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[dcc]

Software Defined Networking (SDN)

Tópicos Avançados em Redes

2023/24

References

The slides from this presentation include contents from many external sources, e.g.:

- "OpenFlow Tutorial", Open Networking Summit, by Brandon Heller, Rob Sherwood, David Erickson, Hideyuki Shimonishi, Srini Seetharaman, Murphy McCauley
- "Software-Defined Networking (SDN)", EE122, Fall 2011, by Scott Shenker

Motivation

- The Internet is complex
  - Started out simple
  - New requirements ➔ add new "stuff" to the current "stuff" ➔ increased complexity
- 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

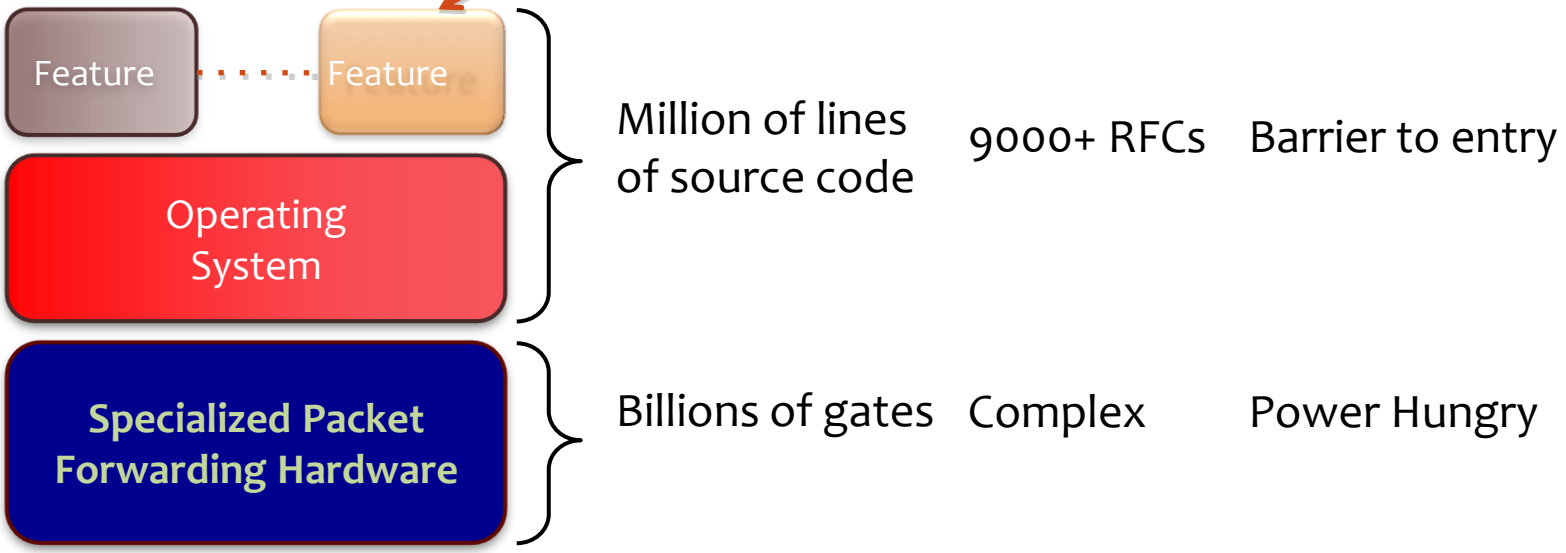
- **Data plane:** process and deliver packets using local forwarding state
  - Forwarding state + packet header ➔ forwarding decision
- **Control plane:** compute the forwarding state for the device (router, switch, …)
  - Determine how and where packets are routed
  - Routing, traffic engineering, firewall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

Software Defined Networking (SDN)

- 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*
- SDN principles
  - Separation of control plane and data plane
  - Centralized control (network viewed as a whole)
  - Programmable (instead of merely configurable)
- SDN 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

Routing, management, mobility management, access control, VPNs, …



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…

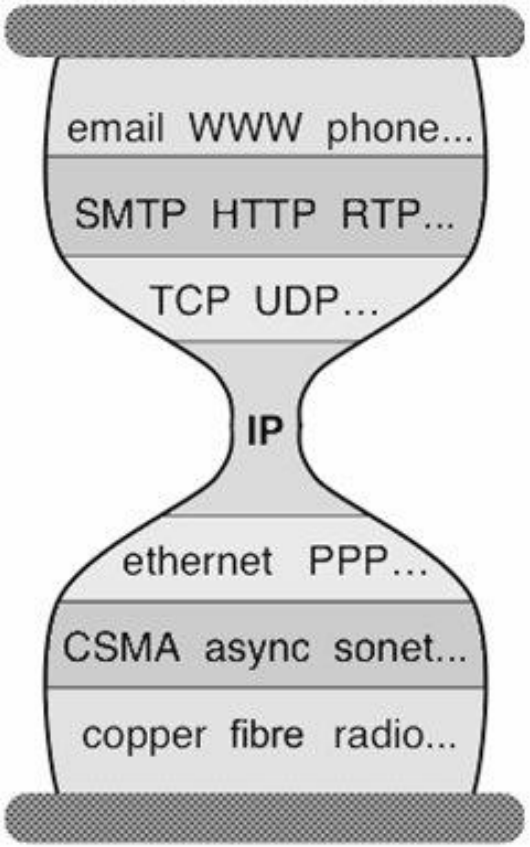
Best-effort global packet delivery

…built on…

Best-effort local packet delivery

…built on…

Physical transfer of bits



Layers concern the data plane

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 **distributed state**

2. Compute the configuration of each physical device
   Need an abstraction that **simplifies configuration**

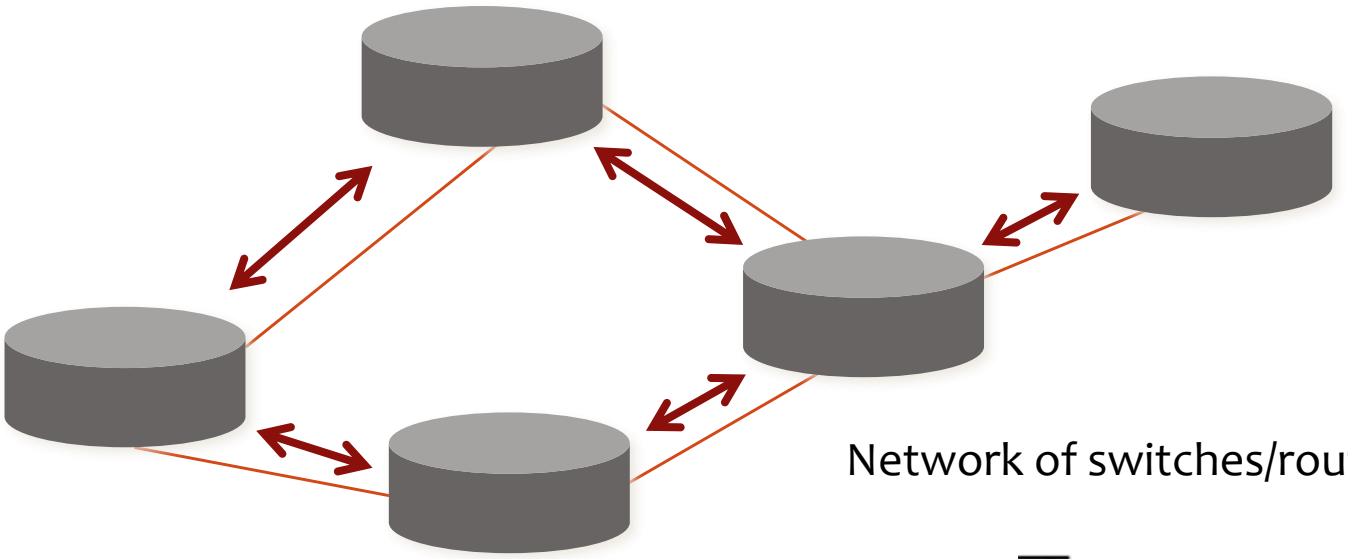
3. Operate within given network-level protocol
   Need an abstraction for general **forwarding model**

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

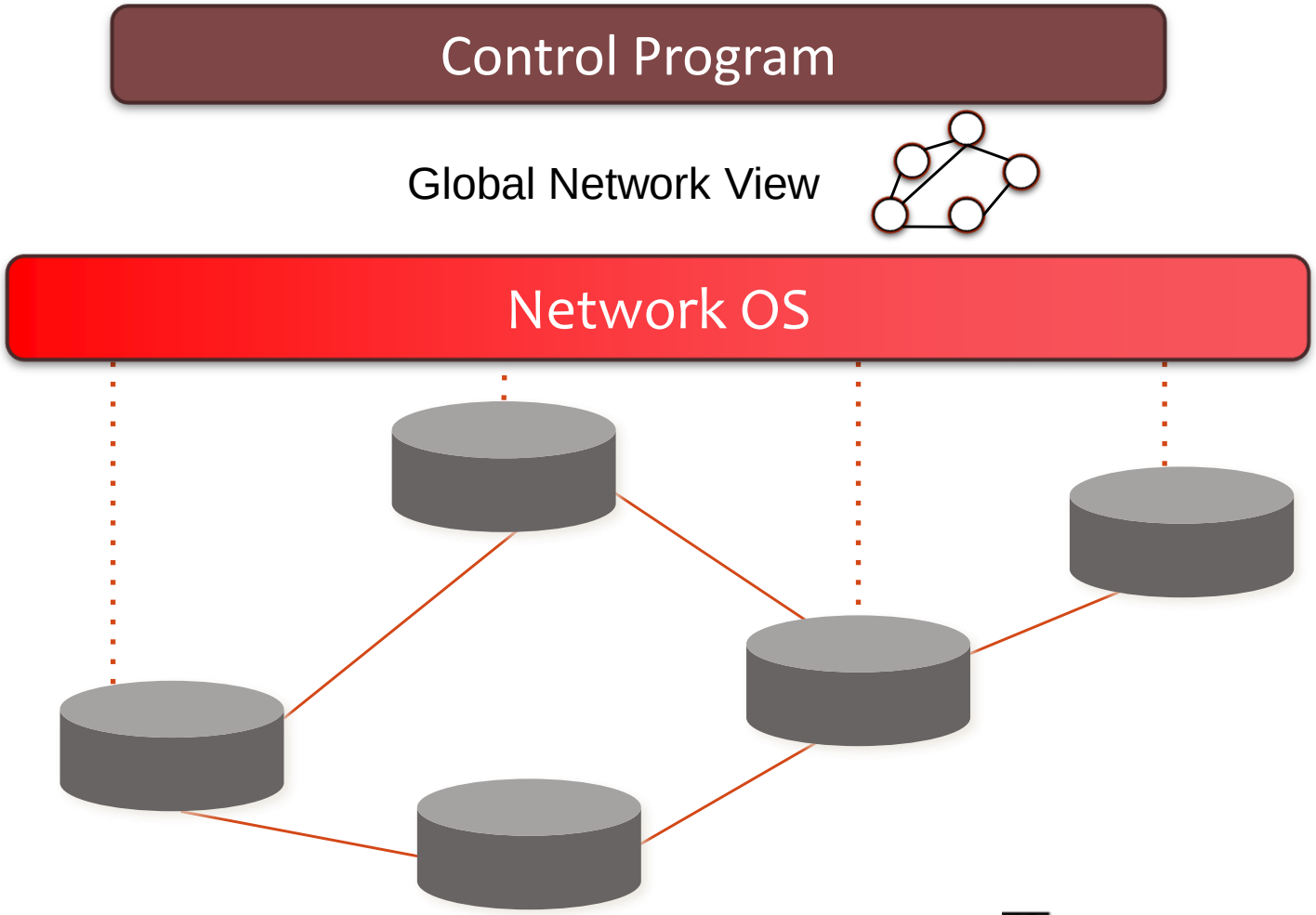
Traditional control mechanism

- Distributed algorithm running between neighbours



Software Defined Network (SDN)

e.g. routing, access control



Major Change in Paradigm

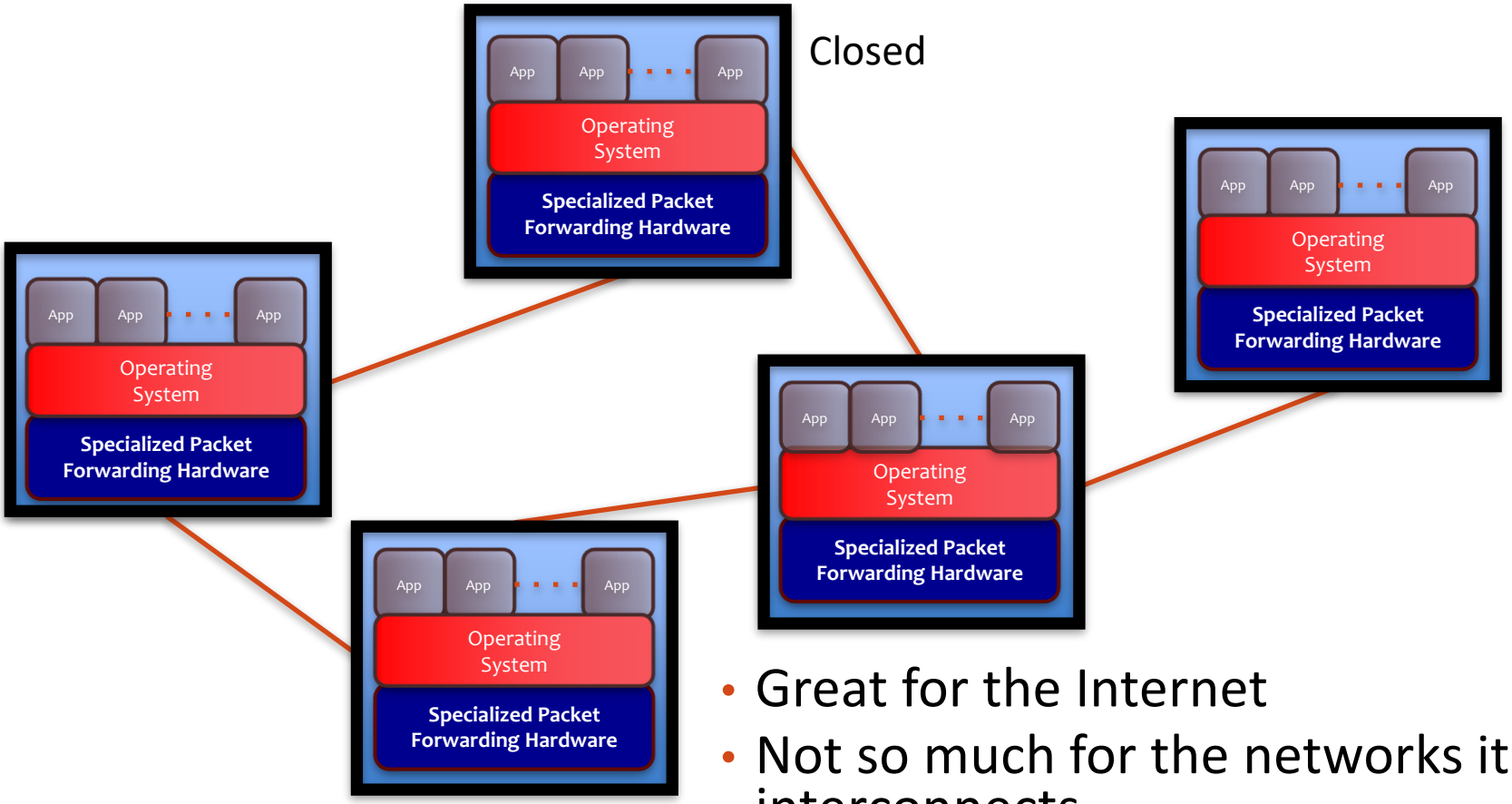
- No longer designing distributed control protocols
  - Design one distributed system (NOS)
  - Use it for *all* control functions

- Now just defining a centralized control ***function***

Configuration = Function(view)

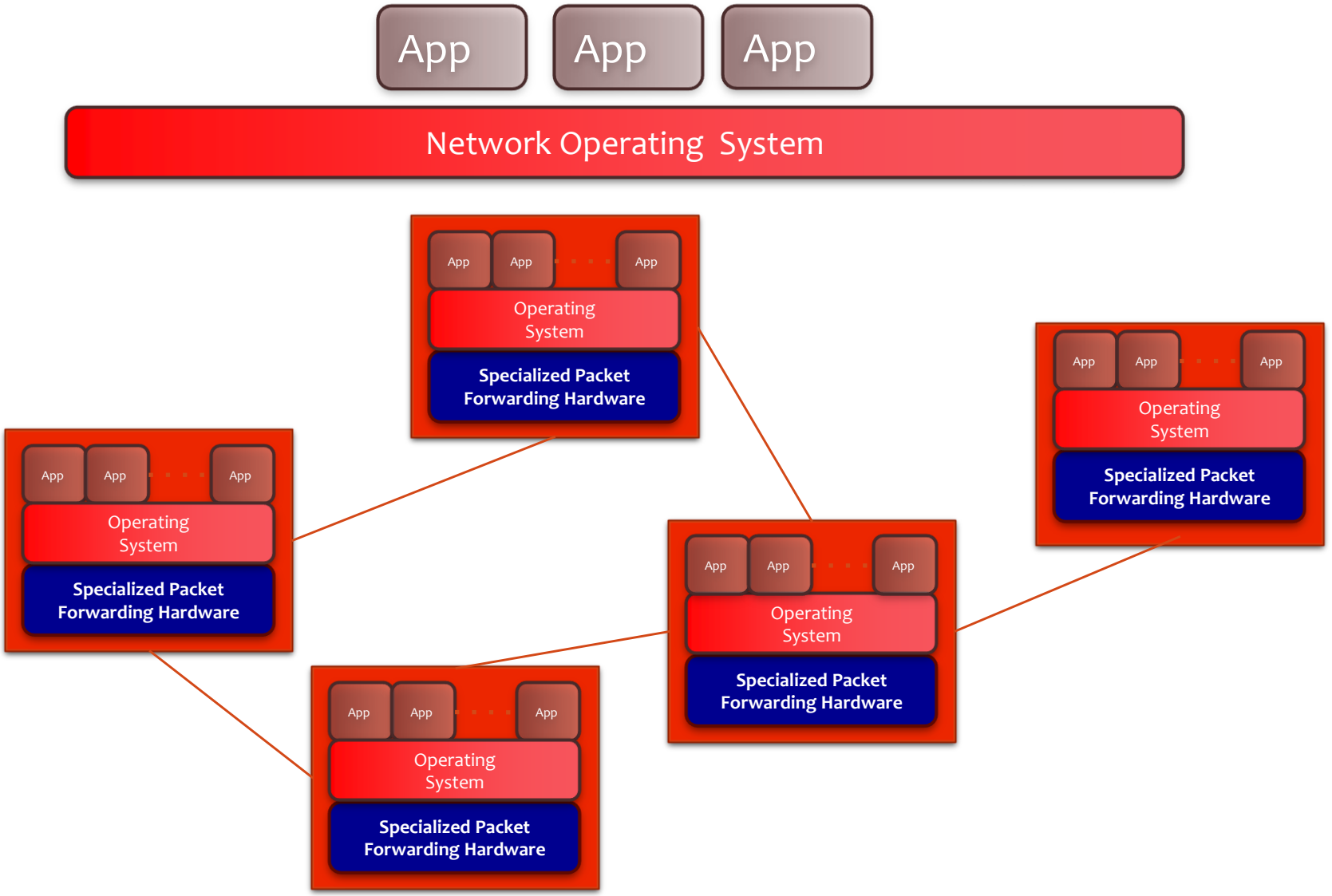
Today

- Closed Boxes, Fully Distributed Protocols

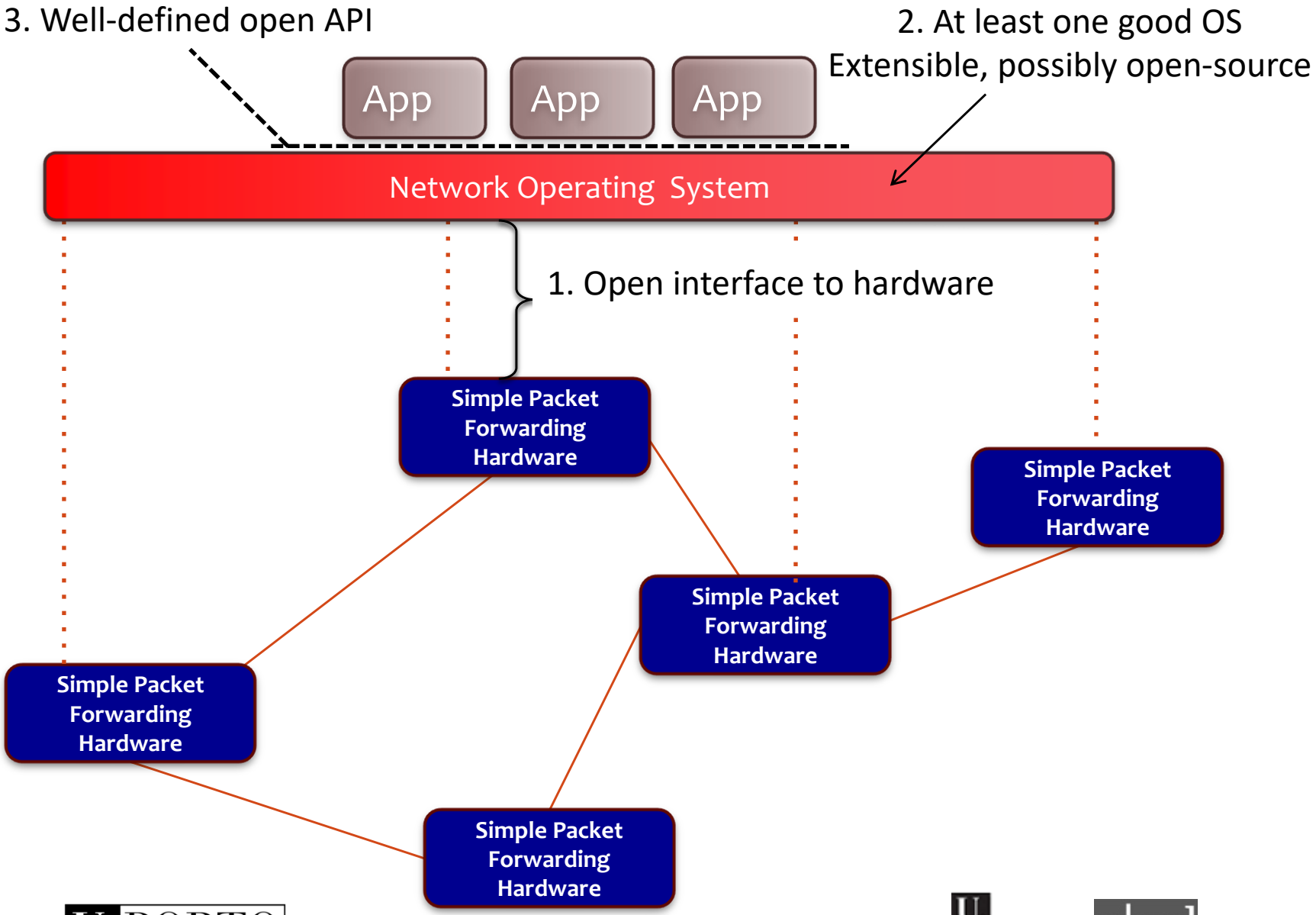


- Great for the Internet
- Not so much for the networks it interconnects…

“SDN” approach to open it



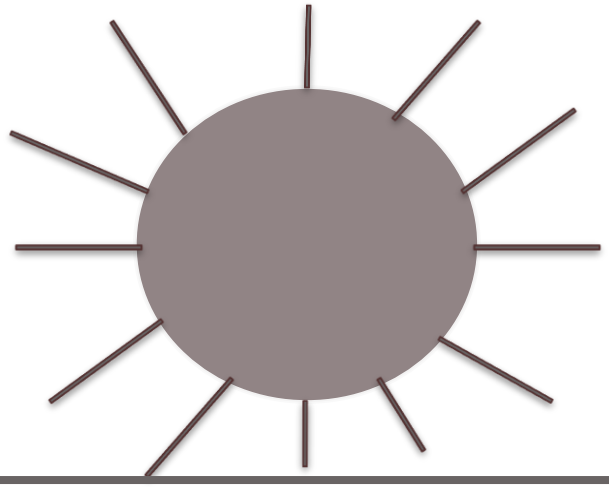
The "Software-defined Network"



2. Specification Abstraction

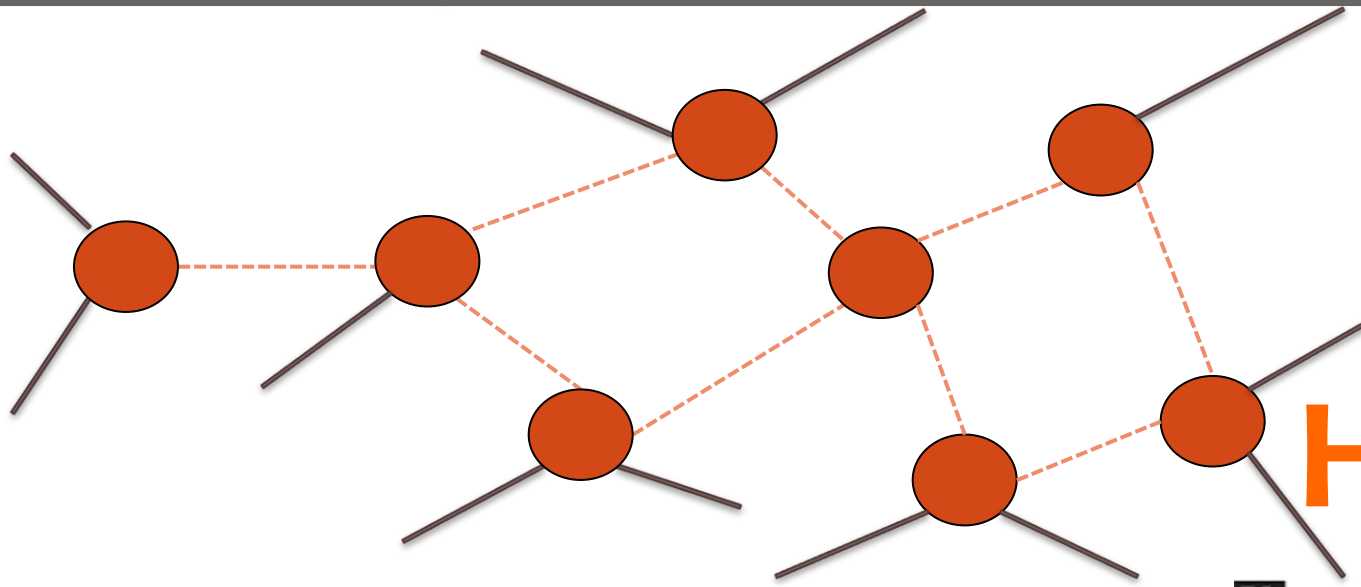
- Control program should express desired behaviour
- It should not be responsible for implementing that behaviour on physical network infrastructure
- Natural abstraction: **simplified model** of network
  - Simple model with only enough detail to specify goals
- Requires a new shared control layer: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

Simple Example: Access Control



What

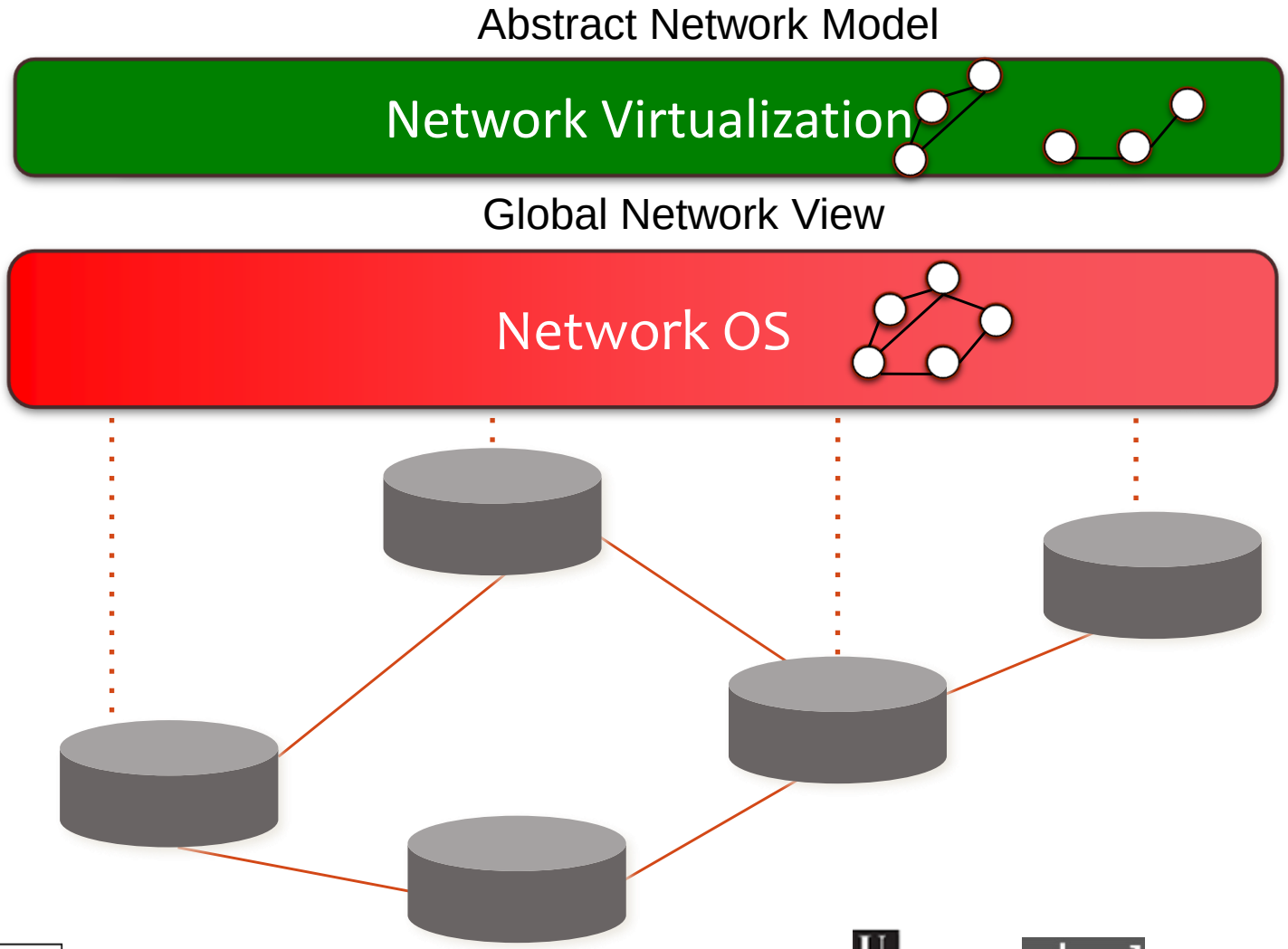
Abstract Network Model



Global Network View

How

SDN: Virtualization



SDN: Virtualization

Specifies behavior

Control Program

Abstract Network Model

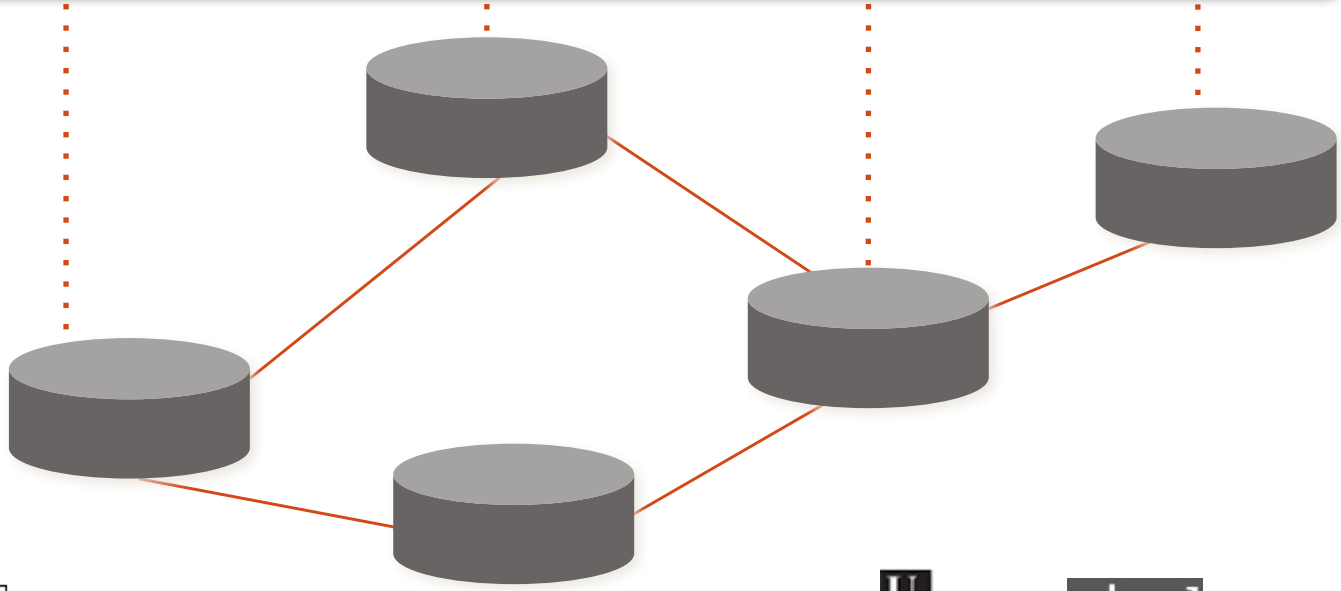
Compiles to topology

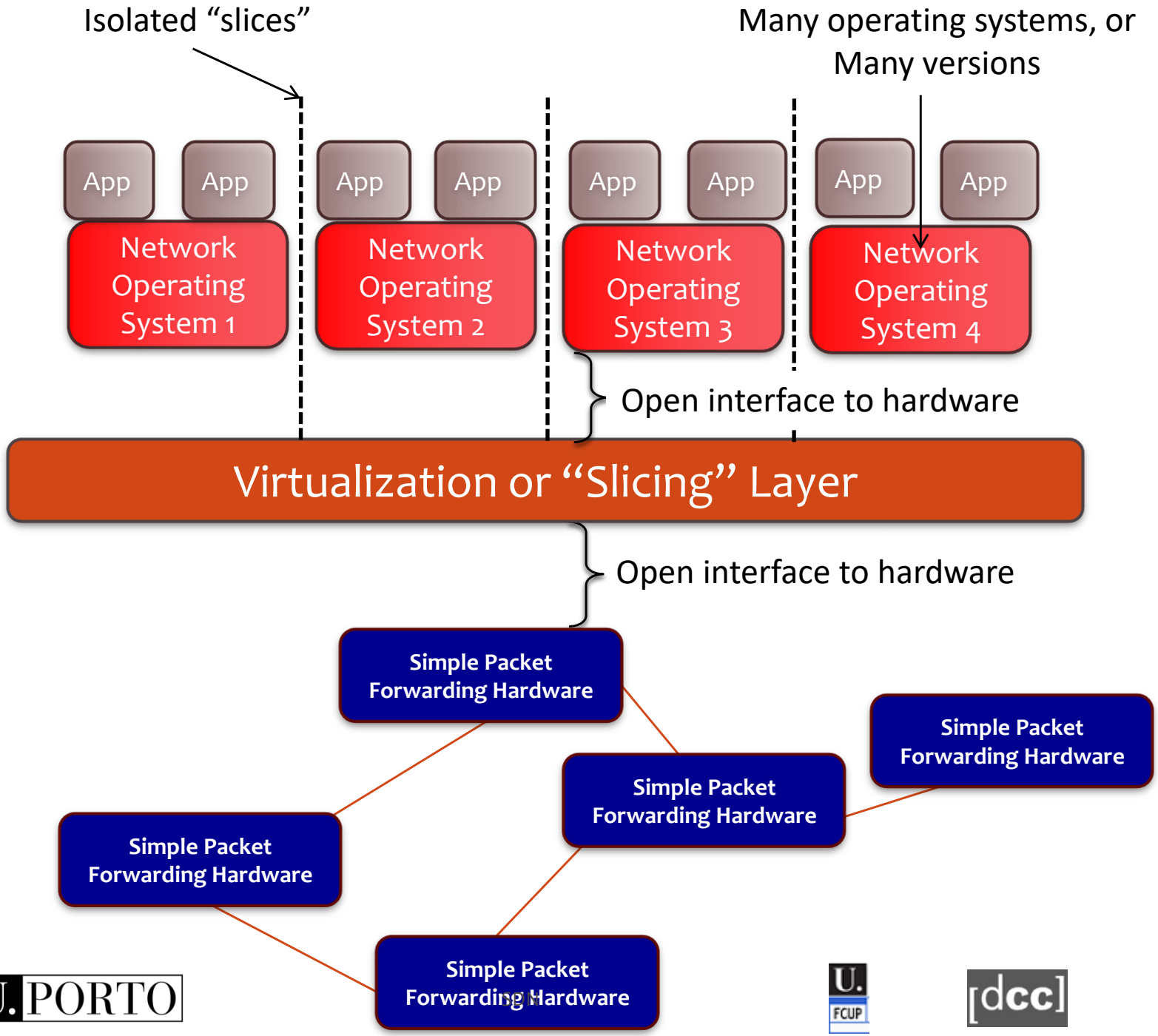
Network Virtualization

Global Network View

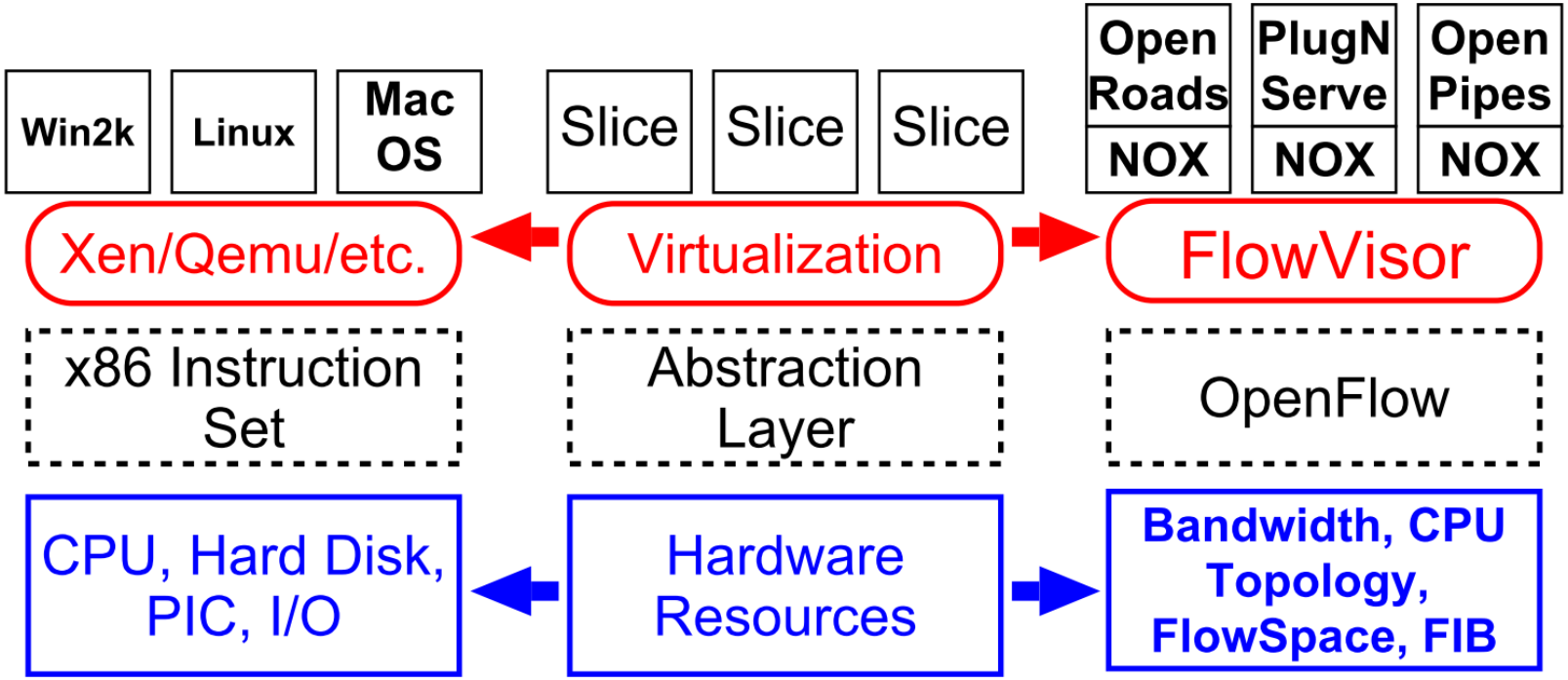
Transmits to switches

Network OS




Isolated “slices”
Many operating systems, or
Many versions
App
App
App
App
App
App
App
App
Network Operating System 1
Network Operating System 2
Network Operating System 3
Network Operating System 4
Open interface to hardware
Virtualization or “Slicing” Layer
Open interface to hardware
Simple Packet Forwarding Hardware
Simple Packet Forwarding Hardware
Simple Packet Forwarding Hardware
Simple Packet Forwarding Hardware
Simple Packet Forwarding Hardware

Slicing as Virtualization

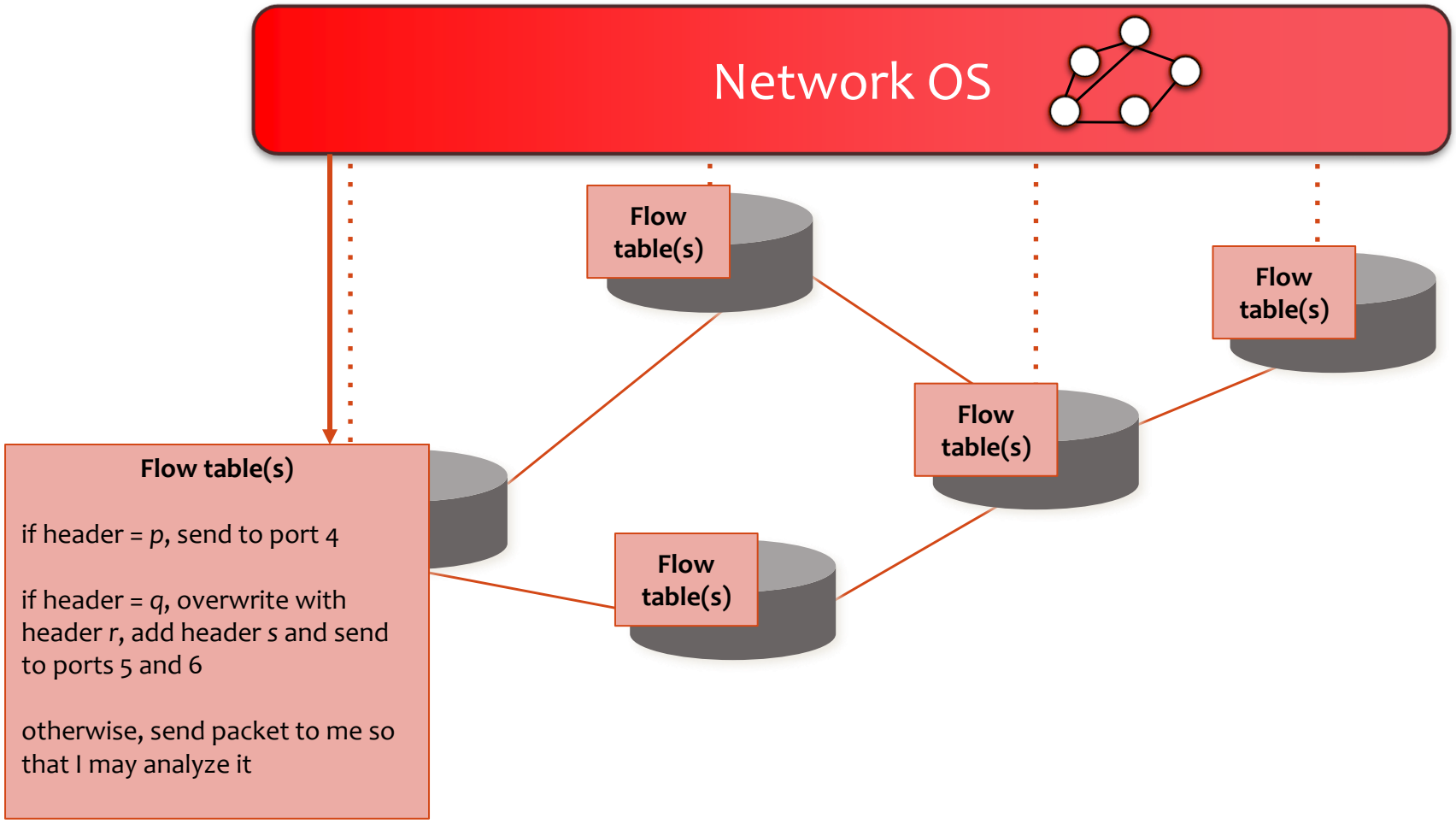


Source: R. Sherwood et al, "FlowVisor: A Network Virtualization Layer"

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)

OpenFlow: Forwarding Abstraction

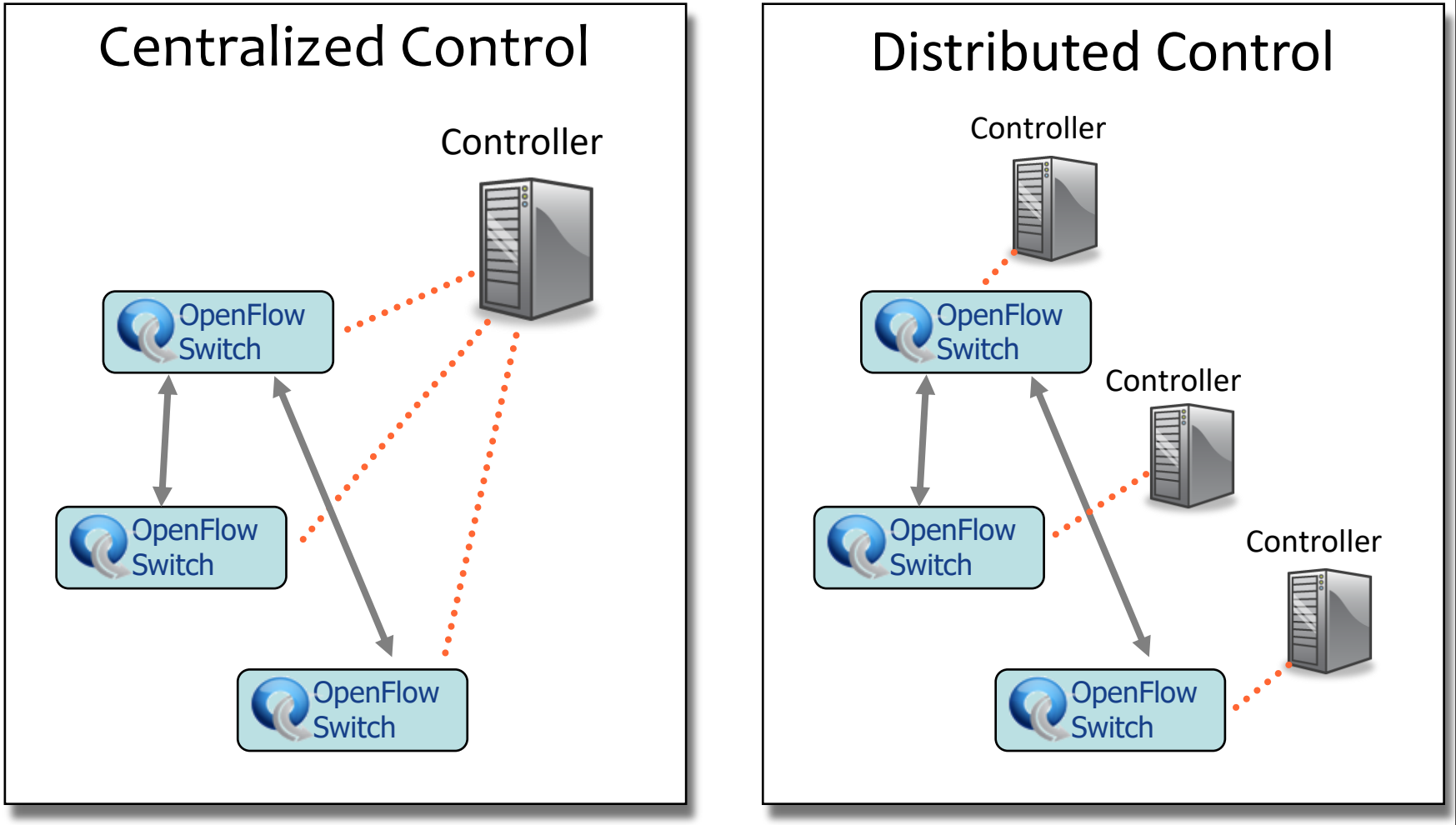


SDN Brings Flexibility

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

- 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

Aggregated

- 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

- 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

Proactive

- 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

- Assumes configurable switching within a host: in the OS or hypervisor
- Software! Memory, processing, arbitrary modifications
- Massive flow rates
- Limited to the hardware below

Physical

- No assumption of software changes; unmodified end hosts
- Greater control over expensive forwarding resources

Fully Consistent vs. Eventually Consistent

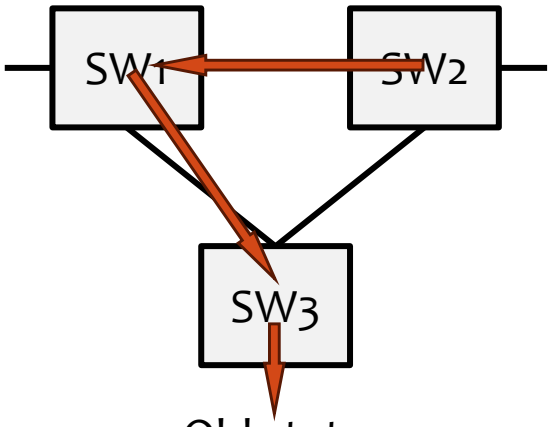
Fully Consistent

- Certainty about state
- Consistent state is harder to scale
- Easier to reason about state and its transitions
- May eliminate route flaps

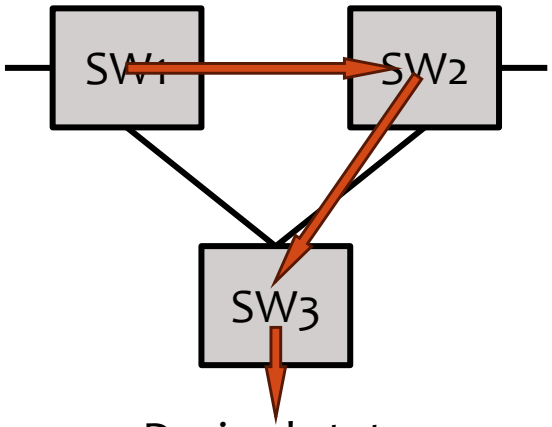
Eventually Consistent

- 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

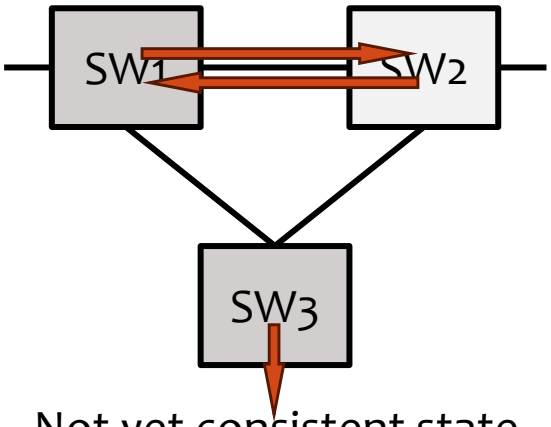
Example Issue w/ Eventual Consistency



Old state



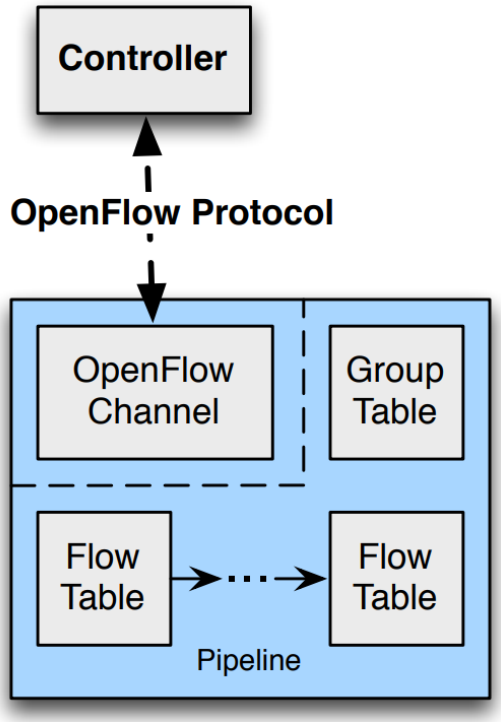
Desired state



Not yet consistent state

http://www.openflow.org/

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*

What is OpenFlow

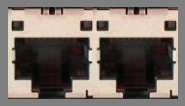
OpenFlow is a forwarding table management protocol

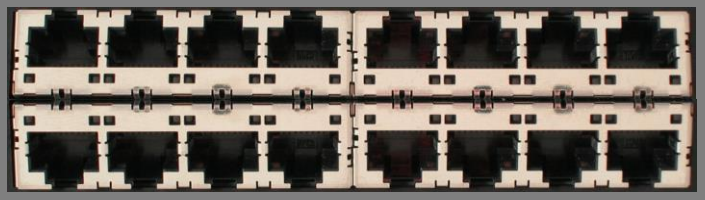
- Abstracts the data plane
- Adds the ability to modify, experiment…
- Adding features to a network still harder than it should be to
  - Analogous to programming in assembly
- Other abstractions are used on top of it

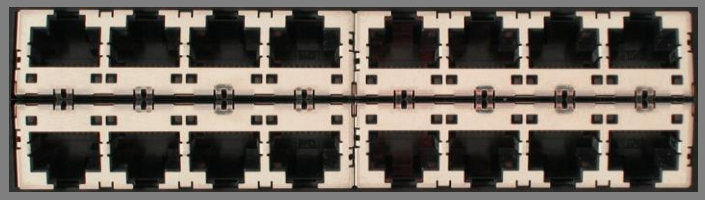
OpenFlow: a pragmatic compromise for research/experimentation

+ 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

Ethernet Switch

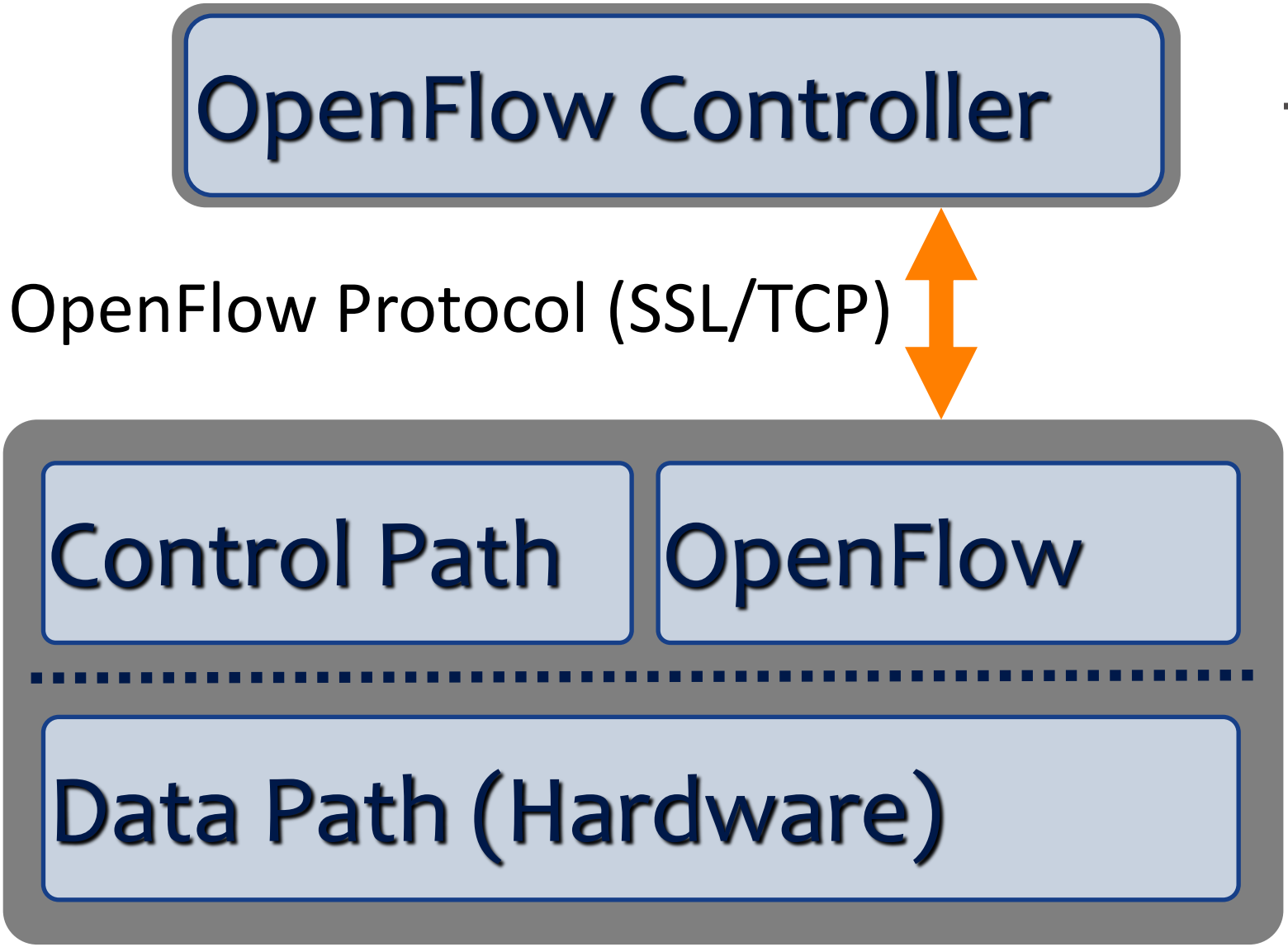




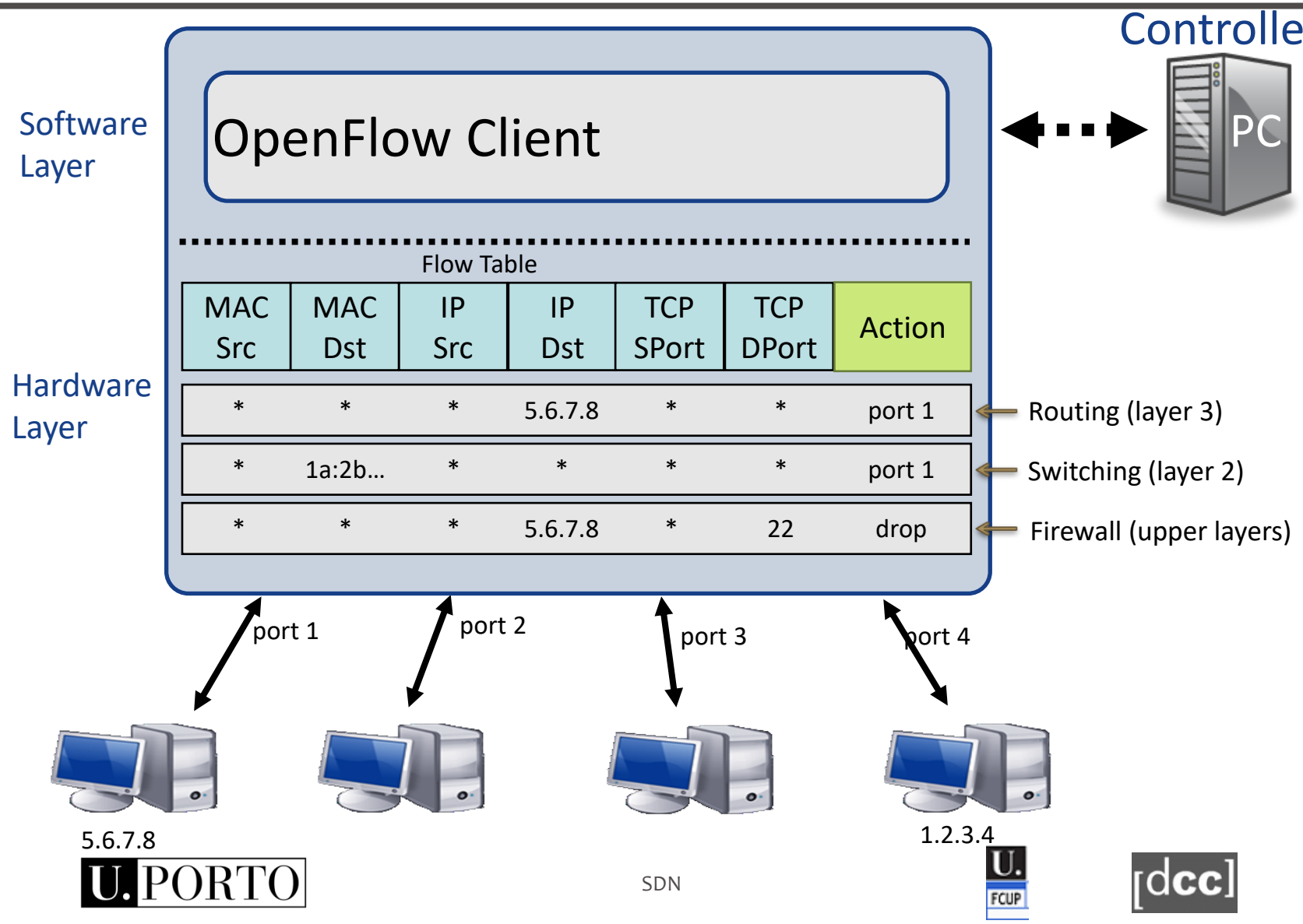


Control Path (Software)

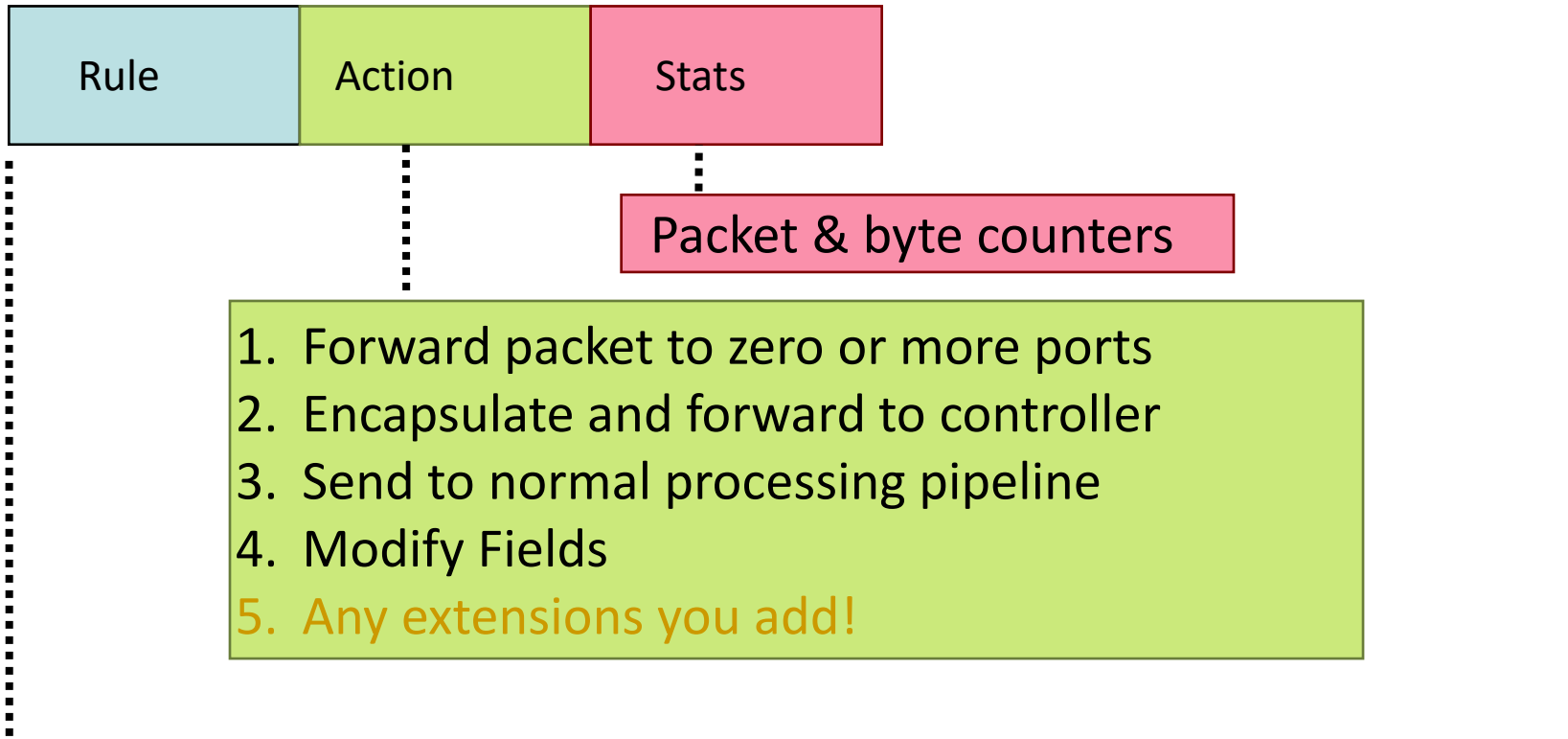
Data Path (Hardware)


OpenFlow Controller
OpenFlow Protocol (SSL/TCP)
Control Path
OpenFlow
Data Path (Hardware)

OpenFlow example



Flow Tables



+ mask specifying which fields to match

Examples

Switching

Switch Port	MAC Src	MAC Dst	Eth Type	VLAN ID	IP Src	IP Dst	IP Prot	TCP Sport	TCP Dport	Action
*	*	00:1f:..	*	*	*	*	*	*	*	port6

Flow Switching

Switch Port	MAC Src	MAC Dst	Eth Type	VLAN ID	IP Src	IP Dst	IP Prot	TCP Sport	TCP Dport	Action
port3	00:20..	00:1f..	0800	vlan1	1.2.3.4	5.6.7.8	4	17264	80	port6

Firewall

Switch Port	MAC Src	MAC Dst	Eth Type	VLAN ID	IP Src	IP Dst	IP Prot	TCP Sport	TCP Dport	Action
*	*	*	*	*	*	5.6.7.8	*	*	22	drop

Examples

Routing

Switch Port	MAC Src	MAC Dst	Eth Type	VLAN ID	IP Src	IP Dst	IP Prot	TCP Sport	TCP Dport	Action
*	*	*	*	*	*	5.6.7.8	*	*	*	port6

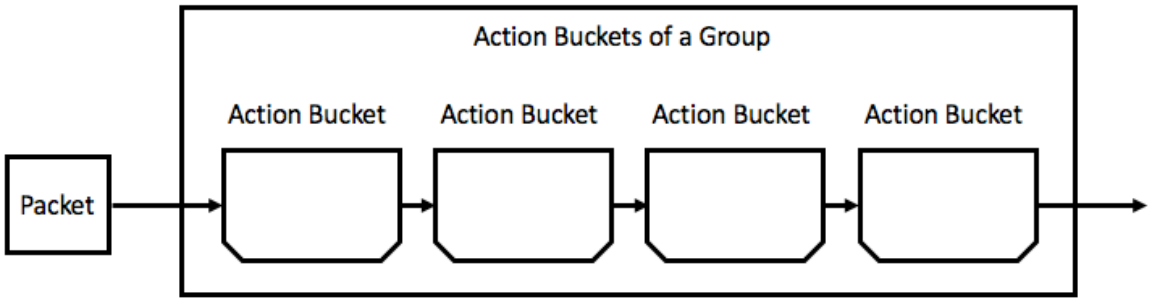
VLAN Switching

Switch Port	MAC Src	MAC Dst	Eth Type	VLAN ID	IP Src	IP Dst	IP Prot	TCP Sport	TCP Dport	Action
*	*	00:1f..	*	vlan1	*	*	*	*	*	port6, port7, port9

Group Table (since v1.1)

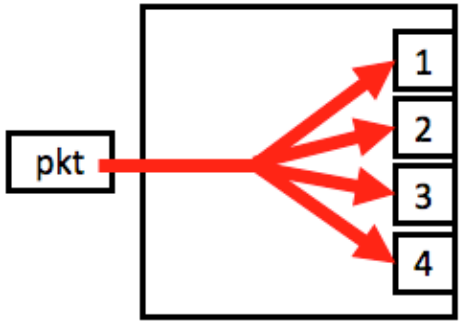
- Allows grouping sets of actions
  - Packet modifications
  - Forwarding to ports
- Layer of indirection
  - Allows reusing sets of actions for different flows
  - Efficient changes to sets of actions shared across flows

Group entry:

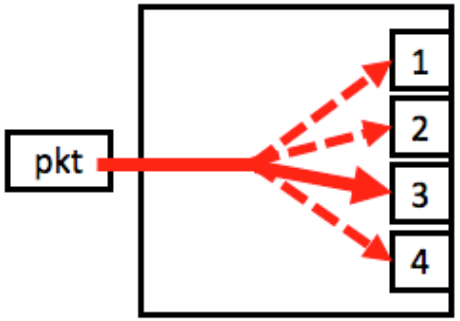


Group Types

All (required)

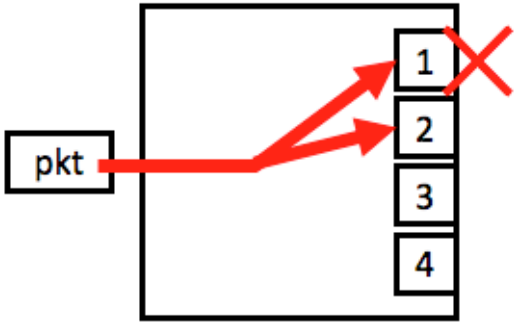


Select (optional)



Select bucket using, e.g., WRR (used for load balancing)

Fast Failover (optional)

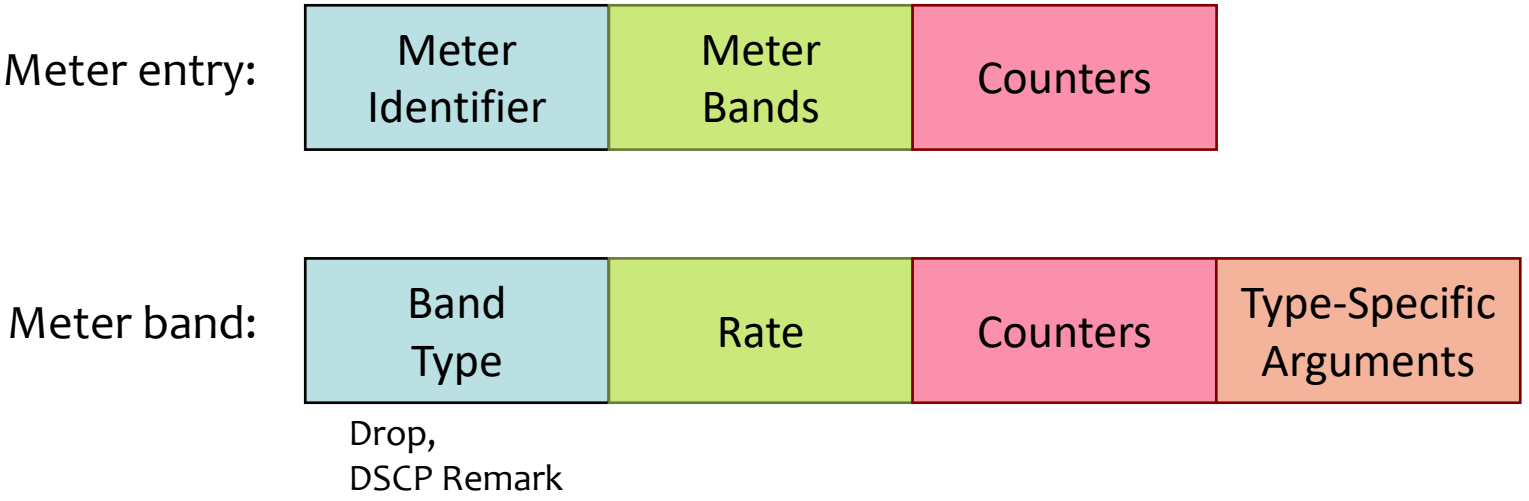


Indirect (required)

- Single bucket
  - Similar to all with 1 bucket
- Allows faster / more efficient changes to shared entries

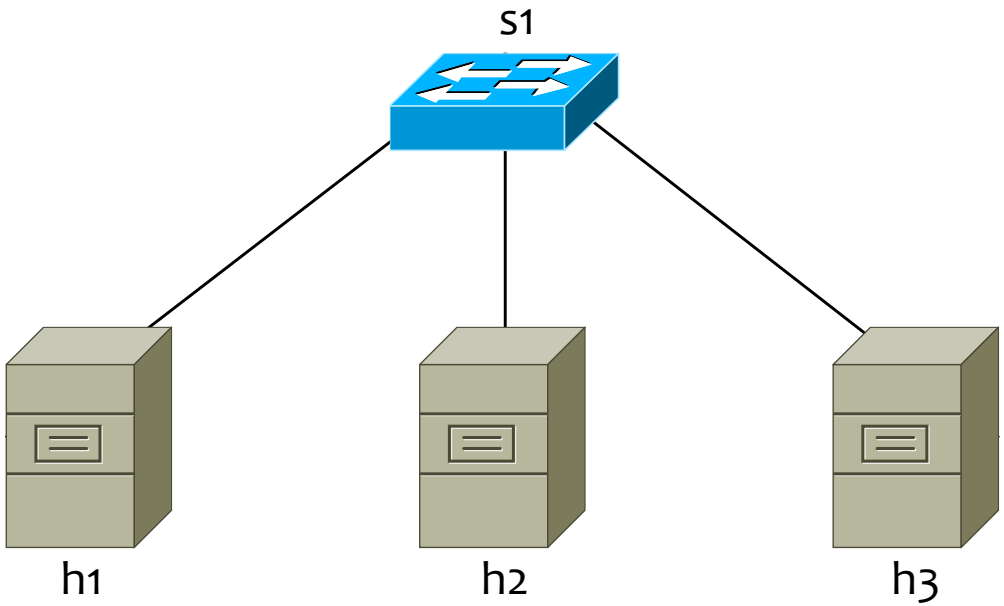
Meter Table (since v1.3)

- 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)



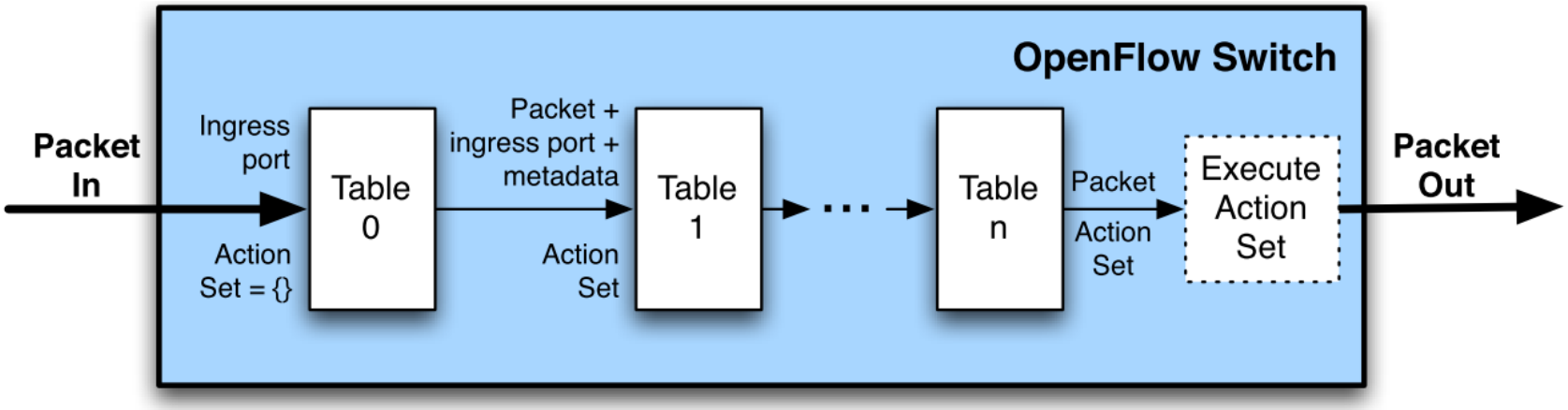
Mininet Demo 1

- One switch, three hosts, no controller



- Experiment with hand-created flow entries

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 site-specific private key
- Bidirectional communication between the switch and the controller is required
  - Even with empty flow tables

OpenFlow Channel

Communication with the controller may be:

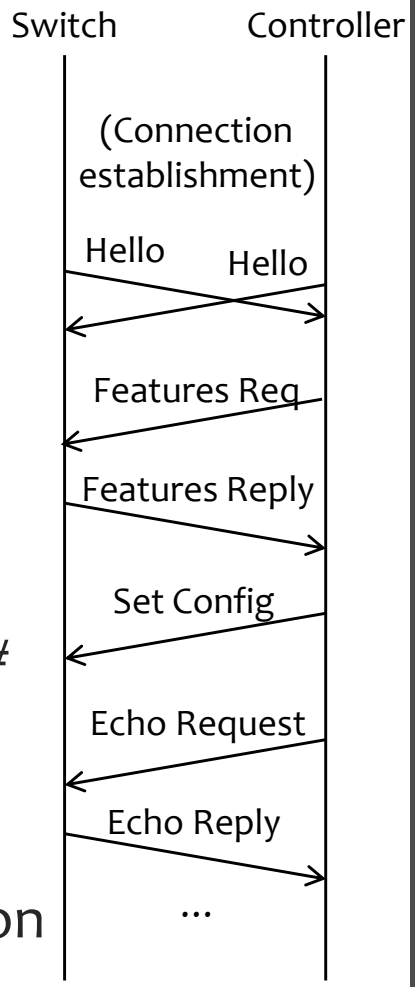
- Out-of-Band
  - Through a separate port with traditional networking stack
- In-Band
  - Through the regular SDN ports
  - Bootstraping problem:
    - OpenFlow Channel required for configuring packet forwarding
    - Packet forwarding required for OpenFlow Channel
    - Solution: use of preloaded rules

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



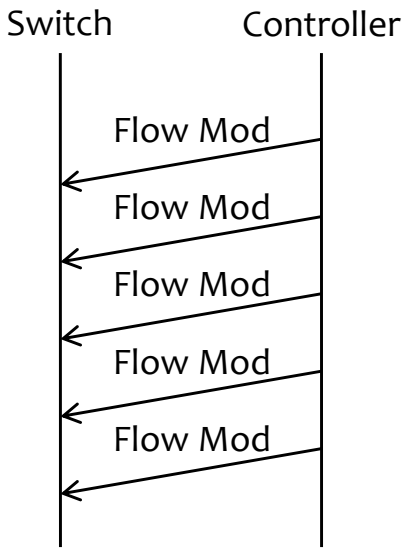
Some OpenFlow Messages (contd.)

- 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

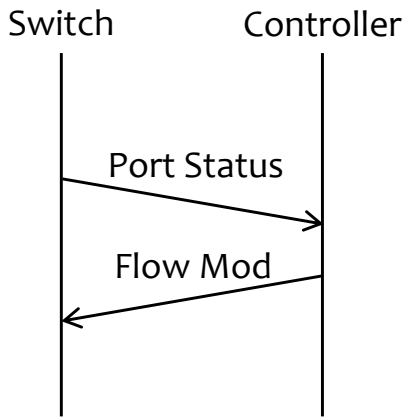
Some OpenFlow Messages (contd.)

- 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)

OpenFlow Messages — Examples

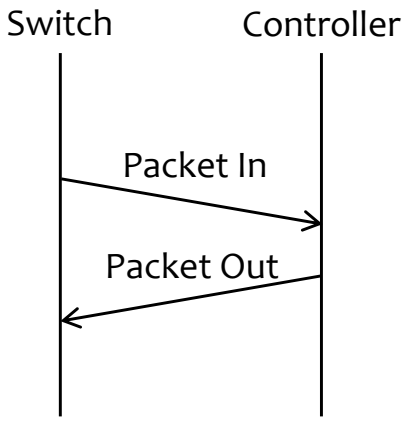


Controller preloads flow entries on the switch.

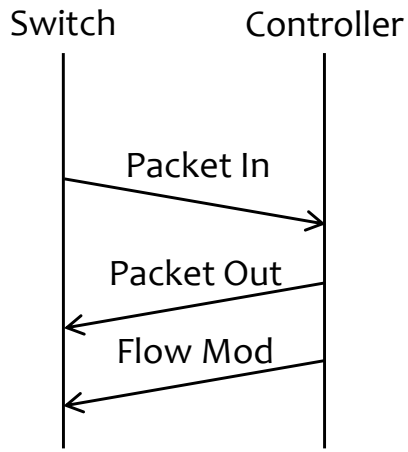


Switch informs Controller of port losing link.
Controller changes existing flow entry using this output port to a different one, to work around the link failure.

OpenFlow Messages — Examples



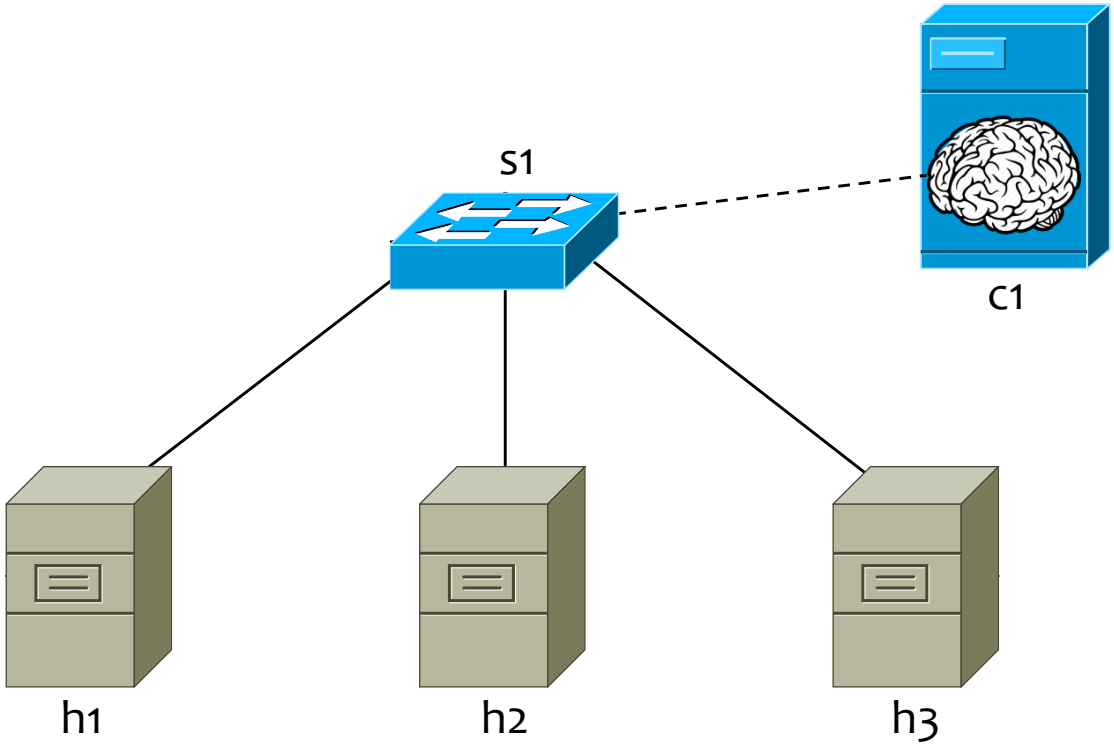
Switch receives a packet not matching any flow entry and sends it to the controller. Controller instructs switch to handle just this packet without installing any flow entries.



Switch receives a packet not matching any flow entry and sends it to controller. Controller tells switch what to do with the packet and installs flow entry for future related packets (e.g., of the same flow).

Mininet Demo 2

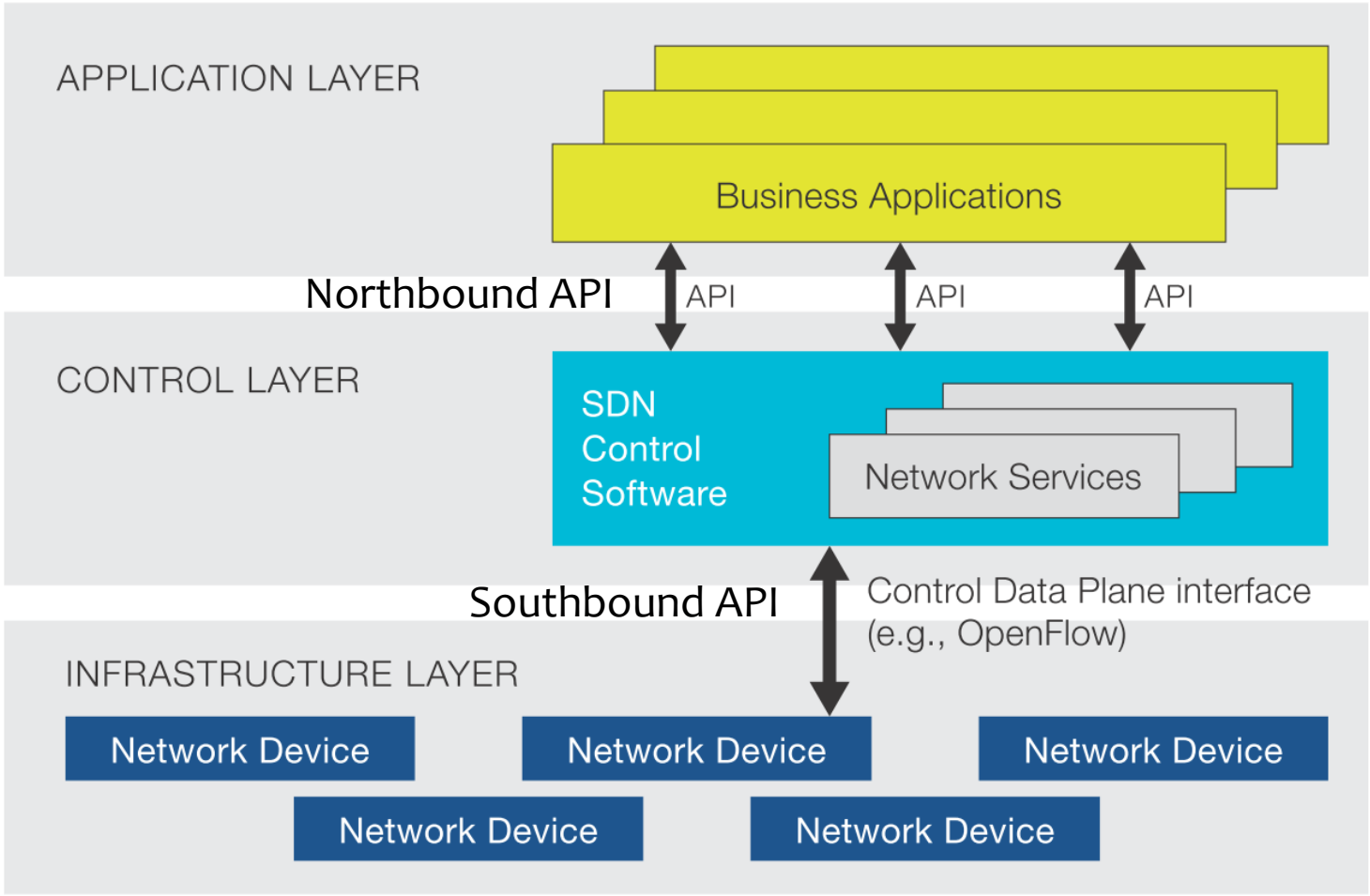
- One switch, three hosts, built-in controller



- Capture OpenFlow messages in Wireshark

SDN and OpenFlow

SDN Architecture

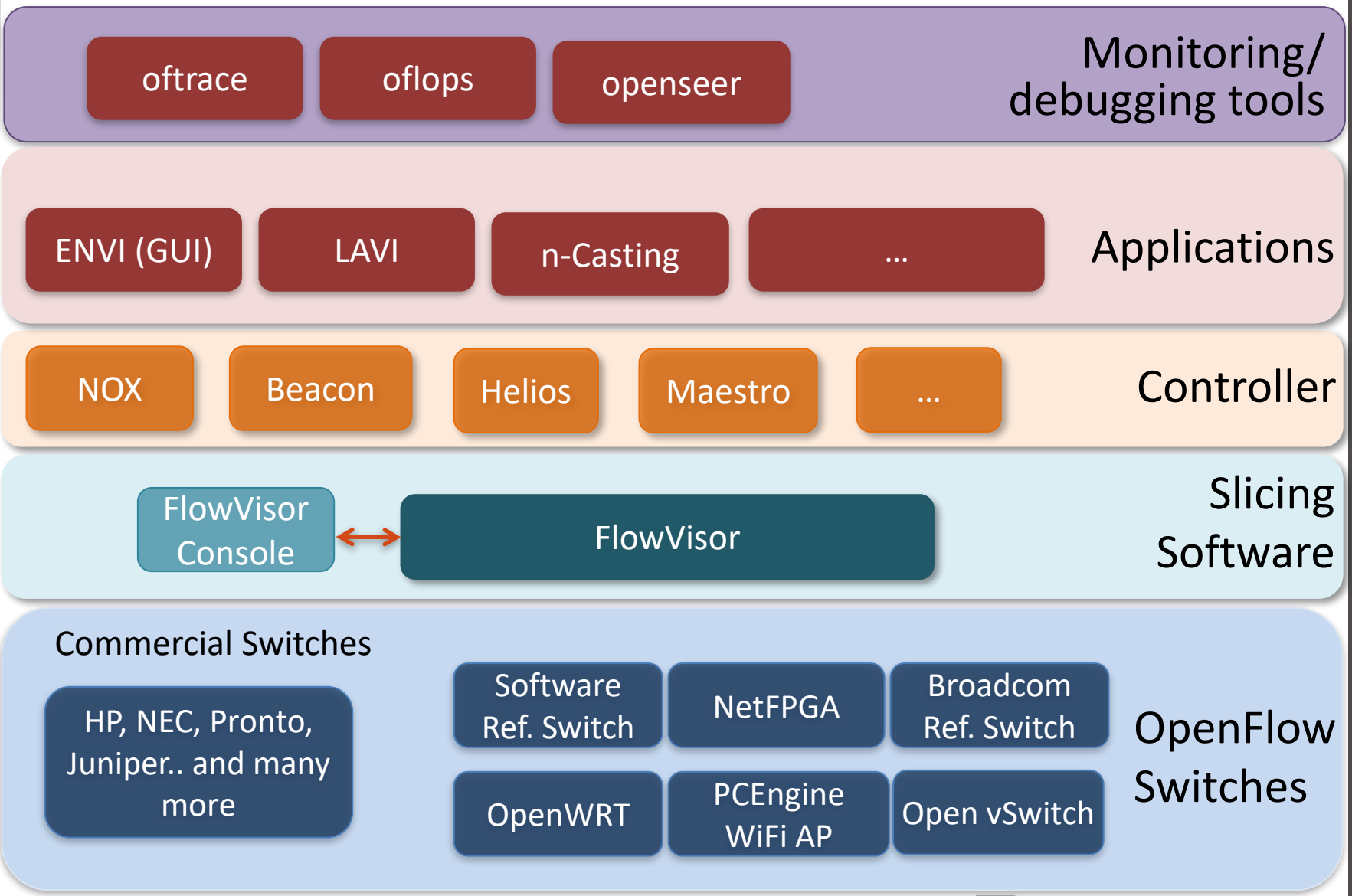


Source: ONF white paper

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)

The end

Acronyms

- ACL – Access Control List
- ASIC – Application Specific Integrated Circuit
- DPI – Deep Packet Inspection
- ECMP – Equal Cost Multi Path
- MPLS – Multiprotocol Label Switching
- NOS – Network OS
- OS – Operating System
- PCP – Priority Code Point
- RFC – Request For Comments
- SDN – Software Defined Networking
- Telco – Telecommunication Operator
- ToS – Type of Service

References

- [Specs] OpenFlow Specifications at Open Networking Foundation,
  - Latest spec 1.5.1 May 2015
  - Interactive specification available
- [WP-ONF] Software-Defined Networking (SDN): The New Norm for Networks, Open Networking Foundation
- [WP-Orig] Nick McKeown etal, "OpenFlow: Enabling Innovation in Campus Networks," March 2008