Introduction to Network Function Virtualization (NFV)

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These slides and audio/video recordings of this class lecture are at:

http://www.cse.wustl.edu/~jain/cse5700-25/

Student Questions

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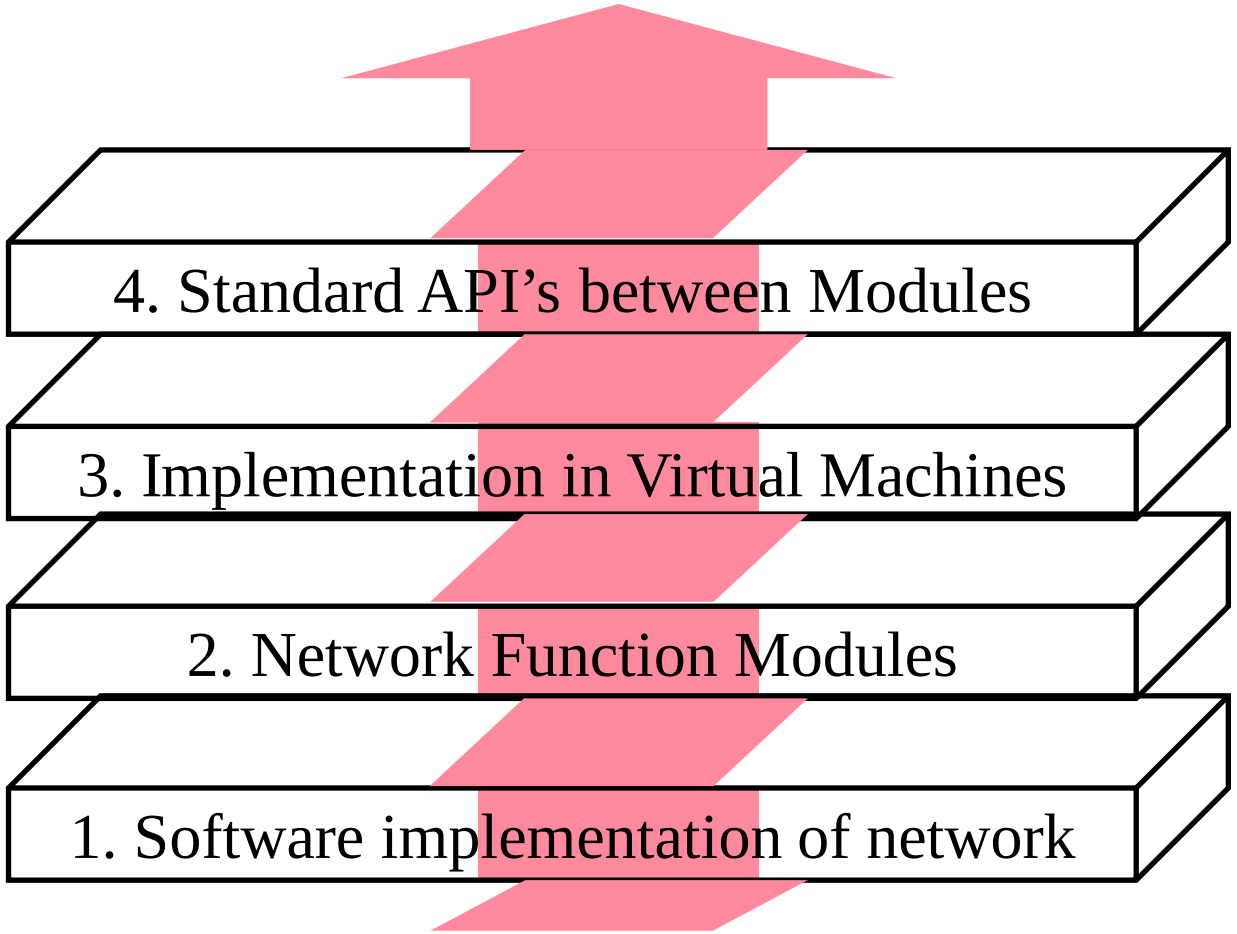
Overview

1. What is NFV?
2. NFV and SDN Relationship
3. ETSI NFV ISG Specifications
4. Concepts, Architecture, Requirements, Use cases
5. Proof of Concepts and Timeline

Note: This module is the 3rd in a series of modules on OpenFlow, SDN, and NFV in this course.

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Four Innovations of NFV

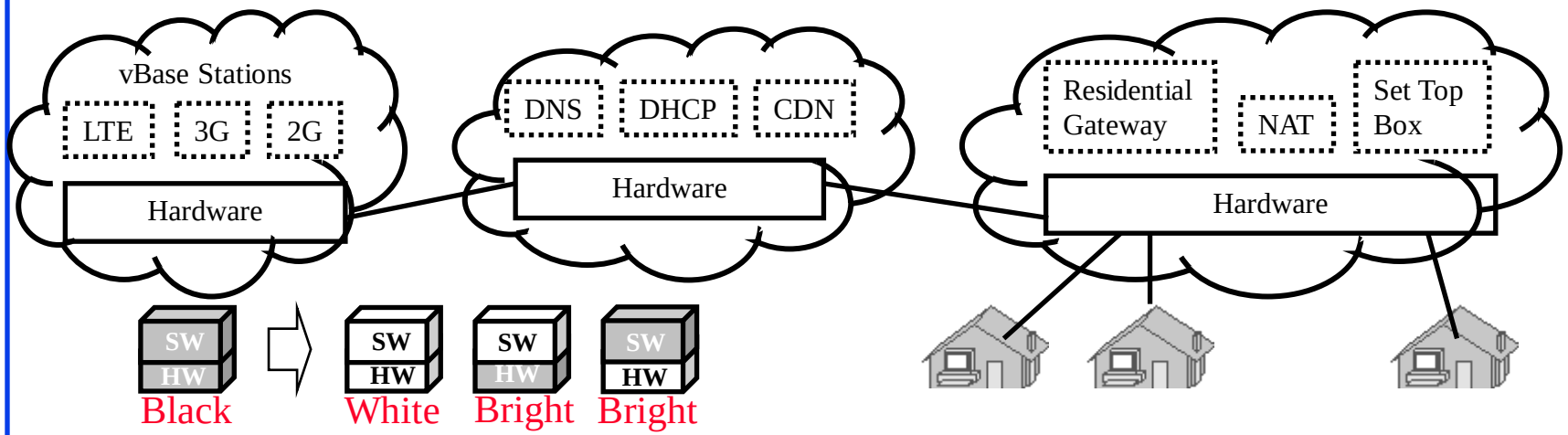


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Network Function Virtualization (NFV)

1. Fast standard hardware ⇒ **Software based devices**
   Routers, Firewalls, Broadband Remote Access Server (BRAS)
   ⇒ A.k.a., *white box* implementation
2. **Function Modules** (Both data plane and control plane)
   ⇒ DHCP (Dynamic Host Control Protocol), NAT (Network Address Translation), Rate Limiting,



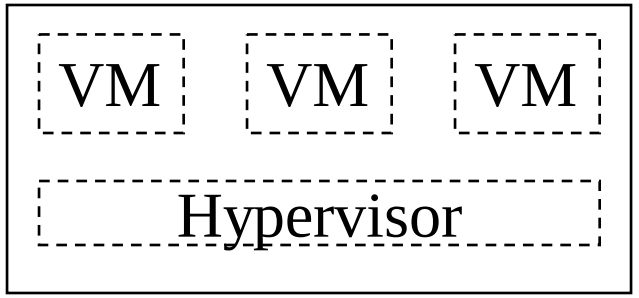
Ref: ETSI, "NFV – Update White Paper V3," Oct 2014, http://portal.etsi.org/NFV/NFV_White_Paper3.pdf (Must read)

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NFV (Cont)

3. **Virtual Machine implementation**
   ⇒ Virtual appliances
   ⇒ All advantages of virtualization (quick provisioning, scalability, mobility, Reduced CapEx, Reduced OpEx, etc.)



Partitioning

4. **Standard APIs**: New ISG (Industry Specification Group) in ETSI (European Telecom Standards Institute) set up in November 2012

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Why do We need NFV?

1. **Virtualization**: Use network resources without worrying about where it is physically located, how much it is, how it is organized, etc.
2. **Orchestration**: Manage thousands of devices
3. **Programmable**: Should be able to change behavior on the fly.
4. **Dynamic Scaling**: Should be able to change the size, quantity
5. **Automation**
6. **Visibility**: Monitor resources, connectivity
7. **Performance**: Optimize network device utilization
8. **Multi-tenancy**
9. **Service Integration**
10. **Openness**: Full choice of Modular plug-ins

Note: These are precisely the same reasons why we need SDN.

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NFV and SDN Relationship

- The concept of NFV originated from SDN
  ⇒ The first ETSI white paper showed an overlapping Venn diagram.
  ⇒ It was removed in the second version of the white paper
- NFV and SDN are complementary.
  One is not strictly dependent upon the other.
  You can do SDN only, NFV only, or SDN and NFV.
- Both have similar goals, but approaches are very different.
- Management/virtualization of large networks becomes easier with SDN
- SDN needs new interfaces, control modules, and applications. NFV requires moving network applications from dedicated hardware to virtual containers on commercial-off-the-shelf (COTS) hardware.
- Multiple flavors of SDN resulted in a debate. Not much debate about NFV.

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Mobile Network Functions

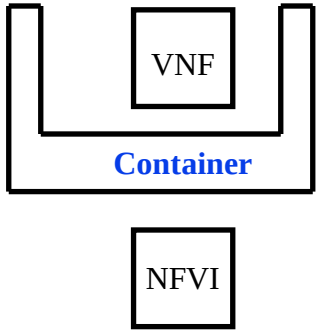
- Switches, e.g., Open vSwitch
- Routers, e.g., Click
- Home Location Register (HLR),
- Serving GPRS Support Node (SGSN),
- Gateway GPRS Support Node (GGSN),
- Combined GPRS Support Node (CGSN),
- Radio Network Controller (RNC),
- Serving Gateway (SGW),
- Packet Data Network Gateway (PGW),
- Residential Gateway (RGW),
- Broadband Remote Access Server (BRAS),
- Carrier Grade Network Address Translator (CGNAT),
- Deep Packet Inspection (DPI),
- Provider Edge (PE) Router,
- Mobility Management Entity (MME),
- Element Management System (EMS)

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VNF

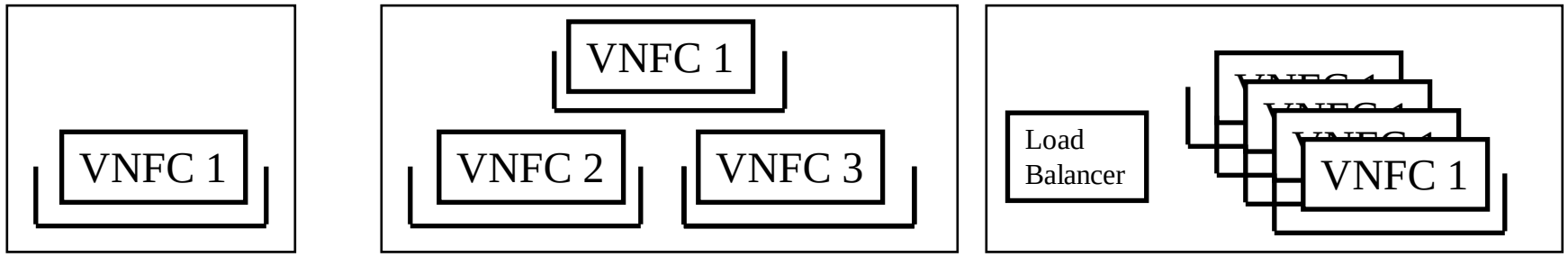
- **NFV Infrastructure (NFVI)**: Hardware and software required to deploy, manage and execute VNFs
- **Network Function (NF):** Functional building block with well-defined interfaces and well-defined functional behavior
- **Virtualized Network Function (VNF)**: Software implementation of NF that can be deployed in a virtualized infrastructure
- **Container**: VNF is independent of NFVI but needs a container software on NFVI to be able to run on different hardware



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NFV Concepts

- **Containers Types**: Related to Computation, Networking, Storage
- **VNF Components (VNFC)**: A VNF may have one or more components
- **VNF Set**: Connectivity between VNFs is not specified, e.g., residential gateways
- **VNF Forwarding Graph**: Service chain when network connectivity order is essential, e.g., firewall, NAT, load balancer



Ref: ETSI, "Architectural Framework," 2015 , https://www.etsi.org/deliver/etsi_gs/NFV/001_099/002/01.02.01_60/gs_NFV002v010201p.pdf

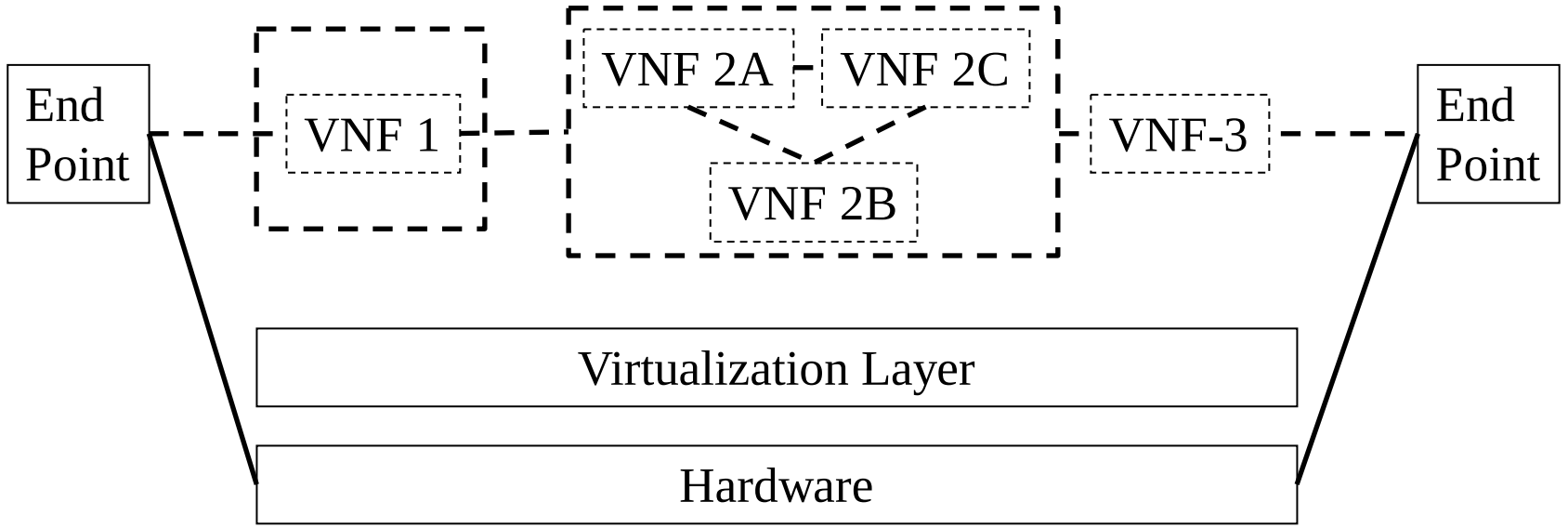
Ref: ETSI, "NFV Terminology for Main Concepts in NFV," 2015, https://www.etsi.org/deliver/etsi_gs/NFV/001_099/003/01.02.01_60/gs_NFV003v010201p.pdf

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Network Forwarding Graph

- An end-to-end service may include nested forwarding graphs



Ref: ETSI, "Architectural Framework," 2015, | https://www.etsi.org/deliver/etsi_gs/NFV/001_099/002/01.02.01_60/gs_NFV002v010201p.pdf

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NFV Concepts (Cont)

- **NFVI Point of Presence (PoP)**: Location of NFVI
- **NFVI-PoP Network**: Internal network
- **Transport Network**: Network connecting a PoP to other PoPs or external networks
- **VNF Manager**: VNF lifecycle management, e.g., instantiation, update, scaling, query, monitoring, fault diagnosis, healing, termination
- **Virtualized Infrastructure Manager**: Management of computing, storage, network, and software resources
- **Network Service**: A composition of network functions defined by its functional and behavioral specification
- **NFV Service**: A network service using NFs with at least one VNF.

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NFV Concepts (Cont)

- **User Service**: Services offered to end users/customers/subscribers.
- **Deployment Behavior**: NFVI resources that a VNF requires, e.g., Number of VMs, memory, disk, images, bandwidth, latency
- **Operational Behavior**: VNF instance topology and lifecycle operations, e.g., start, stop, pause, migration, …
- **VNF Descriptor**: Deployment behavior + Operational behavior
- **NFV Orchestrator**: Automates the deployment, operation, management, and coordination of VNFs and NFVI.
- **VNF Forwarding Graph**: Connection topology of various NFs, of which at least one is a VNF

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NFV Reference Points

Reference Point: Points for inter-module specification

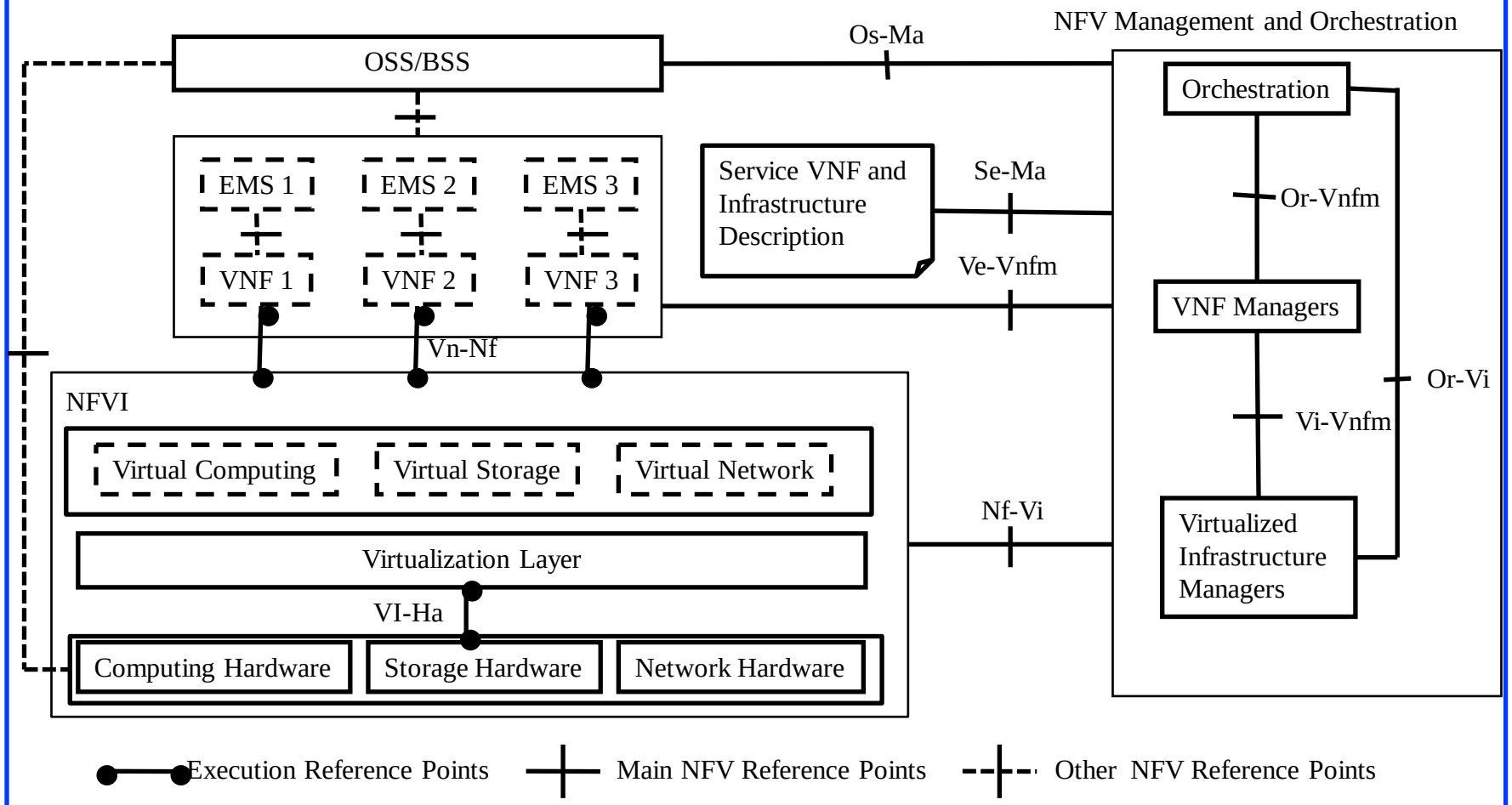
1. Virtualization Layer-Hardware Resources (**VI-Ha**)
2. VNF – NFVI (**Vn-Nf**)
3. Orchestrator – VNF Manager (**Or-Vnfm**)
4. Virtualized Infrastructure Manager – VNF Manager (**Vi-Vnfm**)
5. Orchestrator – Virtualized Infrastructure Manager (**Or-Vi**)
6. NFVI-Virtualized Infrastructure Manager (**Nf-Vi**)
7. Operation Support System (OSS)/Business Support Systems (BSS) – NFV Management and Orchestration (**Os-Ma**)
8. VNF/ Element Management System (EMS) – VNF Manager (**Ve-Vnfm**)
9. Service, VNF, and Infrastructure Description – NFV Management and Orchestration (**Se-Ma**): VNF Deployment template, VNF Forwarding Graph, service-related information, NFV infrastructure information

Ref: ETSI, "Architectural Framework," 2015, https://www.etsi.org/deliver/etsi_gs/NFV/001_099/002/01.02.01_60/gs_NFV002v010201p.pdf

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NFV Architecture



Ref: ETSI, "Architectural Framework," 2015, https://www.etsi.org/deliver/etsi_gs/NFV/001_099/002/01.02.01_60/gs_NFV002v010201p.pdf

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1. Virtualization Layer-Hardware Resources (**VI-Ha**)
2. VNF – NFVI (**Vn-Nf**)
3. Orchestrator – VNF Manager (**Or-Vnfm**)
4. Virtualized Infrastructure Manager – VNF Manager (**Vi-Vnfm**)
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NFV Framework Requirements

1. **General**: Partial or complete Virtualization, Predictable performance
2. **Portability**: Decoupled from the underlying infrastructure
3. **Performance**: as described and facilities to monitor
4. **Elasticity**: Scalable to meet SLAs. Movable to other servers.
5. **Resiliency**: Be able to recreate after failure.
   Specified packet loss rate, calls drops, time to recover, etc.
6. **Security**: Role-based authorization, authentication
7. **Service Continuity**: Seamless or non-seamless continuity after failures or migration

Ref: ETSI, "NFV Virtualization Requirements,", 2015, https://www.etsi.org/deliver/etsi_gs/NFV/001_099/004/01.01.01_60/gs_NFV004v010101p.pdf

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NFV Framework Requirements (Cont)

8. **Service Assurance:** Timestamp and forward copies of packets for Fault detection
9. **Energy Efficiency Requirements**: It should be possible to put a subset of VNF in a power-conserving sleep state
10. **Transition:** Coexistence with Legacy and Interoperability among multi-vendor implementations
11. **Service Models**: Operators may use NFV infrastructure operated by other operators

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NFV Use Cases

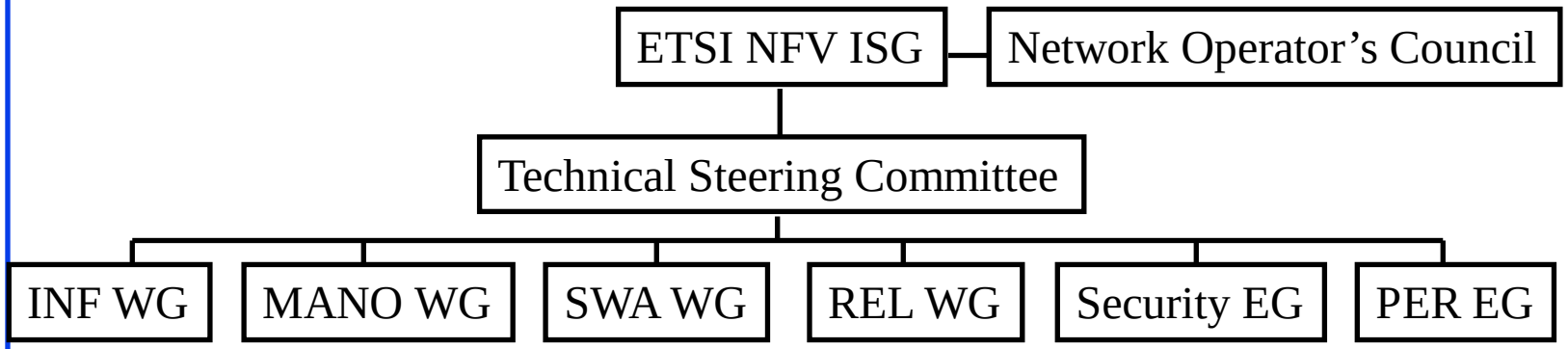
- **Home Environment:** Virtualization of the Home environment
- **CDNS:** Virtualization of Content Distribution Networks
- **Fixed Access Network:** Fixed Access NFV
- **NFVIaaS:** NFVI as a service like IaaS
- **VNFaaS:** VNFs as a service like SaaS
- **VNPaaS:** Virtual Network Platform as a Service like PaaS
- **VNF Forwarding Graph:** VNF forwarding graphs (Service Chains)
- **Mobile Core and IMS:** Virtualization of the Mobile Core Network and IP Multimedia System
- **Mobile Base Station:** Virtualization of Mobile Base Station

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Ref: ETSI, "NFV Use Cases," https://www.etsi.org/deliver/etsi_gs/NFV/001_099/001/01.01.01_60/gs_NFV001v010101p.pdf

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ETSI NFV ISG



- The Industry Specification Group (ISG) aims to define the requirements.
- Four Working Groups:
  - **INF**: Architecture for the Virtualization Infrastructure
  - **MANO**: Management and orchestration
  - **SWA**: Software architecture
  - **REL**: Reliability and Availability, resilience and fault tolerance

Ref: M. Cohn, "NFV, An Insider's Perspective: Part 1: Goals, History, and Promise," Sep 2013, http://www.sdncentral.com/education/nfv-insiders-perspective-part-1-goals-history-promise/2013/09/

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ETSI NFV ISG (Cont)

- Two Expert Groups:
  - **Security** Expert Group: Security
  - **Performance and Portability** Expert Group: Scalability, efficiency, and performance VNFs relative to current dedicated hardware

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ETSI NFV Release 2.0

- 2015-2012. INF, SWA disbanded. Several new groups.
- IFA: Interfaces and Architecture
  - Fault, performance, and lifecycle management of virtualized resources, VNFs, and network services
  - Package and software image management
  - Capacity management, Policy Management
  - Information models
- REL: Reliability and Availability, resilience and fault tolerance
- SEC: Security analysis and management
- EVE: Evolution and Ecosystem working group
  - Charging, Billing, Accounting, License Management
- TST: Testing, DevOps, Continuous Integration

Ref: https://www.etsi.org/technologies-clusters/technologies/689-network-functions-virtualisation

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ETSI NFV Release 3

- 2017-2018
- IFA, EVE, REL, SEC, and TST continue

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NFV Proof of Concepts (PoCs)

ETSI has formed and NFV ISG PoC Forum.

The following modules have been demoed:

1. Virtual Broadband Remote Access Server (BRAS) by British Telecom
2. Virtual IP Multimedia System (IMS) by Deutsche Telekom
3. Virtual Evolved Packet Core (vEPC) by Orange Silicon Valley
4. Carrier-Grade Network Address Translator (CGNAT) and Deep Packet Inspection (DPI), Home Gateway by Telefonica
5. Perimeta Session Border Controller (SBC) from Metaswitch
6. Deep packet inspection from Procera

Most of these are based on Cloud technologies, e.g., OpenStack

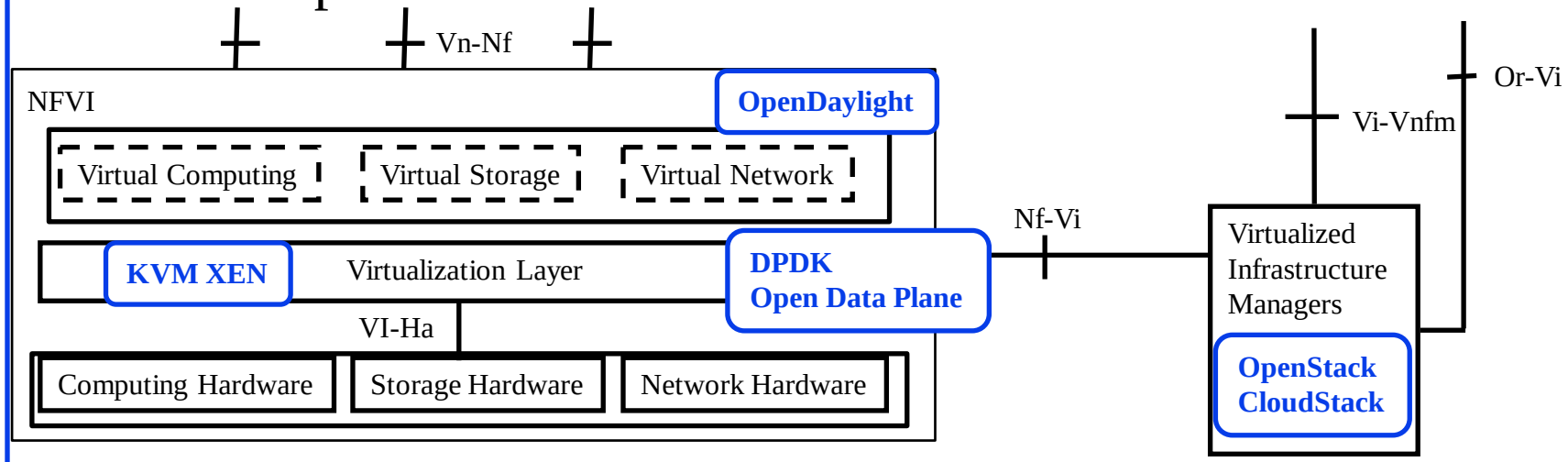
Ref: M. Cohn, "NFV Group Flocks to Proof-of-Concept Demos," Aug 2013, http://www.sdncentral.com/technology/nfv-group-flocks-to-proof-of-concept-models/2013/08/

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OPNFV

- Open Source NFV implementation project under Linux Foundation (Similar to OpenDaylight)
- Founded September 2014
- The initial goal is to integrate KVM, OpenStack, and OpenDaylight
- The integrated project will be run through software testing labs at service providers



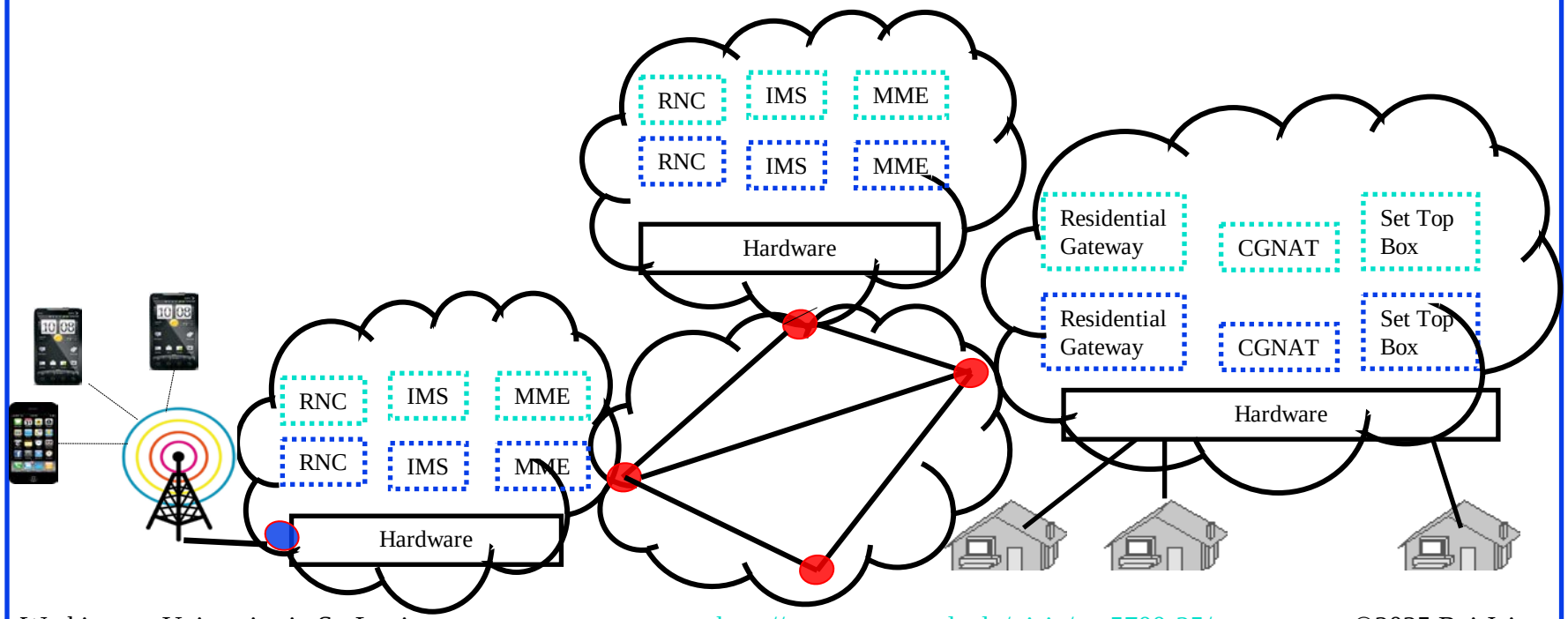
Ref: K. Gray and T. Dadeau, "Network Function Virtualization," Morgan Kaufmann, July 2016, 270 pp., ISBN:0128021195

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Service Chaining in a Multi-Cloud Multi-Tenant Environment

- VNFs (Virtual network functions) belong to tenants. Multiple tenants.
- Each Cloud belongs to a different Cloud Service Provider (CSP)
- Internet infrastructure belongs to an NFVI service provider (NSP)
- Service chain = Workflow



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Challenges in Service Chaining

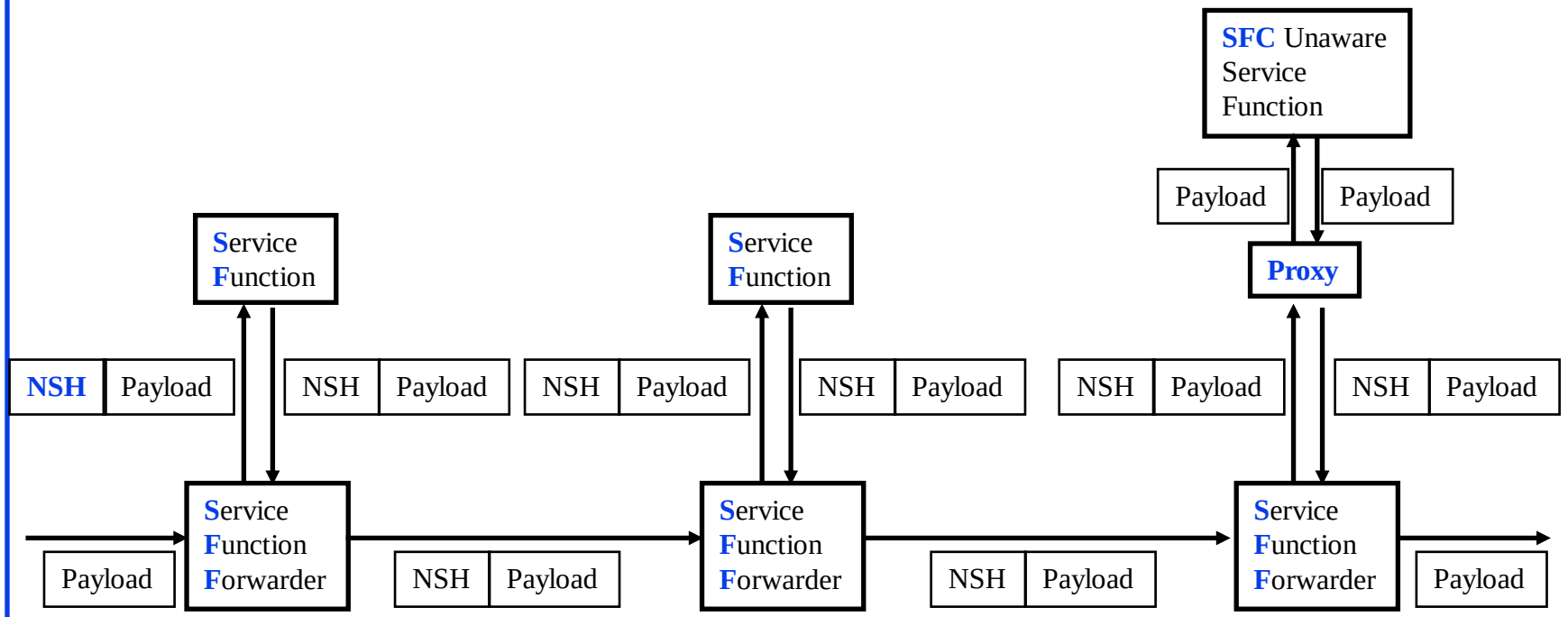
- **Dynamic**:
  - Forwarding changes with the state of the servers, links, …
  - Independent of the physical topology
- **Content sensitive**:
  - Different for different types of videos, read-writes, …
- **Distributed Control**:
  - The equipment belongs to the infrastructure provider
  - Data belongs to Tenants
- **Massive Scale**:
  - Billions of users with different user contexts
- **Stateful Services**:
  - All packets of a flow should be sent to the same replica
    - Message level services (firewalls),
    - Packet-level services (intrusion detection)

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End of Part 1

Service Function Chaining Terminology

- Defined by IETF SFC Working group
- **Service**: E.g., Video streaming. Consists of several functions.
- **Service Function**: E.g., Firewall, Compression, Video Translation



Ref: RFC 7498, "Problem Statement for Service Function Chaining," Nov. 2015, https://www.rfc-editor.org/rfc/pdfrfc/rfc7498.txt.pdf

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SFC Terminology (Cont)

- **Service Function Chain**: A forwarding graph
- A service function may have more than one instance.
- The number and location of instances change with time
- All packets of a flow should be forwarded to the same instance
- **Service Function Path (SFP):** A sequence of service functions for a particular service
- **Network Service Header (NSH):** Added to forward packets dynamically to correct instances of the service function
- **Service Function Forwarder (SFF):** Forwards the packets to the correct instance using NSH. May add/delete NSH if needed.
- **Proxy:** Helps use legacy functions. Removes/Adds NSH header before sending the packet to SFC unaware functions.

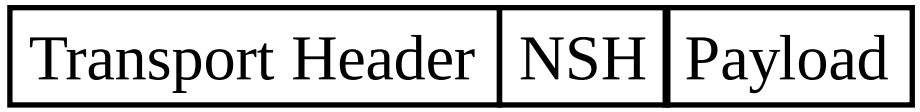
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Ref: RFC 7665, "Service Function Chaining (SFC) Architecture," Nov. 2015, https://www.rfc-editor.org/rfc/pdfrfc/rfc7665.txt.pdf

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SFC Terminology (Cont)

- Transport: Between the SFFs, SFs, and Proxies. E.g., Ethernet, GRE, VXLAN, TCP, …
- NSH encapsulated packet is sent to the next SFC element using the transport header.

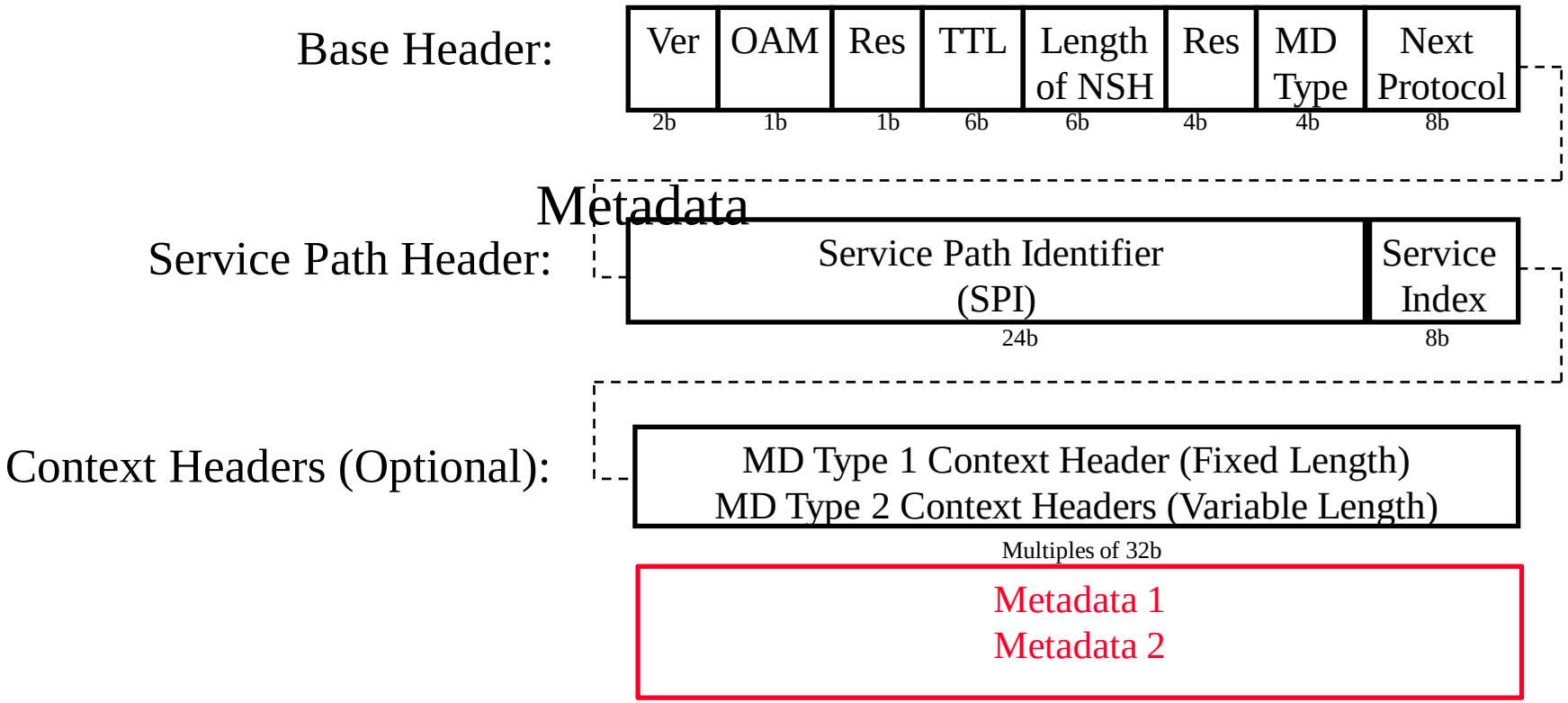


- **Metadata:** Data passed between SFC elements. Part of the NSH
- **Service Path Identifier (SPI):** A service function path may have many instances. Each instance has an SPI.
- **Service Index**: Each function on the SFP has a service index.

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Network Service Header

- It consists of a "*base header*," "*service path header*," and zero or more "*context headers*."



Ref: RFC 8300, "Network Service Header (NSH)," July 2017, https://www.rfc-editor.org/rfc/pdfrfc/rfc8300.txt.pdf

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NSH (Cont)

- TTL: # of SFC hops to live
- Length: Total length of NSH header including base, service path, and context headers in bytes
- MD Type: Type of the metadata (context header)
  1 = Fixed length
  2 = Variable length

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SPRING

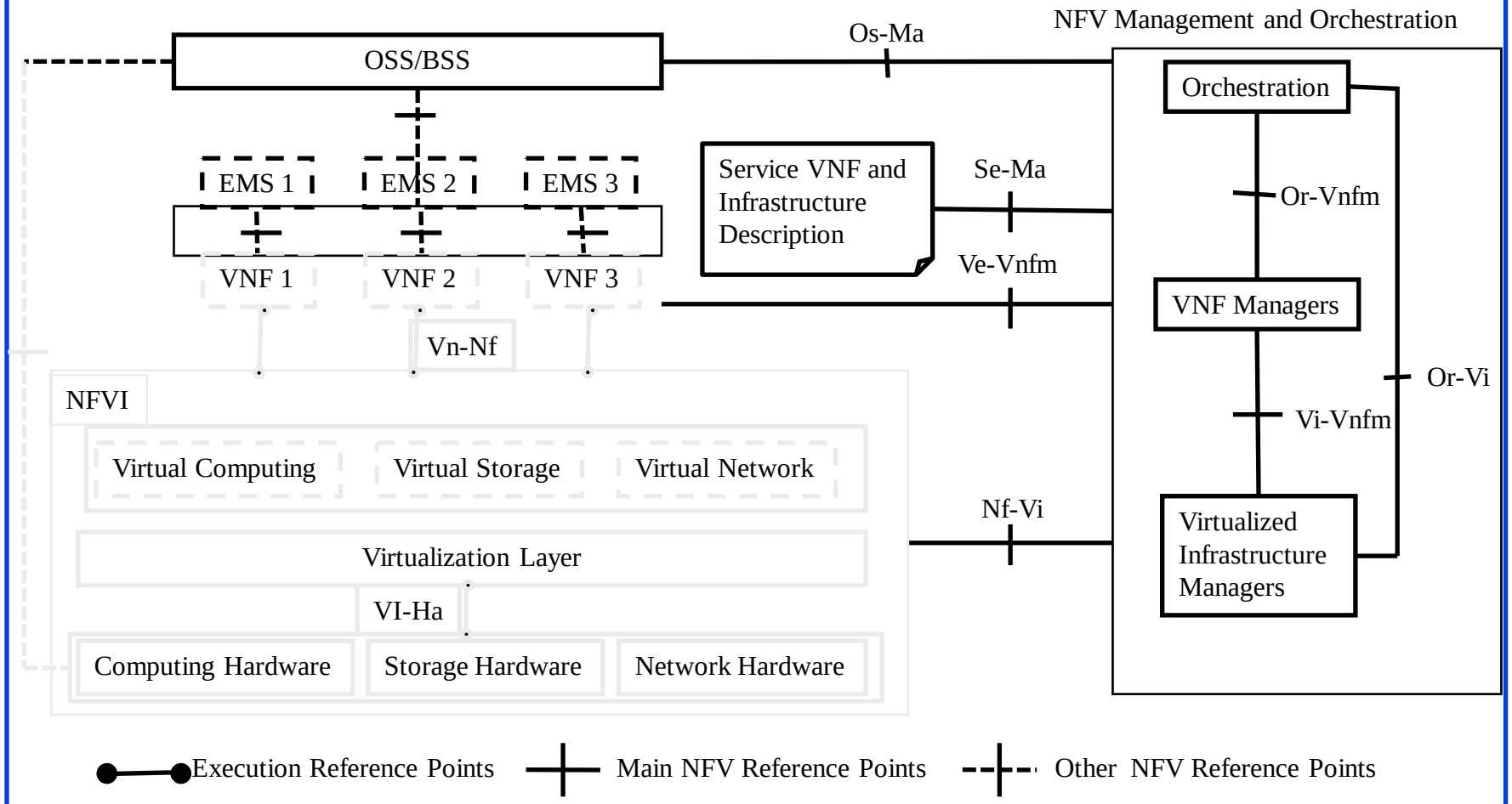
- **S**ource **P**acket **R**outing **i**n **N**etworkin**g** – An IETF working group
- NSH requires maintaining state in all SFFs
- Source routing is an alternative in which no state is maintained in the intermediate nodes. The packet header contains the route.
- Source routing is limited to IP addresses
- Segment Routing = Generalization of source routing
  - MPLS Label = Segment
  - IP address = Segment
- Differentiate between elephant storage flows and mice compute flows
- Although the SPRING working group is not for NFV, Segment routing can be used for Service Function Chaining.

Ref: Source packet Routing in Networking (spring), https://datatracker.ietf.org/wg/spring/about/

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Management and Orchestration (MANO)



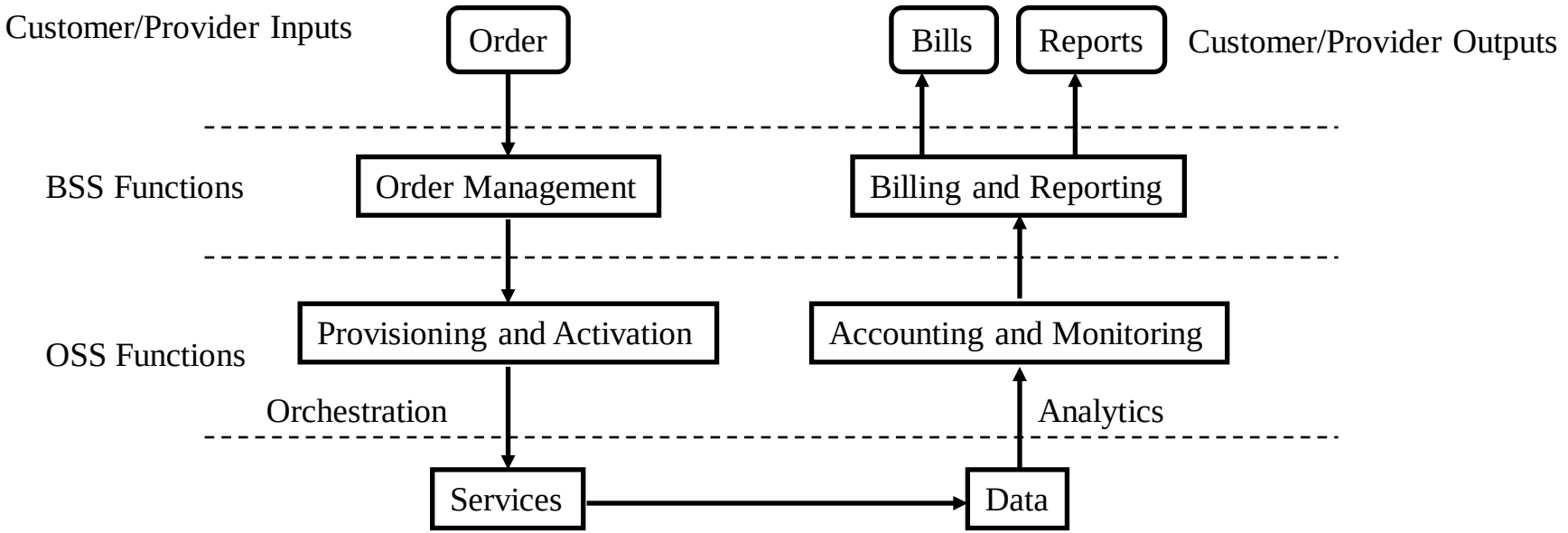
Ref: ETSI, "Architectural Framework," 2015, https://www.etsi.org/deliver/etsi_gs/NFV/001_099/002/01.02.01_60/gs_NFV002v010201p.pdf

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MANO (Cont)

- Operation Support System (OSS)
- Business Support System (BSS)
- Element Management System, VNF Management, Infrastructure Management, Orchestration



Ref: Ken Gray and Thomas Nadeau, "Network Function Virtualization," Morgan Kaufmann, July 2016, 238 pp., ISBN: 978-0-12-802119-4, (Safari Book)

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NGOSS

- Next-Generation OSS
- Service providers have many different OSSs
  Mostly using polling/event monitoring.
  All proprietary and often incompatible ⇒ High OpEx
- Next-Generation OSS (NGOSS) is being discussed in the TeleManagement Forum (TM Forum)
- Enhanced Telecom Operations Map (eTOM): Common language for service providers to describe business processes
- Shared Information/Data Model (SID): Common language for vendors to describe management information
- Technology Neutral Architecture (TNA) and Contract Interface
- NGOSS Compliance: A Suite of tests

Ref: "NGOSS (New Generation Operations Systems and Software)," http://dpnm.postech.ac.kr/NGOSS/NGOSS.html

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Open Source MANO Implementations

- **Open-O**: Linux Foundation project for open orchestration
- **ECOMP**: Linux Foundation project for Enhanced Control, Orchestration, Management, and Policy (Led by AT&T)
- **ONAP**: Open Network Automation Platform
  Open-O and ECOMP merged at the Linux Foundation
- **TACKER**: OpenStack project for NFV orchestration
- **Open Source MANO (OSM):** ETSI effort started by Telefonica in 2015
- **Open Baton**: Closely follows ETSI MANO
- Most of these use TOSCA templates

Ref: https://wiki.open-o.org/, https://about.att.com/content/dam/snrdocs/ecomp.pdf, https://www.onap.org/, https://wiki.openstack.org/wiki/Tacker, https://www.etsi.org/technologies-clusters/technologies/nfv/open-source-mano, https://openbaton.github.io/

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TOSCA

- Topology and Orchestration Specification for Cloud Applications
- TOSCA template for an application describes the resources required to run the application on a cloud
- Resources can be computing, network, storage, databases, etc.
- TOSCA template includes a graph modeling the relationships between various components and operations on them
- Orchestration engines can use the TOSCA template to create an application instance. Resources required are also created in the correct order. For example, a database will be created before the program needs it.

Ref: OASIS, "TOSCA Simple Profile in YAML Version 1.1," Jan 2018, 282 pp., http://docs.oasis-open.org/tosca/TOSCA-Simple-Profile-YAML/v1.1/os/TOSCA-Simple-Profile-YAML-v1.1-os.pdf

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NFV Status

- Release 5.2.1, May 2025
- Enhanced container networking for better orchestration and performance.
- Support for 5G-specific NFV use cases
- VNF configuration enhancements to streamline deployment and lifecycle management.
- Green NFV initiatives aimed at energy efficiency and sustainability.
- Advanced Telco Cloud Data Analytics
- Release 6 has started.

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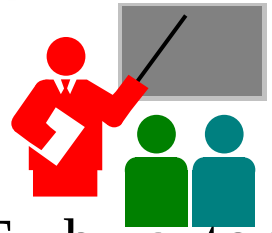
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Any Function Virtualization (FV)

- Network function virtualization of interest to Network service providers
- But the same concept can be used by any other industry, e.g., the financial industry, banks, stock brokers, retailers, and mobile games…
- Everyone can benefit from:
  - Functional decomposition of their industry
  - Virtualization of those functions
  - Service chaining those virtual functions (VFs)
    ⇒ A service provided by the next-gen ISPs

Student Questions

Summary



1. NFV aims to reduce OpEx by automation and scalability provided by implementing network functions as virtual appliances
2. NFV allows all virtualization and cloud computing benefits, including orchestration, scaling, automation, hardware independence, pay-per-use, and fault tolerance…
3. NFV and SDN are independent and complementary. You can do either or both.
4. NFV requires standardization of reference points and interfaces to be able to mix and match VNFs from different sources
5. NFV can be done now. Carriers have already demonstrated several virtual functions.

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Reading List

- Ken Gray and Thomas Nadeau, “Network Function Virtualization,” Morgan Kaufmann, July 2016, 238 pp., ISBN: 978-0-12-802119-4, (Safari Book) – **Recommended Reading**
- Jim Doherty, "SDN and NFV Simplified: A Visual Guide to Understanding Software Defined Networks and Network Function Virtualization," Addison-Wesley Professional, March 2, 2016, 320 pp., ISBN:978-0-13-430739-8 (Safari Book).
- Ying Zhang, "Network Function Virtualization," Wiley-IEEE Press, January 2018, 192 pp., ISBN:978-1-119-39060-2 (Safari Book).
- Rajendra Chayapathi, Syed Farrukh Hassan, Paresh Shah, "Network Functions Virtualization (NFV) with a Touch of SDN," Addison-Wesley Professional, November 2016, 368 pp., ISBN:978-0-13-446431-2 (Safari Book).
- Russ White, Jeff Tantsura, "Navigating Network Complexity: Next-generation Routing with SDN, Service Virtualization, and Service Chaining," Addison-Wesley Professional, November 2015, 320 pp., ISBN:0-13-398792-2 (Safari Book).

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- ETSI, “White Paper on NFV priorities for 5G,” Feb 2017, 15 pp., http://portal.etsi.org/NFV/NFV_White_Paper_5G.pdf
- ETSI, "NFV Terminology for Main Concepts in NFV," 2015, https://www.etsi.org/deliver/etsi_gs/NFV/001_099/003/01.02.01_60/gs_NFV003v010201p.pdf
- ETSI Specifications, see the public download directory at https://docbox.etsi.org/ISG/NFV/Open/Publications_pdf/Specs-Reports

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Acronyms

- API Application Programming Interface
- BRAS Broadband Remote Access Server
- BSS Business Support Systems
- CapEx Capital Expenditure
- CDN Content Distribution Network
- CGNAT Carrier-Grade Network Address Translator
- CGSN Combined GPRS Support Node
- COTS Commercial-off-the-shelf
- DDIO Data Direct I/O Technology
- DHCP Dynamic Host Control Protocol
- DPI Deep Packet Inspection
- EMS Element Management System
- ETSI European Telecom Standards Institute
- GGSN Gateway GPRS Support Node
- GPRS General Packet Radio Service
- HLR Home Location Register
- IaaS Infrastructure as a Service

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Acronyms (Cont)

IETF	Internet Engineering Task Force
IMS	IP Multimedia System
INF	Architecture for the Virtualization Infrastructure
IP	Internet Protocol
ISG	Industry Specification Group
LSP	Label Switched Path
MANO	Management and orchestration
MME	Mobility Management Entity
NAT	Network Address Translation
NF	Network Function
NFV	Network Function Virtualization
NFVI	Network Function Virtualization Infrastructure
NFVIaaS	NFVI as a Service
NIC	Network Interface Card
OpEx	Operational Expenses
OS	Operating System

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Acronyms (Cont)

- OSS Operation Support System
- PaaS Platform as a Service
- PE Provider Edge
- PGW Packet Data Network Gateway
- PoC Proof-of-Concept
- PoP Point of Presence
- PSTN Public Switched Telephone Network
- QoS Quality of Service
- REL Reliability, Availability, resilience, and fault tolerance group
- RGW Residential Gateway
- RNC Radio Network Controller
- SaaS Software as a Service
- SBC Session Border Controller
- SDN Software Defined Networking
- SGSN Serving GPRS Support Node
- SGW Serving Gateway

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Acronyms (Cont)

SIP	Session Initiation Protocol
SLA	Service Level Agreement
SWA	Software architecture
TAS	Telephony Application Server
TMF	TM Forum
vEPC	Virtual Evolved Packet Core
VM	Virtual Machine
VNF	Virtual Network Function
VNFaaS	VNF as a Service
vSwitch	Virtual Switch
VT-d	Virtualization Technology for Direct IO
VT-x	Virtualization Technology

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CSE567M: Computer Systems Analysis (Spring 2013),
https://www.youtube.com/playlist?list=PLjGG94etKypJEKjNAa1n_1X0bWWNyZcof

CSE473S: Introduction to Computer Networks (Fall 2011),



https://www.youtube.com/playlist?list=PLjGG94etKypJWOSPMh8Azcgy5e_10TiDw



Wireless and Mobile Networking (Spring 2016),
https://www.youtube.com/playlist?list=PLjGG94etKypKeb0nzyN9tSs_HCd5c4wXF

CSE571S: Network Security (Fall 2011),



https://www.youtube.com/playlist?list=PLjGG94etKypKvzfVtutHcPFJXumyyg93u



Video Podcasts of Prof. Raj Jain's Lectures,
https://www.youtube.com/channel/UCN4-5wzNP9-ruOzQMs-8NUw

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