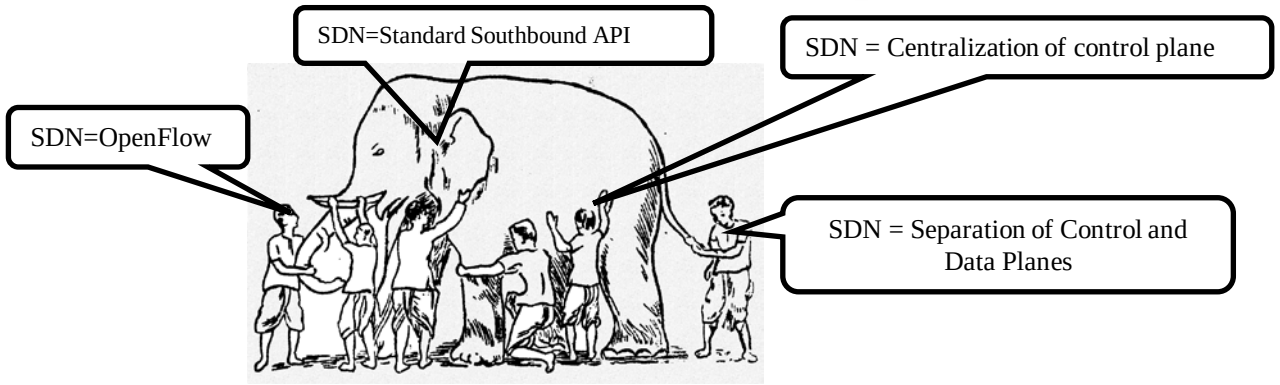
Introduction to Software Defined Networking (SDN)



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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 SDN?
2. SDN Controllers
3. Alternative APIs: XMPP, PCE, ForCES, ALTO
4. RESTful APIs and OSGi Framework

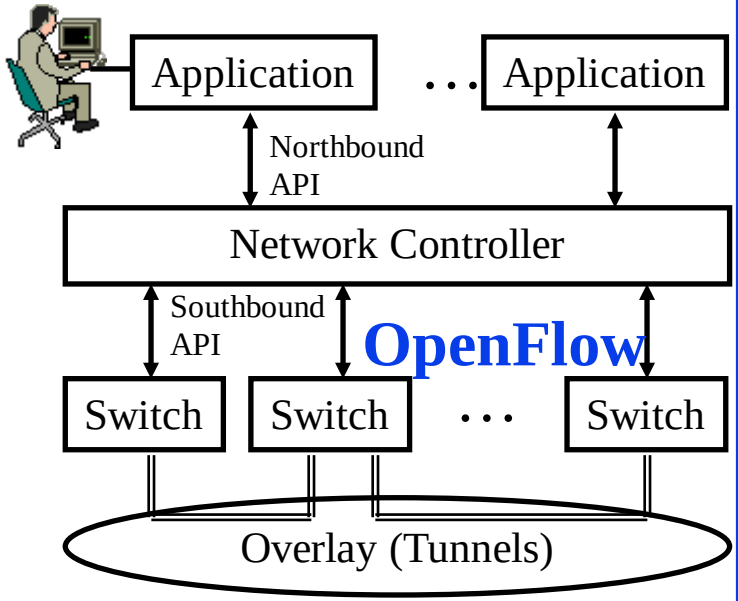
Note: This is the second module of three modules on OpenFlow, SDN, and NFV in this course.

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Origins of SDN

- SDN originated from OpenFlow
- Centralized Controller
  ⇒ Easy to program
  ⇒ Change routing policies on the fly
  ⇒ Software Defined Network (SDN)
- Initially, SDN=
  - Separation of Control and Data Plane
  - Centralization of Control
  - OpenFlow to talk to the data plane
- Now, the definition has changed significantly.



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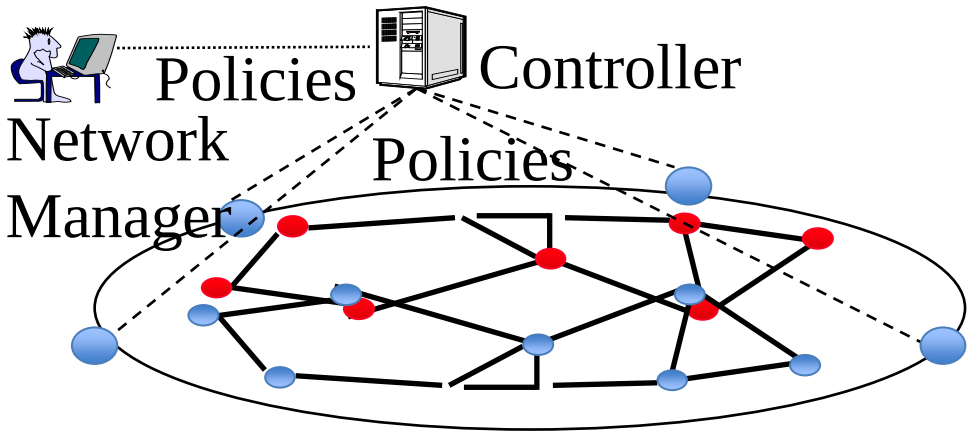
- How is intent systematically compiled for southbound protocols?

Intent is in simple language that is converted to hardware-specific commands using AI.

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Three Features that Define SDN

1. **Abstract the Hardware**: No dependence on physical infrastructure. Software API.
2. **Programmable**: Shift away from static, manual operation to fully configurable and dynamic
3. **Centralized Control of Policies**: Policy delegation and management



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What = Why We need SDN?

1. **Virtualization**: Use network resources without worrying about where it is physically located, how much it is, how it is organized, etc. Abstraction ⇒ Virtualization.
2. **Orchestration**: Should be able to control and manage thousands of devices with one command.
3. **Programmable**: Should be able to change behavior on the fly.
4. **Dynamic Scaling**: Should be able to change the size, quantity Virtualization ⇒ Scaling
5. **Automation**: To lower OpEx and minimize manual involvement
   - Troubleshooting
   - Reduce downtime
   - Policy Enforcement
   - Provisioning/Re-provisioning/Segmentation of resources
   - Add new workloads, sites, devices, and resources

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Why We need SDN? (Cont)

6. **Visibility**: Monitor resources, connectivity
7. **Performance**: Optimize network device utilization
   - Traffic engineering/Bandwidth management
   - Capacity optimization
   - Load balancing
   - High utilization
   - Fast failure handling
8. **Multi-tenancy**: Tenants need complete control over their addresses, topology, routing, security
9. **Service Integration**: Load balancers, firewalls, and Intrusion Detection Systems (IDS) provisioned on demand and placed appropriately on the traffic path

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Why We need SDN? (Cont)

10. Openness: Full choice of "How" mechanisms
⇒ Modular plug-ins
⇒ Abstraction:

- Abstract = Summary = Essence = General Idea
  ⇒ Hide the details.
- Also, the abstract is the opposite of concrete
  ⇒ Define tasks by APIs and not by how they should be done. E.g., send from A to B. Not OSPF.

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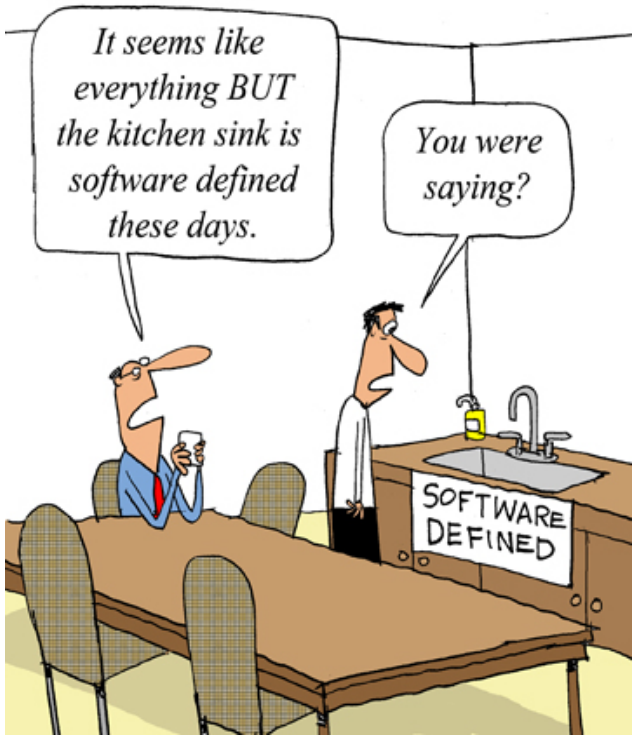
Ref: http://www.networkworld.com/news/2013/110813-onug-sdn-275784.html

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Software Defined Anything (SDx)

- Tsunami of software-defined things
  - Software Defined Networking (SDN)
  - Software Defined Datacenter (SDDC)
  - Software Defined Storage (SDS)
  - Software Defined Compute (SDC)
  - Software Defined Infrastructure (SDI)

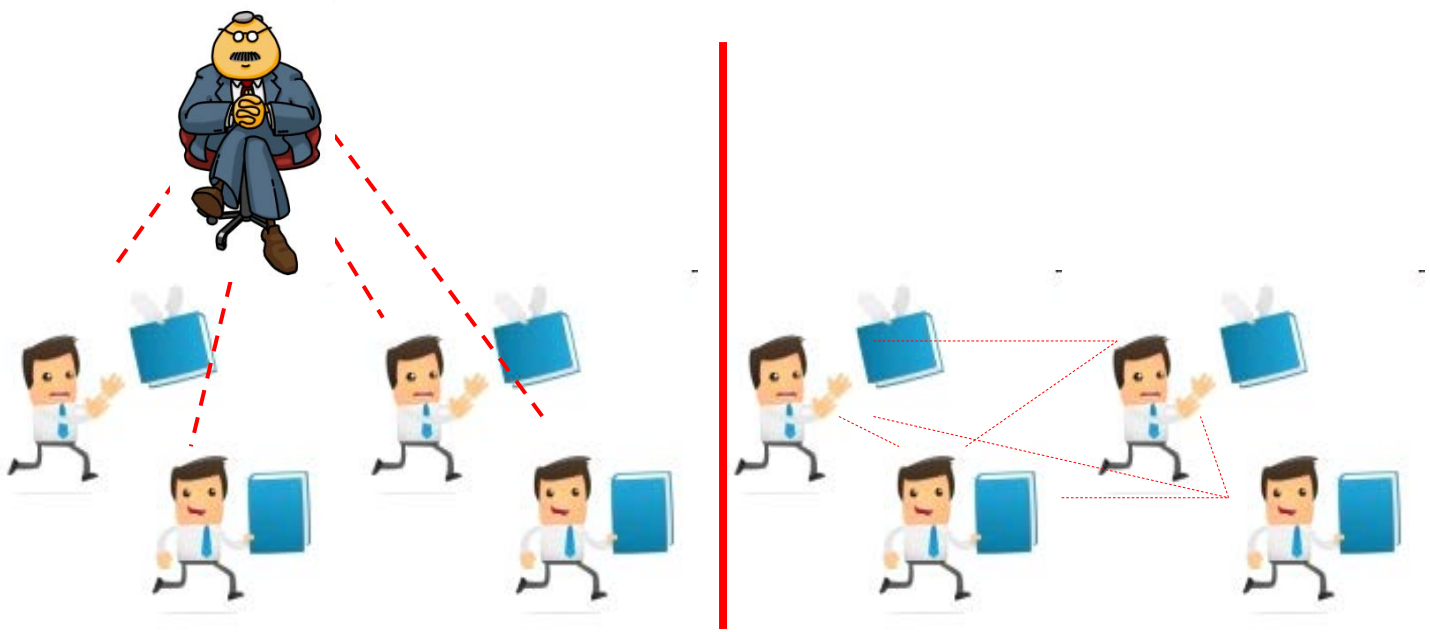




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Centralized vs. Distributed Management



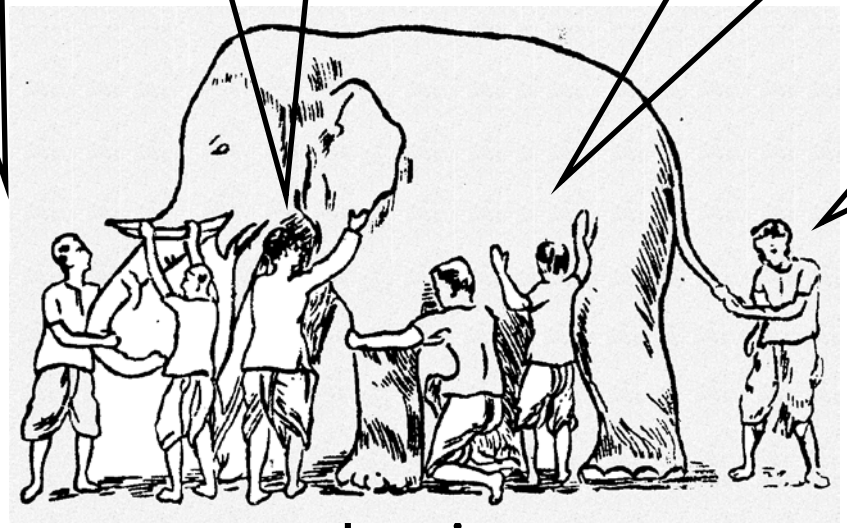
- Fast Response to changes
- Fast Consistency
- Less overhead ⇒ Scalable
- Single Point of Failure

- Time to converge
- Slow consistency
- Not scalable
- Fault Tolerant

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What SDN is Not?



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

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Four Confusions About SDN

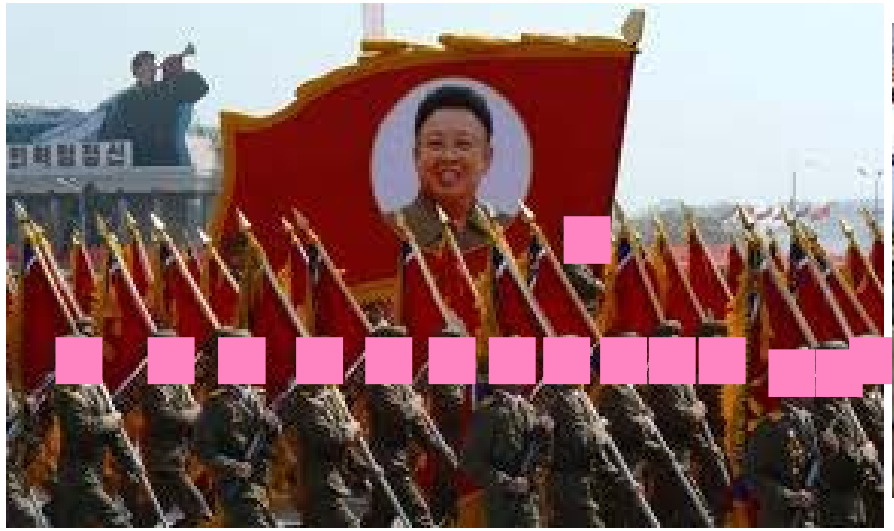
1. Policies vs. Control:
   Control = All bits and messages not sent by the user.
   In IP, control includes all header bits and all routing messages.
2. Separation of Control Plane:
   Elements have only a data plane and have no brains
3. SDN vs. OpenFlow:
   OpenFlow is the father of SDN but not SDN.
4. Need OpenFlow:
   - OpenFlow is micro-management.
   - It is not scalable.
   - For extensive infrastructure, need scalable solutions.

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Separation vs. Centralization

Separation of Control Plane

Centralization of Policies





Micromanagement is not scalable

Student Questions

Flavors of SDN

1. OpenDaylight: Multi-Protocol Southbound
2. Bare Metal Switches + Network Operating System
   a. Switches from Dell, Edgecore, HP, Penguin, QCT, Agema, Supermicro
   b. Open Network Install Environment (ONIE) on a set of programmable switches
   c. Network operating systems: Alcatel-Lucent, Arista, Big Switch, Broadcom, Brocade, Cisco, Cumulus, Dell, Ericsson, Extreme, HP, Juniper, OCP, Pica8, Pluribus
3. Network Virtualization/Overlay: VMWare's NSX
4. ONOS

All provide Abstraction, Programmability, and Centralization

Ref: http://onie.org/, http://www.opencompute.org/wiki/Networking/ONIE/HW_Status, https://en.wikipedia.org/wiki/List_of_SDN_controller_software

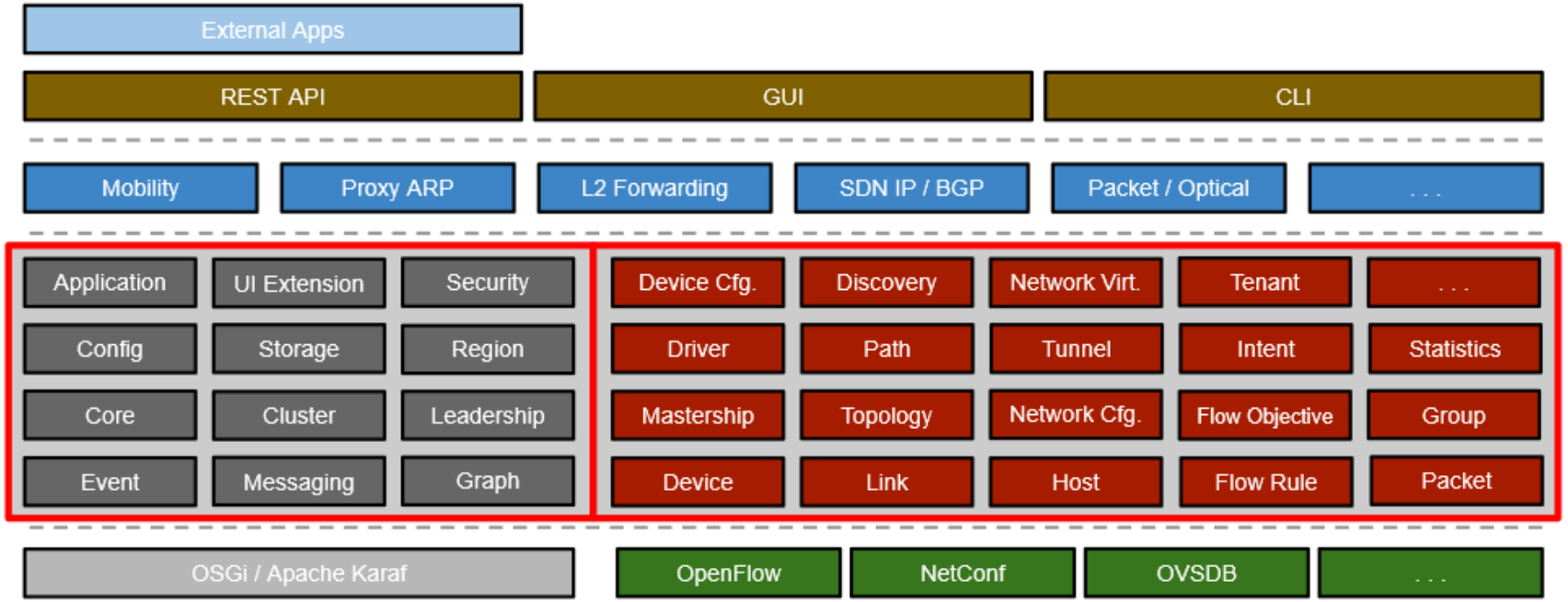
Source: Alan J Weissberger

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ONOS

- Open Network Operating System: Distributed OpenFlow OS for a large WAN
- Initially OpenFlow-only. Now multi-protocol

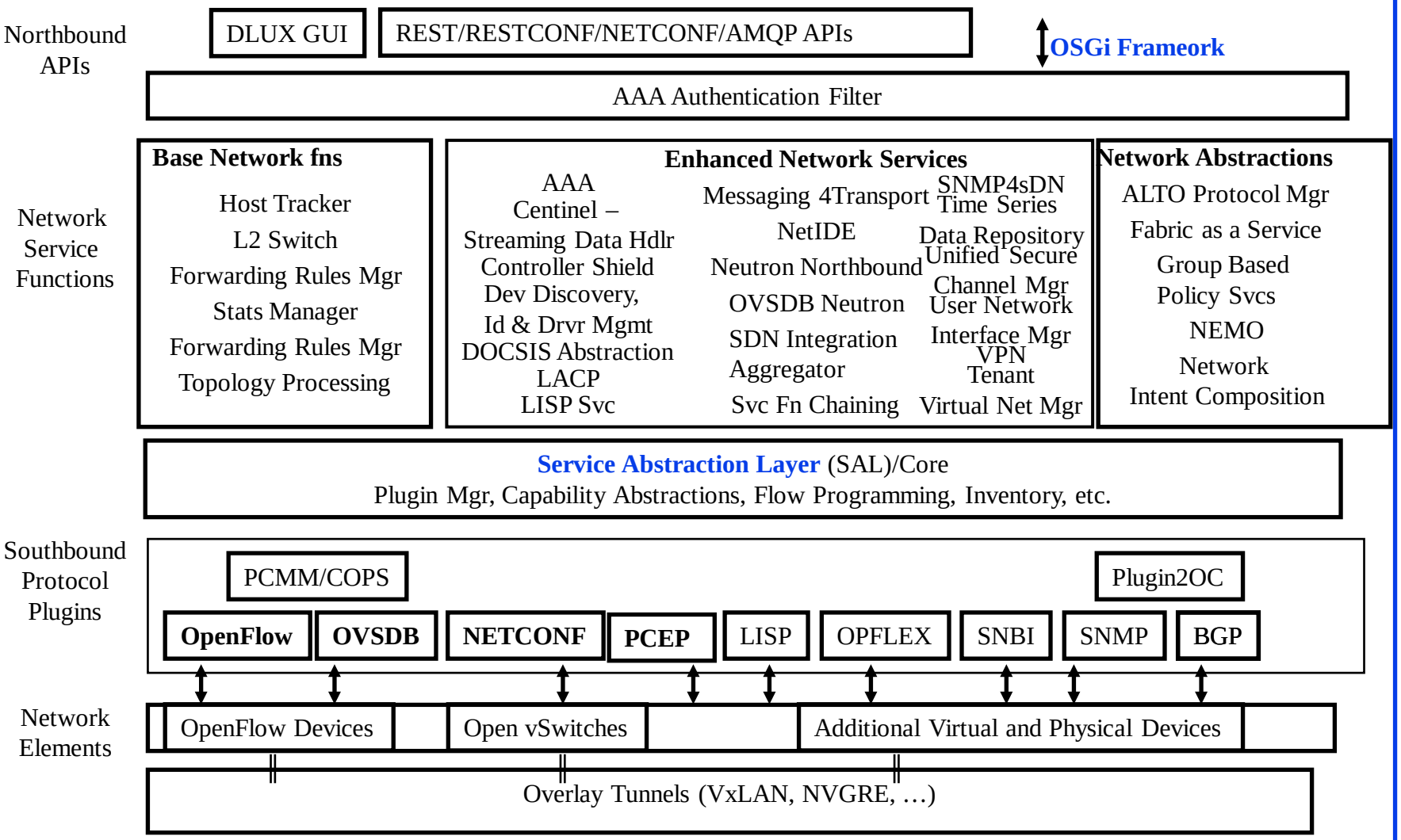


Ref: ONOS Architecture, https://docs.google.com/presentation/d/1Y4S82YZyskqnKAzW4kKm-6IIO04h_nnrRQyfrsCdt-I/edit?usp=sharing

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OpenDaylight: Multi-Protocol SDN



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Student Questions

- Could you please highlight the main point of this page?

1. *SAL can convert Network service functions into southbound protocols.*
2. *There can be any number of southbound protocols.*
3. *Design a controller independent of the "Open Networking Foundation."*

OpenDaylight SDN Controller Platform (OSCP)

- Multi-company collaboration under the Linux Foundation
- Many projects, including OpenDaylight Controller
- Supports multiple southbound protocols via plug-ins, including OpenFlow
- Dynamically linked into a Service Abstraction Layer (SAL) Abstraction ⇒ SAL figures out how to fulfill the service requested by higher layers irrespective of the southbound protocol
- Modular design using **OSGI framework**
- A rich set of North-bound APIs via RESTful services for loosely coupled applications and OSGI services for co-located applications using the same address space

Ref: C. Eckel, "OpenDaylight as a Platform for Network Programmability,"
http://events17.linuxfoundation.org/sites/events/files/slides/OpenDaylight-Network-Programmability.pdf

Student Questions

OpenDaylight Tools

1. **Application**: Provides Virtual Network Segments (VNS) for each tenant
    1. OpenDaylight Network Virtualization (ONV):
    2. OpenDaylight Virtual Tenant Network (VTN)
2. **Services**:
    1. Unified Secure Channel Manager
3. **Northbound APIs**:
    1. **REST:** Representational State Transfer (like HTTP)
    2. **RESTCONF**: RESTful Configuration
    3. **NETCONF**: Network Configuration
    4. **Dlux**: Northbound API using AngularJS, an extension of HTML by Google for dynamic views
    5. **AMQP**: Advanced Message Queuing Protocol

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- What truly counts as a northbound API (intent vs. resource-level semantics)?

Both. Intent is converted to resource-level semantics using AI.

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OpenDaylight Tools (Cont)

4. **Southbound APIs**:
   1. OpenFlow Plug-in + Protocol Library (V1.0, V1.1,…)
   2. Locator ID Separation Protocol (LISP) Mapping Service
   3. SNMP4SDN
   4. BGP Link State Path Control Element Protocol
5. **Overlay**:
   1. Open Distributed Overlay Virtual Ethernet (DOVE): Like VxLAN but does not use IP Multicast
6. **Configuration**:
   1. OpenDaylight YANG Tools: NETCONF
   2. Open vSwitch Database (OVSDB) Integration

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End of Part 1

Open Network Linux (ONL)

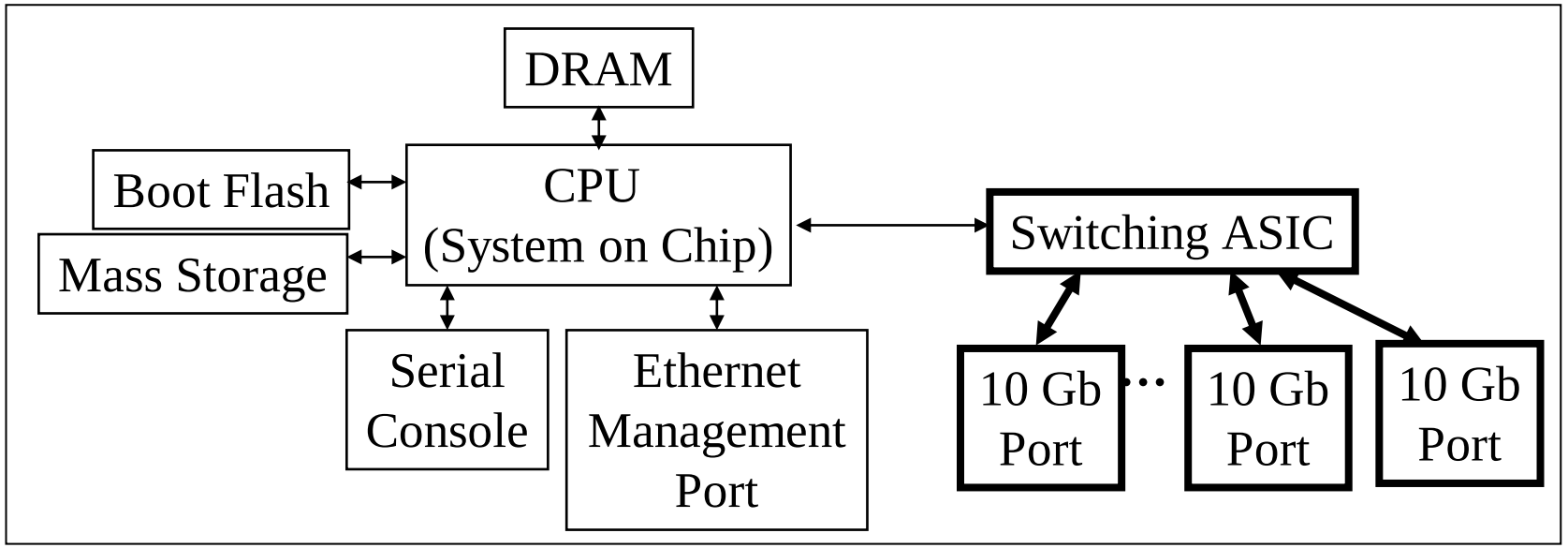
- Linux distribution for "*open hardware*" bare metal switches
- Part of Open Compute Project
- Supports multiple *switch fabric APIs*:
  - **OF-DPA**: OpenFlow Data Plane Abstraction (API) for Broadcom chips
  - **OpenNSL**: Open Network Switch Layer for Broadcom switches
  - **SAI**: Switch Abstraction Interface (vendor-independent API to control forwarding elements)
- Compatible with many open-source *forwarding agents* or routing protocol suites

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Ref: http://opennetlinux.org/ , https://github.com/Broadcom-Switch/OpenNSL, https://github.com/Broadcom-Switch/of-dpa, https://github.com/opencomputeproject/SAI

Bare Metal Switches

- Hardware that can be used to load different network operating systems
- Open Network Linux is supported by hardware from: | Accton/Edge-Core, Quanta, Dell, Mellanox, Netberg, Inventec, Celestica, HPE, DNI, Ingrasys, and Alpha Networks



Ref: ONL Hardware Support and Certification, http://www.opennetlinux.org/hcl

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Open Source Forwarding Agents

- **Quagga**: A popular open-source routing software suite including OSPF, RIP, BGP, …
- **FRRouting**: a fork of Quagga. Linux routing protocol suite including BGP, IS-IS, LDP, OSPF, PIM, and RIP (Free Range Routing?)
- **BIRD**: Internet Routing Daemon developed as a school project at Charles University, Prague. Supports IPv4, IPv6, BGP, RIP, OSPF, …
- Facebook Open Switching System (**FBOSS**): S/w stack for controlling and managing network switches with several user-space applications
- Azure Software for Open Networking in the Cloud (**SONiC**)
- Google **gNOS**

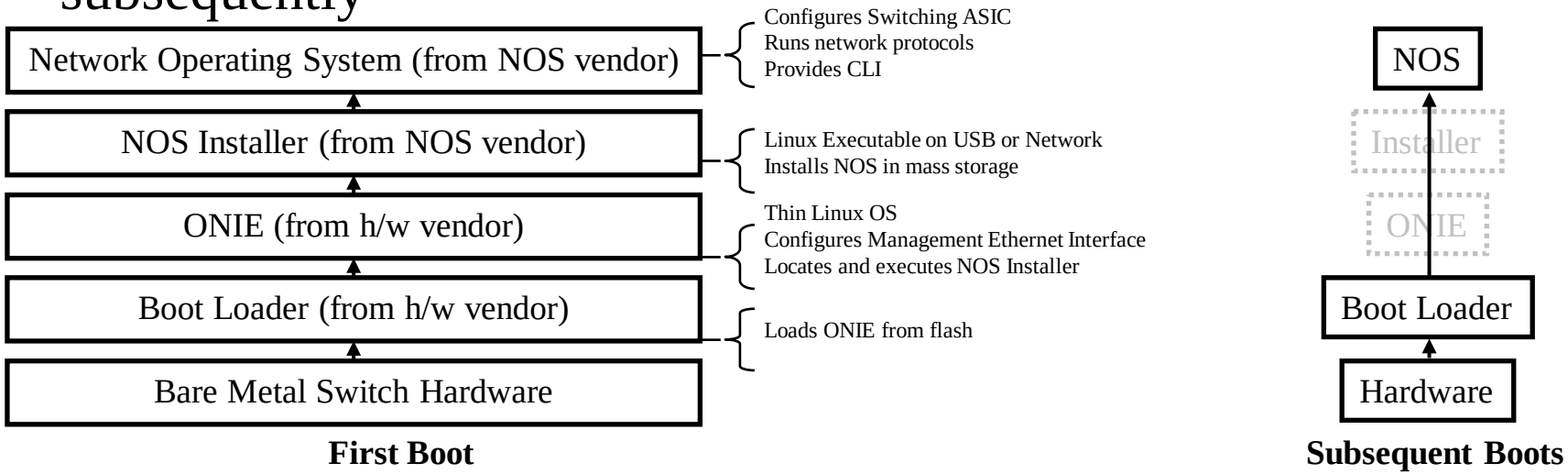
Ref: https://www.nongnu.org/quagga/, https://www.opensourcerouting.org/, http://bird.network.cz/, https://github.com/facebook/fboss, http://azure.github.io/SONiC/

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Open Network Install Environment (ONIE)

- Part of the **Open Compute Project (OCP)** open-source initiative
- Allows many different "**Network Operating Systems (NOS)**" on bare metal network switches
- Like a firmware that locates the NOS boot image and loads it
- ONIE sets the environment on the first boot and is not required subsequently



Ref: ONIE Overview, https://opencomputeproject.github.io/onie/overview/index.html#onie-overview

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Mininet

- Widely used open-source network emulation environment.
- Can simulate several end-hosts, switches, routers, and links on a Linux
- Used for rapid prototyping of software-defined networks
- Built-in Open vSwitch and an OpenFlow capable switch
- Command line launcher and Python API for creating networks of varying sizes, e.g., *mn –topo tree,depth=2, fanout=3*
- Useful diagnostic commands like iperf, ping, and other commands in a host, e.g., *mininet> h11 ifconfig –a*
- Mininet codes for several popular commercial switches are available.

Ref: https://github.com/mininet/mininet , http://www.brianlinkletter.com/set-up-mininet/

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RESTful APIs

- Software architecture style developed by W3C.
- Introduced by Roy Fielding in his Ph.D. thesis.
- WWW uses this style. Very popular in other applications.
- Goals: Scalability, Generality, Independence, and allowing intermediate components
- Client-Server Model: Clients and servers can be developed independently.
- Server is stateless
- Responses can be cached for the specified time
- Intermediate Servers (Proxies) can respond. The endpoint is not critical.

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REST (Cont)

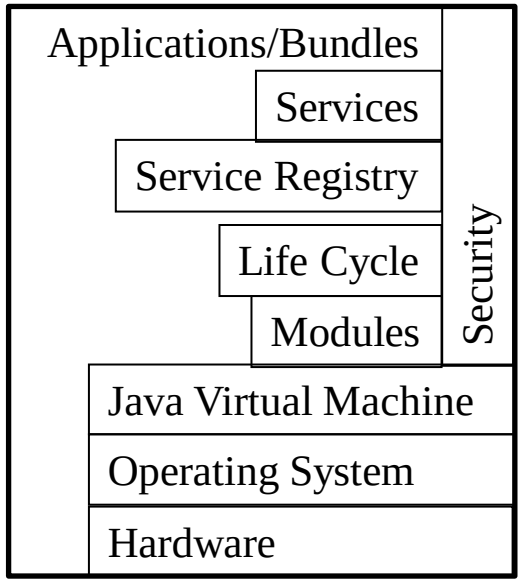
- Create, Read, Update, Delete (CRUD) Operations
- Uniform Interface: GET (Read), POST (Insert), PUT (write), DELETE
- Resources identified by global identifiers, e.g., URI in Web.
- Get http://<fqdn-or-ip-address>/rest/v1/model/<data-type>/<optional-id>?<optional-query-params>
  E.g., GET http://odcp.org/rest/v1/model/controller-node
- Data Types: Controller node, Firewall rule, Topology configuration, Switch, Port, link, flow entry, VLAN, …
- Data types can include commercial entities, such as Big Virtual Switch from Big Switch Networks, vCenter from VMware, etc.…
- If optional-id and query parameters are omitted, the returned text includes all of the items of the given data type.

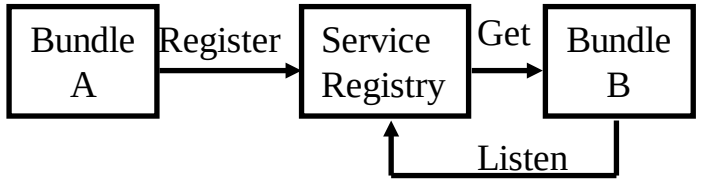
Ref: http://en.wikipedia.org/wiki/Representational_state_transfer

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OSGi Framework

- Initially, **O**pen **S**ervices **G**ateway **I**nitiative
- A set of specifications for dynamic application composition using reusable Java components called bundles
- Bundles publish their services with the OSGi services registry and can find/use services of other bundles





Ref: https://en.wikipedia.org/wiki/OSGi

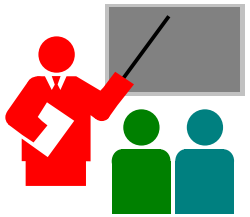
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OSGi (Cont)

- Bundles can be installed, started, stopped, updated, or uninstalled using a lifecycle API
- Modules define how a bundle can import/export code
- The security layer handles security
- The execution environment defines what methods and classes are available in a specific platform
- A bundle can get a service, or it can listen for a service to appear or disappear.
- Each service has properties that allow others to select among multiple bundles offering the same service
- Services are dynamic. A bundle can decide to withdraw its service. Other bundles should stop using it
  $\Rightarrow$ Bundles can be installed and uninstalled on the fly.

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Summary



1. SDN =Abstraction + Programmability + Centralization
   SDN = Disaggregation of h/w and s/w
   = Bare metal switches + ONIE + ONL
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, PCE, ALTO
3. OpenDaylight and ONOS are SDN Controllers.
   Differ on how much is open.
4. Mininet for network simulation
5. REST=HTTP APIs
   OSGI framework for modularity

Student Questions

Reading List

- Thomas D. Nadeau, Ken Gray, "SDN: Software Defined Networks," O'Reilly Media, Inc., August 2013, 384 pp., ISBN:978-1-4493-4230-2 (Safari Book).
- 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).
- Reza Toghraee, "Learning OpenDaylight," Packt Publishing, May 2017, 336 pp., ISBN:978-1-78217-452-3 (Safari Book).
- Antonio Sanchez Monge; Krzysztof Grzegorz Szarkowicz, "MPLS in the SDN Era," O'Reilly Media, Inc., December 2015, 920 pp., ISBN:978-1-4919-0545-6 (Safari Book).

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Wikipedia Links

- http://en.wikipedia.org/wiki/Software-defined_networking
- http://en.wikipedia.org/wiki/Representational_state_transfer
- http://en.wikipedia.org/wiki/OSGI
- http://en.wikipedia.org/wiki/XMPP
- http://en.wikipedia.org/wiki/Path_computation_element

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- Y. Lee, et al., "ALTO Extensions for collecting Data Center Resource Information," http://datatracker.ietf.org/doc/draft-lee-alto-ext-dc-resource/?include_text=1
- http://datatracker.ietf.org/wg/pce/
- http://events17.linuxfoundation.org/sites/events/files/slides/OpenDaylight-Network-Programmability.pdf
- OpenDaylight Components and Tools, https://wiki.opendaylight.org

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- 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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- Paul Goransson, Chuck Black, Timothy Culver, "Software Defined Networks, 2nd Edition," Morgan Kaufmann, October 2016, 436 pp., ISBN:978-0-12-804555-8 (Safari Book).
- Patricia A. Morreale, James M. Anderson, "Software Defined Networking," CRC Press, September 2015, 186 pp., ISBN:1-4822-3864-0 (Safari Book).
- V. Josyula, M. Orr, and G. Page, "Cloud Computing: Automating the Virtualized Data Center," Cisco Press, 2012, 392 pp., ISBN: 1587204347 (Safari Book).
- P. Saint-Andre, et al., "XMPP: The Definitive Guide," O'Reilly, 2009, 320 pp., ISBN:9780596521264 (Safari Book)

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Acronyms

- ACI Application Policy Infrastructure
- ACL Access Control List
- AEX Application Information Exposure
- ALG Application Level Gateway
- ALTO Application-Layer Traffic Optimization
- AMQP Advanced Message Queueing Protocol
- ANDSF Access Network Discovery and Selection Function
- API Application Programming Interface
- APIC Application Policy Infrastructure Controller
- ARP Address Resolution Protocol
- ATIS Association for Telecom Industry Solutions
- ATM Asynchronous Transfer Mode
- AVNP Active Virtual Network Management Protocol
- BGP Border Gateway Protocol
- BNC Big Switch Network Controller
- BSD Berkeley Software Distribution

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Acronyms (Cont)

- BUM Broadcast, Unknown, and Multicast
- CDN Content Distribution Network
- CDNI Content Distribution Network Interconnection
- CE Control Element
- CLI Command Line Interface
- CMS Content Management System
- CPU Central Processing Unit
- CRUD Create, Read, Update, Delete
- CSP Cloud Service Provider
- DHCP Dynamic Host Control Protocol
- DNS Domain Name System
- DOCSIS Data over Cable Service Interface Specification
- DOVE Distributed Overlay Virtual Ethernet
- DVS Distributed Virtual Switch
- EID Endpoint Identifier
- ETSI European Telecommunications Standards Institute

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Acronyms (Cont)

FCAPS	Faults, configuration, accounting, performance , and security
FE	Forwarding Element
FE	Forwarding Element
ForCES	Forwarding and Control Element Separation
GMPLS	Generalized Multi-Protocol Label Switching
GUI	Graphical User Interface
HTML	Hypertext Markup Language
HTTP	Hypertext Tranfer Protocol
I2AEX	Infrastructure to Application Information Exposure
IaaS	Infrastructure as a Service
ID	Identifier
IDS	Intrusion Detection System
IEEE	Institution of Electrical and Electronic Engineers
IETF	Internet Engineering Task Force
IGP	Interior Gateway Protocol
IoT	Internet of Things

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Acronyms (Cont)

IP	Internet Protocol
IPv4	Internet Protcol version 4
IPv6	Internet Protcol version 6
IRTF	Internet Research Taskforce
IS-IS	Intermediate System to Intermediate System
ISO	International Standards Organization
L2	Layer 2
LACP	Link Aggregation Control Protocol
LAN	Local Area Network
LISP	Locator-ID Separation Protocol
LS	Link State
MAC	Media Access Control
MPLS	Multi-protocol Label Switching
NAT	Network Address Translation
NetIDE	Network Interactive Development Environment
NEMO	File Manager for Linux Distribution

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Acronyms (Cont)

- NFV Network Function Virtualization
- NTP Network Time Protocol
- NVGRE Network Virtualization using Generic Routing Encapsulation
- NVO3 Network Virtualization over L3
- NVP Network Virtualization Platform
- OF OpenFlow
- OnePK Open Network Environment Platform Kit
- ONF Open Networking Forum
- ONV OpenDaylight Network Virtualization
- OpEx Operational Expenses
- OS Operating System
- OSCP OpenDaylight SDN Controller Platform
- OSGi Open Services Gateway Initiative
- OSPF Open Shortest Path First
- OVS Open Virtual Switch
- OVSDB Open Virtual Switch Database

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Acronyms (Cont)

- PCC Path Computation Client
- PCE Path Computation Element
- PCEP Path Computation Element Protocol
- POP Post Office Protocol
- PWE3 Pseudowire Emulation Edge to Edge
- QoS Quality of Service
- REST Representational State Transfer
- RFC Request for Comments
- RLOC Routing Locator
- RLOC Routing Locator
- RS Routing System
- SAL Service Abstraction Layer
- SDN Software Defined Networking
- SMTP Simple Mail Transfer Protocol
- SNMP Simple Network Management Protocol

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Acronyms (Cont)

SNMP4SDN	SNMP for SDN
SSH	Secure Socket Host
STT	Stateless TCP-like Transport
TCP	Transmission Control Protocol
TE	Traffic Engineering
TIA	Telecom Industry Association
TRILL	Transparent Interconnection of Lots of Links
URI	Uniform Resource Identifier
vBridge	Virtual Bridge
VIRL	Virtual Internet Routing Lab
VLAN	Virtual Local Area Network
VM	Virtual Machine
VNS	Virtual Network Segement
VPN	Virtual Private Network
vTep	Virtual Tunnel End Point
VTN	Virtual Tenant Network

Student Questions

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Acronyms (Cont)

- VxLAN Virtual Extensible Local Area Network
- WAN Wide Area Network
- XML Extensible Markup Language
- XMPP Extensible Messaging and Presence Protocol

Student Questions

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Style Guide

Correct	Incorrect
ACL	Acl or acl
API	api
ARP	Arp or arp
IPsec	IPSEC or ipsec
IPv4 or IPv6	Ipv4, Ipv6, ipv4, ipv6, IPV4, or IPV6
Karaf	karaf
Linux	LINUX or linux
NETCONF	Netconf or netconf
Neutron	neutron
OSGi	osgi or OSGI
Open vSwitch	OpenvSwitch, OpenVSwitch, or Open V Switch.
OpenDaylight	Opendaylight, Open Daylight, or OpenDayLight.
OpenFlow	Openflow, Open Flow, or openflow.
OpenStack	Open Stack or Openstack
QoS	Qos, QOS, or qos
RESTCONF	Restconf or restconf
RPC	Rpc or rpc
URL	Url or url

Source: http://docs.opendaylight.org/en/stable-nitrogen/documentation.html

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SDN Related Organizations and Projects

- Linux Foundation Open Source Networking, https://www.linuxfoundation.org/projects/networking/
- Open Networking Foundation (ONF): www.opennetworking.org
- Telecom Industry Association (TIA): www.tiaonline.org
- European Telecommunications Standards Institute (ETSI): www.etsi.org/
- Association for Telecom Industry Solutions (ATIS): www.atis.org/topsc/sdn.asp
- Internet Engineering Task Force (IETF): www.ietf.org
- OpenStack Quantum: https://wiki.openstack.org/wiki/Quantum
- OpenDaylight: www.opendaylight.org

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http://rajjain.com

http://www.cse.wustl.edu/~jain/cse5700-25/m_15sdn.htm

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Related Modules



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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