Software Defined Networking (SDN)

Index

Motivation

- The Internet started simple but grew complex with added functionalities
- Network development focus on faster (not better) development
- No clear separation between control and data planes
  - OSPF and IP packets on the same "level"
- Closed systems (vendor hardware)

Data Plane and Control Plane

- **Data plane:** process and deliver packets using local forwarding state
  - Forwarding state + packet header ➔ forwarding decision
- **Control plane:** compute the forwarding state for the device (router, switch, ...)
  - Determine how and where packets are routed
  - Routing, traffic engineering, firewall state, ...
  - Implemented with distributed protocols, manual configuration (and scripting) or centralized computation
- These two planes require different abstractions

SDN

- Definition (according to the ONF)
  - The physical separation of the network control plane from the forwarding (data) plane, and where a control plane controls several devices
- Principles
  - Separation of control plane and data plane
  - Centralized control (network viewed as a whole)
  - Programmable (instead of merely configurable)
- Provides
  - Abstraction and modularity to the network as they exist on software programming
  - More flexibility in managing networks independently of the hardware vendor lock-in, domain, network

Traditional Networking Industry

- Many complex functions baked into the infrastructure
  - OSPF, BGP, multicast, differentiated services, Traffic Engineering, NAT, firewalls, MPLS, redundant layers, ...

- An industry with a "mainframe-mentality"
- Little ability for non-telco network operators to get what they want
- Functionality defined by standards, put in hardware, deployed on nodes

Internet: Layers

Applications ...built on... Reliable (or unreliable) transport ...built on... Best-effort global packet delivery ...built on... Best-effort local packet delivery ...built on... Physical transfer of bits

New requirements ➔ Adding complexity

- Isolate traffic ➔ VLANs, ACLs
- Traffic engineering ➔ MPLS, ECMP
- Packet processing ➔ Firewalls, NATs
- Payload analysis ➔ Deep packet inspection (DPI)
- This was usually added to each network component (switch, router, NAT box, etc.)
- All adding to the control plane while keeping the data plane modular/simple

From mastering complexity to extracting simplicity

- Networking still focused on mastering complexity
    - Little emphasis on extracting simplicity from control plane
- Extracting simplicity builds intellectual foundations
    - Necessary for creating a discipline...

Example: Programming

- Machine languages: no abstractions
    - Mastering complexity was crucial
- Higher-level languages: OS and other abstractions
    - File system, virtual memory, abstract data types, ...
- Modern languages: even more abstractions
    - Object orientation, garbage collection, ...

      Abstractions key to extracting simplicity
- Good abstractions obviate the need for mastering all complexity

Requirements to Abstractions

- Networks impose the following requirements that can be tackled by the abstractions:
    1. Operate without communication guarantees

       Need an abstraction for <u>distributed state</u>
    2. Compute the configuration of each physical device

       Need an abstraction that <u>simplifies configuration</u>
    3. Operate within given network-level protocol

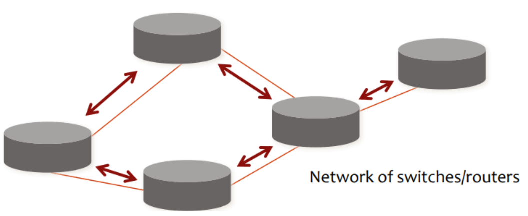
       Need an abstraction for general <u>forwarding model</u>

1. Distributed State Abstraction

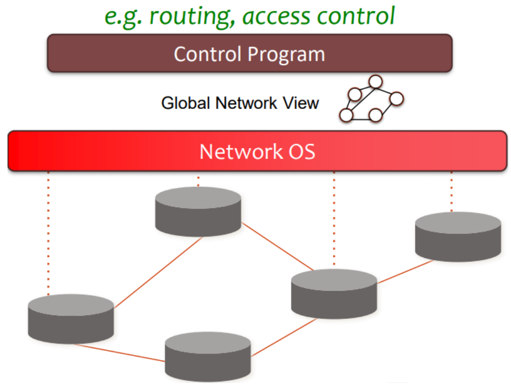
- Shield control mechanisms from state distribution while allowing access to this state

- Natural abstraction: global network view
    - Annotated network graph provided through an API
- Implemented with a "Network Operating System"
    - Abstracts from the network hardware just like an OS abstracts from the computer hardware
- Control mechanism becomes a program using an API
    - No longer a distributed protocol, now just a graph algorithm
    - Much easier to reason about

Traditional control mechanism	**Software Defined Network (SDN)**



Distributed algorithm running between neighbours

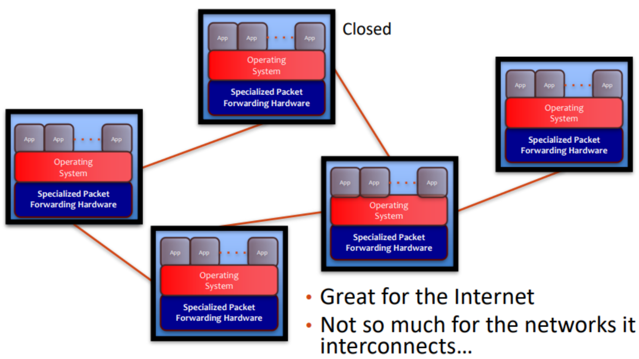


Major Change in Paradigm

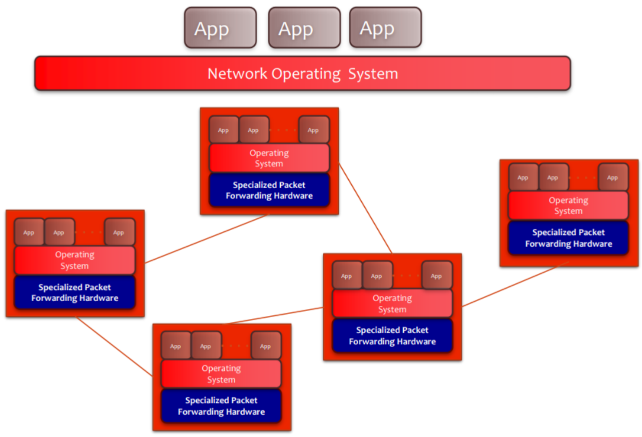
- No longer designing distributed control protocols
    - Design one distributed system (NOS)
    - Use it for all control functions
- Now just defining a centralized control **function**

  Configuration = Function(view)

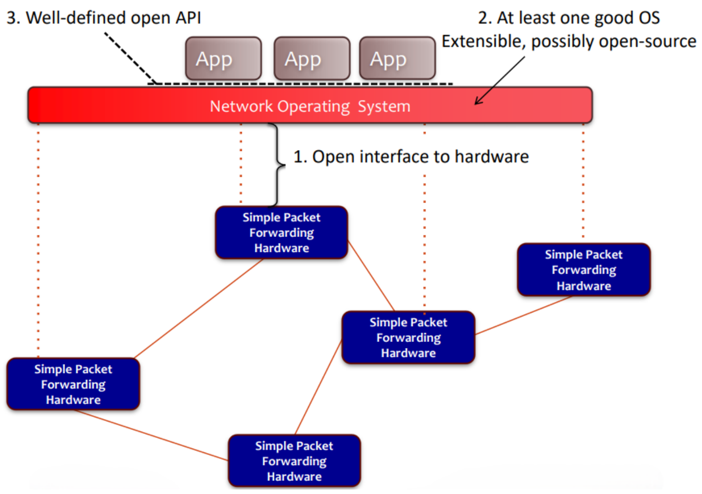
Today	**"SDN" approach to open it**



Closed Boxes, Fully Distributed Protocols



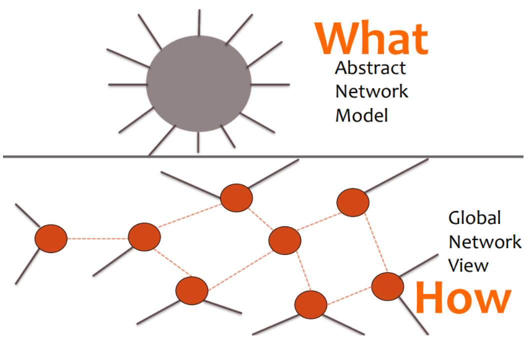
The "Software-defined Network"



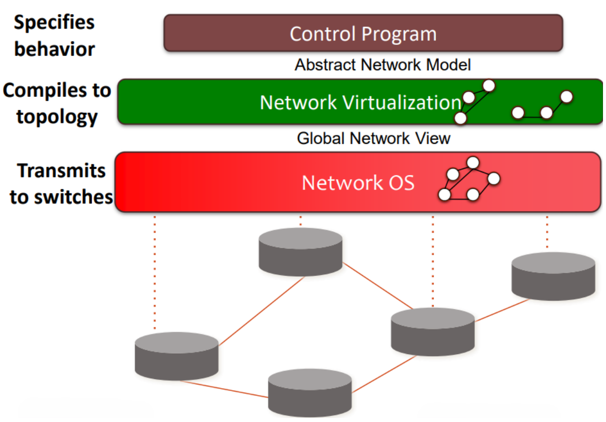
2. Specification Abstraction

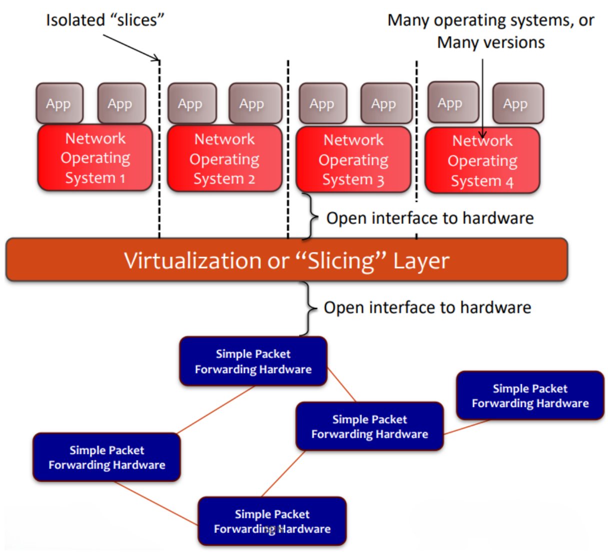
- Control program should express desired behaviour
- It should not be responsible for implementing that behaviour on physical network infrastructure
- Natural abstraction: **simplified model** of network
  - Simple model with only enough detail to specify goals
- Requires a new shared control layer:
  - Map abstract configuration to physical configuration
- This is "network virtualization"

Simple Example: Access Control

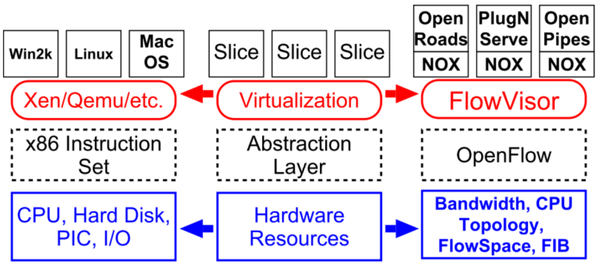


SDN: Virtualization



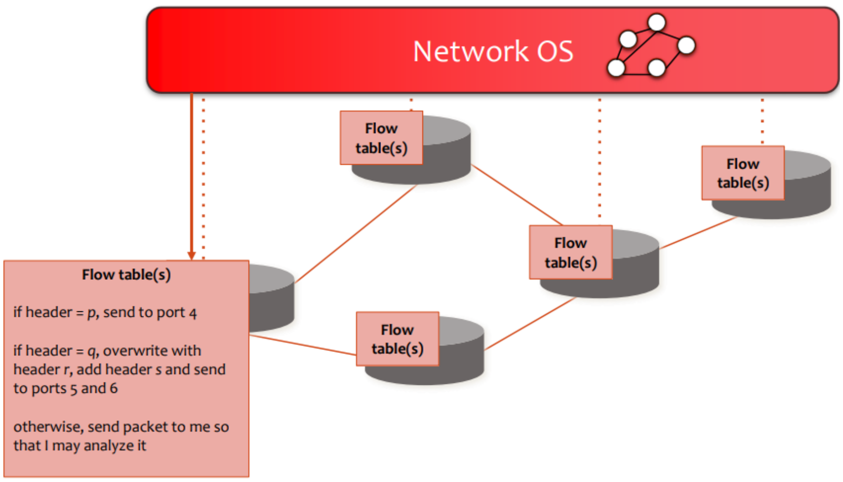


Slicing as Virtualization



3. Forwarding Abstraction

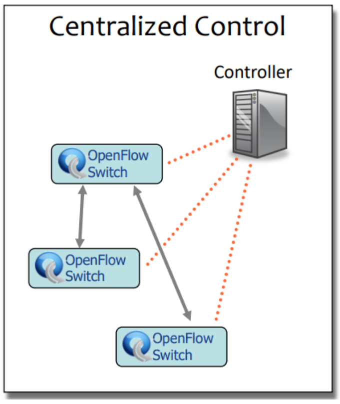
- Switches have two "brains"
  - Management CPU (smart but slow)
  - Forwarding ASIC (fast but dumb)
- Need a forwarding abstraction for both
  - CPU abstraction can be almost anything
- ASIC abstraction is much more subtle: OpenFlow
- OpenFlow:
  - Control switch by inserting <header;action> entries
  - Essentially gives NOS remote access to forwarding tables
  - Instantiated in hardware and software switches (e.g., Open vSwitch)

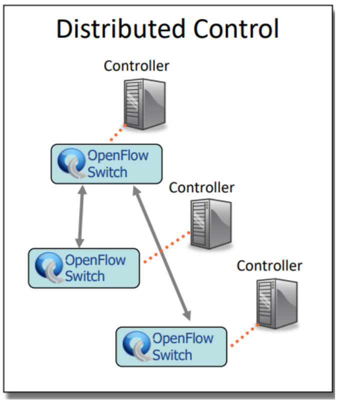


SDN Brings Flexibility

- Provides the ability to tweak between the following configuration/control "settings"
  - Centralized vs. Distributed Control
  - Microflow vs. Aggregated
  - Reactive vs. Proactive (pre-populated)
  - Virtual vs. Physical
  - Fully Consistent vs. Eventually Consistent

Centralized vs. Distributed Control





Microflow vs. Aggregated

Microflow	Aggregated
• Every flow is individually set up by controller • Exact-match flow entries • Flow table contains one entry per flow Good for fine grain control, policy, and monitoring, e.g., campus (access) network	• One flow entry covers large groups of flows • Wildcard flow entries • Flow table contains one entry per category of flows Good for large number of flows, e.g., backbone

Reactive vs. Proactive (pre-populated)

Reactive	Proactive
• First packet of flow triggers controller to insert flow entries • Efficient use of flow table • Every flow incurs small additional flow setup time • If control connection lost, switch has limited utility • Extremely simple fault recovery	• Controller pre-populates flow table in switch • Zero additional flow setup time • Loss of control connection does not disrupt traffic • Essentially requires aggregated (wildcard) rules

Virtual vs. Physical

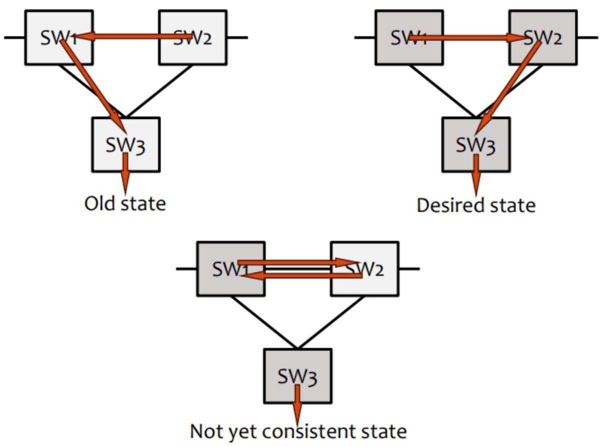
Virtual	Physical

Virtual	**Physical**
• Assumes configurable switching within a host: in the OS or hypervisor • Software! Memory, processing, arbitrary modifications • Massive flow rates • Limited to the hardware below	• No assumption of software changes; unmodified end hosts • Greater control over expensive forwarding resources

Fully Consistent vs. Eventually Consistent

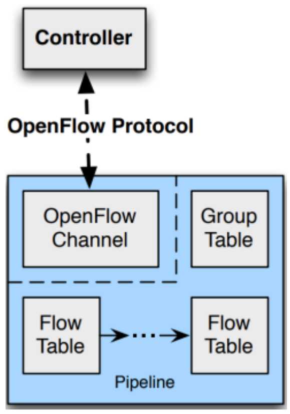
Fully Consistent	**Eventually Consistent**
• Certainty about state • Consistent state is harder to scale • Easier to reason about state and its transitions • May eliminate route flaps	• Uncertainty about state now, but eventually converges • Probabilistic state is easier to scale • Introduces the possibility of long-lived route flaps and unstable control systems

Example Issue w/ Eventual Consistency



OpenFlow

What is OpenFlow



- First standard protocol for communication between SDN controllers and packet switches
- Allows remote configuration of the forwarding (data) plane
- Based on the abstraction of flow tables containing rules for matching packets and associated actions

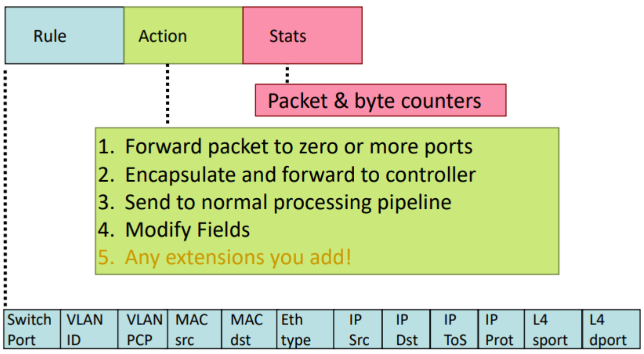
- OpenFlow is a forwarding table management protocol
    - Abstracts the data plane

- Adds the ability to modify, experiment...
- Adding features to a network still harder than it should be to
    - Analogous to programming in assembly
- Other abstractions are used on top of it

OpenFlow: a pragmatic compromise for research/experimentation

- + Speed, scale, fidelity of vendor hardware
- + Flexibility and control of software and simulation
- + Vendors don’t need to expose implementation
- + Leverages hardware inside most switches today (ACL tables)
- - Least-common-denominator interface may prevent using all hardware features
- - Limited table sizes
- - Switches not designed for this
- - New failure modes to understand

Flow Tables

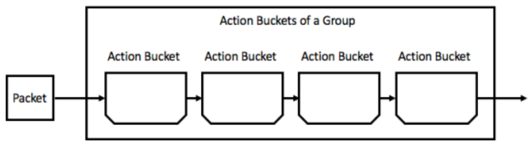


+ mask specifying which fields to match

Group Table (since v1.1)

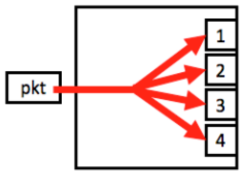
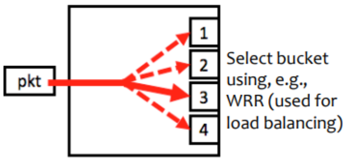
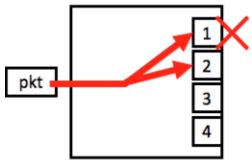
- Allows grouping sets of actions
    - Packet modifications
    - Forwarding to ports
- Layer of indirection
    - Allows reusing sets of actions for different flows
    - Efficient changes to sets of actions shared across flows

Group entry:



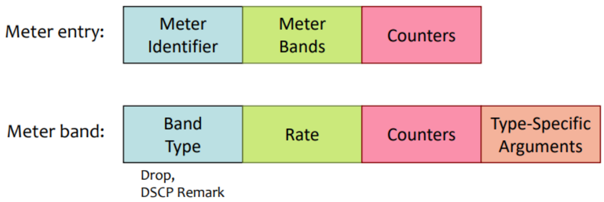
Group Types

All (required)	**Select (optional)**	**Fast Failover (optional)**	**Indirect (required)**

All (required)	Select (optional)	Fast Failover (optional)	Indirect (required)
			• Single bucket ◦ Similar to all with 1 bucket • Allows faster / more efficient changes to shared entries

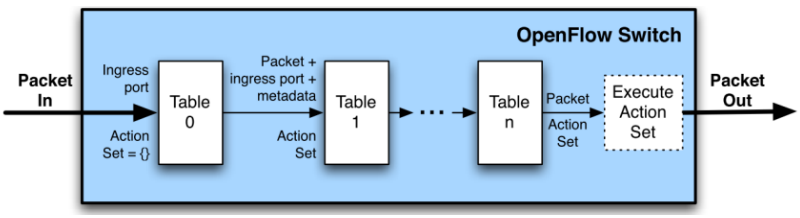
Meter Table (since v1.3)

- Contains meter entries defining per-flow meters
- Enables simple QoS operations (e.g., rate limiting)
- May be combined with per-port queues to implement complex QoS (e.g., DiffServ)



OpenFlow Pipeline

- A packet is matched against Table 0
- A matching entry may specify that it be further matched against other (higher-numbered) tables
- A table may specify that misses be matched against other tables



OpenFlow Channel

- Interface connecting an OF switch to the controller
- TCP connection from the switch to the controller
  - Switch must be configured with the IP address and port of the controller
- Usually encrypted with TLS
  - Mutual authentication using certificates signed with a sitespecific private key
- Bidirectional communication between the switch and the controller is required
  - Even with empty flow tables
- Communication with the controller may be:
  - Out-of-Band
    - Through a separate port with traditional networking stack
  - In-Band
    - Through the regular SDN ports
    - Bootstraping problem:
      - OpenFlow Channel required for configuring packet forwarding
      - Packet forwarding required for OpenFlow Channel
      - Solution: use of preloaded rules

OpenFlow Main Message Types

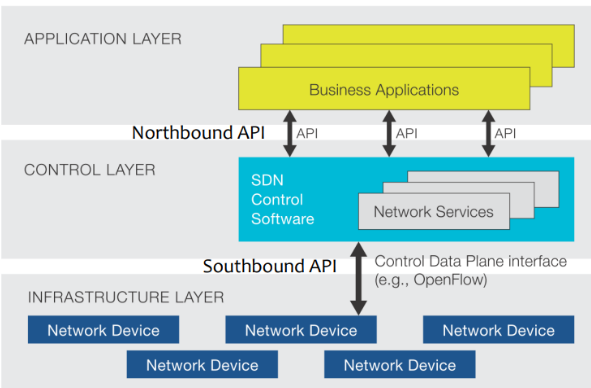
- **Controller-to-Switch:** Initiated by the controller. May or may not require a response from the switch
- **Asynchronous:** Sent unsolicited from the switch to the controller
- **Symmetric:** Sent unsolicited in either direction

Some OpenFlow Messages

Hello (Symmetric)	Sent by the switch and the controller for version negotiation
Features Request / Reply (C to S)	Allows controller to determine the features supported by the switch
Set Configuration (C to S)	Specify handling of fragmented packets and # of bytes of a packet to send to the controller
Echo Request / Reply (Symmetric)	Used to check the controller-switch connection and measure latency and bandwidth
Packet-in (Async)	When no match is found, the packet is sent to the controller. Only first N bytes if packet can be buffered, the entire packet otherwise
Packet-out (C to S)	Instruct switch to send packet (possibly received in Packet-in) on a specified port. May refer to a buffer
Flow Mod (C to S)	Add / modify / delete flow entries. May be triggered by Packet-In
Port Mod (C to S)	Modify port state (PortDown, NoFlood, NoFwd, ...)
Port Status (Async)	Report port addition, removal or modification (e.g., link down) to the controller
Flow Removed (Async)	Report flow entry removal (inactivity or hard timeout)

SDN and OpenFlow

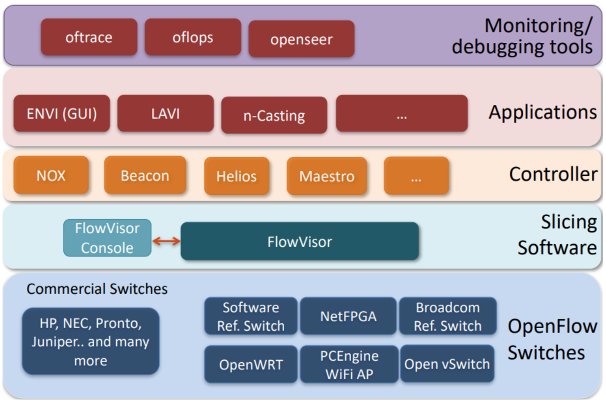
SDN Architecture



SDN APIs

- Southbound API
  - Typically OpenFlow (others possible)
  - Low level (the "assembly" of SDN)
- Northbound API
  - HTTP REST, Java, others
  - Higher level
- East/West interfaces possible for coordination among controllers

The SDN Stack



SDN Summary

- Provides a modularity/abstraction for networking
- Allows greater flexibility in managing networks
  - And virtualization of physical resources
- OpenFlow is a protocol for configuring rules on net equipment managed by a controller
  - Expose tables from said equipment
- Opens up new avenues for research and network usage (provider view)

Some Final Notes on SDN

- SDN is not a panacea
- Some swear it is the future of networking, others assert it is dead or dying
- SDN will probably not become the dominant paradigm, but has some fields of application
  - E.g., campus network, cloud
- Eventually, it will succeed in new incarnation
  - New paradigms are hard to get right at first attempt (OpenFlow)
- SDN Lowers the barrier for new approaches (e.g., applying Machine Learning to networking)