Software-defined Networking Session II

Advanced Computer Networks

David Koll

Exam Information

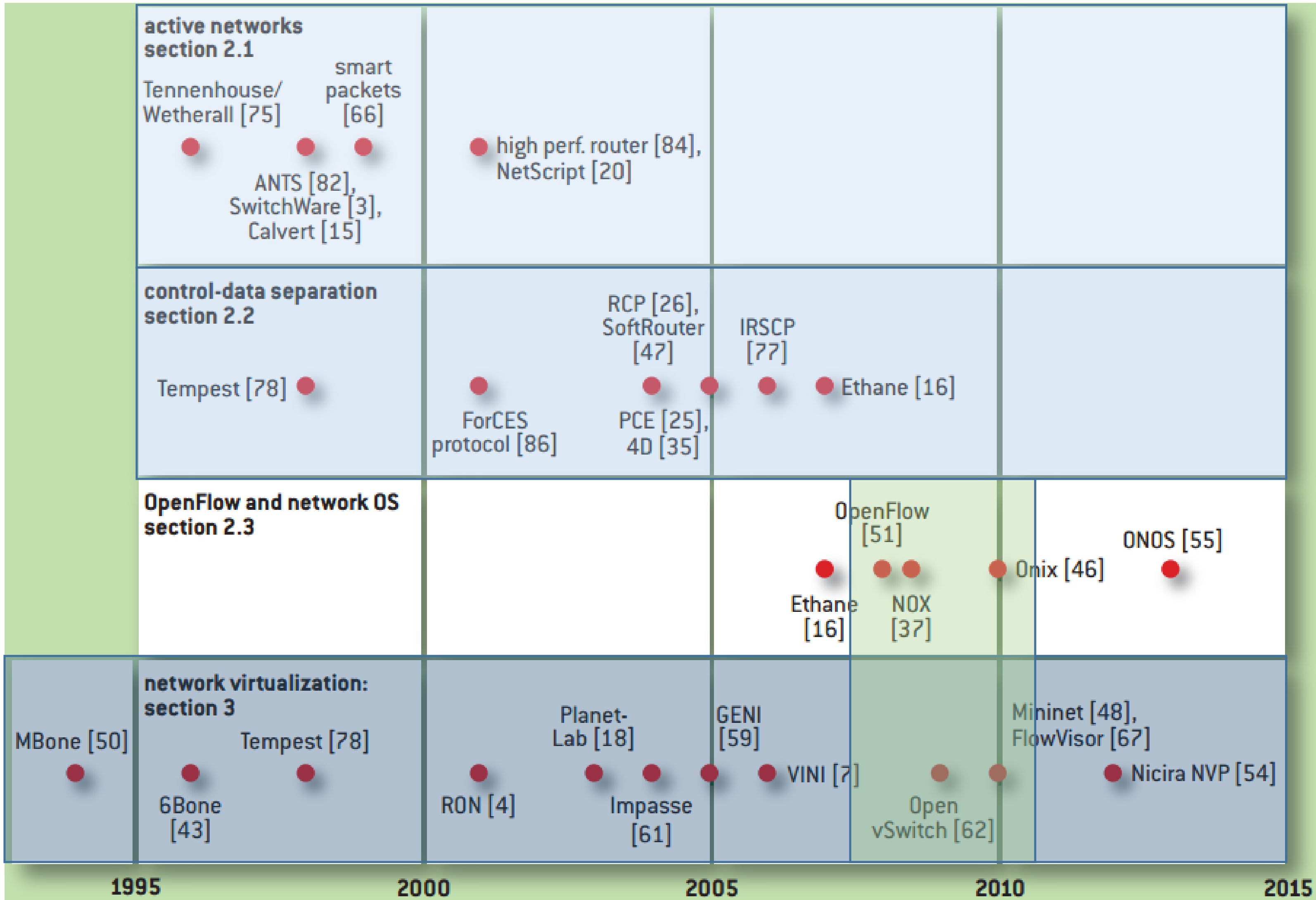
- July 16th, 10-12AM
- Room: MN08
- Written exam
  - Bring a non-erasable blue/black pen (no pencils!)
  - Bring your student ID
  - We provide paper
  - No additional tools allowed (e.g., no calculator)

Exam Information

- All topics of the lecture will be covered.
  - Wireless
  - P2P
  - ICN/CCN
  - SDN
  - DCN
  - (Guest talk not relevant for exam)
- Know how concepts work, you will be asked to perform some operations
  - e.g., lookup in a Chord DHT
- Know why we need the concepts
  - (e.g., what are the reasons for using SDN or CCN

Partly based on slides of Nick McKeown, Scott Shenker, Nick Feamster, Jin Xin, and Jennifer Rexford

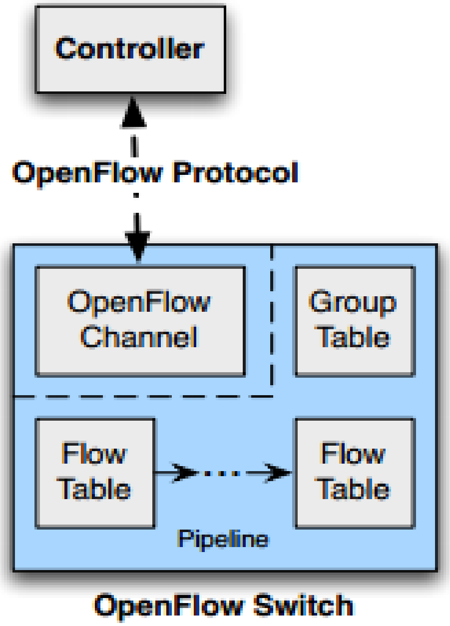
Recap



N. Feamster et al.: „The Road to SDN – An intellectual history of programmable networks" *ACM SIGCOMM Computer Communication Review* 44.2 (2014): 87-98.

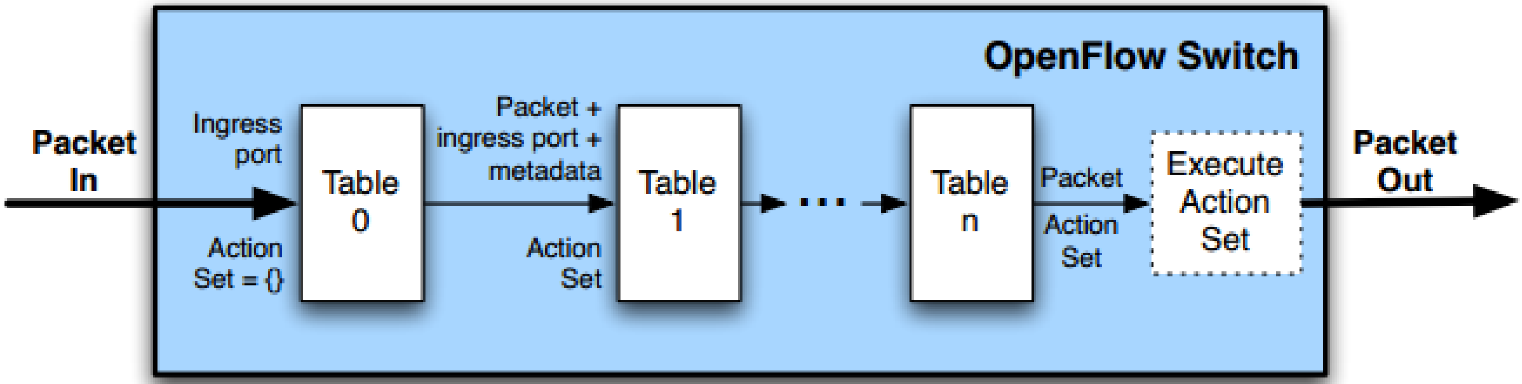
Recap: OpenFlow – A SDN Protocol

- Main components: *Flow* and *Group Tables*
  - Controller can manipulate these tables via the OpenFlow protocol (*add, update, delete*)
  - Flow Table: reactively or proactively defines how incoming packets are forwarded
  - Group Table: additional processing



Recap: OpenFlow – Switches

- Incoming packets are matched against Table 0 first
- Find highest priority match and execute instructions (might be a Goto-Table instruction)
- Goto: Only possible forward



Recap: 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

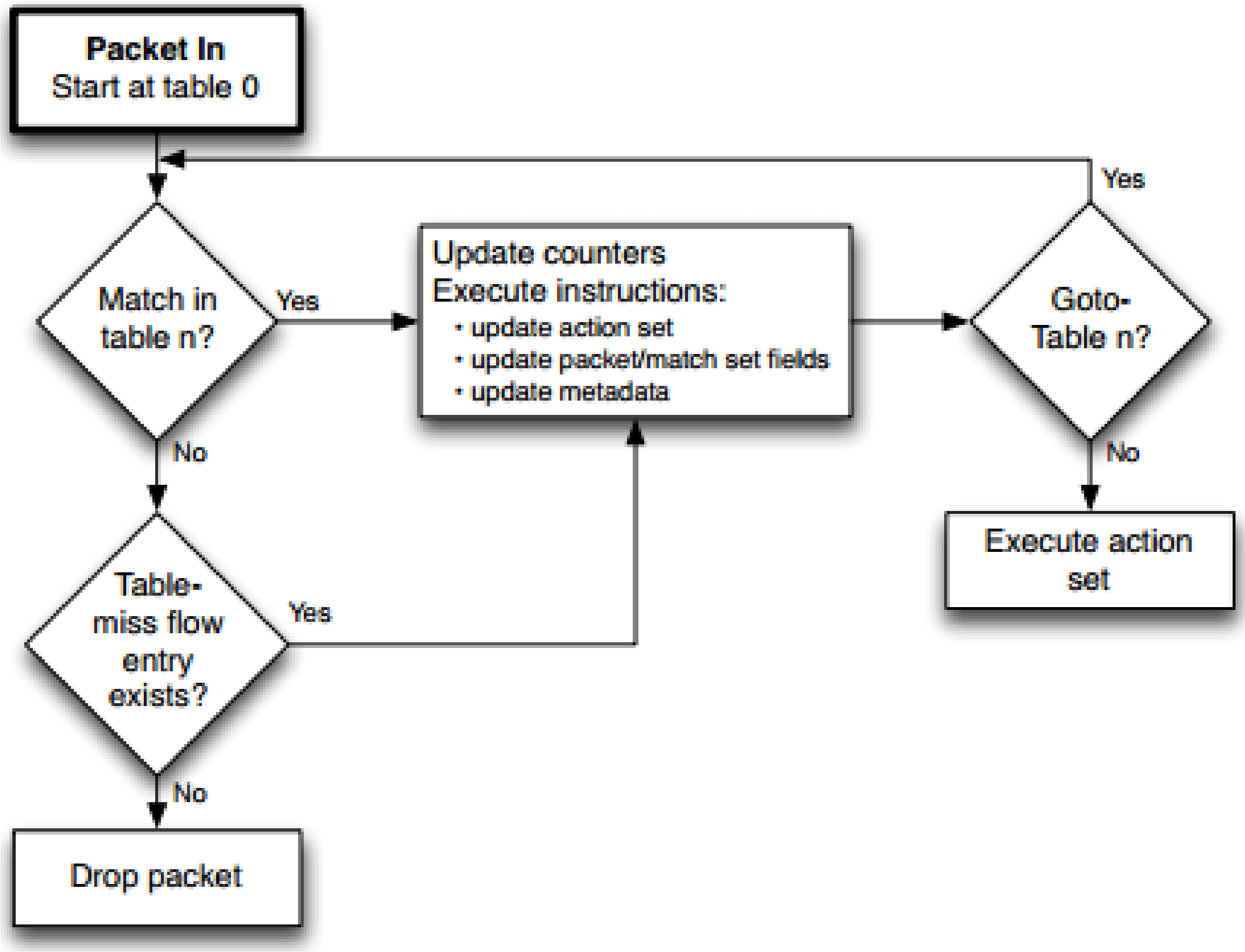
Flow Switching

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
*	*	*	*	*	*	*	*	*	22	drop

OpenFlow - Matching



OpenFlow Controllers

OpenFlow Controllers

Controller Summary

	NOX	POX	Ryu	Floodlight	ODL OpenDaylight
Language	C++	Python	Python	JAVA	JAVA
Performance	Fast	Slow	Slow	Fast	Fast
Distributed	No	No	Yes	Yes	Yes
OpenFlow	1.0 / 1.3	1.0	1.0 to 1.4	1.0	1.0 / 1.3
Learning Curve	Moderate	Easy	Moderate	Steep	Steep
		Research, experimentation, demonstrations	Open source Python controller	Maintained Big Switch Networks	Vendor App support

Source: Georgia Tech SDN Class

World Wide Technology, Inc.

…and many more: Beacon, Trema, OpenContrail, POF, etc.

computer NETWORKS

That‘s a Lot of Controllers!?

„There are almost as many controllers for SDNs as there are SDNs“ – Nick Feamster

Which controller should I use for what problem?

Which controller?

Concept?

Architecture?

Programming language and model?

Advantages / Disadvantages?

Learning Curve?

Developing Community?

Type of target network?

NOX [1]

- **The first controller**
  - Open source
  - Stable
    - No longer supported
    - „New“ NOX: C++ only
      - OF version supported: 1.0

[1] Gude et al. "NOX: towards an operating system for networks." *ACM SIGCOMM CCR* 38.3 (2008): 105-110.

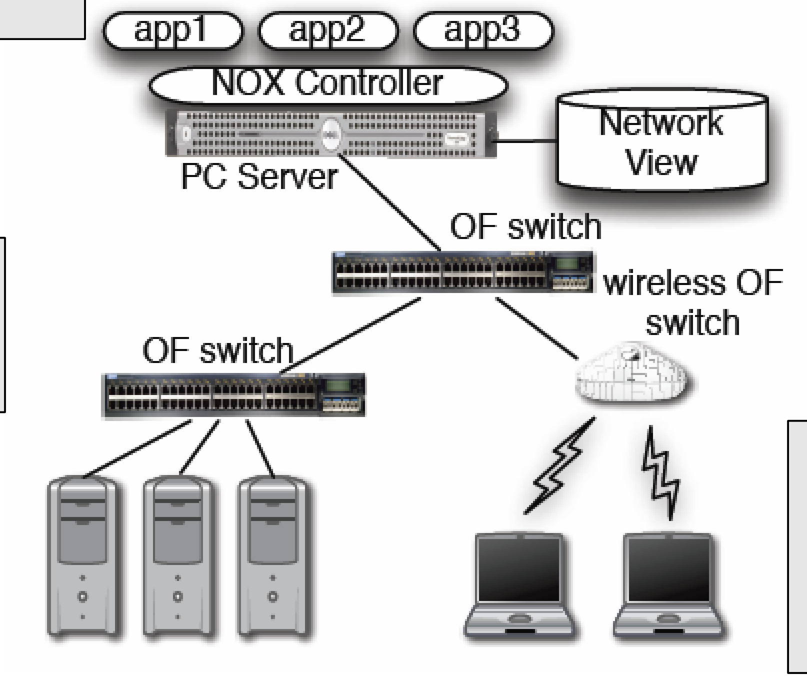
NOX Architecture

Granularity of Control: Per Flow

Controller maintains a network view

switches and attached servers

OpenFlow is used to control switches



[1] Gude et al. "NOX: towards an operating system for networks." *ACM SIGCOMM CCR* 38.3 (2008): 105-110.

NOX Architecture

Programming model: Controller listens for OF events

Programmer writes action handlers for events

When to use NOX

- Need to use low-level semantics of OpenFlow
  - NOX does not come with many abstractions
- Need of good performance (C++)
  - E.g.: production networks

POX [1]

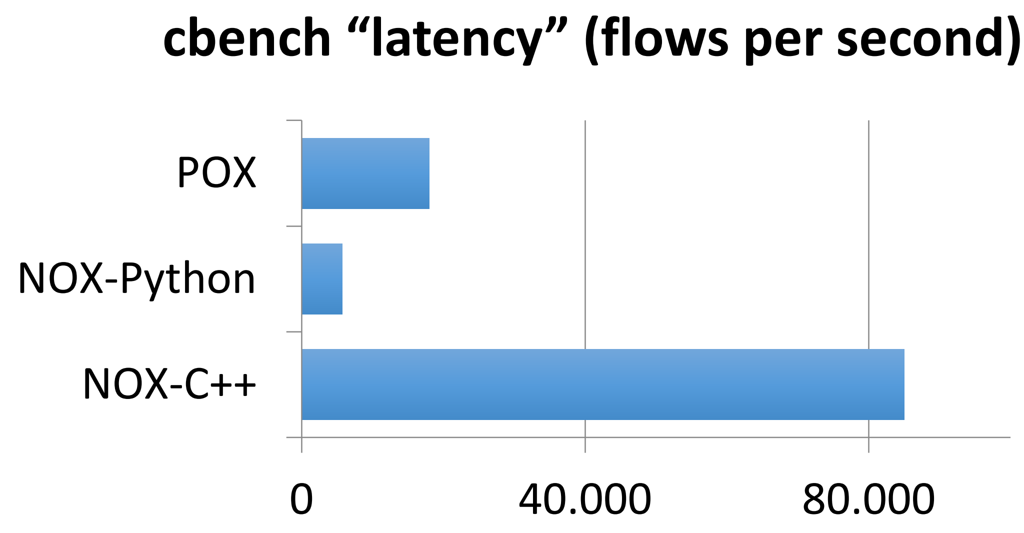
- **POX = NOX in Python**

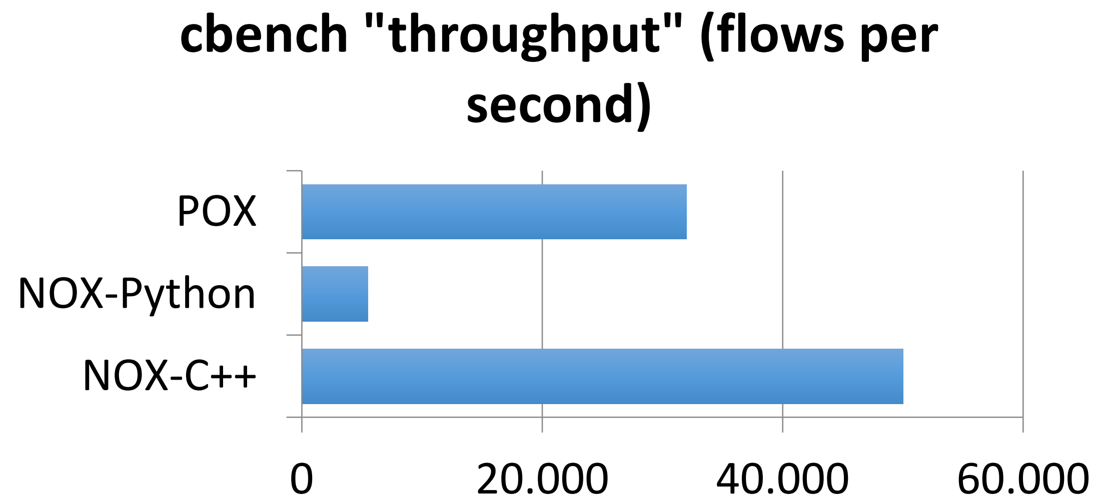
- Advantages:
  - Widely used, maintained and supported
  - Relatively easy to write code for

- Disadvantage:
  - Performance (Python is slower than C++)
  - But: can feed POX ideas back to NOX for production use

[1] Mccauley, J. "Pox: A python-based openflow controller." http://www.noxrepo.org/pox/about-pox/

POX





http://www.noxrepo.org/pox/about-pox/

When to use POX

- Learning, testing, debugging, evaluation

- Probably not in large production networks

Programming POX

- Recall: controller listens for OF events, here: packetIn

```
def _handle_PacketIn (self, event):
  """
  Handles packet in messages from the switch.
  """

  packet = event.parsed # This is the parsed packet data.
  if not packet.parsed:
    log.warning("Ignoring incomplete packet")
    return

  packet_in = event.ofp # The actual ofp_packet_in message.

  # process packet like a switch
  self.act_like_switch(packet, packet_in)
```

Programming POX

```
def act_like_switch (self, packet, packet_in):
    """
    The controller will check whether or not the destination host
    is in the MAC-TO-PORT table.
    IF that is the case, the controller instructs the switch to
    forward via the corresponding port.
    IF NOT, the controller instructs the switch to flood the packet.
    """

    #update MAC-TO-PORT table for source of packet
    self.mac_to_port[packet.src] =  packet_in.in_port

    if packet.dst in self.mac_to_port:
        out_port = self.mac_to_port[packet.dst]
        # Send packet out the associated port
        self.resend_packet(packet_in, self.mac_to_port[packet.dst])

    else:
        self.resend_packet(packet_in, of.OFPP_ALL)
```

Programming POX

```python
def resend_packet (self, packet_in, out_port):
    """
    Instructs the switch to resend a packet that it had sent to us.
    "packet_in" is the ofp_packet_in object the switch had sent to the
    controller due to a table-miss.
    """
    msg = of.ofp_packet_out()
    msg.data = packet_in

    # Add an action to send to the specified port
    action = of.ofp_action_output(port = out_port)
    msg.actions.append(action)

    # Send message to switch
    self.connection.send(msg)
```

Just one more: Floodlight [1]

- Java

- Advantages:
  - Documentation,
  - REST API conformity
  - Production-level performance

- Disadvantage:
  - Steep learning curve

[1] http://www.projectfloodlight.org/floodlight/

Floodlight: Users

Floodlight Adopters:

- University research
- Networking vendors
- Users
- Developers / startups

Floodlight Overview

- FloodlightProvider (IFloodlightProviderService)
- TopologyManager (ITopologyManagerService)
- LinkDiscovery (ILinkDiscoveryService)
- Forwarding
- DeviceManager (IDeviceService)
- StorageSource (IStorageSourceService)
- RestServer (IRestApiService)
- StaticFlowPusher (IStaticFlowPusherService)
- VirtualNetworkFilter (IVirtualNetworkFilterService)

- Floodlight is a collection of modules
- Some modules (not all) export services
- All modules in Java
- Rich, extensible REST API

Taken from: Cohen et al, “Software-Defined Networking and the Floodlight Controller”, available at http://de.slideshare.net/openflowhub/floodlight-overview-13938216

Floodlight Overview

Module	Description
FloodlightProvider (IFloodlightProviderService)	• Translates OF messages to Floodlight events • Managing connections to switches via Netty
TopologyManager (ITopologyManagerService)	• Computes shortest path using Dijsktra • Keeps switch to cluster mappings
LinkDiscovery (ILinkDiscoveryService)	• Maintains state of links in network • Sends out LLDPs
Forwarding	• Installs flow mods for end-to-end routing • Handles island routing
DeviceManager (IDeviceService)	• Tracks hosts on the network • MAC -> switch,port, MAC->IP, IP->MAC
StorageSource (IStorageSourceService)	
RestServer (IRestApiService)	• Implements via Restlets (restlet.org) • Modules export RestletRoutable
StaticFlowPusher (IStaticFlowPusherService)	• Supports the insertion and removal of static flows • REST-based API
VirtualNetworkFilter (IVirtualNetworkFilterService)	• Create layer 2 domain defined by MAC address

Taken from: Cohen et al, "Software-Defined Networking and the Floodlight Controller", available at http://de.slideshare.net/openflowhub/floodlight-overview-13938216

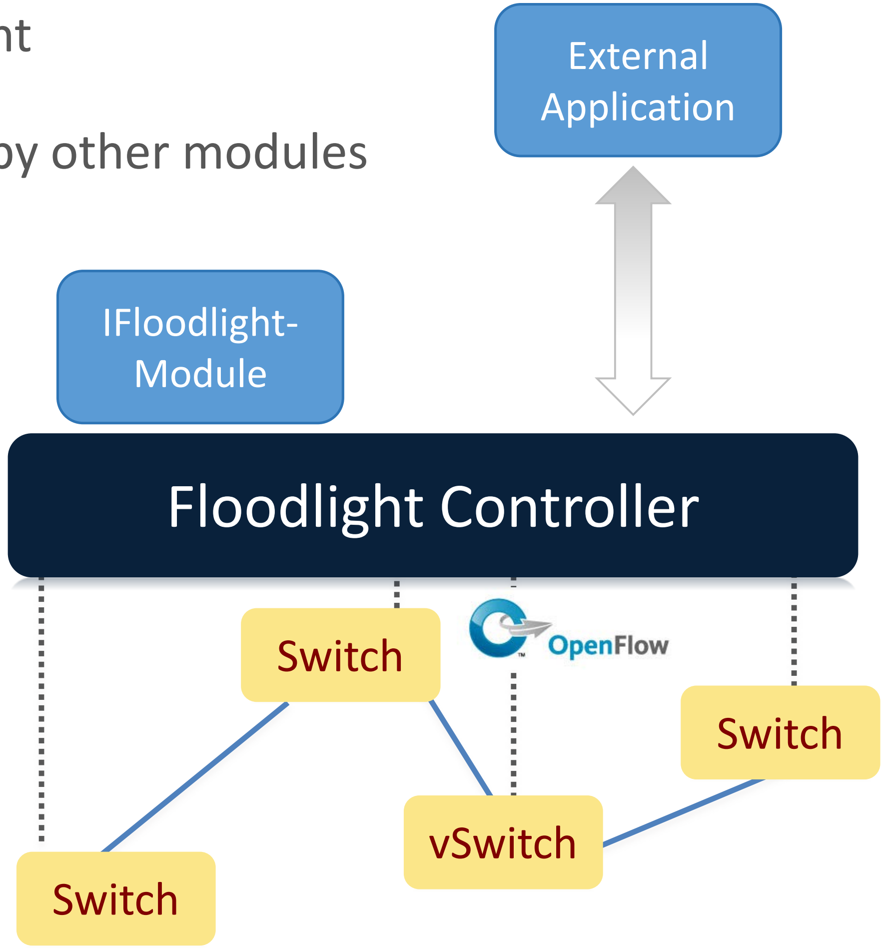
Floodlight Programming Model

IFloodlightModule

- Java module that runs as part of Floodlight
- Consumes services and events exported by other modules
  - OpenFlow (ie. Packet-in)
  - Switch add / remove
  - Device add /remove / move
  - Link discovery

External Application

- Communicates with Floodlight via REST



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Floodlight Modules

Network State

- List Hosts
- List Links
- List Switches
- GetStats (DPID)
- GetCounters (OFType…)

Static Flows

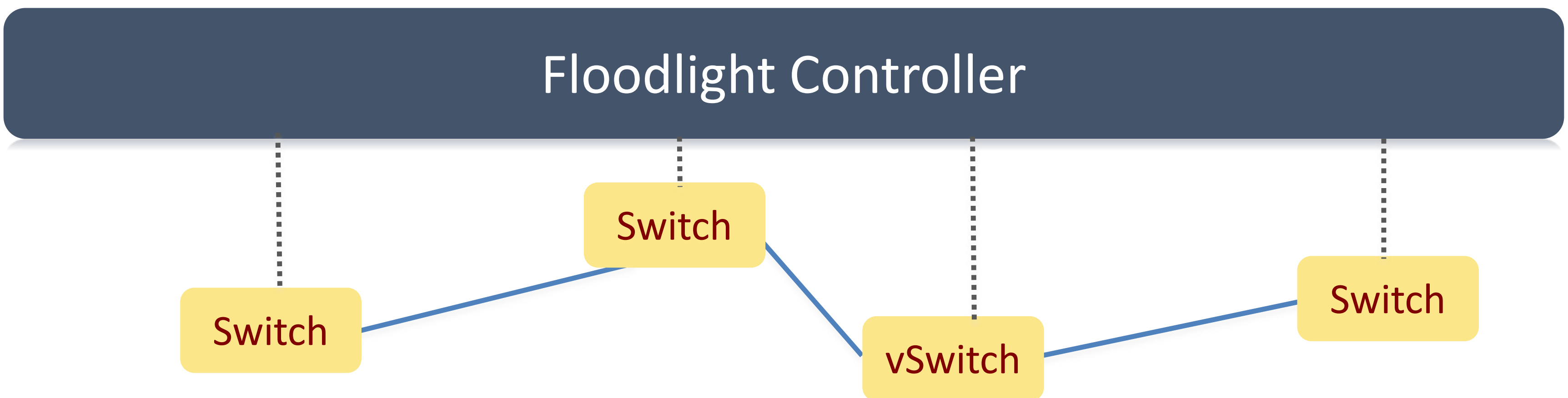
- Add Flow
- Delete Flow
- List Flows
- RemoveAll Flows

Virtual Network

- Create Network
- Delete Network
- Add Host
- Remove Host

User Extensions

…



Taken from: Cohen et al, "Software-Defined Networking and the Floodlight Controller", available at http://de.slideshare.net/openflowhub/floodlight-overview-13938216

When to use Floodlight

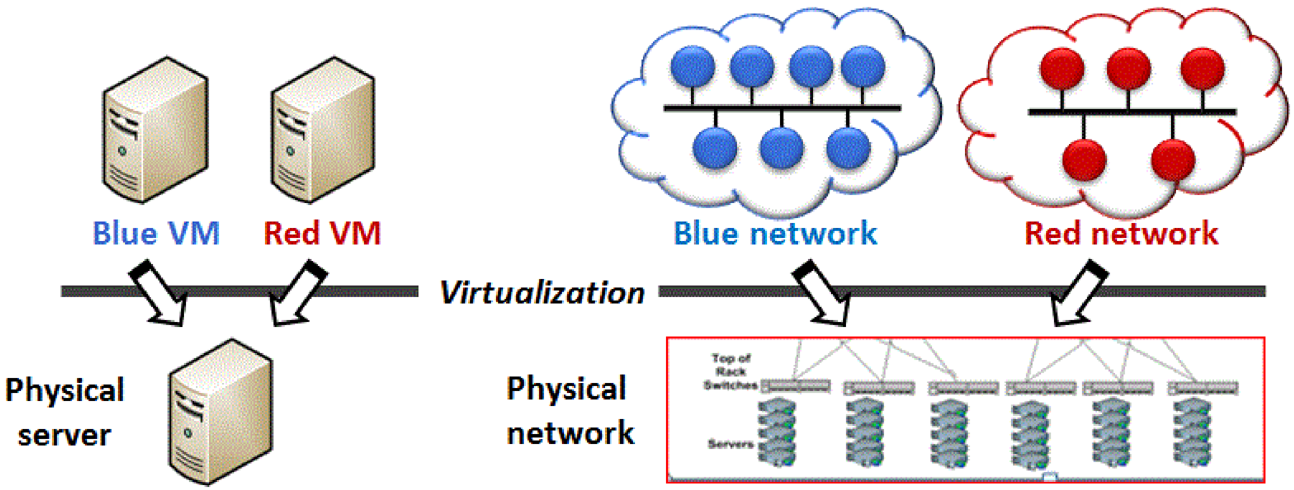
- If you know JAVA
- If you need production-level performance
- Have/want to use REST API

Network Virtualization with OpenFlow

Virtualizing OpenFlow

- Network operators “Delegate” control of subsets of network hardware and/or traffic to other network operators or users
- Multiple controllers can talk to the same set of switches
- Imagine a hypervisor for network equipments
- Allow experiments to be run on the network in isolation of each other and production traffic

Virtualizing OpenFlow



Server virtualization

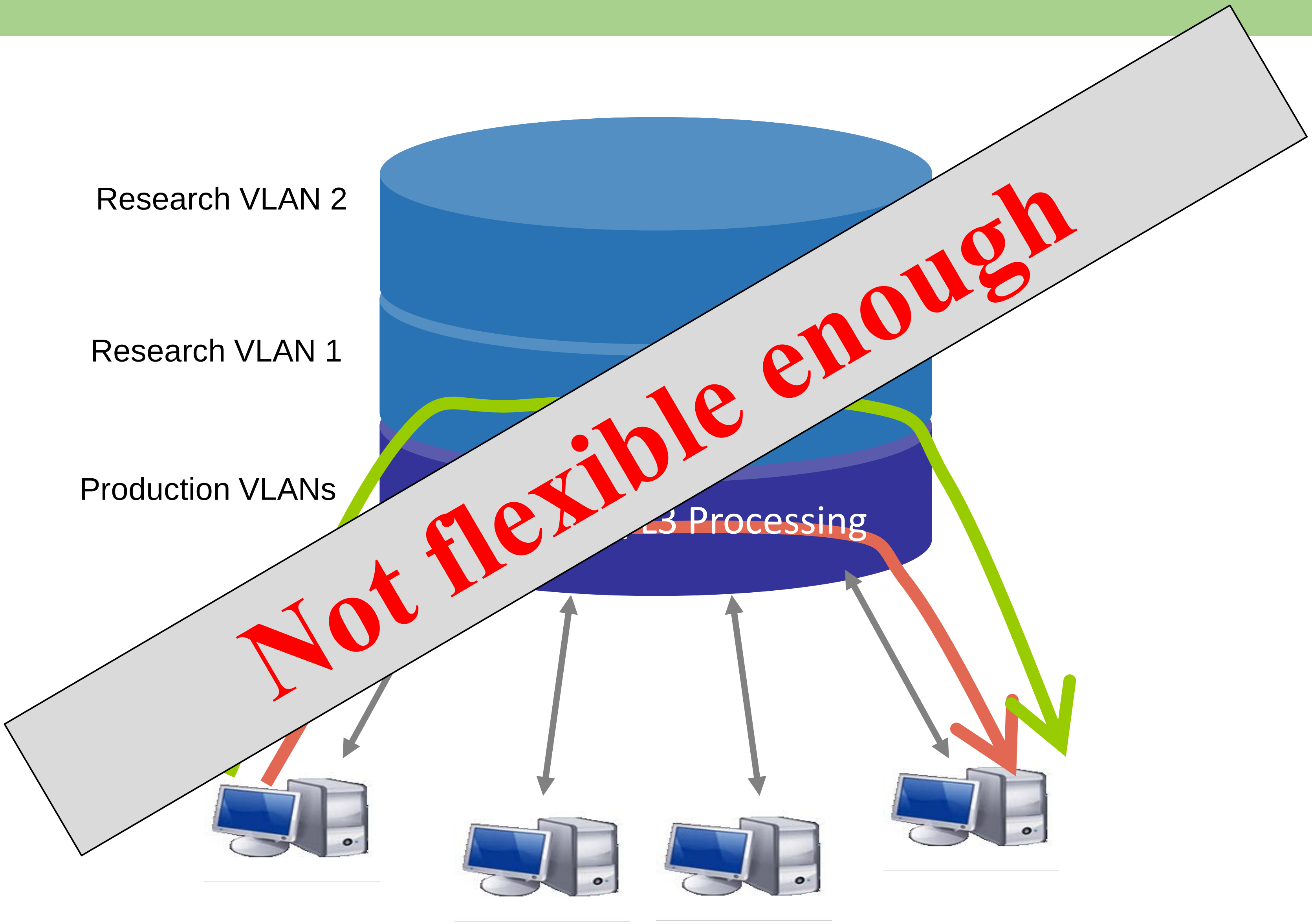
- Run multiple virtual servers on a physical server
- Each VM has illusion it is running as a physical server

Network virtualization

- Run multiple virtual networks on a physical network
- Each virtual network has illusion it is running as a physical network

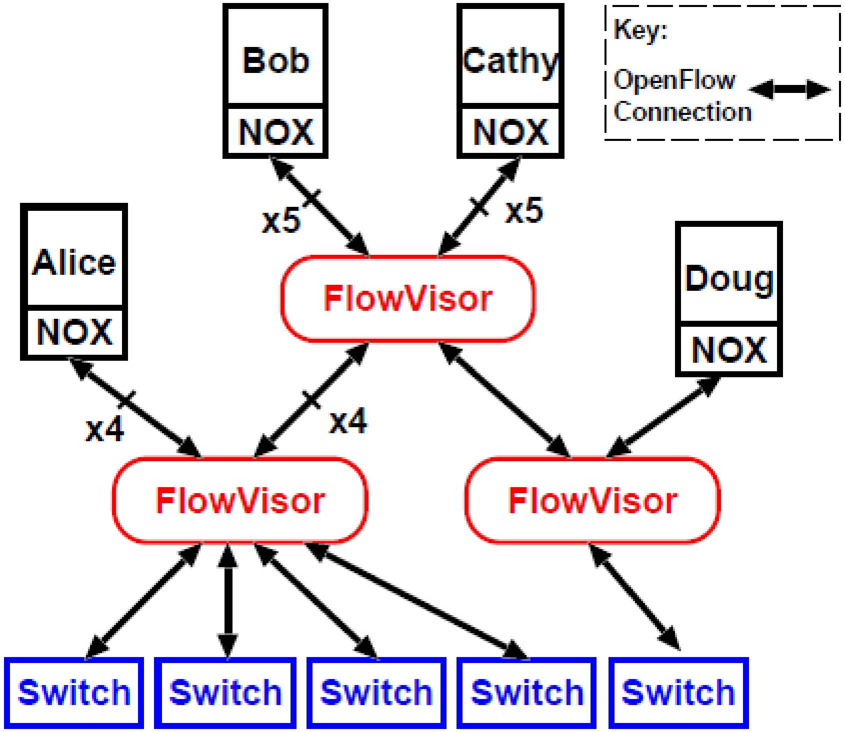
https://gallery.technet.microsoft.com/scriptcenter/Simple-Hyper-V-Network-d3efb3b8

Virtualization: VLANs



FlowVisor [1]

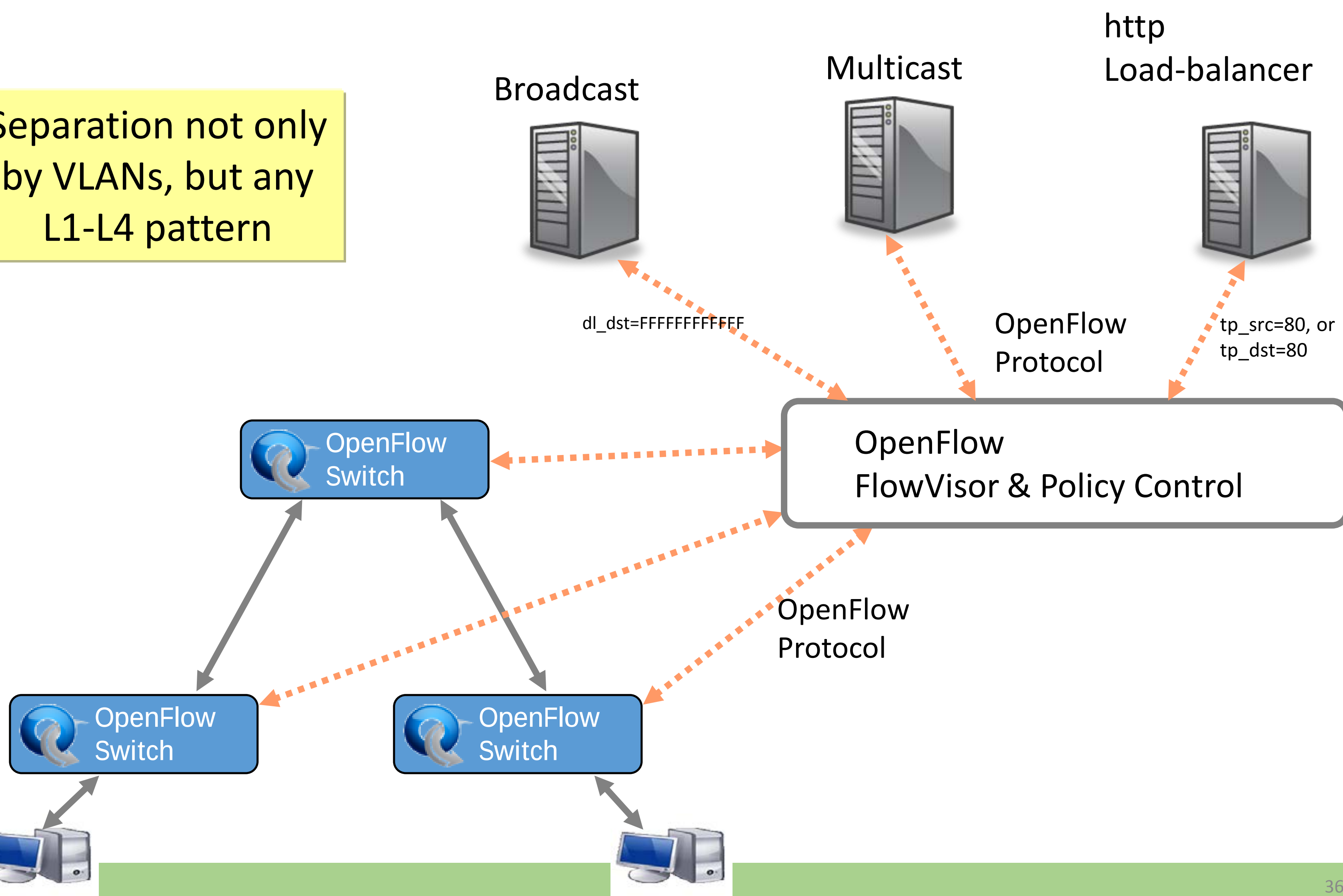
- A network hypervisor developed by Stanford
- A software proxy between the forwarding and control planes of network devices



[1] Sherwood, et al. *"Flowvisor: A network virtualization layer." OpenFlow Switch Consortium, Tech. Rep* (2009).

FlowVisor-based Virtualization

Separation not only by VLANs, but any L1-L4 pattern



Slicing Policies

- The policy specifies resource limits for each slice:
  - Link bandwidth
  - Maximum number of forwarding rules
  - Topology
  - Fraction of switch/router CPU

  - *FlowSpace: which packets does the slice control?*

FlowVisor Resource Limits

- FV assigns hardware resources to "Slices"
  - Topology
    - Network Device or Openflow Instance (DPID)
    - Physical Ports
  - Bandwidth
    - Each slice can be assigned a per port queue with a fraction of the total bandwidth

FlowVisor Resource Limits (cont.)

- FV assigns hardware resources to “Slices”
  - CPU
    - Employs Course Rate Limiting techniques to keep new flow events from one slice from overrunning the CPU
  - Forwarding Tables
    - Each slice has a finite quota of forwarding rules per device

FlowVisor FlowSpace

- FlowSpace is defined by a collection of packet headers and assigned to "Slices"
  - Source/Destination MAC address
  - VLAN ID
  - Ethertype
  - IP protocol
  - Source/Destination IP address
  - ToS/DSCP
  - Source/Destination port number

Use Case: VLAN Partitioning

- Basic Idea: Partition Flows based on Ports and VLAN Tags
  - Traffic entering system (e.g. from end hosts) is tagged
  - VLAN tags consistent throughout substrate

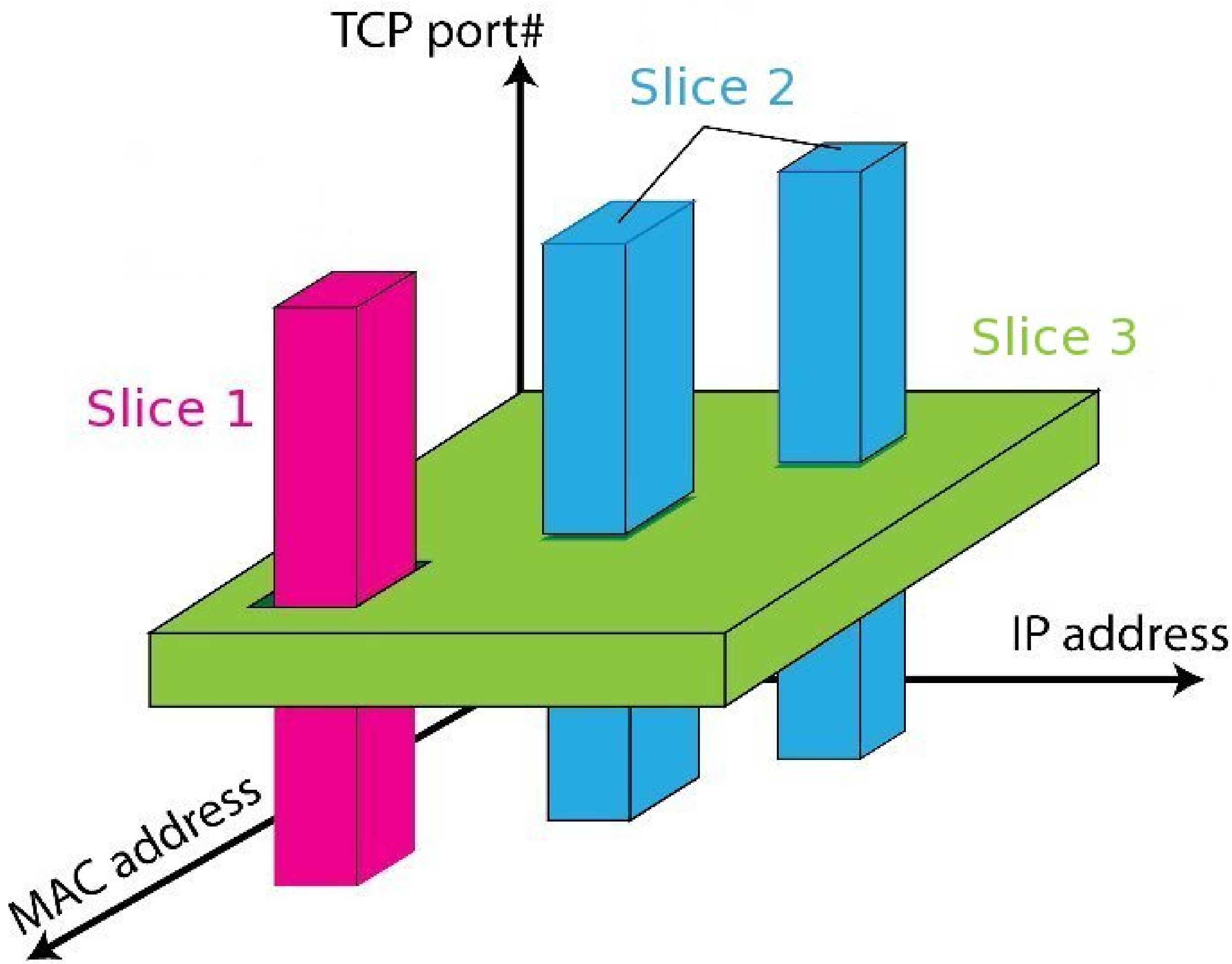
	Switch Port	MAC src	MAC dst	Eth type	VLAN ID	IP Src	IP Dst	IP Prot	TCP sport	TCP dport
Dave	*	*	*	*	1,2,3	*	*	*	*	*
Larry	*	*	*	*	4,5,6	*	*	*	*	*
Steve	*	*	*	*	7,8,9	*	*	*	*	*

Use Case: Content Distribution Network

- Basic Idea: Build a CDN where you control the entire network
  - All traffic to or from CDN IP space controlled by Experimenter
  - All other traffic controlled by default routing
  - Topology is the entire network

	Switch Port	MAC src	MAC dst	Eth type	VLAN ID	IP Src	IP Dst	IP Prot	TCP sport	TCP dport
From CDN	*	*	*	*	*	84.65.*	*	*	*	*
To CDN	*	*	*	*	*	*	84.65.*	*	*	*
Default	*	*	*	*	*	*	*	*	*	*

FlowSpace: Maps Packets to Slices



Taken from: Rob Sherwood's presentation at ONS:
http://www.opennetsummit.org/archives/apr12/sherwood-mon-flowvisor.pdf

FlowVisor Slicing Policy

- FlowVisor intercepts OpenFlow messages from devices
  - Send control plane messages to the slice controller only if source is in slice topology.
  - Rewrite OpenFlow feature negotiation messages so the slice controller only sees the ports in it's slice
  - Port up/down messages are pruned and only forwarded to affected slices

FlowVisor Slicing Policy

- FlowVisor intercepts OpenFlow messages from controllers
  - Rewrites flow insertion, deletion & modification rules so they don't violate the slice definition
    - Flow definition – ex. Limit Control to HTTP traffic only
    - Actions – ex. Limit forwarding to only ports in the slice

FlowVisor Slicing Policy

- FlowVisor intercepts OpenFlow messages from controllers
  - Expand Flow rules into multiple rules to fit policy
    - Flow definition – ex. If there is a policy for John's HTTP traffic and another for Uwe's HTTP traffic, FV would expand a single rule intended to control all HTTP traffic into 2 rules.
    - Actions – ex. Rule action is send out all ports. FV will create one rule for each port in the slice.

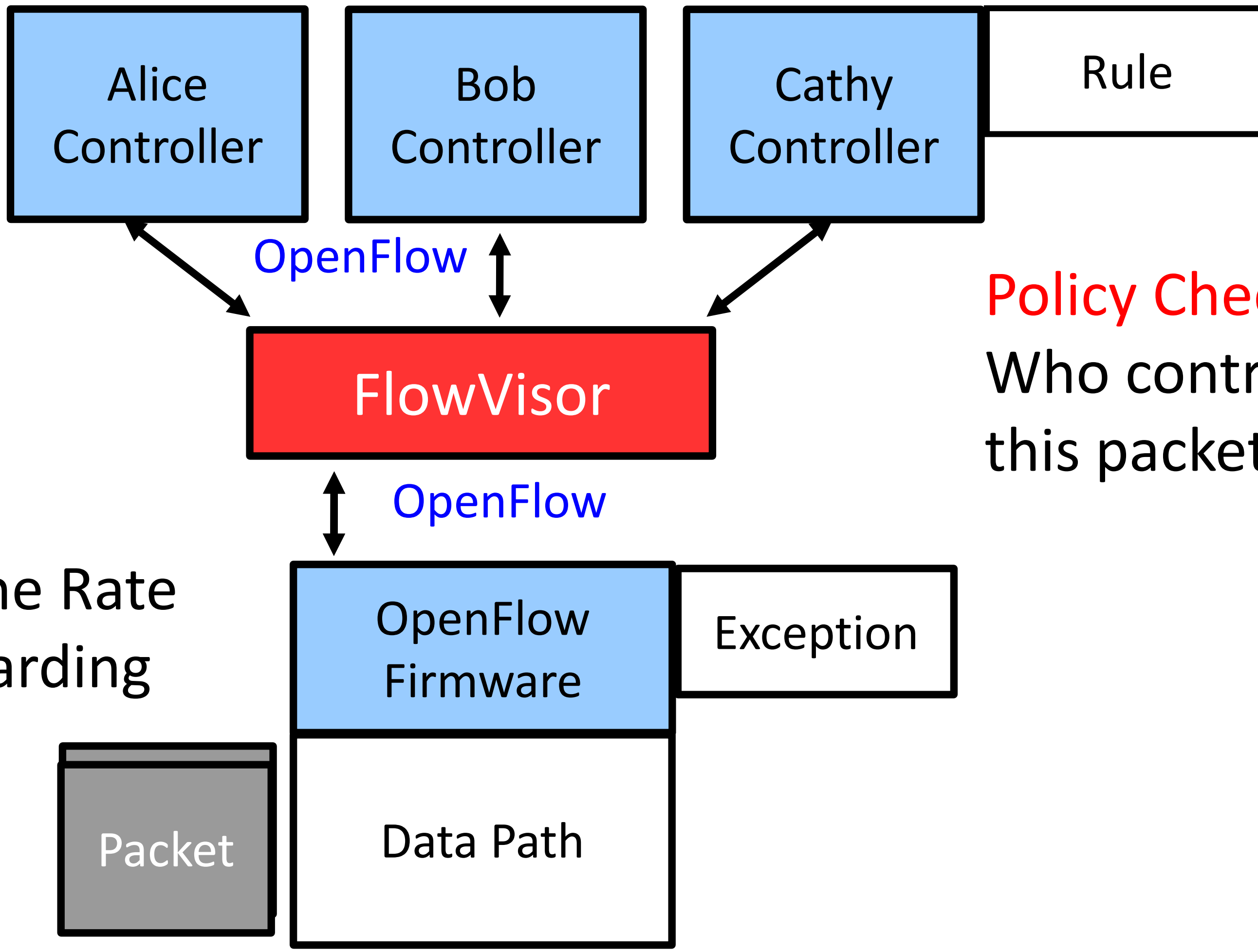
    - Returns "action is invalid" error if trying to control a port outside of the

FlowVisor Message Handling

Policy Check: Is this rule allowed?

Policy Check: Who controls this packet?

Full Line Rate Forwarding



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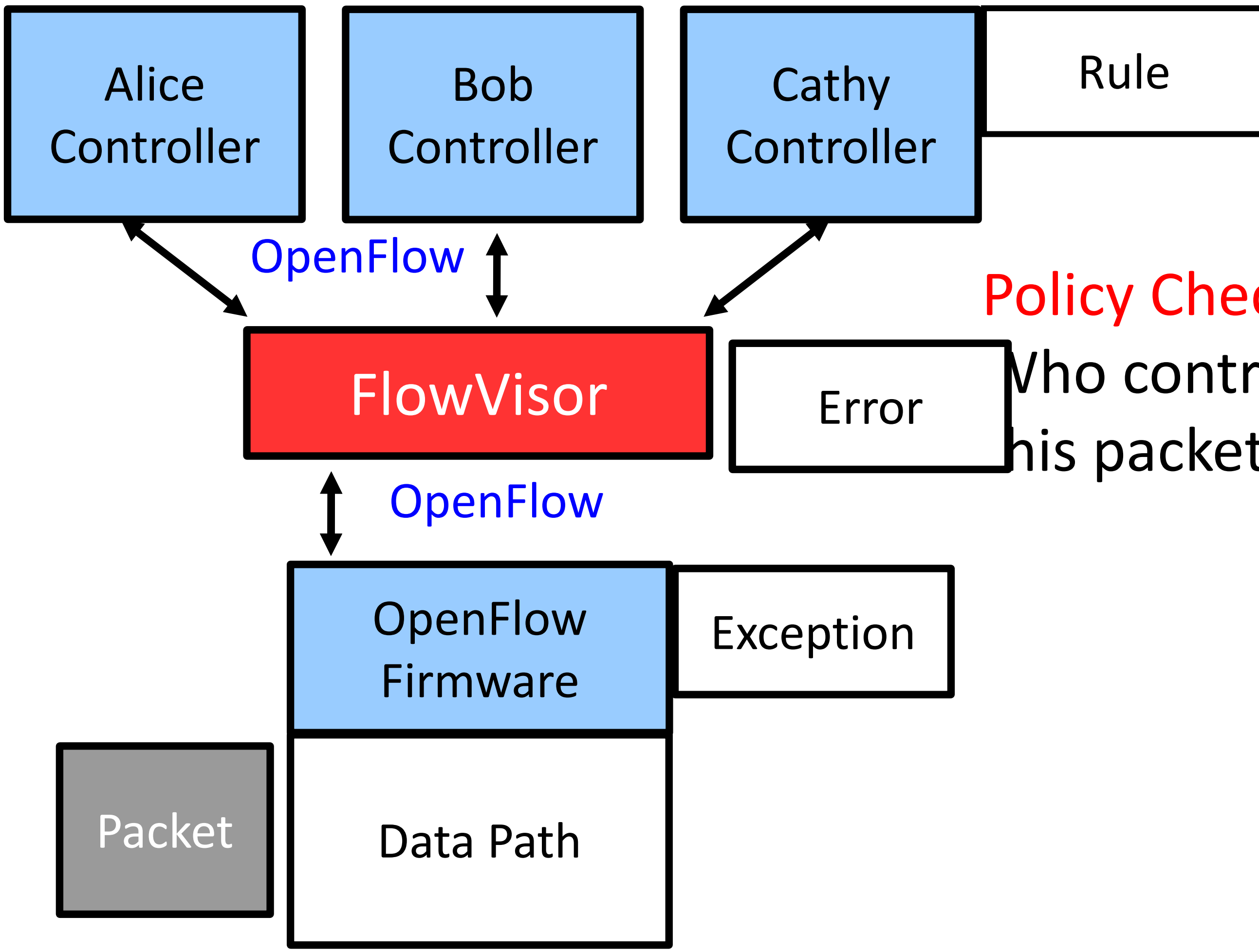
FlowVisor Message Handling



Policy Check:
Is this rule allowed?

Policy Check:
Who controls this packet?

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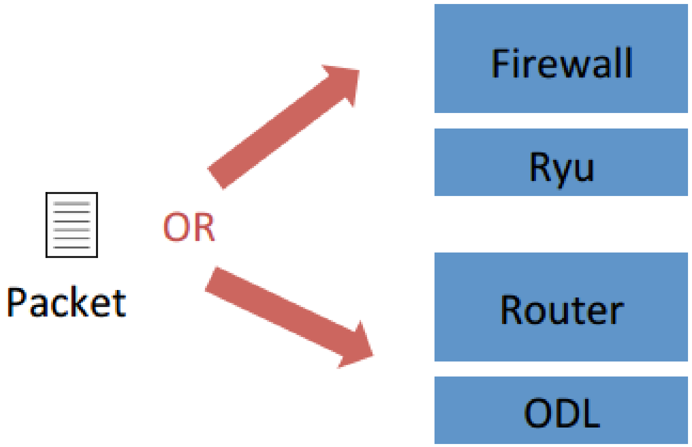
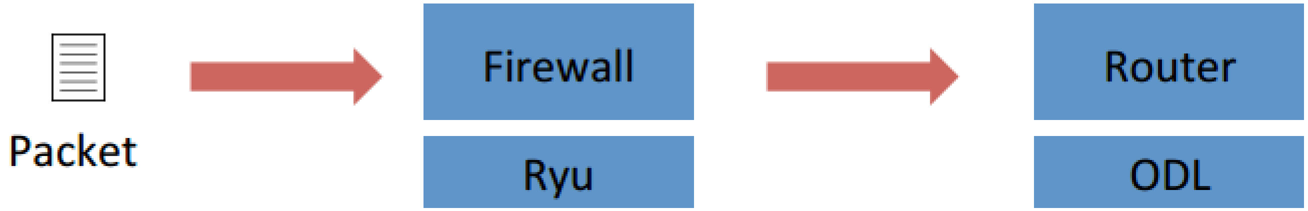
CoVisor [1]

- FlowVisor allows controllers to work on disjoint slices of traffic only



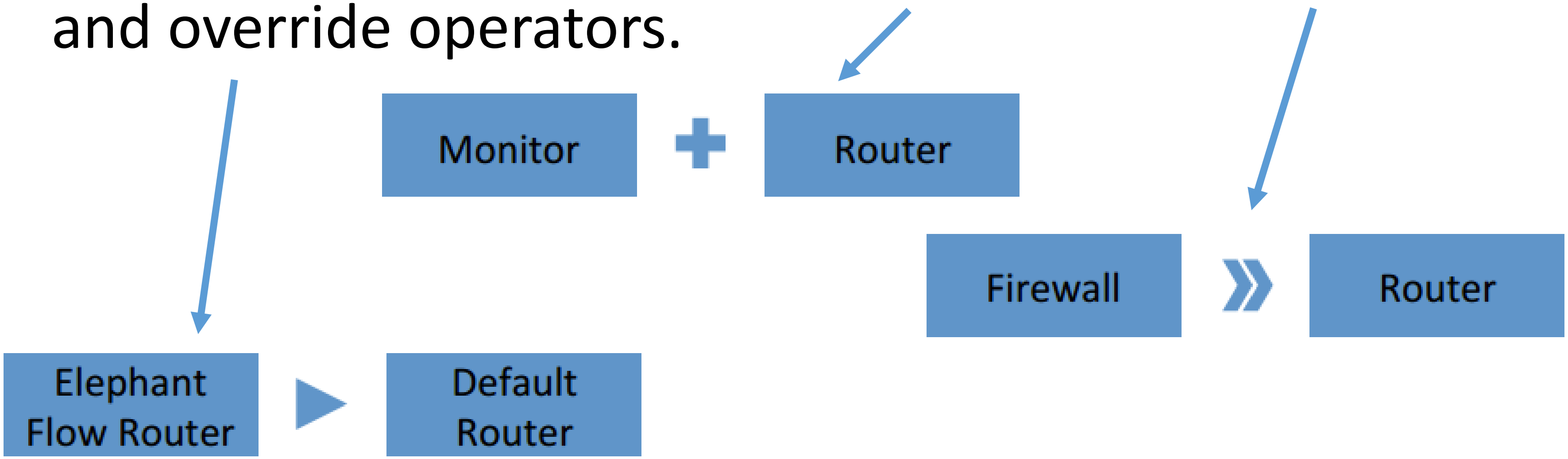
- How about multiple controllers collaborating on the same traffic?



[1] **Jin et al:** "CoVisor: A Compositional Hypervisor for Software-Defined Networks", *USENIX NSDI 2015*
Slides from the presentation at NSDI'15

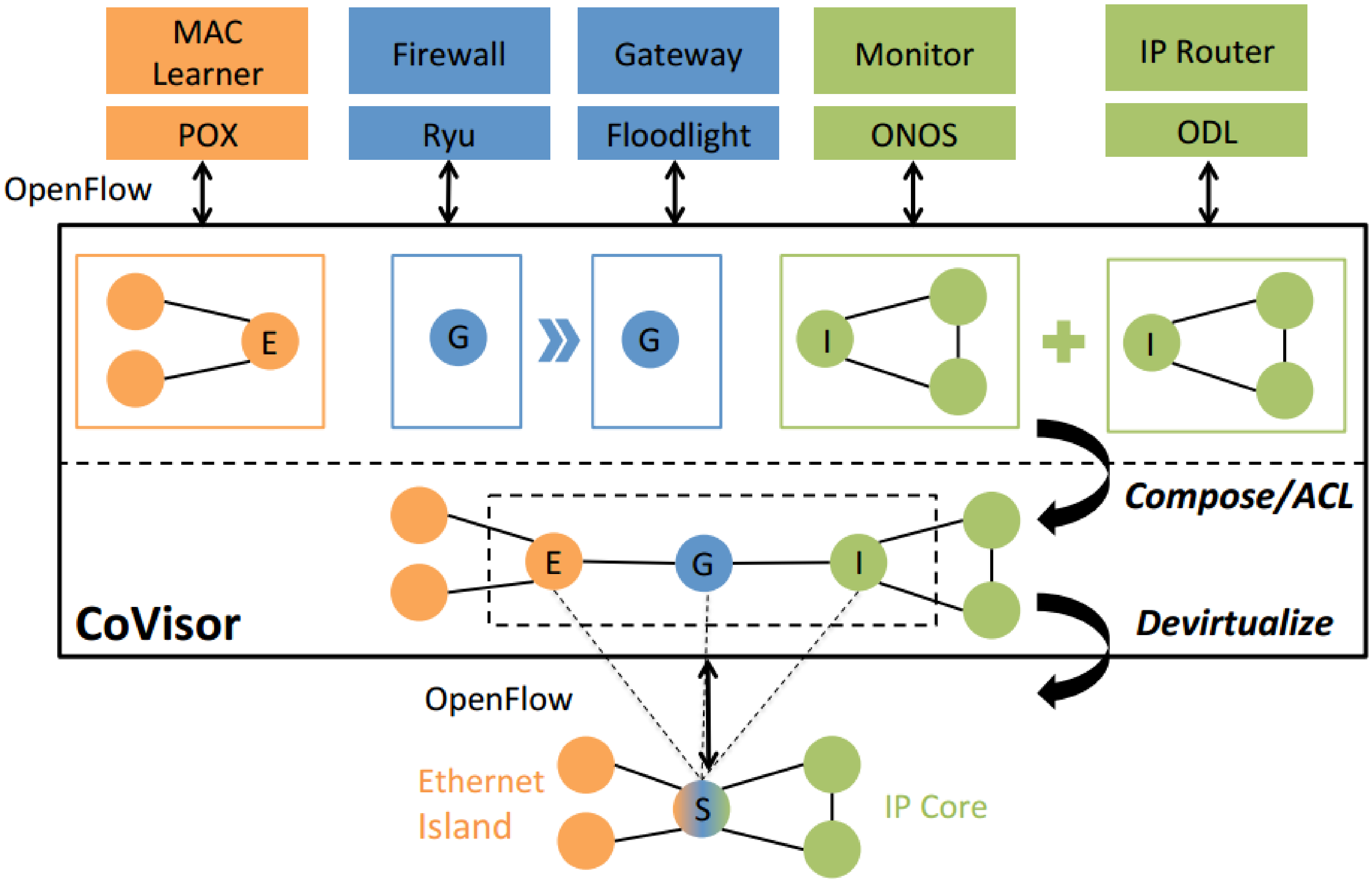
CoVisor – Controller Composition

- CoVisor allows combinations of parallel, sequential and override operators.



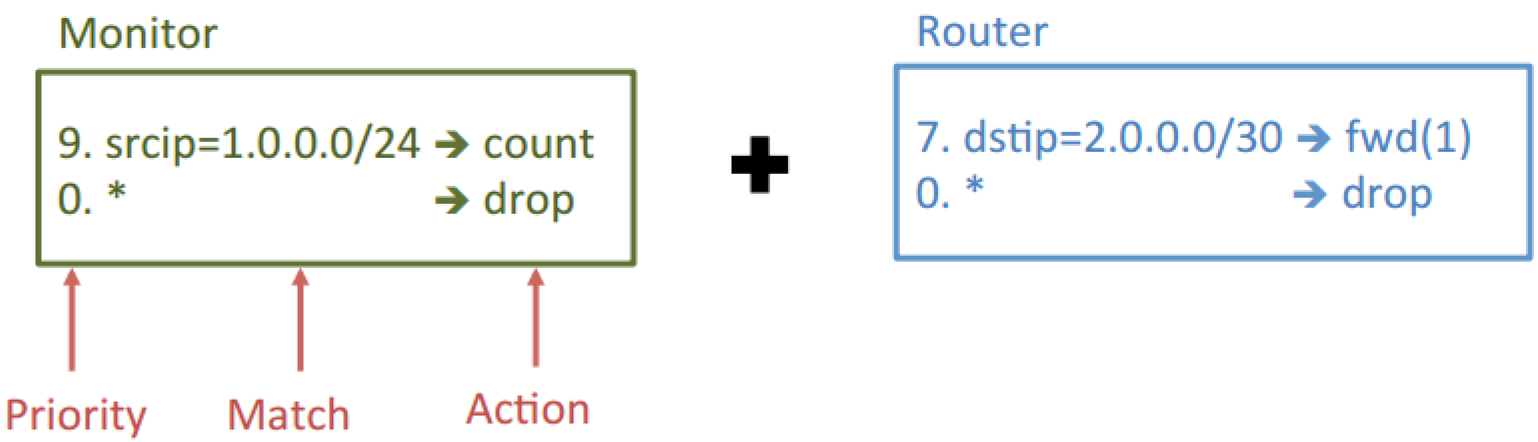
- Combination:

CoVisor – Overview



CoVisor – Policy Composition

- Policy: a list of rules
- Compile policies from controllers to a single policy



CoVisor – Policy Composition

- Policy: a list of rules
- Compile policies from controllers to a single policy

Monitor

9. srcip=1.0.0.0/24 → count
0. * → drop

+

Router

7. dstip=2.0.0.0/30 → fwd(1)
0. * → drop

=

?. srcip=1.0.0.0/24, dstip=2.0.0.0/30 → count, fwd(1)

CoVisor – Policy Composition

Monitor

9. srcip=1.0.0.0/24 → count
0. * → drop

+

Router

7. dstip=2.0.0.0/30 → fwd(1)
0. * → drop

=

?. srcip=1.0.0.0/24, dstip=2.0.0.0/30 → count, fwd(1)
?. srcip=1.0.0.0/24 → count
?. dstip=2.0.0.0/30 → fwd(1)
?. * → drop

CoVisor – Policy Composition

- Controllers continuously update their policies
- Hypervisor recompiles them and update switches

Monitor

9. srcip=1.0.0.0/24 ➔ count
0. * ➔ drop

➕

Router

7. dstip=2.0.0.0/30 ➔ fwd(1)
3. dstip=2.0.0.0/26 ➔ fwd(2)
0. * ➔ drop

=

?. srcip=1.0.0.0/24, dstip=2.0.0.0/30 ➔ count, fwd(1)
?. srcip=1.0.0.0/24 ➔ count
?. dstip=2.0.0.0/30 ➔ fwd(1)
?. * ➔ drop

?

CoVisor – Policy Composition

- Computation overhead
  - The computation to recompile the new policy
- Rule-update overhead
  - The rule-updates to update switches to the new policy

Monitor

9. srcip=1.0.0.0/24 ➔ count
0. * ➔ drop

+

Router

7. dstip=2.0.0.0/30 ➔ fwd(1)
3. dstip=2.0.0.0/26 ➔ fwd(2)
0. * ➔ drop

=

?. srcip=1.0.0.0/24, d[illegible]=2.0.0.0/30 ➔ count, fwd(1)
?. srcip=1.0.0.0/24 ➔ count
?. dstip=2.0.0.0/30 ➔ fwd(1)
?. * ➔ drop

?

CoVisor – Naïve Policy Composition

- Assign priorities from top to bottom by decrement of 1

Monitor

9. srcip=1.0.0.0/24 → count
0. * → drop

+

Router

7. dstip=2.0.0.0/30 → fwd(1)
0. * → drop

=

3. srcip=1.0.0.0/24, dstip=2.0.0.0/30 → count, fwd(1)
2. srcip=1.0.0.0/24 → count
1. dstip=2.0.0.0/30 → fwd(1)
0. * → drop

CoVisor – Naïve Policy Composition

- Assign priorities from top to bottom by decrement of 1

Monitor

9. srcip=1.0.0.0/24 ➔ count
0. * ➔ drop

✚

Router

7. dstip=2.0.0.0/30 ➔ fwd(1)
3. dstip=2.0.0.0/26 ➔ fwd(2)
0. * ➔ drop

=

5. srcip=1.0.0.0/24, dstip=2.0.0.0/30 ➔ count, fwd(1)
4. srcip=1.0.0.0/24, dstip=2.0.0.0/26 ➔ count, fwd(2)
3. srcip=1.0.0.0/24 ➔ count
2. dstip=2.0.0.0/30 ➔ fwd(1)
1. dstip=2.0.0.0/26 ➔ fwd(2)
0. * ➔ drop

CoVisor – Naïve Policy Composition

- Assign priorities from top to bottom by decrement of 1

3. srcip=1.0.0.0/24, dstip=2.0.0.0/30 → count, fwd(1)
2. srcip=1.0.0.0/24 → count
1. dstip=2.0.0.0/30 → fwd(1)
0. * → drop

↓ Update

5. srcip=1.0.0.0/24, dstip=2.0.0.0/30 → count, fwd(1)
4. srcip=1.0.0.0/24, dstip=2.0.0.0/26 → count, fwd(2)
3. srcip=1.0.0.0/24 → count
2. dstip=2.0.0.0/30 → fwd(1)
1. dstip=2.0.0.0/26 → fwd(2)
0. * → drop

Computation overhead

- Recompute the entire switch table and assign priorities

Rule-update overhead

- Only 2 new rules, but 3 more rules change priority

CoVisor – Incremental Solution

- Add priorities for parallel composition

Monitor

9. srcip=1.0.0.0/24 → count
0. * → drop

+

Router

7. dstip=2.0.0.0/30 → fwd(1)
0. * → drop

=

9+7 = 16. srcip=1.0.0.0/24, dstip=2.0.0.0/30 → count, fwd(1)

CoVisor – Incremental Solution

- Add priorities for parallel composition

Monitor

9. srcip=1.0.0.0/24 → count
0. * → drop

+

Router

7. dstip=2.0.0.0/30 → fwd(1)
0. * → drop

=

9+7=16.	srcip=1.0.0.0/24, dstip=2.0.0.0/30	→ count, fwd(1)
9+0=9.	srcip=1.0.0.0/24	→ count
0+7=7.	dstip=2.0.0.0/30	→ fwd(1)
0+0=0.	*	→ drop

CoVisor – Incremental Solution

- Add priorities for parallel composition

Monitor

9. srcip=1.0.0.0/24 → count
0. * → drop

\+

Router

7. dstip=2.0.0.0/30 → fwd(1)
3. dstip=2.0.0.0/26 → fwd(2)
0. * → drop

=

9+7=16. srcip=1.0.0.0/24, dstip=2.0.0.0/30 → count, fwd(1)
9+3=12. srcip=1.0.0.0/24, dstip=2.0.0.0/26 → count, fwd(1)
9+0=9. srcip=1.0.0.0/24 → count
0+7=7. dstip=2.0.0.0/30 → fwd(1)
0+3=3. dstip=2.0.0.0/26 → fwd(1)
0+0=0. * → drop

CoVisor – Incremental Solution

- Add priorities for parallel composition

```
16. srcip=1.0.0.0/24, dstip=2.0.0.0/30 → count, fwd(1)
9.  srcip=1.0.0.0/24                   → count
7.  dstip=2.0.0.0/30                   → fwd(1)
0.  *                                  → drop
```

↓ Update

```
16. srcip=1.0.0.0/24, dstip=2.0.0.0/30 → count, fwd(1)
12. srcip=1.0.0.0/24, dstip=2.0.0.0/26 → count, fwd(2)
9.  srcip=1.0.0.0/24                   → count
7.  dstip=2.0.0.0/30                   → fwd(1)
3.  dstip=2.0.0.0/26                   → fwd(2)
0.  *                                  → drop
```

Computation overhead

- Only compose the new rule with rules in monitor

Rule-update overhead

- Add 2 new rules

CoVisor – Incremental Solution

- Add priorities for parallel composition
- Concatenate priorities for sequential composition

Load Balancer

```
3. srcip=0.0.0.0/2, dstip=3.0.0.0 → dstip=2.0.0.1
1. dstip=3.0.0.0                  → dstip=2.0.0.2
0. *                              → drop
```

»

Router

```
1. dstip=2.0.0.1 → fwd(1)
1. dstip=2.0.0.2 → fwd(2)
0. *             → drop
```

=

```
.
3 >> 1 = 25, srcip=0.0.0.0/2, dstip=3.0.0.0 → dstip=2.0.0.1, fwd(1)
.
.
```

011	001
High Bits	Low Bits

CoVisor – Incremental Solution

- Add priorities for parallel composition
- Concatenate priorities for sequential composition

Load Balancer

3. srcip=0.0.0.0/2, dstip=3.0.0.0 ➔ dstip=2.0.0.1
1. dstip=3.0.0.0 ➔ dstip=2.0.0.2
0. * ➔ drop

»

Router

1. dstip=2.0.0.1 ➔ fwd(1)
1. dstip=2.0.0.2 ➔ fwd(2)
0. * ➔ drop

=

25. srcip=0.0.0.0/2, dstip=3.0.0.0 ➔ dstip=2.0.0.1, fwd(1)
9. dstip=3.0.0.0 ➔ dstip=2.0.0.2, fwd(2)
0. * ➔ drop

CoVisor – Incremental Solution

- Add priorities for parallel composition
- Concatenate priorities for sequential composition

Load Balancer

3. srcip=0.0.0.0/2, dstip=3.0.0.0 → dstip=2.0.0.1
1. dstip=3.0.0.0 → dstip=2.0.0.2
0. * → drop

»

Router

1. dstip=2.0.0.1 → fwd(1)
1. dstip=2.0.0.2 → fwd(2)
0. * → drop

=

25. srcip=0.0.0.0/2, dstip=3.0.0.0 → dstip=2.0.0.1, fwd(1)
9. dstip=3.0.0.0 → dstip=2.0.0.2, fwd(2)
0. * → drop

CoVisor – Incremental Solution

- Add priorities for parallel composition
- Concatenate priorities for sequential composition
- Stack priorities for override composition

Elephant Flow Router

1. srcip=1.0.0.0, dstip=3.0.0.0 ➔ fwd(3)

▷

Default Router (Max priority = 8)

1. dstip=2.0.0.1 ➔ fwd(1)
1. dstip=2.0.0.2 ➔ fwd(2)
0. * ➔ drop

=

1 + 8 = 9. srcip=1.0.0.0, dstip=3.0.0.0 ➔ fwd(3)
1. dstip=2.0.0.1 ➔ fwd(1)
1. dstip=2.0.0.2 ➔ fwd(2)
0. * ➔ drop

CoVisor – Incremental Solution

- Add priorities for parallel composition
- Concatenate priorities for sequential composition
- Stack priorities for override composition

Elephant Flow Router

1. srcip=1.0.0.0, dstip=3.0.0.0 ➔ fwd(3)

▷

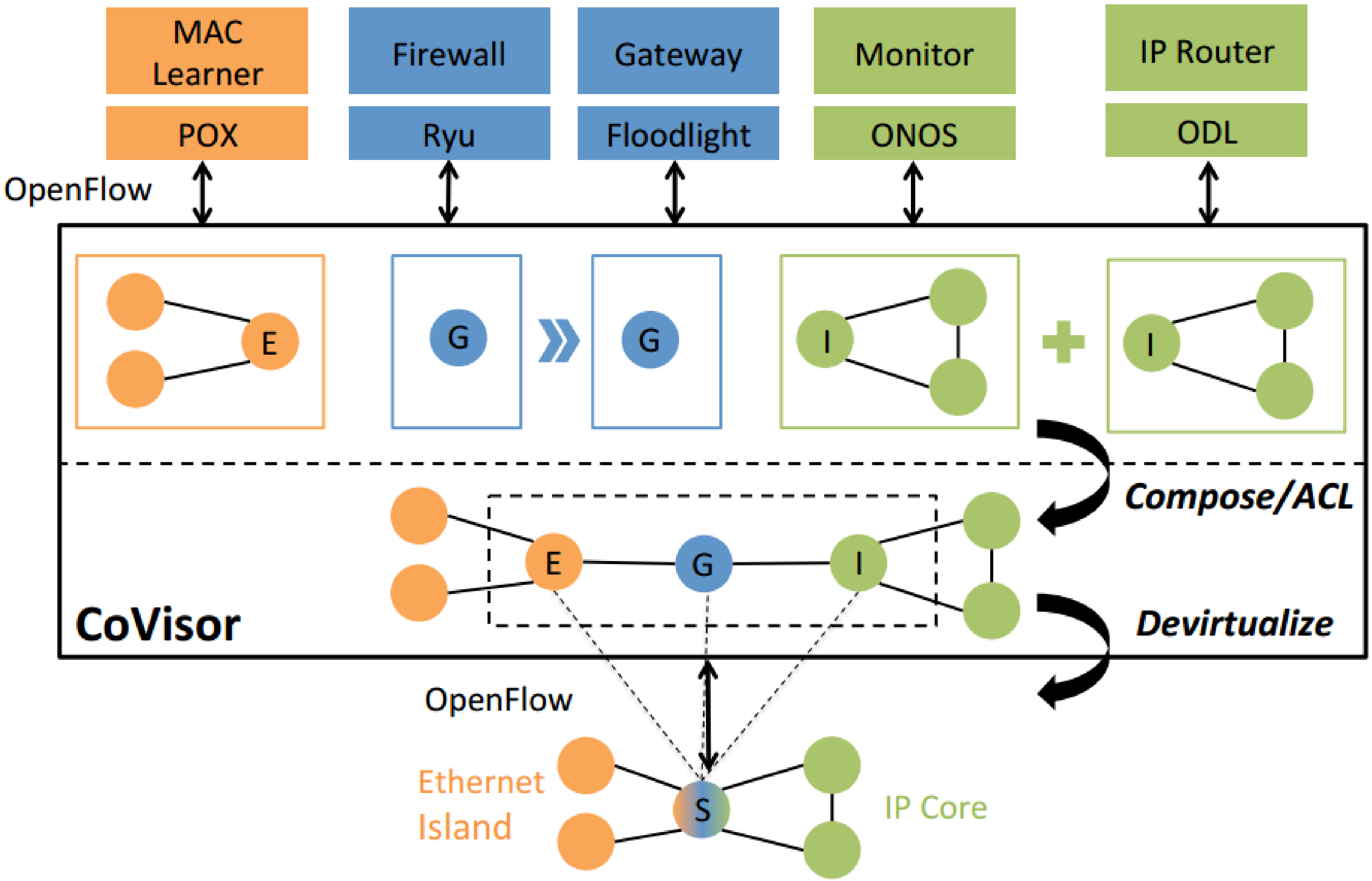
Default Router (Max priority = 8)

1. dstip=2.0.0.1 ➔ fwd(1)
1. dstip=2.0.0.2 ➔ fwd(2)
0. * ➔ drop

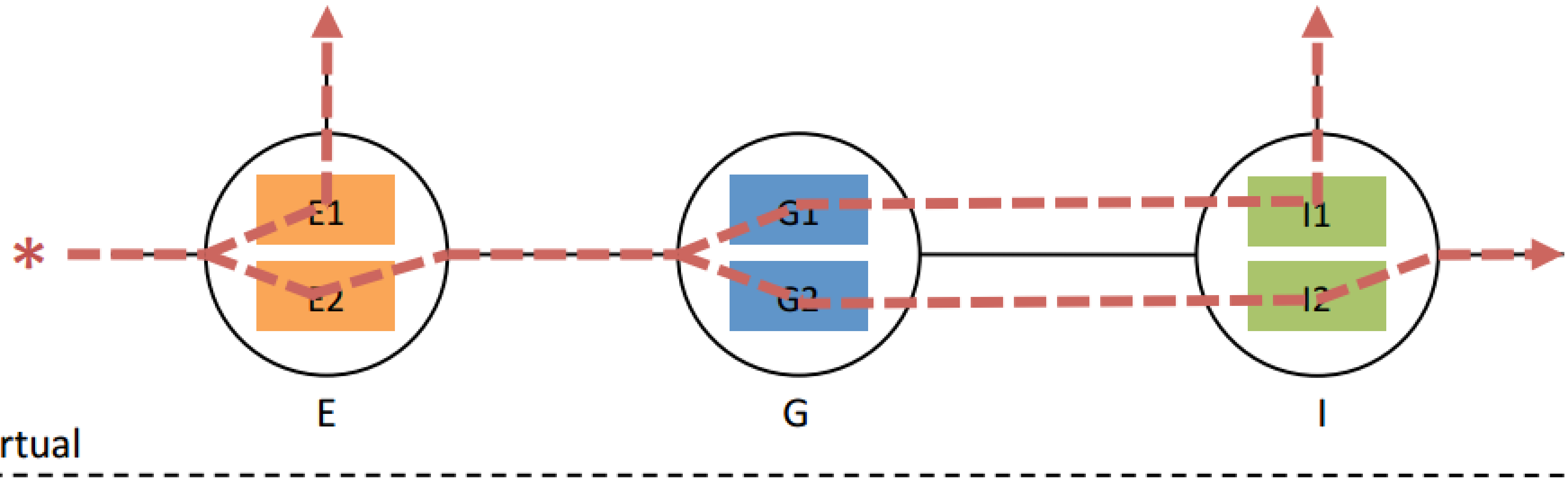
=

1 + 8 = 9. srcip=1.0.0.0, dstip=3.0.0.0 ➔ fwd(3)
1. dstip=2.0.0.1 ➔ fwd(1)
1. dstip=2.0.0.2 ➔ fwd(2)
0. * ➔ drop

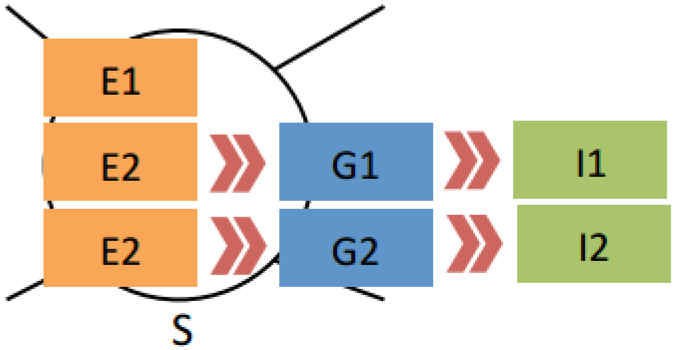
CoVisor – Overview



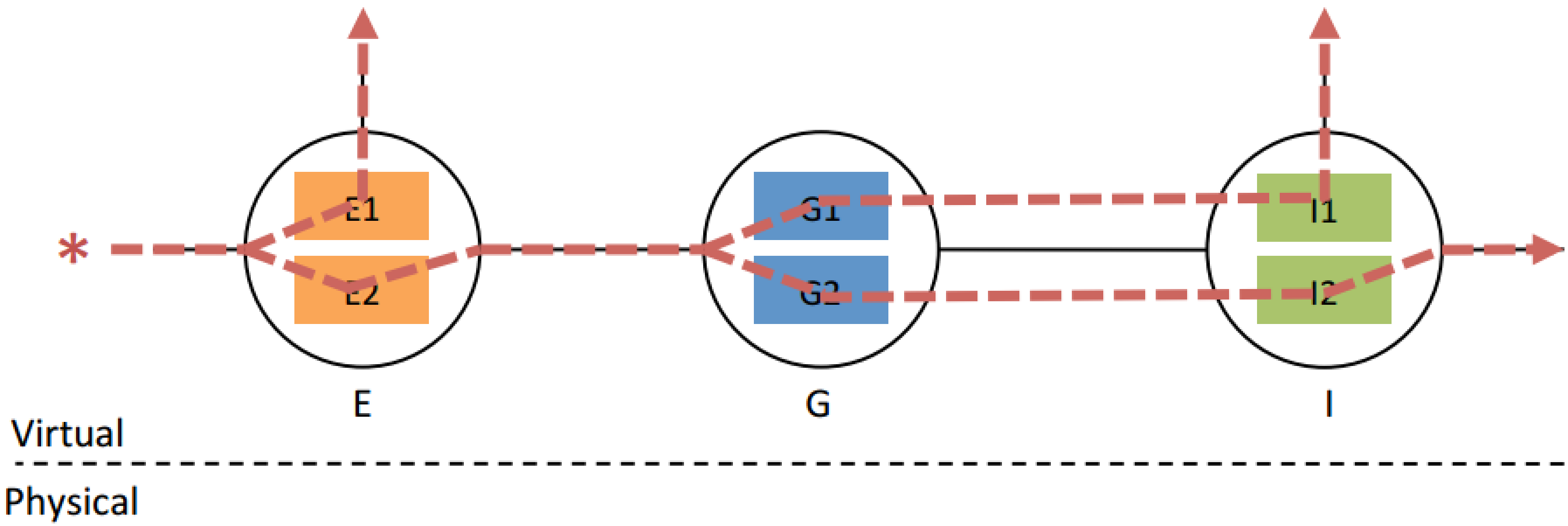
CoVisor - Devirtualization



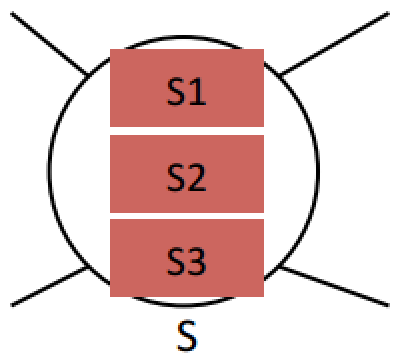
- Symbolic path generation
- Sequential composition



CoVisor - Devirtualization



- Symbolic path generation
- Sequential composition
- Priority augmentation



Summary SDN

- SDN as a new way of networking that exploits existing concepts
  - Separation of planes, etc.

- OpenFlow as the de-facto standard protocol
- Controllers as operating systems

- Application: network virtualization
  - Slicing
  - Co-existence of different controllers
    - On disjoint traffic
    - On same traffic

Outlook SDN

- There is a lot more, just a small subset covered so far

- If you're interested:
  - Block courses on Software-defined Networking (probably at the end of the upcoming winter semester, i.e., March 2016)
    - Introduction to SDN (1 week)
    - Advanced SDN (1 week)
  - Some things from this lecture will be familiar
  - Add-ons: practical work on SDNs, researching on SDNs