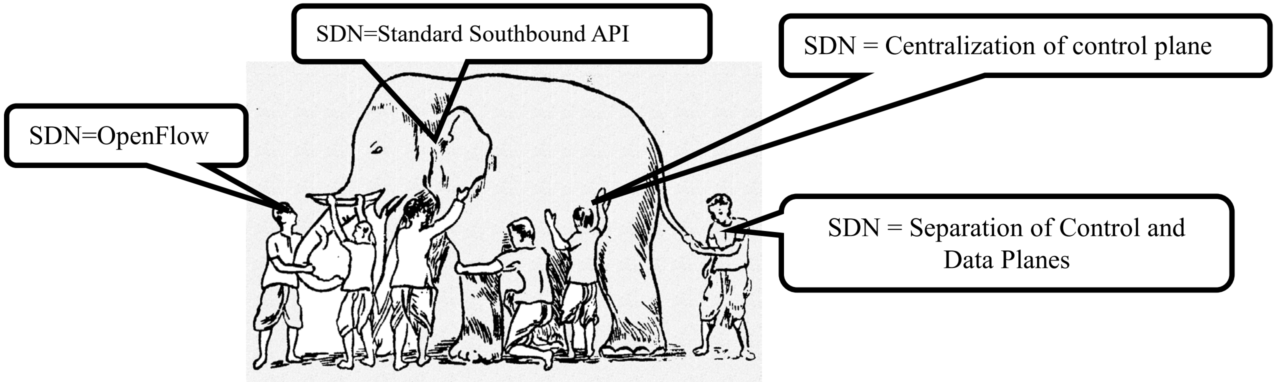
Introduction to Software Defined Networking (SDN)



SDN=Standard Southbound API

SDN = Centralization of control plane

SDN=OpenFlow

SDN = Separation of Control and Data Planes

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

http://www.cse.wustl.edu/~jain/cse570-18/

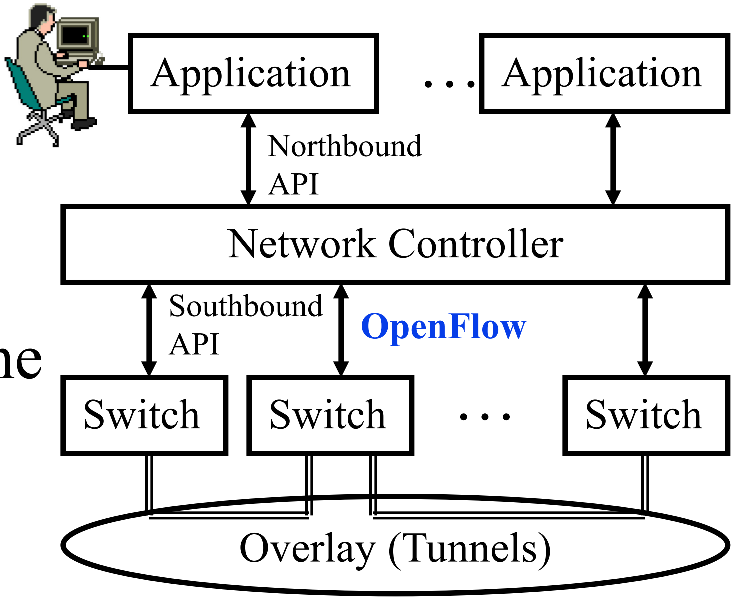
Overview

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.

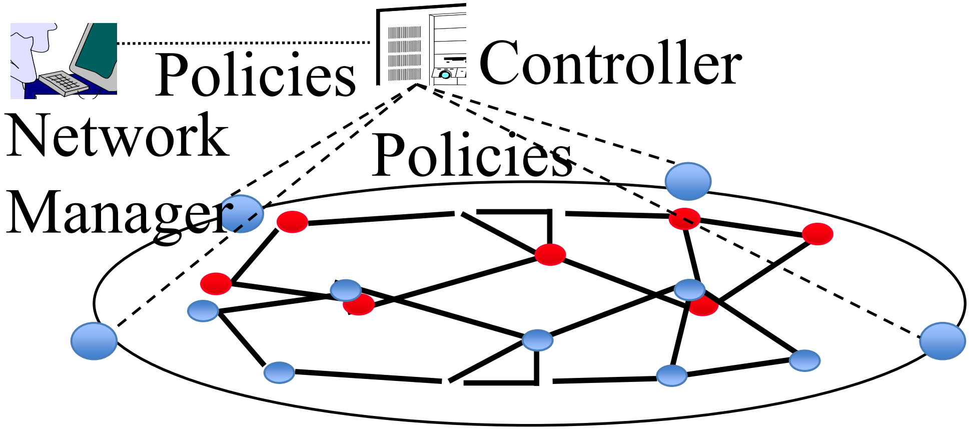
Origins of SDN

- ❑ 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.



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



What = Why We need SDN?

1. **Virtualization**: Use network resource 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 size, quantity Virtualization ⇒ Scaling
5. **Automation**: To lower OpEx minimize manual involvement
   - Troubleshooting
   - Reduce downtime
   - Policy enforcement
   - Provisioning/Re-provisioning/Segmentation of resources
   - Add new workloads, sites, devices, and resources

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, and routing, security
9. **Service Integration**: Load balancers, firewalls, Intrusion Detection Systems (IDS), provisioned on demand and placed appropriately on the traffic path

Why We need SDN? (Cont)

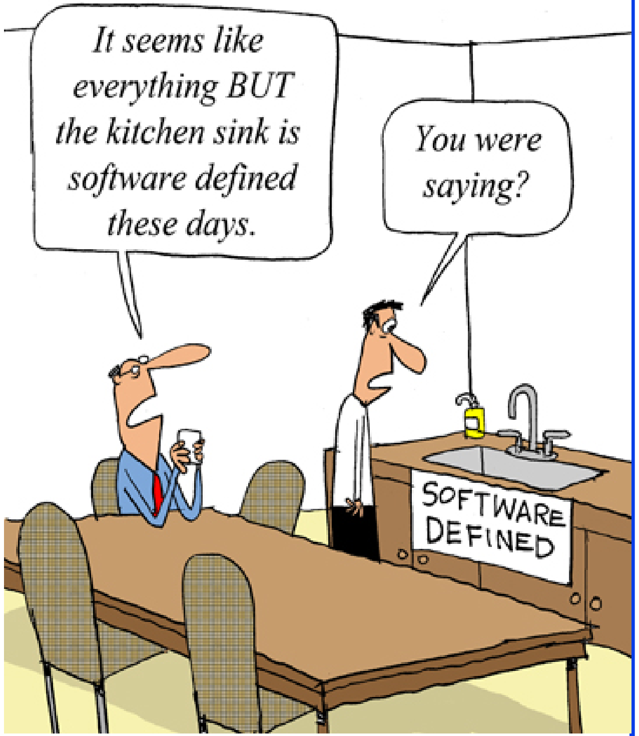
10. **Openness**: Full choice of "How" mechanisms
    ⇒ Modular plug-ins
    ⇒ Abstraction:
    - Abstract = Summary = Essence = General Idea
      ⇒ Hide the details.
    - Also, abstract is opposite of concrete
      ⇒ Define tasks by APIs and not by how it should be done.
      E.g., send from A to B. Not OSPF.

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

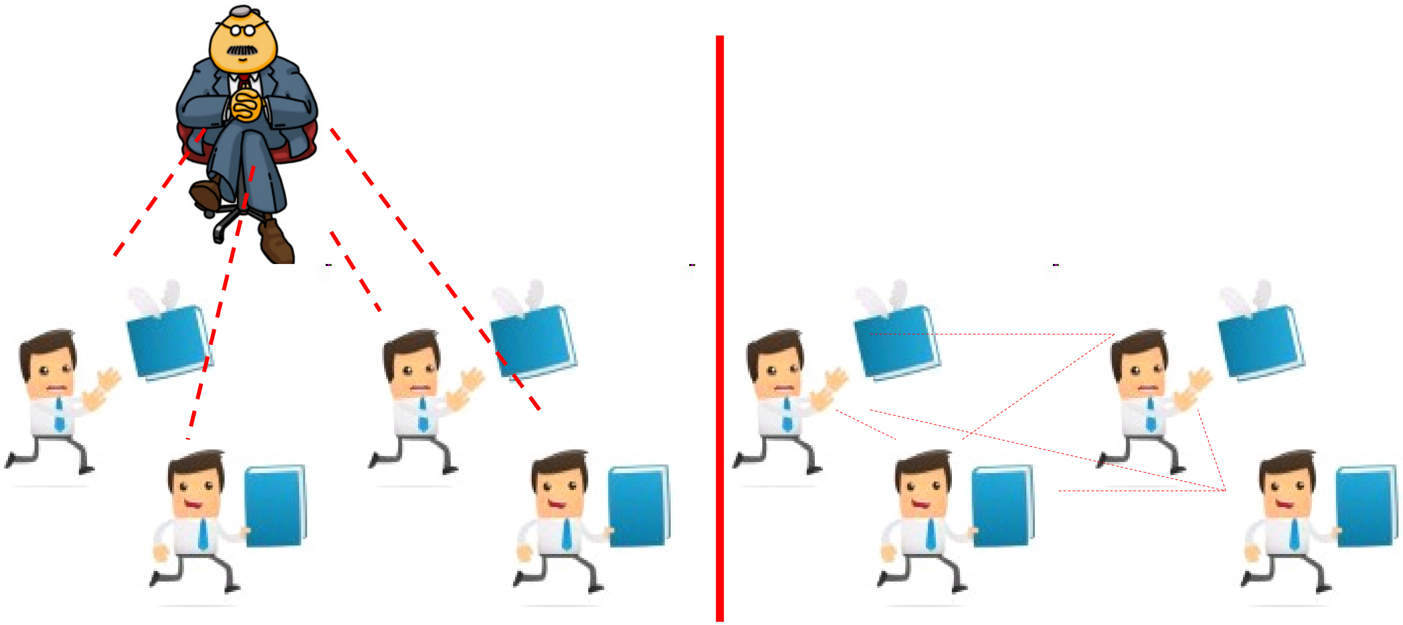
Ref: Open Data Center Alliance Usage Model: Software Defined Networking Rev 1.0,"
http://www.opendatacenteralliance.org/docs/Software_Defined_Networking_Master_Usage_Model_Rev1.0.pdf URL Invalid

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)


It seems like everything BUT the kitchen sink is software defined these days.
You were saying?
SOFTWARE DEFINED

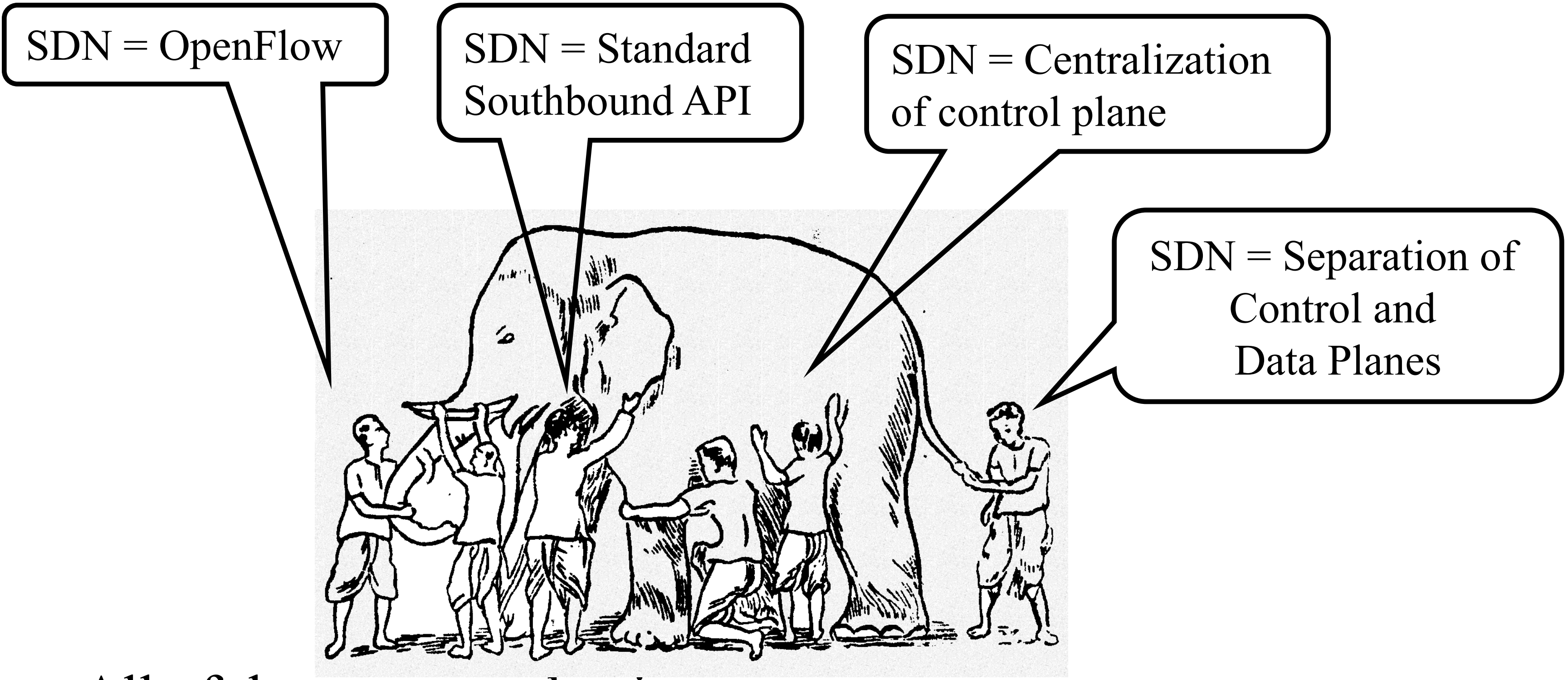
Centralized vs. Distributed



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

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

What SDN is Not?



SDN = OpenFlow

SDN = Standard Southbound API

SDN = Centralization of control plane

SDN = Separation of Control and Data Planes

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

Four Confusions About SDN

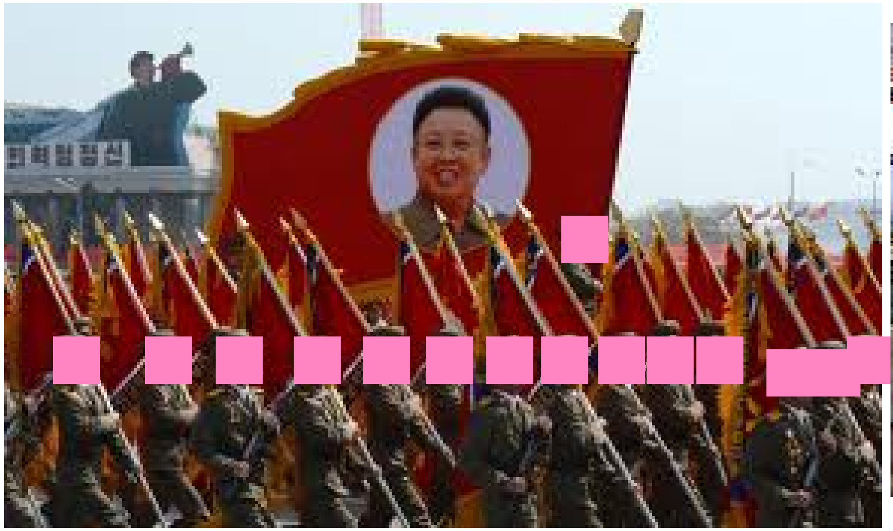
1. Policies vs. Control:
   Control = All bits and messages not sent by the user
   In IP, control includes all header bits and all routing messages.
2. Separation of Control Plane:
   Elements have only data plane and have no brains
3. SDN vs. OpenFlow:
   OpenFlow is the father of SDN but not SDN.
4. Need OpenFlow:

- OpenFlow is micro-management.
- It is not scalable.
- For large infrastructure, need scalable solutions.

Separation vs. Centralization

Separation of Control Plane

Centralization of Policies



Micromanagement is not scalable

Current SDN Debate: What vs. How?

1. SDN is easy if control is centralized but not necessary. Distributed/hierarchical solutions may be required for fail-safe operation.
2. 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

Current SDN Debate: What vs. How? (Cont)

3. SDN is easy with a standard southbound protocol like OpenFlow but one protocol may not work/scale in all cases
    1. Diversity of protocols is a fact of life.
    2. There are no standard operating systems, processors, routers, or Ethernet switches.
4. If industry finds an easier way to solve the same problems by another method, that method may win. E.g., ATM vs. MPLS.

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 switch
   c. Network operating system: 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. ONF SDN: OpenFlow southbound

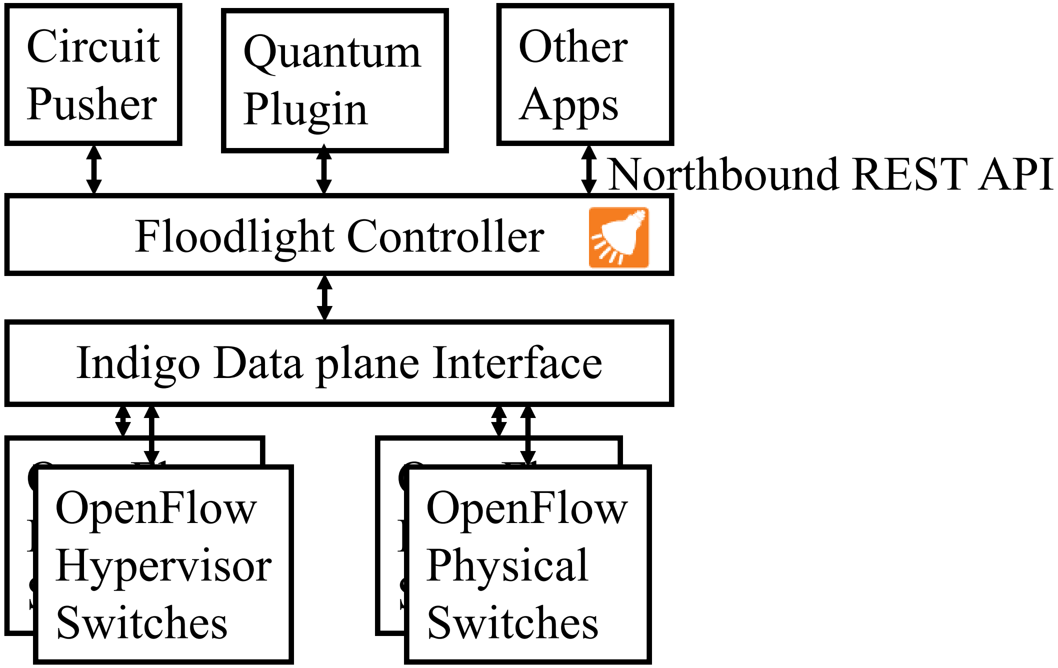
All provide: Abstraction, Programmability, and Centralization

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

Floodlight

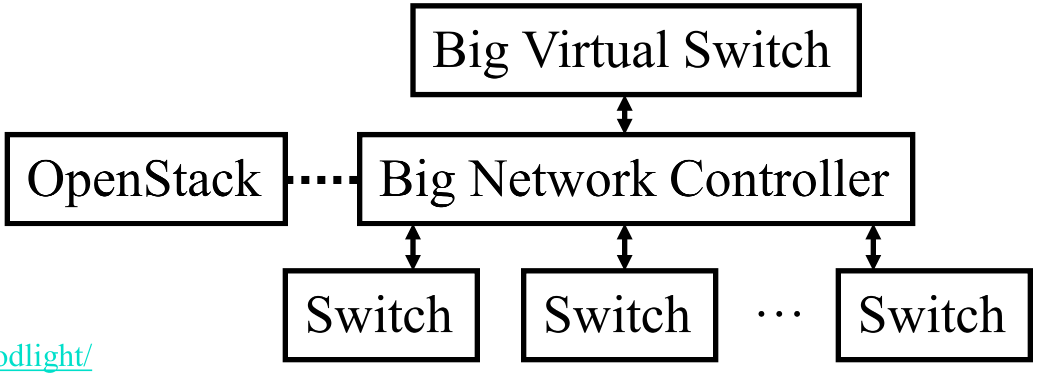
- **Java** based OpenFlow controller based on Beacon runs within a JVM. Developers from Big Switch Networks
- Indigo: Software to make switch hardware OpenFlow compatible
- Floodlight is the core of Big Switch Controller from Big Switch Networks


Circuit Pusher
Quantum Plugin
Other Apps
Northbound REST API
Floodlight Controller
Indigo Data plane Interface
OpenFlow Hypervisor Switches
OpenFlow Physical Switches

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

Floodlight (Cont)

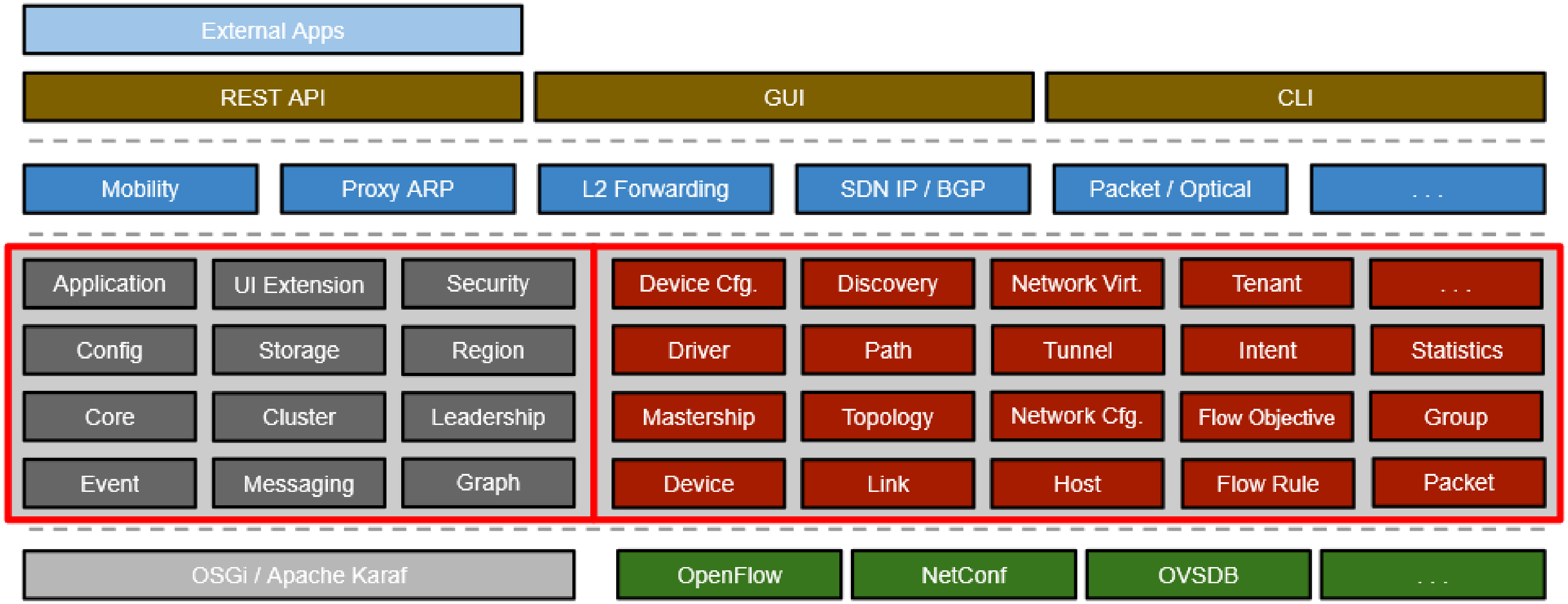
- A number of real-world networking applications
  - **Neutron plug-in** for OpenStack cloud management system
  - **Static Flow Pusher**: Allows users to manually insert flows
  - **Circuit Pusher**: Creates permanent entries on all switches along the path
  - **Firewall**: Enforces access control list (ACL) rules on packets
  - **Big Virtual Switch:** Automates network provisioning for a large scale data centers. Includes provisioning, multi-tenant partitioning



Ref: http://www.projectfloodlight.org/floodlight/

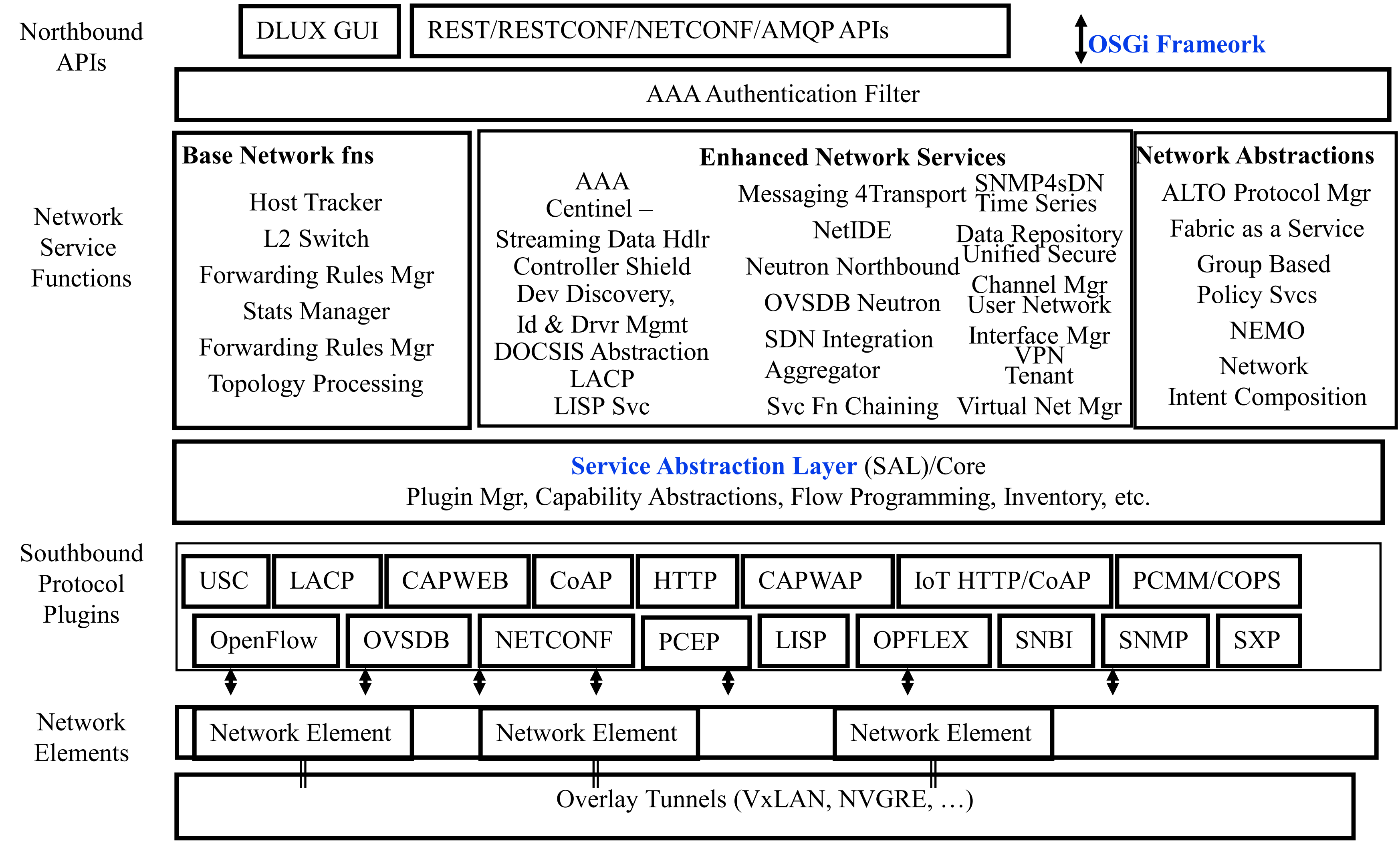
ONOS

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



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

OpenDaylight: Multi-Protocol SDN



Northbound APIs

DLUX GUI

REST/RESTCONF/NETCONF/AMQP APIs

OSGi Frameork

AAA Authentication Filter

Network Service Functions

Base Network fns

Host Tracker
L2 Switch
Forwarding Rules Mgr
Stats Manager
Forwarding Rules Mgr
Topology Processing

Enhanced Network Services

AAA
Centinel –
Streaming Data Hdlr
Controller Shield
Dev Discovery,
Id & Drvr Mgmt
DOCSIS Abstraction
LACP
LISP Svc

Messaging 4Transport
NetIDE
Neutron Northbound
OVSDB Neutron
SDN Integration
Aggregator
Svc Fn Chaining

SNMP4sDN
Time Series
Data Repository
Unified Secure
Channel Mgr
User Network
Interface Mgr
VPN
Tenant
Virtual Net Mgr

Network Abstractions

ALTO Protocol Mgr
Fabric as a Service
Group Based
Policy Svcs
NEMO
Network
Intent Composition

Service Abstraction Layer (SAL)/Core
Plugin Mgr, Capability Abstractions, Flow Programming, Inventory, etc.

Southbound Protocol Plugins

USC | LACP | CAPWEB | CoAP | HTTP | CAPWAP | IoT HTTP/CoAP | PCMM/COPS

OpenFlow | OVSDB | NETCONF | PCEP | LISP | OPFLEX | SNBI | SNMP | SXP

Network Elements

Network Element | Network Element | Network Element

Overlay Tunnels (VxLAN, NVGRE, …)

OpenDaylight SDN Controller Platform (OSCP)

- Multi-company collaboration under Linux foundation
- Many projects including OpenDaylight Controller
- Supports multiple southbound protocols via plug-ins including OpenFlow
- Dynamically linked in to 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

https://wiki.opendaylight.org/view/Main_Page

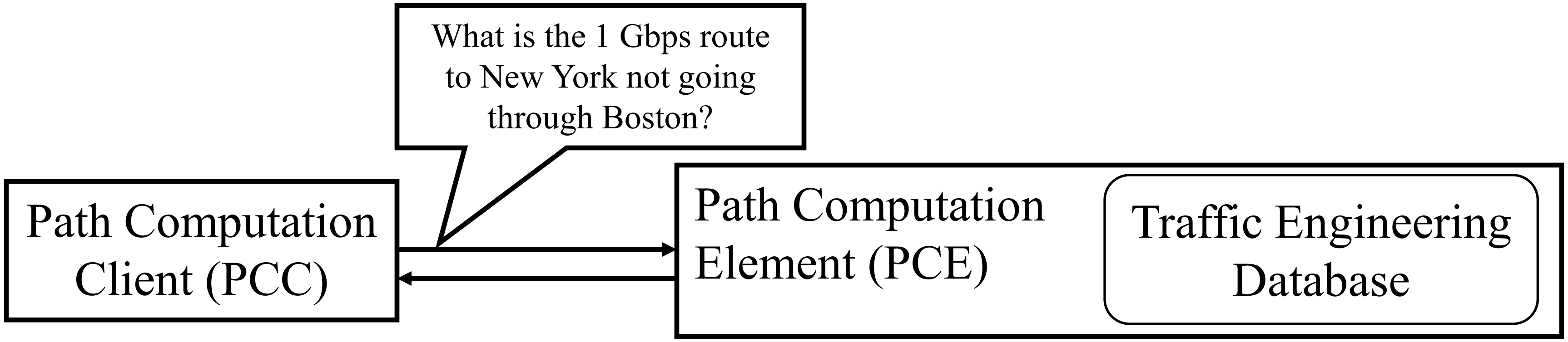
Examples Alternative APIs

- Southbound APIs: PCEP, BGP, …
- Northbound APIs: ALTO, …
- Overlay: VxLAN, TRILL, LISP, …
- Configuration API: NETCONF, RESTCONF, …
- Controller: PCE, …

Ref: T. Nadeau and K. Gray, "SDN," O'Reilly, 2013, 384 pp, ISBN:978-1-449-34230-2 (Safari Book)

Path Computation Element (PCE)

- MPLS and GMPLS require originating routers to find paths that satisfy multiple constraints including not using any backup routers and having a given bandwidth etc.
- This may require more computer power or network knowledge than a router may have.
- IETF PCE working group has developed a set of protocols that allow a Path computation client (PCC), i.e., router to get the path from path computation element (PCE)
- PCE may be centralized or may be distributed in many or every router.


What is the 1 Gbps route to New York not going through Boston?
Path Computation Client (PCC)
Path Computation Element (PCE)
Traffic Engineering Database

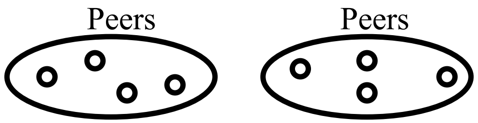
PCE (Cont)

- PCE separates the route computation function from the forwarding function.
- Both functions may be resident in the same box or different boxes.
- 25+ RFCs documenting protocols for:
  - PCE-to-PCC communication
  - PCE-to-PCE communication (Multiple PCEs)
  - PCE discovery

Ref: http://datatracker.ietf.org/wg/pce/

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

Application Layer Traffic Optimization (ALTO)



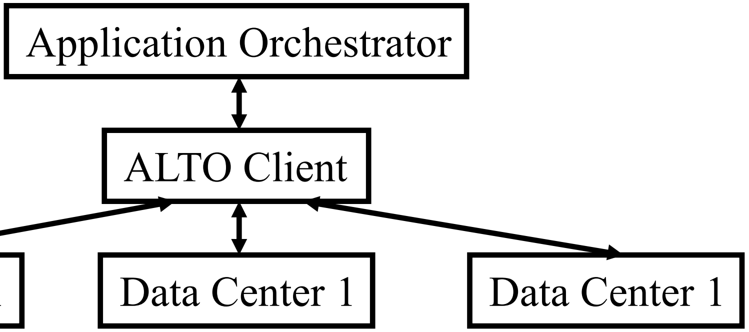
- IETF working group to optimize P2P traffic
  ⇒ Better to get files from nearby peers
- Provide guidance in peer selection
- ALTO Server: Has knowledge of distributed resources
- ALTO Client: Requests information from servers about the appropriate peers
- Ratio Criteria: Topological distance, traffic charges, …
- ALTO Server could get information from providers or from nodes about their characteristics, e.g., flat-rate or volume based charging
- A client may get the list of potential peers and send it to the server, which can return a ordered list
- Also need a protocol for ALTO server discovery

Ref: J. Seedorf and E. Berger, "ALTO Problem Statement," http://datatracker.ietf.org/doc/rfc5693/?include_text=1

Ref: 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

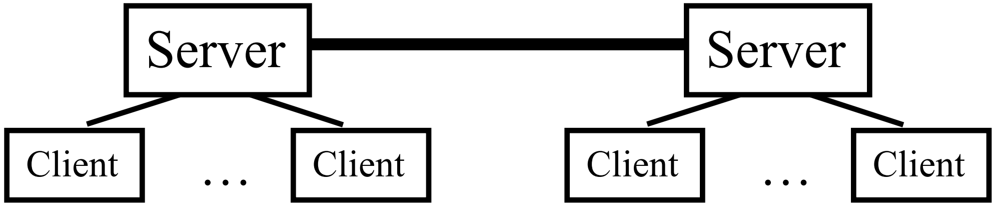
ALTO Extension

- Now being extended to locate resources in data centers
- Need to be able to express
  - resource (memory, storage, CPU, network) availability
  - Cost of these resources
  - Constraints on resources, e.g., bandwidth
  - Constraints on structure, e.g., Power consumption
- ALTO client gets the info from various providers
- Issue of privacy of resource and cost info for the provider



XMPP

- Extensible Messaging and Presence Protocol
- **Extensible** ⇒ Using XML
- Similar to SMTP email protocol but for near real-time communication
- Each client has an ID, e.g., john@wustl.edu/mobile (John's mobile phone)
- Client sets up a connection with the server ⇒ Client is online
- **Presence**: Server maintains contact addresses and may let other contacts know that this client is now on-line
- **Messaging**: When a client sends a "chat" message to another clients, it is forwarded to these other clients
- Messages are "*pushed*" (⇒ real-time) as opposed to "*polled*" as in SMTP/POP emails.



Ref: P. Saint-Andre, et al., "XMPP: The Definitive Guide," O'Reilly, 2009, 320 pp., ISBN:9780596521264 (Safari Book)

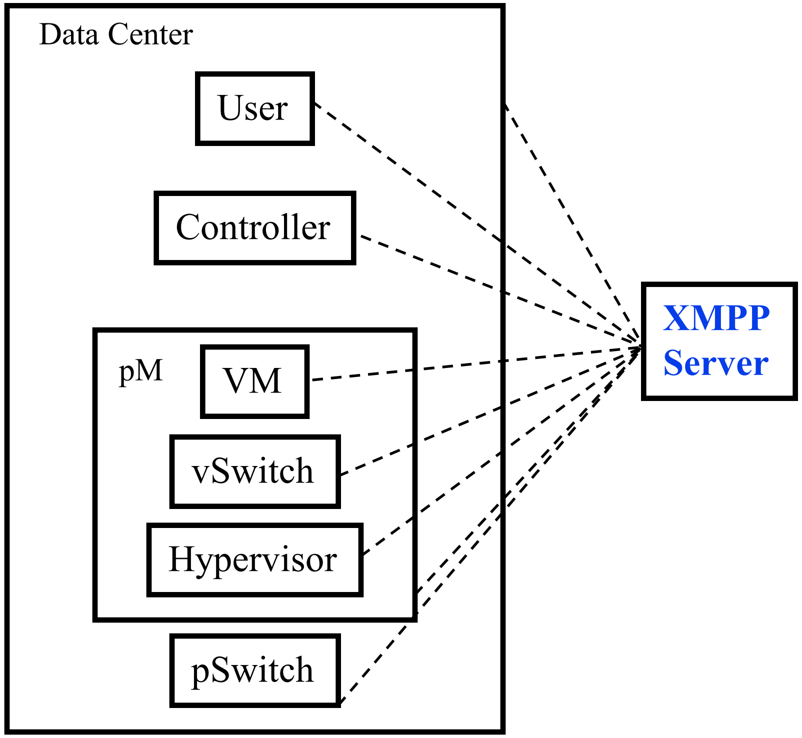
XMPP (Cont)

- XMPP is IETF standardization of Jabber protocol
- RFC 6121 defines XMPP using TCP connections. But HTTP is often used as transport to navigate firewalls
- All messages are XML encoded
  ⇒ Not efficient for binary file transfers
  ⇒ Out-of-band binary channels are often used with XMPP.
- A number of open-source implementations are available
- Variations of it are widely used in most instant messaging programs including Google, Skype, Facebook, …, many games
- Used in IoT and data centers for management. Network devices have XMPP clients that respond to XMPP messages containing CLI management requests ⇒ You can manage your network using any other XMPP client, e.g., your mobile phone
- Arista switches can be managed by XMPP, Juniper uses XMPP as a southbound protocol for SDN

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

XMPP in Data Centers

- Everything is an XMPP entity.
  It has its own contact list and authorizations.



Ref: https://github.com/ArchipelProject/Archipel/wiki/Architecture-%26-Concepts

OpenDaylight Tools

1. **Applications**: 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

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

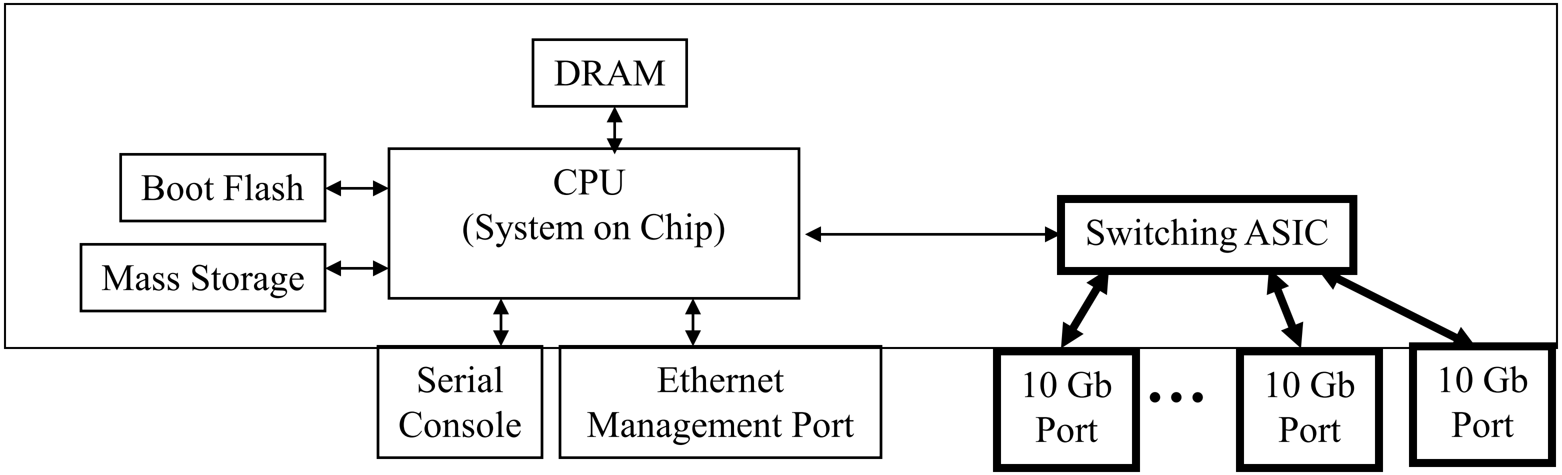
Open Network Linux

- 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

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

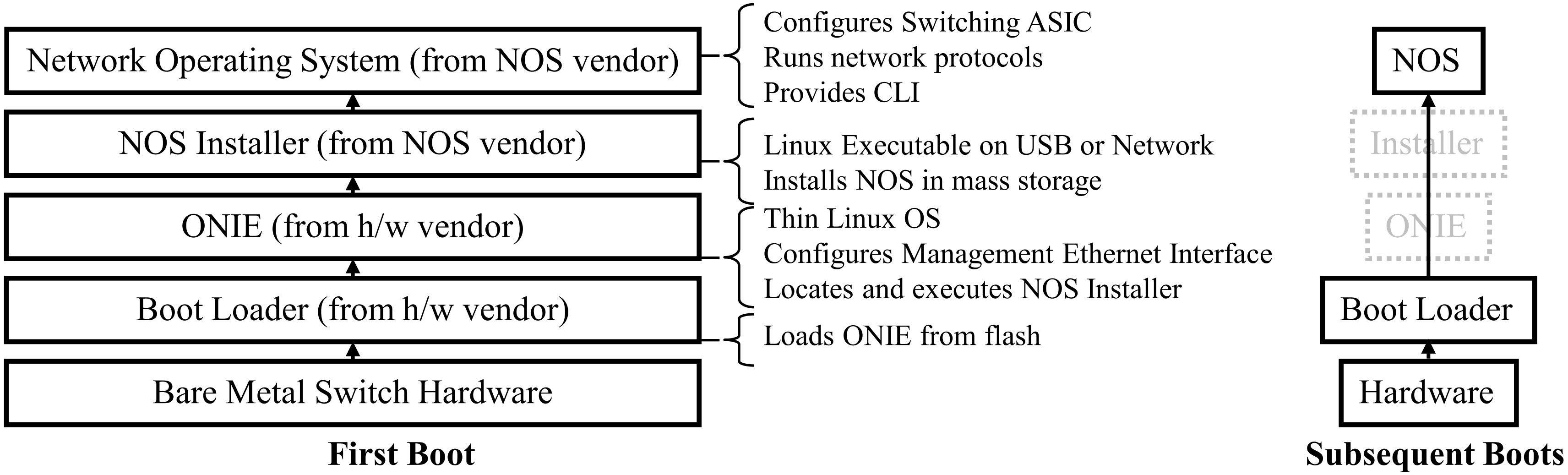
Open Source Forwarding Agents

- **Quagga**: A popular open source routing software suite including OSPF, RIP, BGP, …
- **FRRouting**: a fork of Qagga. 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/

Open Network Install Environment (ONIE)

- Part of **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


Network Operating System (from NOS vendor)
NOS Installer (from NOS vendor)
ONIE (from h/w vendor)
Boot Loader (from h/w vendor)
Bare Metal Switch Hardware
Configures Switching ASIC
Runs network protocols
Provides CLI
Linux Executable on USB or Network
Installs NOS in mass storage
Thin Linux OS
Configures Management Ethernet Interface
Locates and executes NOS Installer
Loads ONIE from flash
First Boot
NOS
Installer
ONIE
Boot Loader
Hardware
Subsequent Boots

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

Mininet

- Widely used open source network emulation environment.
- Can simulate a number of end-hosts, switches, routers, links on a Linux
- Used for rapid prototyping of software define networks
- Built-in Open vSwitch, and a 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 diagnositc commands like iperf, ping, and other commands in a host, e.g., *mininet> h11 ifconfig –a*
- Mininet code for several popular commercial switches are available.

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

RESTful APIs

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

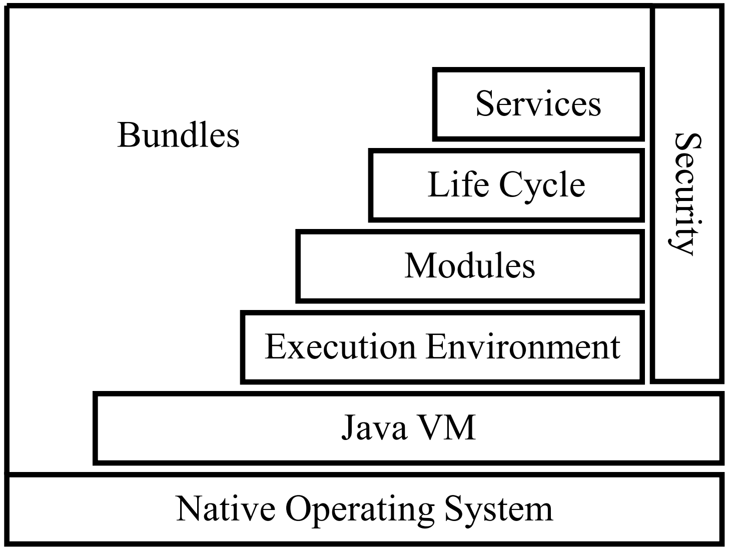
REST (Cont)

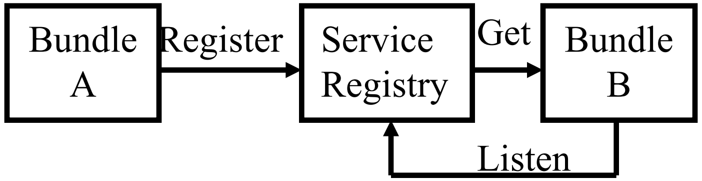
- Create, Read, Update, Delete (CRUD) Operations
- Uniform Interface: GET (Read), POST (Insert), PUT (write), DELETE
- Resources identified by global identifiers, e.g., URI in Web.
- Get http://<fqdn-or-ip-address>/rest/v1/model/<data-type>/<optional-id>?<optional-query-params>
  E.g., GET http://odcp.org/rest/v1/model/controller-node
- 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, …
- 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

OSGi Framework

- Initially, Open Services Gateway initiative
- A set of specifications for dynamic application composition using reusable Java components called bundles
- Bundles publish their services with OSGi services registry and can find/use services of other bundles



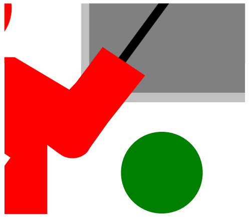


Ref: http://www.osgi.org/Technology/WhatIsOSGi

OSGi (Cont)

- Bundles can be installed, started, stopped, updated or uninstalled using a lifecycle API
- Modules defines how a bundle can import/export code
- Security layer handles security
- 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
  ⇒ Bundles can be installed and uninstalled on the fly.

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 open.
4. Mininet for network simulation
5. REST=HTTP APIs
   OSGI framework for modularity

Reading List

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- 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).

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://www.osgi.org/Technology/WhatIsOSGi
- http://www.sdncentral.com/sdn-use-cases /
- https://wiki.opendaylight.org/view/OpenDaylight_SDN_Controller_Platform_%28OSCP%29:Proposal
- http://datatracker.ietf.org/wg/pce/
- https://wiki.opendaylight.org/view/Main_Page
- http://events17.linuxfoundation.org/sites/events/files/slides/OpenDaylight-Network-Programmability.pdf
- OpenDaylight Components and Tools, https://wiki.opendaylight.org

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- Scott S. Lowe, Matt Oswalt, Jason Edelman, "Network Programmability and Automation," O'Reilly Media, Inc., February 2018, 581 pp., ISBN:978-1-4919-3125-7 (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).
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- P. Saint-Andre, et al., "XMPP: The Definitive Guide," O'Reilly, 2009, 320 pp., ISBN:9780596521264 (Safari Book)

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

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

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

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

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 Expences
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

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

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

Acronyms (Cont)

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

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

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

SDN Web Sites

- SDN Central, http://www.sdncentral.com
- SDN Open Source Projects, http://www.sdncentral.com/comprehensive-list-of-open-source-sdn-projects/
- SDN Products and Services, http://www.sdncentral.com/announced-sdn-products/
- HotSDN 2012, http://yuba.stanford.edu/~casado/of-sw.html (Papers downloadable)
- SDN-OpenFlow Research and Projects, http://searchsdn.techtarget.com/resources/SDN-OpenFlow-research-and-projects

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

CSE473S: Introduction to Computer Networks (Fall 2011),
https://www.youtube.com/playlist?list=PLjGG94etKypJWOSPMh8Azcgy5e_10TiDw

Wireless and Mobile Networking (Spring 2016),
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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