

Network Function Virtualization and (Some) Cloud Applications

Gabriel Scalosub

Borrowed extensively from:

Elisha Rozensweig, Erez Biton

and various other papers/resources (see list at the end)

Outline

- Network Function Virtualization (NFV)
- Additional Cloud Technologies & Applications
 - Examples

...-as-a-Service

- Infrastructure, Platform, Software, ...
- Network-as-a-service
 - Composed of one (or more) network functions
 - Service function chains
- Traditionally
 - Functions / services implemented by dedicated middleware on the flow path
- Network Function Virtualization (NFV)
 - Implement functions / services on COTS* servers in the datacenter
 - Data plane / control plane
 - Drive traffic to servers to provide service
 - Virtual Network Functions (VNFs)

Requirement: VNF Chain

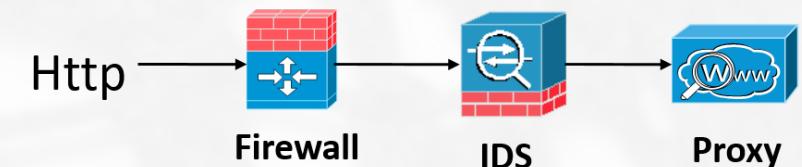


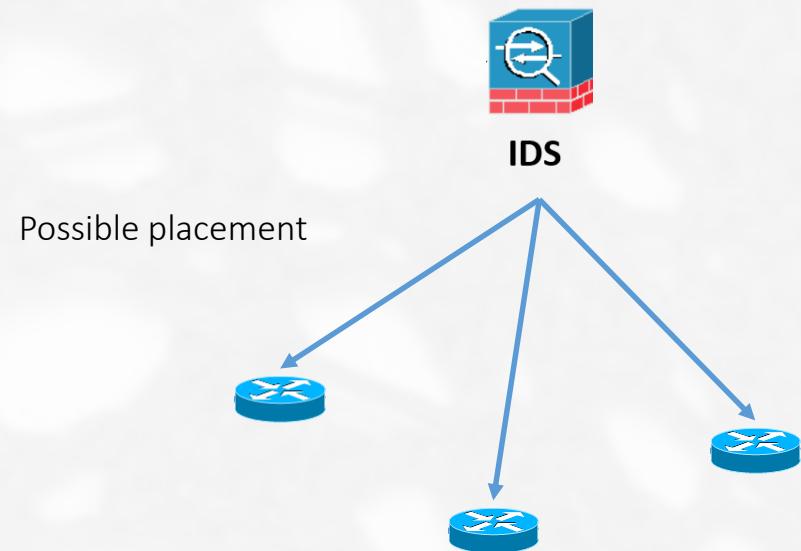
Image: Li & Qian (2016)

* COTS: Commercial off-the-shelf

Reminder*: Where to Place VNFs?

- Beyond “simple” VM placement
- Simple VNF
 - Single location, “in isolation”
 - E.g., choosing where to place an IDS

Requirement: Single VNF



* Lecture 4...

Reminder*: Where to Place VNFs?

- Beyond “simple” VM placement
- Simple VNF
 - Single location, “in isolation”
 - E.g., choosing where to place an IDS
- VNF chaining
 - Logical traffic steering
 - Implemented by actual placement
 - And forwarding rules... (SDN)
- Concretization of Network Function Virtualization (NFV)
 - \neq SDN

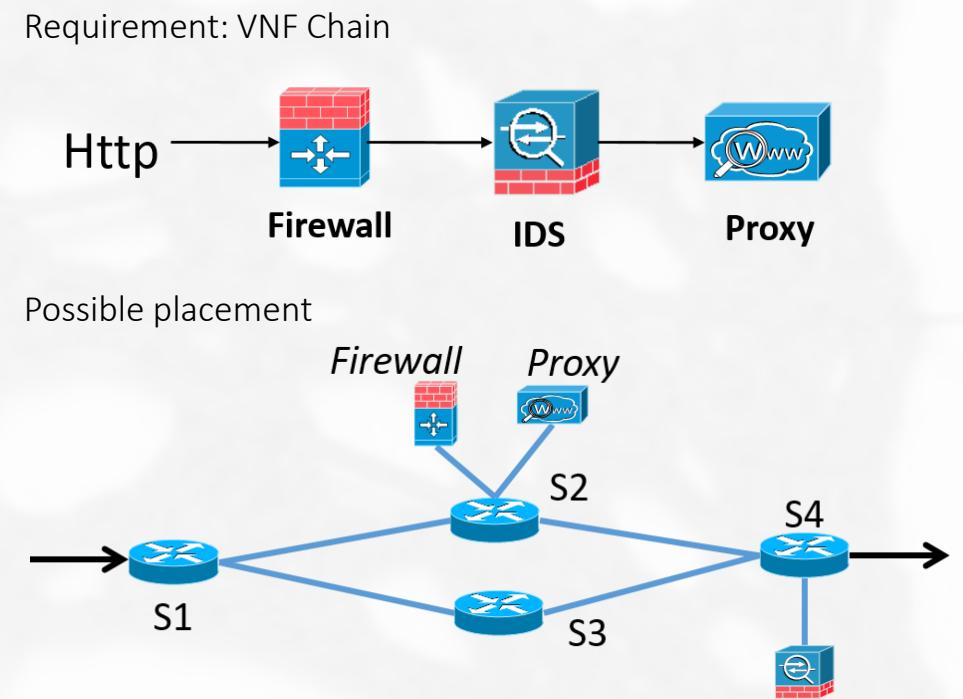


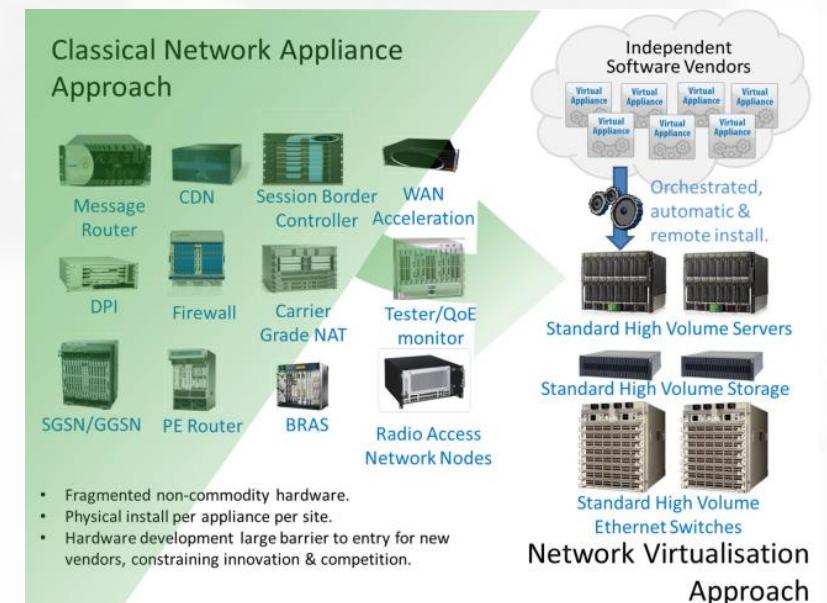
Image: Li & Qian (2016)

* Lecture 4...

Network Function Virtualization (NFV)

- How network technology evolves
 - Very slow innovation in the network
 - New service -> wait for new “box” (middleware) -> slow deployment (if any)
 - Middleware: HW-SW bundling
 - Lots of boxes, very costly experimentation (hence almost none...)
 - High-end HW required
- Requirement:
 - Decouple HW from SW
 - “Write once, run anywhere”
 - Support migration, scaling (in/out), ...
- Sounds familiar? Virtualization? Cloud?

Image: Chiosi et al (2012)



A Network Oriented Cloud

- Building efficient, secure, and reliable cloud for distributed and interconnected applications
 - Existing clouds are seldom used
 - E.g., ISPs will not be hosting their DNS on public clouds
 - Build various “private” clouds/DCs for internal networking usage
 - Reduced costs (virtualization), scaling, ...
 - Distributed clouds...
 - A lot of unanswered questions
 - Conforming with SLAs
 - Automated network configuration
 - Location....

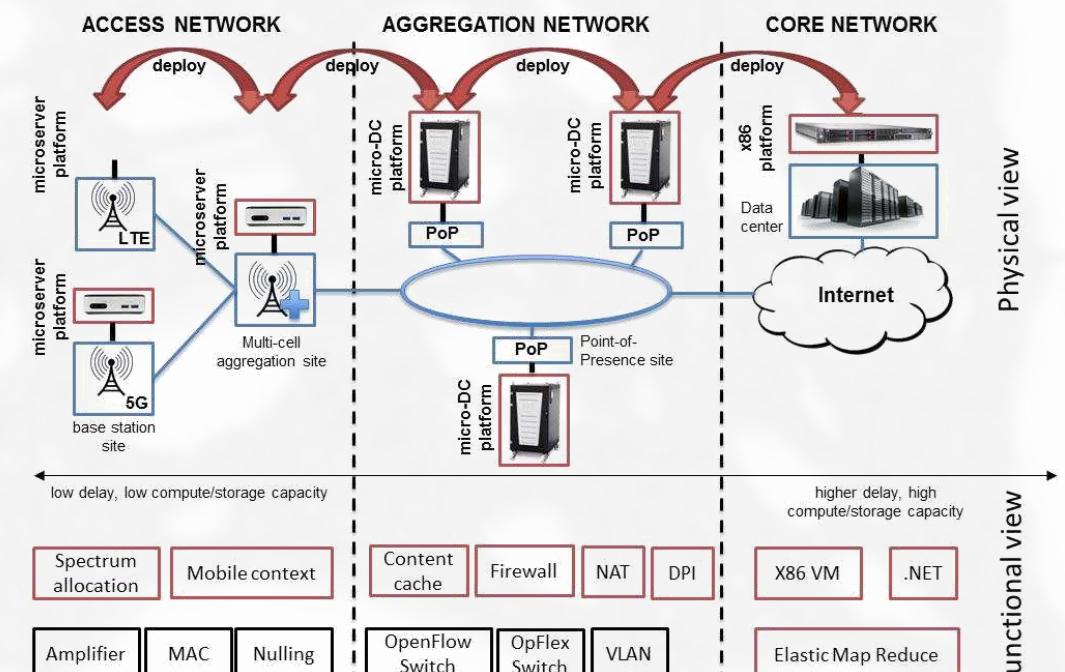


Image: Superfluidity (2014)

- Networks in various shapes/sizes

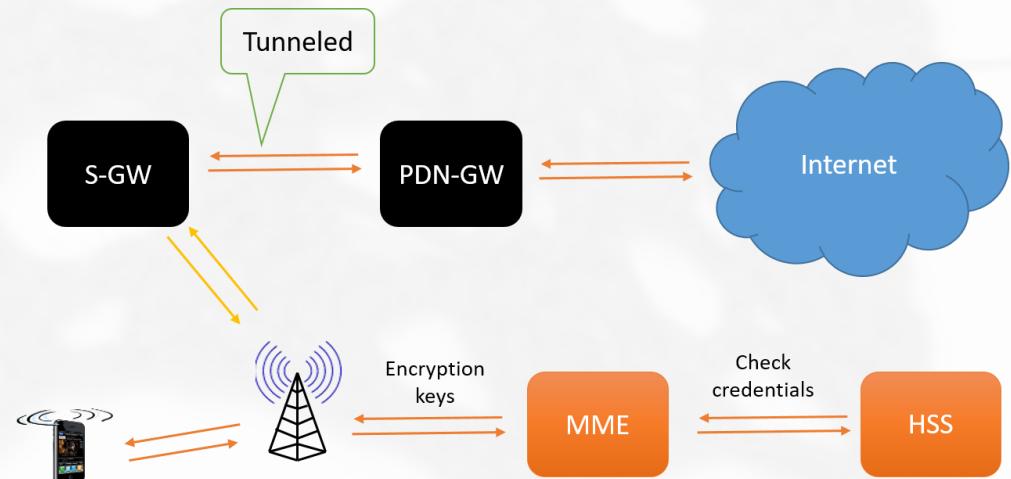
Example of Virtualizing Networks: vCPE

- Customer Premises Equipment (CPE)
 - Residential gateway
 - Residential LAN, IP routing, NAT, DHCP, Firewall, VOIP
 - Set top box
 - Multimedia, high-quality video support (game consoles, IPTV, DVR)
 - High-BW features: REC, FFW, RWND
- Costly maintenance
 - Support, repair/replacement, various types of HW/SW (legacy), upgrades
- How can CPEs be virtualized?
 - Universal CPE (uCPE): COTS “whiteboxes”
 - Programmable, managed by SD-WAN Controller
 - Software-defined WAN (SD-WAN)



Example of Virtualizing Networks: vEPC

- Evolved Packet Core (EPC)
 - Interconnect radio network and wired network (mainly Internet)
 - Support seamless connectivity for mobile devices
 - Components/Functions:
 - Mobility Management Equipment (MME)
 - Keep track of User Equipment (UE) location
 - Home Subscriber Service (HSS)
 - DB of user metadata (access call, roaming, ...)
 - Packet Data Network Gateway (PDN-GW)
 - GW to Internet, assign IPs to UEs
 - Serving Gateway (S-GW)
 - Set up and manage tunnels between eNB & PDN GW
 - Can EPC components be virtualized?



Example of Virtualizing Networks: C-RAN

- “C” for Cloud
- Radio Access Network (RAN)
 - Centralized cloud manages RAN resources
 - Software-defined radio (SDR)
 - Simple Remote Radio Units (RRUs)
 - Enables:
 - Joint transmission, virtual MIMO, ...
 - Support for multiple technologies using COTS HW
- Cornerstone of 5G
 - C-RAN deployments (China Mobile)

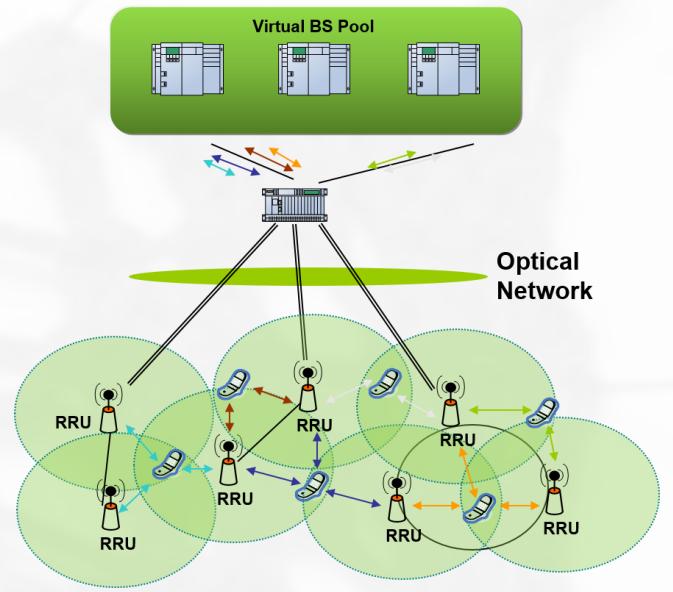
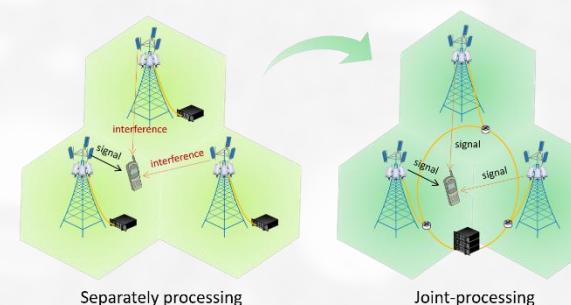
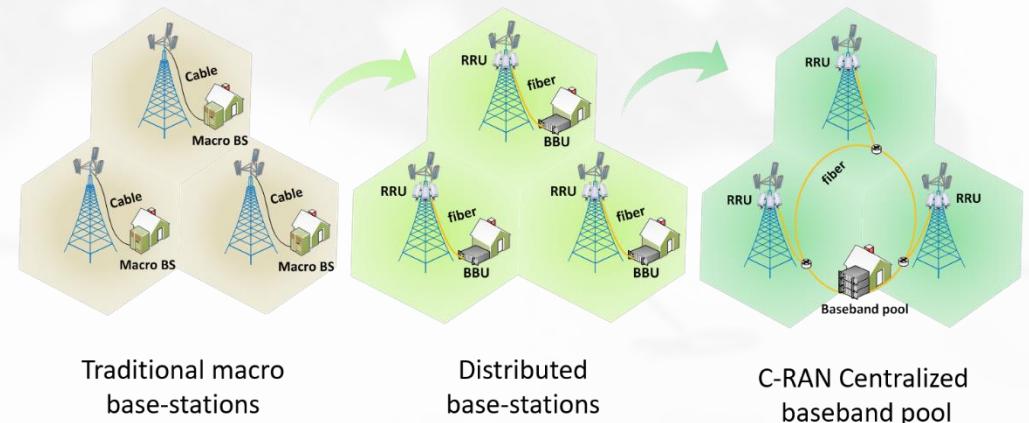


Image: China Mobile (2012)



SDN vs. NFV

- What SDN is all about?
 - Separating control plane from data plane
- What NFV is all about?
 - Separating HW from SW
 - “Classic” virtualization
- SDN is a (strong) enabler of NFV adoption / potential success
 - Not necessarily a requirement
- Developed side-by-side

ETSI-ISG-NFV (or just ETSI-NFV)

- ETSI: European Telecommunications Standards Institute
- ISG: Industry Specification Group
- Releases: 1, 2, 3, ...
- Operator/Telco viewpoint
 - How to virtualize complex network services
 - Move from dedicated HW, to COTS (virtualized HW)
- Quite a few members
 - Partial list...



More on the Telco Viewpoint

- OSS/BSS
 - Operations Support System (OSS)
 - Controls actual network operation
 - Business Support System (BSS)
 - Handles business side
 - Customers, billing, ...
- “Orders-Down, Faults-Up” model
 - Customer requirements (orders) flow down
 - To be fulfilled by the network
 - Via network-configuration
 - Gathered by BSS, forwarded to OSS
 - Network faults are reported up
 - Identified by the system, not the customer (hopefully...))!!

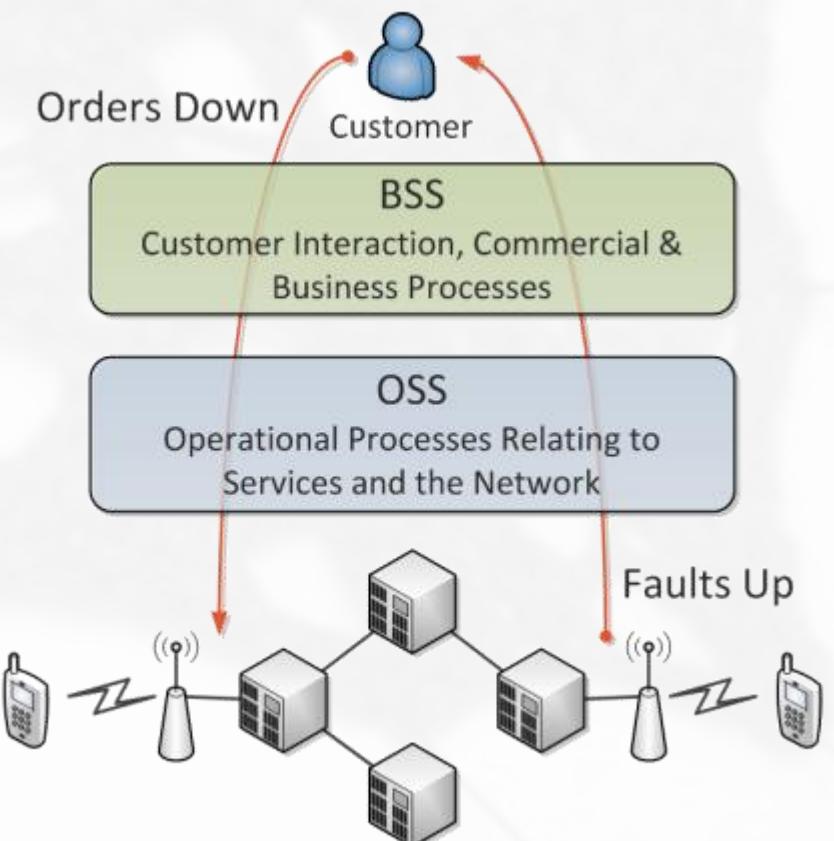


Image: Pullen (2019)

ETSI-NFV Architecture

- Real VNFs running on Infrastructure
 - And providing services...
 - Facilitating the operator's OSS/BSS
- Management and Orchestration (MANO)
- FCAPS
 - Observe and manage:
 - Fault
 - Configuration
 - Accounting
 - Performance
 - Security
 - Integrated throughout the MANO framework

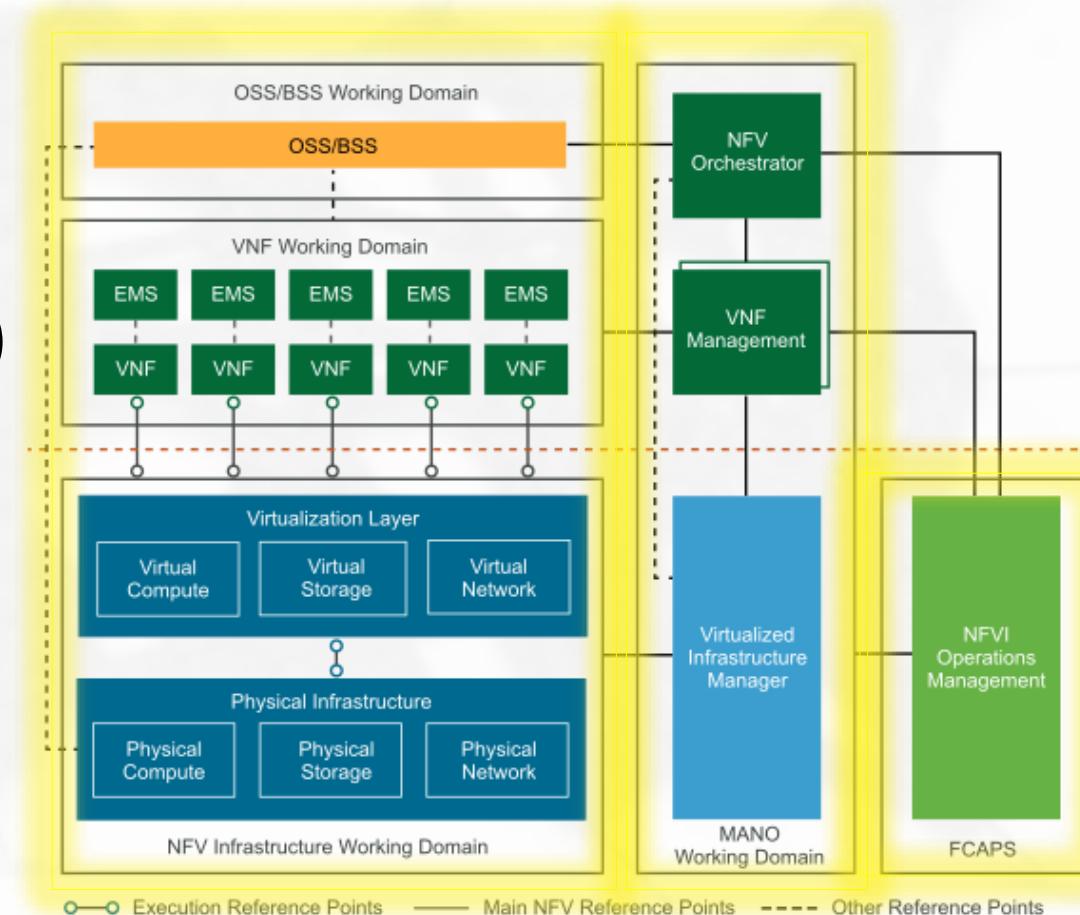


Image: vmware.com

ETSI-NFV Architecture

- NFV Infrastructure (NFVI)
 - The actual cloud infrastructure
 - Virtual on top of physical
 - Virtual resources (VMs) sometimes called “containers”
 - VNF Component (VNFC)
 - Each such **VM** running a specific VNF
- Virtualized Infrastructure Manager (VIM)
 - Manages the NFVI
 - E.g., OpenStack...

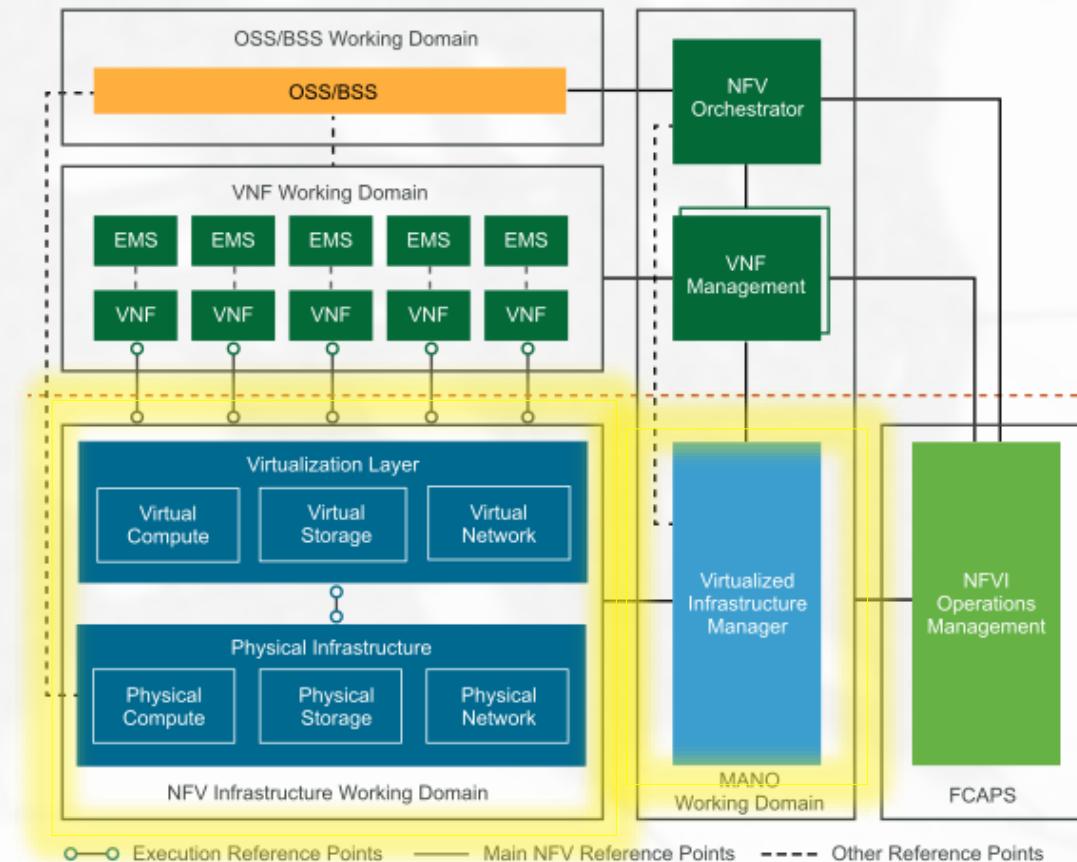
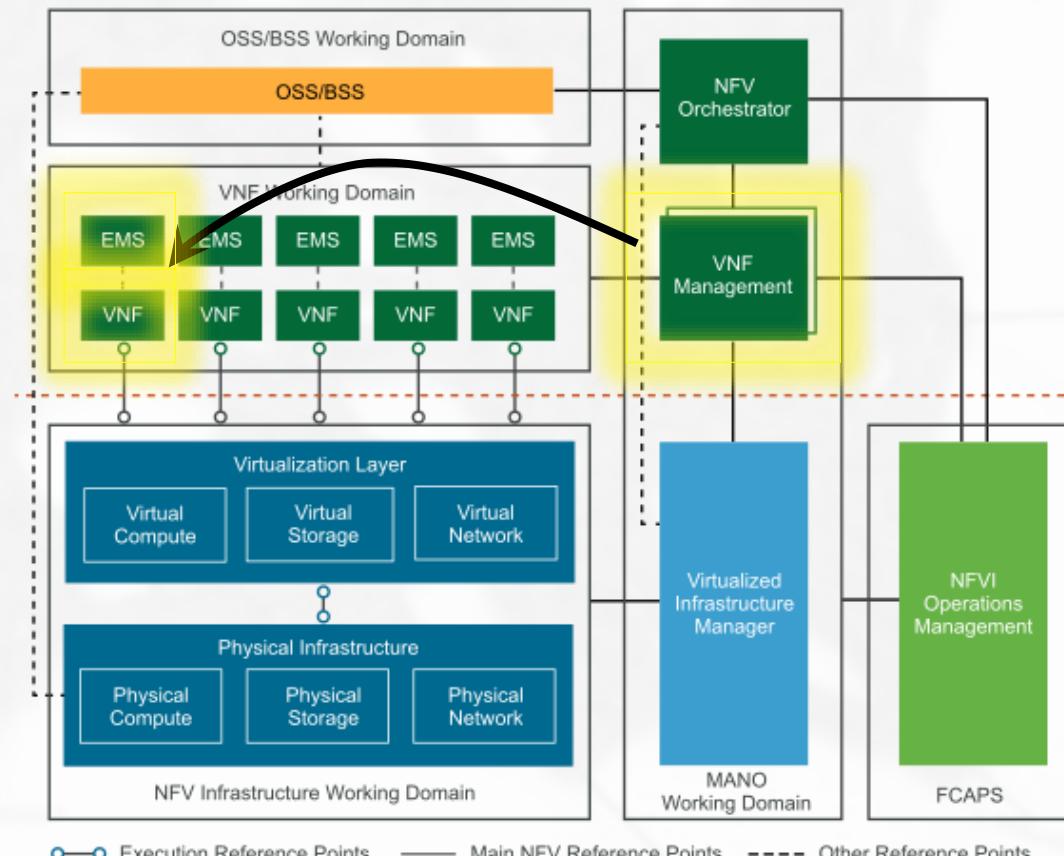


Image: vmware.com

ETSI-NFV Architecture

- Virtual Network Function (VNF)
 - Consists of possibly various virtual resources
 - E.g. multiple VNFCs (VMs) running on various hosts
 - Resembles a “service” in Kubernetes
 - Pre-NFV:
 - Commonly implemented by dedicated HW
- VNF Manager
 - Each one manages a specific VNF
 - VNF lifecycle
 - Setup, maintenance, tear-down
- Element Management System (EMS)
 - Monitors the specific VNF/application KPIs
 - According to operator’s viewpoint & requirements



Key Performance Indicator

Image: vmware.com

ETSI-NFV Architecture

- Network Service (NS)
 - A VNF forwarding graph

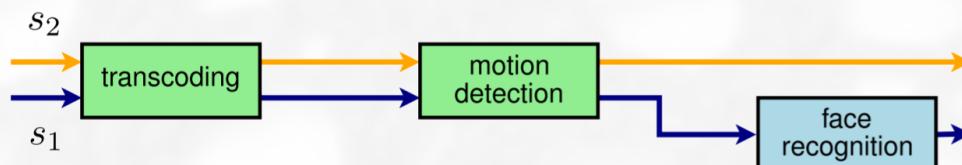


Image: Malandrino et al. (2019)

- NFVO: NFV Orchestrator
 - Managing network services
 - Onboarding, scaling, monitoring, policies
 - Managing catalog of possible NSs
 - Global resource management
 - All the way “down” to NFVI

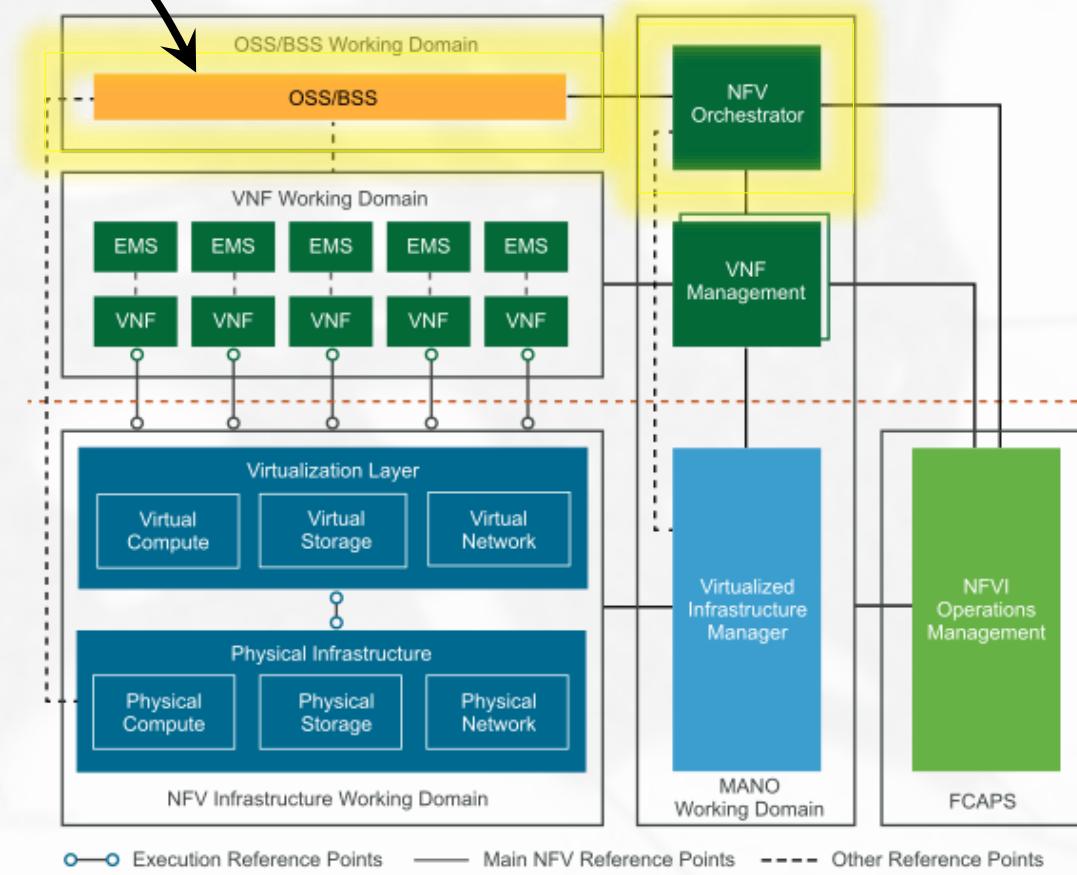
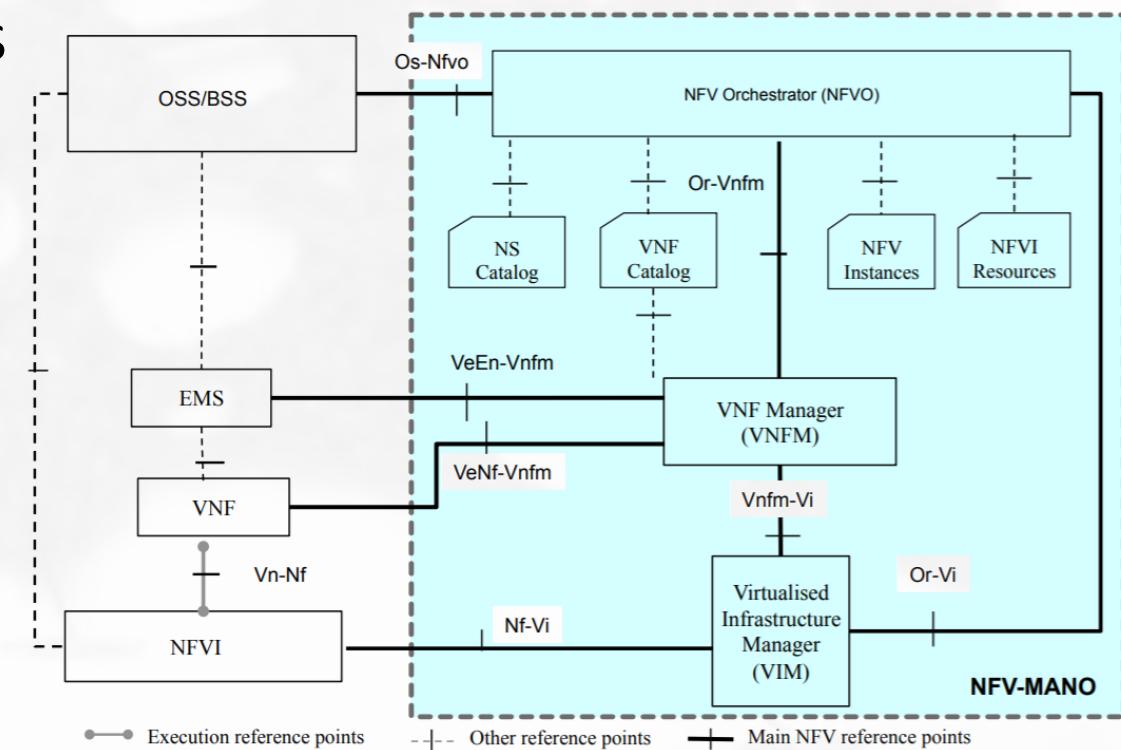


Image: vmware.com

ETSI-NFV Architecture

- ETSI-NFV Management and Orchestration (MANO)
 - Automated deployment of complex VNFs
- Architecture defines a set of interfaces
 - Also information elements exchanges among entities
- Rest-API



Outline

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High-speed Networking

- InfiniBand (IB)
 - Switched fabric interconnect architecture
 - Not a shared bus
 - Benefits: multi-path, path redundancy, scalability
 - Within the datacenter / HPC cluster
 - Connecting server clusters, network storage
- RDMA over Converged Ethernet (RoCE)
 - RDMA: Remote Direct Memory Access
 - Transfer data directly from application memory buffers
 - Zero-copy, kernel bypass
 - Close to wire-speed performance
 - “Cornerstone” of HPC
 - Also in ML, big data, storage
 - Originally L2, recently also L3

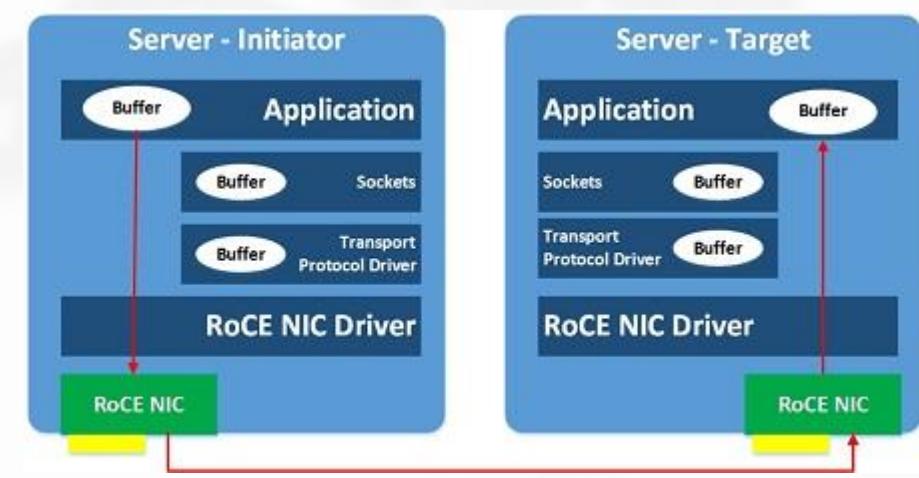


Image: mellanox.com

Serverless Computing

Private Cloud	IaaS Infrastructure as a Service	PaaS Platform as a Service	FaaS Function as a Service	SaaS Software as a Service
Function	Function	Function	Function	Function
Application	Application	Application	Application	Application
Runtime	Runtime	Runtime	Runtime	Runtime
Operating System	Operating System	Operating System	Operating System	Operating System
Virtualization	Virtualization	Virtualization	Virtualization	Virtualization
Server	Server	Server	Server	Server
Storage	Storage	Storage	Storage	Storage
Networking	Networking	Networking	Networking	Networking

- Provisioning and deployment is done on the level of *code*
 - Not servers/containers/microservices!
- Commonly known also as Function-as-a-service (FaaS)
 - Micro-payment for running a function
 - E.g., executing a python function
 - Function gets executed when triggered by an event
 - E.g., transcoding video upon upload to an object store, real-time analysis/backup, ...
 - Auto scaling in response to workload variation
- Examples:
 - AWS Lambda, Google Cloud Functions, Azure Functions
 - Also open-source frameworks
 - E.g., Apache OpenWhisk, Fission, ...
 - Compatible with Kubernetes
 - Containers that can run the code instantiated when needed

this wasn't here before,
was it??



Google Cloud Functions



Cloud Native

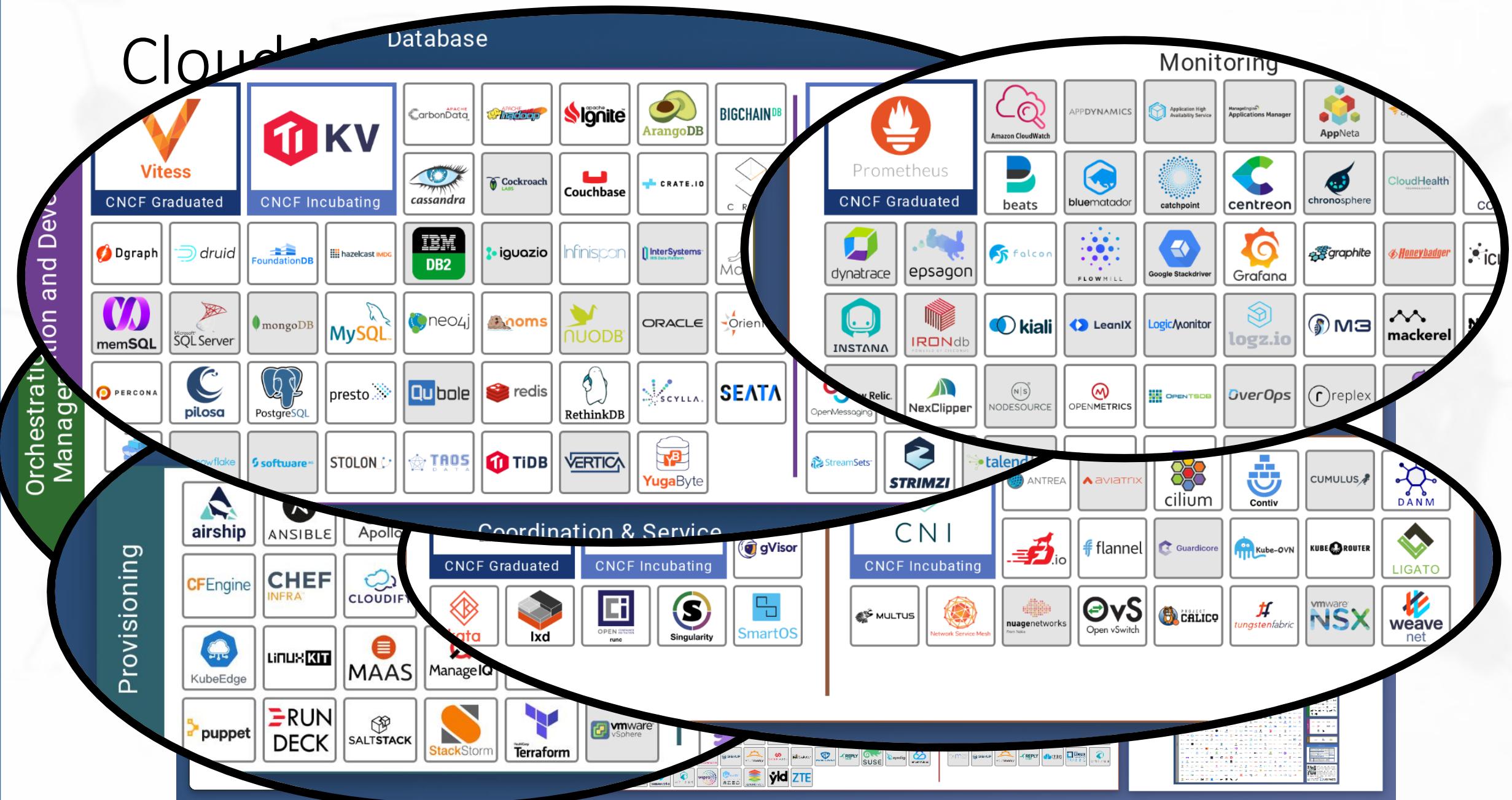
- A paradigm for designing software
 - Shift from fixed, high-cost infrastructure to the Cloud
 - Horizontal scaling, distributed/parallel processing
 - Design principles:
 - Automation
 - Infrastructure, CI/CD, scaling, monitoring
 - Stateless whenever possible
 - Allows for easy scaling, repairing, load balancing, ...
 - Plug-and-play, mix-and-match
 - Combine services (also managed, provided by operator)
 - Secure by constant authentication
 - Constant evolution
 - Adoption of new technologies to address new requirements

Closing Note: Cloud Native

- Open-source software foundation
 - Part of the Linux Foundation
 - <https://www.linuxfoundation.org/projects/>
 - Sponsors open-source projects related to cloud computing
 - Kubernetes, Prometheus, Envoy Proxy, etc.
- Moto: Cloud portability without vendor lock-in
- A few unknown contributing members...
- Various others foundations
 - Open Container Initiative, Cloud Foundry, ...



From Lecture 3...



Outline

- Network Function Virtualization (NFV)
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5G

- Mobile Network Operators (MNOs) expectation:

- 10x less latency
- 100x higher rates
- 1000x more capacity

- Key component: Cloud!

- Along with SDN, NFV, automation & Network Slicing (stay tuned)

- Architecture strongly based on:

- Cloud Native framework
 - Agility and flexibility, container based, easily scalable
- ETSI-NFV
 - VNFs, highly customizable MANO

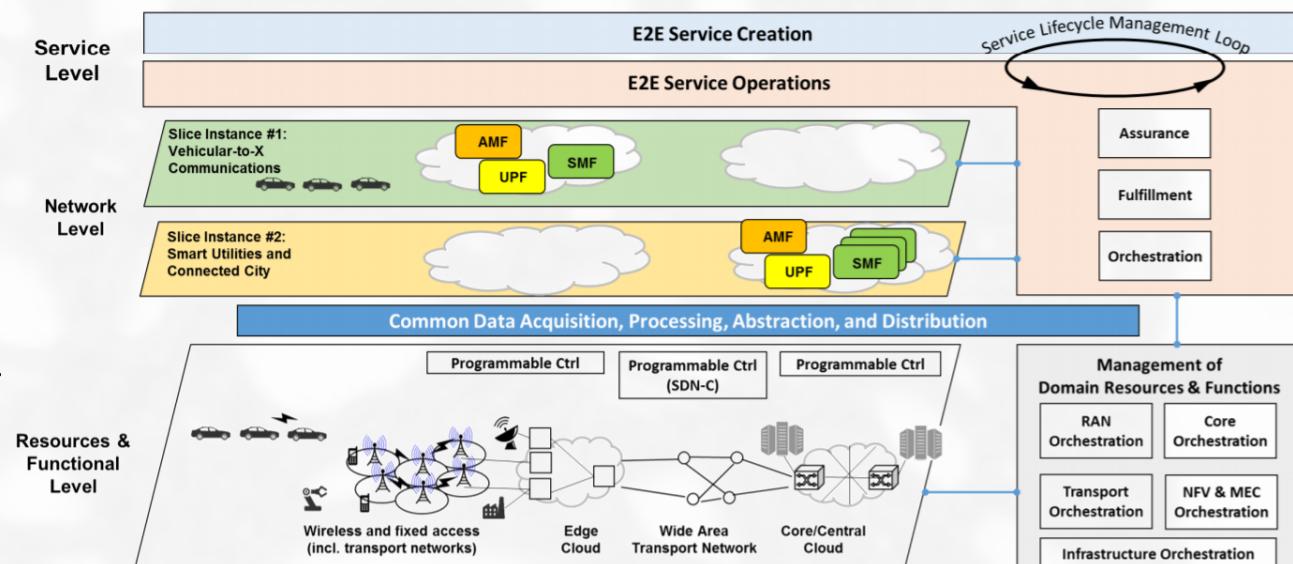


Image: 5g-ppp.eu

Network Slicing

- E2E logical network running on a common infrastructure
- A term strongly coupled with 5G
- Some properties
 - High-reliability, scalability, and Isolation
 - Network slices do not affect each other, easily scalable
 - Automation
 - Auto-scaling, migration, healing, dynamic optimization
 - Programmability
 - Via exposed APIs, configuration-as-code
 - Slices are customizable
 - By using SDN, NFV

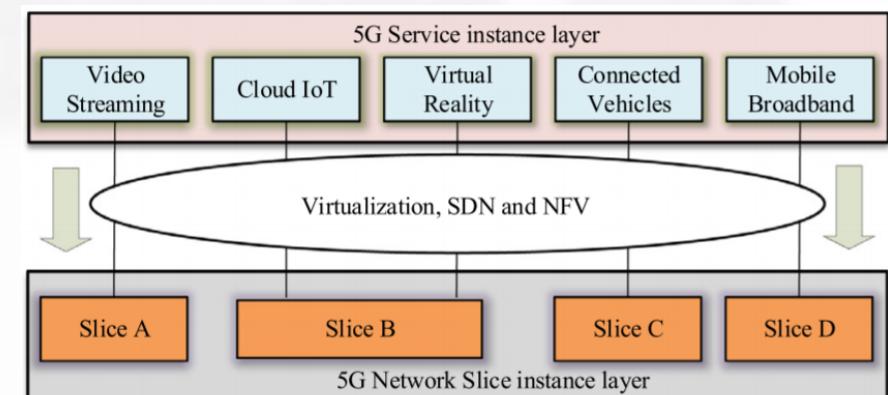
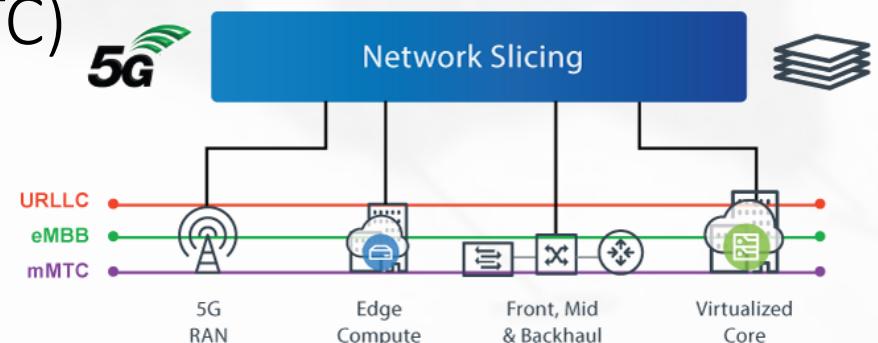


Image: Barakabitze et al. (2020)

5G & Network Slicing Use Cases

- Ultra-reliable Low-Latency Communications (urLLC)
 - Vehicle-to-X (X=vehicle, infrastructure, ...)
 - Require provisioning of mobile edge computing (MEC)
 - Stay tuned...
- Extreme/enhanced Mobile Broadband (eMBB)
 - High-bandwidth applications (e.g., video)
 - Main elephants in the mobile network
- Massive Machine-Type Communications (mMTC)
 - AKA, Internet-of-Things (IoT)
 - Stay tuned...
 - A lot(!!!) of mice

Image: blueplanet.com



Big Data

- Analysis of huge amounts of data
 - E.g., using MR, but also many other components
 - E.g., Apache Spark
- Data mining
 - Techniques/algorithms/data structures for getting insights out of data
- Some example use-cases

Online retail	
Finance	<ul style="list-style-type: none">• Banking• High-frequency-trading
Cyber security	
Transportation	<ul style="list-style-type: none">• Route planning• Safety

Personalized Healthcare	
Targeted advertising	<ul style="list-style-type: none">• Google• Facebook
Physical systems	<ul style="list-style-type: none">• Weather forecast• Nuclear reactions
Government & Defense	<ul style="list-style-type: none">• Tax evasion• National security

Machine Learning & AI

- One of the biggest forces pushing the cloud into businesses

- E.g.,

- Deep learning
 - Train huge(!) neural networks, distributed/parallel
 - Transfer learning
 - Use “general” models as a basis, adjust according to need
 - E.g., language model -> specific text analysis task

- Easy access to ML-accelerating HW

- GPUs, TPUs

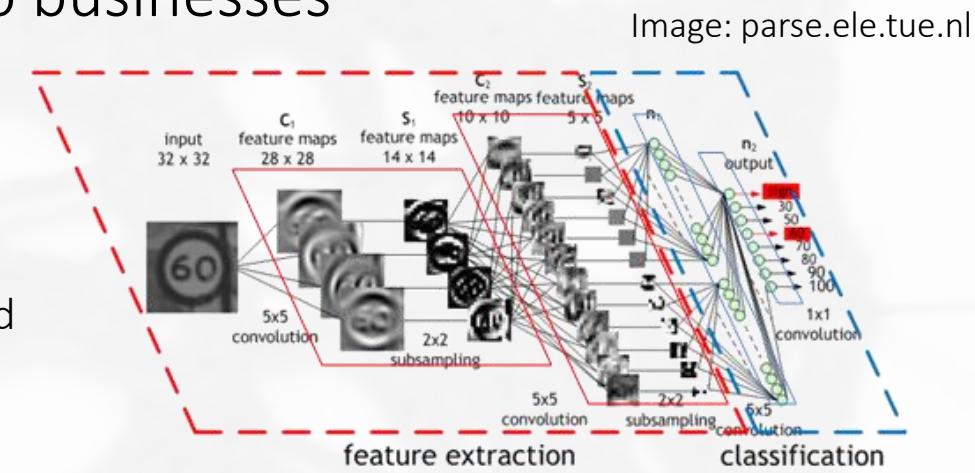
- Cloud-based solutions

- Pros:

- Flexibility / ease of use, pay-for-what-you-use, scalability, time-to-market

- Cons:

- more expensive (for long stretches / high-volume)
 - Should consider on-prem solutions once beyond a certain size



Azure Machine Learning

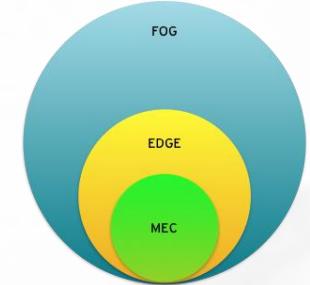
Internet-of-Things (IoT)

- Store/manage everything on/from the cloud
 - Monitoring and logging
 - Triggering
- Some use-cases
 - Industry processes
 - Monitor/manage production floors, quality assurance
 - Connected home
 - Home automation, security, networking
 - Commercial/governmental applications
 - Traffic monitoring, public safety
 - Health & personalization
 - Wearables, health monitoring
 - Weather & agriculture



Image: edps.europa.eu

Edge/Fog Computing



- Edge/Fog computing
 - Bringing the cloud to the edge of the network
 - IoT is one of the main forces driving such paradigms
 - E.g., data aggregation
 - Some additional use-cases
 - Transportation safety
 - Fast ML inference
 - CDN & Caching
- Multi-access/Mobile Edge Computing (MEC)
 - Cloud computing at the edge of the cellular/radio network
 - Formally defined by ETSI

} lower latency

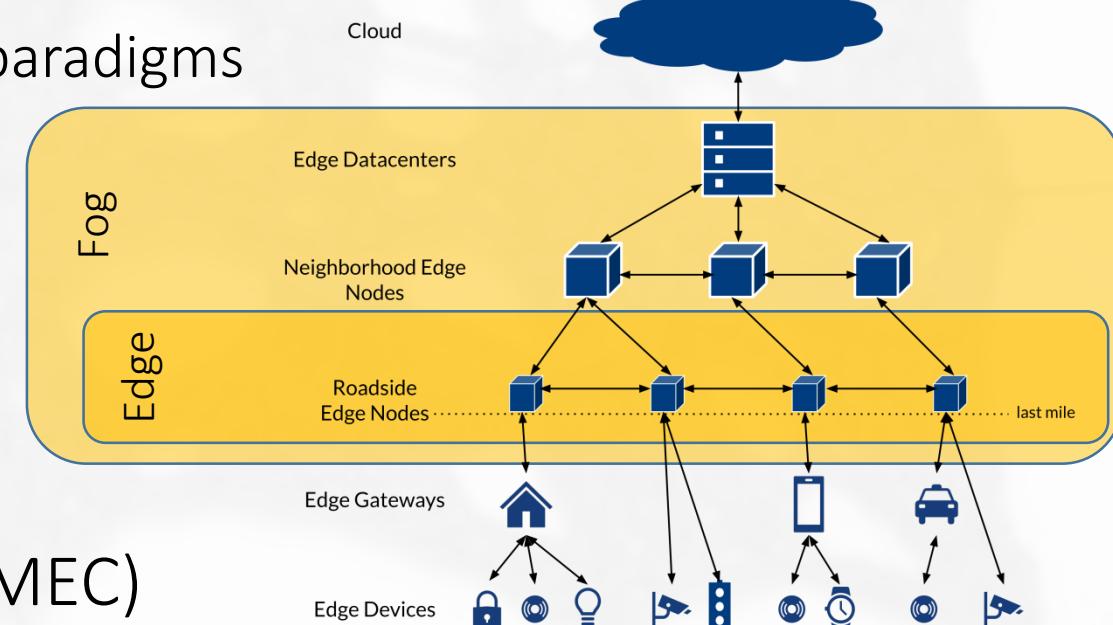


Image: inovex.de

Autonomous Vehicles

- Strong reliance on
 - Edge-computing
 - Small latency
 - Significant processing power
 - Use cases:
 - Fast ML inference
 - 5G
 - Small latency connectivity of V2X
- Cloud as a backend for large data volumes
 - Car positioning, movement
 - Shared High-definition map



Mobileye Picks Amazon Web Services to Handle Autonomous Vehicle Cloud Data

In October, Mobileye announced a partnership with Volkswagen Group and Israeli car importer and distributor Champion Motors to launch a self-driving taxi service in Israel in early 2019

Lilach Baumer 09:00 27.11.18

Source: calcalistech.com

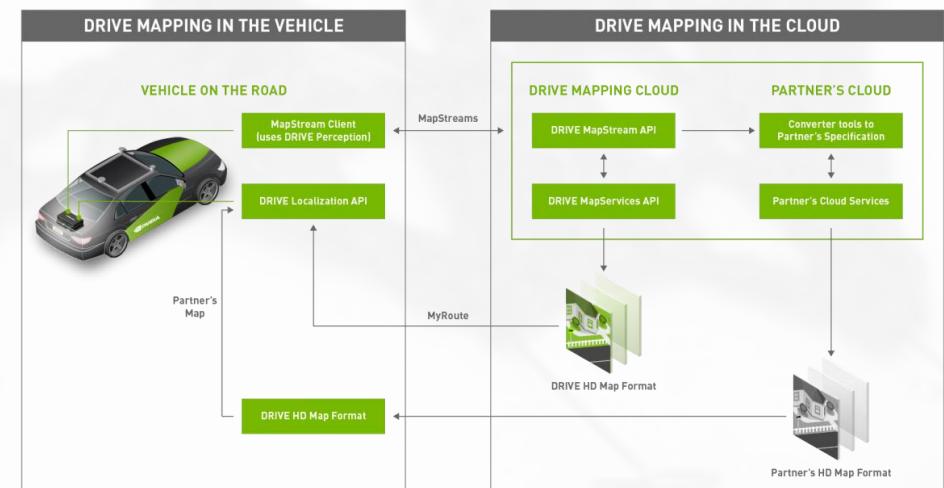


Image: nvidia.com/drive

A Few More Use Cases (You Might Know...)

- Social networks
 - Facebook, Twitter, Whatsapp, LinkedIn, ...
- Online retail
 - Amazon.com, Walmart, AliExpress, ...
- Media
 - YouTube, Netflix, Spotify, ...
- Storage
 - Google Drive, Dropbox, ...
- Misc. Services
 - Office365, Gmail, Zoom, Skype, ...



(Partial) Bibliography

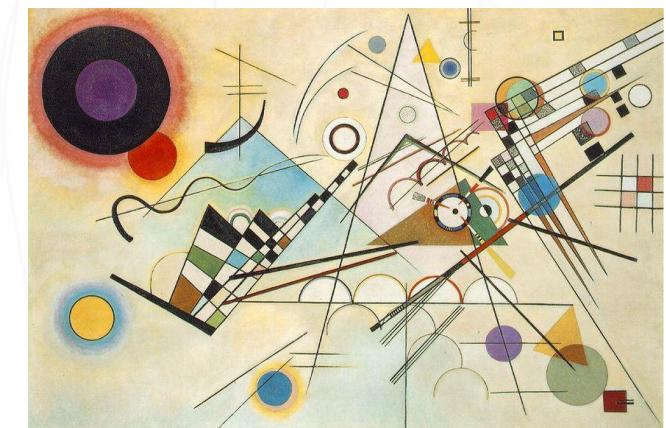
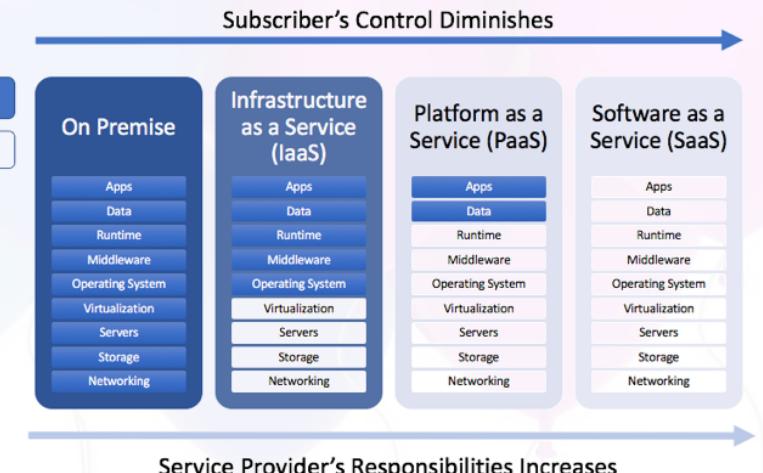
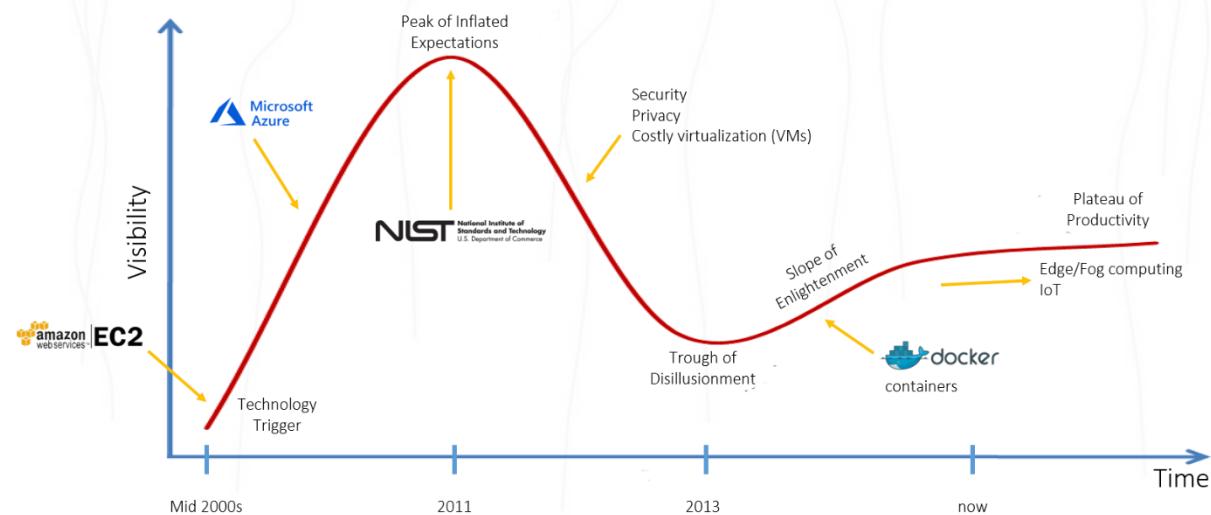
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Virtualization and Cloud Computing: Wrap-up and Review

Gabriel Scalosub

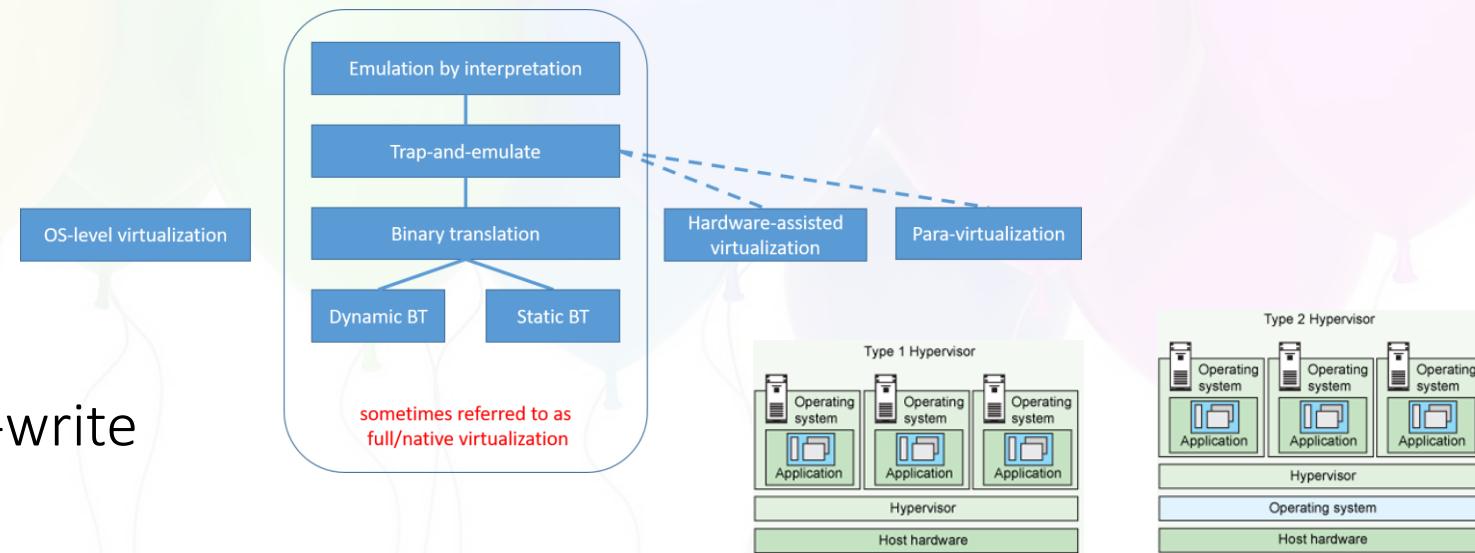
Introduction to Cloud Computing & Virtualization

- What is “Cloud”
 - Economics (“It’s all about the money...”)
- Virtualization
 - The art of abstraction
- The Cloud Hype Cycle



VMs & Containers

- Map of virtualization
- VMs & hypervisors
- Containers & Docker
 - cgroups, namespaces
 - Union filesystems, copy-on-write
- VMs vs. containers

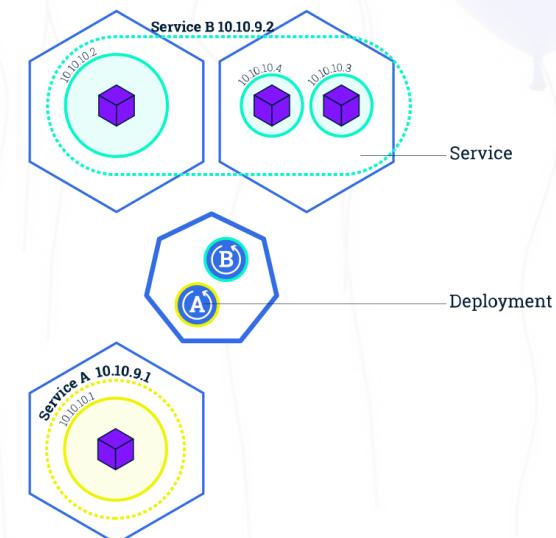
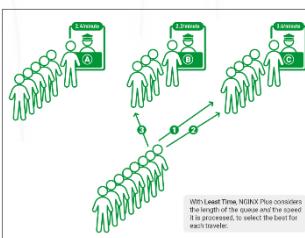
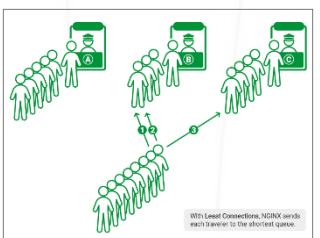
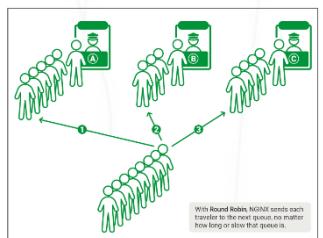


DevOps & Container Orchestration

- DevOps & CI/CD
- Kubernetes
 - Container orchestration
 - Pods, services, deployments
- Load balancing & Makespan

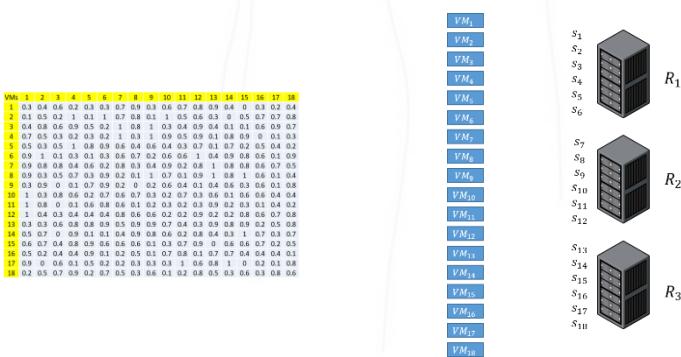
List Scheduling (LS) Algorithm

1. sort jobs arbitrarily, J_1, J_2, \dots, J_n
2. for $j = 1, \dots, n$ do
3. assign J_j to currently least loaded machine
4. end for

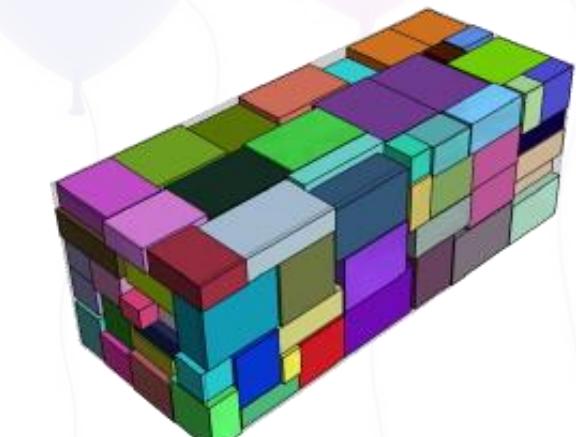
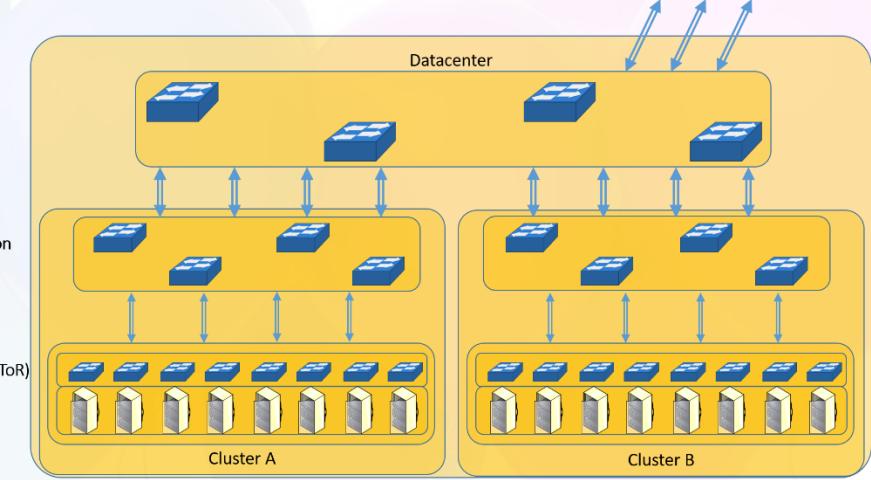


Placement

- The Datacenter
- Bin Packing
 - FirstFit, BestFit, WorstFit, NextFit, ...
 - Multidimensional
 - Many related problems
 - Makespan, Knapsack, Facility Location, ...
- Network awareness

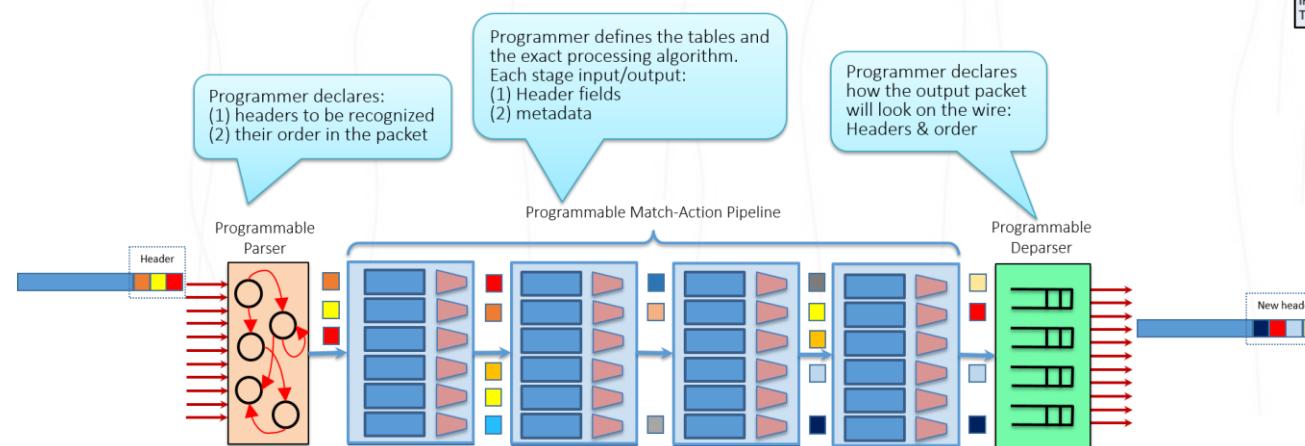


slot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
2	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
4	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
6	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
7	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
8	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
10	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
11	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
12	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
13	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
14	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
15	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
16	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
17	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
18	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	

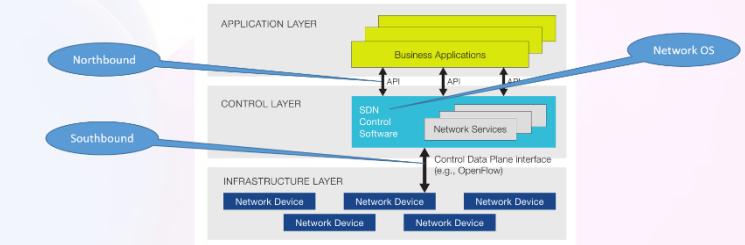


SDN & P4

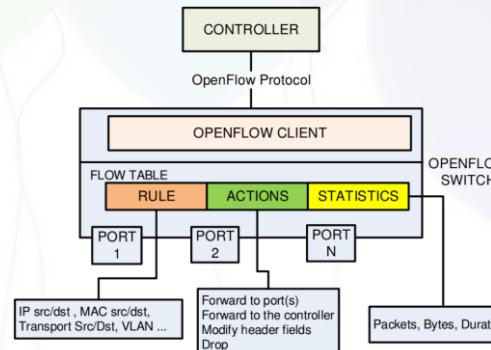
- SDN
 - Control plane vs. data plane
 - OpenFlow
- OvS & Mininet
- VXLAN
- P4



> sudo mn

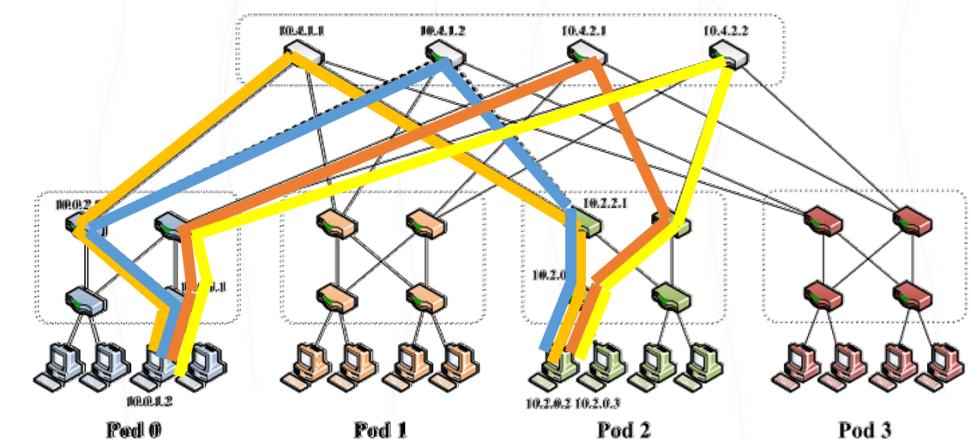
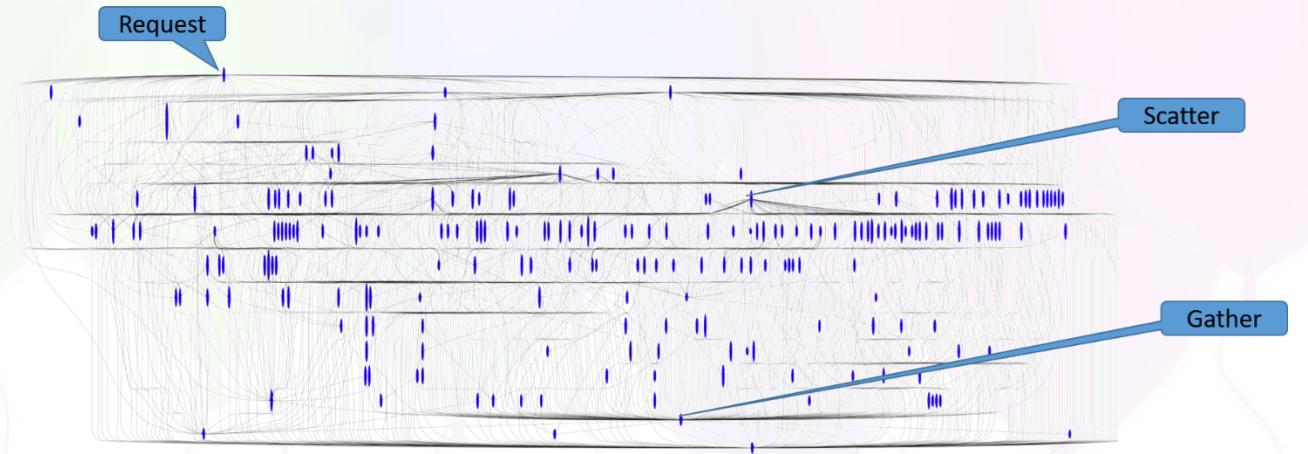
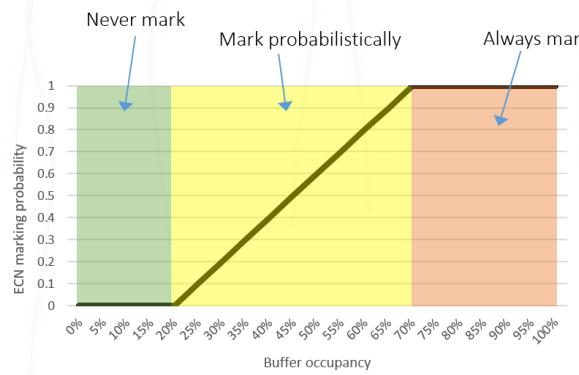
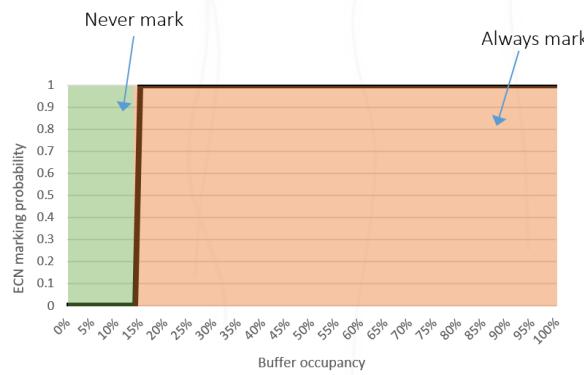


Switching											
Switch	MAC src	MAC dst	Eth type	VLAN ID	IP Src	IP Dst	IP Prot	TCP sport	TCP dport	Action	
*	*	00:1f..	*	*	*	*	*	*	*	port6	
Flow Switching											
Switch	MAC src	MAC dst	Eth type	VLAN ID	IP Src	IP Dst	IP Prot	TCP sport	TCP dport	Action	
port3	00:20..	00:1f..	0800	vlan1	1.2.3.4	5.6.7.8	4	17264	80	port6	
Firewall											
Switch	MAC src	MAC dst	Eth type	VLAN ID	IP Src	IP Dst	IP Prot	TCP sport	TCP dport	Action	
*	*	*	*	*	*	*	*	*	*	22	drop
Routing											
Switch	MAC src	MAC dst	Eth type	VLAN ID	IP Src	IP Dst	IP Prot	TCP sport	TCP dport	Action	
*	*	*	*	*	*	5.6.7.8	*	*	*	port6	
VLAN Switching											
Switch	MAC src	MAC dst	Eth type	VLAN ID	IP Src	IP Dst	IP Prot	TCP sport	TCP dport	Action	
*	*	00:1f..	*	vlan1	*	*	*	*	*	port6, port7, port9	



Datacenter Networking

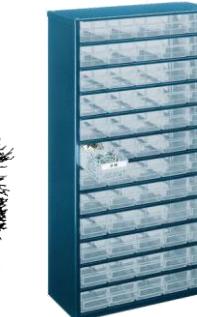
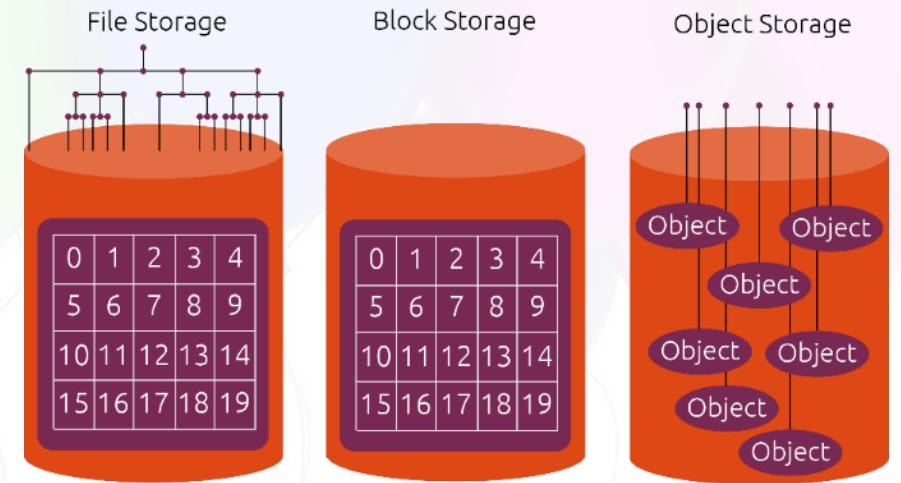
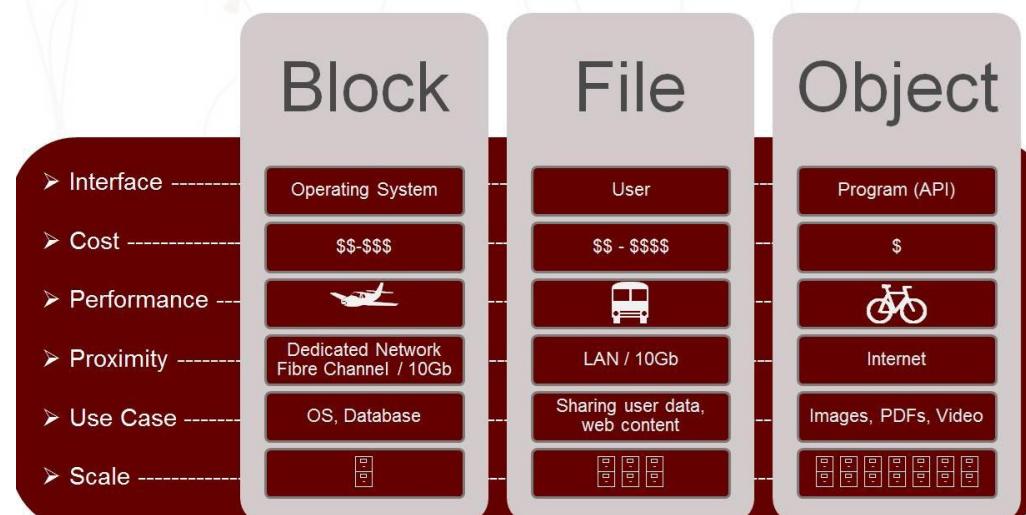
- Scatter-gather
- Cloud network architecture
 - Clos, fat-trees
- Protocols
 - ECMP
 - DC-TCP



Cloud Storage

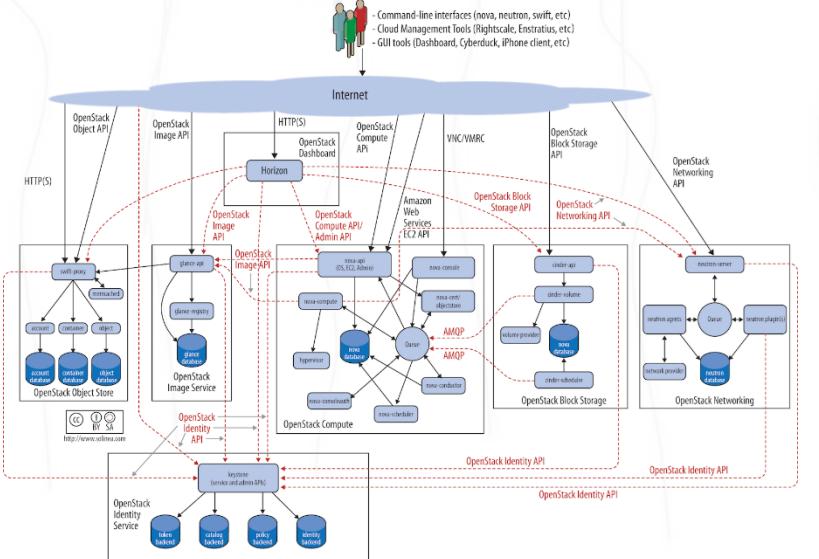
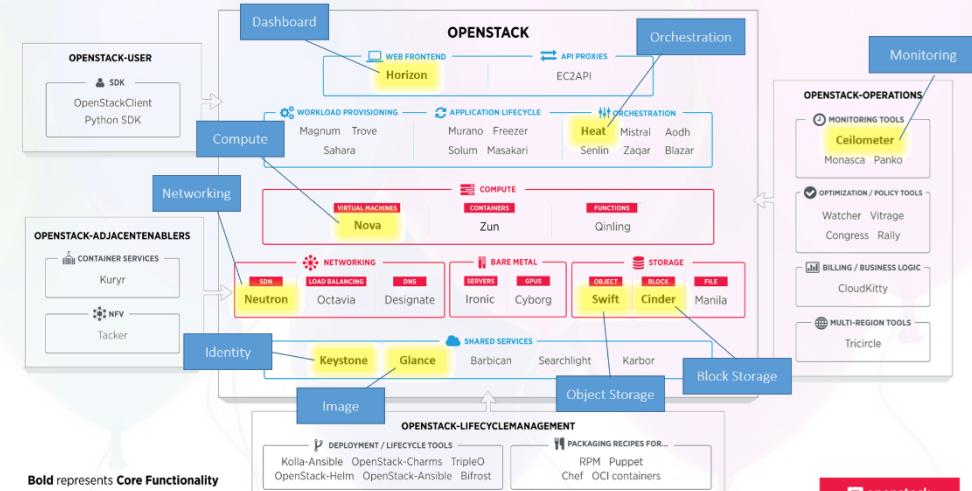
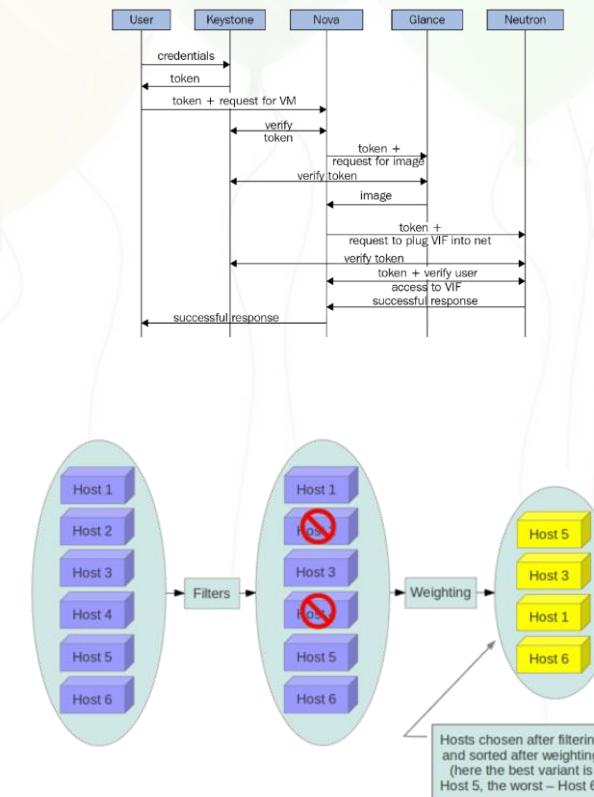
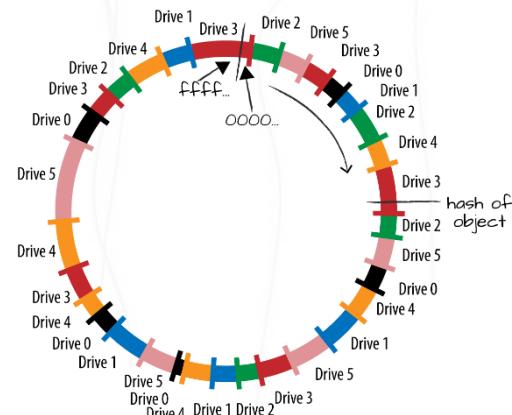


- Storage
 - Block
 - Also ephemeral
 - Object
 - File System



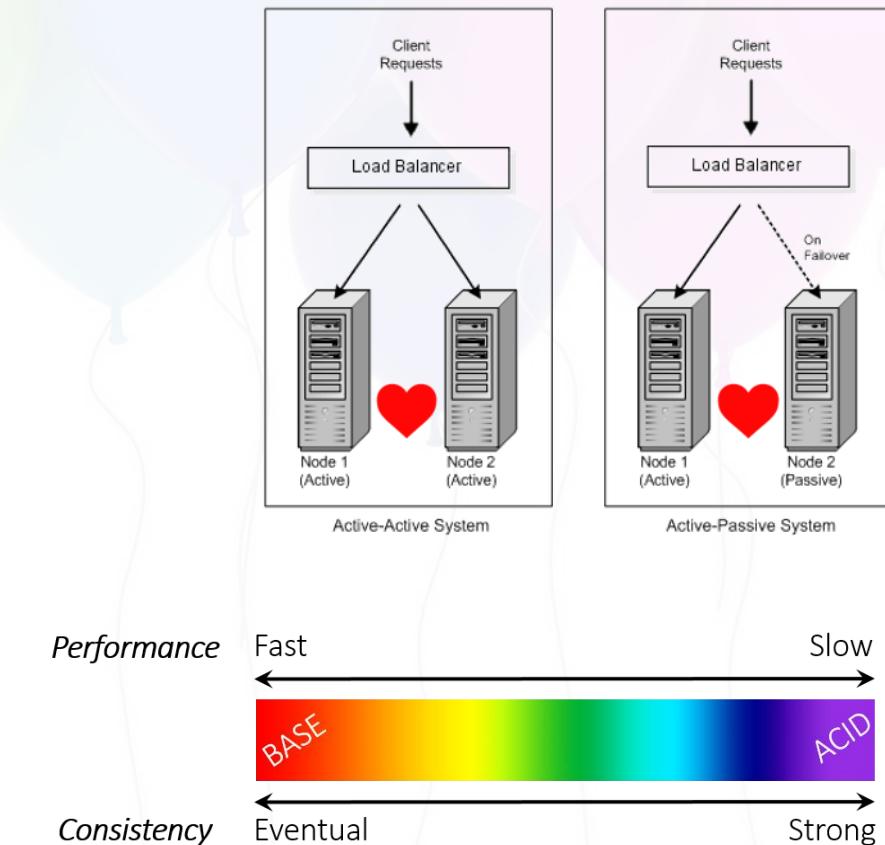
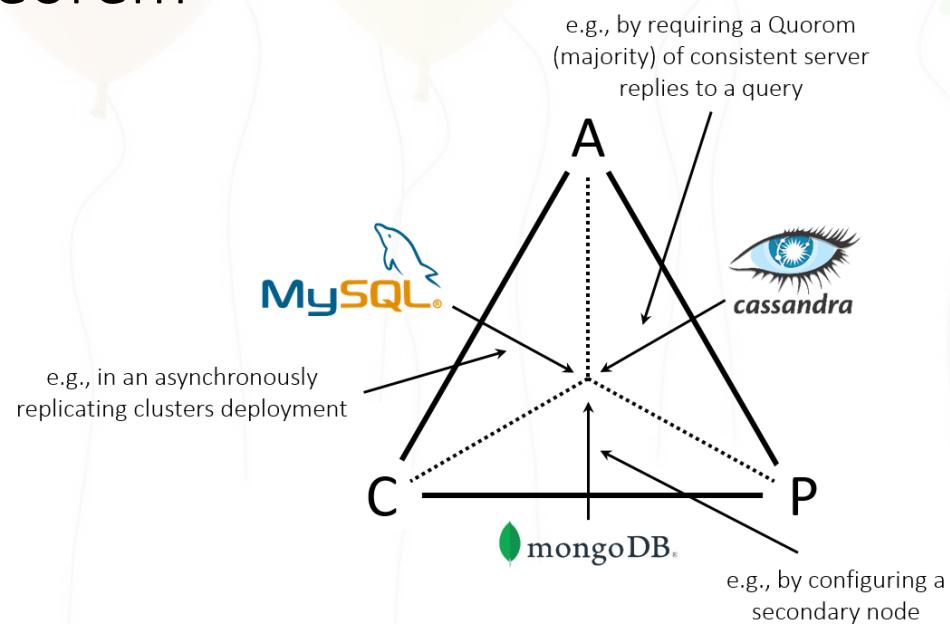
VM Management: OpenStack

- OpenStack
 - Architecture & components/services
 - Under the hood
- OpenStack zoom-in
 - Scheduling
 - Consistent hashing



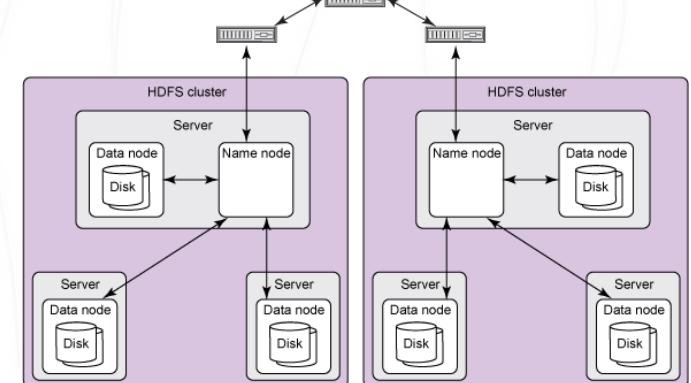
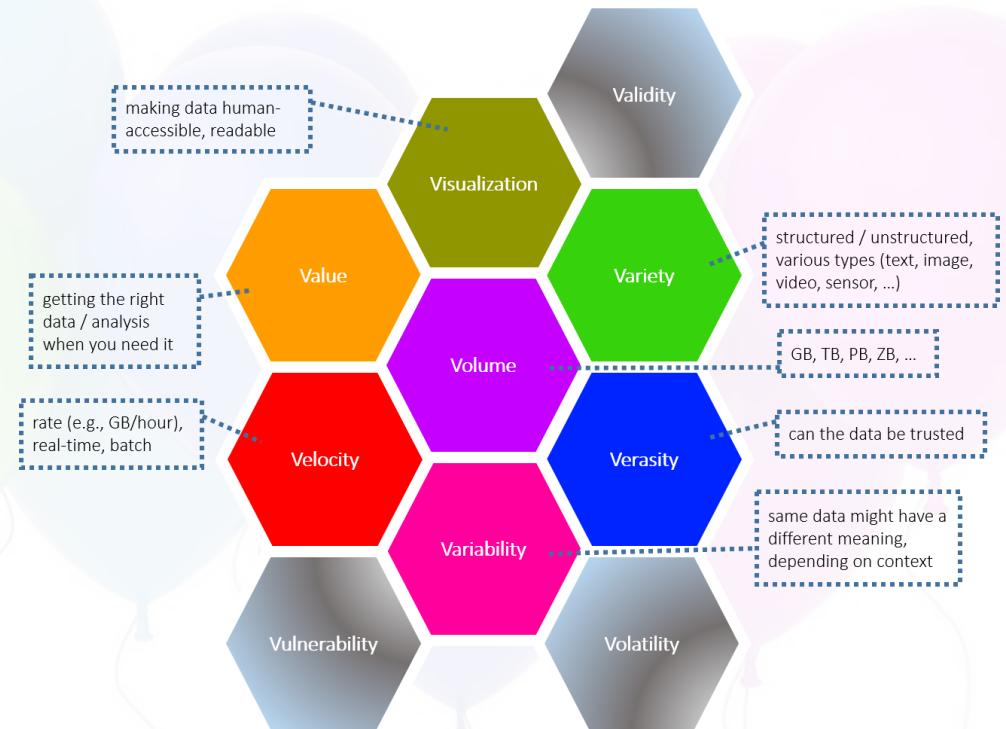
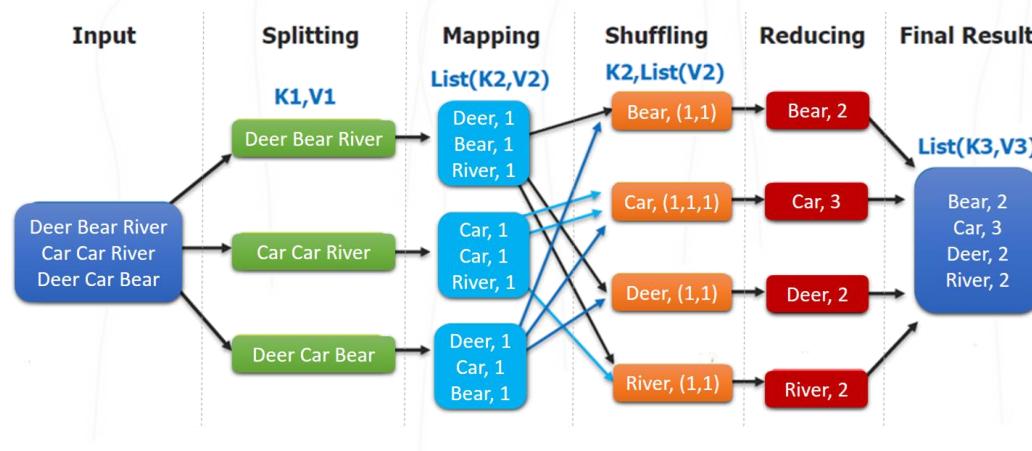
Availability & Consistency

- High-availability
- Consistency
 - ACID vs. BASE
- CAP Theorem



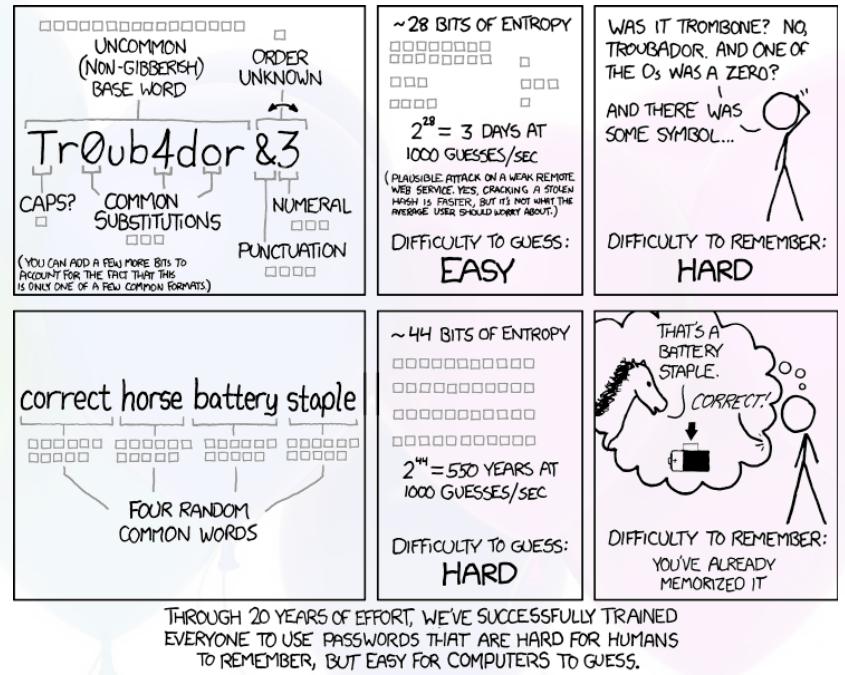
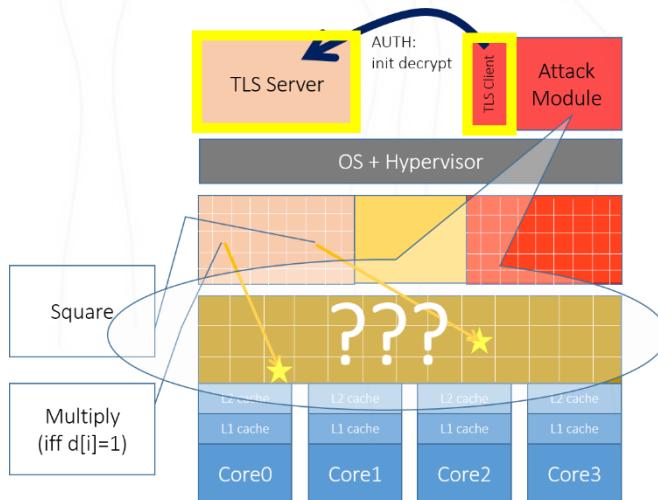
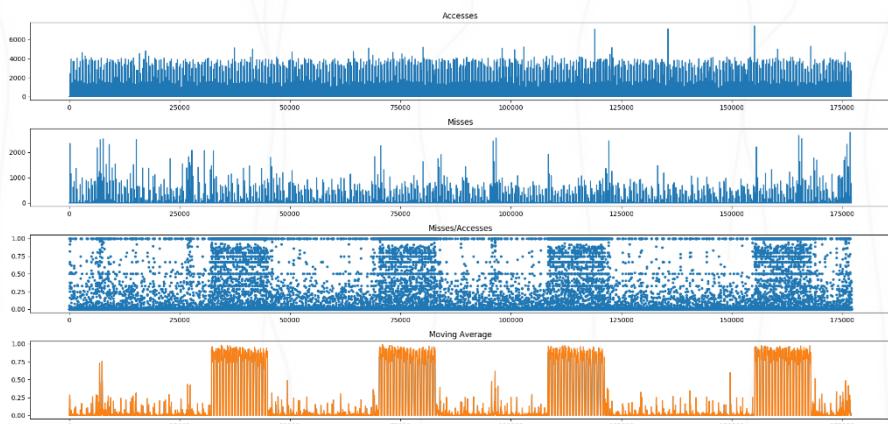
Programming in the Cloud

- Big-data $V^{1000\dots}$
- HDFS (Hadoop)
 - Architecture
- MapReduce
 - Programming paradigm...

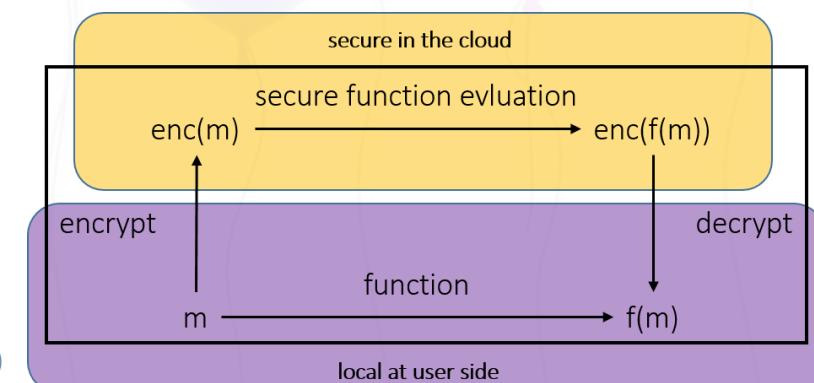


Cloud Security

- Data centric security
 - Homomorphic encryption
- Cache side-channels
 - Attacks
 - Monitoring

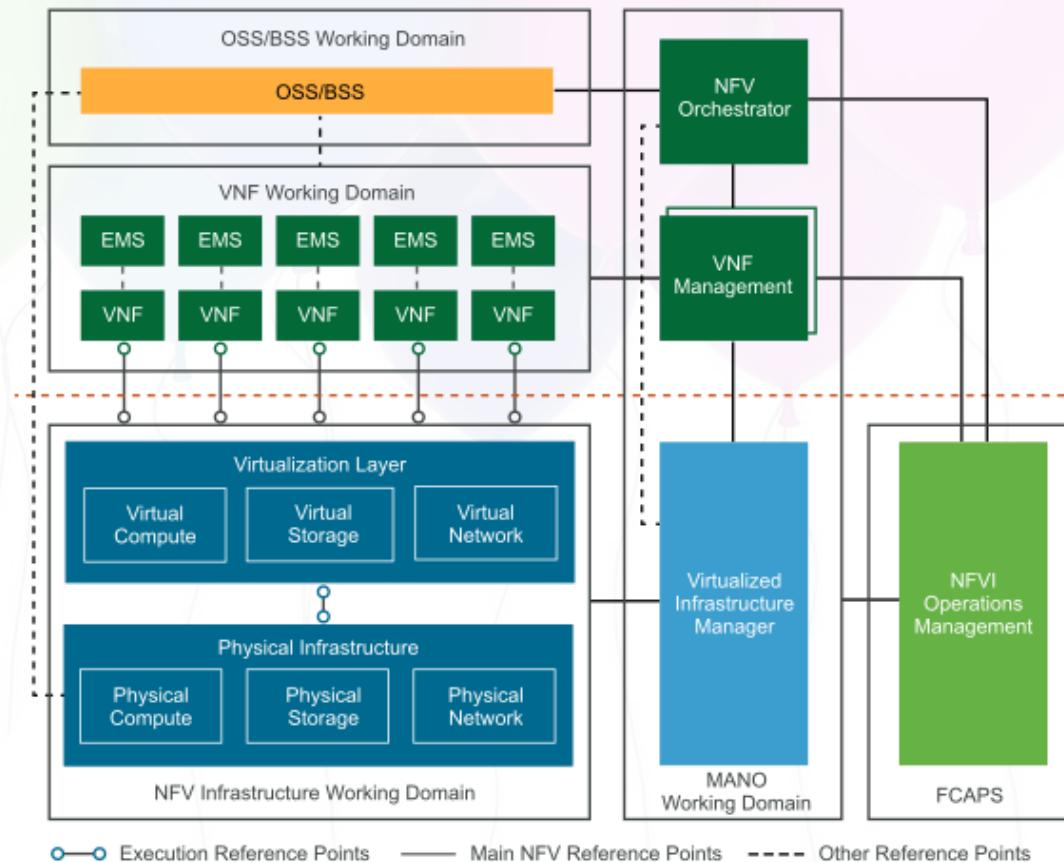


THROUGH 20 YEARS OF EFFORT, WE'VE SUCCESSFULLY TRAINED EVERYONE TO USE PASSWORDS THAT ARE HARD FOR HUMANS TO REMEMBER, BUT EASY FOR COMPUTERS TO GUESS.



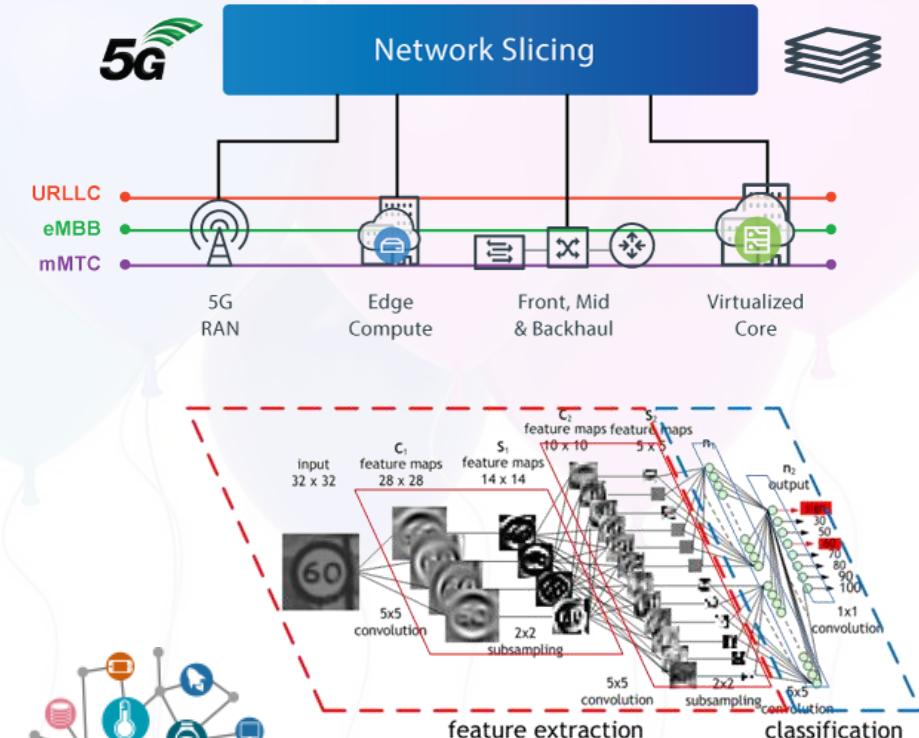
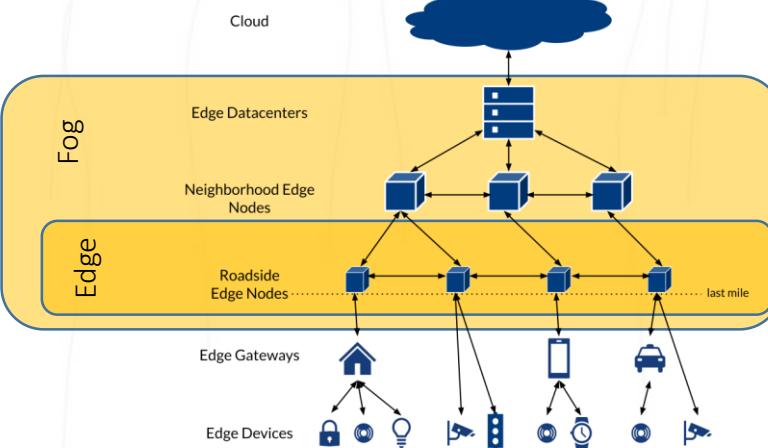
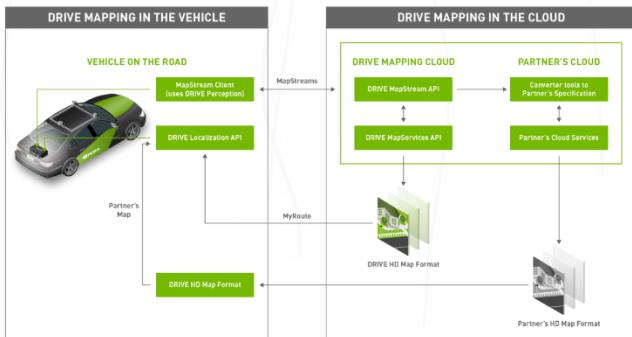
NFV

- Virtualizing HW
 - “classic” virtualization
 - Everything-as-SW
- Telco-supported standardization
 - ETSI-NFV
- Main technological enabler
 - 5G!!
 - Edge computing
 - IoT
 - Autonomous driving
 -

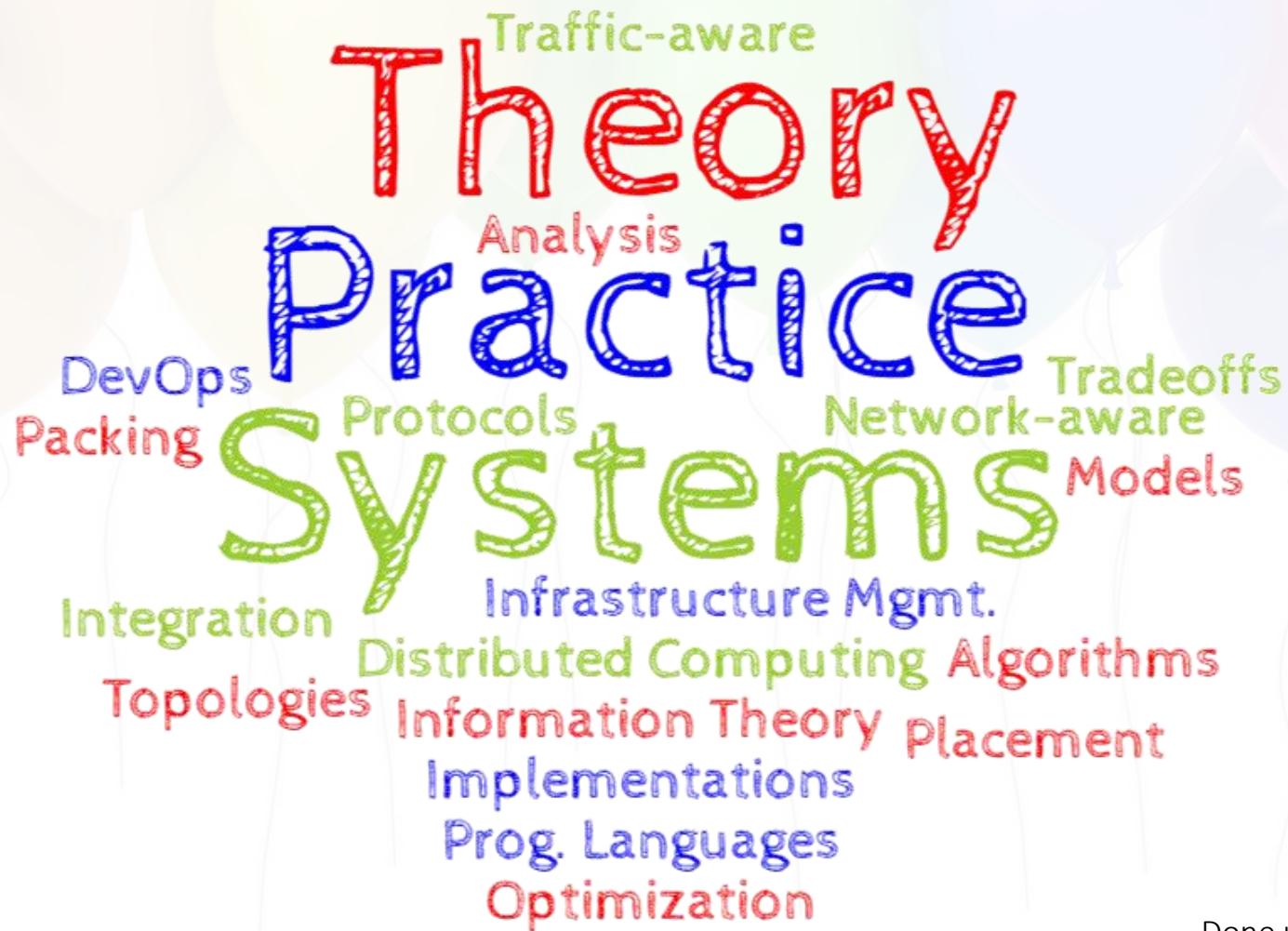


Cloud Applications

- 5G & network slicing
- Big data, ML & AI, data mining
- IoT
- Edge/Fog Computing
- Autonomous driving
- Many more...



Lots of Research Directions





See you @ MSc!!