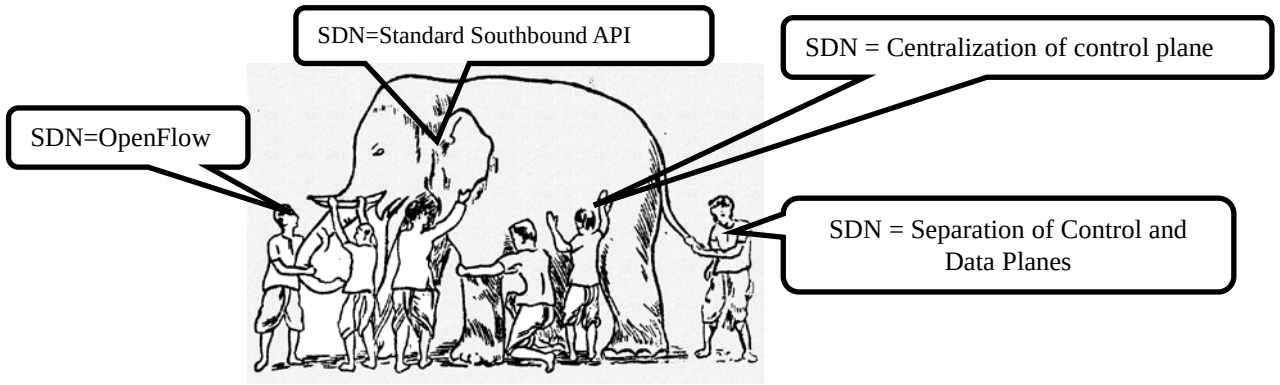
Introduction to Software Defined Networking (SDN)



Raj Jain
Washington University in Saint Louis
Saint Louis, MO 63130
Jain@cse.wustl.edu

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

http://www.cse.wustl.edu/~jain/cse570-23/

Student Questions

Overview

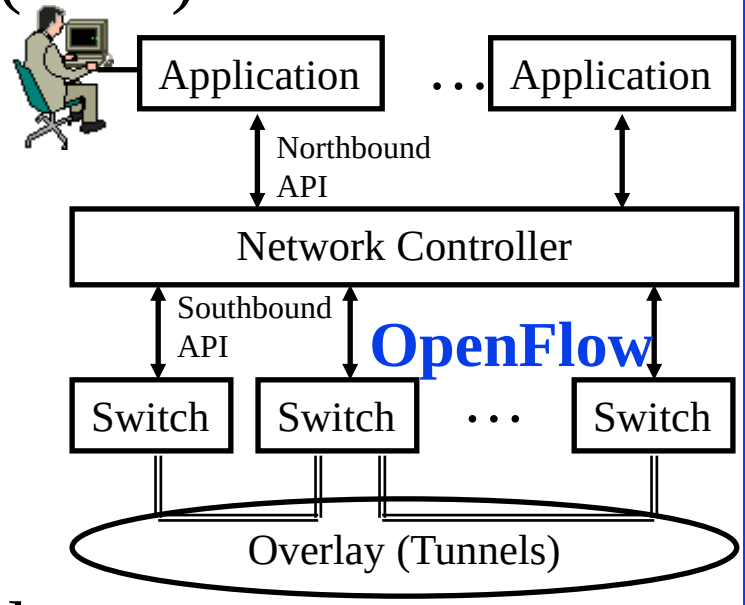
1. What is SDN?
2. SDN Controllers
3. Alternative APIs: XMPP, PCE, ForCES, ALTO
4. RESTful APIs and OSGi Framework

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

Student Questions

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.



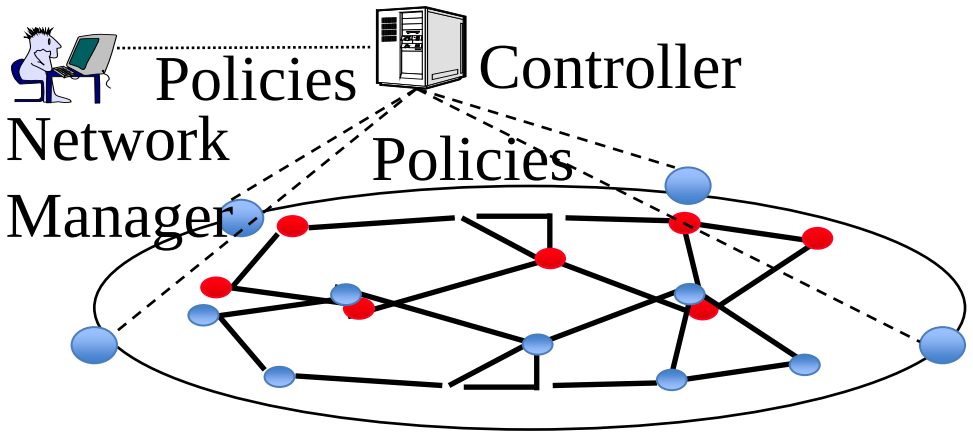
Student Questions

- Please can you explain further the difference between control and centralized?

Controller = Boss who makes policies
Distributed Controllers = Many bosses
Centralized Controller = One boss

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



Student Questions

- Where is the SDN being deployed? Is it on server machines? Networking hardware like switches?

Networking hardware, like routers and switches, load balancers, and firewalls, can be software-defined. SDN is not limited to networking.

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

Student Questions

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

Student Questions

Why We need SDN? (Cont)

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

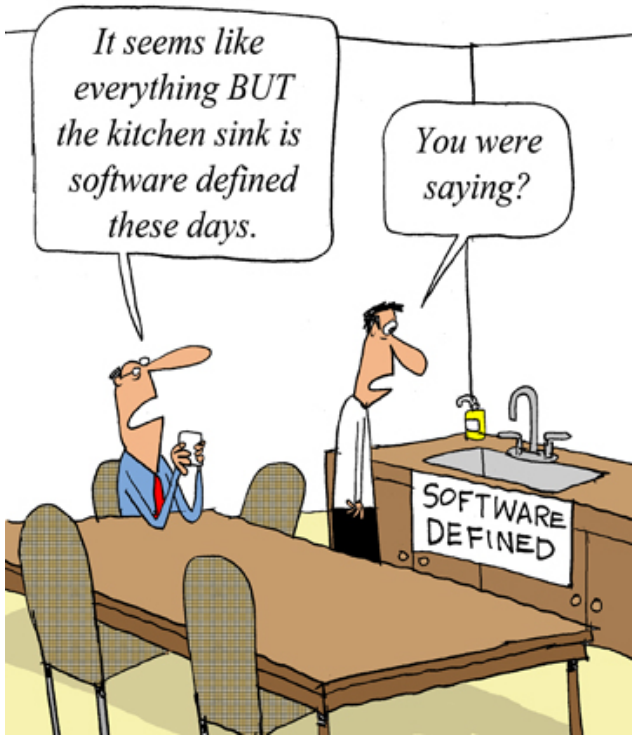
- Abstract = Summary = Essence = General Idea
  ⇒ Hide the details.
- Also, the abstract is the opposite of concrete
  ⇒ Define tasks by APIs and not by how they should be done. E.g., send from A to B. Not OSPF.

Student Questions

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

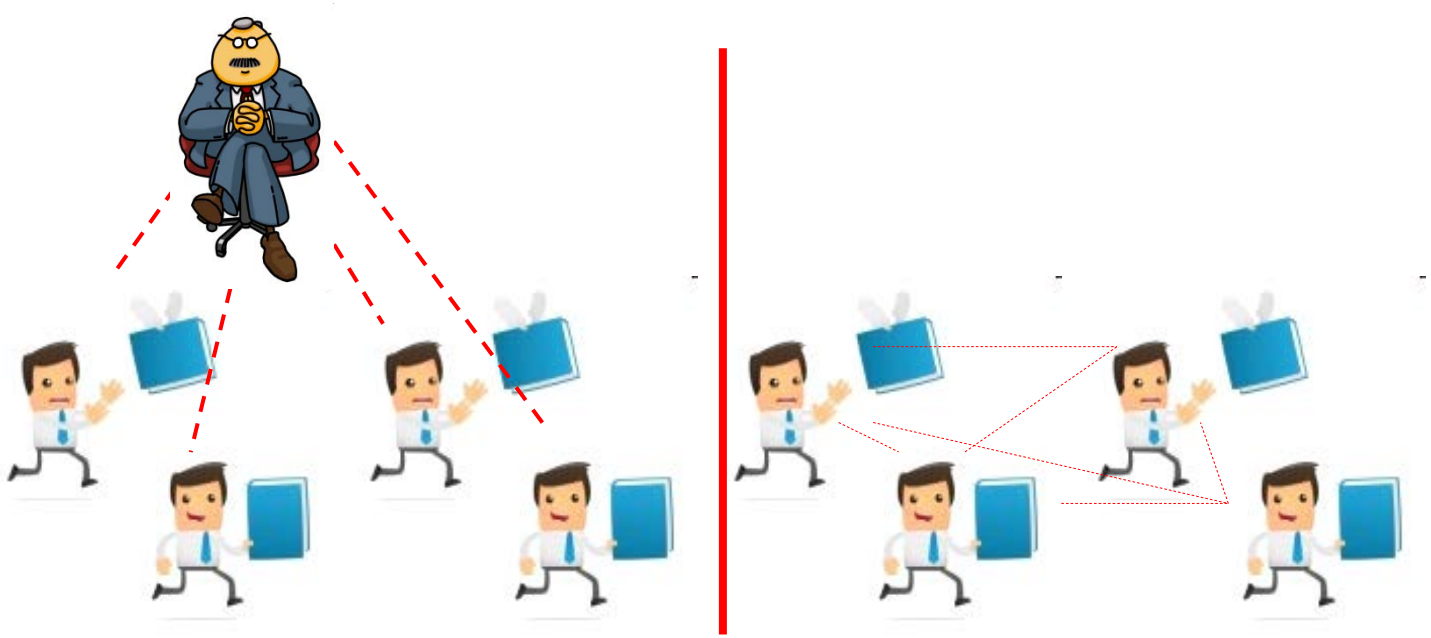
Software Defined Anything (SDx)

- 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)



Student Questions

Centralized vs. Distributed

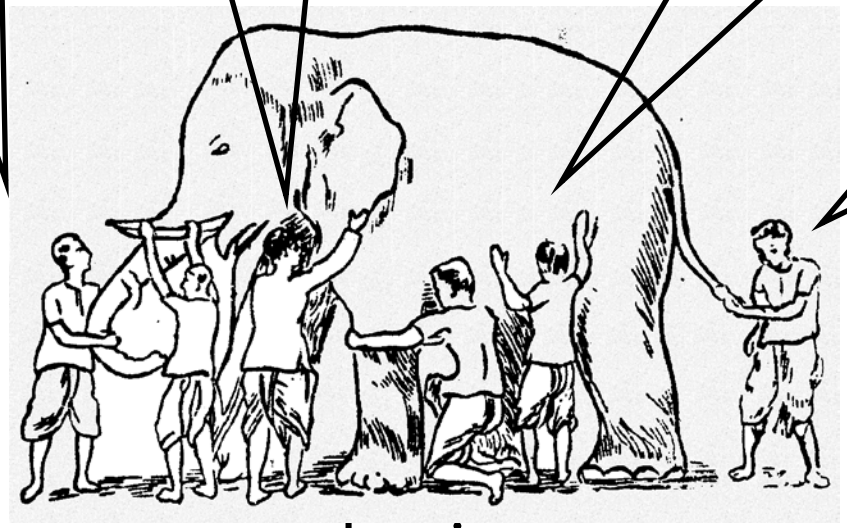


- Fast Response to changes
- Fast Consistency
- Less overhead ⇒ Scalable
- Single Point of Failure

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

Student Questions

What SDN is Not?



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

Student Questions

- Is SDN a conceptual thing? I'm still confused.

SDN is a concept. Everyone has a different meaning of this concept. Like, "Beauty is in the eyes of the beholder." Beauty is a concept.

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.

Student Questions

- Is the SDN scalable?

Every centralized concept has its scalability limit. SDN, depending upon how you define and implement it, has its limit." Distributed has a much higher limit, but then there is an issue of consistency.

- Can you say more about point 1? Is the idea that it is INCORRECT to say that the user does not send any control data?

The user specifies control indirectly to the service layer. The service layer makes the control bits as needed.
Policies are rules.

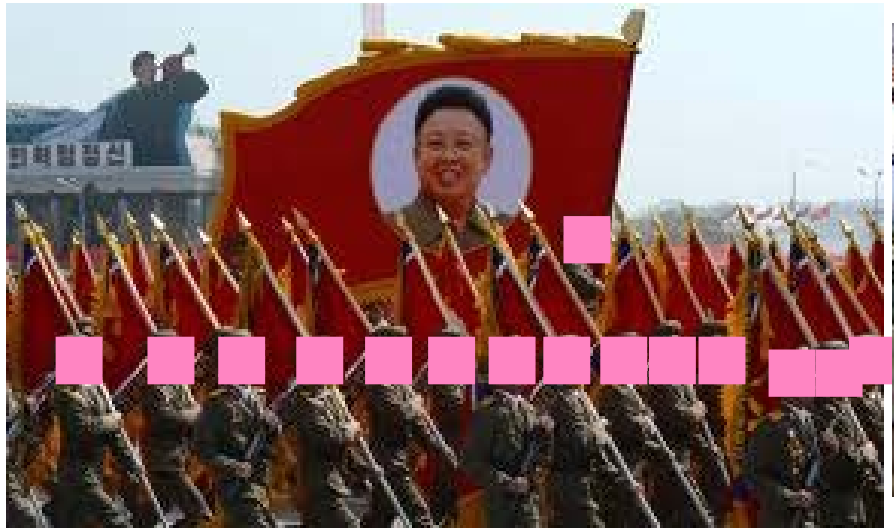
- To clarify once more, are these confusions all incorrect? Can you explain the three again?

Yes. Point 3 states that OpenFlow is one of many ways to do SDN. I have seen papers breaking the security of SDN. They were breaking the security of OpenFlow.

Separation vs. Centralization

Separation of Control Plane

Centralization of Policies



Micromanagement is not scalable

Student Questions

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 the control plane may be harmful.
   The exact division of the control plane between a centralized controller and distributed forwarders is yet to be worked out.

Student Questions

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

3. SDN is accessible 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 the industry finds an easier way to solve the same problems by another method, that method may win. E.g., ATM vs. MPLS.

Student Questions

- Is there a security risk in using SDN? The controller of SDN is software installed on Windows or Linux, which makes the controller and the operating system face the same risk when attacked.

Attacks on the controller can have a devastating effect since they can turn off the whole network. So, the controller is heavily guarded, monitored, and secured (locked).

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 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. ONF SDN: OpenFlow southbound

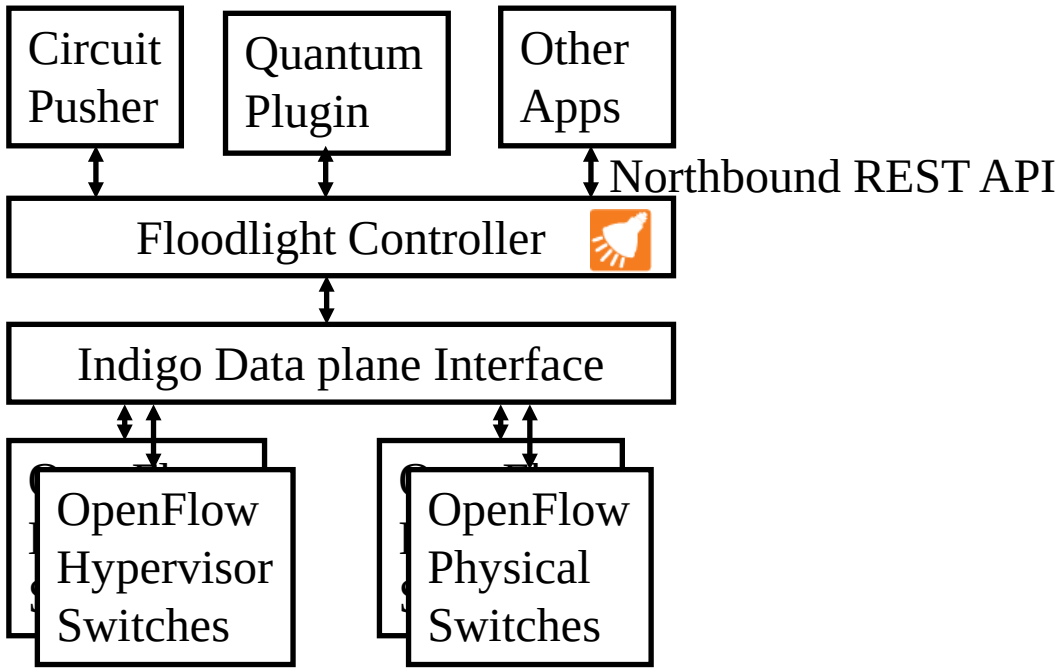
All provide Abstraction, Programmability, and Centralization

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

Student Questions

Floodlight

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

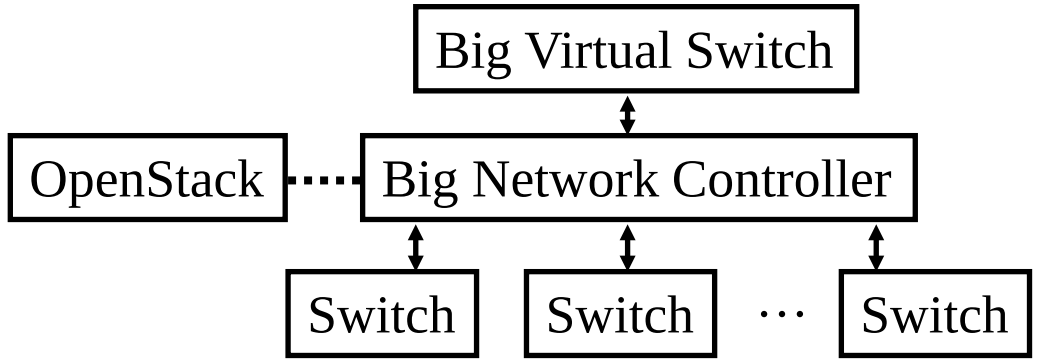


Ref: S. Azodolmolky, "Software Defined Networking with OpenFlow," Packt Publishing, October 2013, 152 pp., ISBN:978-1-84969-872-6 (Safari Book)

Student Questions

Floodlight (Cont)

- Several real-world networking applications
  - **Neutron plug-in** for OpenStack cloud management system
  - **Static Flow Pusher**: Allows users to insert flows manually
  - **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 large-scale data centers. Includes provisioning, multi-tenant partitioning

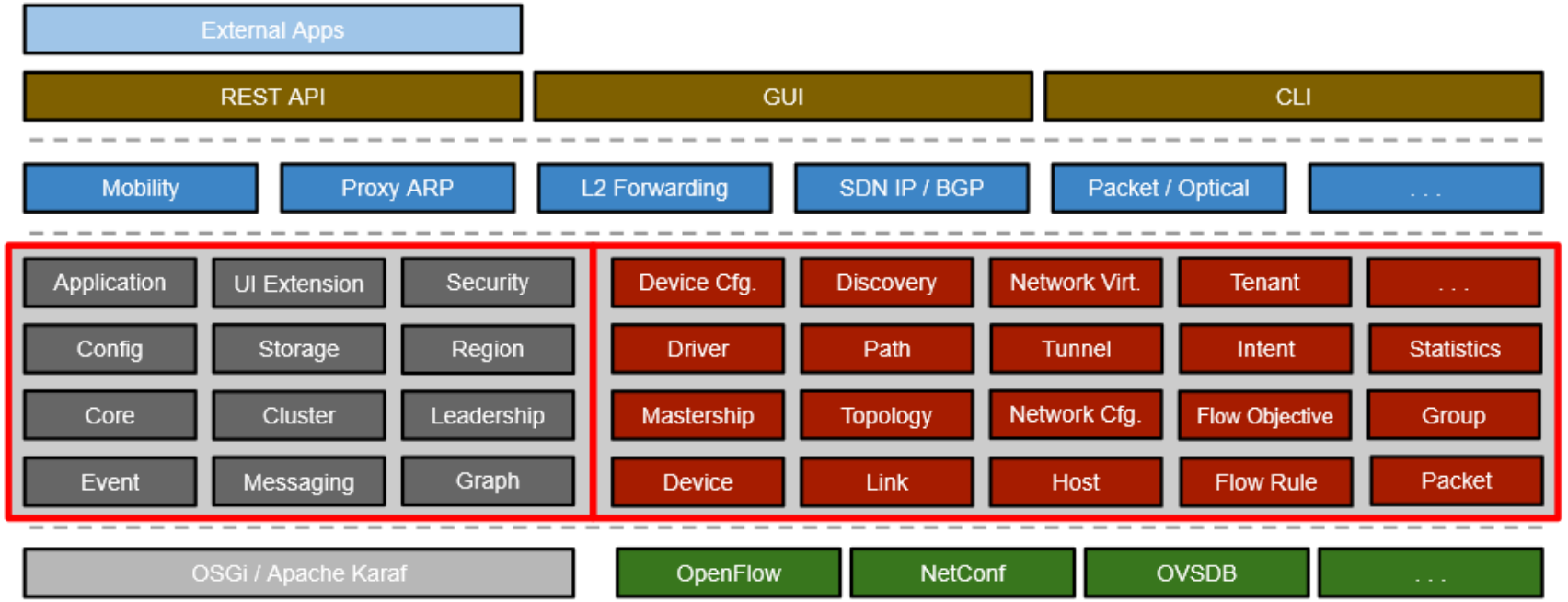


Ref: http://www.projectfloodlight.org/floodlight/

Student Questions

ONOS

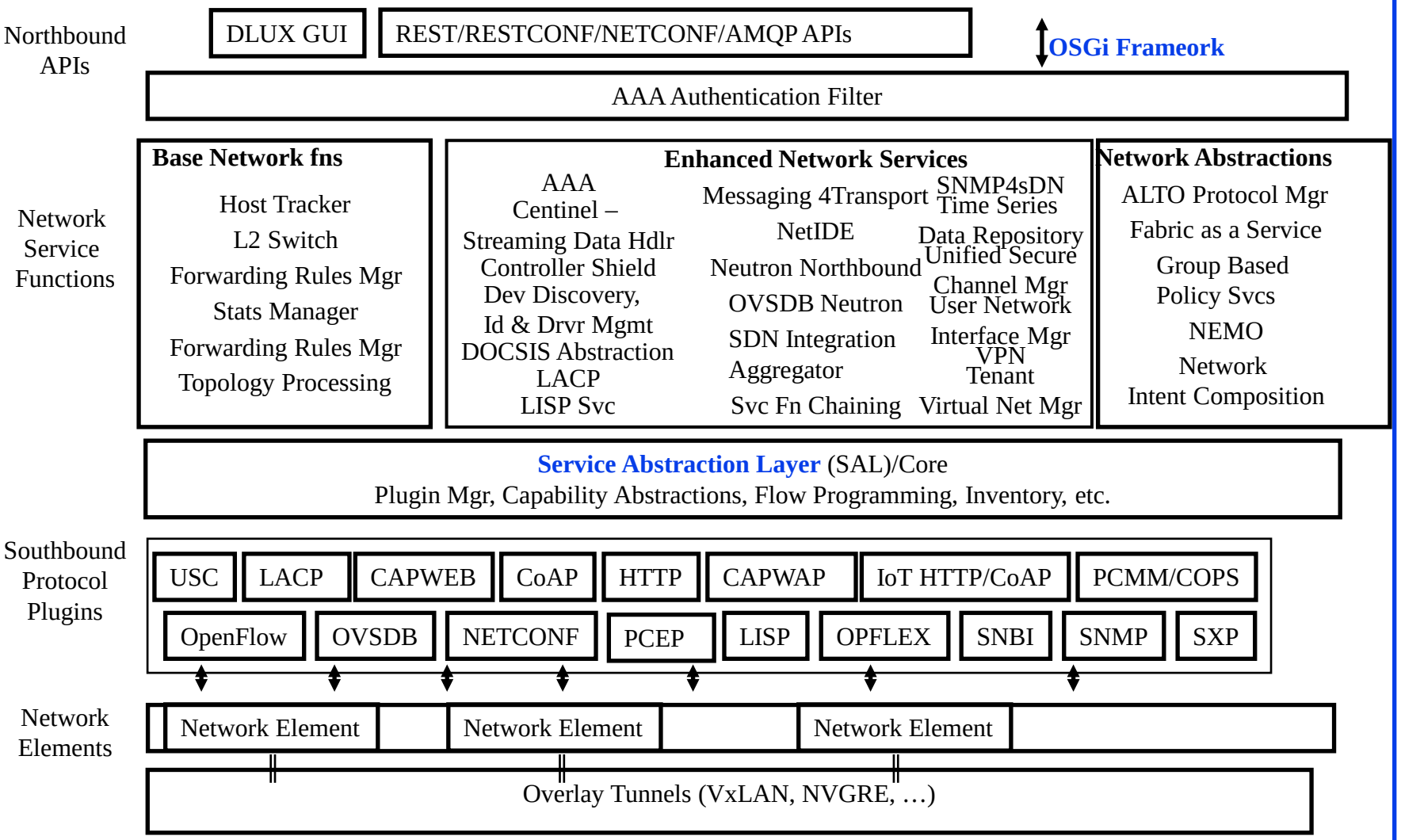
- Open Network Operating System: Distributed OpenFlow OS for a large WAN
- Initially OpenFlow-only. Now multi-protocol



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

Student Questions

OpenDaylight: Multi-Protocol SDN



Student Questions

- What is the role of AAA here?

AAA= Authentication, Authorization, and Access Control
Authentication=You are who you say you are.
Authorization = Use only what you are allowed.
Access Control = You have access to what you are allowed and no access to what you are not.

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

- What is a RESTful service?

RE*presenational*
S*tate*
T*ransfer*
A method of service that makes servers' jobs easy by not requiring them to maintain a state. This is how web servers work.

- What was the OSGI framework here? Does it allow for the modular feature of OpenDaylight?

OSGI Framework is a method to architect and implement software in a modular style.
OpenDaylight uses the OSGI framework.

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)

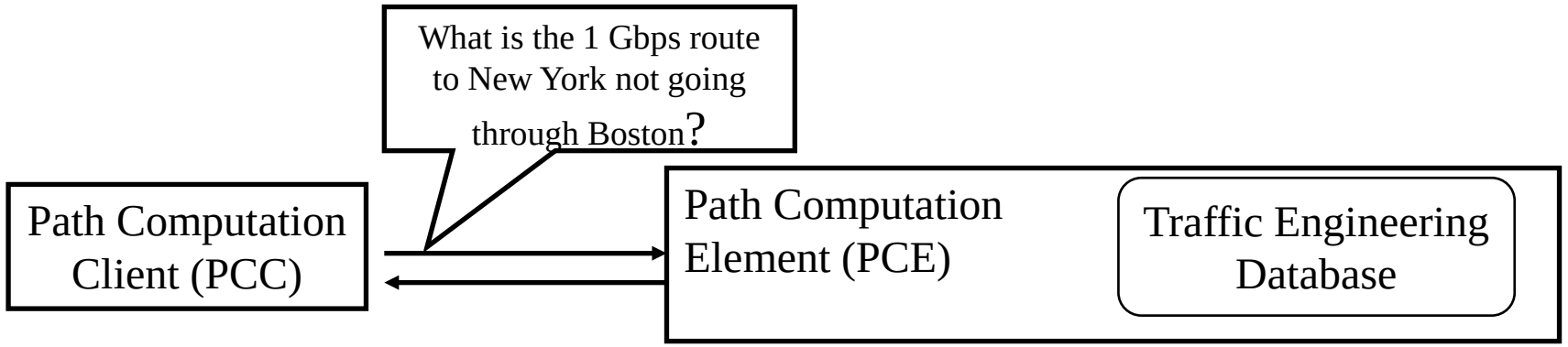
Student Questions

- Is it still north = clients, south = servers?

North = up
South = Down
If you show clients on the top, clients are north. If you show clients on the bottom, clients are south. In this module so far, we have shown the user on the top.

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 computing power or network knowledge than a router may have.
- The 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 the path computation element (PCE)
- PCE may be centralized or distributed in many or every router.



Student Questions

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

Student Questions

Application Layer Traffic Optimization (ALTO)

- IETF working group to optimize P2P traffi
  ⇒ Better to get files from nearby peers
- Guide peer selection
- ALTO Server: Knows 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 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 an ordered list
- Also, need a protocol for ALTO server discovery

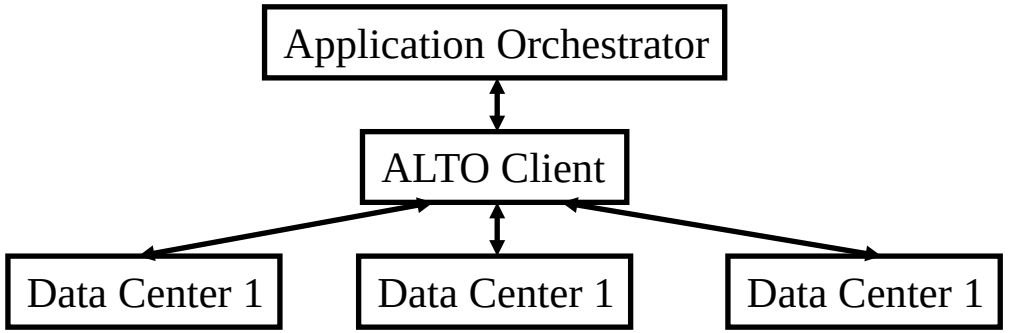
Ref: J. Seedorf and E. Berger, "ALTO Problem Statement," http://datatracker.ietf.org/doc/rfc5693/?include_text=1

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

Student Questions

ALTO Extension

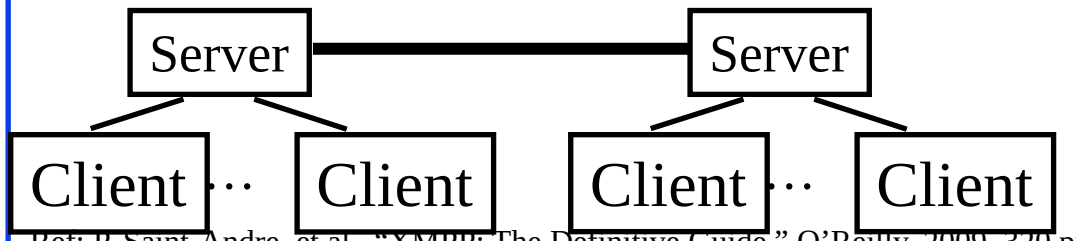
- Now being extended to locate resources in data centers
- Need to be able to express
  - resource (memory, storage, CPU, network) availability
  - Cost of these resources
  - Constraints on resources, e.g., bandwidth
  - Constraints on structure, e.g., Power consumption
- ALTO client gets the info from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



Student Questions

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**: The server maintains contact addresses and may let other contacts know that this client is now online
- **Messaging**: When a client sends a "chat" message to another client, 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)

Student Questions

XMPP (Cont)

- XMPP is the 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.
- Several 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
- XMPP can manage Arista switches, and Juniper uses XMPP as a southbound protocol for SDN

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

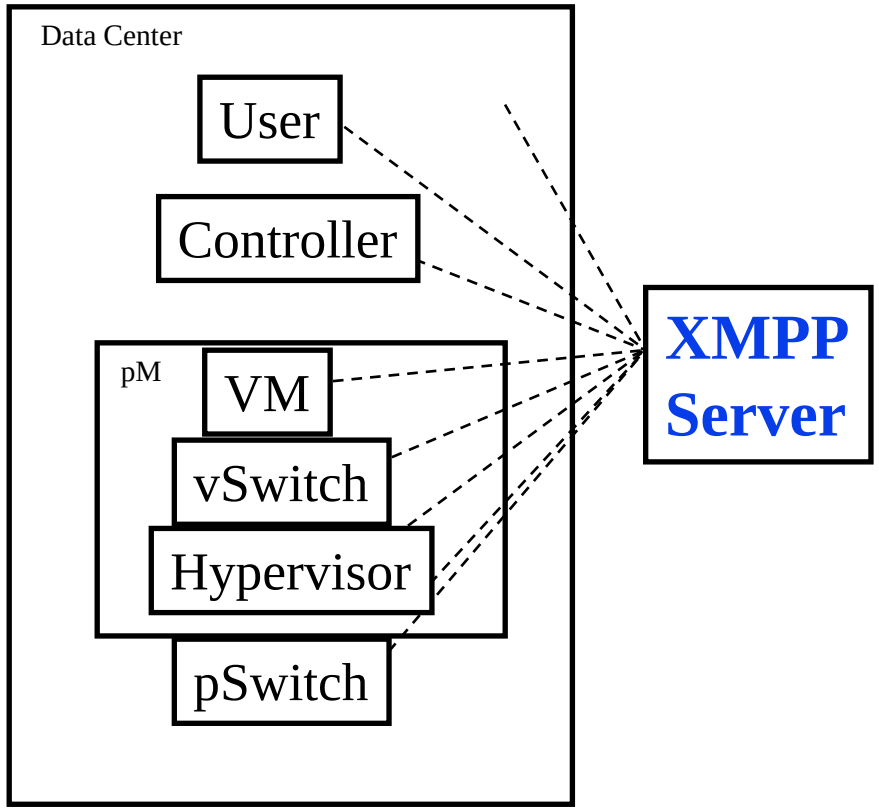
Student Questions

- What is the primary network structure of XMPP?

See slide 15.28.

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

Student Questions

- Which Layer is XMPP on?

XMPP server is a controller. It is not a layer. It is a plane.

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

Student Questions

- Can you refresh our memory on Northbound vs. Southbound in this context?

See Q&A on slide 15.21

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

Student Questions

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

Student Questions

- ONL supports Broadcom SDK, which means it should use Broadcom ASICs. So, our ONL should use a bare metal switch that uses Broadcom ASICs. Broadcom also gives us OF-DPA and Open-NSL, and by using these two, we can interact with the SDK and ASIC. So, we cannot use other vendors' ASICs, and we have to use Broadcom products. So, what is the benefit of "openness"? Is the SDK or ASIC open? If not, we have to buy a complete package from Broadcom.

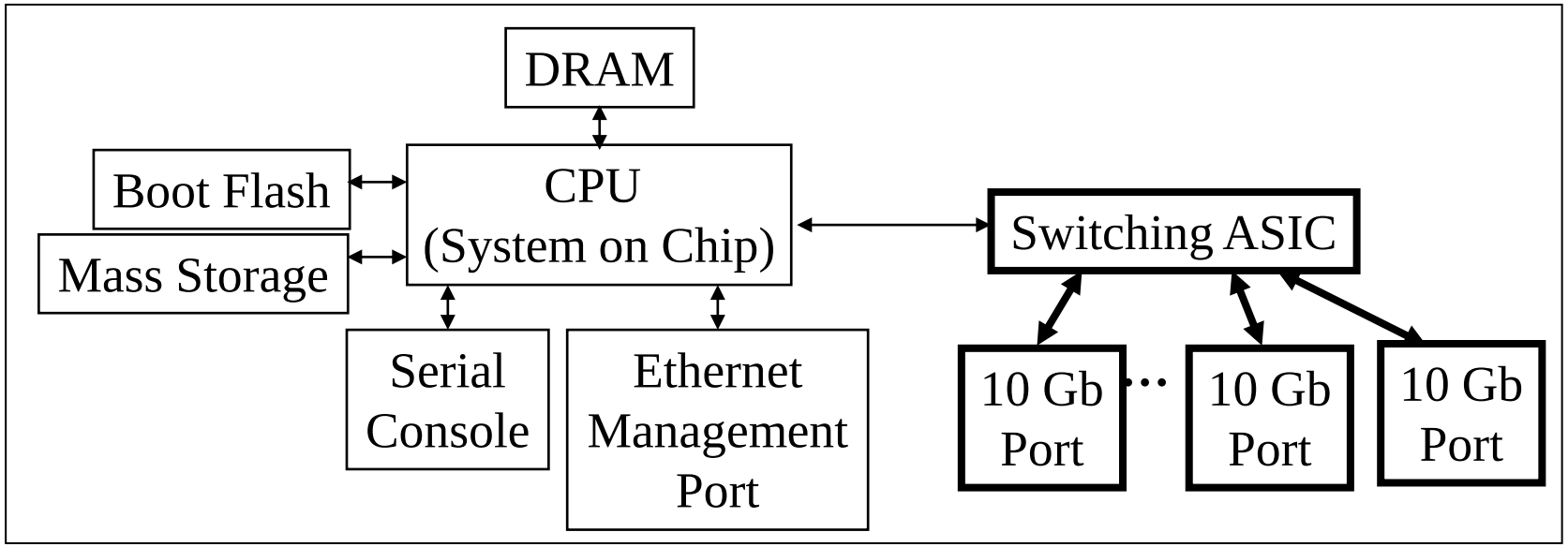
Broadcom contributed its SDK, OF_DPA, and OpenNSL to the Open Compute Project. They released their copyright to it. This allows any vendor to develop its hardware. The users do not have to worry about the hardware because they all provide the same interface. Many vendors have already implemented such switches, as indicated in Slide 15.32.

- From the perspective of a company, doesn't disaggregation reduce monopoly power or profitability?

Yes. This is good for the consumers.

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

Student Questions

Open Source Forwarding Agents

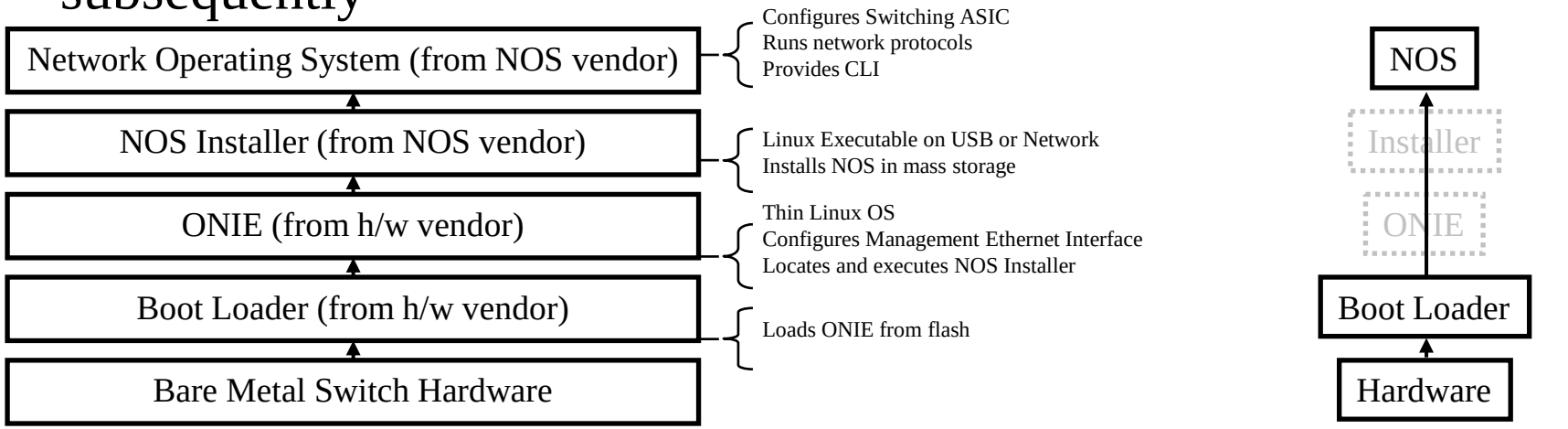
- **Quagga**: A popular open-source routing software suite including OSPF, RIP, BGP, …
- **FRRouting**: a fork of Quagga. Linux routing protocol suite including BGP, IS-IS, LDP, OSPF, PIM, and RIP (Free Range Routing?)
- **BIRD**: Internet Routing Daemon developed as a school project at Charles University, 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/

Student Questions

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

Student Questions

- Can you please explain the figure on the left?

Sure.

- To double check, would we use ONIE to load Open Network Linux (a NOS) onto a bare metal switch?

Yes, only on the first boot.

- Could you explain more about what a forwarding agent does?

The forwarding agent looks up a table to decide the action on a received packet.

- Why do we need ONIE? Can't we install Open Network Linux (ONL) on Bare Metal Switches without ONIE?

Without ONIE, the hardware and the software should come from the same vendor.

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/

Student Questions

- Does Mininet run on physical switches (make pSwitches into vSwitches and emulate their connection) or run on computers (like a software application)?

It runs on computers, PCs/Macs. Windows/Linux.

- Will we do the Mininet lab you refer to in the video? If not, can you post the instructions for that lab somewhere in case we are interested?

This year, we are not going to do it. See the course web page in 2018.
https://www.cse.wustl.edu/~jain/cse570-18/index.html

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.

Student Questions

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

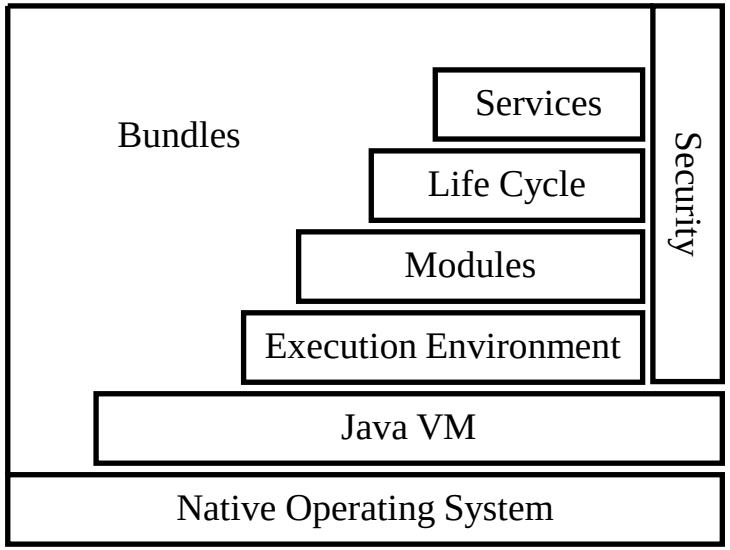
Student Questions

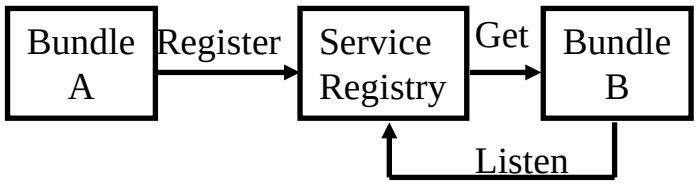
- Does RESTful API allow Conditional GET requests?

Yes, it is allowed as long as the condition does not require maintaining a state. For example, HTTP allows get if-not-modified-since 1-nov-2021.

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





Student Questions

- What kind of communication is required to find services?

OSGI specifies an API.

- Doesn't the OSGI framework complicate the system to some degree?

No. It is just a few commands at the start of a service. The results can be cached and refreshed only if needed.

- Do RESTful APIs use minimal computing and system resources?

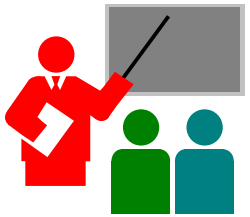
Not necessarily. They minimize state, which is helpful to keep scalability and reliability in case of failures.

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.

Student Questions

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

- Having a mind map for the SDN module would be very helpful!

Sure. Will try.

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).

Student Questions

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

Student Questions

References

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

Student Questions

References (Cont)

- Oswald Coker, Siamak Azodolmolky, "Software-Defined Networking with OpenFlow - Second Edition," Packt Publishing, October 2017, 246 pp., ISBN:978-1-78398-429-9 (Safari Book).
- William Stallings, "Foundations of Modern Networking: SDN, NFV, QoE, IoT, and Cloud," Addison-Wesley Professional, October 2015, 544 pp., ISBN:0-13-417539-5 (Safari Book).
- Russ White, Jeff Tantsura, "Navigating Network Complexity: Next-generation Routing with SDN, Service Virtualization, and Service Chaining," Addison-Wesley Professional, November 2015, 320 pp., ISBN:0-13-398792-2 (Safari Book).
- Abhishek Ratan, "Practical Network Automation," Packt Publishing, November 2017, 266 pp., ISBN:978-1-78829-913-8 (Safari Book).
- 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).
- Guy Pujolle, "Software Networks," John Wiley & Sons, August 2015, 260 pp., ISBN:978-1-119-00796-8 (Safari Book).

Student Questions

References (Cont)

- Sriram Subramanian, Sreenivas Voruganti, "Software-Defined Networking (SDN) with OpenStack," Packt Publishing, October 2016, 216 pp., ISBN:978-1-78646-599-3 (Safari Book).
- 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)

Student Questions

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

Student Questions

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

Student Questions

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

Student Questions

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

Student Questions

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

Student Questions

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

Student Questions

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

Acronyms (Cont)

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

Student Questions

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

Student Questions

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

Student Questions

SDN Web Sites

- HotSDN 2012, http://yuba.stanford.edu/~casado/of-sw.html (Papers downloadable)

Student Questions

Scan This to Download These Slides

Raj Jain
http://rajjain.com

http://www.cse.wustl.edu/~jain/cse570-23/m_15sdn.htm

Student Questions

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

Student Questions