Recent Advances in Networking: Network *Virtualization*, *Software Defined Networking for Cloud Computing, and IoT*

RAJ JAIN

Washington University in Saint Louis

Saint Louis, MO 63130, Jain@cse.wustl.edu

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These slides and a video recording of the tutorial are at:

http://www.cse.wustl.edu/~jain/tutorials/medes14.htm

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1. Five concepts/events that have changed the networking world: Virtualization, Cloud, Smart Phones, SDN, NFV
2. Network Virtualization: Data Center Bridging, Virtual Bridging
3. SDN: OpenFlow, What really is SDN?, SDN 1.0 vs. SDN 2.0
4. Network Function Virtualization: Service Chaining
5. Future Cloud Computing: Multi-Cloud
6. Internet of Things

Recent Developments

Recent Buzzwords:

1. **Virtual**: Virtual Storage, Virtual Machines, Virtual Computing, Virtual Networks, …
2. **Cloud**: Cloud Computing, Cloud Storage, Cloud-based Apps, …
3. **Smart**: Smart Phones, Smart Grid, Smart devices, …
4. **Open**: OpenFlow, OpenDaylight, OpenStack
5. **Software Defined**: Software defined networking, Software defined storage, Software defined data centers, …

Virtualization

- Internet ⇒ Virtualization of life ⇒ Virtual Networking

- No need to get out for
  - Office
  - Shopping
  - Education
  - Entertainment

- Virtual Workplace
- Virtual Shopping
- Virtual Education
- Virtual Sex
- Virtual Computing
- Virtual Storage

Virtualization Definition

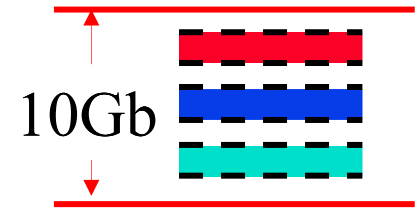
"Virtualization means that Applications can use a resource without any concern for where it resides, what the technical interface is, how it has been implemented, which platform it uses, and how much of it is available."

-Rick F. Van der Lans

in Data Virtualization for Business Intelligence Systems

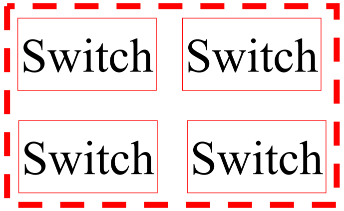
5 Reasons to Virtualize

1. Sharing: Break up a large resource
   Large Capacity or high-speed
   ⇒ Multi-Tenant



2. Isolation: Protection from other tenants

3. Aggregating: Combine many resources in to one



4. Dynamics: Fast allocation, Change/Mobility, Follow the sun (active users) or follow the moon (cheap power)

5. Ease of Management
   ⇒ Cost Savings. fault tolerance

Cloud Computing

- August 25, 2006: Amazon announced EC2 ⇒ Birth of Cloud Computing in reality (Prior theoretical concepts of computing as a utility)
- *Web Services To Drive Future Growth For Amazon* ($2B in 2012, $7B in 2019) - Forbes, Aug 12, 2012
- Cloud computing was made possible by computing virtualization
- **Networking**: Plumbing of computing
  - IEEE: Virtual Bridging, …
  - IETF: Virtual Routers, …
  - ITU: Mobile Virtual Operators, …

Smart Phones and Mobile Apps

- June 29, 2007: Apple announced iPhone
  $\Rightarrow$ Birth of Mobile Internet, Mobile Apps
- Almost all services are now mobile apps: Google, Facebook, Bank of America, …
- Almost all services need to be global (World is flat)
- Almost all services use cloud computing (Easy management)
- What's smart about smart phones?

Ref: Top 500 sites on the web, http://www.alexa.com/topsites

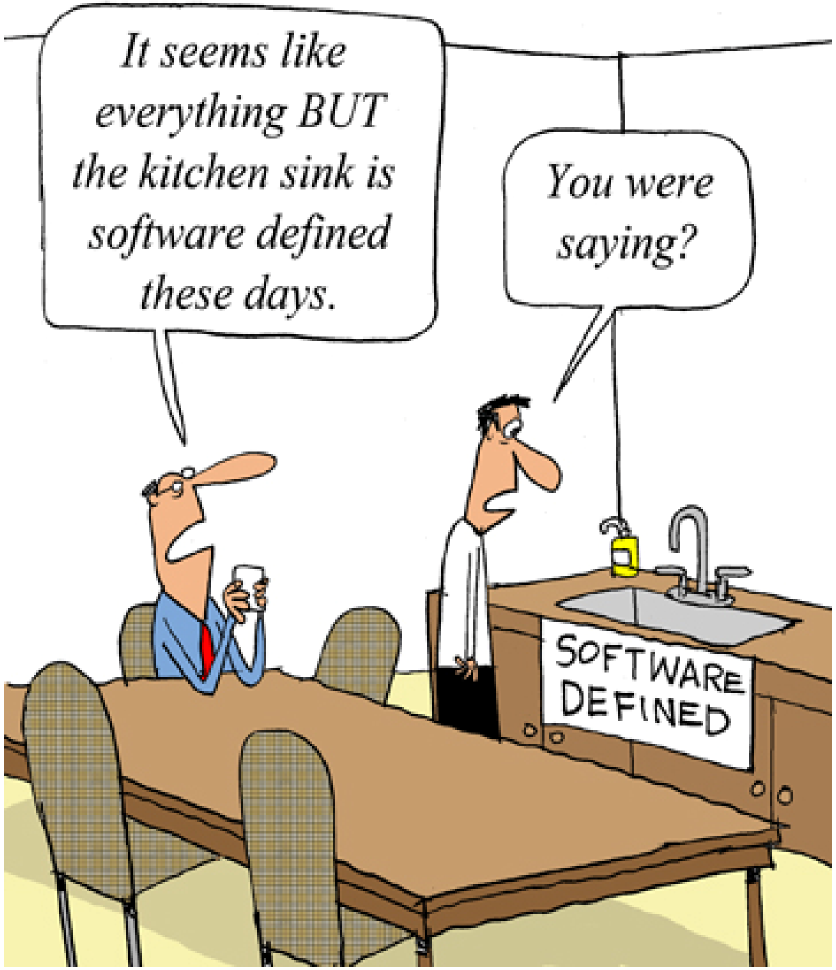
Software Defined Networking

- 2006: Martin Casado, a PhD student at Stanford and team propose a clean-slate security architecture (SANE) which defines a centralized control of security (in stead of at the edge as normally done). Ethane generalizes it to all access policies.
- April 2008: OpenFlow paper in ACM SIGCOMM CCR
- 2009: Stanford publishes OpenFlow V1.0.0 specs
- June 2009: Martin Casado co-founds Nicira
- March 2011: Open Networking Foundation is formed
- Oct 2011: First Open Networking Summit. Software Defined Networking is coined by Casado. Juniper, Cisco announce plans to incorporate.
- July 2012: VMware buys Nicira for $1.26B
- Nov 6, 2013: Cisco buys Insieme for $838M

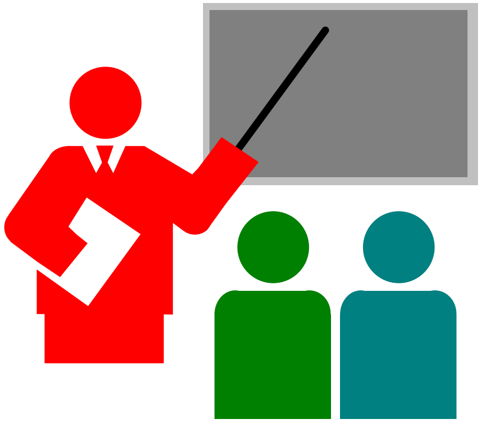
Ref: ONF, "The OpenFlow Timeline," http://openflownetworks.com/of_timeline.php

SDN Everywhere

- Software Defined Switches
- Software Defined Routers
- Software Defined Data Center
- Software Defined Storage
- Software Defined Base Stations
- Software Defined GPS
- Software Defined Radio
- Software Defined Infrastructure
- Software Defined Optical Switches

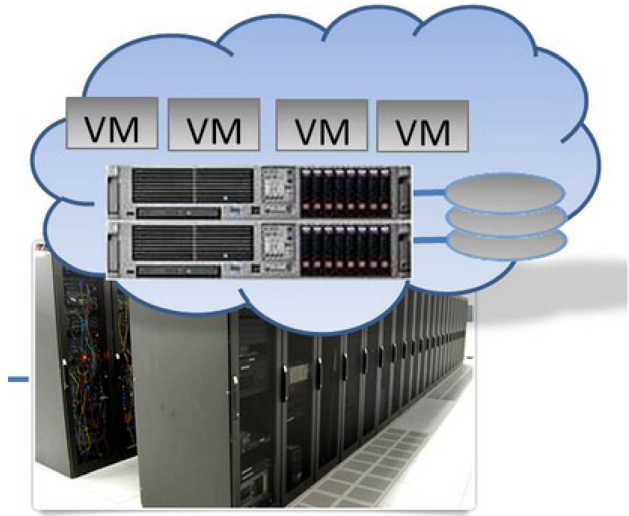


Recent Developments: Summary



1. Virtualization enables sharing a data center ⇒ Cloud computing
2. Cloud computing enables smart phones apps and enterprise computing
3. SDN allows managing and sharing a data center ⇒ Better Cloud Computing

Network Virtualization

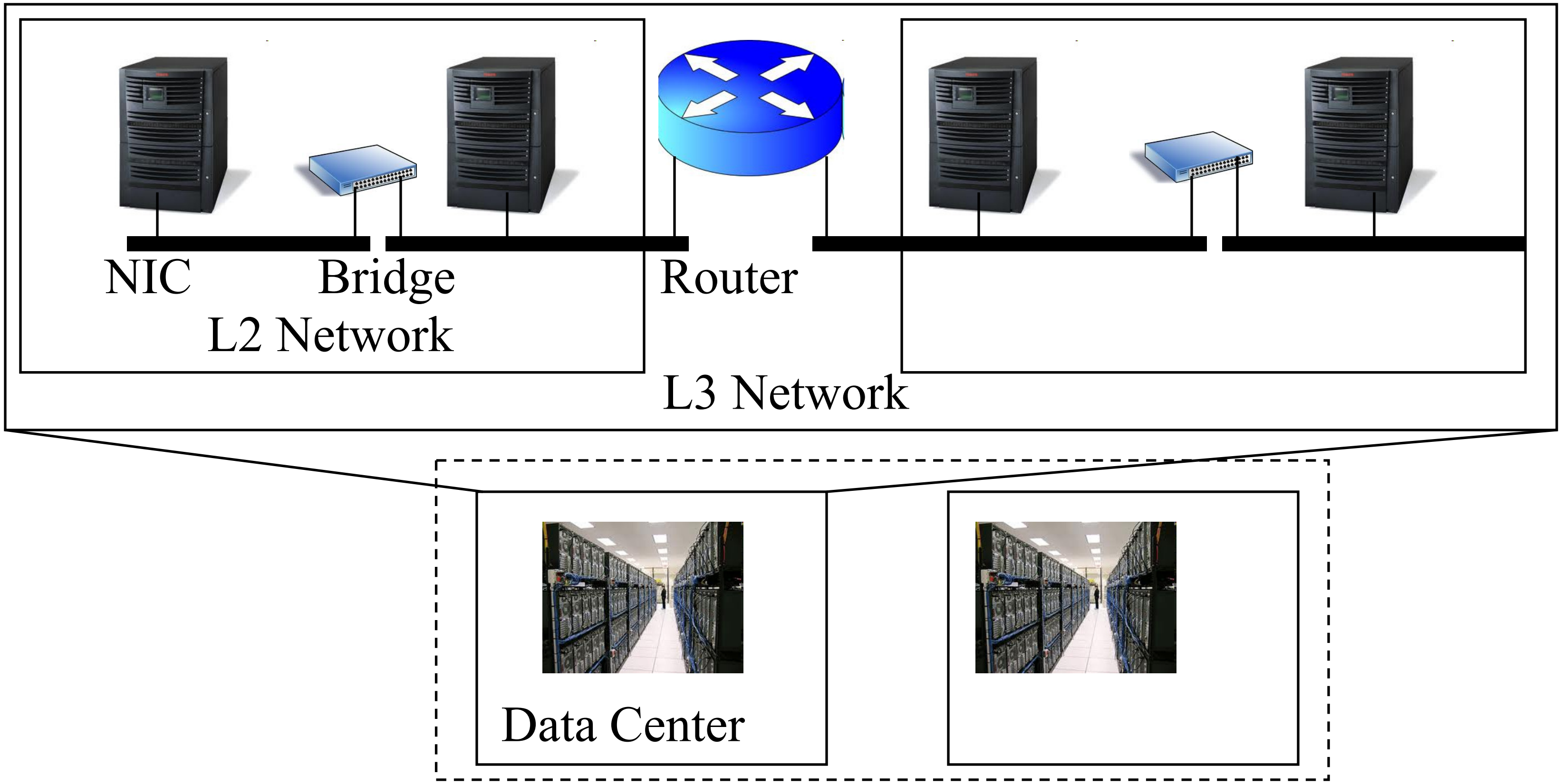


1. Levels of Network Virtualization
2. Network Virtualization Techniques
3. Names, IDs, Locators
4. Interconnection Devices
5. Fallacies Taught in Networking Classes

Why Virtualize a Network?

1. Network virtualization allows tenants to form an overlay network in a multi-tenant network such that tenant can control:
    1. Connectivity layer: Tenant network can be L2 while the provider is L3 and vice versa
    2. Addresses: MAC addresses and IP addresses
    3. Network Partitions: VLANs and Subnets
    4. Node Location: Move nodes freely
2. Network virtualization allows providers to serve a large number of tenants without worrying about:
    1. Internal addresses used in client networks
    2. Number of client nodes
    3. Location of individual client nodes
    4. Number and values of client partitions (VLANs and Subnets)
3. Network could be a single physical interface, a single physical machine, a data center, a metro, … or the global Internet.
4. Provider could be a system owner, an enterprise, a cloud provider, or a carrier.

Levels of Network Virtualization



- Networks consist of: **Network Interface Card (NIC)** – **L2 Links** - **L2 Bridges** - **L2 Networks** - L3 Links - L3 Routers - L3 Networks – **Data Centers** – **Global Internet.**
- Each of these needs to be virtualized

Network Virtualization Techniques

Entity	Partitioning	Aggregation/Extension/Interconnection**
NIC	SR-IOV	MR-IOV
Switch	VEB, VEPA	VSS, VBE, DVS, FEX
L2 Link	VLANs	LACP, Virtual PortChannels
L2 Network using L2	VLAN	PB (Q-in-Q), PBB (MAC-in-MAC), PBB-TE, Access-EPL, EVPL, EVP-Tree, EVPLAN
L2 Network using L3	NVO3, VXLAN, NVGRE, STT	MPLS, VPLS, A-VPLS, H-VPLS, PWoMPLS, PWoGRE, OTV, TRILL, LISP, L2TPv3, EVPN, PBB-EVPN
Router	VDCs, VRF	VRRP, HSRP
L3 Network using L1		GMPLS, SONET
L3 Network using L3*	MPLS, GRE, PW, IPSec	MPLS, T-MPLS, MPLS-TP, GRE, PW, IPSec
Application	ADCs	Load Balancers

*All L2/L3 technologies for L2 Network partitioning and aggregation can also be used for L3 network partitioning and aggregation, respectively, by simply putting L3 packets in L2 payloads.

**The aggregation technologies can also be seen as partitioning technologies from the provider point of view.

Names, IDs, Locators

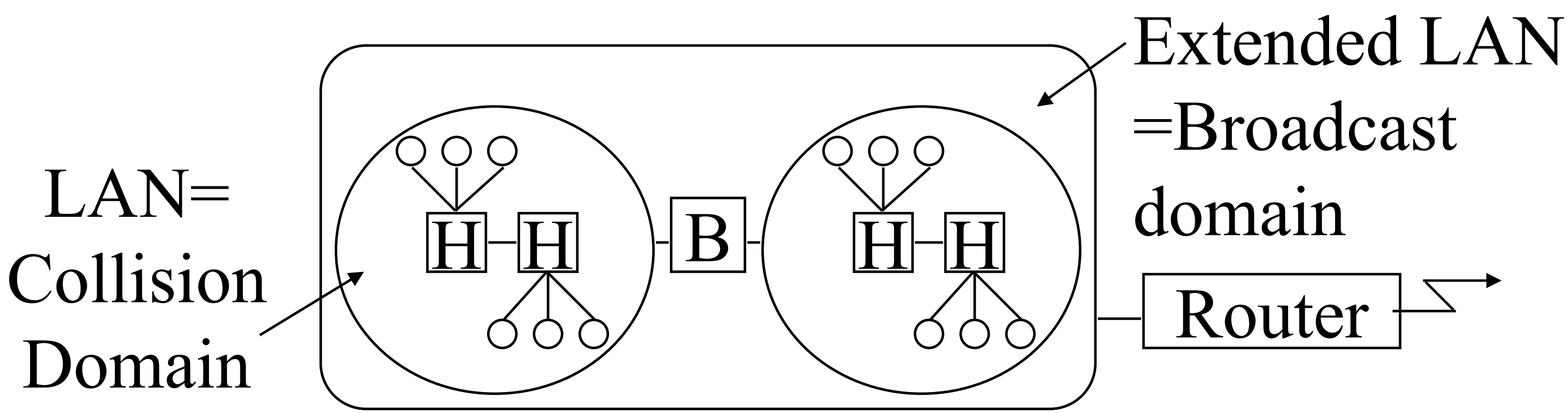
Name: John Smith

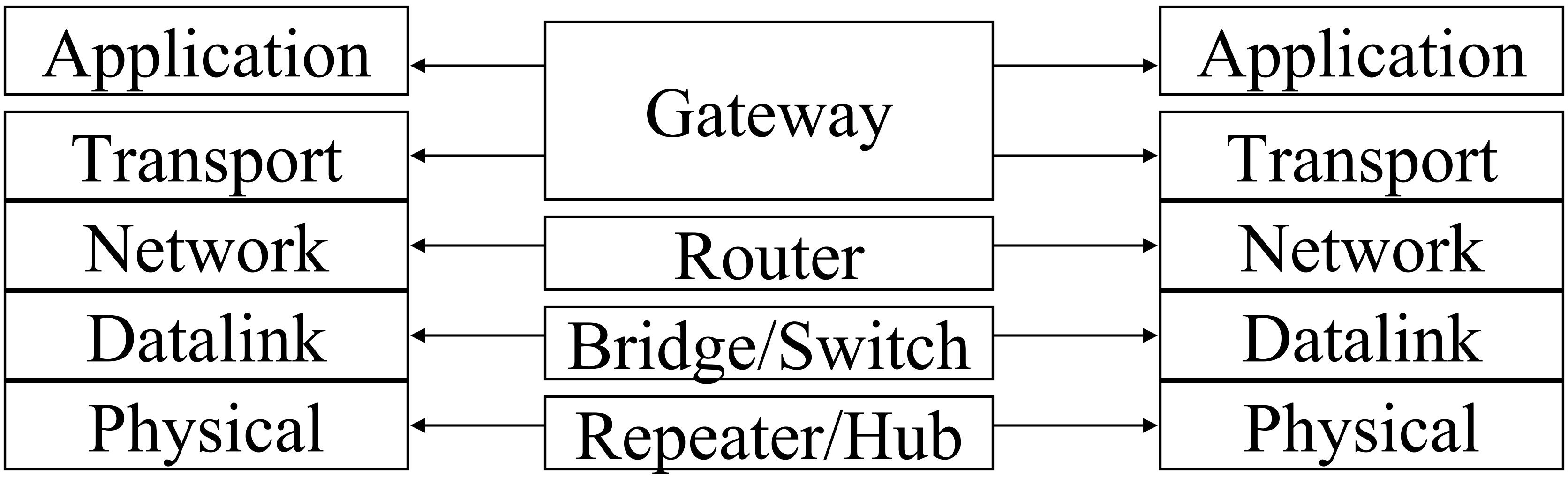
ID: 012-34-5678

Locator:
1234 Main Street
Big City, MO 12345
USA

- Locator changes as you move, ID and Names remain the same.
- **Examples**:
  - Names: Company names, DNS names (Microsoft.com)
  - IDs: Cell phone numbers, 800-numbers, Ethernet addresses, Skype ID, VOIP Phone number
  - Locators: Wired phone numbers, IP addresses

Interconnection Devices





Interconnection Devices (Cont)

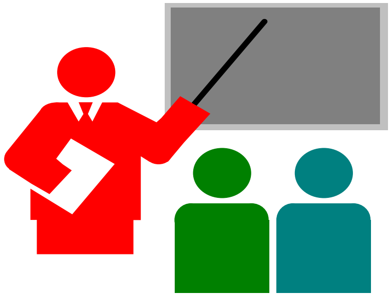
- **Repeater**: PHY device that restores data and collision signals
- **Hub**: Multiport repeater + fault detection and recovery
- **Bridge**: Datalink layer device connecting two or more collision domains. MAC multicasts are propagated throughout "extended LAN."
- **Router**: Network layer device. IP, IPX, AppleTalk. Does not propagate MAC multicasts.
- **Switch**: Multiport bridge with parallel paths
- These are functions. Packaging varies.

Fallacies Taught in Networking Classes

1. Ethernet is a local area network (Local $\leq$ 2km)
2. Token ring, Token Bus, and CSMA/CD are the three most common LAN access methods.
3. Ethernet uses CSMA/CD.
   No CSMA/CD in 10G and up
   No CSMA/CD in practice now even at home or at 10 Mbps
4. Ethernet bridges use spanning tree for packet forwarding.
5. Ethernet frames are limited to 1518 bytes.
6. Ethernet does not provide any delay guarantees.
7. Ethernet has no congestion control.
8. Ethernet has strict priorities.

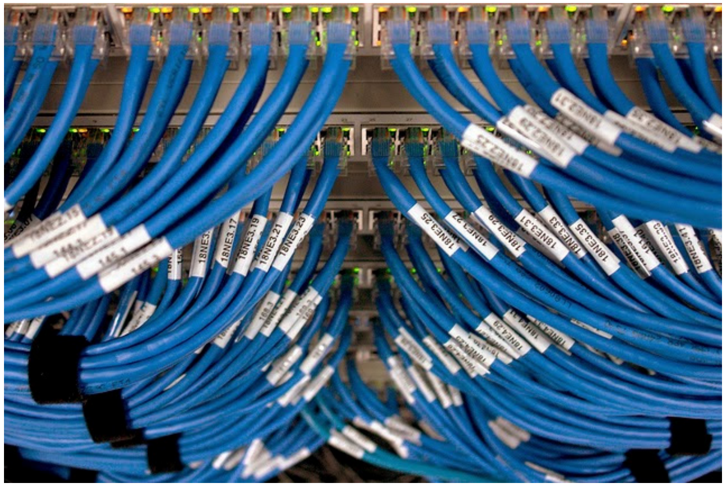
Ethernet has changed.
All of these are now false or are becoming false.

Network Virtualization: Summary



1. Virtualization allows applications to use resources without worrying about its location, size, format etc.
2. Ethernet's use of IDs as addresses makes it very easy to move systems in the data center ⇒ Keep traffic on the same Ethernet
3. Cloud computing requires Ethernet to be extended globally and partitioned for sharing by a very large number of customers who have complete control over their address assignment and connectivity
4. Many of the previous limitations of Ethernet have been overcome in the last few years.

Ethernet in Data Center



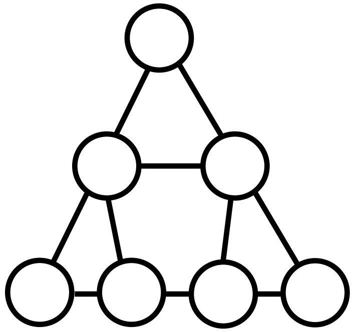
1. Residential vs. Data Center Ethernet
2. Spanning Tree and its Enhancements
3. Shortest Path Bridging
4. Virtual Bridges to connect virtual machines
5. IEEE Virtual Edge Bridging Standard:VEB, VEPA
6. Bridges with massive number of ports: VBE

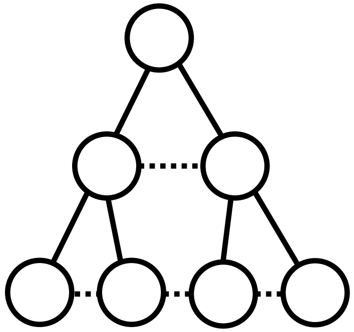
Residential vs. Data Center Ethernet

Residential	**Data Center/Cloud**
❑ Distance: up to 200m	❑ No limit
❑ Scale: ➢ Few MAC addresses ➢ 4096 VLANs	 ❑ Millions of MAC Addresses ❑ Millions of VLANs Q-in-Q
❑ Protection: Spanning tree	❑ Rapid spanning tree, … (Gives 1s, need 50ms)
❑ Path determined by spanning tree	❑ Traffic engineered path
❑ Simple service	❑ Service Level Agreement. Rate Control.
❑ Priority ⇒ Aggregate QoS	❑ Need per-flow/per-class QoS
❑ No performance/Error monitoring (OAM)	❑ Need performance/BER

Spanning Tree and its Enhancements

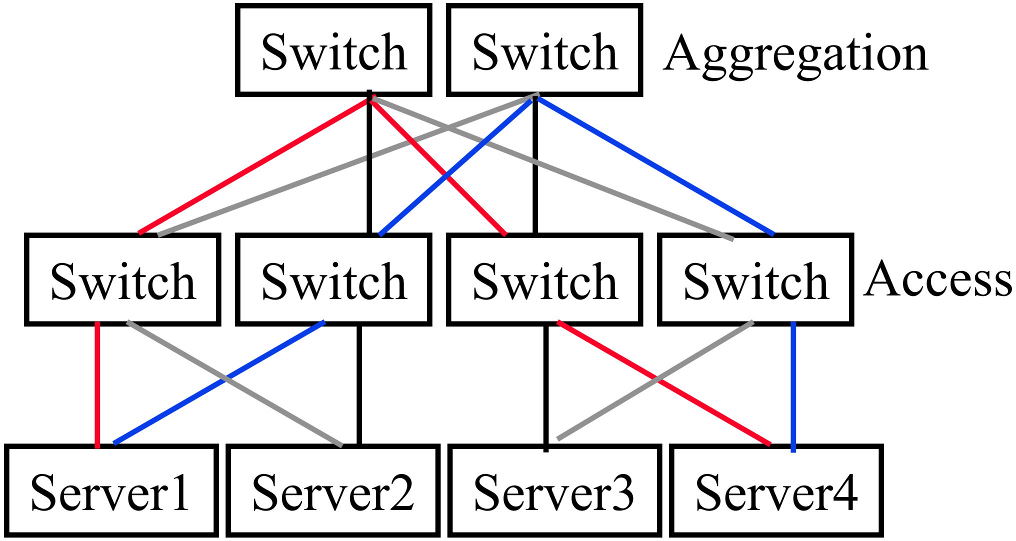
- Helps form a tree out of a mesh topology
- A topology change can result in 1 minute of traffic loss with STP ⇒ All TCP connections break
- Rapid Spanning Tree Protocol (RSTP) IEEE 802.1w-2001 incorporated in IEEE 802.1D-2004
- One tree for all VLANs ⇒ Common spanning tree
- Many trees ⇒ Multiple spanning tree (MST) protocol IEEE 802.1s-2002 incorporated in IEEE 802.1Q-2005
- One or more VLANs per tree.





Shortest Path Bridging

- IEEE 802.1aq-2012
- Allows all links to be used ⇒ Better CapEx
- IS-IS link state protocol (similar to OSPF) is used to build shortest path trees for each node to every other node within the SPB domain
- Equal-cost multi-path (ECMP) used to distribute load

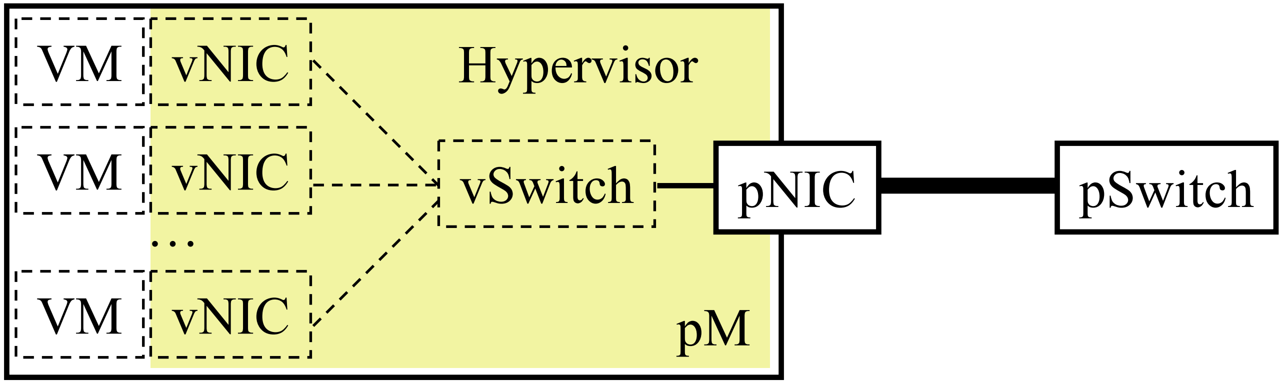


Ref: http://en.wikipedia.org/wiki/Shortest_Path_Bridging

http://www.cse.wustl.edu/~jain/tutorials/medes14.htm

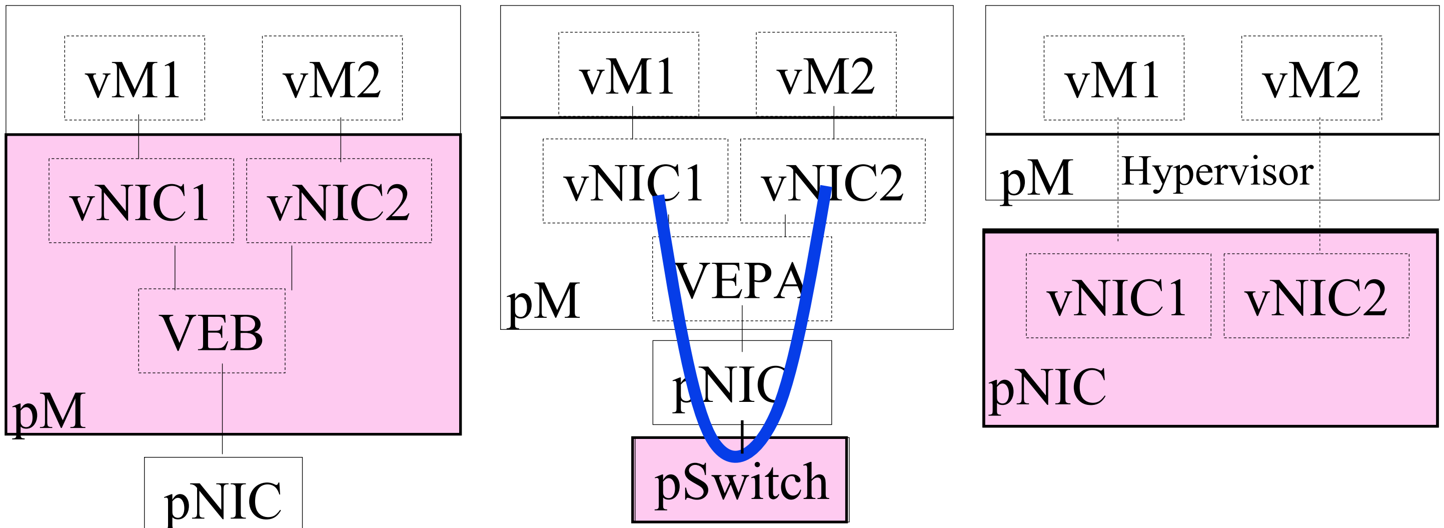
vSwitch

- **Problem**: Multiple VMs on a server need to use one physical network interface card (pNIC)
- **Solution**: Hypervisor creates multiple vNICs connected via a virtual switch (vSwitch)
- pNIC is controlled by hypervisor and not by any individual VM
- **Notation**: From now on prefixes p and v refer to physical and virtual, respectively. For VMs only, we use upper case V.



Ref: G. Santana, "Datacenter Virtualization Fundamentals," Cisco Press, 2014, ISBN: 1587143240

Virtual Bridging

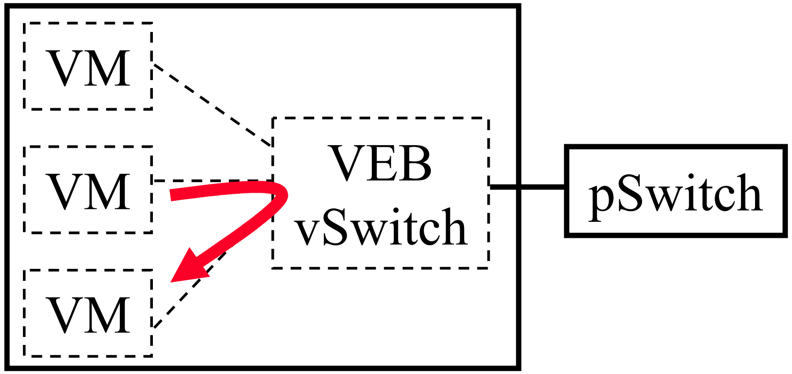


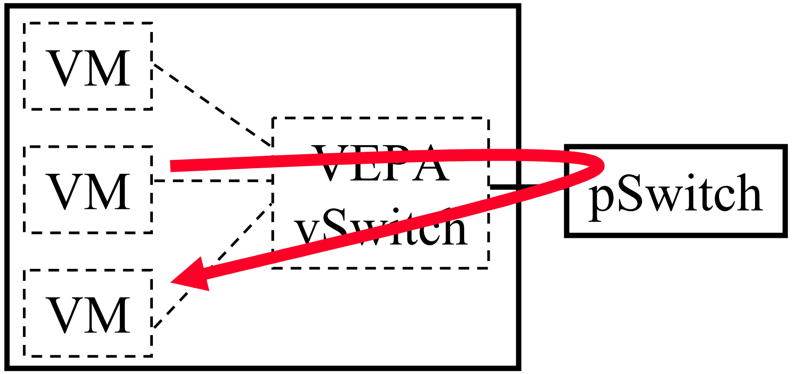
Where should most of the tenant isolation take place?

1. VM vendors: S/W NICs in Hypervisor w Virtual Edge Bridge (**VEB**)(overhead, not ext manageable, not all features)
2. Switch Vendors: Switch provides virtual channels for inter-VM Communications using virtual Ethernet port aggregator (**VEPA**): **802.1Qbg** (s/w upgrade)
3. NIC Vendors: NIC provides virtual ports using Single-Route I/O virtualization (**SR-IOV**) on PCI bus

Virtual Edge Bridge

- IEEE 802.1Qbg-2012 standard for vSwitch
- Two modes for vSwitches to handle *local* VM-to-VM traffic:
  - **Virtual Edge Bridge (VEB):** Switch internally.
  - **Virtual Ethernet Port Aggregator (VEPA):** Switch externally
- VEB
  - could be in a hypervisor or network interface card
  - may learn or may be configured with the MAC addresses
  - VEB may participate in spanning tree or may be configured\
  - Advantage: No need for the external switch in some cases





Virtual Ethernet Port Aggregator (VEPA)

- VEPA simply relays all traffic to an external bridge
- External bridge forwards the traffic. Called "*Hairpin Mode*." Returns local VM traffic back to VEPA
  Note: Legacy bridges do not allow traffic to be sent back to the incoming port within the same VLAN
- **VEPA Advantages**:
  - Visibility: External bridge can see VM to VM traffic.
  - Policy Enforcement: Better. E.g., firewall
  - Performance: Simpler vSwitch $\Rightarrow$ Less load on CPU
  - Management: Easier
- Both VEB and VEPA can be implemented on the same NIC in the same server and can be cascaded.

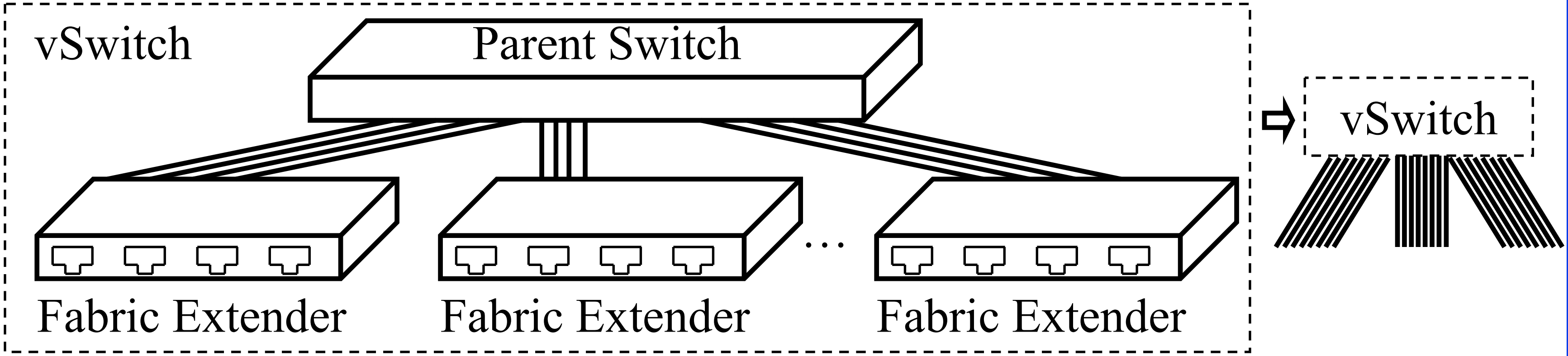
Ref: HP, "Facts about the IEEE 802.1Qbg proposal," Feb 2011, 6pp., http://h20000.www2.hp.com/bc/docs/support/SupportManual/c02877995/c02877995.pdf

Combining Bridges

- **Problem**:
  - Number of VMs is growing very fast
  - Need switches with very large number of ports
  - Easy to manage one bridge than 100 10-port bridges
  - How to make very large switches ~1000 ports?
- **Solutions**: Multiple pSwitches to form a single switch
  1. Fabric Extension (FEX)
  2. Virtual Bridge Port Extension (VBE)

Fabric Extenders

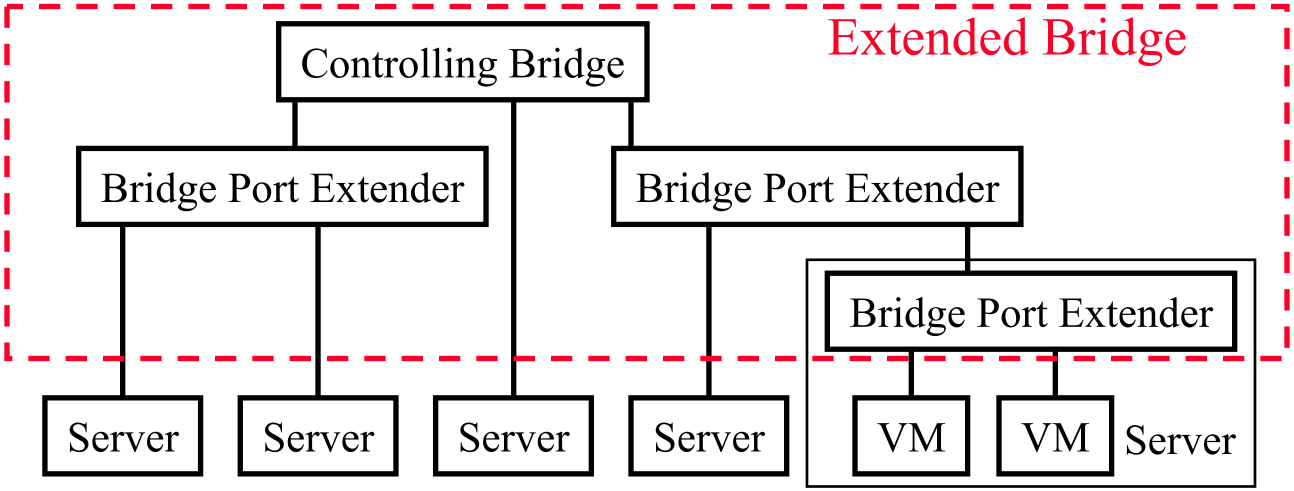
- Fabric extenders (FEX) consists of ports that are managed by a remote parent switch
- 12 Fabric extenders, each with 48 host ports, connected to a parent switch via 4-16 10 Gbps interfaces to a parent switch provide a virtual switch with 576 host ports
  ⇒ **Chassis Virtualization**
- All software updates/management, forwarding/control plane is managed centrally by the parent switch.
- A FEX can have an active and a standby parent.



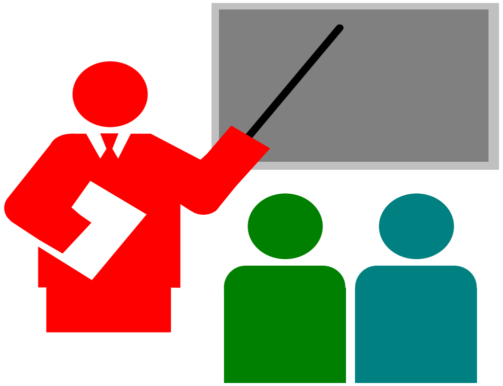
Ref: P. Beck, et al., "IBM and Cisco: Together for a World Class Data Center," IBM Red Book, 2013, 654 pp., ISBN: 0-7384-3842-1, http://www.redbooks.ibm.com/redbooks/pdfs/sg248105.pdf

Virtual Bridge Port Extension (VBE)

- IEEE 802.1BR-2012 standard for fabric extender functions
- Specifies how to form an extended bridge consisting of a controlling bridge and Bridge Port Extenders
- Extenders can be cascaded.
- Some extenders may be in a vSwitch in a server hypervisor.
- All traffic is relayed by the controlling bridge
  $\Rightarrow$ Extended bridge is a bridge.



Virtual Bridging: Summary



1. Network virtualization includes virtualization of NICs, Bridges, Routers, and L2 networks.
2. Virtual Edge Bridge (VEB) vSwitches switch internally while Virtual Ethernet Port Aggregator (VEPA) vSwitches switch externally.
3. Fabric Extension and Virtual Bridge Extension (VBE) allows creating switches with a large number of ports using port extenders (which may be vSwitches)

OpenFlow

1. Planes of Networking
2. OpenFlow
3. OpenFlow Operation
4. OpenFlow Evolution

Planes of Networking

- **Data Plane**: All activities involving as well as resulting from data packets sent by the end user, e.g.,
  - Forwarding
  - Fragmentation and reassembly
  - Replication for multicasting
- **Control Plane**: All activities that are necessary to perform data plane activities but do not involve end-user data packets
  - Making routing tables
  - Setting packet handling policies (e.g., security)

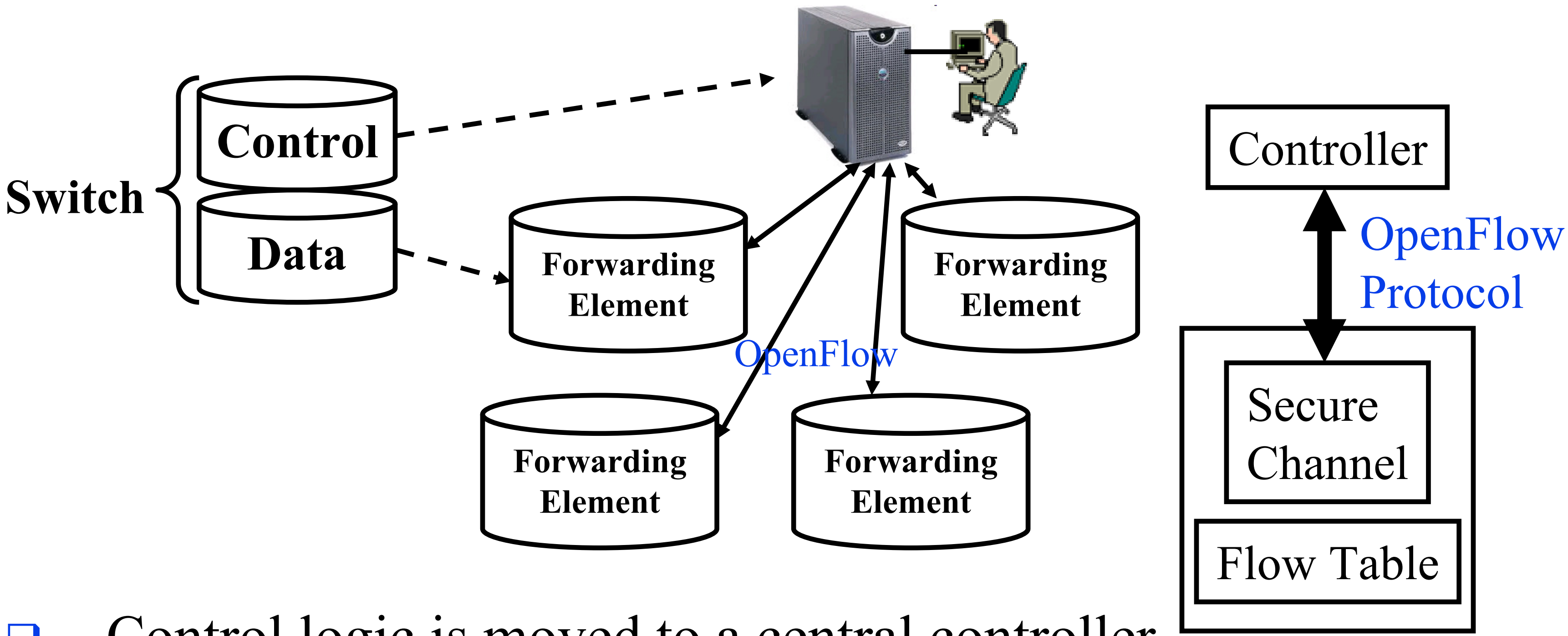
Dest.	Output Port	Next Hop

Ref: Open Data Center Alliance Usage Model: Software Defined Networking Rev 1.0,"
http://www.opendatacenteralliance.org/docs/Software_Defined_Networking_Master_Usage_Model_Rev1.0.pdf

Planes of Networking (Cont)

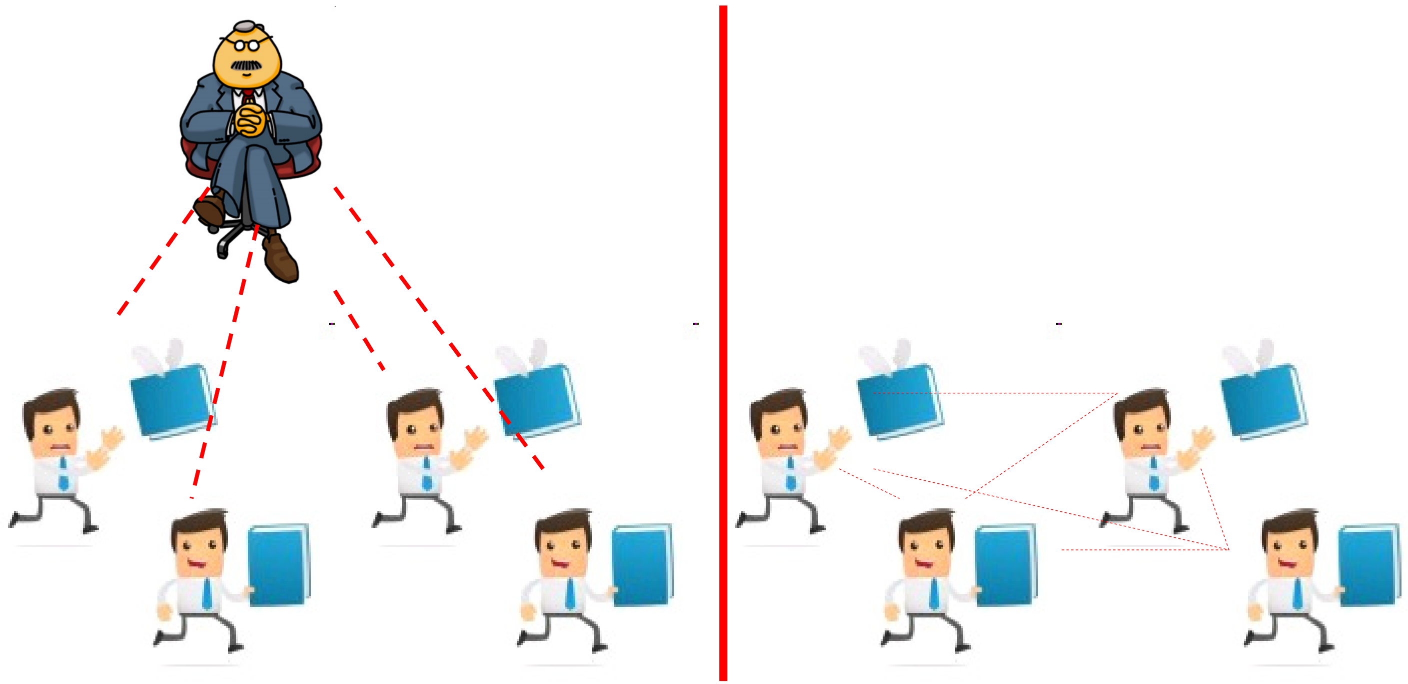
- **Management Plane**: All activities related to provisioning and monitoring of the networks
  - Fault, Configuration, Accounting, Performance and Security (**FCAPS**).
  - Instantiate new devices and protocols (Turn devices on/off)
  - Optional ⇒ May be handled manually for small networks.
- **Services Plane**: Middlebox services to improve performance or security, e.g.,
  - Load Balancers, Proxy Service, Intrusion Detection, Firewalls, SSL Off-loaders
  - Optional ⇒ Not required for small networks

Separation of Control and Data Plane



- Control logic is moved to a central controller
- Switches only have forwarding elements
- One expensive controller with a lot of cheap switches
- OpenFlow is the protocol to send/receive forwarding rules from controller to switches
- Flow based: Rules for each flow

Centralization of Control Plane



Centralized vs. **Distributed**

- Consistency
- Fast Response to changes
- Easy management of lots of devices

Networking and Religion

Both are based on a set of beliefs

OpenFlow V1.0

- On packet arrival, match the header fields with flow entries in a table, if any entry matches, update the counters indicated in that entry and perform indicated actions

Flow Table:

Header Fields	Counters	Actions
Header Fields	Counters	Actions
…	…	…
Header Fields	Counters	Actions

Ingress Port	Ether Source	Ether Dest	VLAN ID	VLAN Priority	IP Src	IP Dst	IP Proto	IP ToS	Src L4 Port	Dst L4 Port

Ref: http://archive.openflow.org/documents/openflow-spec-v1.0.0.pdf

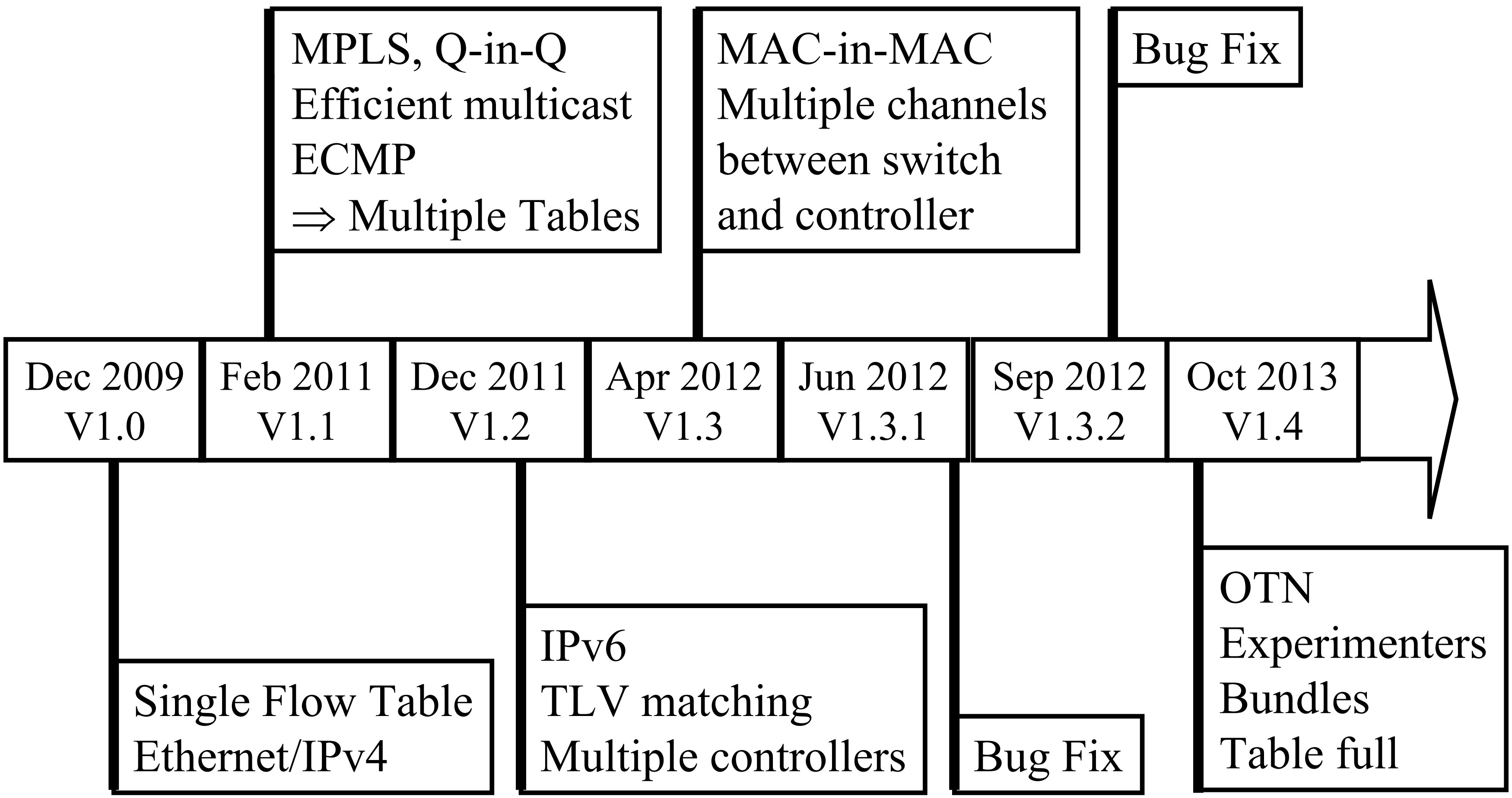
Flow Table Example

Port	Src MAC	Dst MAC	VLAN ID	Priority	EtherType	Src IP	Dst IP	IP Proto	IP ToS	Src L4 Port ICMP Type	Dst L4 Port ICMP Code	Action	Counter
*	*	0A:C8:*	*	*	*	*	*	*	*	*	*	Port 1	102
*	*	*	*	*	*	*	192.168.*.*	*	*	*	*	Port 2	202
*	*	*	*	*	*	*	*	*	*	21	21	Drop	420
*	*	*	*	*	*	*	*	0x806	*	*	*	Local	444
*	*	*	*	*	*	*	*	0x1*	*	*	*	Controller	1

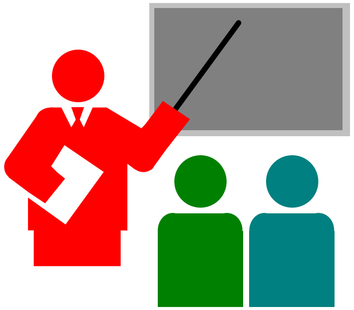
- Idle timeout: Remove entry if no packets received for this time
- Hard timeout: Remove entry after this time
- If both are set, the entry is removed if either one expires.

Ref: S. Azodolmolky, "Software Defined Networking with OpenFlow," Packt Publishing, October 2013, 152 pp., ISBN:978-1-84969-872-6 (Safari Book)

OpenFlow Evolution Summary



Summary: OpenFlow



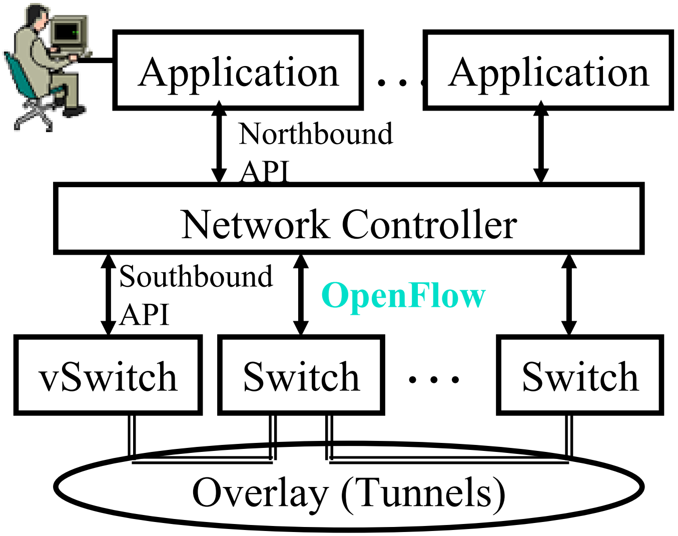
1. Four planes of Networking: Data, Control, Management, Service
2. OpenFlow separates control plane and moves it to a central controller ⇒ Simplifies the forwarding element
3. Switches match incoming packets with flow entries in a table and handle it as instructed. The controller supplies the flow tables and other instructions.
4. OpenFlow has been extended to IPv4, MPLS, IPv6, and Optical Network. But more work ahead.

Software Defined Networking (SDN)

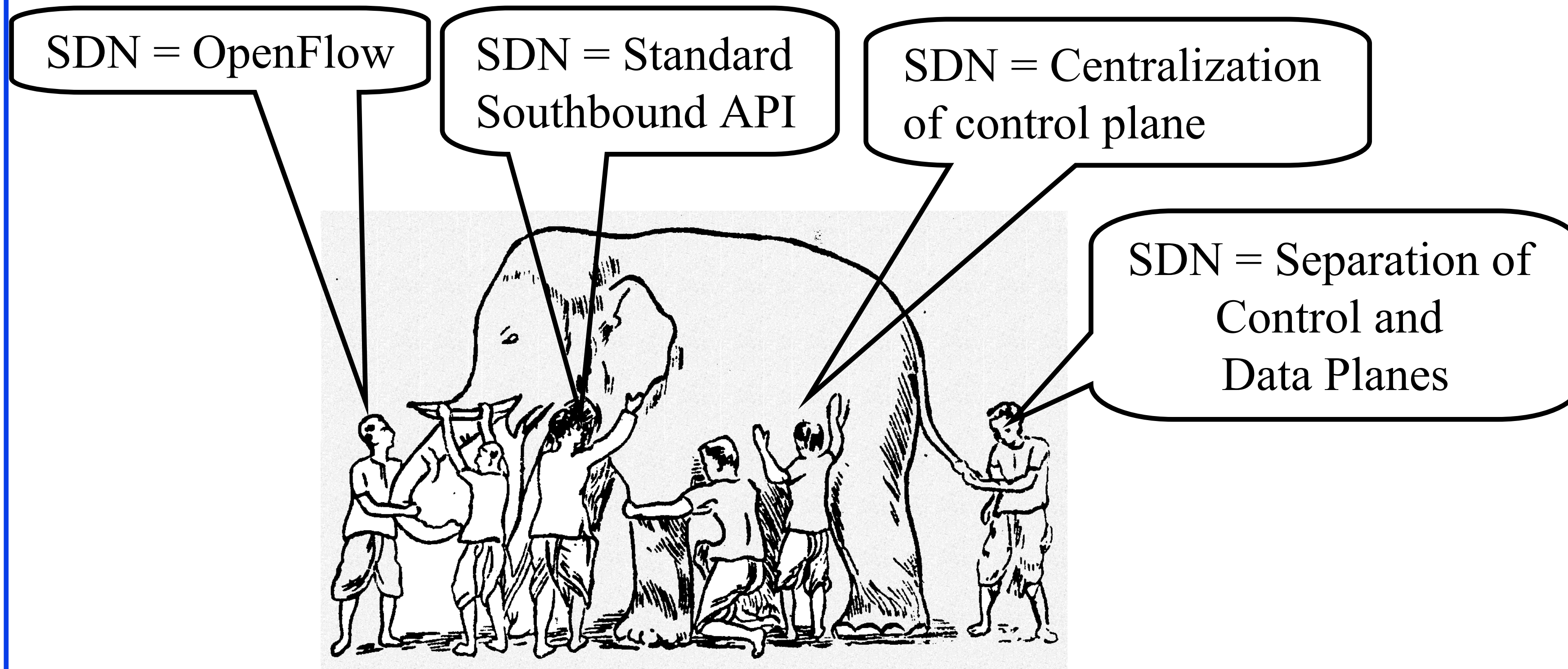
- What really is SDN?
- Alternatives to OpenFlow
- OpenDaylight SDN Controller Platform and Tools

SDN 1.0: SDN Based on OpenFlow

- SDN originated from OpenFlow
- Centralized Controller
  ⇒ Easy to program
  ⇒ Change routing policies on the fly
  ⇒ Software Defined Network (SDN)
- Initially, SDN = OpenFlow



What is SDN?



- All of these are mechanisms.
- SDN is *not* about a mechanism.
- It is a framework to solve a set of problems ⇒ Many solutions

ONF Definition of SDN

"What is SDN?

The physical separation of the network control plane from the forwarding plane, and where a control plane controls several devices."

1. Directly programmable
2. Agile: *Abstracting control from forwarding*
3. Centrally managed
4. Programmatically configured
5. Open standards-based vendor neutral

The above definition includes *How*.

Now many different opinions about ***How***.

⇒SDN has become more general.

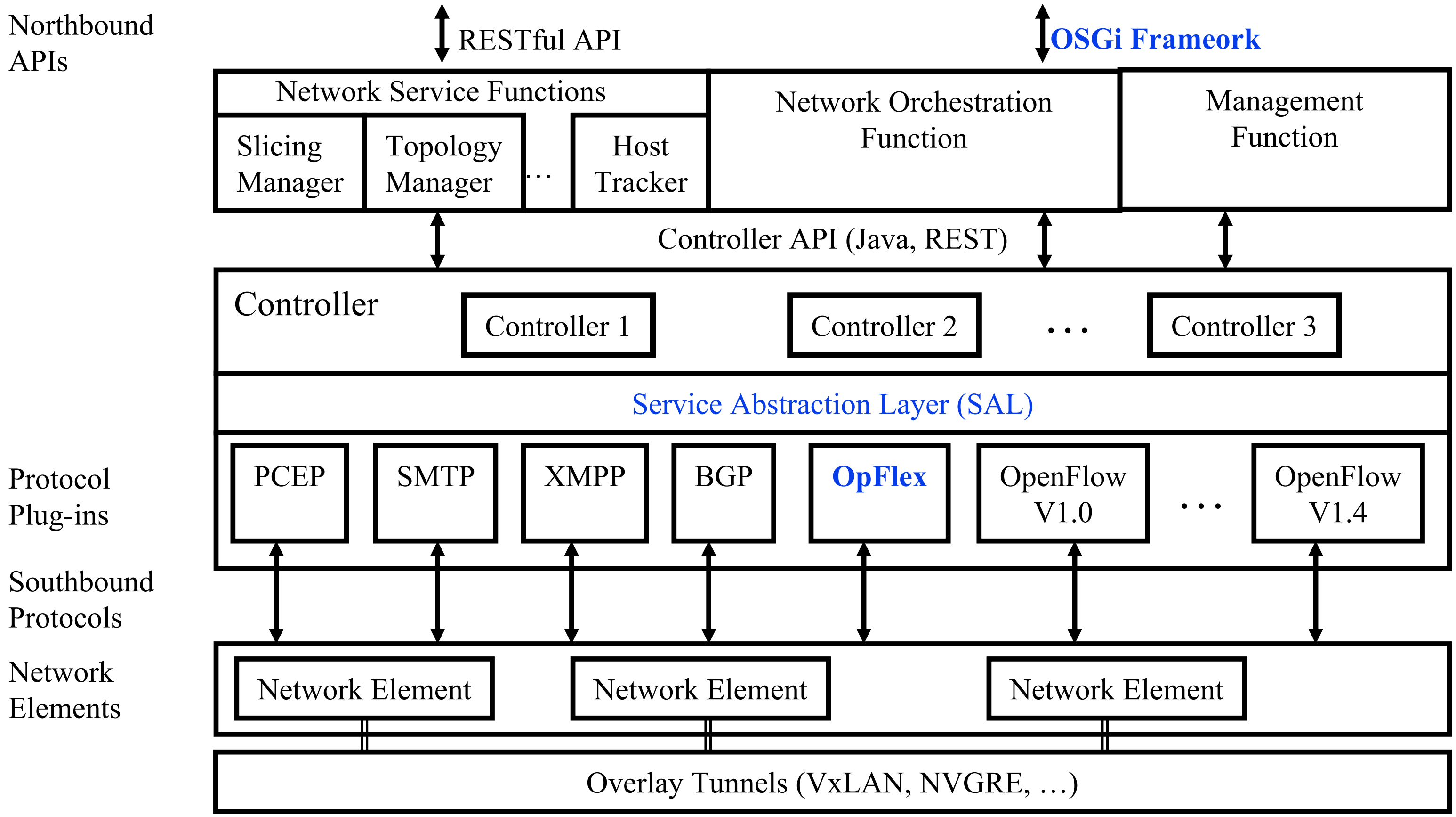
Need to define by ***What***?

Ref: https://www.opennetworking.org/index.php?option=com_content&view=article&id=686&Itemid=272&lang=en

What do We need SDN for?

1. **Virtualization**: Use network resource 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 size, quantity
5. **Automation**: Lower OpEx
6. **Visibility**: Monitor resources, connectivity
7. **Performance**: Optimize network device utilization
8. **Multi-tenancy**: Sharing expensive infrastructure
9. **Service Integration**
10. **Openness**: Full choice of Modular plug-ins
11. **Unified management** of computing, networking, and storage

SDN 2.0: OpenDaylight Style SDN



- **NO-OpenFlow** (**Not Only** OpenFlow) Multi-Protocol
- New work in **IETF** XMPP, ALTO, I2RS, PCEP, ….
- Linux Foundation

Open Everything

- Open Networking Foundation
- OpenFlow
- OpenStack
- OpenDaylight
- Open Access
- Open Source

Current SDN Debate: What vs. How?

- SDN is easy if control plane is centralized but not necessary. Distributed solutions may be required for legacy equipment and for fail-safe operation.
- Complete removal of control plane may be harmful. Exact division of control plane between centralized controller and distributed forwarders is yet to be worked out
- SDN is easy with a standard southbound protocol like OpenFlow but one protocol may not work/scale in all cases
  - Diversity of protocols is a fact of life.
  - There are no standard operating systems, processors, routers, or Ethernet switches.
- If industry finds an easier way to solve the same problems by another method, that method may win. E.g., ATM vs. MPLS.

How to SDN?

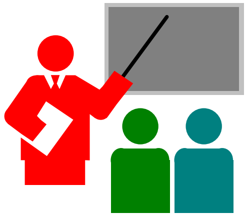
Separation vs. Centralization

Separation of Control Plane

Centralization of Control ~~Plane~~

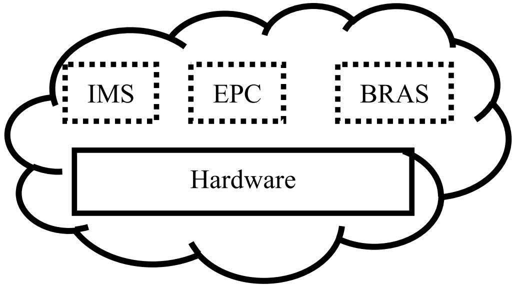
Micromanagement is not scalable

Summary: SDN



1. SDN is the framework to automatically manage and control a large number of network devices and services in a multi-tenant environment
2. OpenFlow originated SDN but now many different southbound and northbound APIs, intermediate services and tools are being discussed and implemented by the industry, e.g., XMPP, ForCES, PCE, ALTO
3. OpenDaylight SDN Controller platform is the leading open source SDN controller project under Linux Foundation
4. Its modular implementation allows many southbound protocols

Network Function Virtualization (NFV)

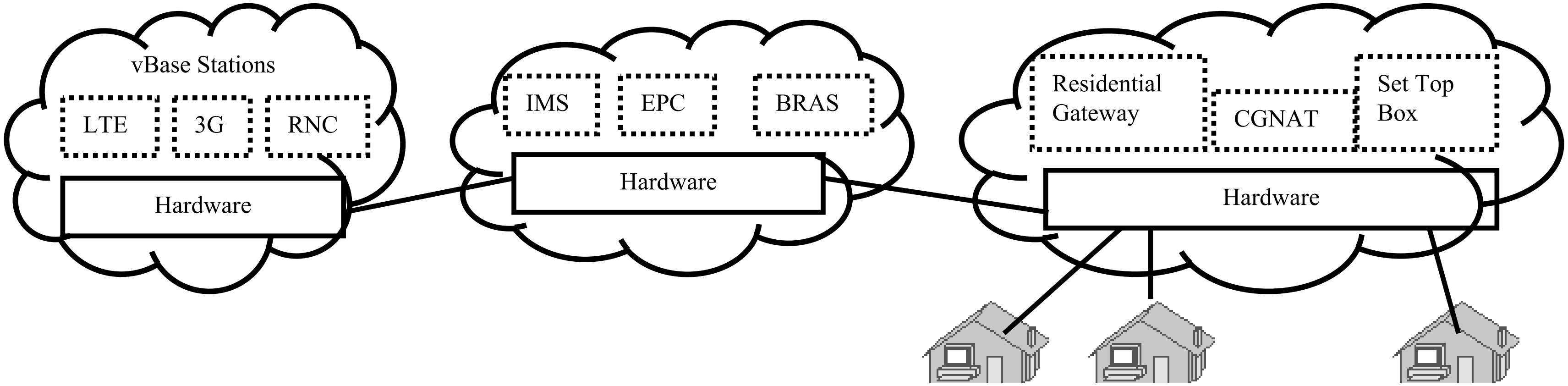


1. What is NFV?
2. NFV and SDN Relationship
3. Proof-of-Concepts

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



Ref: ETSI, "NFV – Update White Paper," Oct 2013, http://www.tid.es/es/Documents/NFV_White_PaperV2.pdf (Must read)

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)

NFV Proof of Concepts (PoCs)

ETSI has formed and NFV ISG PoC Forum.
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/

Service-Infrastructure Separation

- With cloud computing, anyone can super-compute on demand.
  - Physical infrastructure is owned by Cloud Service Provider (CSP). Tenants get virtual infrastructure
  - **Win-Win** combination
- With virtualization, an ISP can set up all virtual resources on demand
  - Physical Infrastructure owned by NFV infrastructure service provider (NSP) and tenant ISPs get virtual NFVI services
  - **Win-Win** combination

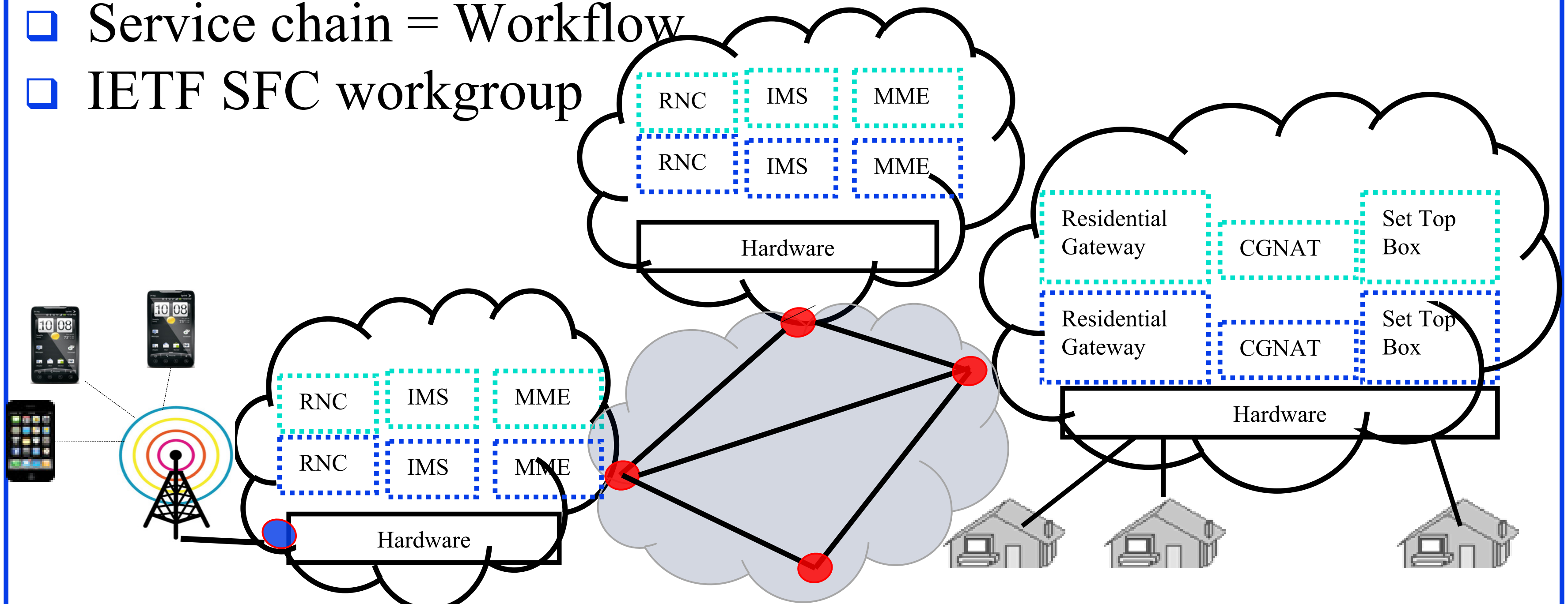
What can NFV do?

1. **Virtualization**: Use network resource 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 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

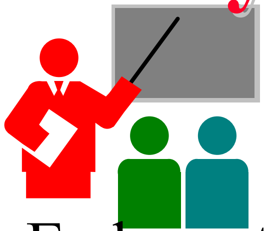
Note: These are almost the **same** reasons why we need SDN.

Service Chaining

- VNFs (Virtual network fns) 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
- IETF SFC workgroup



Summary: NFV

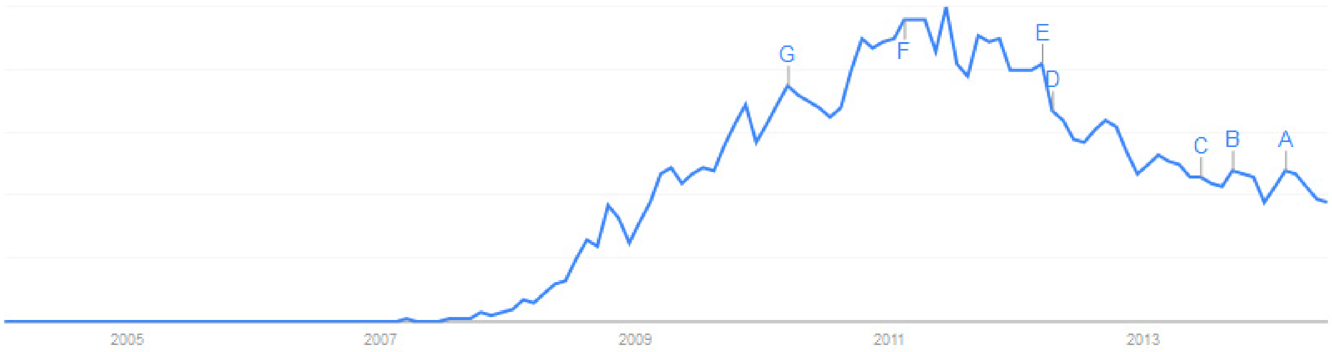


1. NFV aims to reduce OpEx by automation and scalability provided by implementing network functions as virtual appliances
2. NFV allows all benefits of virtualization and cloud computing including orchestration, scaling, automation, hardware independence, pay-per-use, fault-tolerance, …
3. NFV and SDN 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. Several of virtual functions have already been demonstrated by carriers.

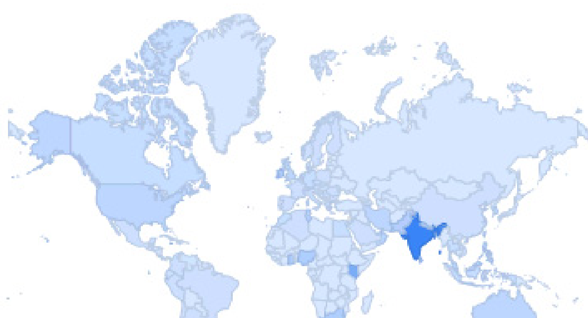
Multi-Cloud Computing

1. Google Trends: Cloud Computing
2. Any Function Virtualization (FV)
3. Trend: Multi-Clouds
4. Inter-Cloud Problem
5. Services in a Cloud of Clouds

Google Trends: Cloud Computing



Regional interest



Region | Town/City

India	100	
Kenya	57	
Singapore	38	
Sri Lanka	32	
Jamaica	30	

Cloud Computing started in 2007 and is now past the peak

Ref: http://www.google.com/trends/explore#q=cloud%20computing

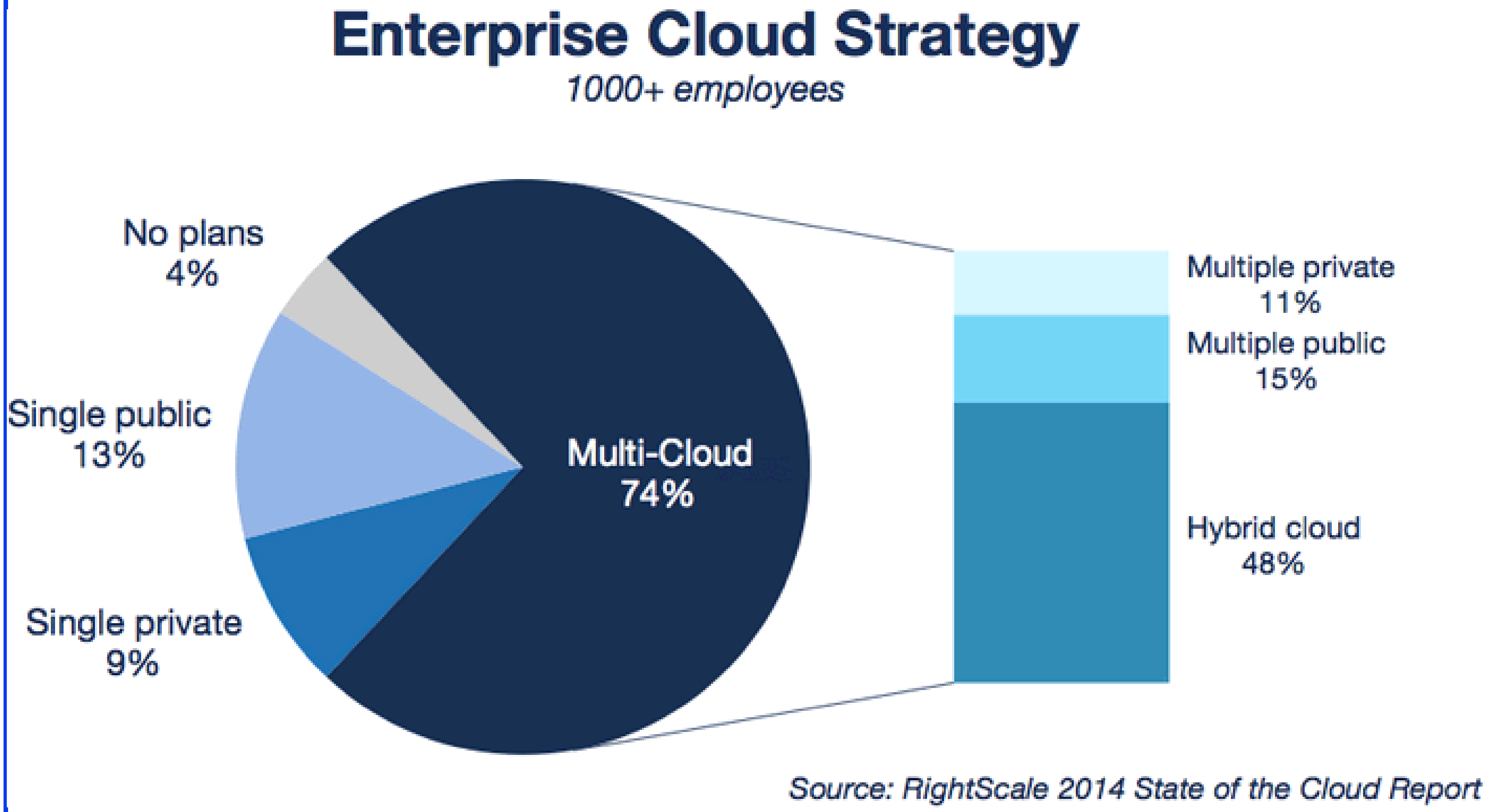
Any Function Virtualization (FV)

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

Enterprise App Market: Lower CapEx

Virtual IP Multimedia System

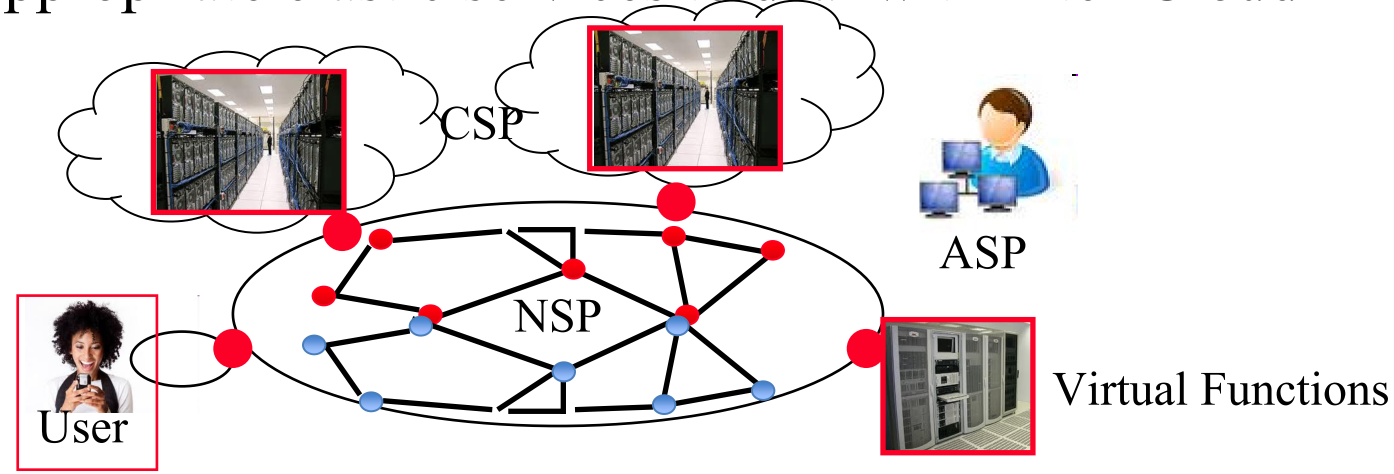
Trend: Multi-Clouds



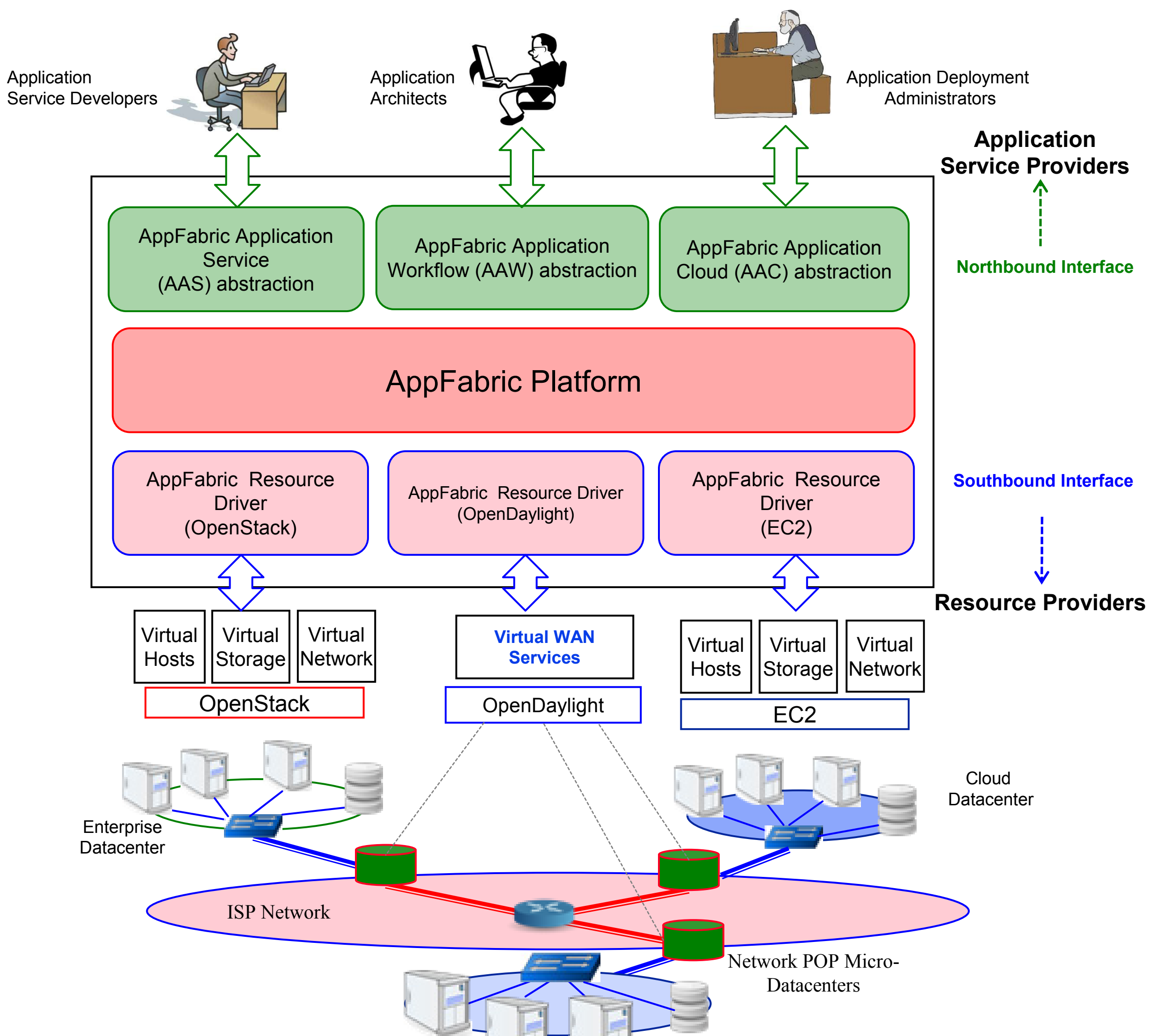
Ref: http://www.rightscale.com/blog/cloud-industry-insights/cloud-computing-trends-2014-state-cloud-survey

Multi-Cloud Problem

- **Cloud Service Providers (CSPs):** Provide elastic computing, storage, and networking inside the cloud and among their own clouds
- **Application Service Providers**: Need to be able to mix and match cloud providers to Follow the Sun or Follow the Moon.
- **Network Service Providers (NSPs):** No appropriate elastic services to deal with Inter-Cloud



Services in a Cloud of Clouds



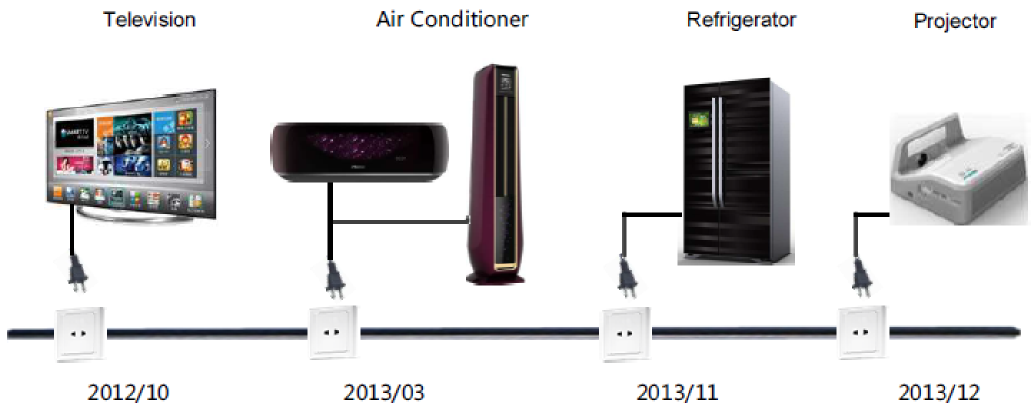
AppFabric Features

- Allows **application architects** to specify guidelines for creation of new workflows including middleboxes
- Allows **application developers** to specify their resource requirements and design their application without worrying about physical infrastructure
- Allows **Deployment Administrators** specify policies for quantity and location of resources inside various clouds.
- **Automates** the entire process of creating new workflows and installing them, managing them during runtime, uninstalling them as necessary
- Workflow creation includes virtual networks, computers, storage inside the clouds as well as the network between the clouds
- **WAN bandwidth** and latency is the key to placement. Allows manual approval and override.
- All interfaces initially XML based. GUI based in future.

Multi-Cloud Computing: Summary

1. Function virtualization in enterprises will result in enterprise apps that will be instantiated on demand in multiple clouds
2. AppFabric provides an automated management of multi-cloud application delivery

Internet of Things



1. What are Things?
2. What's Smart?
3. Why IoT Now?
4. Business/Research Opportunities in IoT
5. Recent Protocols for IoT

What are Things?

- Thing = Not a computer
- Phone, watches, thermostats, cars, Electric Meters, sensors, clothing, band-aids, TV,…
- Anything, Anywhere, Anytime, Anyway, Anyhow (5 A's)

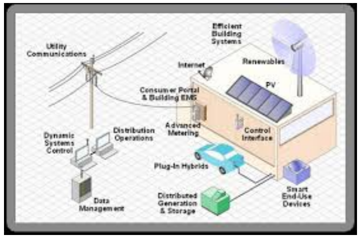
Ref: http://blog.smartthings.com/iot101/iot-adding-value-to-peoples-lives/

Internet of Things

- Only 1% of things around us is connected.
  Refrigerator, car, washing machine, heater, a/c, garage door, should all be connected but are not.
- From 10 Billion today to 50 Billion in 2020
  Should include processes, data, things, and people.
- $14 Trillion over 10 years
  ⇒ Third in the list of top 10 strategic technologies by Gartner (After Mobile devices, Mobile Apps, but before Clouds, …)
- a.k.a. **Internet of Everything** by Cisco
  Smarter Planet by IBM

Ref: "Gartner Identifies Top 10 Strategic Technologies," http://www.cioinsight.com/it-news-trends/gartner-identifies-top-10-strategic-technologies.html
Ref: J. Bradley, "The Internet of Everything: Creating Better Experiences in Unimaginable Ways," Nov 21, 2013, http://blogs.cisco.com/ioe/the-internet-of-everything-creating-better-experiences-in-unimaginable-ways/#more-131793

Sample IoT Applications



Smart Grid

Smart Health

Smart Home

Smart Cities

Smart Industries

Smart TV

Smart Watch

Smart Car

Smart Kegs

What's Smart?

- Smart = Sensing + Internet + Cloud Computing + Big Data Analytics
- Instrumented, Interconnected, Intelligently processed (3 I's)
- Smart = Can think ⇒ Can compute
  This is the old definition
- Smart = Can find quickly, Can Delegate ⇒ Communicate = Networking
- Smart Grid, Smart Meters, Smart Cars, Smart homes, Smart Cities, Smart Smoke Detectors, …

4 Levels of Smartness

1. **Passive**: Communicate only when queried. Passive RFID, QR codes,
2. **Active**: Communicate when needed. Sensors. Home automation
3. **Aware**: Action based on simple computation. E.g., tele-health,
4. **Autonomous**: Can make decisions based on rules. E.g., autonomous cars, smart grid

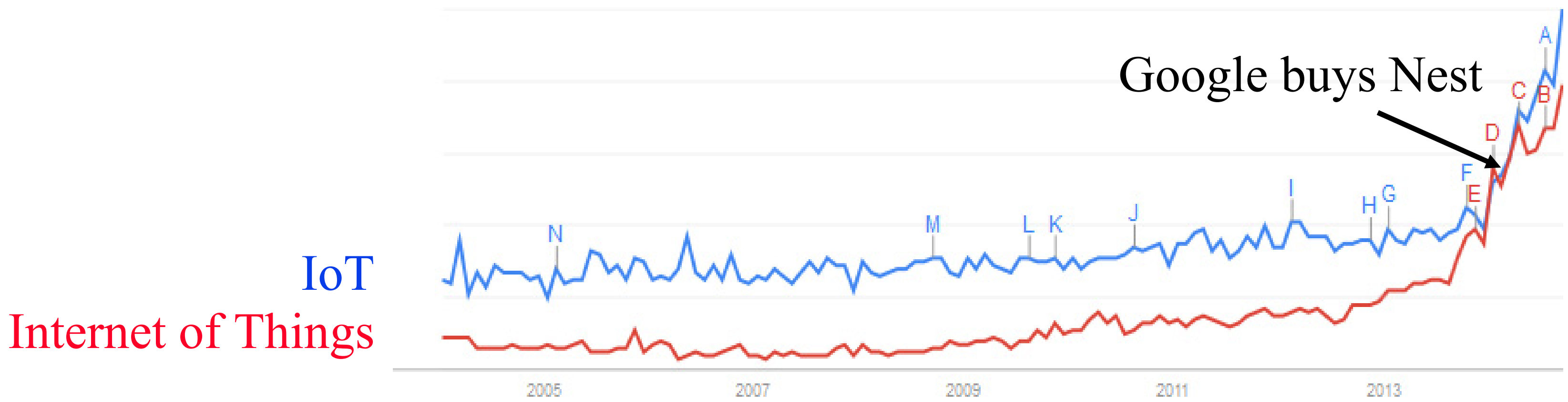
Ref: http://go.gigaom.com/rs/gigaom/images/gigaomresearch_the_internet_of_things_report.pdf

Why IoT Now?

- IoT = Sensing + Communication + Computation
- Micro-Sensors: Temperature, Moisture, Pressure, air quality, …
- Tags: Radio Frequency Id (RFID), Quick Response (QR) Codes,
- Energy Efficient Communication: Small or no batteries, Personal area communication (PAN), Bluetooth, ZigBee, …
- Micro-Computing: Micro multi-core chips, Raspberry Pi, Intel Galileo, Arduino
- Cloud Computing: Little or no local computing
- Open/Small operating systems: Linux

Ref: CTIA, "Mobile Cyber security and the Internet of Things," http://www.ctia.org/docs/default-source/default-document-library/ctia-iot-white-paper.pdf

Google Trends



- Around for 10 years
- IERC-European Research Cluster on the Internet of Things funded under 7th Framework in 2009
  ⇒ "Internet of European Things"
- US interest started in 2009 w $4B funding for **smart grid** in American Recovery and Reinvestment Act of 2009

Funding for IoT

- 70 M € in European Research program FP7
  ⇒ Internet of European Things
- Networking and Information Technology Research and Development (NITRD)
  - Group of 15 Federal agencies: NSF, NIH, NASA, DOE, DARPA, ONR, …
  - Recommends supplement to the president's annual budget
  - CPS is one of the areas recommended by NITRD starting 2012 ⇒ Smart infrastructure
    - Smart Grid, Smart Bridges, Smart Cars, tele-operational surgical robots, Smart **Buildings**
- March 2014: £45M for IoT research in UK by David Cameron

Ref: NITRD, http://www.nitrd.gov/

Business Opportunities

- Smart Objects: Smart TV, Camera, Watch, …
- Components: Sensors, wireless radios, protocols,
- Systems: Buildings, Cars, Health, …
- Network service providers: ISP
- Application Service Providers: Monitoring, Analytics, Apps, …

Venture Activities in IoT

- $1.1B invested in IoT startups by VCs in 153 deals in 2013
  - Quantified Self: Know your body and mind
  - Healthcare sensors: Wearable clock, sleep monitors
  - Energy management
  - Home Automation: Kitchenware, locks,
  - Environmental monitoring: Air Quality sensors, personal weather stations
- January 2014: Google buys NEST for 3.3B
- May 2014: $150M in VC investments in IoT by Cisco

Ref: http://www.cbinsights.com/blog/internet-of-things-investing-snapshot/
http://www.zdnet.com/cisco-invests-150m-in-internet-of-things-startups-7000028964/

Recent IoT Products

NEST Thermostat

Corventis: Wireless Cardiac Monitor

WEMO Remote

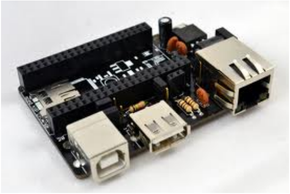
Tractive Pet Tracker

Ninja Blocks

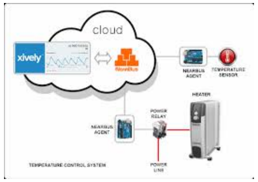
Revolve Home Automation

ThingWorx Application Platform

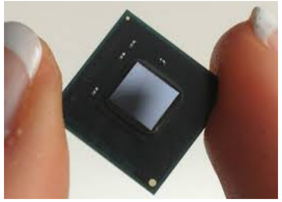
Lings Cloud Platform



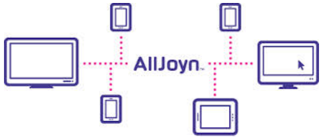
Mbed Development Platform



Xively Remote Access API



Intel Quark Processor



AllJoyn S/W Framework

IoT Research Challenges

- Naming and Addressing, Search and Discovery
  48-bit IEEE 802 addresses are too short
- Service Orchestration
- Power/Energy/Efficient resource management
- Miniaturization
- Things to Cloud: Computation and Communication Gateways
- Big Data Analytics: 35 ZB of data $2B in value by 2020
- Virtualization
- Privacy/Security/Trust/Identity
  Target Pregnancy Prediction
- Malware/Virus/attack

Internet of Harmful Things

Imagine, as researchers did recently at Black Hat, someone hacking your connected toilet, making it flush incessantly and closing the lid repeatedly and unexpectedly.

News

Worm may create an Internet of Harmful Things, says Symantec (Take note, Amazon)

Security firm Symantec says it has found a Linux worm aimed at Internet of Things devices

By Patrick Thibodeau

December 3, 2013 01:22 PM ET Add a comment

Share 6 Like 7 More

Computerworld - Security researchers are gradually raising warnings that the Internet of Things will increase, by multitudes, the number of things that can be hacked and attacked.

The Hitchcockian plotlines are endless. Replace *The Birds* with flying Amazon delivery drones. Or imagine, as researchers did recently at Black Hat, someone hacking your connected toilet, making it flush incessantly and closing the lid repeatedly and unexpectedly.

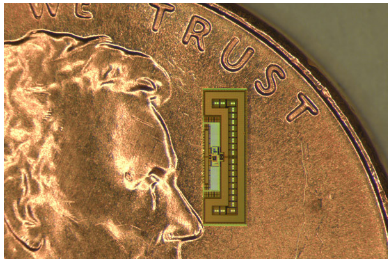
Internet of Brains

- Brain-to-Brain Interface
- A person's brain can send signals to other person's brain
- Useful for handicap people to communicate with others

Ref: http://homes.cs.washington.edu/~rao/brain2brain/experiment.html

Ant-Sized IoT Passive Radios

- Computer + Sensor + Radio in 3.7x1.2 mm from Stanford
- Can be added to dollar bills, band-aids, tools, …
- Monitor temperature, location
- 3 m range
- Extremely low power ⇒ No battery required (Similar to passive RFID
- Continuously monitor every part of the body of every patient



Ref: http://www.computerworld.com/article/2682854/stanfords-ant-sized-radios-could-connect-the-world.html?source=CTWNLE_nlt_pm_2014-09-12#tk.rss_all
http://web.stanford.edu/~arbabian/Home/Welcome.html

Last 100m Protocols

- The Last Mile: Mobile and Broadband Access revolution
  Smart Grid, Smart Cities, Smart Industries
- The last 100m: Smart home
- The last meter: Smart Healthcare, Smart Wearable's

Recent Protocols for IoT

1. ZigBee Smart
2. Bluetooth Smart
3. MQ Telemetry Transport (MQTT) from IBM
4. ETSI M2M Architecture
5. HomePlug GreenPHY: Powerline Communications
6. IPv6 over Low Power Wireless Personal Area Network (6LowPAN)
7. 6-to-Non-IP
8. Routing Protocol for Low Power and Lossy Networks (RPL)
9. Oauth 2.0 Open Authorization (IETF)
10. ANT+ wireless sensor network multicast
11. NFC Near field communication
12. Weightless Communication

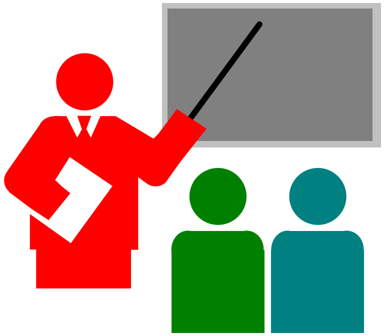
Ref: http://tools.ietf.org/html/draft-rizzo-6lo-6legacy-00, http://en.wikipedia.org/wiki/OAuth, http://en.wikipedia.org/wiki/ANT%2B http://en.wikipedia.org/wiki/Near_field_communication, http://en.wikipedia.org/wiki/Weightless_%28wireless_communications%29

- IEEE 1905.1-2013 Convergent Digital Home Network for Heterogeneous Technologies
- IEEE 1451 smart transducer interface for sensors and actuators

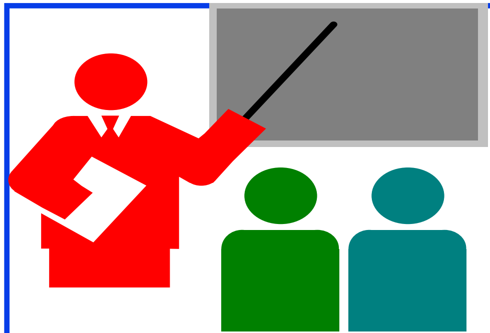
Legacy IoT Protocols

- BACnet
- LonWorks
- ModBus
- KNX
- Z-Wave
- M-Bus
- ANSI CI-12
- Device Language Message Specification (DLMS)/Company Specification for Energy Metering (COSEM)

IoT: Summary



1. Only 1% of things are connected ⇒ Big opportunity for IoT
2. Smart Grid and Energy management is leading the change.
3. Smartness comes from communication capability since the computation can be delegated
4. Naming and Addressing, Search and Discovery, Service Orchestration, Power/Energy/Efficient resource management, Miniaturization, Data Analytics, Privacy/Security/Trust
5. Many recent protocols for the last 100m including Bluetooth smart, ZigBee Smart, HomePlug GP, …



Overall Summary

1. Cloud computing requires Ethernet to be extended globally and partitioned for sharing by a very large number of customers who have complete control over their address assignment and connectivity and requires rapid provisioning of a large number of virtual NICs and switches
2. Virtual Edge Bridge (VEB) vSwitches switch internally while Virtual Ethernet Port Aggregator (VEPA) vSwitches switch externally.
3. OpenFlow separates control plane and moves it to a central controller ⇒ Simplifies the forwarding element

Overall Summary (Cont)

4. SDN is the framework to automatically manage and control a large number of multi-tenant network devices and services
5. NFV reduces OpEx by automation and scalability provided by implementing network functions as virtual appliances
6. AppFabric allows application delivery from multiple clouds
7. Internet of things will extend connectivity to everything.

References

- Raj Jain and Subharthi Paul, "**Network Virtualization and Software Defined Networking for Cloud Computing - A Survey**," IEEE Communications Magazine, Nov 2013, pp. 24-31, http://www.cse.wustl.edu/~jain/papers/net_virt.htm

Acronyms

- 6LowPAN IPv6 over Low Power Wireless Personal Area Network
- ACI Application Policy Infrastructure
- ACL Access Control List
- ADC Application Delivery Controller
- AEX Application Information Exposure
- ALG Application Level Gateway
- ALTO Application Layer Traffic Optimization
- ANDSF Access Network Discovery and Selection Function
- ANSI American National Standards Insitute
- API Application Programming Interface
- APIC Application Policy Infrastructure Controller
- ARP Address Resolution Protocol
- ASICs Application Specific Integrated Circuit
- ATIS Association for Telecom Industry Solutions
- ATM Asynchronous Transfer Mode
- AVNP Active Virtual Network Management Protocol

Acronyms (Cont)

- BER Bit Error Rate
- BFD Bidirectional Forwarding Detection
- BGP Border Gateway Protocol
- BIRD Bird Internet Routing Daemon
- BNC Big Switch Network Controller
- BRAS Broadband Remote Access Server
- BSD Berkeley Software Distribution
- BSS Business Support Systems
- BUM Broadcast, Unknown, and Multicast
- CapEx Capital Expenditure
- CD Compact Disk
- CDN Content Distribution Network
- CDNI Content Distribution Network Interconnection
- CE Control Element
- CFI Canonical Format Indicator
- CFM Connectivity Fault Management

Acronyms (Cont)

- CGNAT Carrier-Grade Network Address Translator
- CGSN Combined GPRS Support Node
- CLI Command Line Interface
- CMS Content Management System
- COTS Commercial-off-the-shelf
- CPS Cyber Physical Systems
- CPU Central Processing Unit
- CRC Cyclic Redundancy Check
- CRUD Create, Read, Update, Delete
- CSMA/CD Carrier Sense Multiple Access with Collision Detection
- CSP Cloud Service Provider
- DA Destination Address
- DARPA Defense Advance Research Project Agency
- DCB Data Center Bridging
- DCBX Data Center Bridging Exchange
- DDIO Data Direct I/O Technology

Acronyms (Cont)

- DEI Drop Eligibility Indicator
- DFCA Dynamic Frequency Channel Allocation
- DHCP Dynamic Host control Protocol
- DLMS Device Language Message Specification
- DNS Domain Name Service
- DOE Department of Energy
- DOVE Distributed Overlay Virtual Ethernet
- DPI Deep Packet Inspection
- DSCP Differentiated Service Control Point
- DVS Distributed Virtual Switch
- ECMP Equal-cost multi-path
- EID Endpoint Identifier
- EMS Element Management System
- ENNI Ethernet Network to Network Interface
- EPL Ethernet Private Line
- ESP Encrytec Security Payload

Acronyms (Cont)

- ETS Enhanced Transmission Service
- ETSI European Telecom Standards Institute
- EVC Ethernet Virtual Channel
- EVP-Tree Ethernet Virtual Private Tree
- EVPL Ethernet Virtual Private Line
- EVPLAN Ethernet Virtual Private LAN
- EVPN Ethernet Virtual Private Network
- FCAPS Faults, configuration, accounting, performance, and security
- FCoE Fibre Channel over Ethernet
- FE Forwarding Element
- FEX Fabric Extension
- FIB Forwarding information base
- ForCES Forwarding and Control Element Separation
- GB Giga Byte
- GGSN Gateway GPRS Support Node
- GMPLS Generalized Multi-Protocol Label Switching

Acronyms (Cont)

GP	GreenPHY
GRE	Generic Routing Encapsulation
GreenPHY	Green Physical Layer
GUI	Graphical User Interface
HLR	Home Location Register
HSRP	Hot Standby Router Protocol
HTML	Hypertext Markup Language
HTTP	Hypertext Transfer Protocol
I2AEX	Infrastructure to Application Information Exposure
IaaS	Infrastructure as a Service
IANA	Internet Addressing and Naming Authority
ICMP	Internet Control Message Protocol
ICSI	International Computer Science Institute
ID	Identifier
IDS	Intrusion Detection System
IEEE	Institution of Electrical and Electronic Engineers

Acronyms (Cont)

- IERC IoT European Research Cluster
- IETF Internet Engineering Task Force
- IGMP Internet Group Management Protocol
- IGP Interior Gateway Protocol
- IMS IP Multimedia System
- INF Architecture for the virtualization Infrastructure
- IO Input/Output
- IoT Internet of Things
- IP Internet Protocol
- IPFIX IP Flow Information Export Protocol
- IPSec IP Security
- IPv4 Internet Protcol version 4
- IPv6 Internet Protocol version 6
- IRTF Internet Research Taskforce
- IS-IS Intermediate System to Intermediate System
- iSCSI Internet Small Computer Storage Interconnect

Acronyms (Cont)

❑	ISG	Industry Specification Group
❑	ISO	International Standards Organization
❑	JSON	Java Script Object Notation
❑	JVM	Java Virtual Machine
❑	kB	Kilo Byte
❑	KVM	Kernel-based Virtual Machine
❑	LACP	Link Aggregation Control Protocol
❑	LAN	Local Area Network
❑	LISP	Locator-ID Separation Protocol
❑	LLDP	Link Layer Discovery Protocol
❑	LRO	Large Receive Offload
❑	LS	Link State
❑	LSO	Large Send Offload
❑	LSP	Label Switched Path
❑	MAC	Media Access Control
❑	MAN	Metropolitan Area Network

Acronyms (Cont)

- MANO Management and orchestration
- MDI Media Dependent Interface
- MME Mobility Management Entity
- MPLS Multi-protocol Label Switching
- MQTT MQ Telemetry Transport
- MR-IOV Multi-Root I/O Virtualization
- MSB Most Significant Byte
- MSS Maximum Segment Size
- MST Multiple spanning tree
- MSTP Multiple Spanning Tree Protocol
- MTU Maximum Transmission Unit
- MVGRE Network Virtualization Using GRE
- NASA National Aeronautical and Space Administration
- NAT Network Address Translation
- NF Network Function
- NFC Near field communication

Acronyms (Cont)

- NFV Network Function Virtualization
- NFVI Network Function Virtualization Infrastructure
- NFVIaaS NFVI as a Service
- NIB Network Information Base
- NIC Network Interface Card
- NIH National Institute of Health
- NITRD Networking and Information Technology Research and Development
- NNI Network-to-Network Interface
- NSF National Science Foundation
- NTP Network Time Protocol
- NTT Nippon Telegraph and Telephone
- NVGRE Network Virtualization using Generic Routing Encapsulation
- NVO3 Network Virtualization over L3
- NVP Network Virtualization Platform
- OAM Operation, Administration, and Management
- OF OpenFlow

Acronyms (Cont)

- OFlops OpenFlow Operations Per Second
- OLSR Optimized Link State Routing
- ON.LAB Open Networking Lab at Stanford
- OnePK Open Network Environment Platform Kit
- ONF Open Networking Foundation
- ONR Office of Naval Research
- ONV OpenDaylight Network Virtualization
- openQRM Open Clusters Resource Manager
- OpenWRT Open WRT54G (Linksys product name) software
- OpEx Operation Expenses
- OS Operating System
- OSCP OpenDaylight SDN Controller Platform
- OSGi Open Services Gateway Initiative
- OSPF Open Shortest Path First
- OSS Operation Support System
- OTN Optical Transport Network

Acronyms (Cont)

OTV	Overlay Transport Virtualization
OVS	Open Virtual Switch
OVSDB	Open Virtual Switch Database
PaaS	Platform as a Service
PAN	Personal area communication
PB	Provider Bridge
PBB-TE	Provider Backbone Bridge with Traffic Engineering
PBB	Provider Backbone Bridge
PBEB	Provider Backbone Edge Bridge
PCC	Path Computation Client
PCE	Path Computation Element
PCEP	Path Computation Element Protocol
PCI-SIG	PCI Special Interest Group
PCI	Peripheral Component Interconnect
PCIe	PCI Express
PCP	Priority Code Point

Acronyms (Cont)

- PE Provider Edge
- PF Physical Function
- PFC Priority-based Flow Control
- PGW Packet Data Network Gateway
- PHY Physical Layer
- PIM-SM Protocol Independent Multicast - Sparse Mode
- PIM Protocol Independent Multicast
- pM Physical Machine
- pNIC Physical Network Interface Card
- PoC Proof-of-Concept
- PoP Point of Presence
- PPP Point-to-Point Protocol
- PSTN Public Switched Telephone Network
- pSwitch Physical Switch
- PW Pseudo wire
- PWE3 Pseudo wire Emulation Edge to Edge

Acronyms (Cont)

PWoGRE	Pseudo wire over Generic Routing Encapsulation
PWoMPLS	Pseudo wire over Multi Protocol Label Switching
QCN	Quantized Congestion Notification
QoS	Quality of Service
QR	Quick Response
RAID	Redundant Array of Independent Disks
RAN	Radio area networks
RBridge	Routing Bridge
REL	Reliability, Availability, resilience and fault tolerance group
REST	Representational State Transfer
RFC	Request for Comments
RFID	Radio Frequency Id
RGW	Residential Gateway
RIB	Routing Information Base
RIP	Routing Information Protocol
RLOC	Routing Locator

Acronyms (Cont)

RNC	Radio Network Controller
RPC	Remote Procedure Call
RPL	Routing Protocol for Low Power and Lossy Networks
RS	Routing System
RSPAN	Remote Switch Port Analyzer
RSTP	Rapid Spanning Tree Protocol
SA	Source Address
SaaS	Software as a Service
SAL	Service Abstraction Layer
SBC	Session Border Controller
SDH	Synchronous Digital Hierarchy
SDN	Software Defined Networking
SGSN	Serving GPRS Support Node
SGW	Serving Gateway
SID	Service Identifier
SIP	Session Initiation Protocol

Acronyms (Cont)

- SLA Service Level Aggrement
- SMTP Simple Mail Transfer Protocol
- SNAC Name of an OpenFlow controller
- SNIA Storage Network Industry Association
- SNMP Simple Network Management Protocol
- SONET Synchronous Optical Network
- SPAN Switch Port Analyzer
- SPB Shortest Path Bridging
- SR-IOV Single Root I/O Virtualization
- SSH Secure Socket Host
- SSL Secure Socket Layer
- STP Spanning Tree Protocol
- STT Stateless TCP-like Transport
- SWA Software architecture
- TAS Telephony Application Server
- TCAM Ternary Content Addressable Memory

Acronyms (Cont)

- TCL Tool Command Language
- TCP Transmission Control Protocol
- TE Traffic Engineering
- TIA Telecom Industry Association
- TLS Transport Level Security
- TLV Type-Length-Value
- TMF TM Forum
- ToS Type of Service
- TP Transport Protocol
- TPI Tag Protocol Identifier
- TRILL Transparent Interconnection of Lots of Links
- TTL Time to Live
- TTP Table Typing Patterns
- TV Television
- UC University of California
- UCA Use Customer Address

Acronyms (Cont)

- UDP User Datagram Protocol
- UNI User Network Interface
- URI Uniform Resource Identifier
- VBE Virtual Bridge Port Extension
- vBridge Virtual Bridge
- VC Venture Capital
- VDC Virtual Device Contexts
- VEB Virtual Edge Bridge
- VEM Virtual Ethernet Module
- VEPA Virtual Ethernet Port Aggregator
- vEPC Virtual Evolved Packet Core
- VF Virtual Function
- VID VLAN ID
- VIRL Virtual Internet Routing Lab
- VLAN Virtual LAN
- VM Virtual Machine

Acronyms (Cont)

VNF	Virtual Network Function
VNFaaS	VNF as a Service
VNI	Virtual Network ID
vNIC	Virtual Network Interface Card
VNS	Virtual Network Segement
VoD	Video on Demand
VOIP	Voice over IP
vPC	Virtual Port Channels
VPLS	Virtual Private LAN Service
VPN	Virtual Private Network
VRF	Virtual Routing and Forwarding
VRRP	Virtual Router Redundancy Protocol
VSID	Virtual Subnet Identifier
VSM	Virtual Switch Module
VSS	Virtual Switch System
vSwitch	Virtual Switch

Acronyms (Cont)

- VT-d Virtualization Technology for Direct IO
- VT-x Virtualization Technology
- VTEP Virtual Tunnel End Point
- VTN Virtual Tenant Network
- VXLAN Virtual Extensible LAN
- WAN Wide Area Network
- WG Working Group
- XML Extensible Markup Language
- XMPP Extensible Messaging and Presence Protocol
- XORP eXensible Open Router Platform