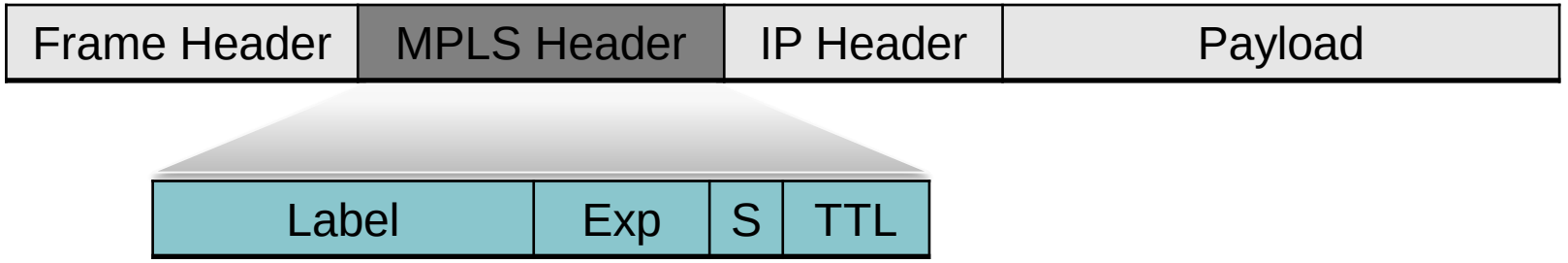


Multi-Protocol Label Switching (MPLS)

- MPLS encapsulates IP packets into frames (Ethernet, PPP)
  - ✓ Reliable link virtualization
  - ✓ Fast lookup based on a fixed-length label
  - ✓ Deployed by ISPs



MPLS Header



- MPLS header fields:
  - 20-bit Label value
  - 3-bit Traffic Class field for QoS
  - 1-bit field for stacked MPLS headers
  - 8-bit TTL (Time-to-Live)

MPLS Switching

- An MPLS-capable router (a.k.a. label switch router – LSR) maintains MPLS forwarding tables:

in label	out label	prefix	output interface
8	13	15.1.3	1
12	4	15.4.6	2

- An LSR forwards packets as follows:
  - examines the packet label value
  - performs a label lookup to determine the “out label” and the output interface
  - swaps the packet label value with the “out label” value
  - forwards the packet to the output interface

MPLS Switching at the Edge

in label	out label	prefix	output interface
–	1	15.1.3	1
–	5	15.4.6	2

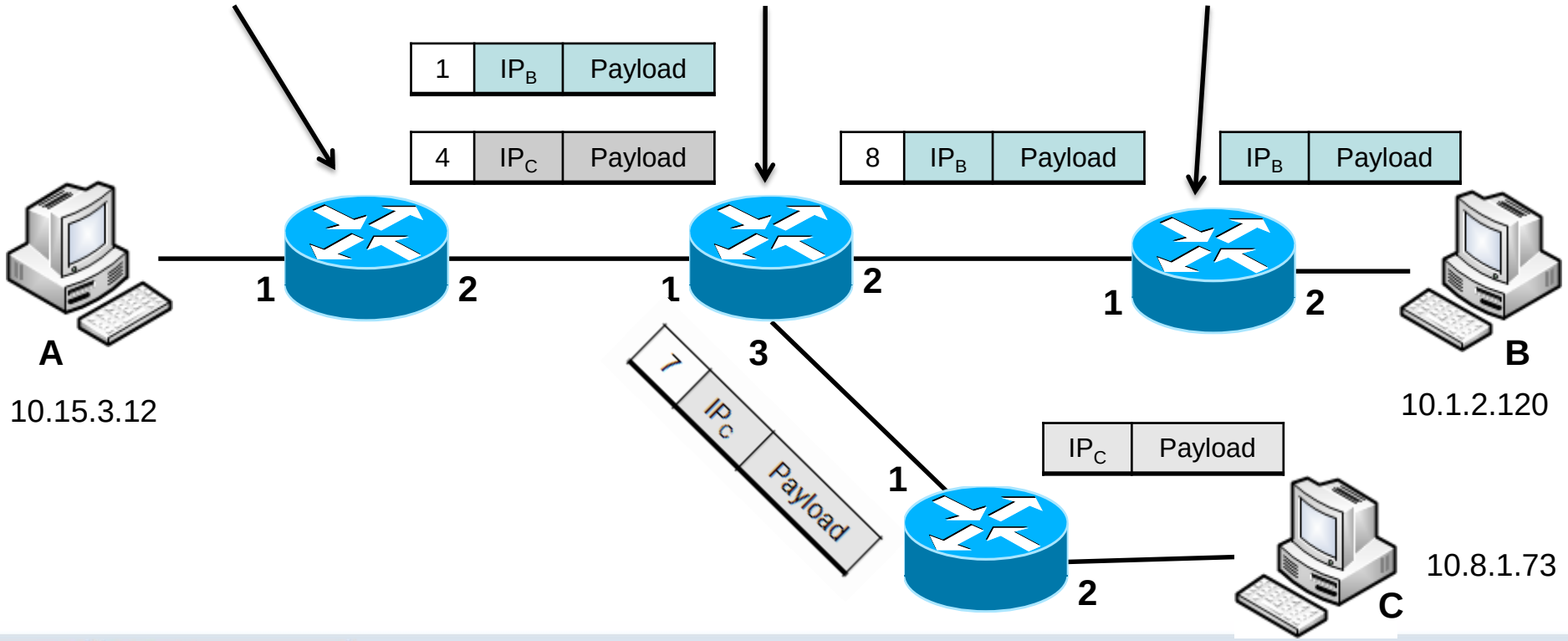
- An edge MPLS-capable router (a.k.a. label edge router – LER) forwards packets as follows:
  - examines the packet IP header
  - performs an IP lookup to determine the “out label” and the output interface
  - sets the “out label” value to the packet label value
  - forwards the packet to the output interface

MPLS Example

in label	out label	prefix	output interface
–	1	10.1.2	2
–	4	10.8.1	2

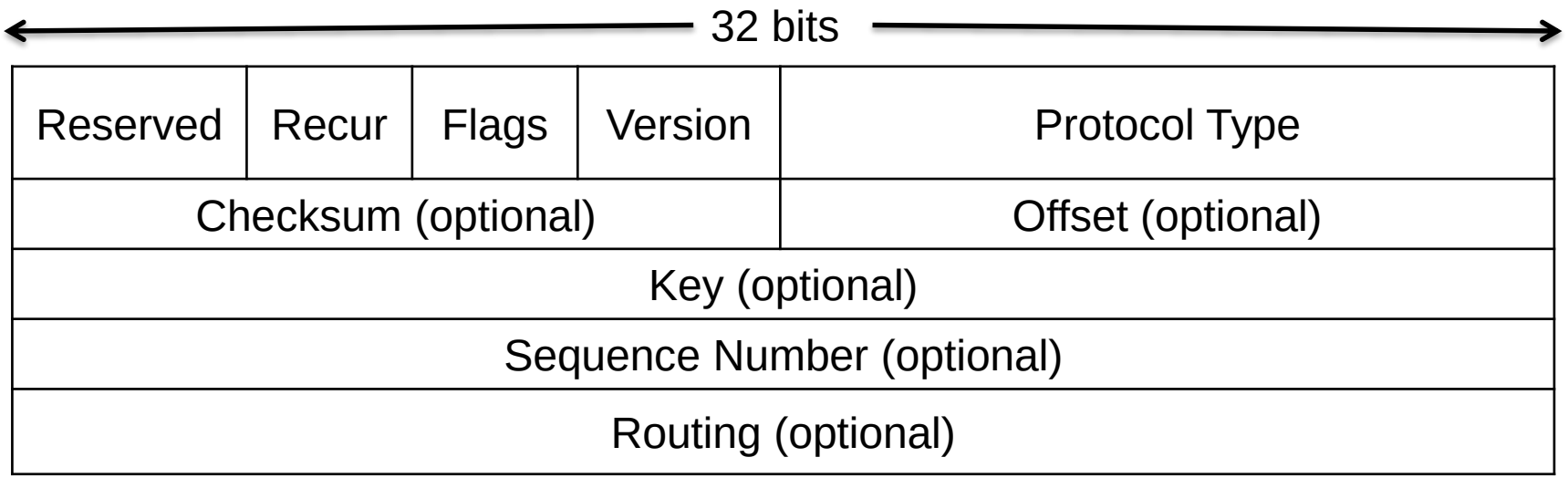
in label	out label	prefix	output interface
1	8	10.1.2	2
4	7	10.8.1	3

in label	out label	prefix	output Interface
8	–	10.1.2	2



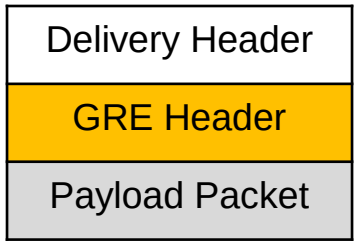
Generic Routing Encapsulation (GRE)

- Generic Routing Encapsulation (GRE)
  - ✓ General packaging protocol (can package any protocol's packets)
  - ✓ 4-byte (optional) key for de-multiplexing
  - ✓ Small encapsulation overhead (4 bytes without optional header fields)

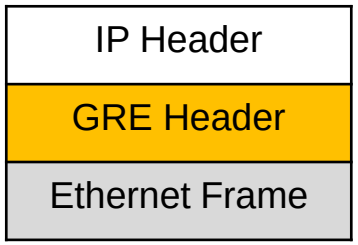


GRE Encapsulation

- A GRE encapsulation packet has the form:

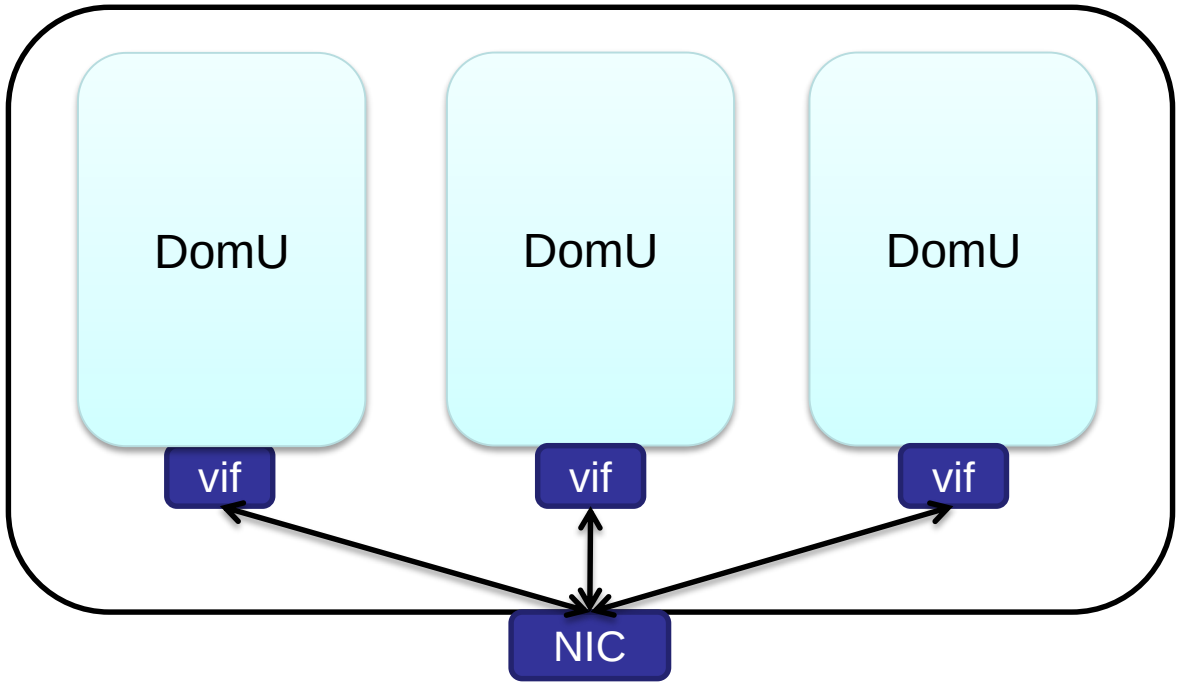


- Ethernet over GRE (EGRE):



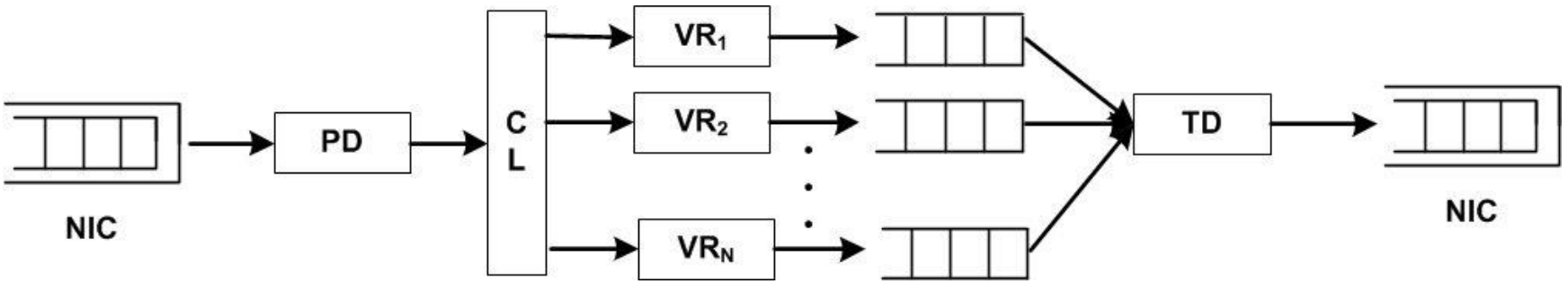
Network Interface Virtualization

Network Interface Sharing



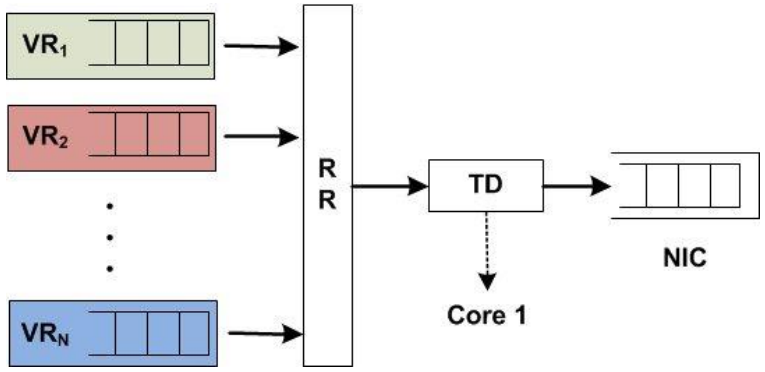
- Multiple virtual nodes/routers might have to share a physical network interface
  - Packets should be classified among the virtual nodes/routers

Packet Classification in Software

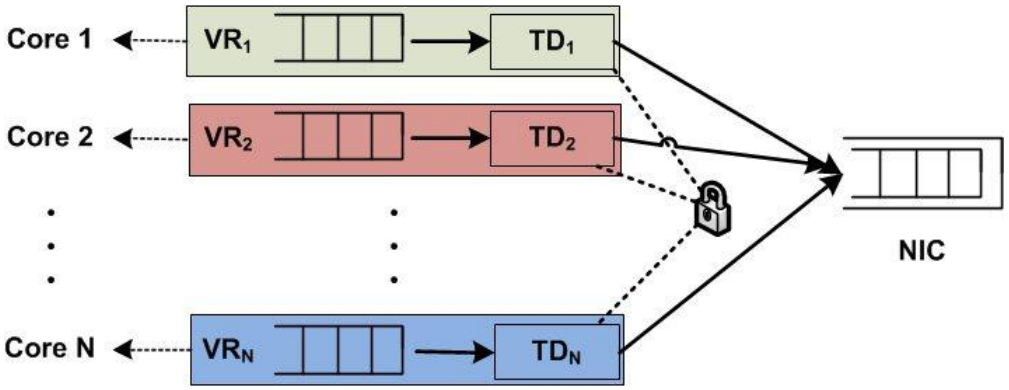


- ✓ Widely available (e.g., Click Modular Router, OpenvSwitch)
- ✓ Easy to enforce policies (e.g., weighted fair queuing)
- ✘ Resource utilization with multi-core CPUs

- Use Case: Output processing

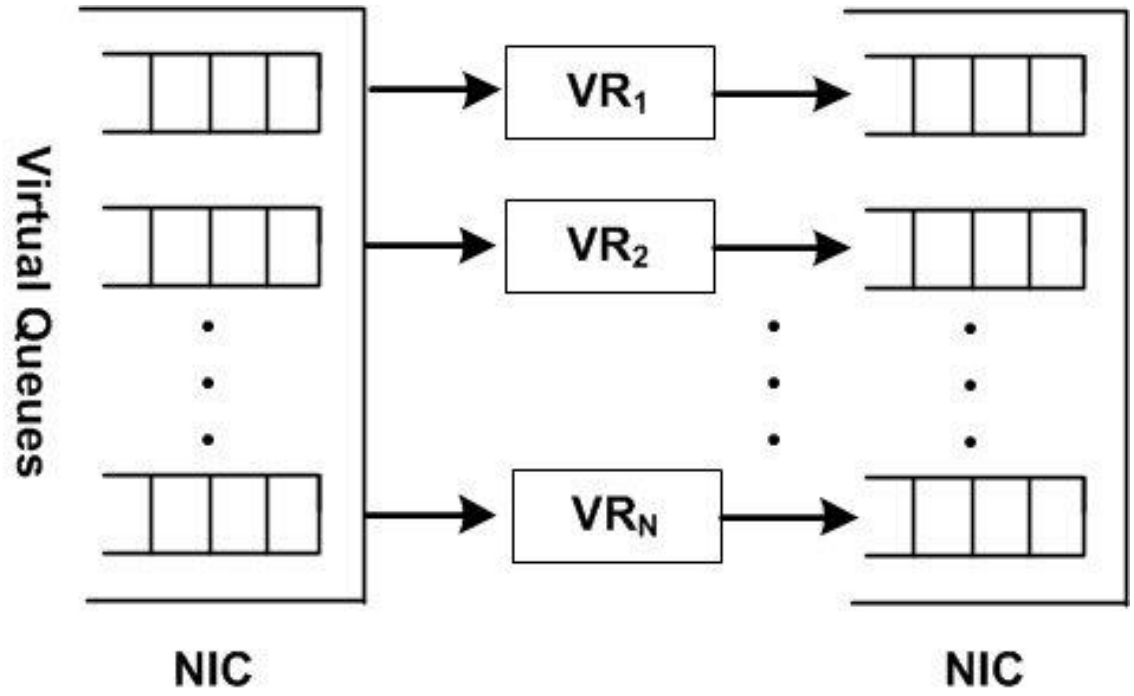


CPU-limited



concurrency-limited

Packet Classification in Hardware



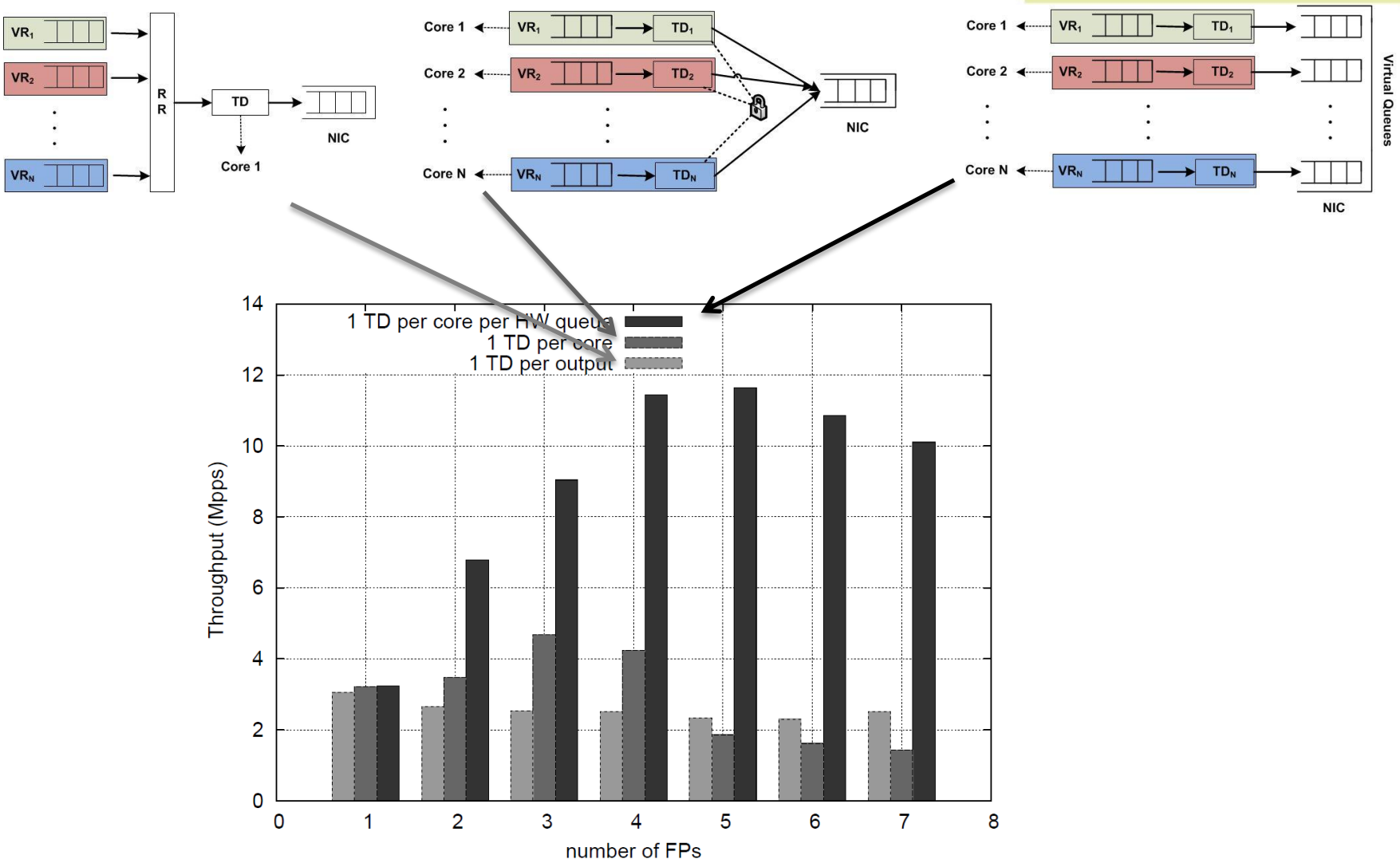
- ✓ Packet classification in hardware, off-loading the CPU
- ✘ Currently only round-robin scheduling is available

NIC Multi-Queuing Technologies

- Intel's VMDq:
  - Classification in multiple queues based on the destination MAC address
  - Possible packet reordering

- Microsoft's Receiver-side Scaling (RSS):
  - Classification in multiple queues using a hash function
  - Flow-based classification

Performance with Output Processing

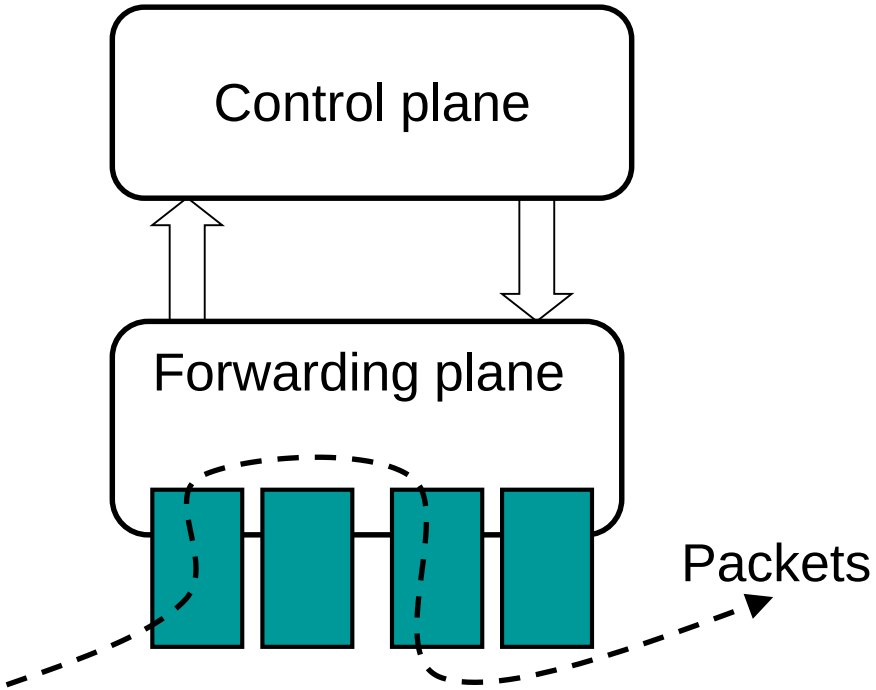


Router Virtualization

Software Routers on Commodity Hardware

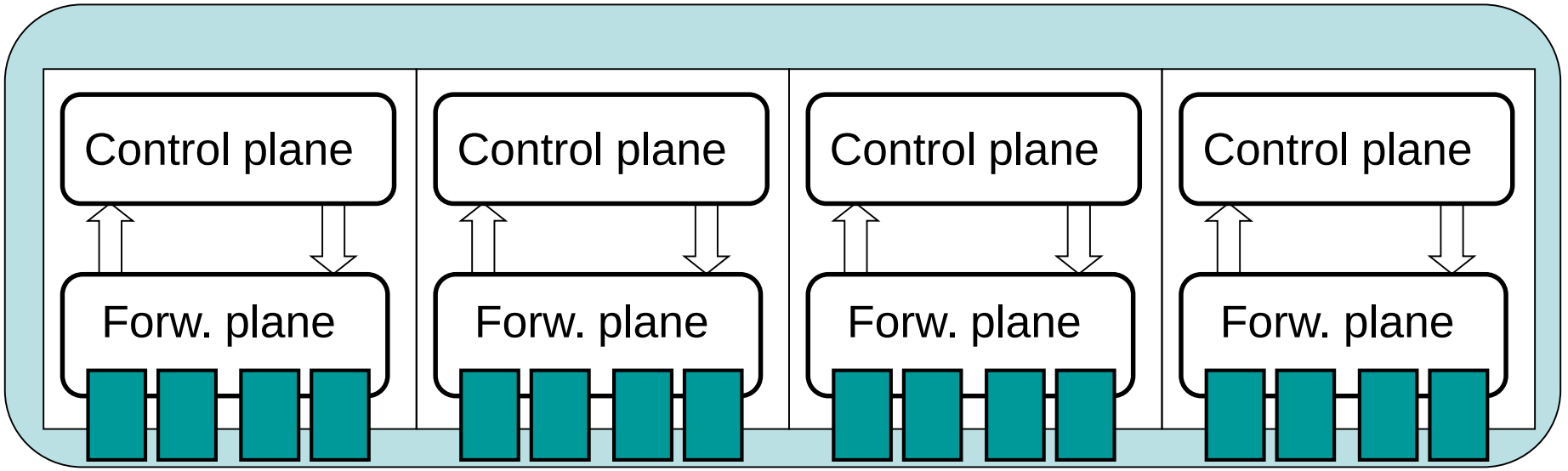
- Programmability:
  - Fully programmable forwarding plane (e.g., Click Modular Router)
  - Extensible control plane (e.g., XORP)

- High Performance:
  - Forwarding small packets at several Mpps
  - Limited by main memory accesses
  - Plenty of spare CPU cycles: much potential for virtualization



Virtual Routers on Commodity Hardware

- One box fulfills the role of multiple routers
  - Dedicated forwarding and control planes for each virtual router
  - Server virtualization technologies can be used to virtualise and isolate software routers



Router Virtualization Benefits (1)

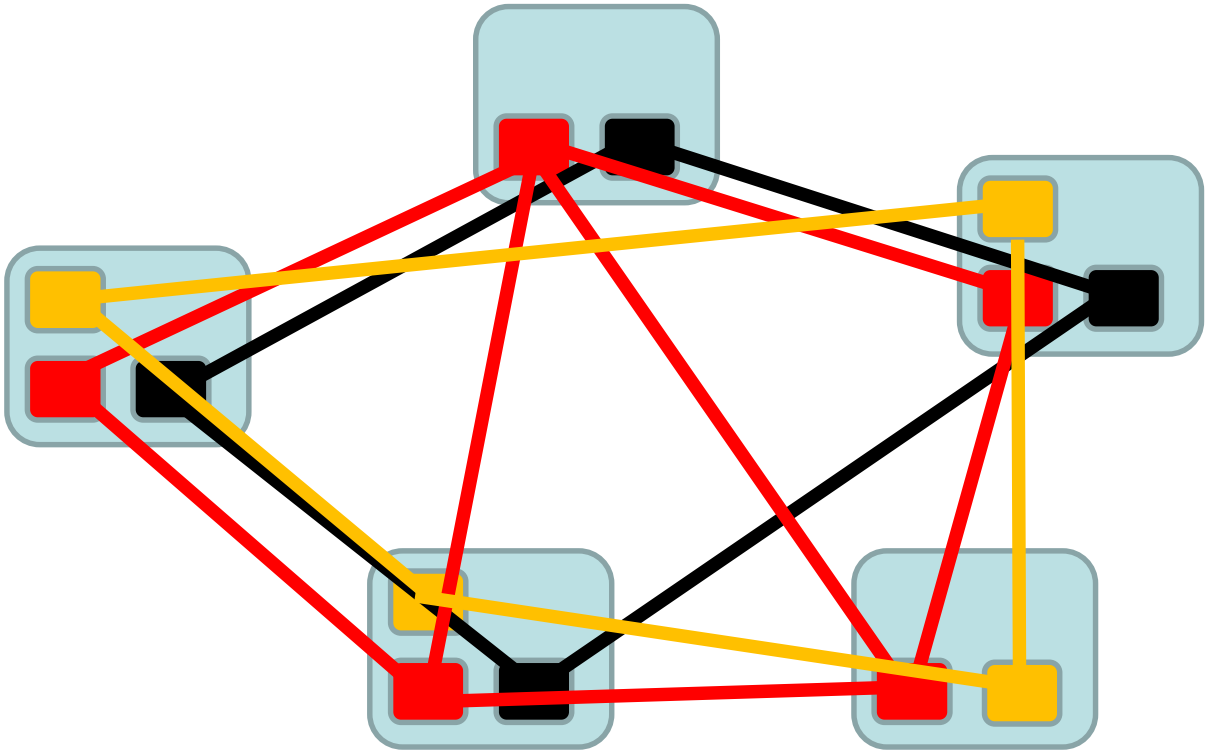
- One box fulfils the role of multiple routers
  - Independent and flexible management, leasing the Internet
  - Resource sharing (many available CPU cycles)
  - Lower hardware and support cost

    e.g., Small businesses within the same building sharing the same router, each managing its own VR

- Excellent platform for experimentation
  - Rolling out new and unstable solutions without risk

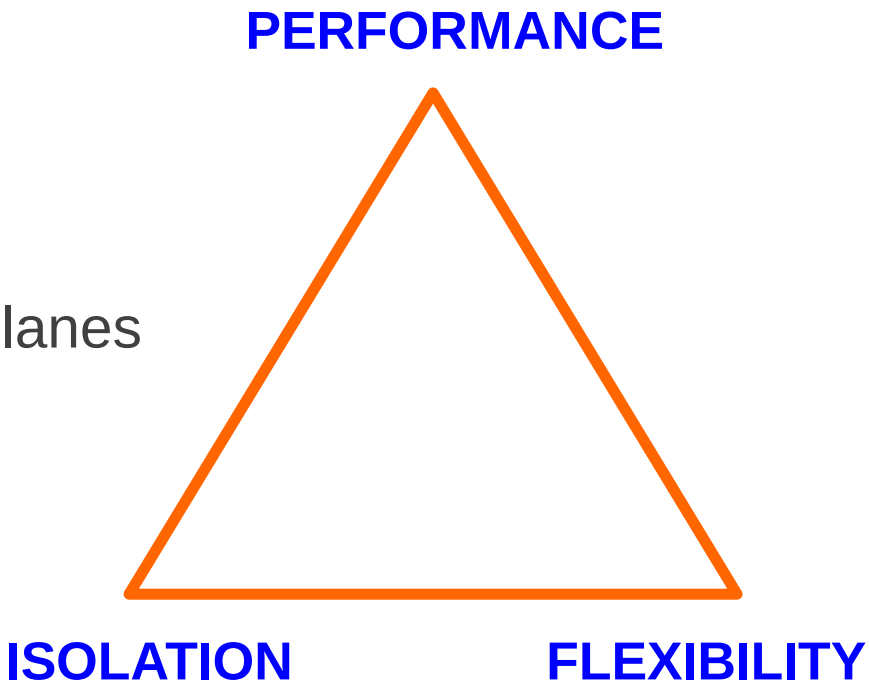
Router Virtualization Benefits (2)

- Innovation in network architecture design
  - Each virtual network has dedicated virtual routers with customized forwarding planes and routing protocols



Challenges in Router Virtualization

- Isolating the virtual routers from each other
- Minimizing the overhead of virtualization
- Highly configurable forwarding planes

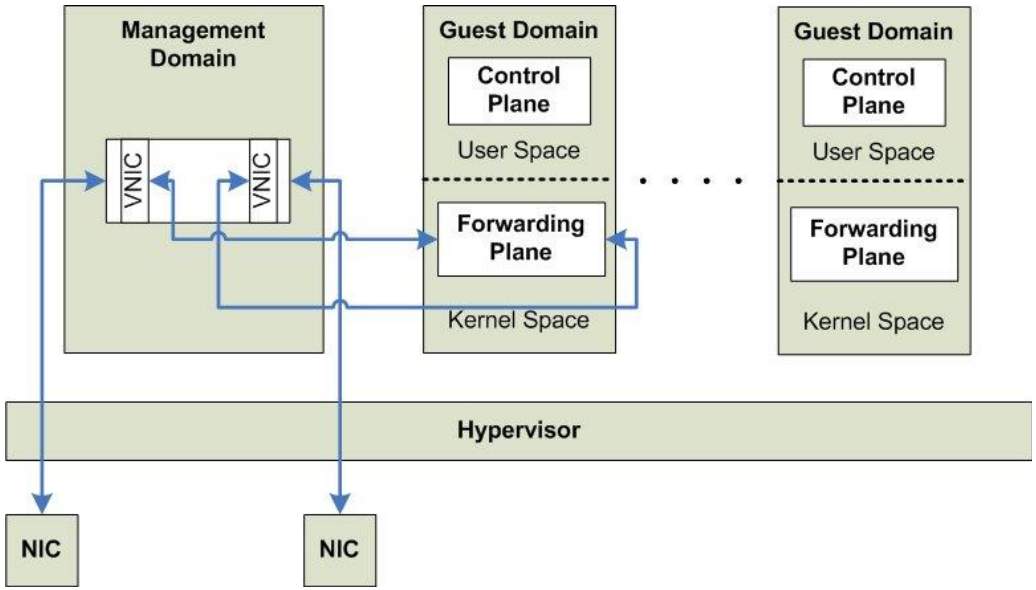


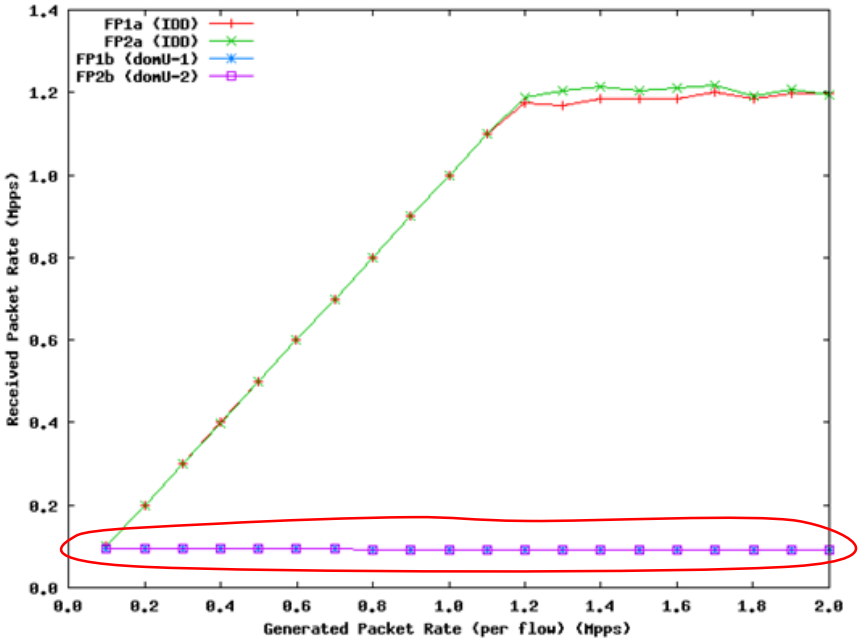
Case Study: Xen-based Virtual Routers

- Hosting forwarding planes
  - Determine the most suitable virtual forwarding configuration for high performance, flexibility and isolation

- Virtual forwarding scenarios:
  - Forwarding using I/O channels
  - Common forwarding plane
  - Forwarding with direct-mapped network interfaces

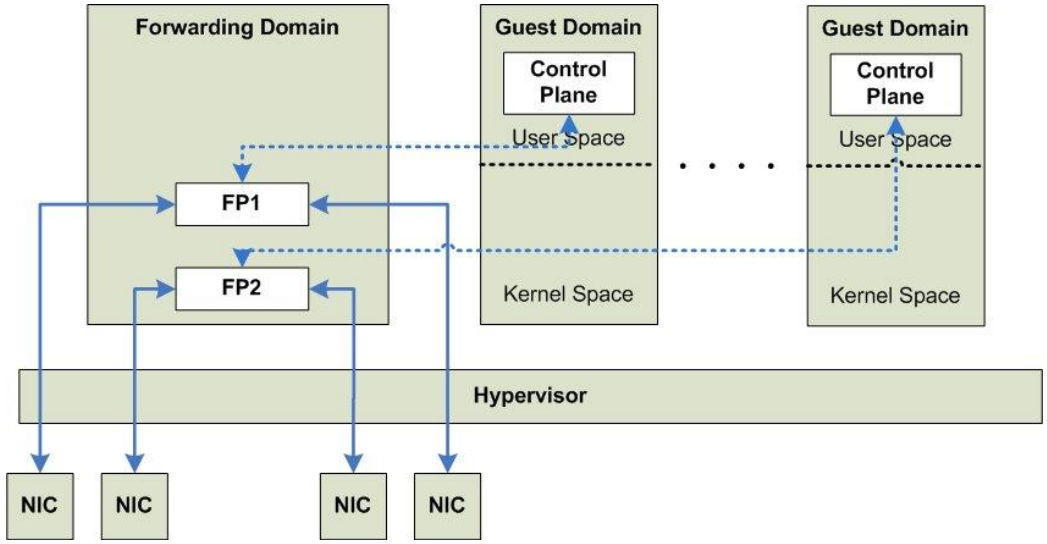
Forwarding using I/O Channels

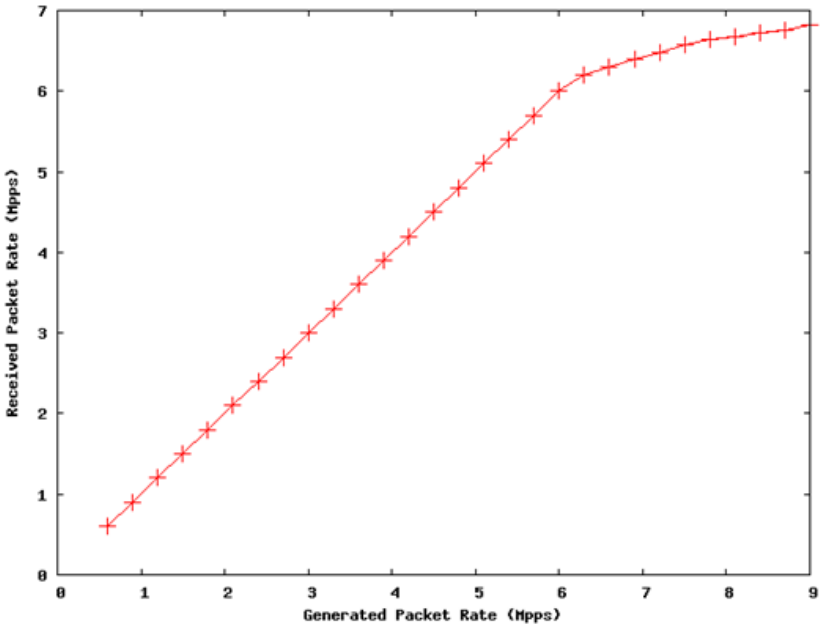




- ✓ Isolation
- ✘ Low performance (due to costly hypervisor domain switching)

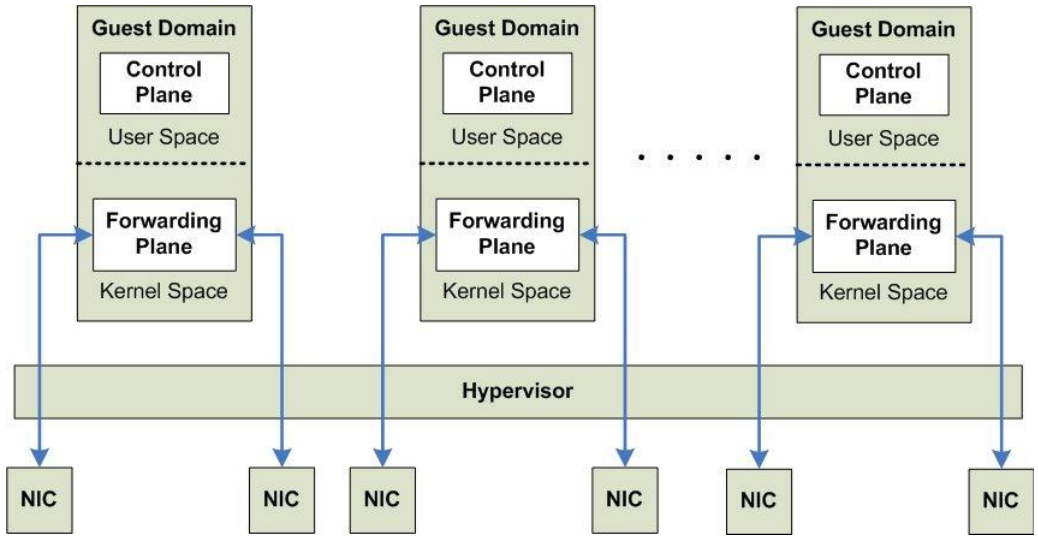
Common Forwarding Plane

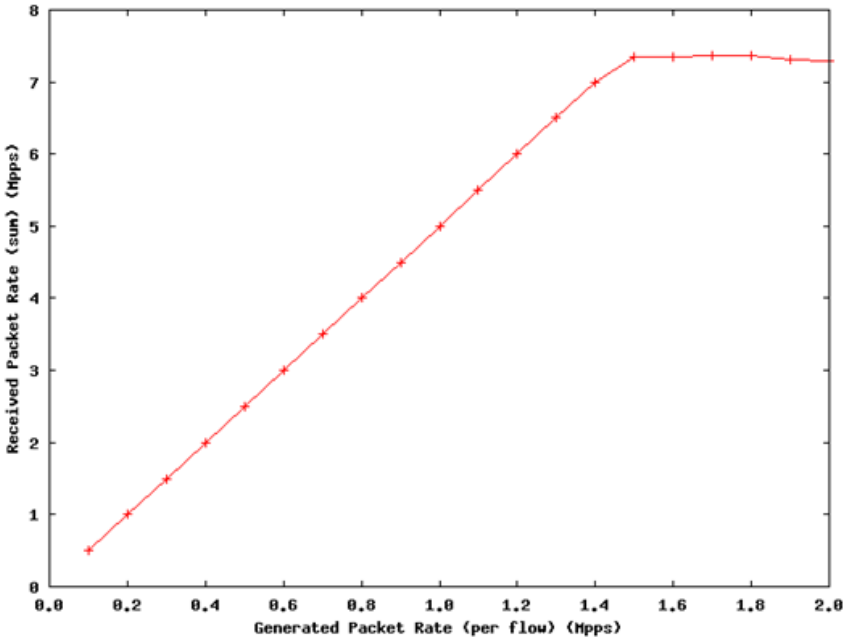




- ✓ High performance
- ✘ Isolation (it should be enforced with proper core allocation and scheduling)

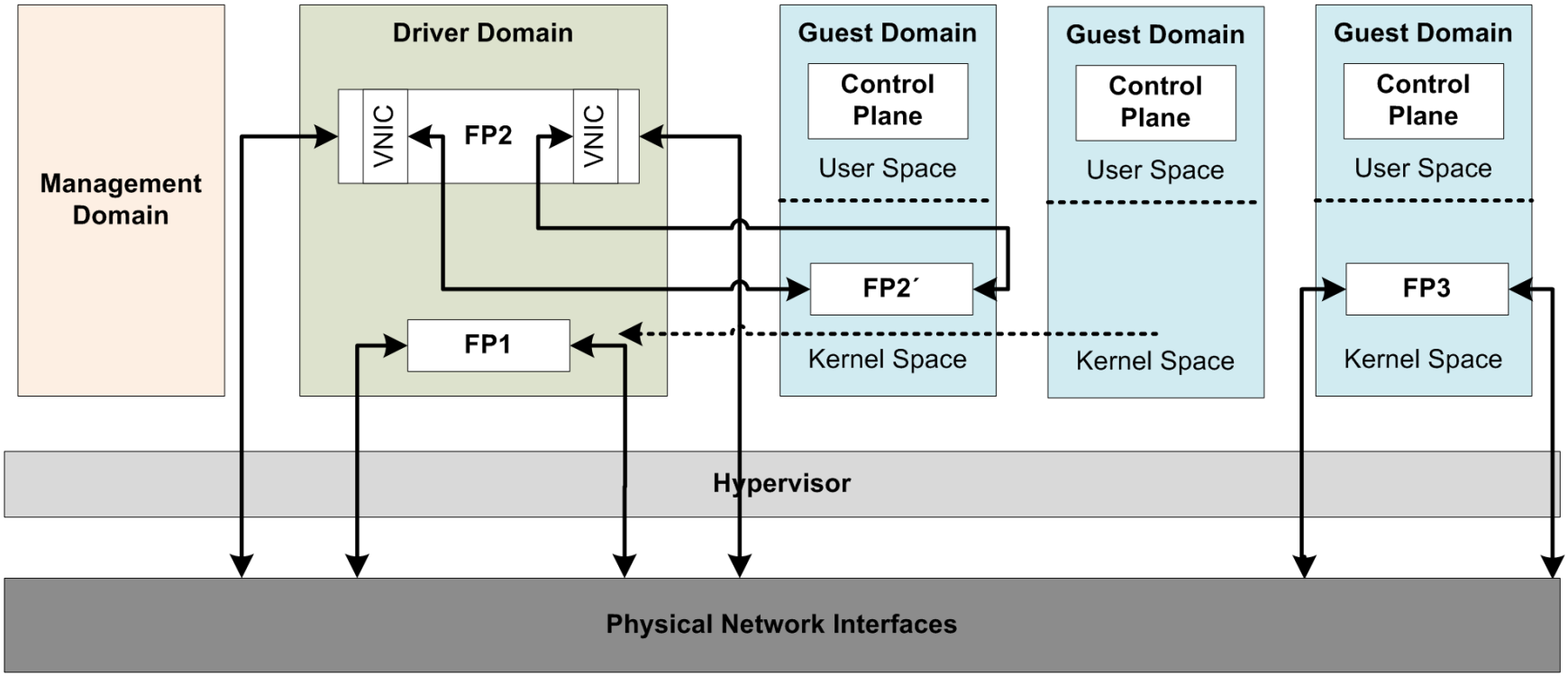
Forwarding with Direct-Mapped NICs





- ✓ High performance
- ✓ Isolation
- ✘ Requires NIC multi-queuing to scale

A Virtual Router Platform on Commodity HW

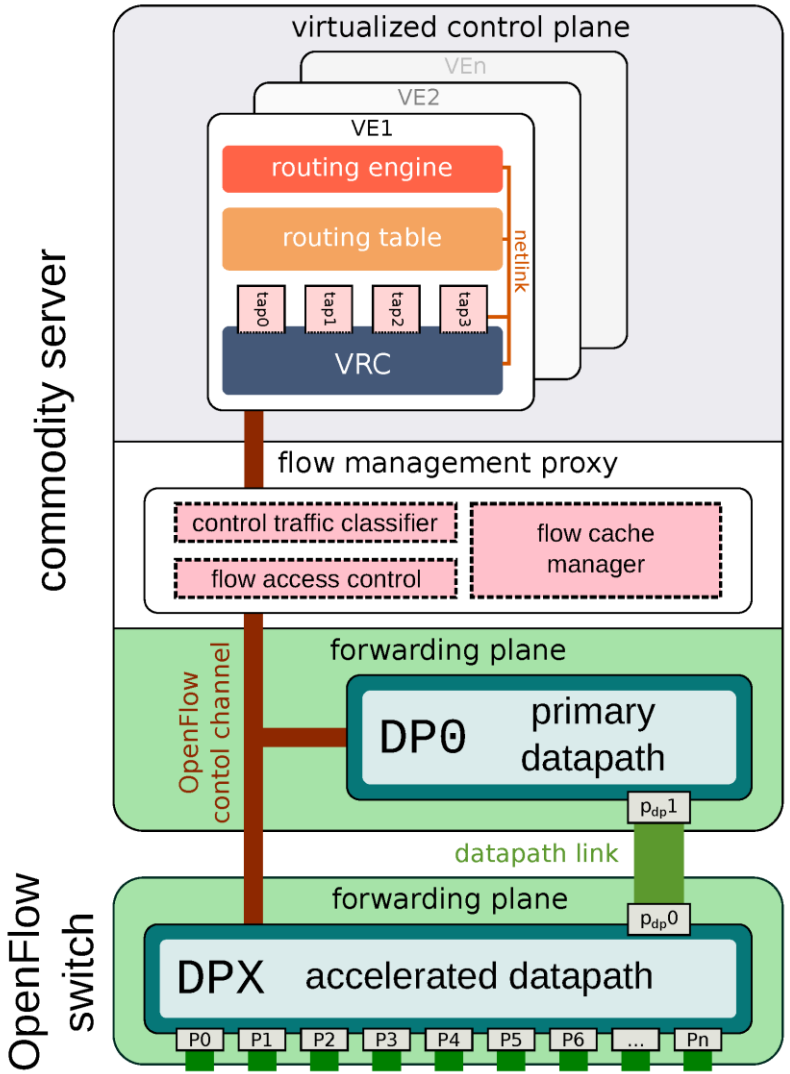


- Forwarding within a common domain (FP1)
- Forwarding with I/O Channels (FP2 ↔ FP2´)
- Forwarding in Guest Domains with direct NIC mapping (FP3)

Accelerated Software Virtual Routers

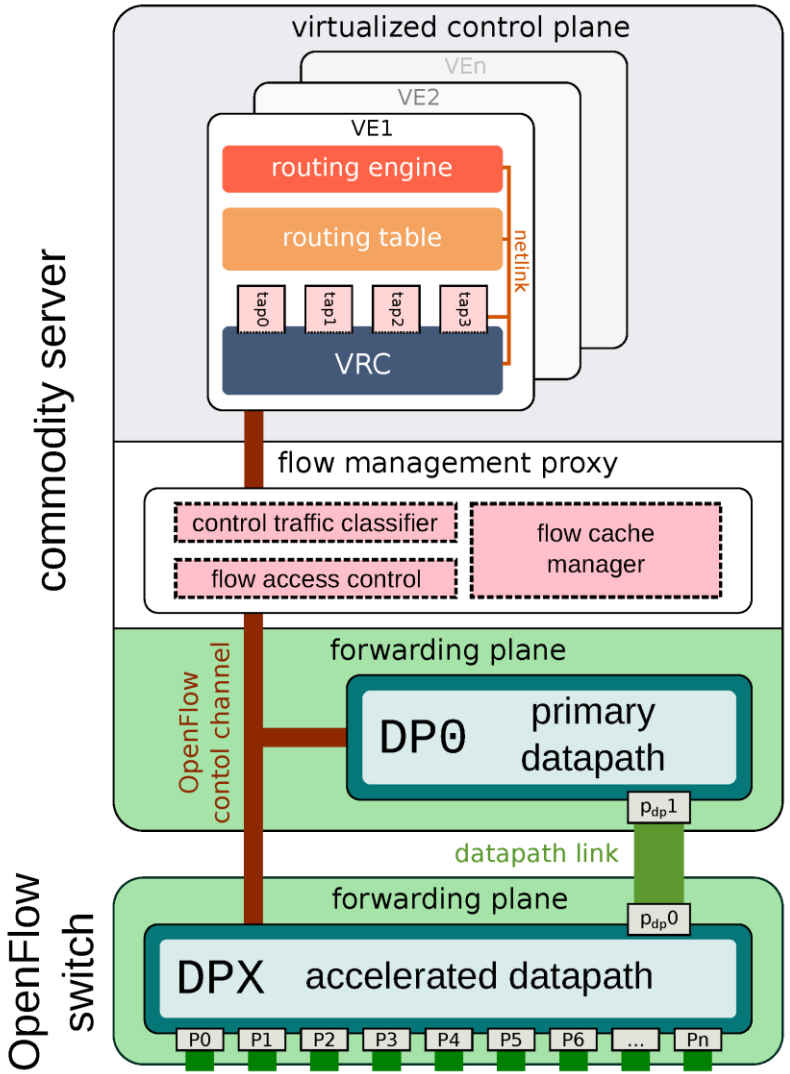
Accelerating Software Virtual Routers

- Features:
  - Control-plane extensibility
  - Forwarding-plane programmability
  - High performance
  - High port density
- Main components:
  - Forwarding plane composed of primary and accelerated datapath
  - Virtualized control plane
  - Flow management proxy:
    - Transparent layer between the forwarding and control plane



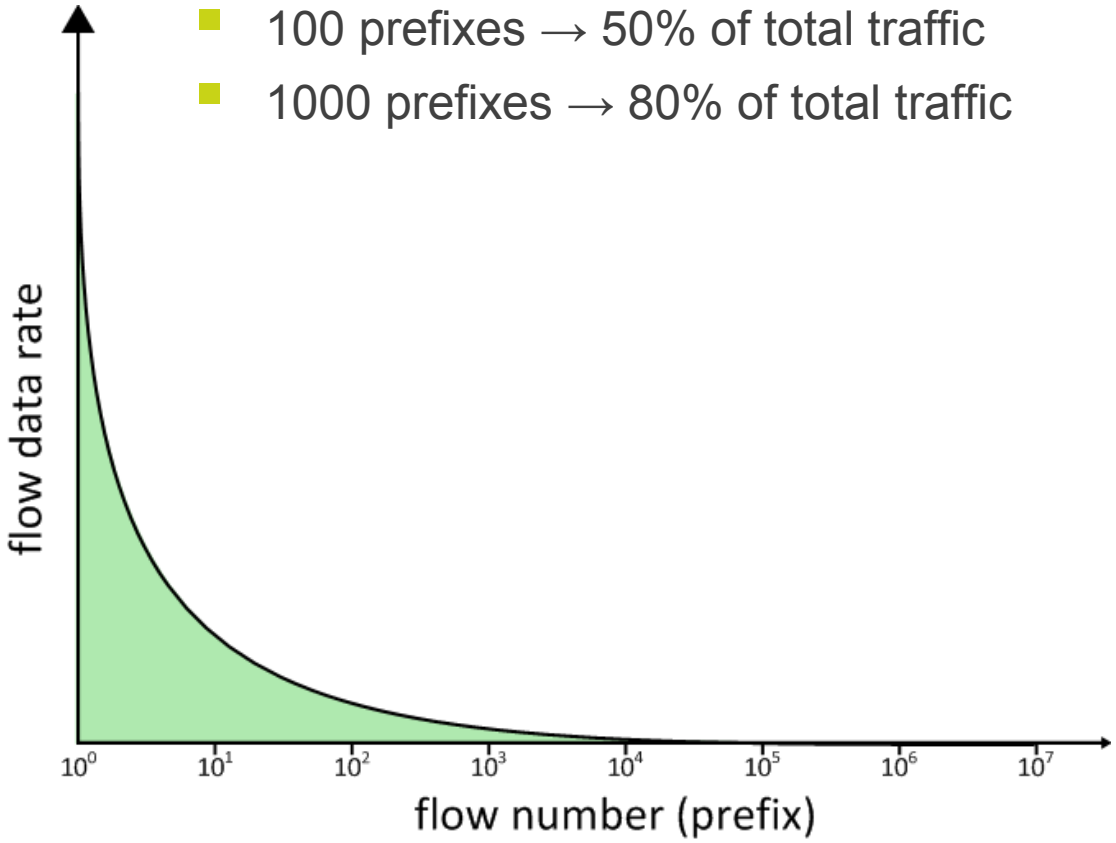
Flow Table Size Limitation

- Main limitation:
  - OpenFlow switch flow table has very small size (few Mbytes)
    - can store only a few thousands of flow entries
- This limitation seems to make such a platform infeasible:
  - A full BGP routing table includes nearly 400K entries



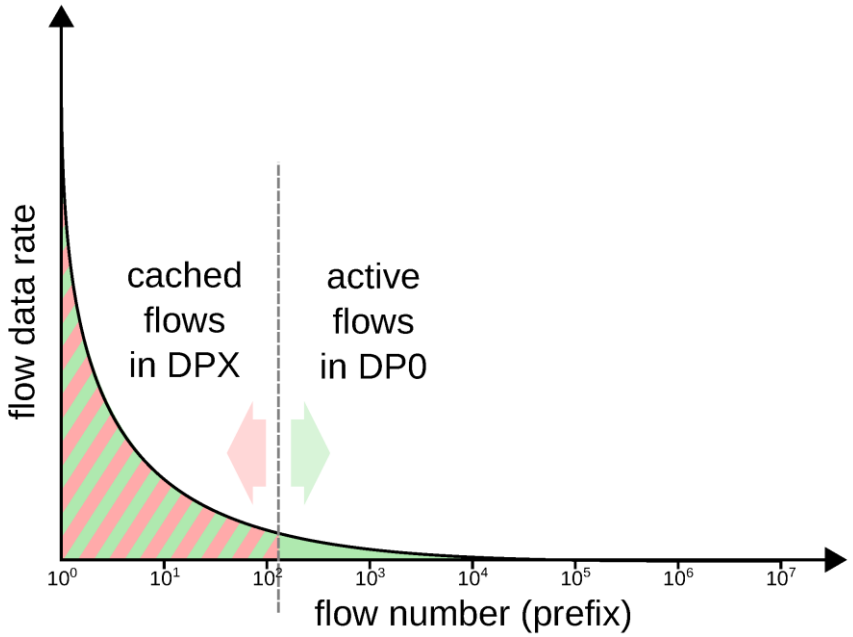
Flow Distribution in the Internet

- Flow distribution in the Internet:
  - A small subset of flows carries most of Internet traffic
    - Traffic statistics from an access router at a large European ISP
      - 100 prefixes → 50% of total traffic
      - 1000 prefixes → 80% of total traffic



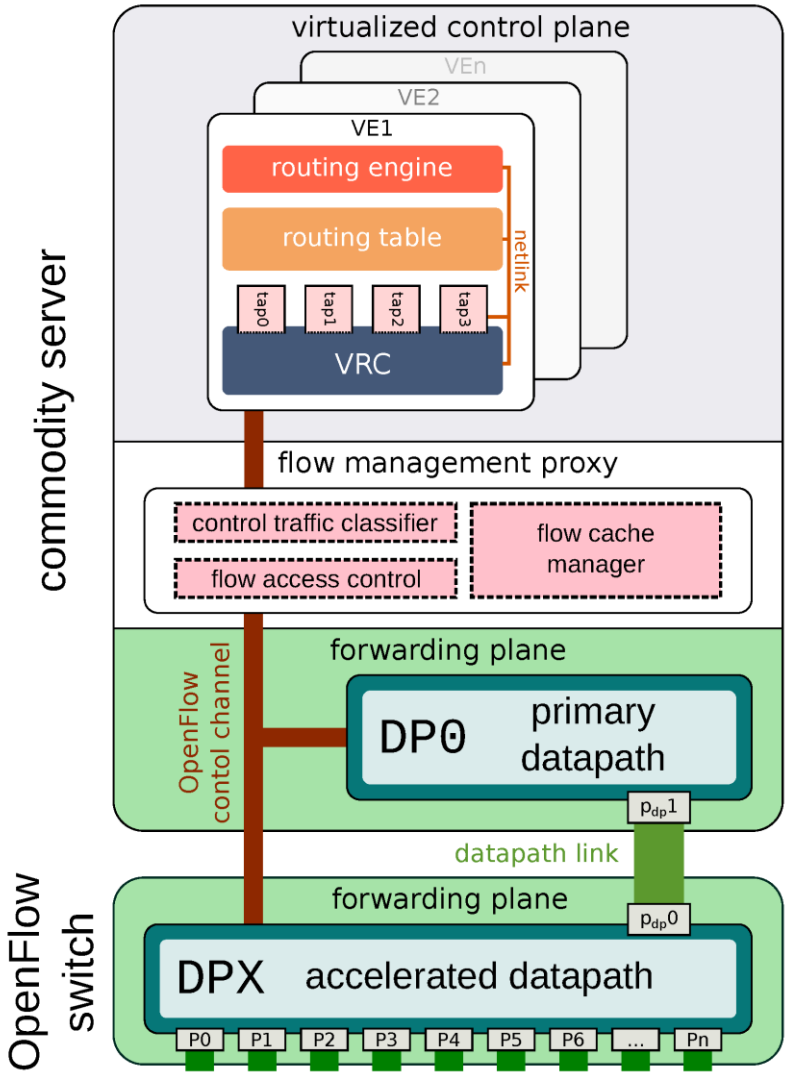
Towards an Accelerated Software Router

- Leverage on Internet flow distribution:
  - Dual-datapath approach:
    - Primary datapath (DP0) in a commodity server with forwarding entries for all flows
    - Accelerated datapath (DPX) in OpenFlow switch with forwarding entries for the subset of large-volume flows



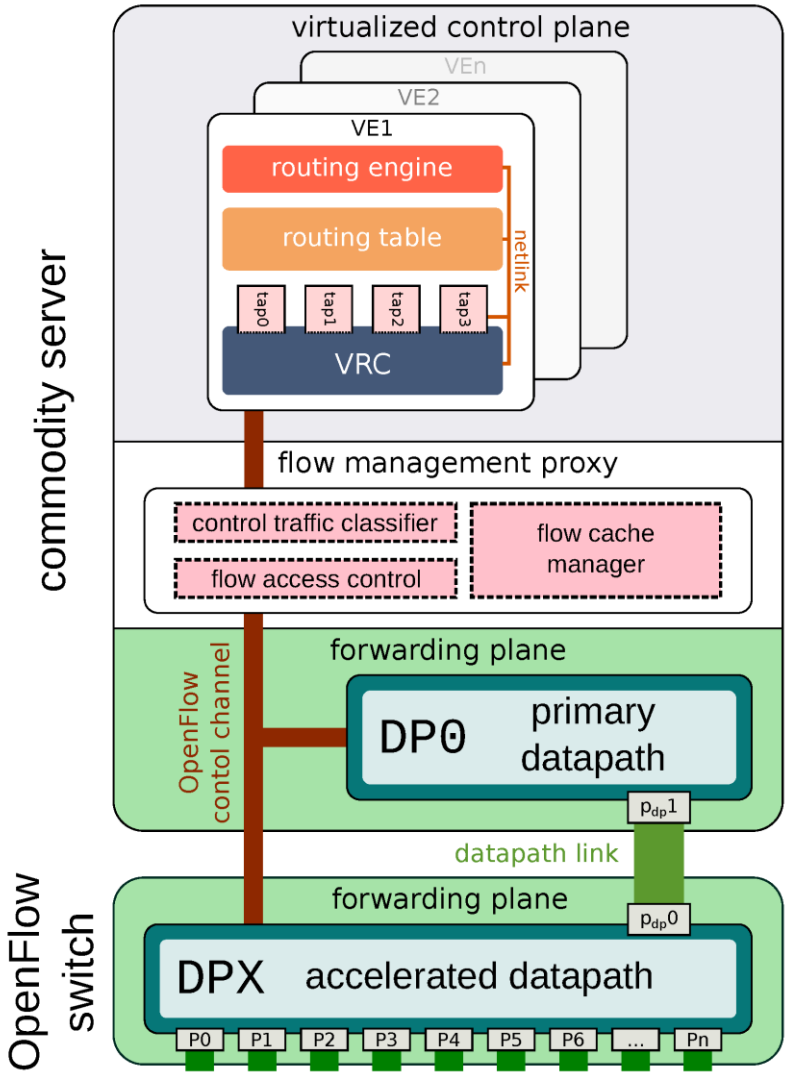
Virtualized Control Plane

- Virtual interfaces mapped to the physical ports:
  - Mapping registered with FMP
- Virtual Router Controller (VRC):
  - Forwards control messages to virtual interfaces
  - Generates flow insertion/ deletion commands
    - Listens on Netlink socket for routing table or ARP updates

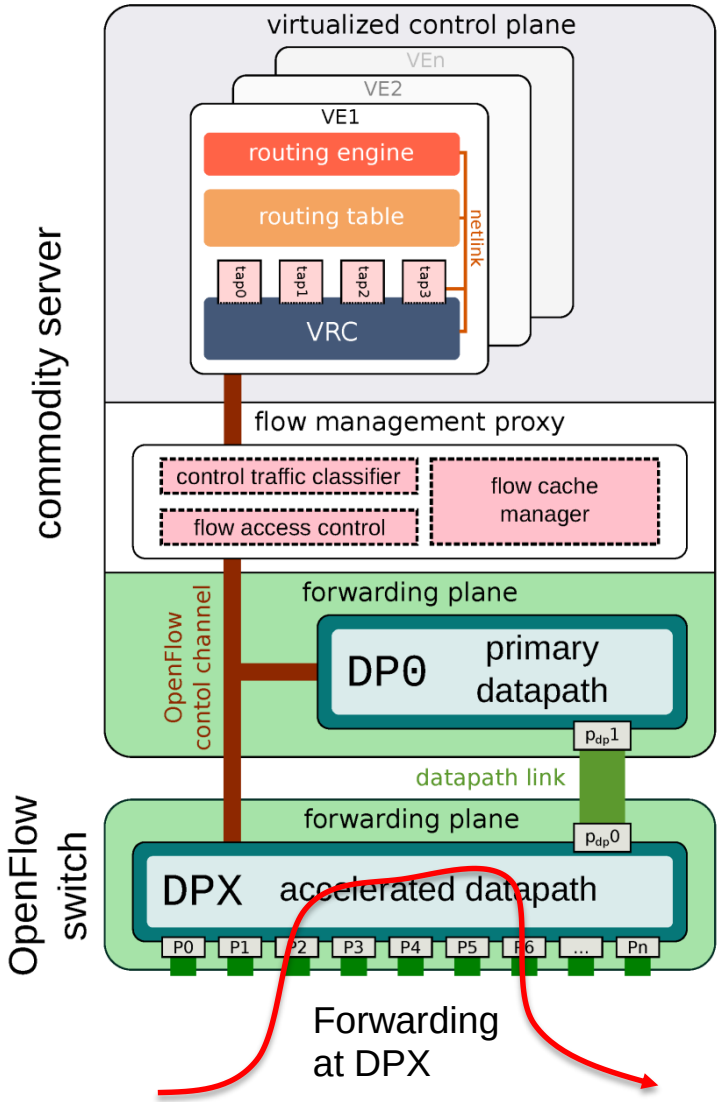


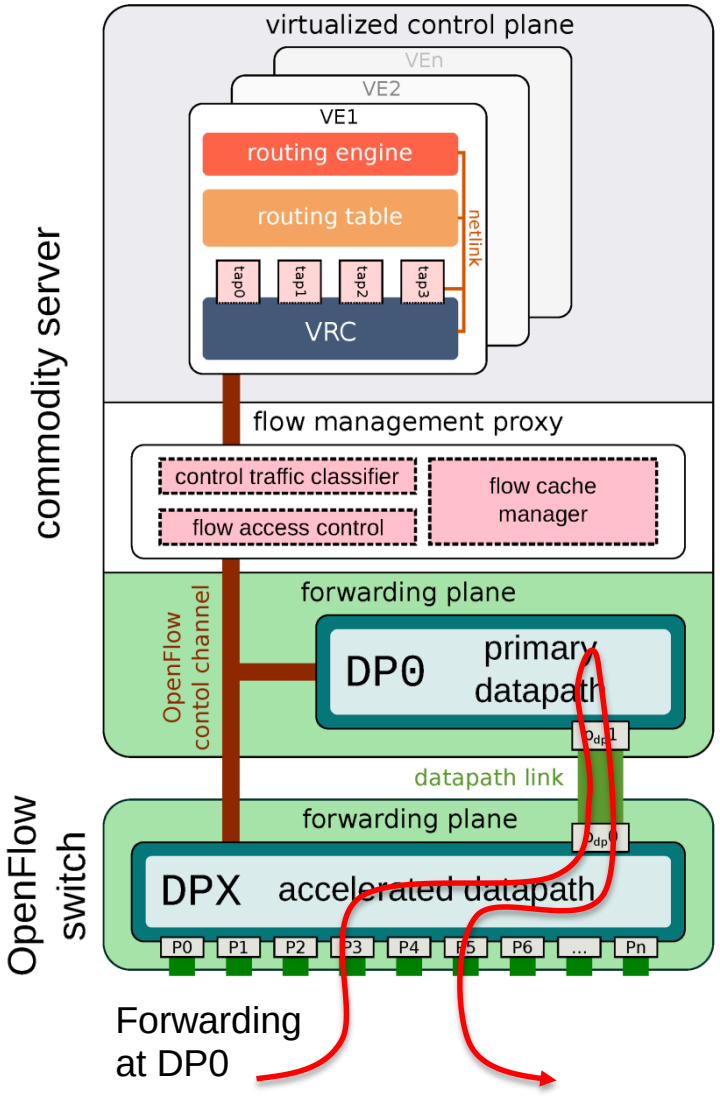
Flow Management Proxy

- Control message classification among virtualized control planes
- Access control on flow insertion/ deletion commands generated by a VRC
- Flow caching in the DPX
  - Least recently used (LRU)
  - Least frequently used (LFU)



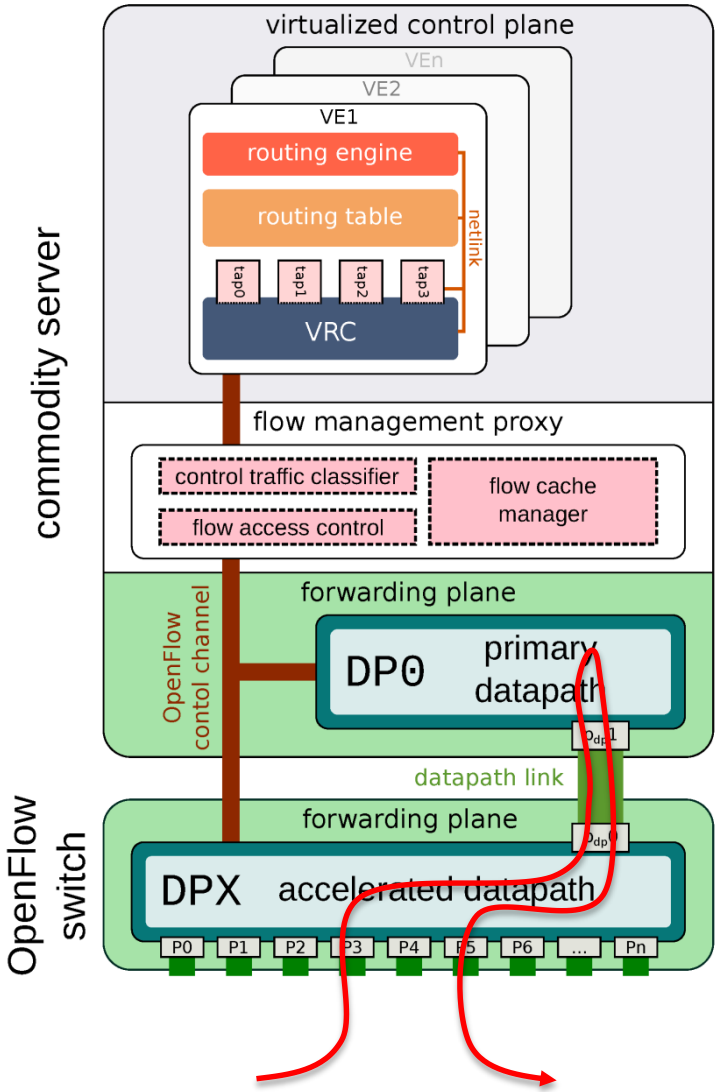
Forwarding Plane



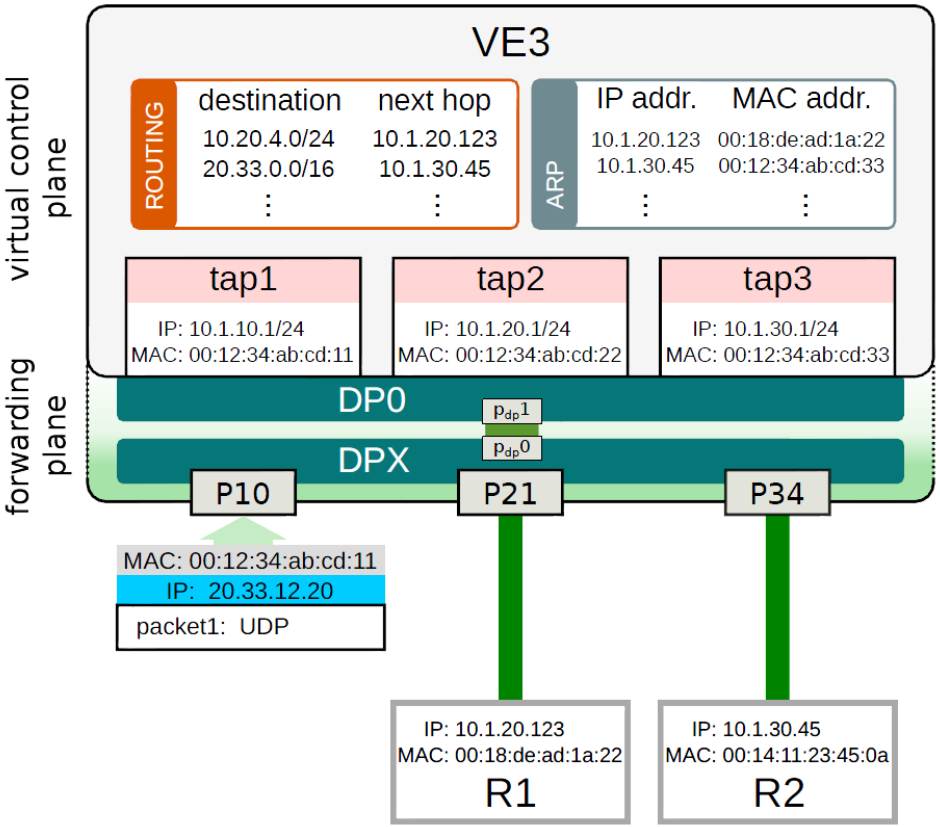


Flow Entry Types at DPX

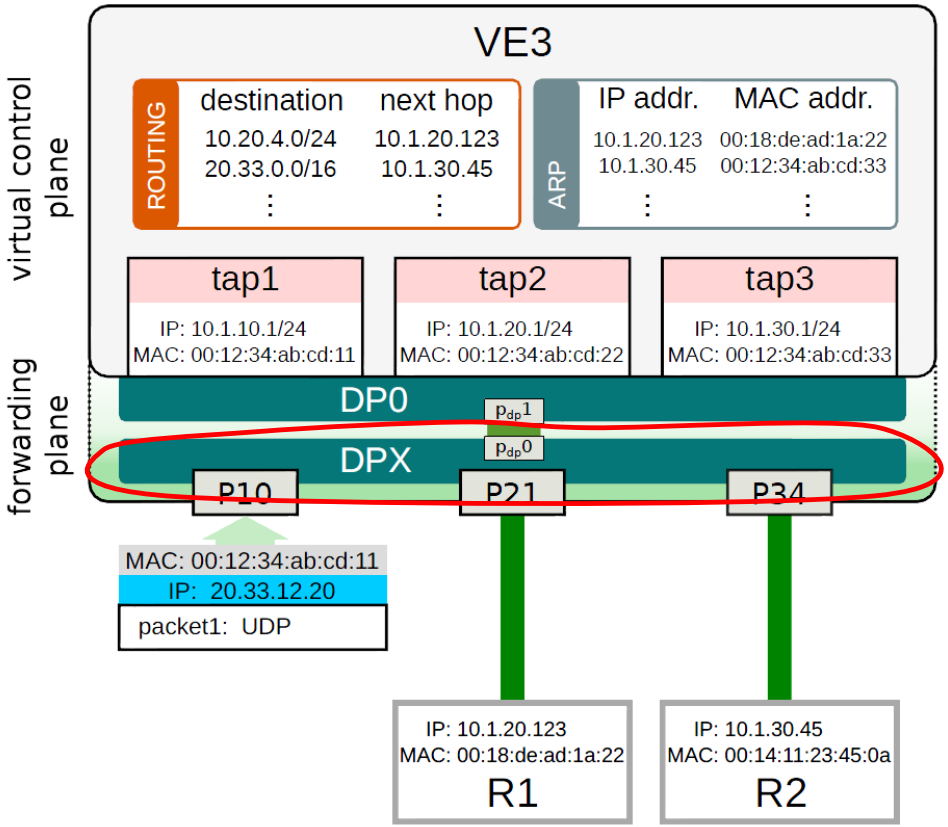
- Input redirection flow entries
- Output flow entries
- Cached routing flow entries
- Local control flow entries:
  - Routing updates
  - ARP resolution

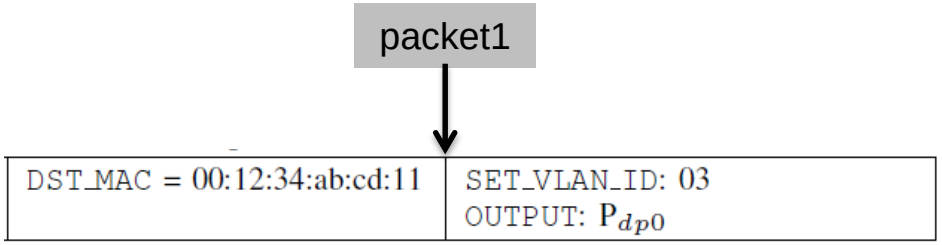


Exemplary Packet Forwarding at DP0



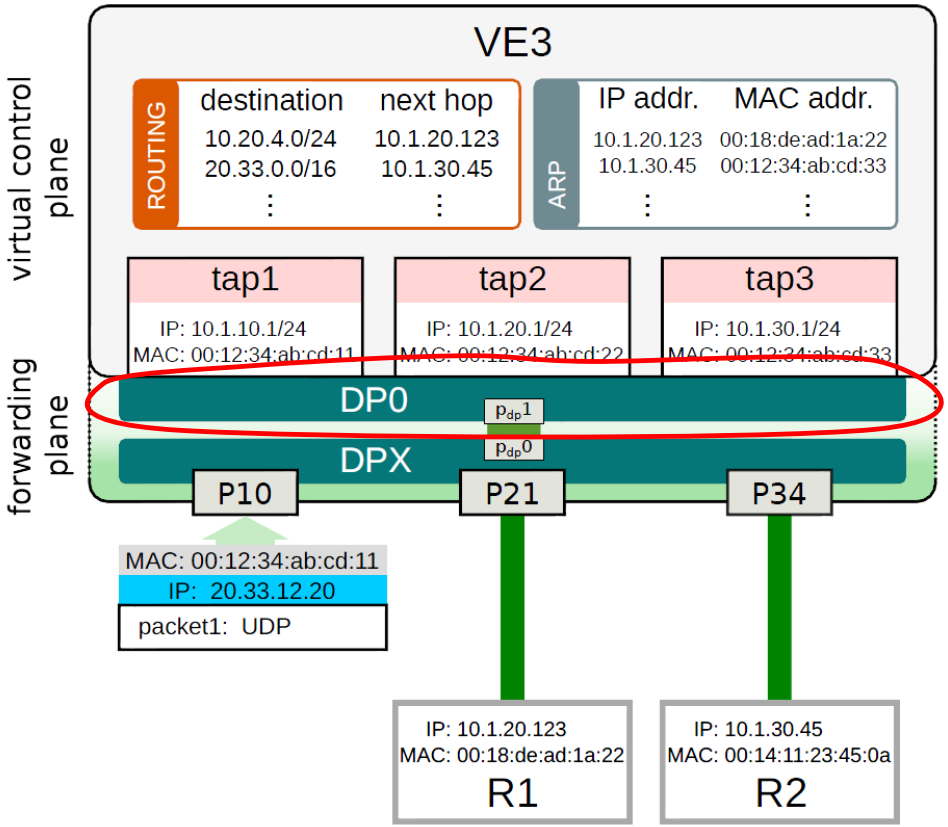
Exemplary Packet Forwarding at DP0





Redirection flow entries (DPX)

Exemplary Packet Forwarding at DP0



packet1

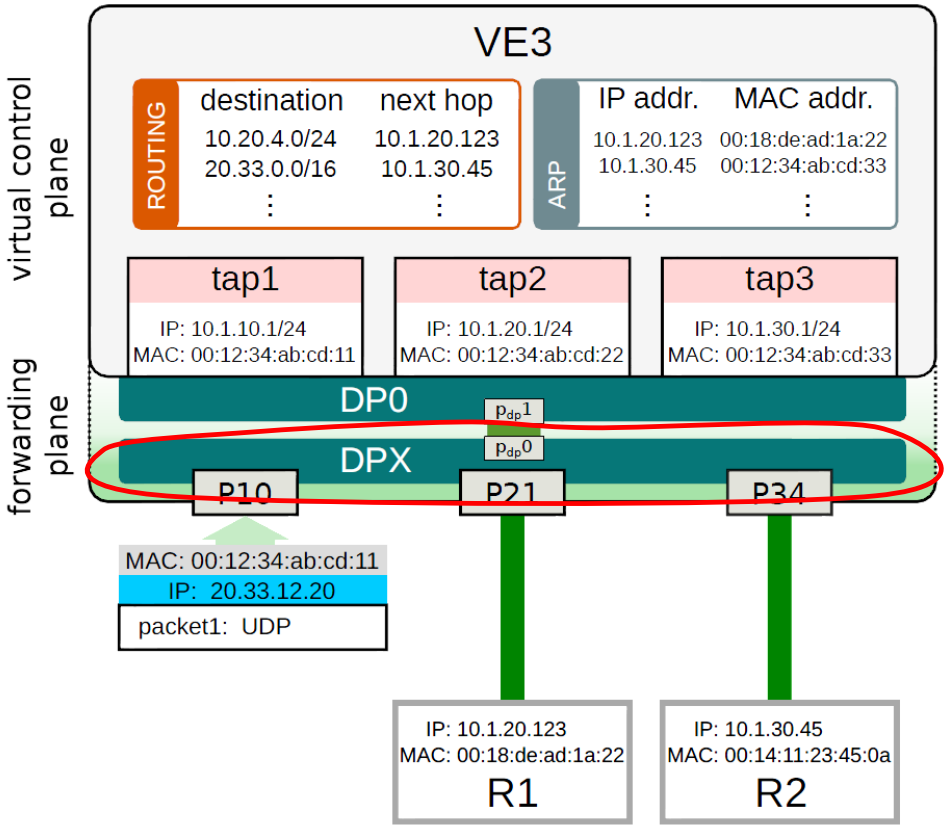
DST_MAC = 00:12:34:ab:cd:11	SET_VLAN_ID: 03 OUTPUT: P_{dp0}

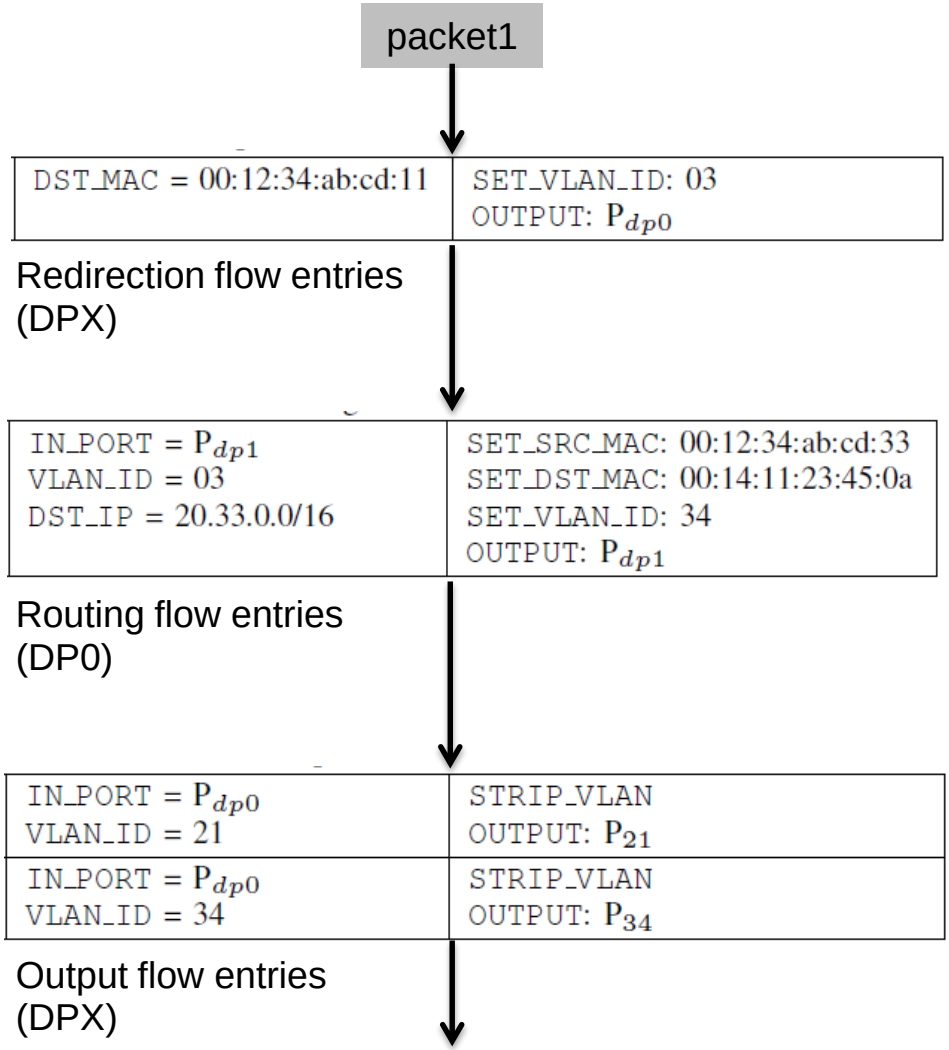
Redirection flow entries (DPX)

IN_PORT = P_{dp1} VLAN_ID = 03 DST_IP = 20.33.0.0/16	SET_SRC_MAC: 00:12:34:ab:cd:33 SET_DST_MAC: 00:14:11:23:45:0a SET_VLAN_ID: 34 OUTPUT: P_{dp1}

Routing flow entries (DP0)

Exemplary Packet Forwarding at DP0





DPX Flowspace Requirements

- One input redirection entry per virtual port ($\sum_{i=1}^{N} M_i$ entries)
- One local control entry per virtual port ($\sum_{i=1}^{N} M_i$ entries)
- One output entry per physical port (P entries)

$$2\sum_{i=1}^{N} M_i + P$$

Hundreds of entries

N: number of virtual routers

M_i: number of virtual ports for i^{th} virtual router

P: number of physical ports

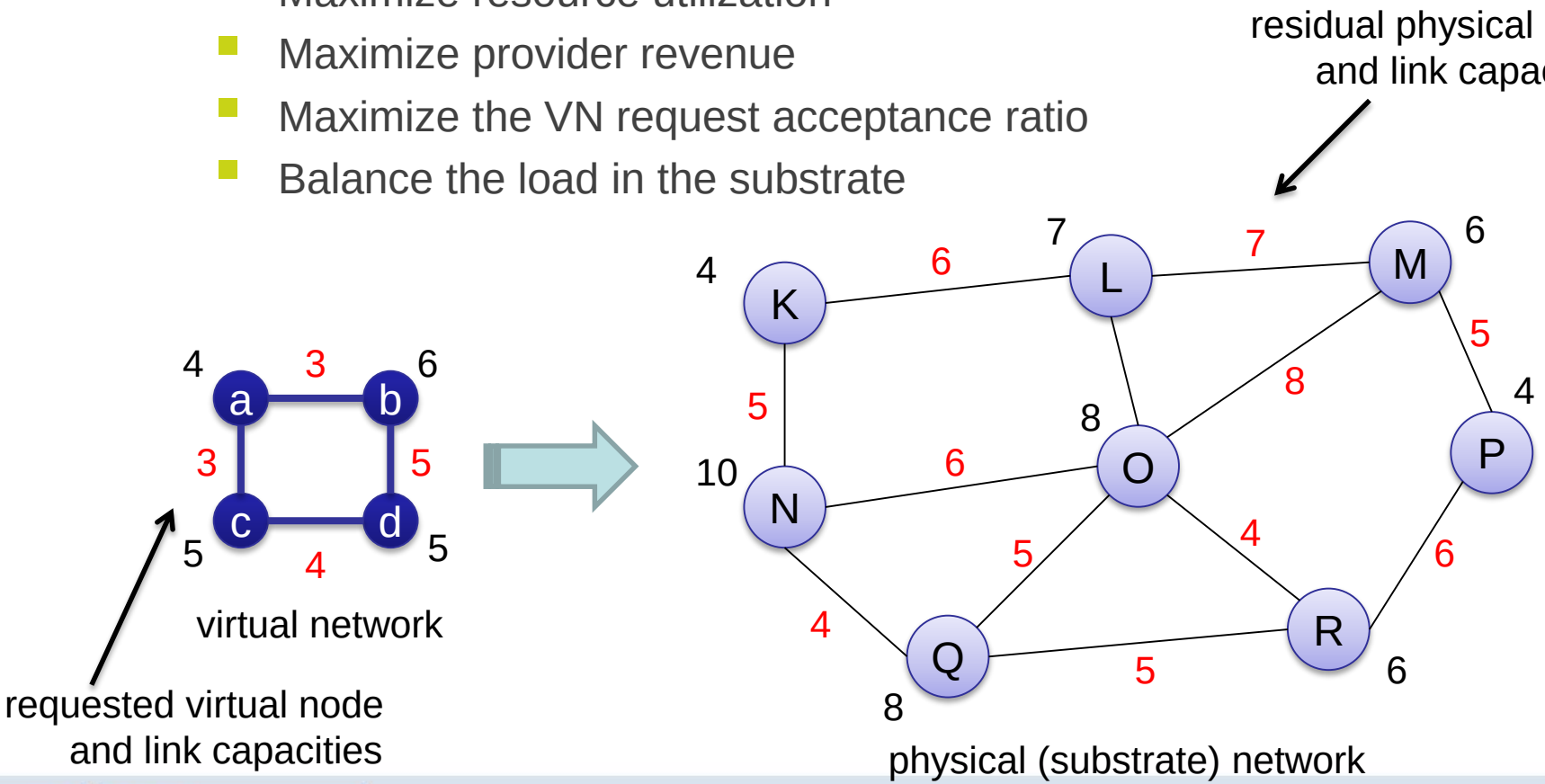
Performance Evaluation

- DP0 (Pronto Switch)
  - Forwarding at line rate
  - Latency: 4 µs
  - Flow insertion rate: ~1000 flows/sec
- DPX (Server)
  - Forwarding rate: ~1Mpps per core
  - Latency: 15 µs
  - Flow insertion rate: ~6000 flows/sec

Virtual Network Embedding

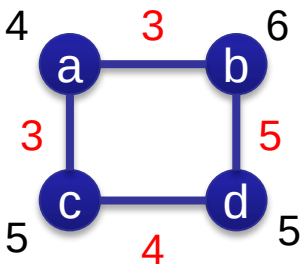
Virtual Network Embedding

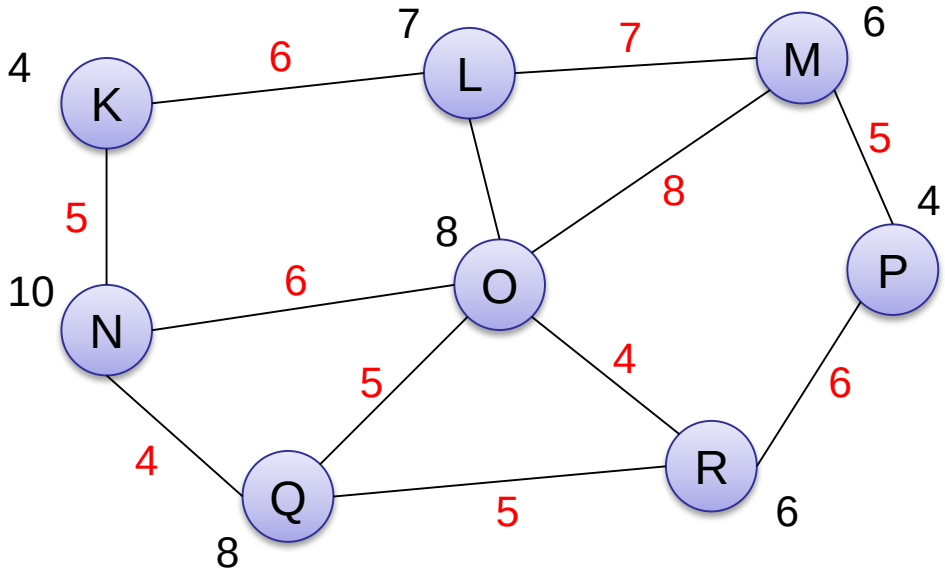
- Virtual network embedding:
  - Compute a mapping of a virtual network onto a physical network given an objective, e.g.,:
    - Maximize resource utilization
    - Maximize provider revenue
    - Maximize the VN request acceptance ratio
    - Balance the load in the substrate



Virtual Network Embedding Algorithm

- VN embedding algorithm with simultaneous virtual node and link assignment
  - Objective: Load balancing across the substrate





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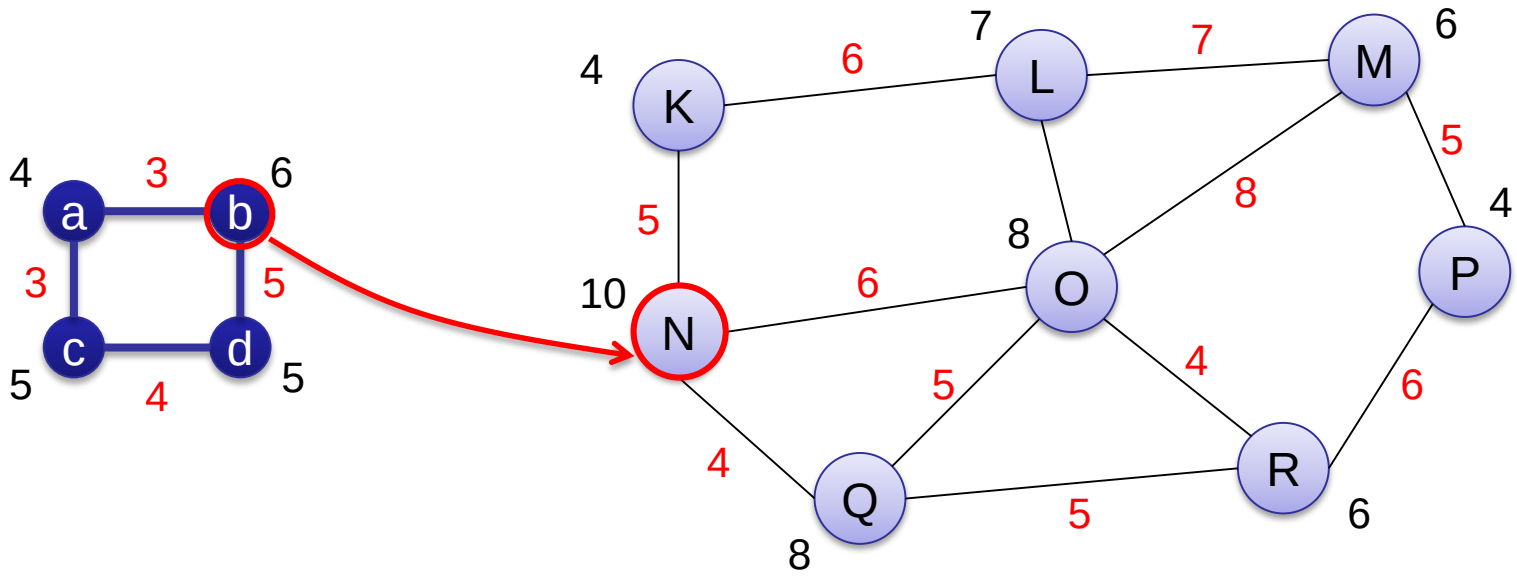

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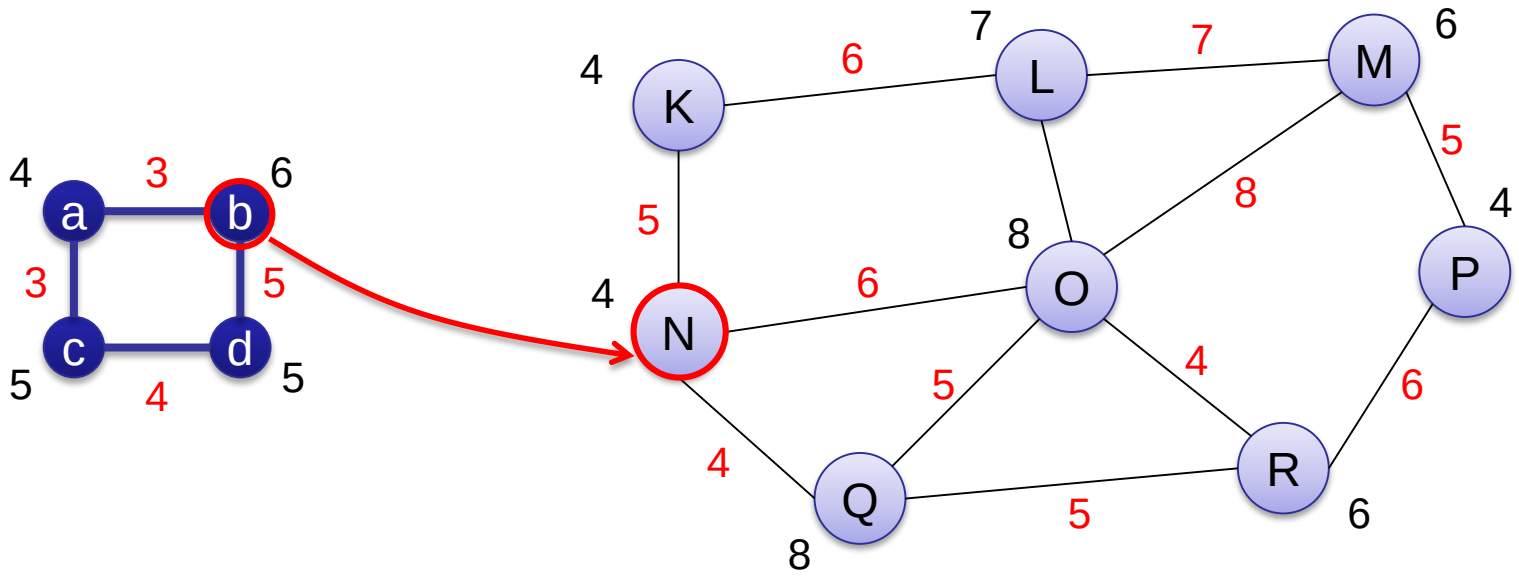

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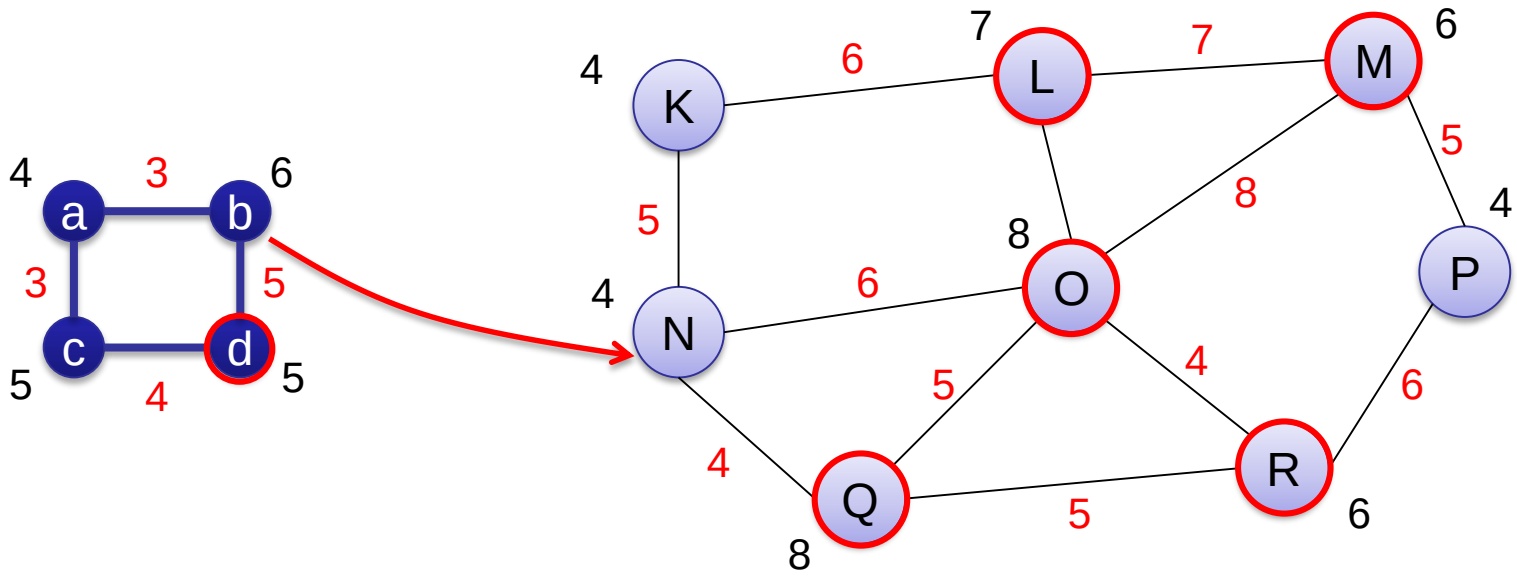

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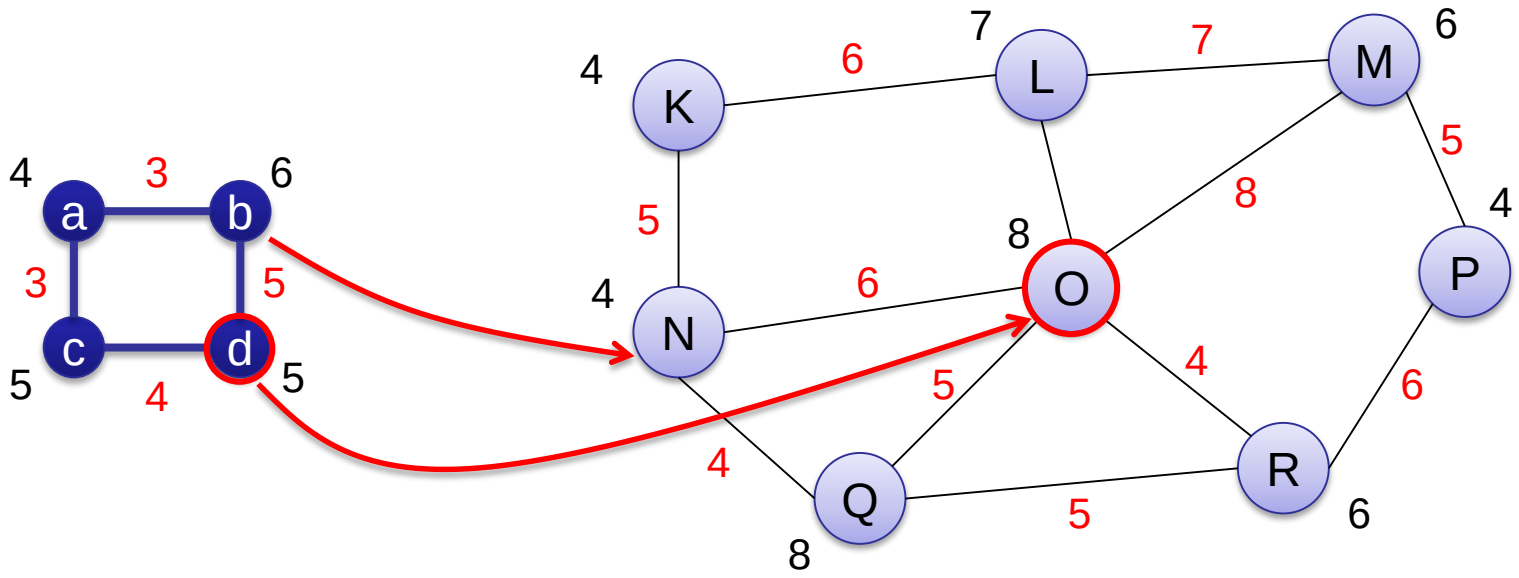

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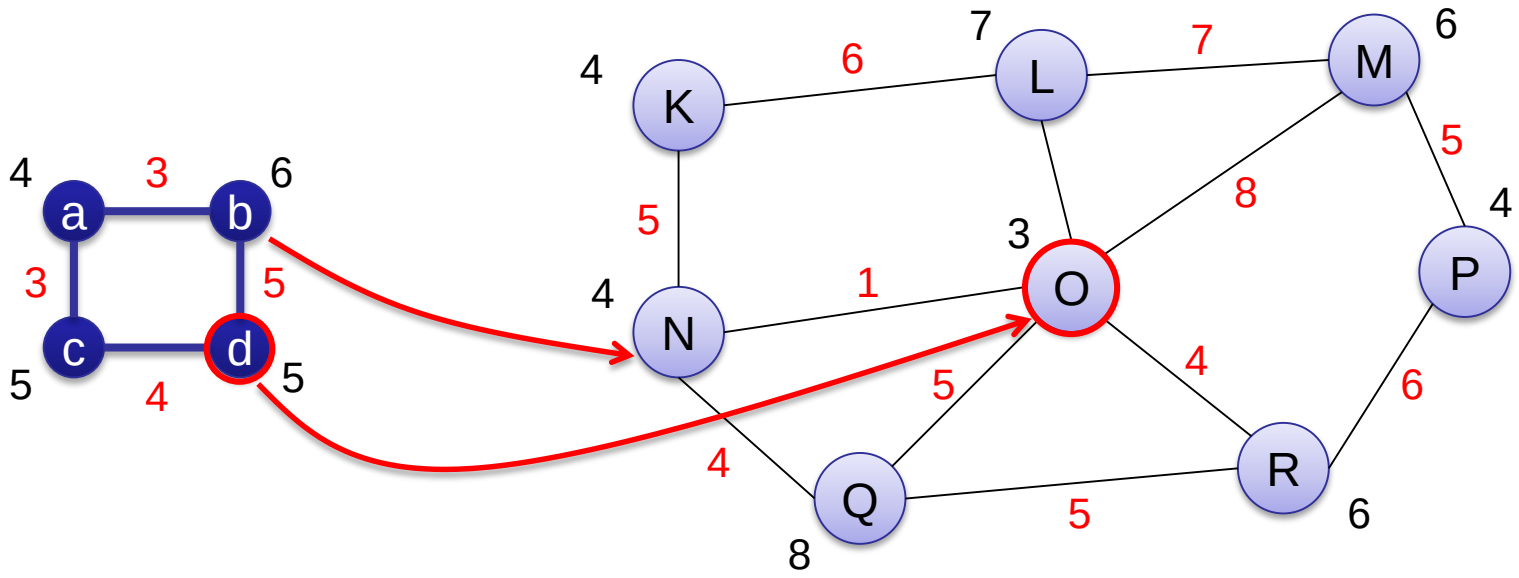

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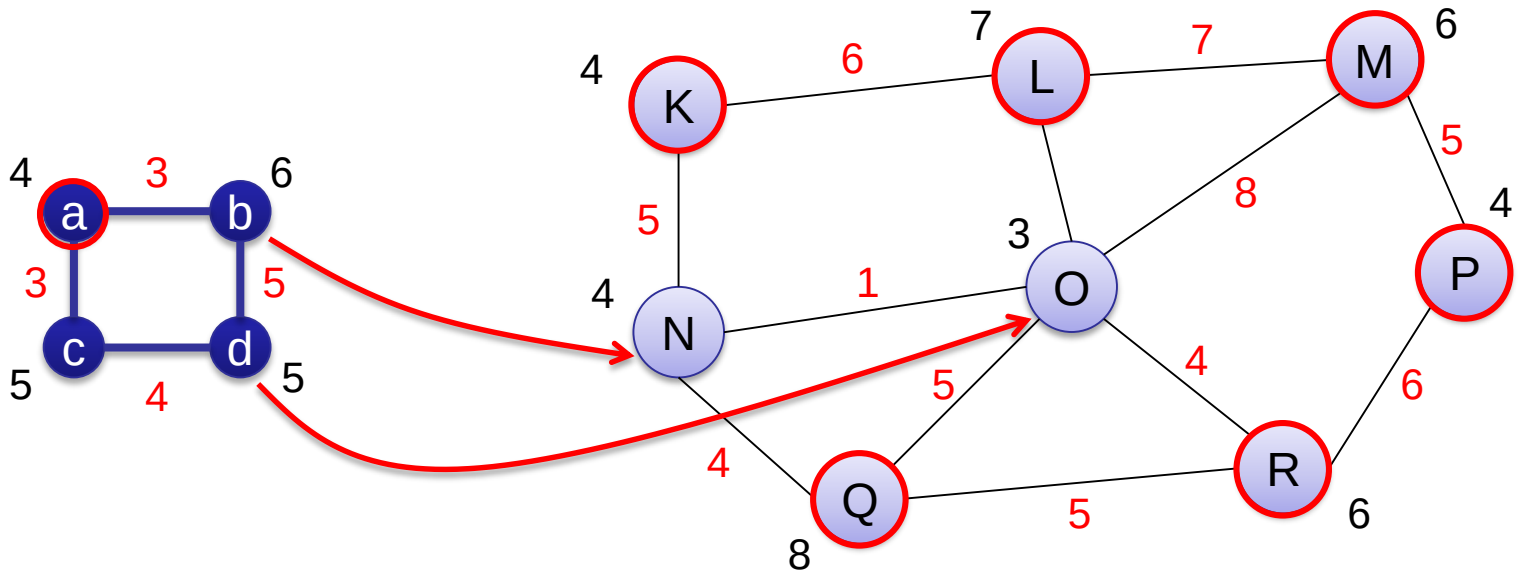

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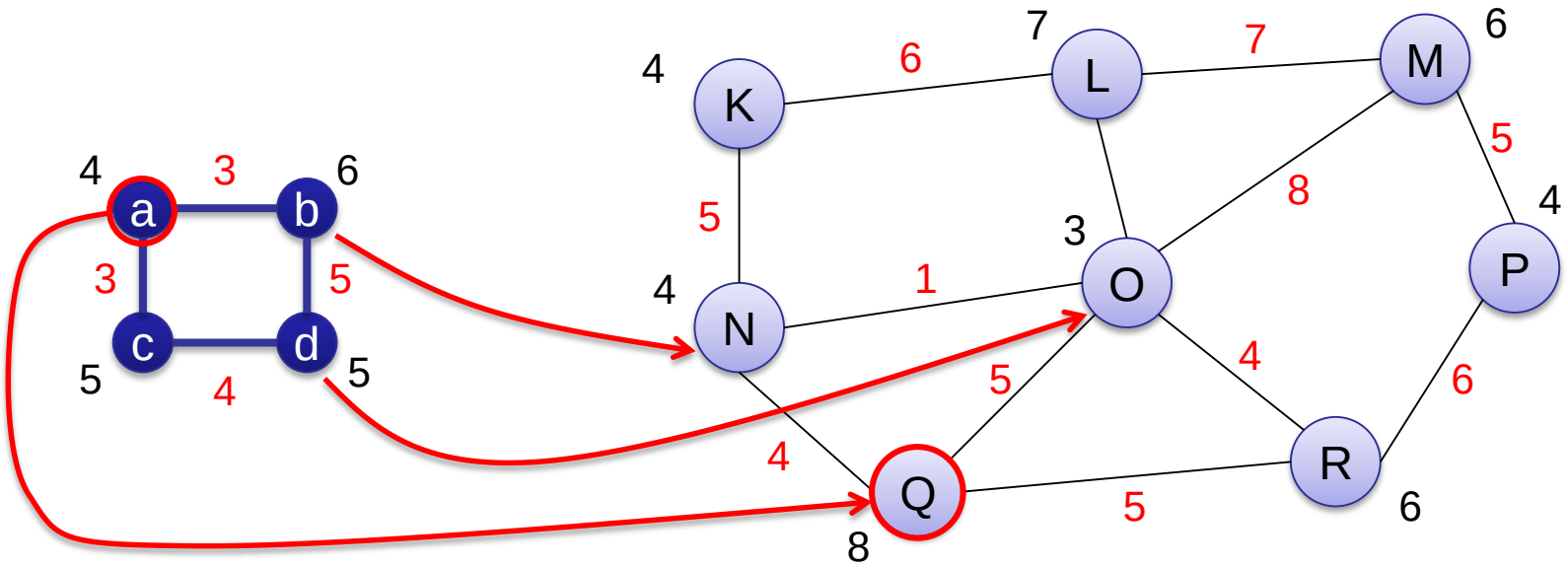

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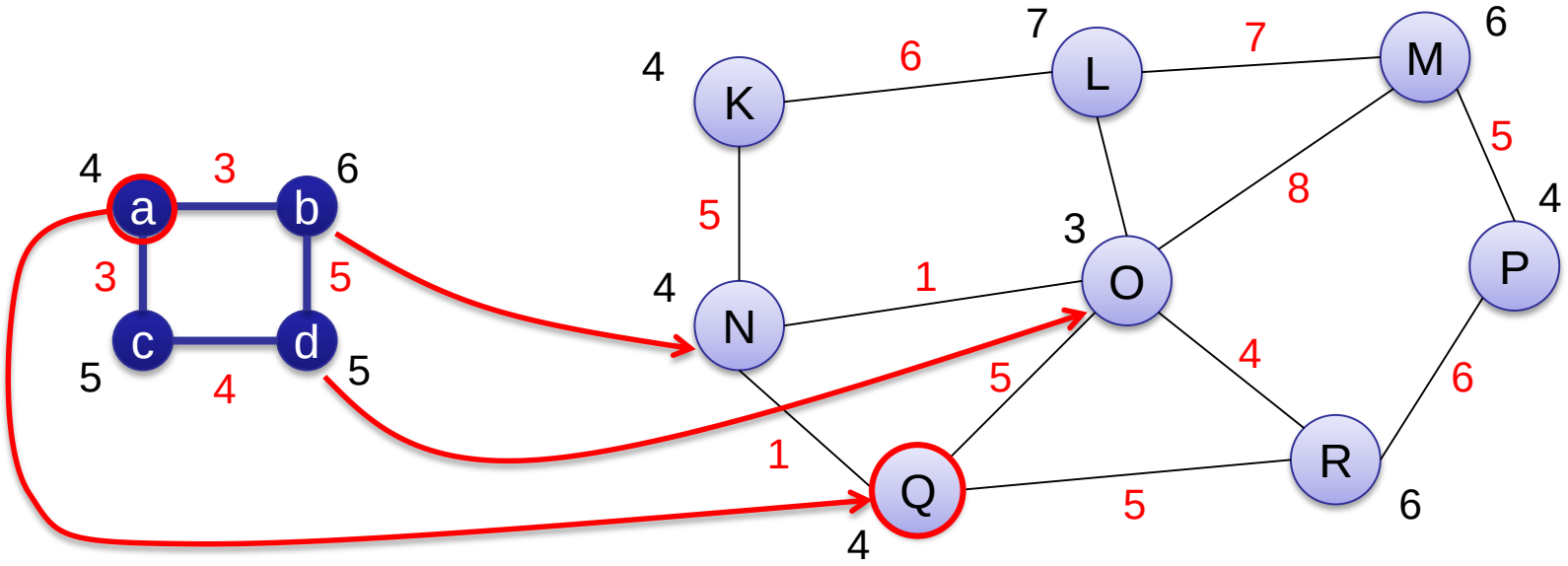
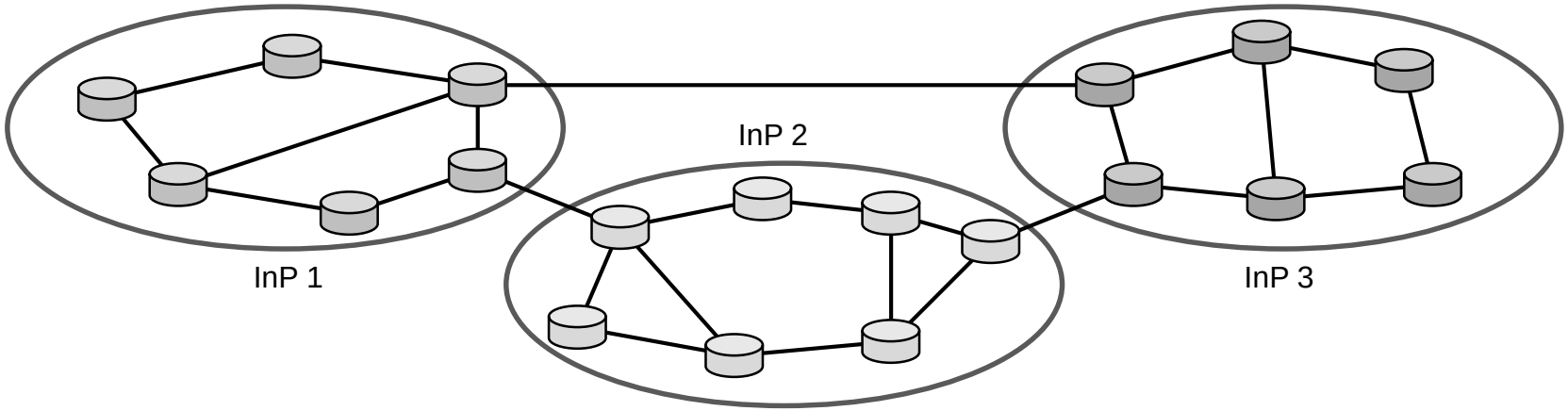
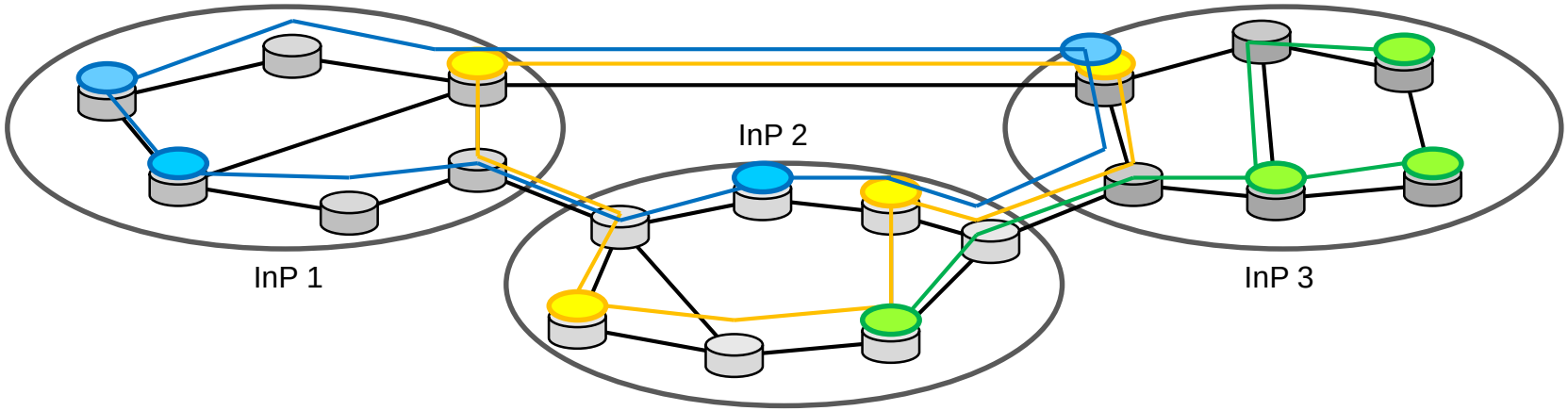


Virtual Network Embedding Across Multiple Substrate Networks

Wide-Area Virtual Network Deployment



Wide-Area Virtual Network Deployment

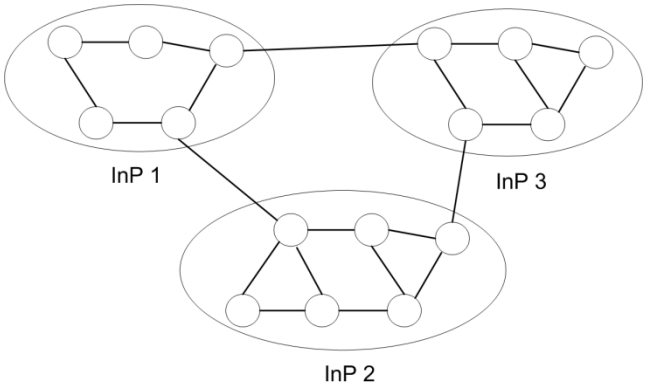


Roles and Actors

- Service Provider (SP)
  - Deploys services on VNs

Service Provider

- Infrastructure Provider (InP)
  - Owns and manages the physical infrastructure
  - Leases resources for VNs



Roles and Actors

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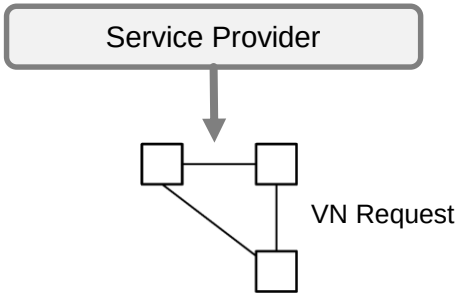

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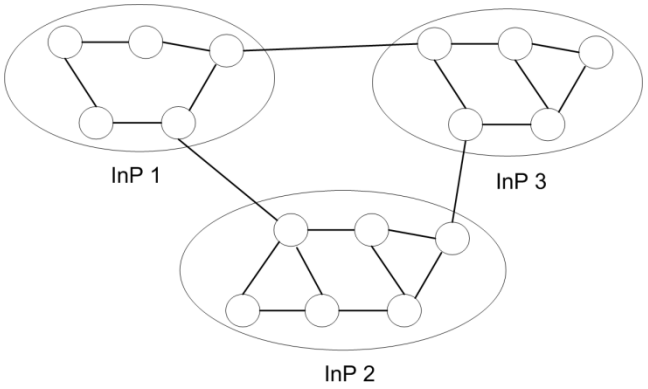

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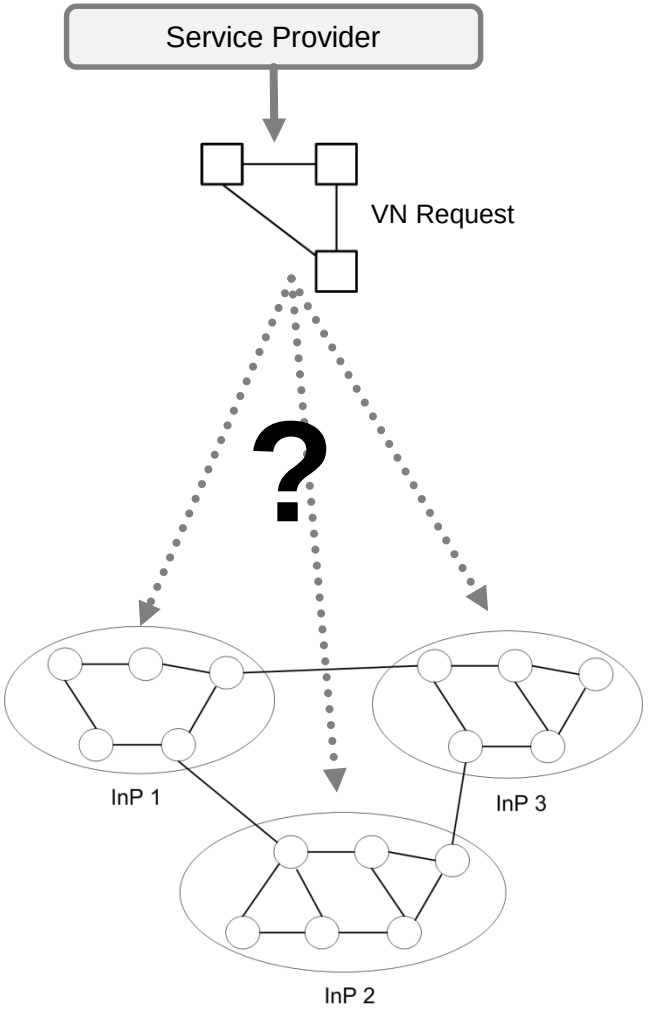
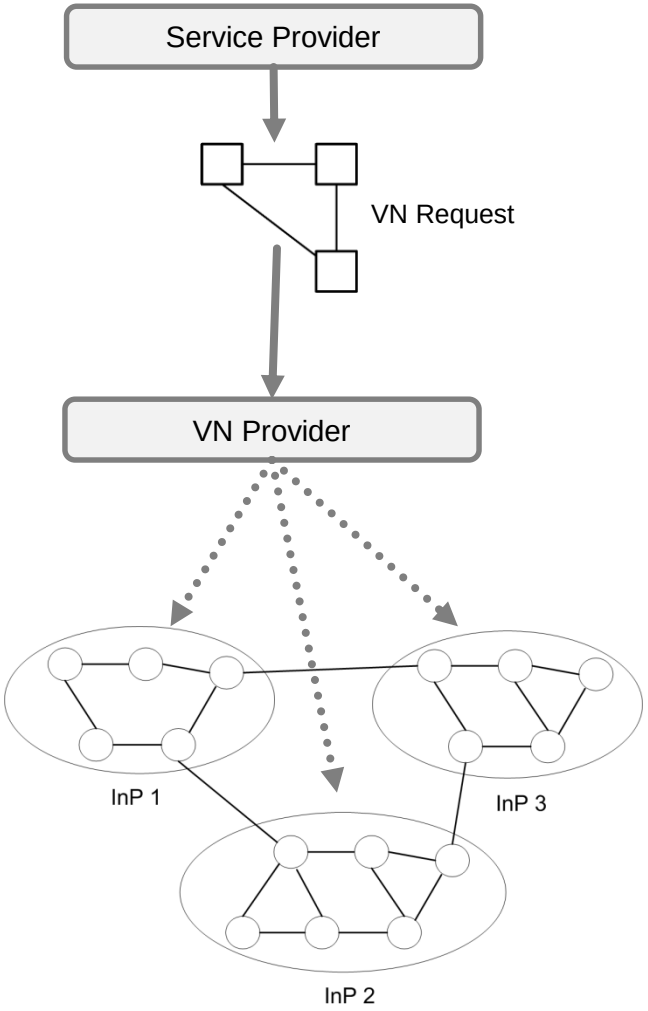


- Infrastructure Provider (InP)
  - Owns and manages the physical infrastructure
  - Leases resources for VNs

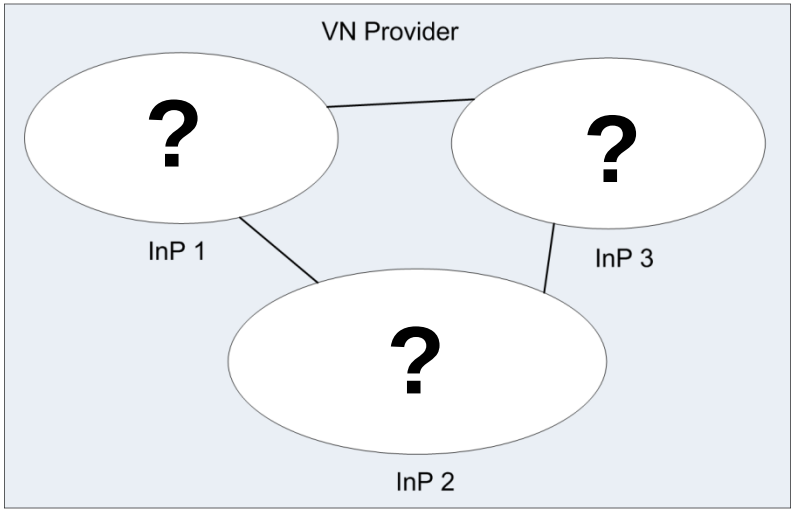
Roles and Actors

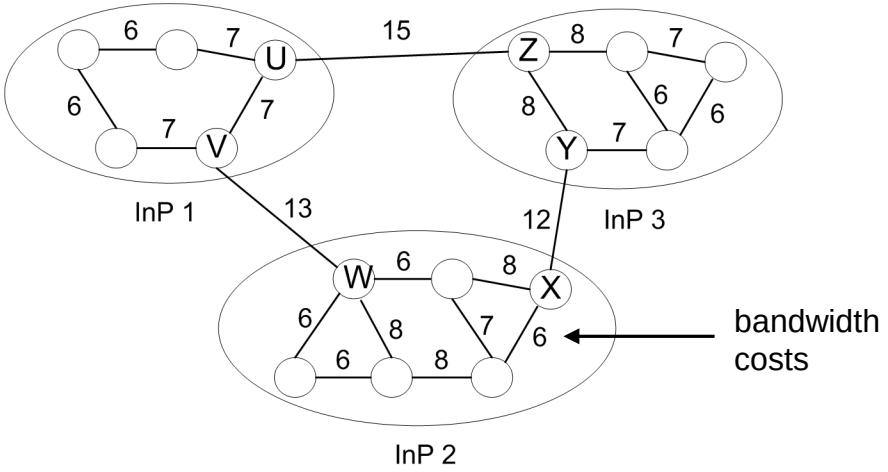
- Service Provider (SP)
  - Deploys services on VNs
- Virtual Network Provider (VNP)
  - Assembles resources from one or multiple InPs into a VN
- Infrastructure Provider (InP)
  - Owns and manages the physical infrastructure
  - Leases resources for VNs



Substrate Network Visibility

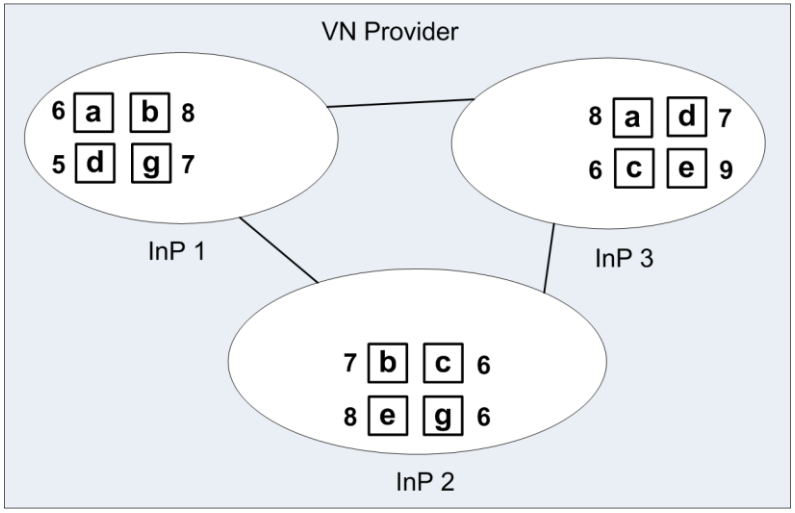
- VN Provider‘s visibility on substrate network topology and resources is limited to:

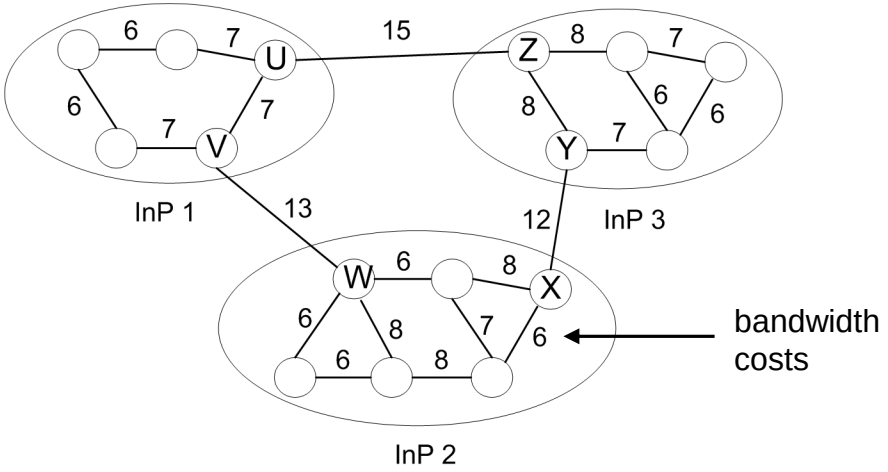




Substrate Network Visibility

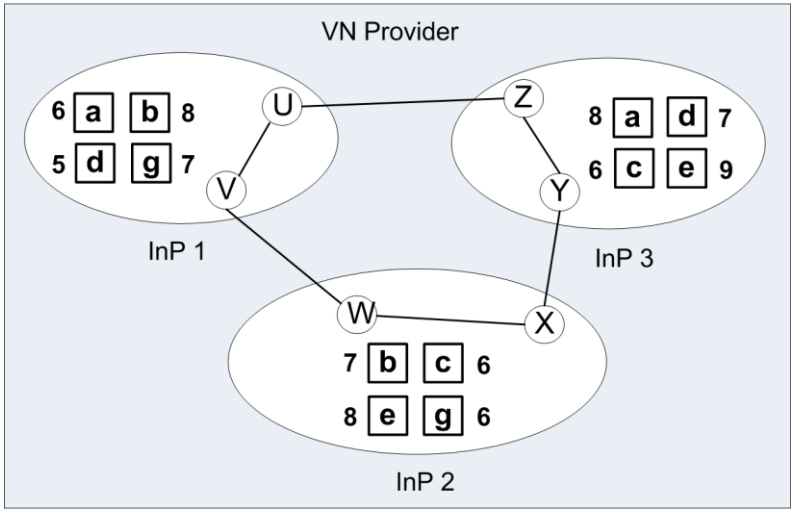
- VN Provider‘s visibility on substrate network topology and resources is limited to:
  - Offered virtual node types (similar to Amazon EC2)

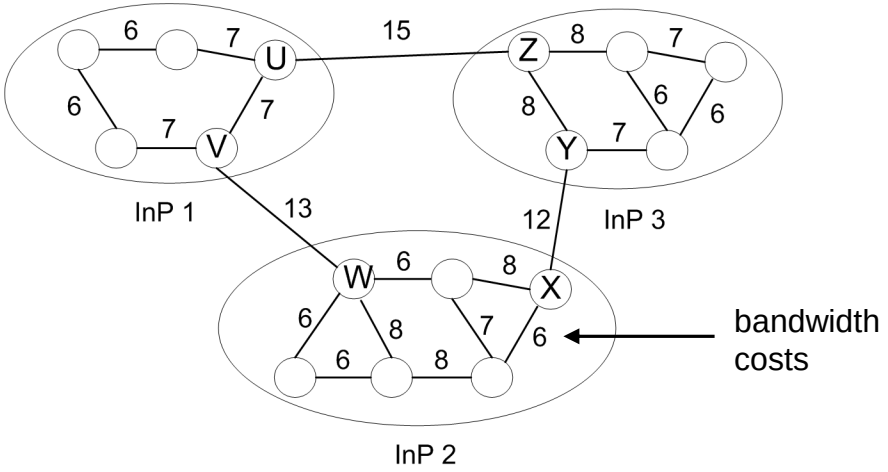




Substrate Network Visibility

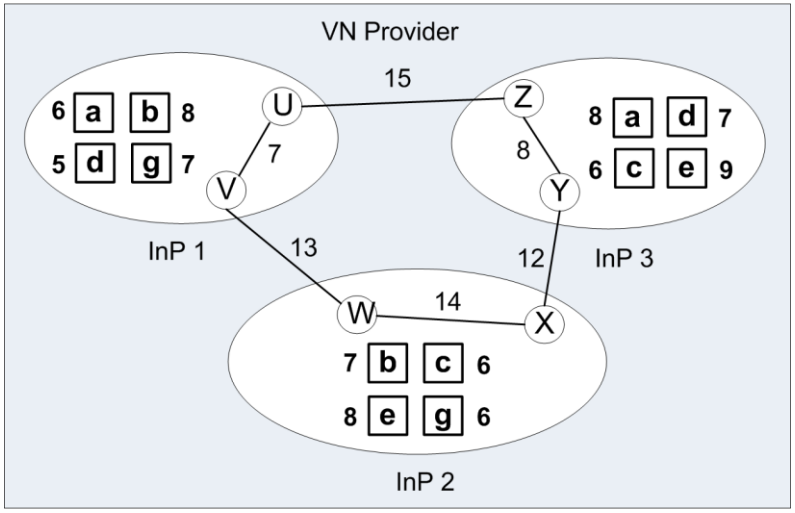
- VN Provider's visibility on substrate network topology and resources is limited to:
  - Offered virtual node types (similar to Amazon EC2)
  - Location of peering nodes

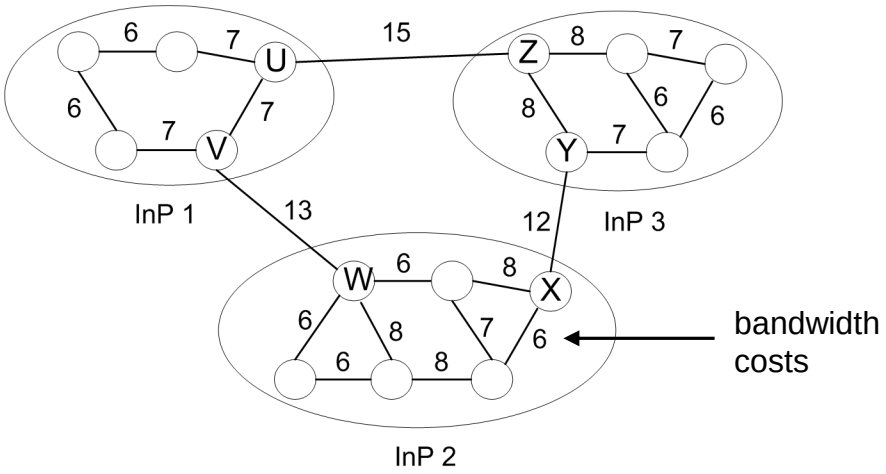




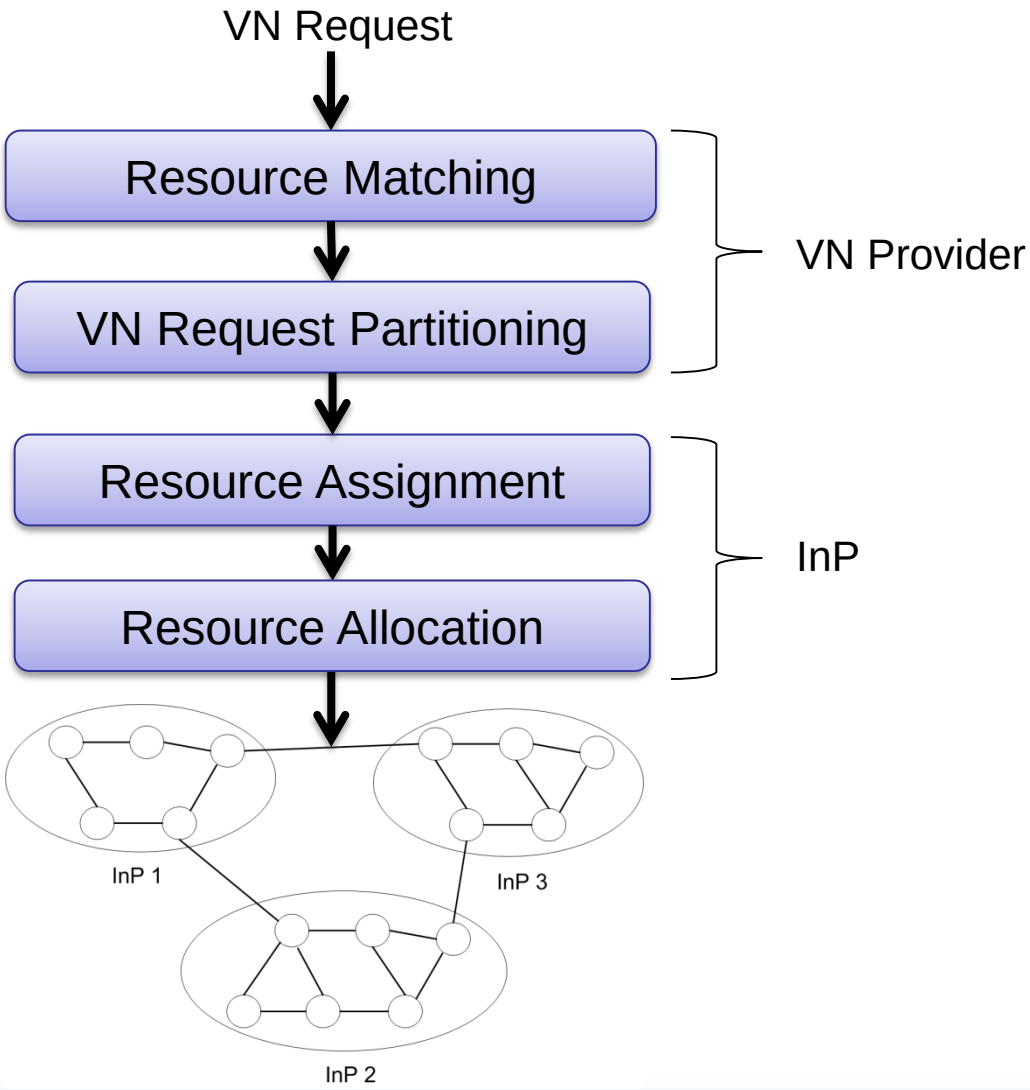
Substrate Network Visibility

- VN Provider's visibility on substrate network topology and resources is limited to:
  - Offered virtual node types (similar to Amazon EC2)
  - Location of peering nodes
  - Bandwidth cost over links between peering nodes

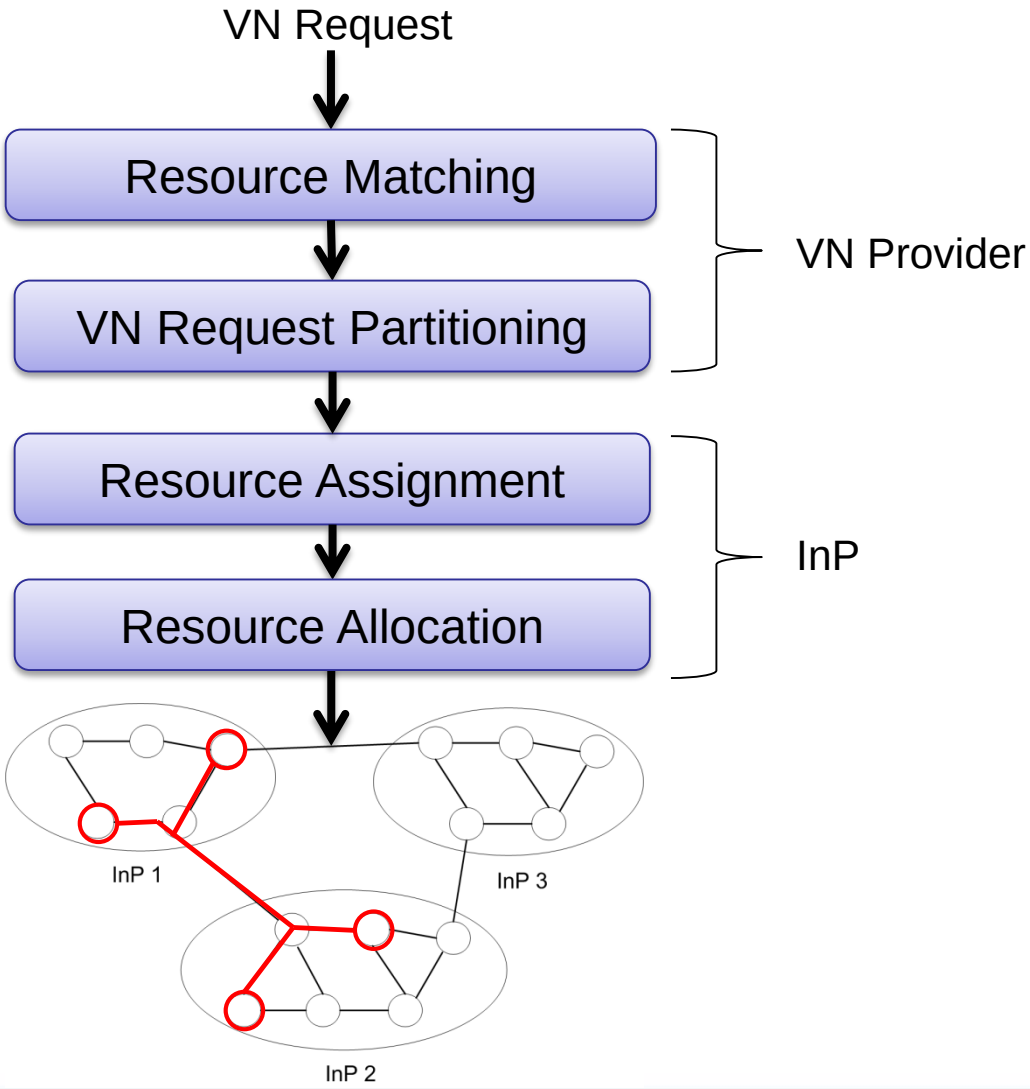




Multi-Domain Virtual Network Embedding

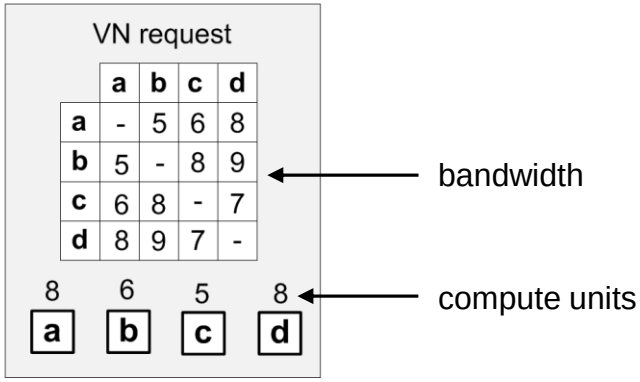


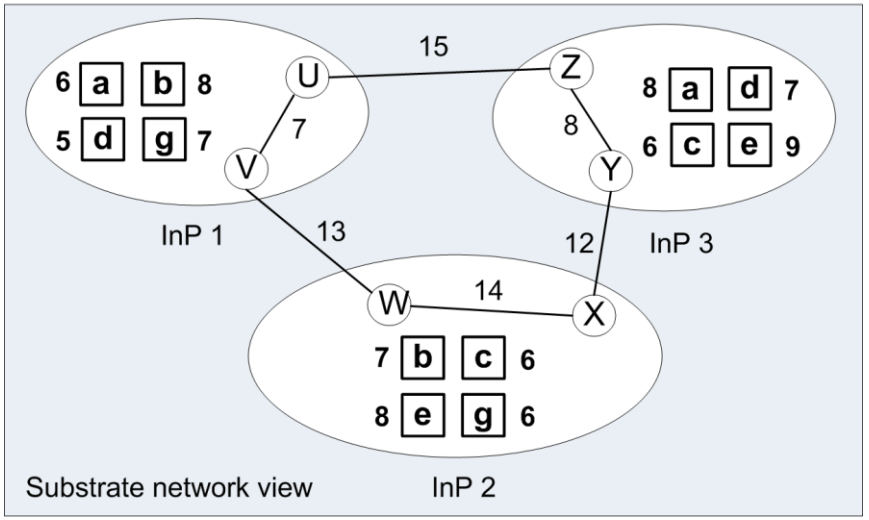
Multi-Domain Virtual Network Embedding



Resource Matching

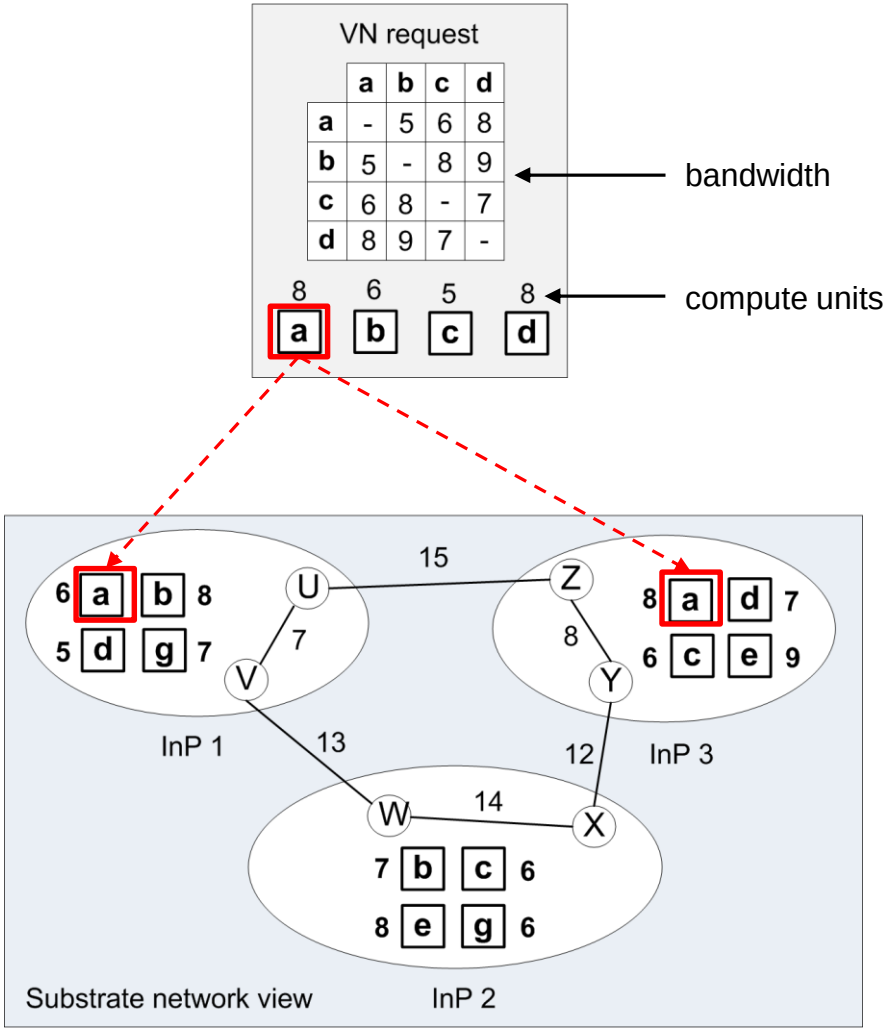
- VN Provider matches requested to advertised resources
  - Candidates for each requested resource are identified





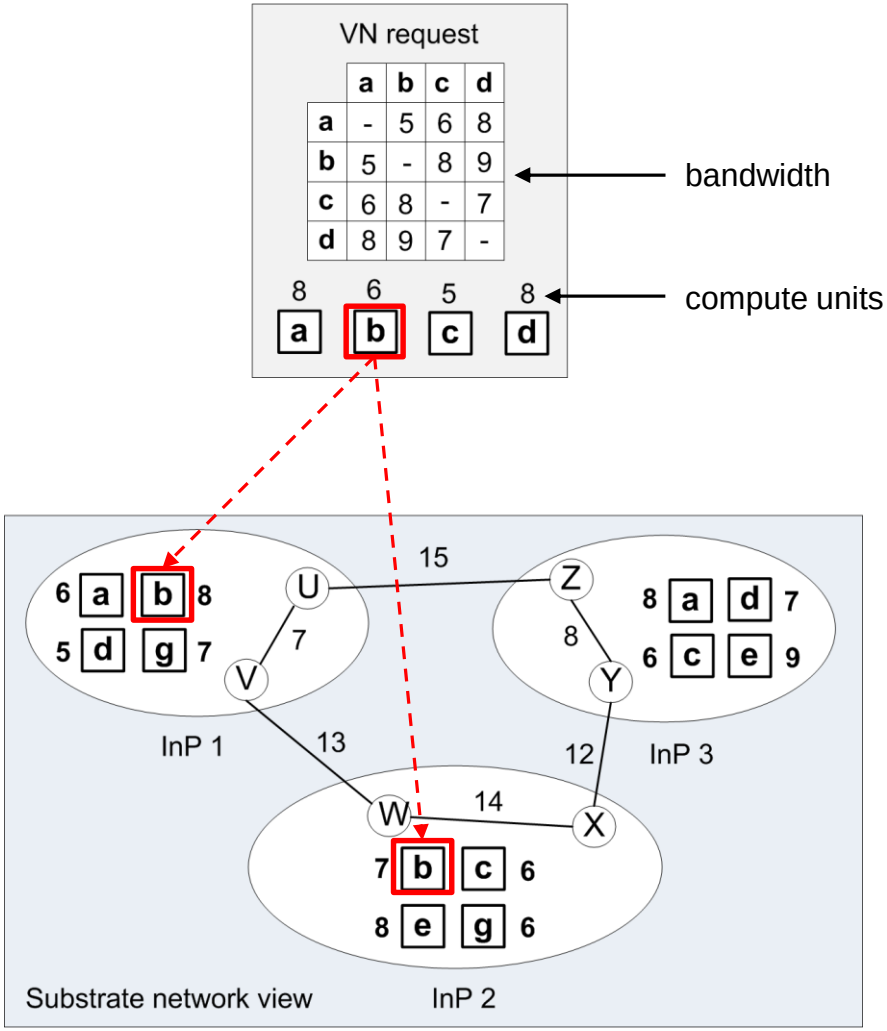
Resource Matching

- VN Provider matches requested to advertised resources
  - Candidates for each requested resource are identified
    - `a: {InP1, InP3}`



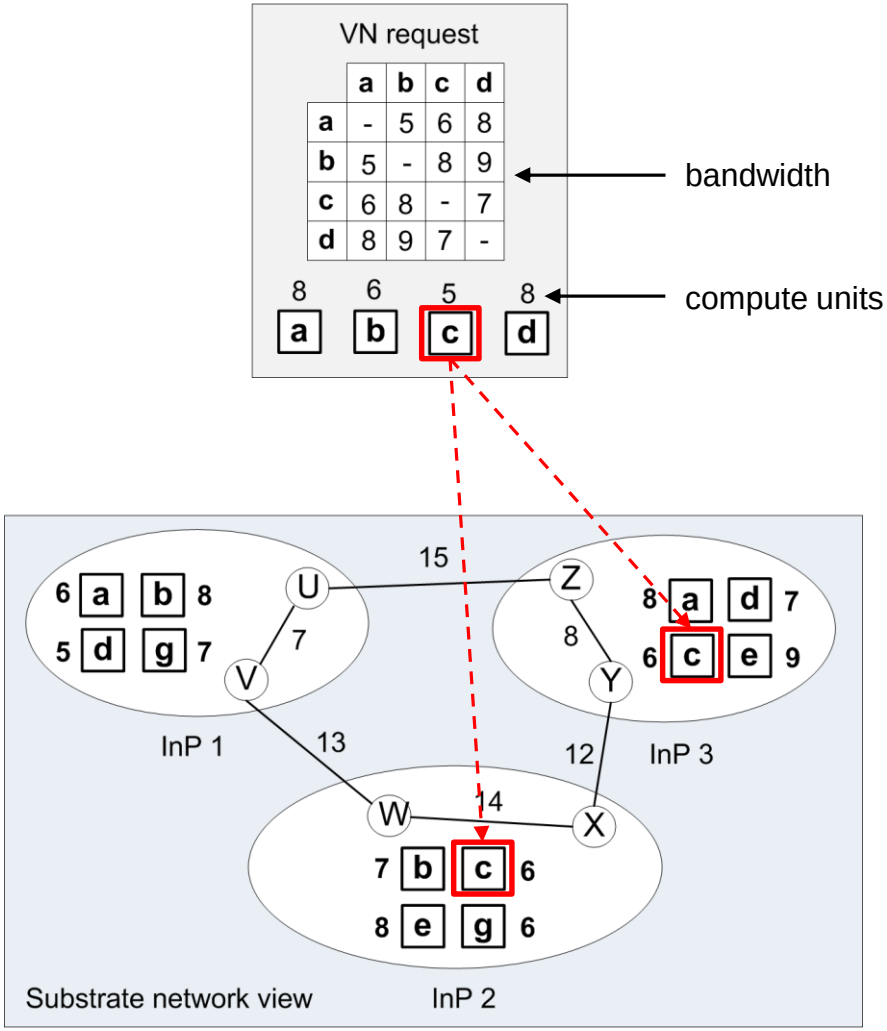
Resource Matching

- VN Provider matches requested to advertised resources
  - Candidates for each requested resource are identified
    - `a: {InP1, InP3}`
    - `b: {InP1, InP2}`



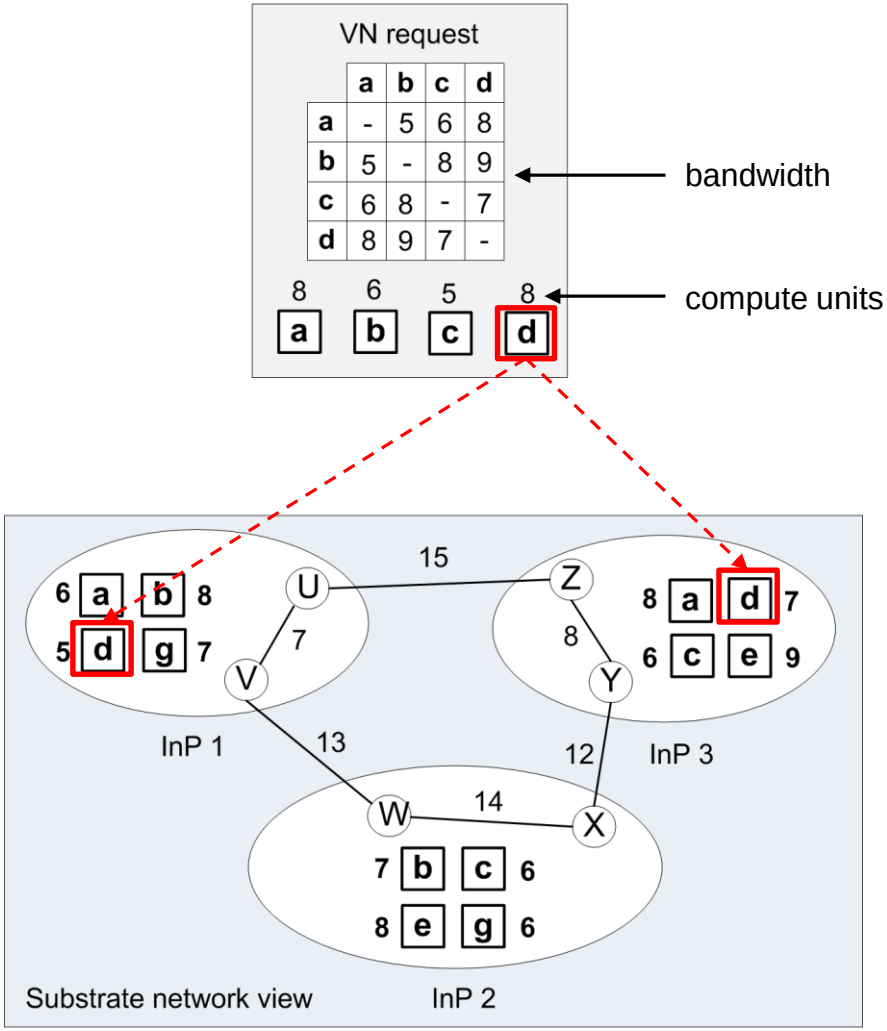
Resource Matching

- VN Provider matches requested to advertised resources
  - Candidates for each requested resource are identified
    - `a: {InP1, InP3}`
    - `b: {InP1, InP2}`
    - `c: {InP2, InP3}`



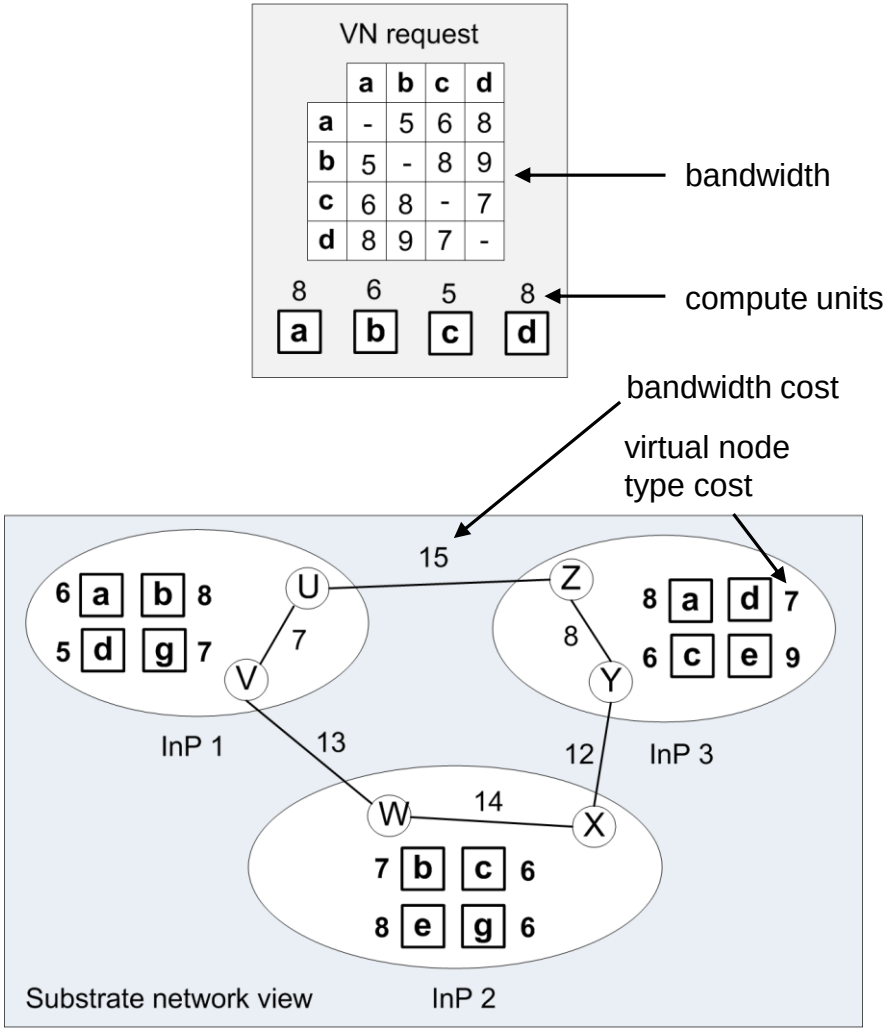
Resource Matching

- VN Provider matches requested to advertised resources
  - Candidates for each requested resource are identified
    - a: {InP1, InP3}
    - b: {InP1, InP2}
    - c: {InP2, InP3}
    - d: {InP1, InP3}



VN Request Partitioning

- Binary integer program:
  - Objective:
    - Minimize the cost for the Service Provider



VN Request Partitioning

- Binary integer program:
  - Objective:
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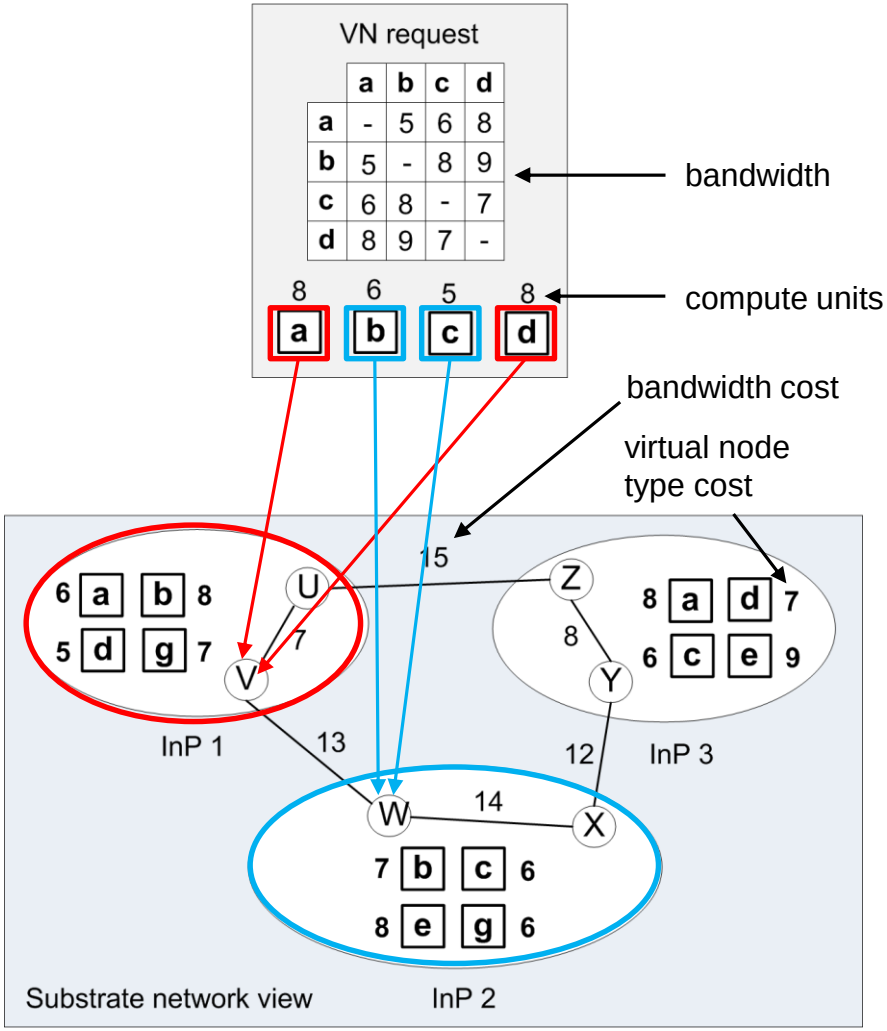
  - Solution:
    - Virtual node to peering node assignment



VN Request Partitioning

- Binary integer program:
  - Objective:
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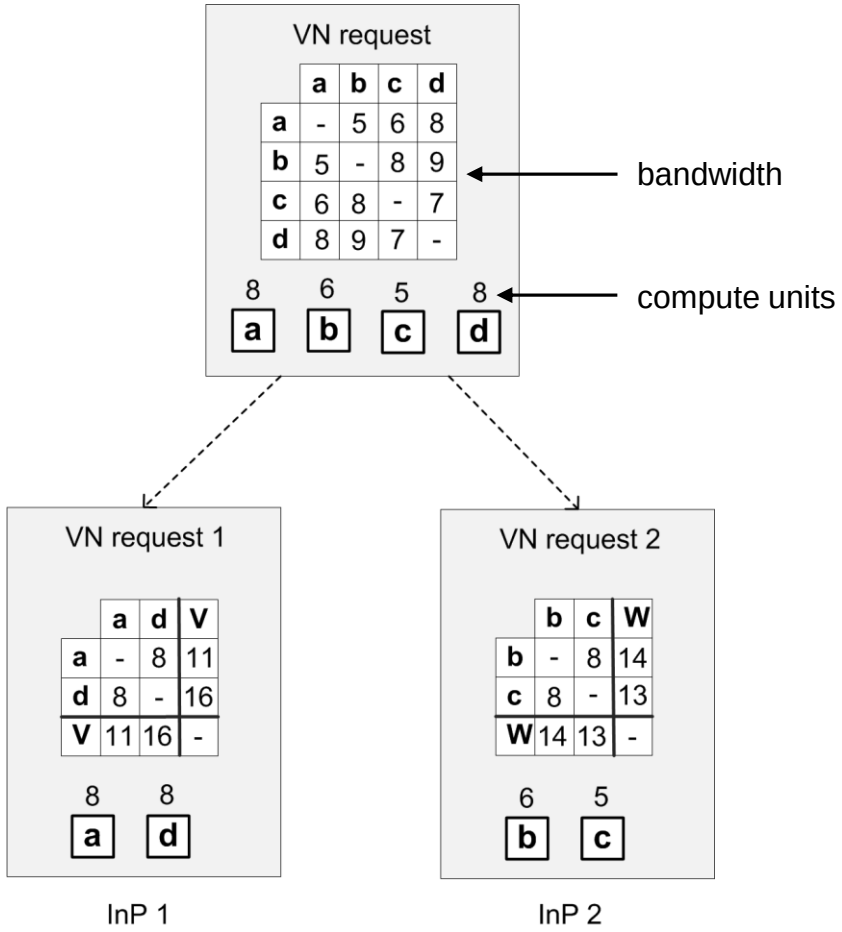
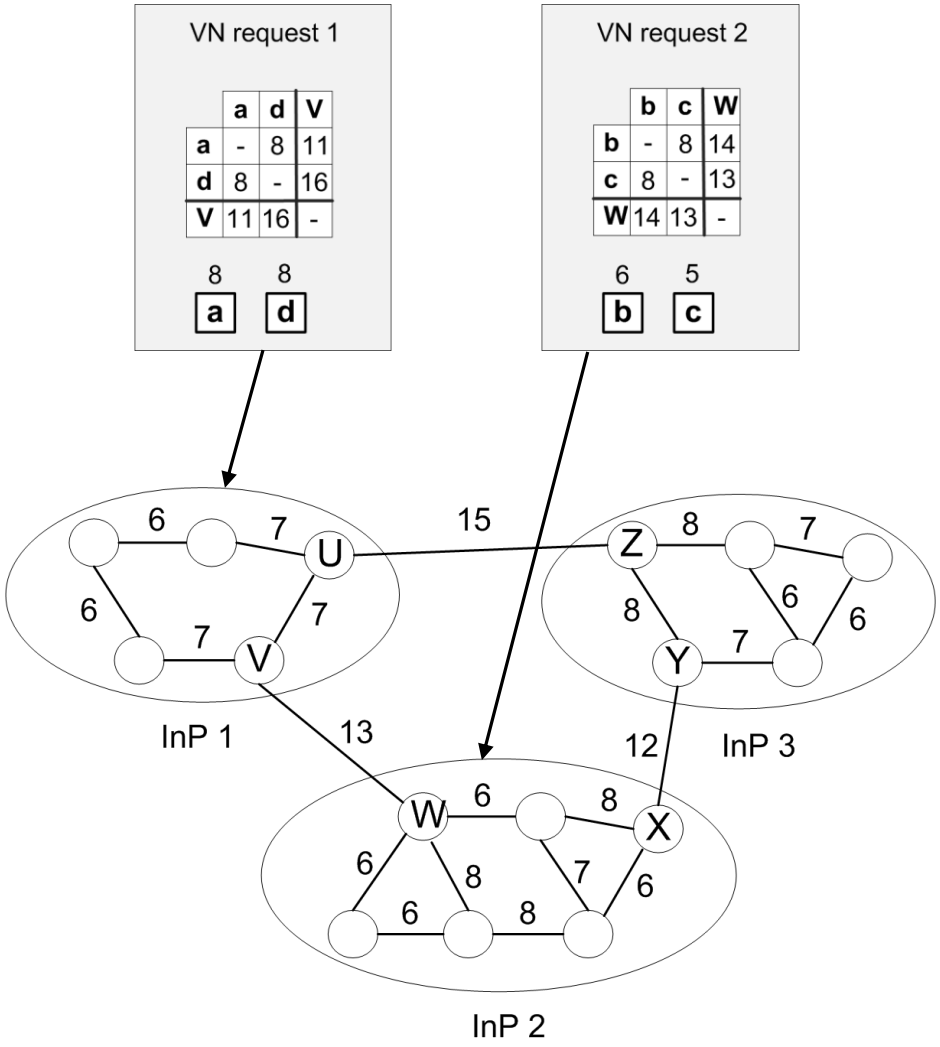
  - Solution:
    - Virtual node to peering node assignment
- VN segment description:
  - Virtual node specifications
  - Bandwidth demands between virtual nodes and peering nodes



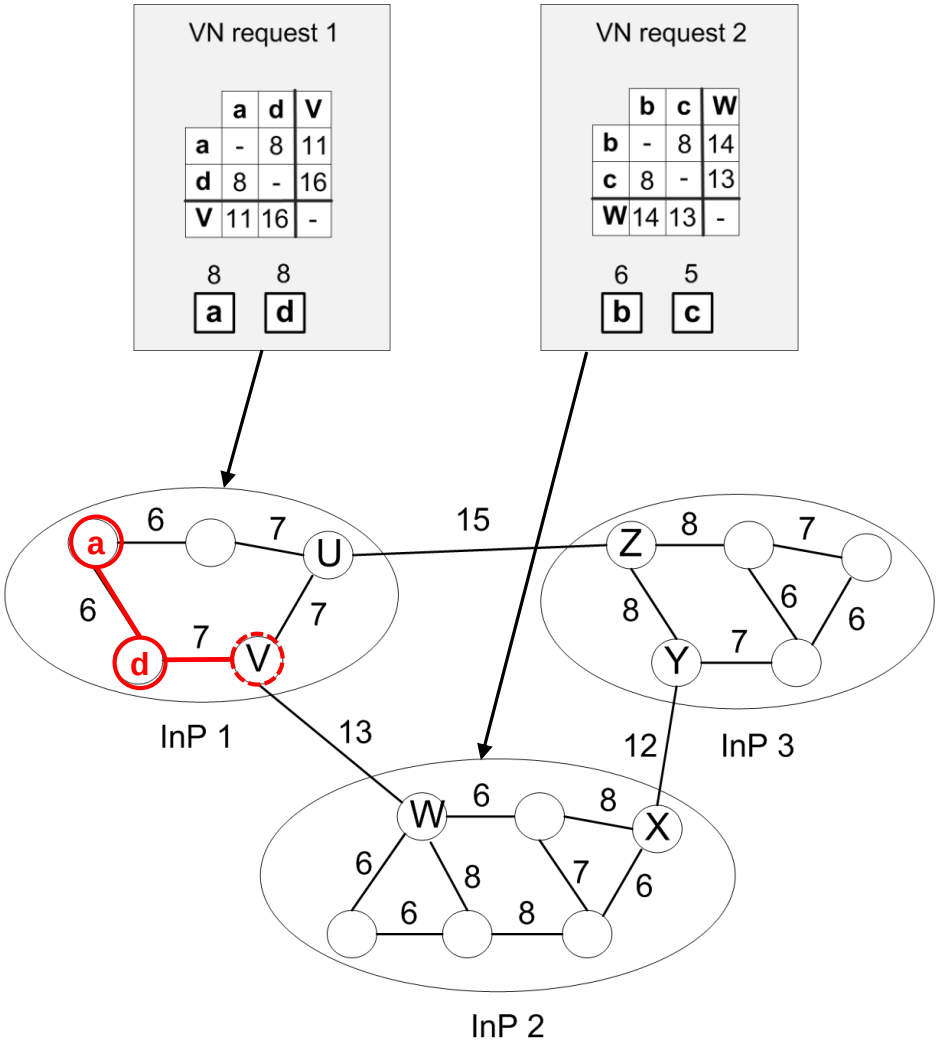
VN Segment Mapping

- Mixed integer multi-commodity flow problem:
  - Objective:
    - Minimize the embedding cost



VN Segment Mapping

- Mixed integer multi-commodity flow problem:
  - Objective:
    - Minimize the embedding cost
  - Solution:
    - VN segment mapping onto the substrate network
      - Compliance with virtual node to peering node bindings



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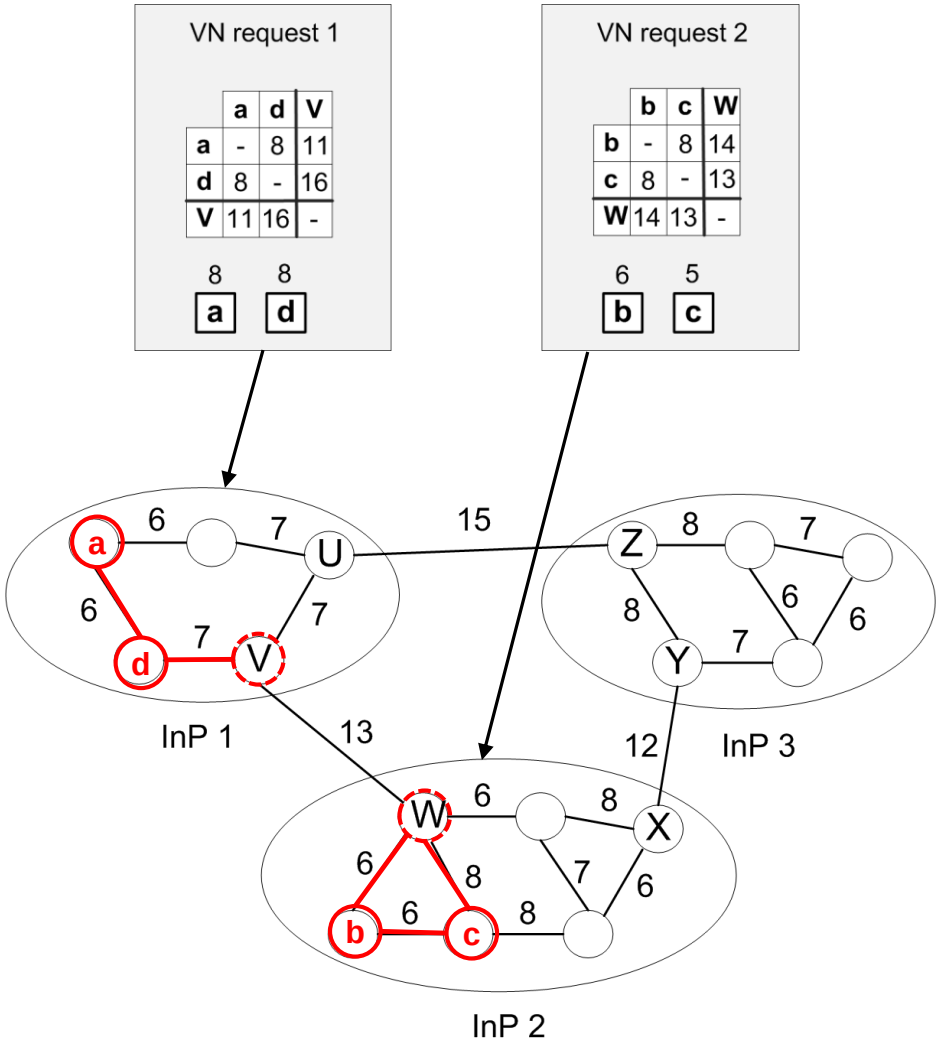

VN Segment Mapping

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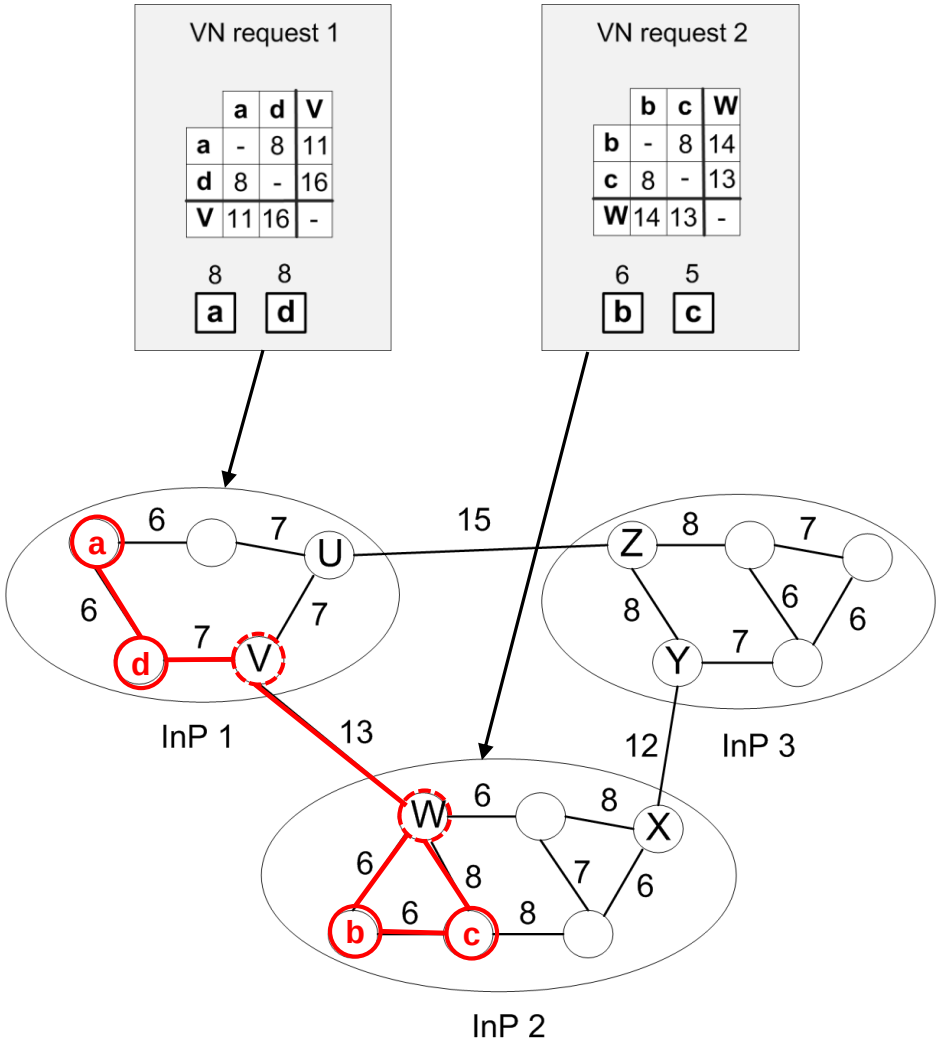
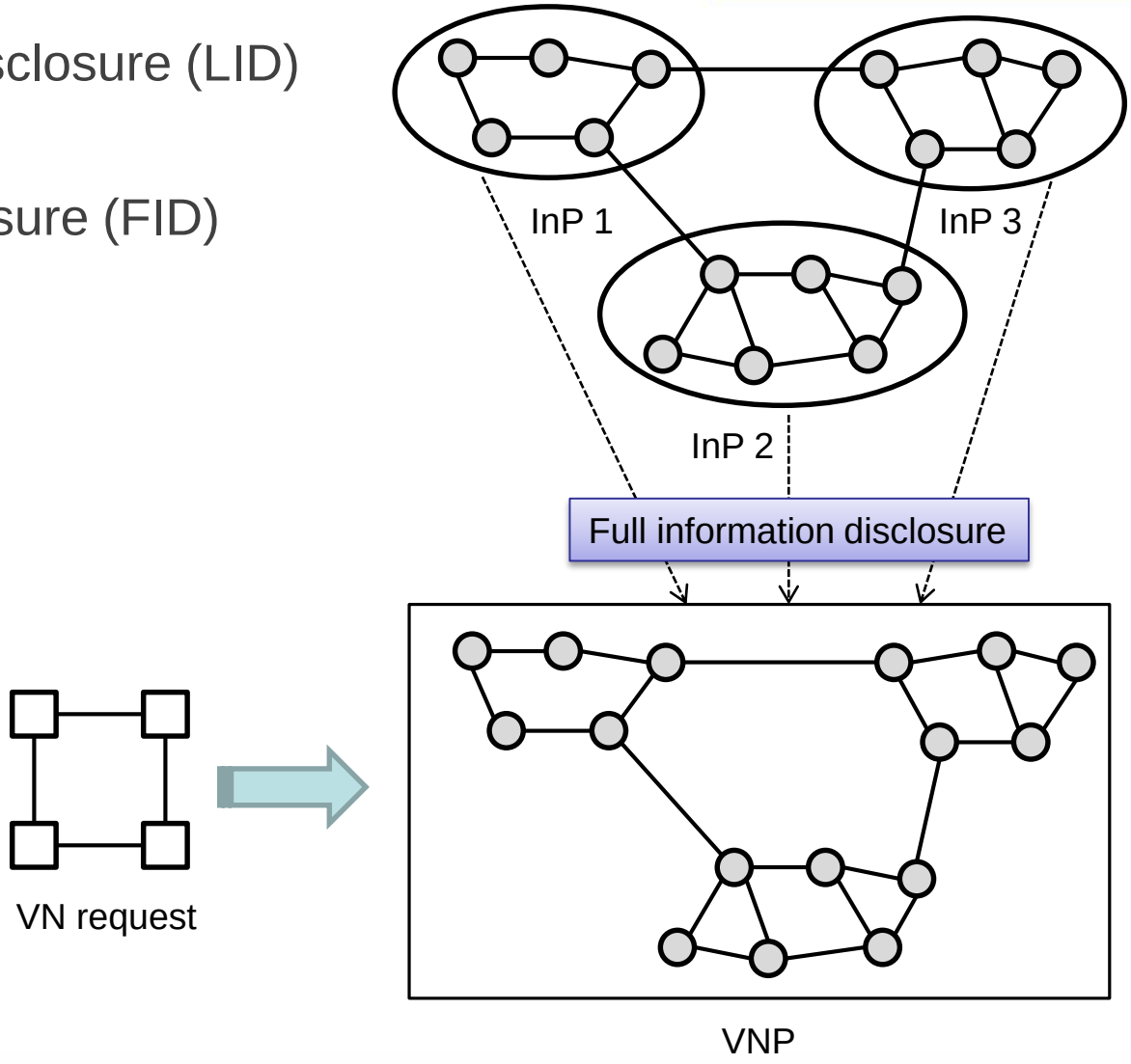


VN Embedding Efficiency

Limited information disclosure (LID)

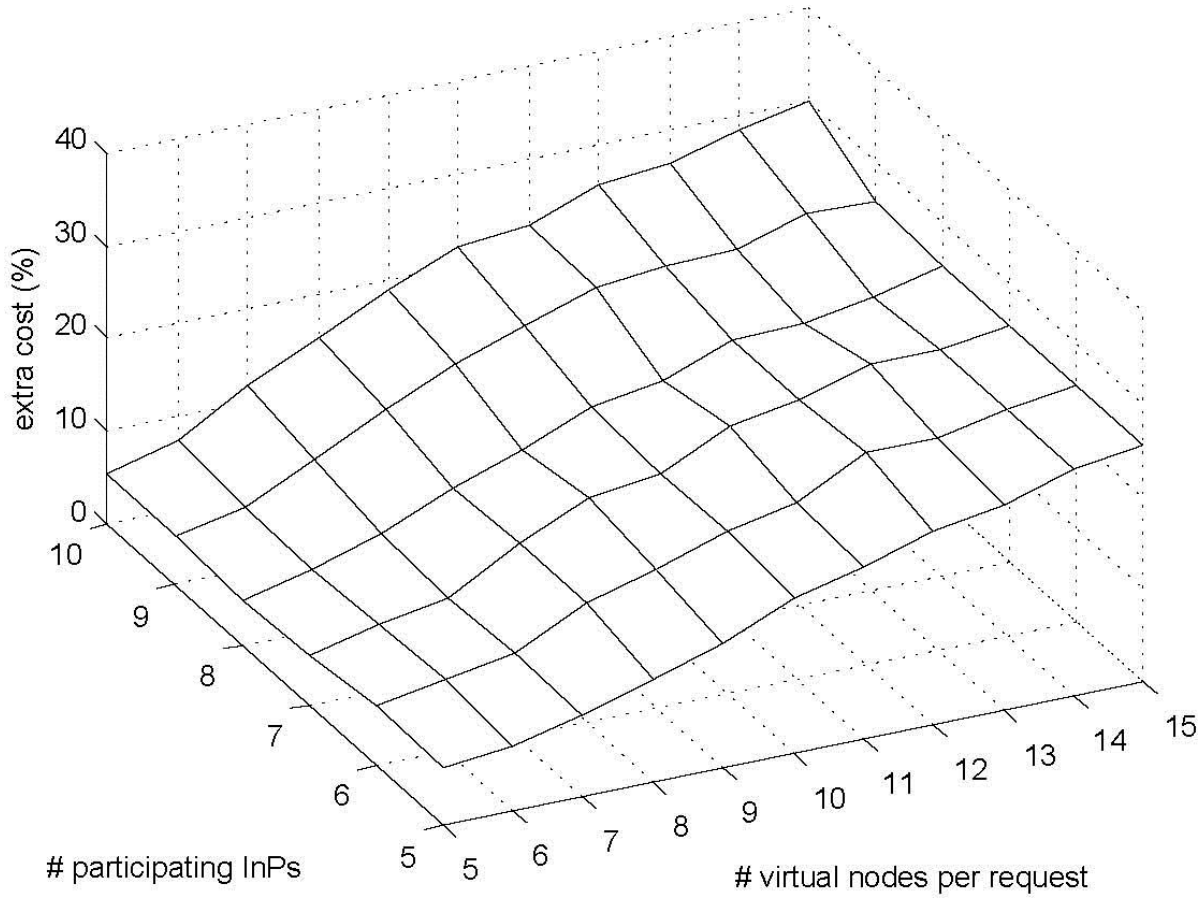
vs.

Full information disclosure (FID)



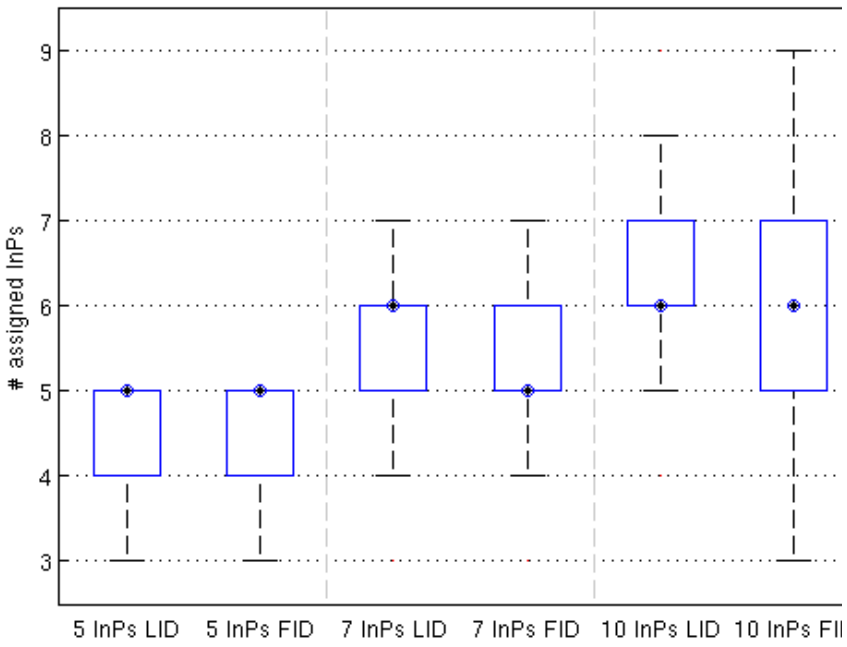
Extra Cost under LID

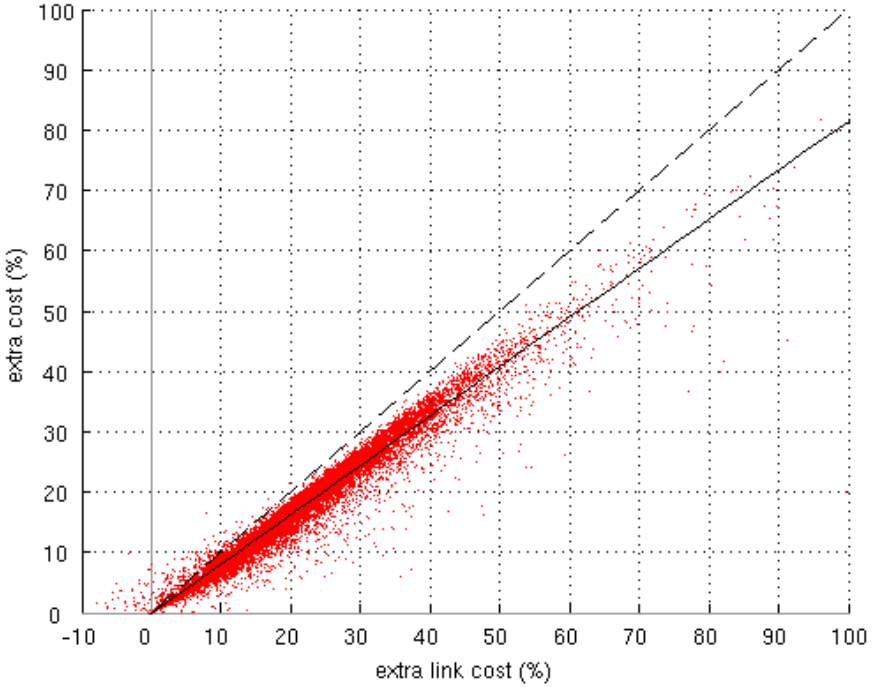
- LID incurs 5-30% extra cost



Origins of Extra Cost

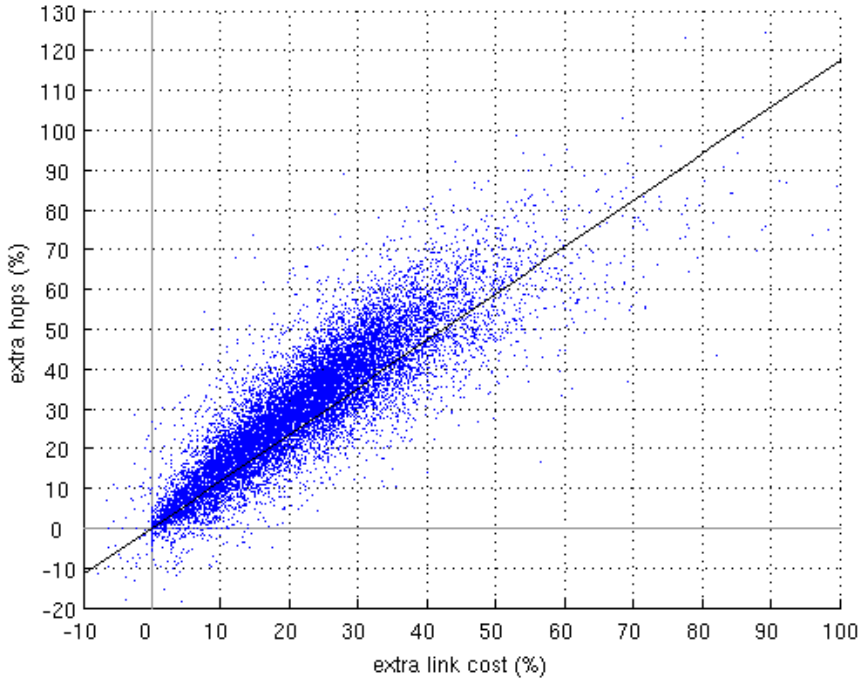
- Same number of assigned InPs under LID and FID
- Extra cost is correlated with extra link cost

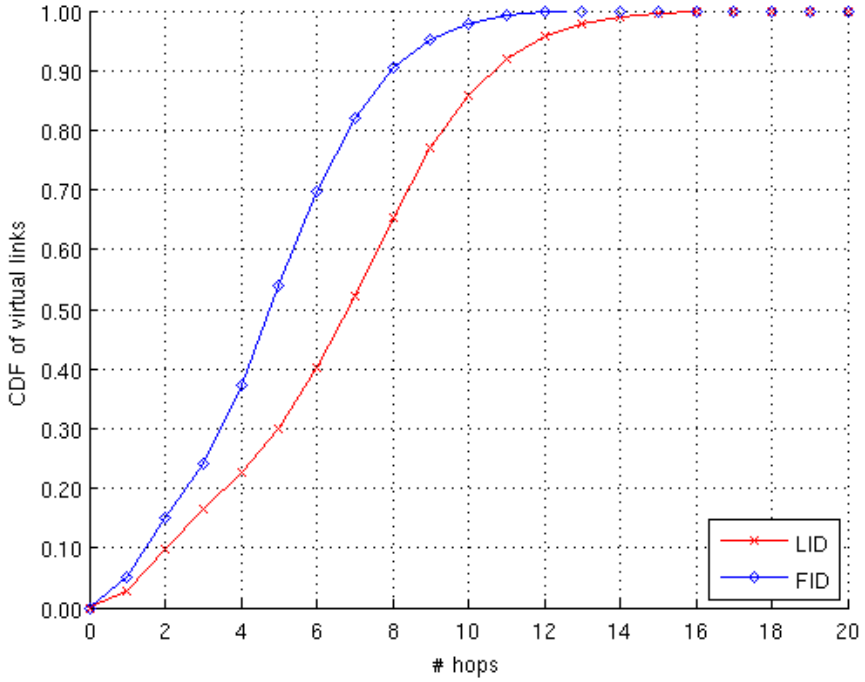




Origins of Extra Link Cost

- Extra link cost is due to increased hop count





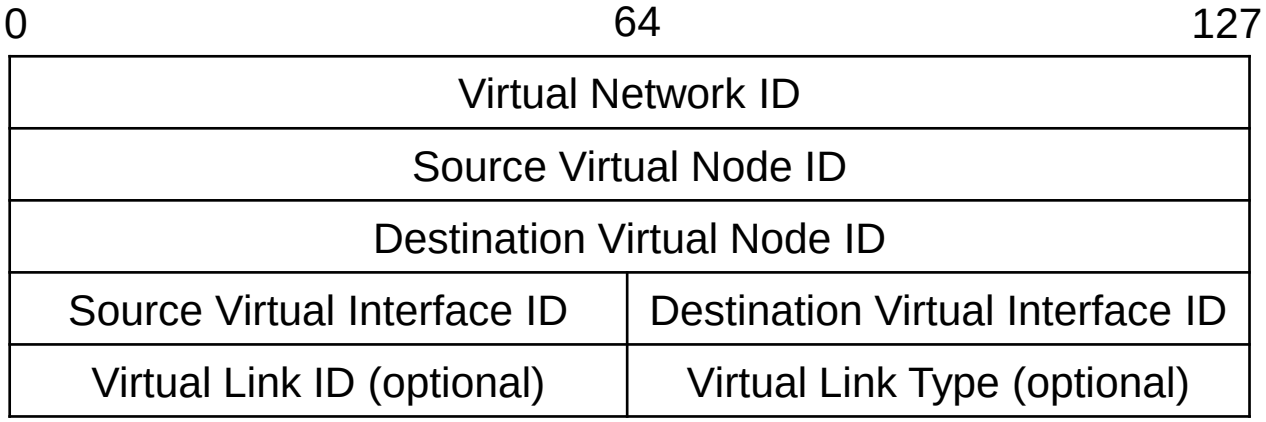
Virtual Link Setup

Virtual Link Setup

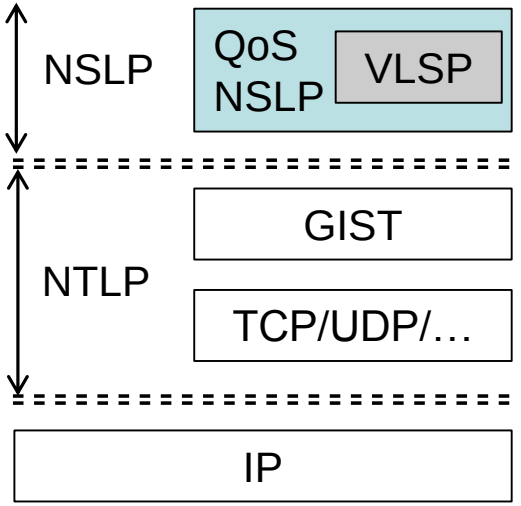
- Objective:
  - Interoperable solution for virtual link setup with QoS guarantees across InPs
- Approach:
  - Couple virtual link setup signaling with QoS reservation signaling for efficiency
    - Rely on existing QoS resource reservation protocol (IETF NSIS)
    - Add new object to NSIS QoS NSLP to carry the required information for virtual link setup
- Requirements:
  - NSIS support in routers
  - IP-based substrate
  - New QoS NSLP object support (only) in virtual link end-points

Virtual Link Setup Protocol (VLSP)

- NSIS QoS NSLP extension with new Virtual Link Setup Protocol (VLSP) object:
  - Virtual link setup at the end-points via VLSP
  - Resource reservation and QoS via NSLP object at the intermediate nodes

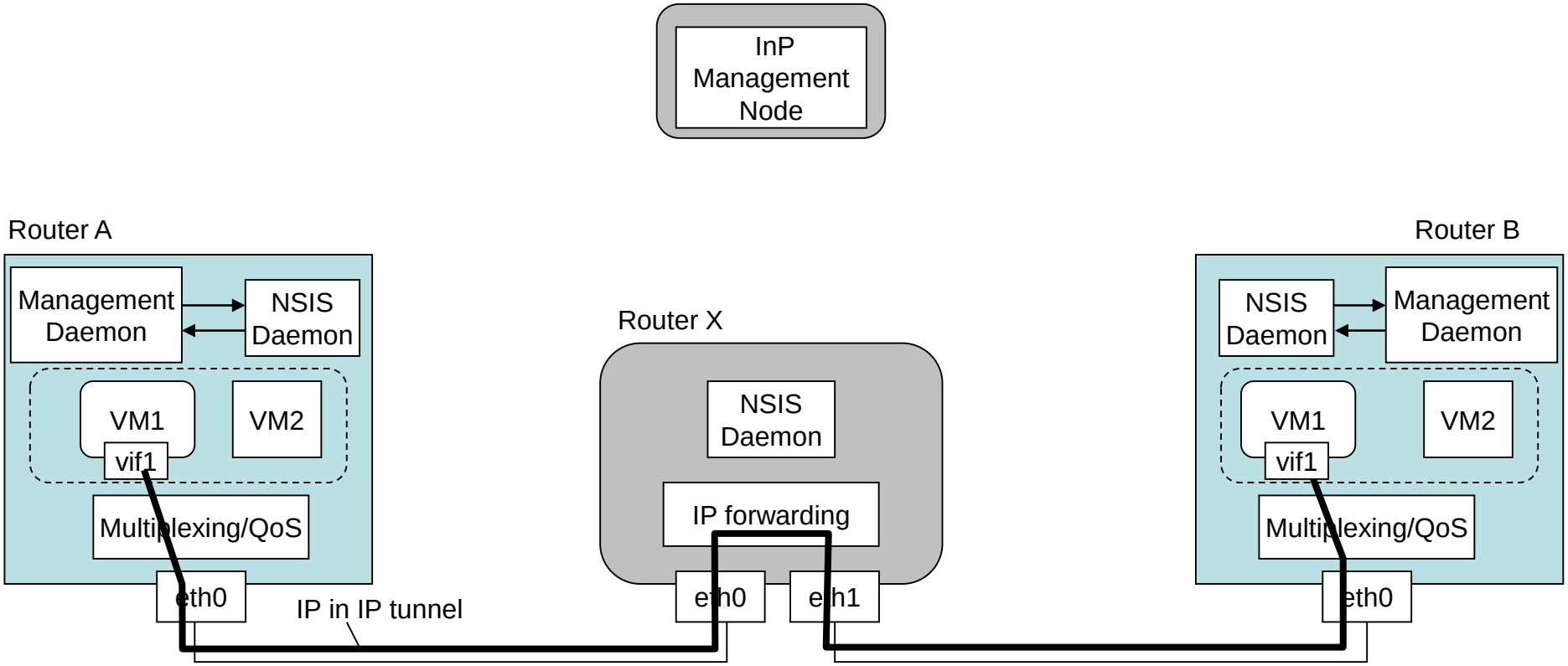


VLSP object

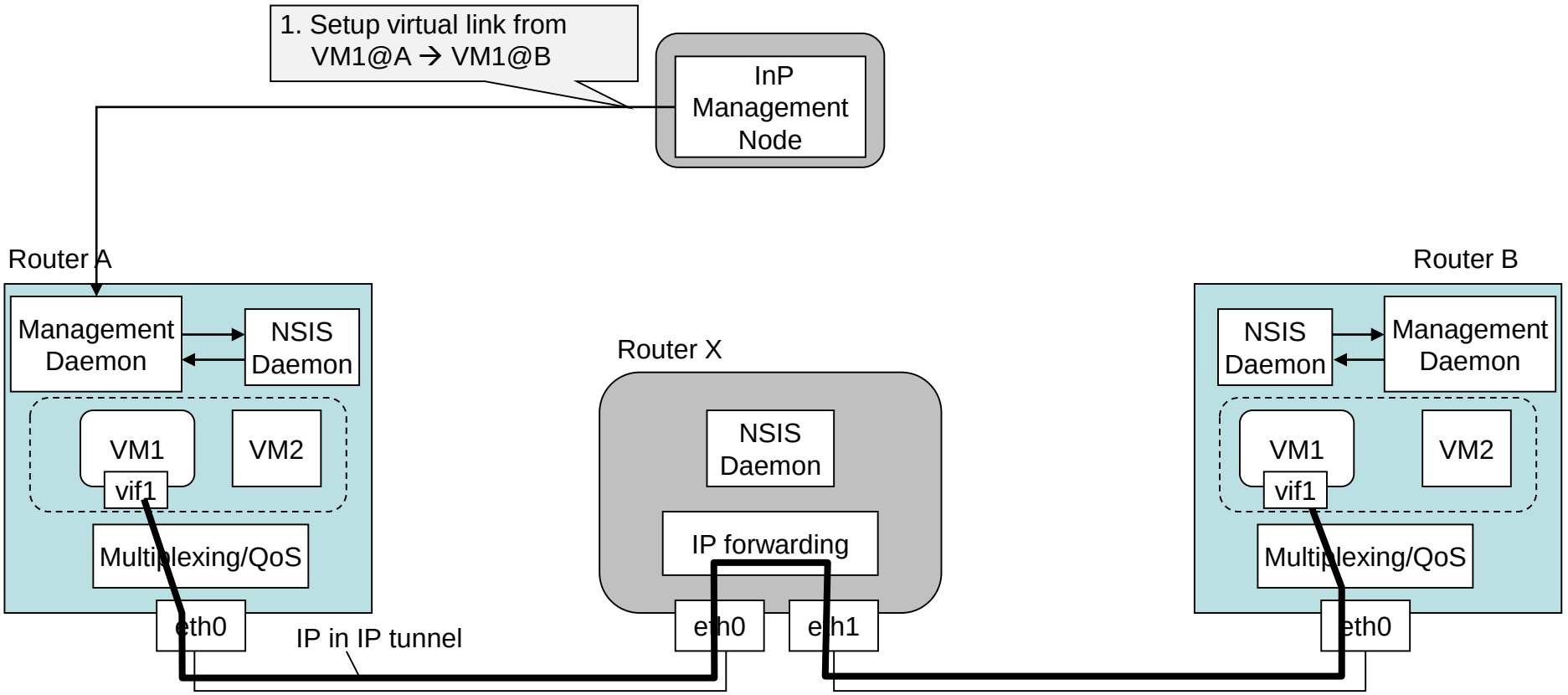


NSIS QoS NSLP/VLSP

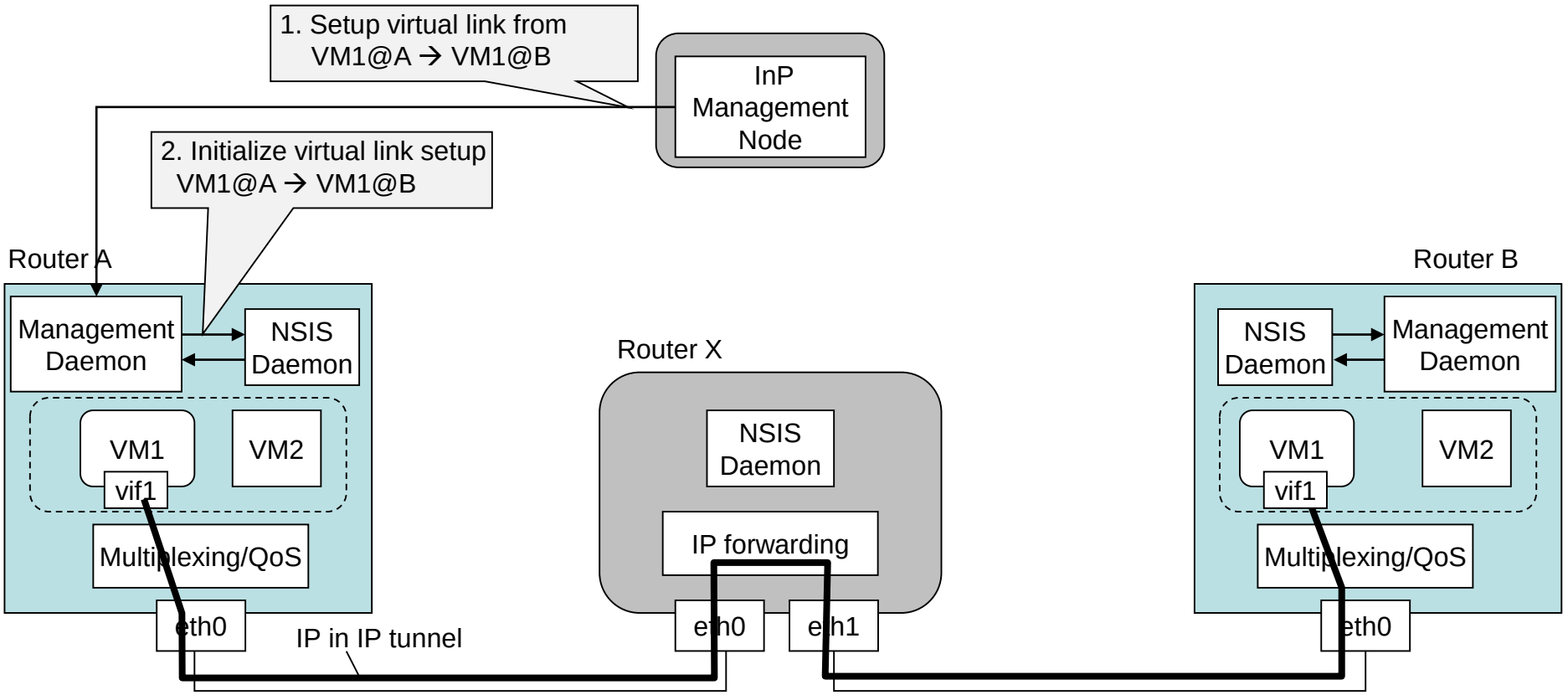
Virtual Link Setup Workflow



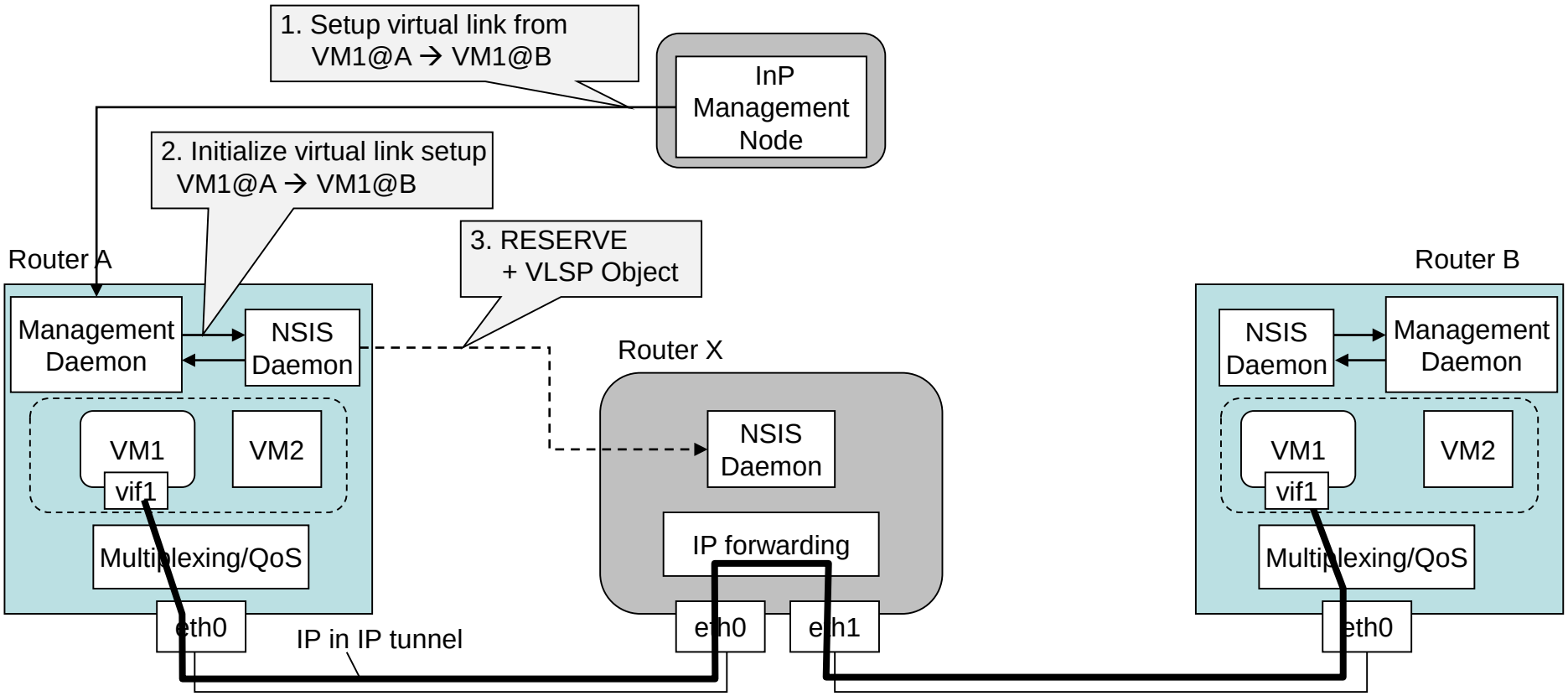
Virtual Link Setup Workflow



Virtual Link Setup Workflow



Virtual Link Setup Workflow



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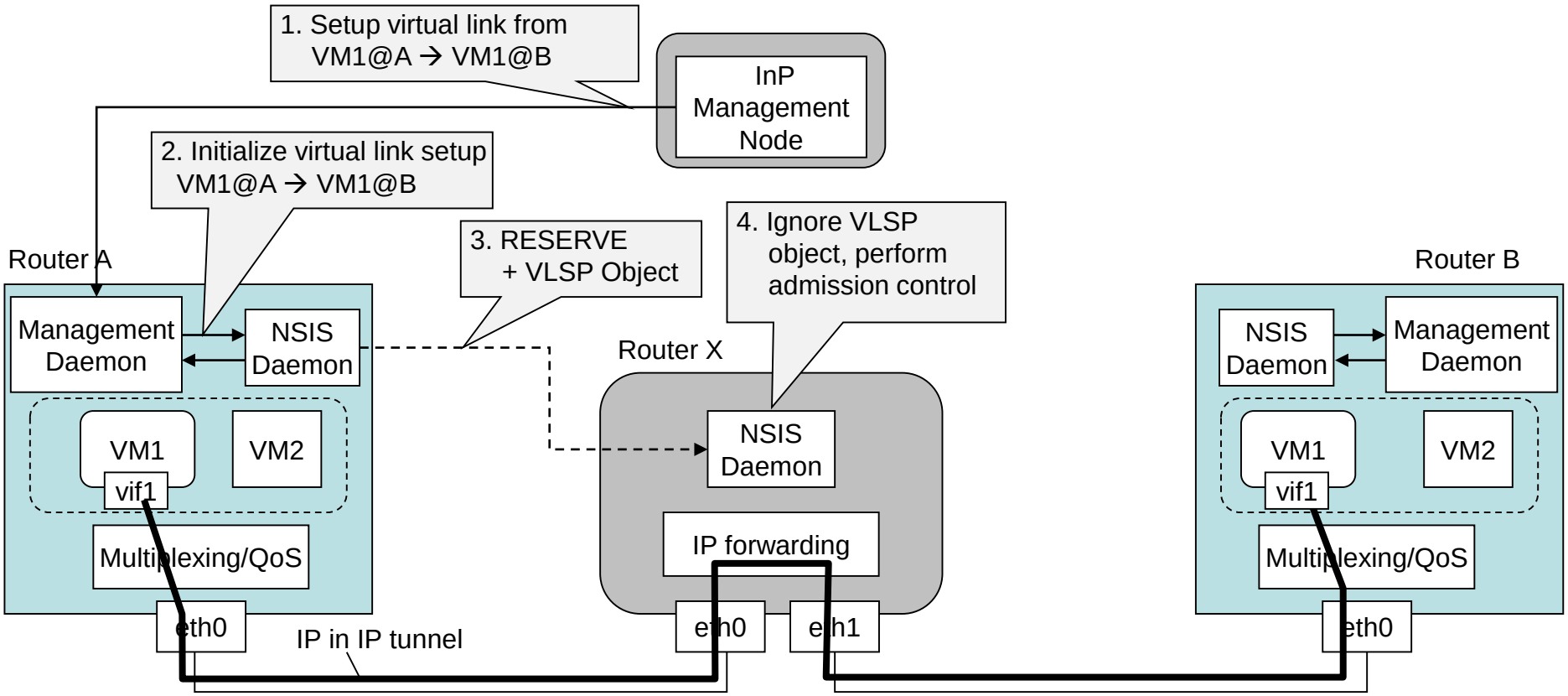

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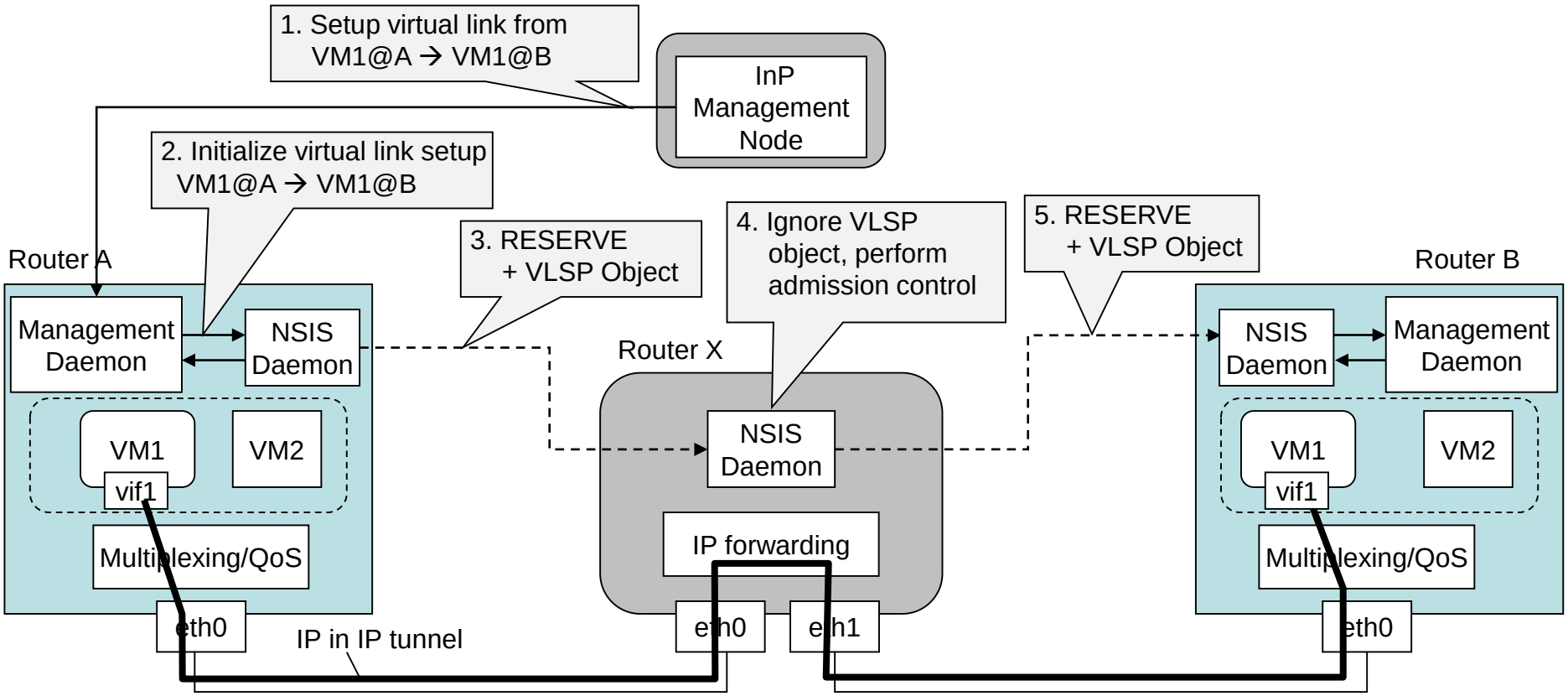

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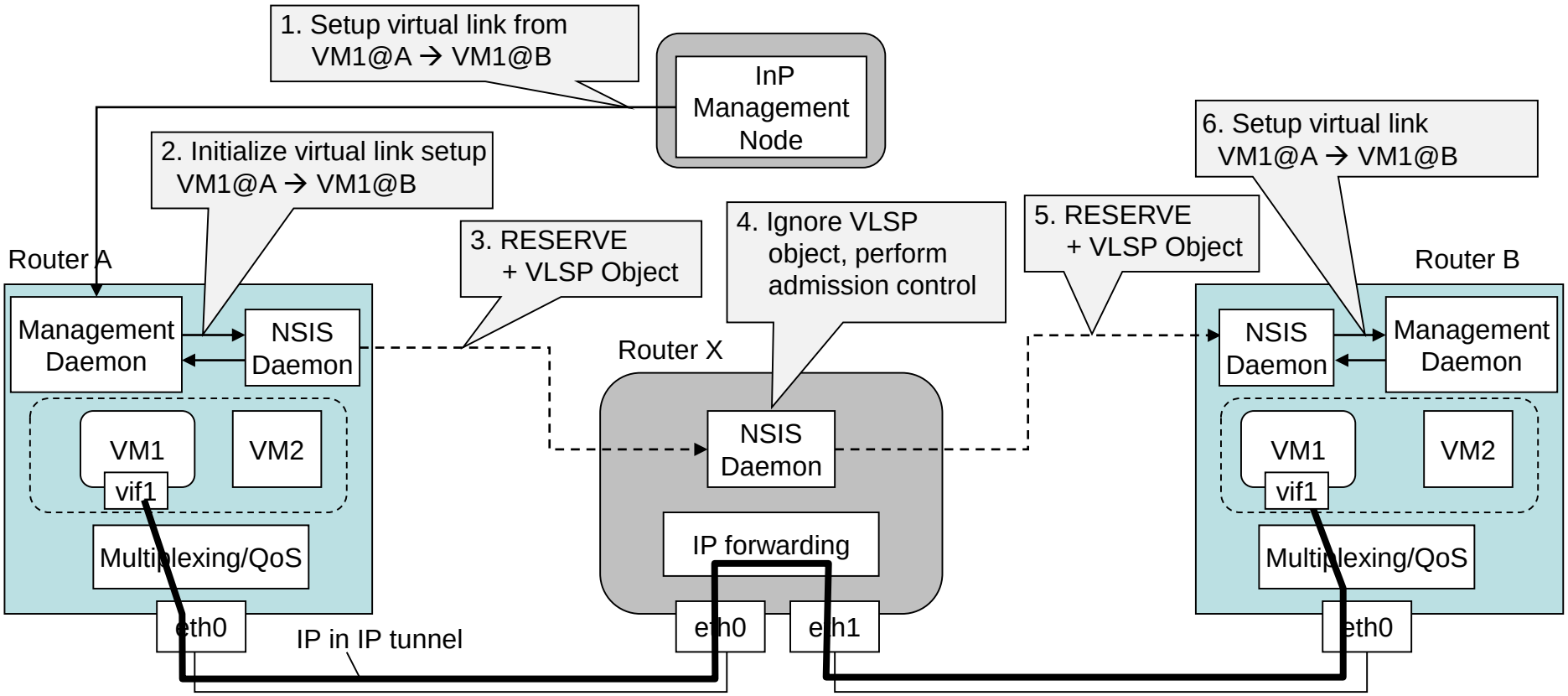

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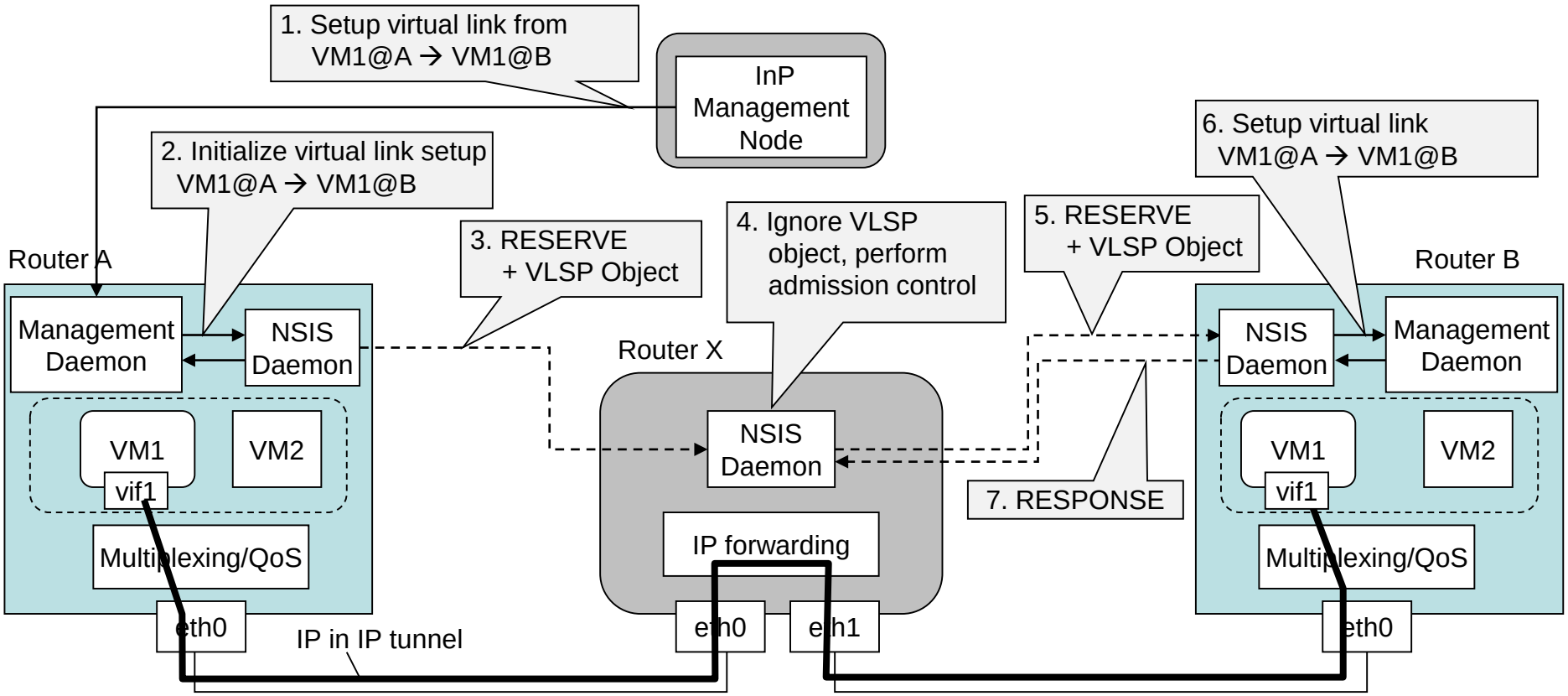

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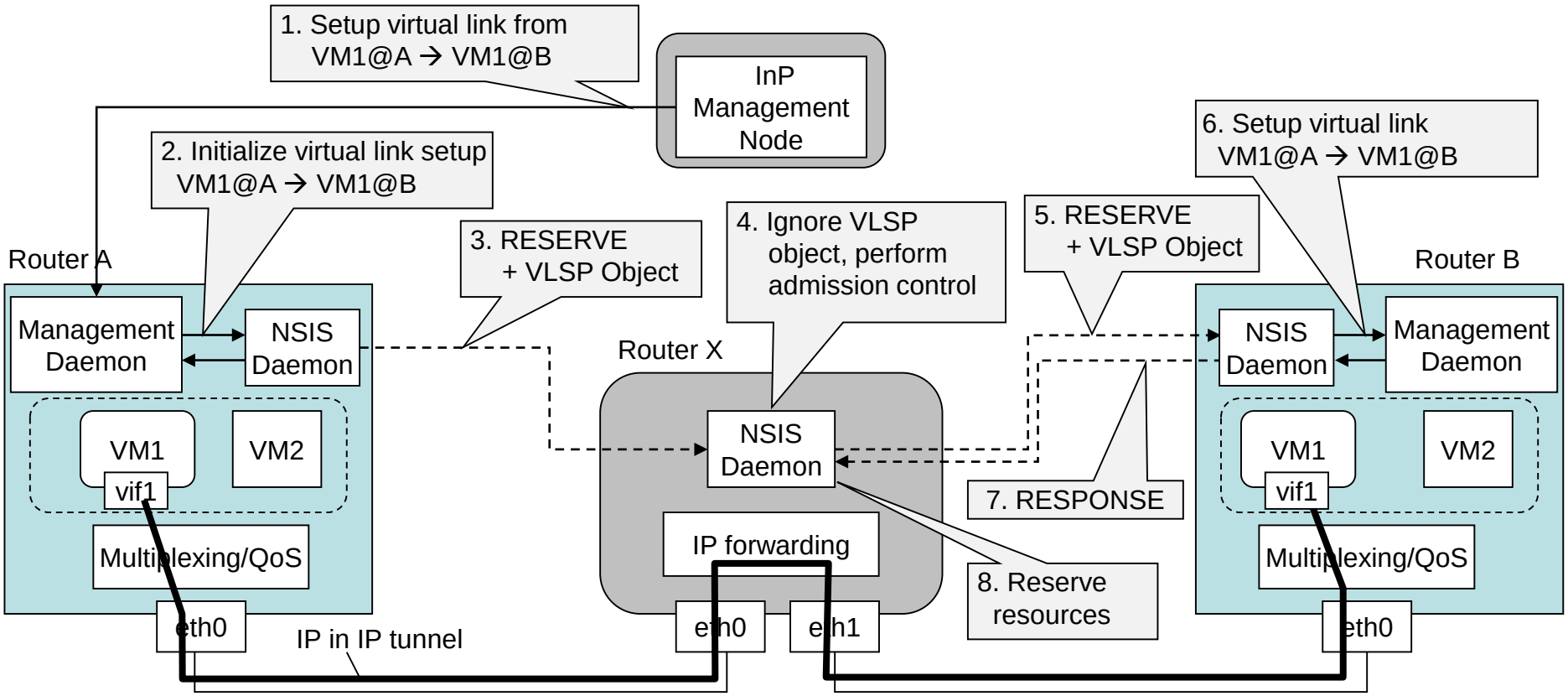

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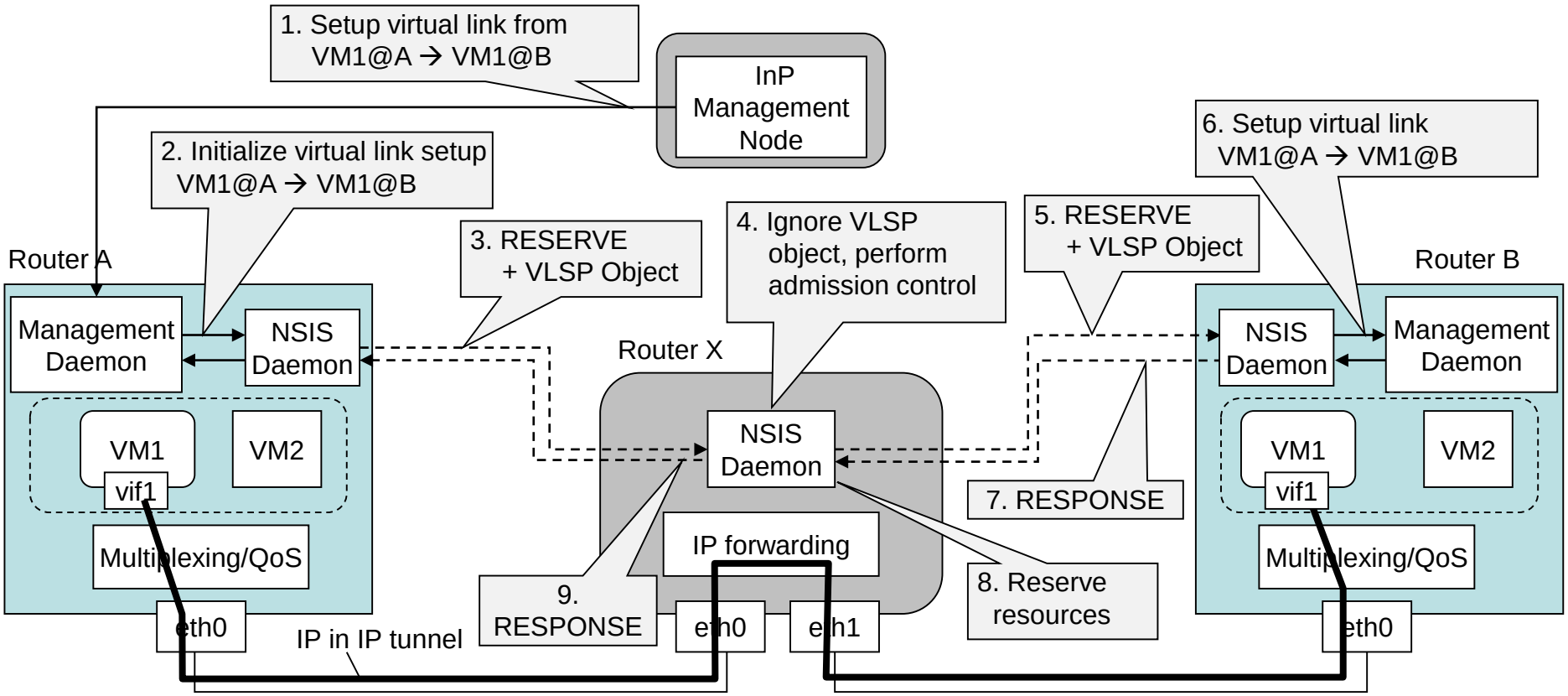
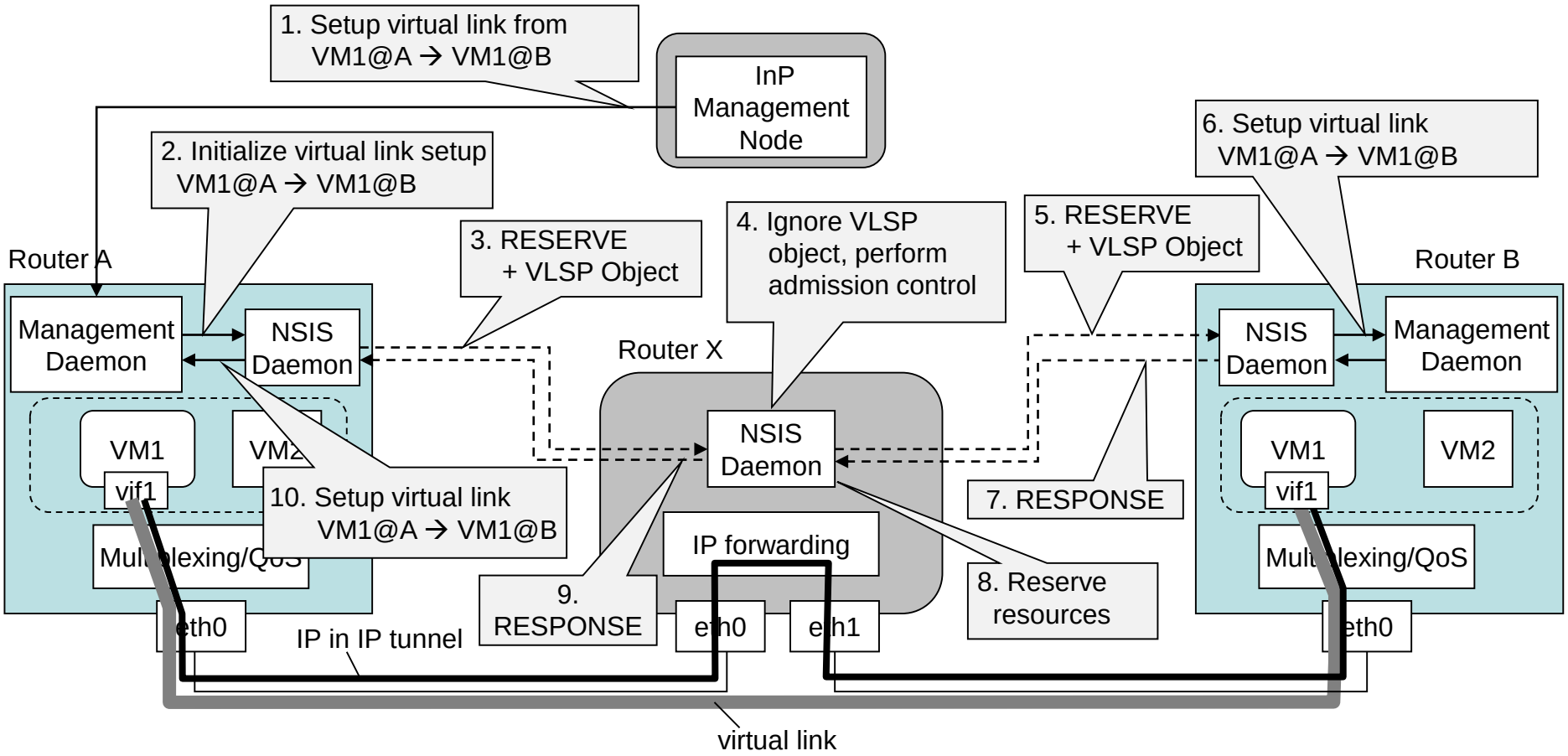


Virtual Link Setup Workflow



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