Introduction to OpenFlow



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

http://www.cse.wustl.edu/~jain/cse5700-25/

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Overview

1. Planes of Networking
2. OpenFlow
3. OpenFlow Operation
4. OpenFlow Switches, including Open vSwitch
5. OpenFlow Evolution
6. Current Limitations and Issues

Note: This is the first module of four modules on OpenFlow, OpenFlow Controllers, SDN, and NFV in this course.

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Planes of Networking

- **Data Plane**: All activities involving as well as resulting from data packets sent by the end user, e.g.,
  - Forwarding
  - Fragmentation and reassembly
  - Replication for multicasting
- **Control Plane**: All activities that are necessary to perform data plane activities but do not involve end-user data packets
  - Making routing tables
  - Setting packet handling policies (e.g., security)
  - Base station beacons announcing the availability of services

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

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Planes of Networking (Cont)

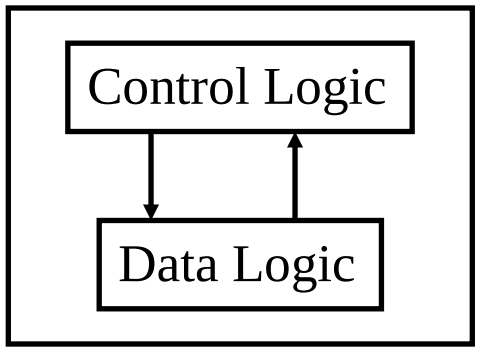
- **Management Plane**: All activities related to provisioning and monitoring of the networks
  - Fault, Configuration, Accounting, Performance, and Security (**FCAPS**).
  - Instantiate new devices and protocols (Turn devices on/off)
  - Optional ⇒ May be handled manually for small networks.
- **Services Plane**: Middlebox services to improve performance or security, e.g.,
  - Load Balancers, Proxy Service, Intrusion Detection, Firewalls, SSL Off-loaders
  - Optional ⇒ Not required for small networks

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Data vs. Control Logic

- Data plane runs at a line rate,
  e.g., 100 Gbps for 100 Gbps Ethernet ⇒ Fast Path
  ⇒ Typically implemented using special hardware,
  e.g., Ternary Content Addressable Memories (TCAMs)
- Some exceptional data plane activities are handled by the CPU in the switch ⇒ Slow path
  e.g., Broadcast, Unknown, and Multicast (BUM) traffic
- All control activities are generally handled by the CPU



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OpenFlow: Key Ideas

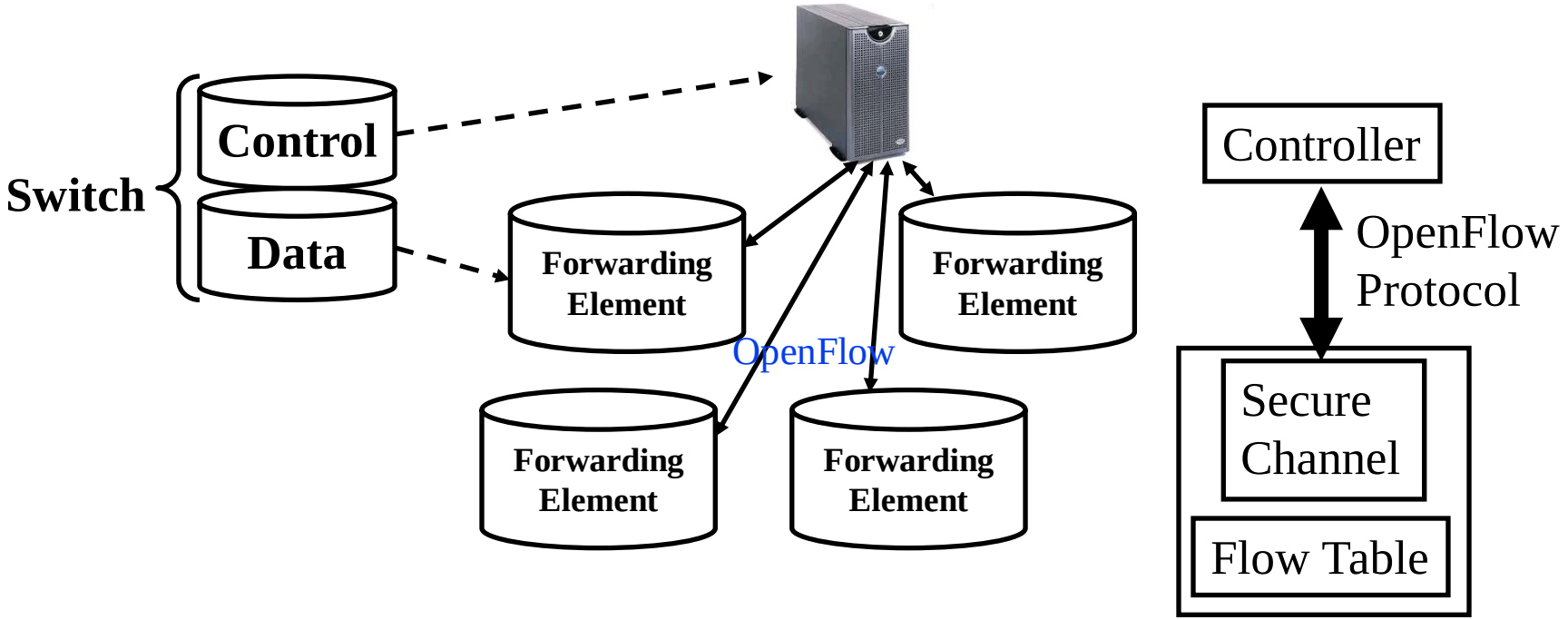
1. Separation of control and data planes
2. Centralization of control
3. Flow-based control

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Ref: N. McKeown, et al., ``OpenFlow: Enabling Innovation in Campus Networks," ACM SIGCOMM CCR, Vol. 38, No. 2, April 2008, pp. 69-74.

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Separation of Control and Data Plane



- Control logic is moved to a controller
- Switches only have forwarding elements
- One expensive controller with a lot of cheap switches
- OpenFlow is the protocol to send/receive forwarding rules from the controller to switches

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OpenFlow V1.0

- On packet arrival, match the header fields with flow entries in a table; if any entry matches, update the counters indicated in that entry and perform indicated actions

Flow Table:

Header Fields	Counters	Actions
Header Fields	Counters	Actions
…	…	…
Header Fields	Counters	Actions

Ingress Port	Ether Source	Ether Dest	VLAN ID	VLAN Priority	IP Src	IP Dst	IP Proto	IP ToS	Src L4 Port	Dst L4 Port

Ref: http://archive.openflow.org/documents/openflow-spec-v1.0.0.pdf

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Flow Table Example

Port	Src MAC	Dst MAC	VLAN ID	Priority	EtherType	Src IP	Dst IP	IP Proto	IP ToS	Src L4 Port ICMP Type	Dst L4 Port ICMP Code	Action	Counter
*	*	0A:C8:*	*	*	*	*	*	*	*	*	*	Port 1	102
*	*	*	*	*	*	*	192.168.*.*	*	*	*	*	Port 2	202
*	*	*	*	*	*	*	*	*	*	21	21	Drop	420
*	*	*	*	*	*	*	*	0x806	*	*	*	Local	444
*	*	*	*	*	*	*	*	0x1*	*	*	*	Controller	1

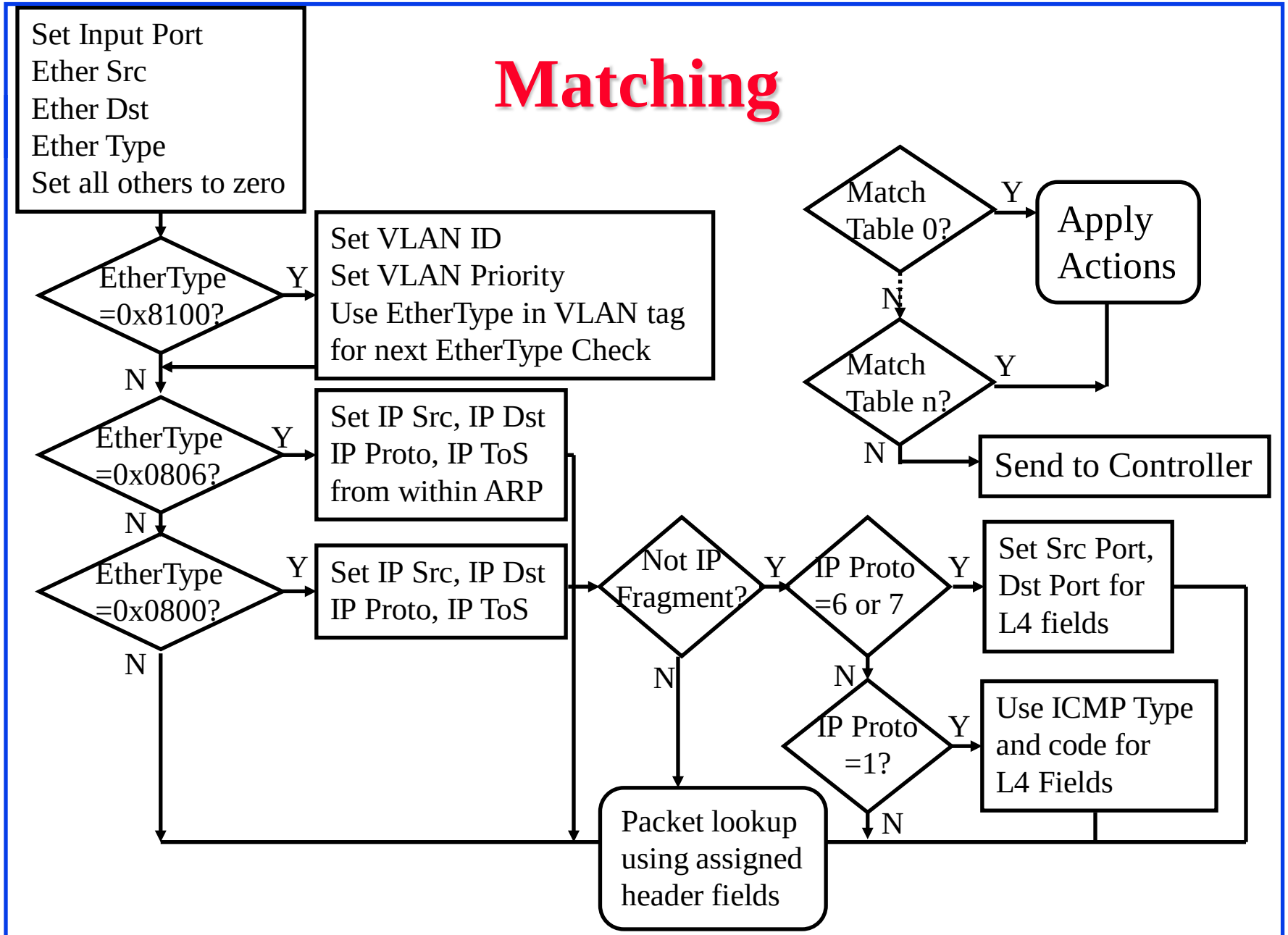
- Idle timeout: Remove entry if no packets are received for this time
- Hard timeout: Remove entry after this time
- If both are set, the entry is removed if either expires.

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

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Matching



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Counters

Per Table	Per Flow	Per Port	Per Queue
Active Entries	Received Packets	Received Packets	Transmit Packets
Packet Lookups	Received Bytes	Transmitted Packets	Transmit Bytes
Packet Matches	Duration (Secs)	Received Bytes	Transmit overrun errors
	Duration (nanosecs)	Transmitted Bytes	
		Receive Drops	
		Transmit Drops	
		Receive Errors	
		Transmit Errors	
		Receive Frame Alignment Errors	
		Receive Overrun erorrs	
		Receive CRC Errors	
		Collisions	

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Actions

- Forward to Physical Port *i* or to *Virtual Port*:
  - **All**: to all interfaces except the incoming interface
  - **Controller**: encapsulate and send to controller
  - **Local**: send to its local networking stack
  - **Table**: Perform actions in the flow table
  - **In_port**: Send back to input port
  - **Normal**: Forward using traditional Ethernet
  - **Flood**: Send along minimum spanning tree except for the incoming interface
- Enqueue: To a particular queue in the port ⇒ QoS
- Drop
- Modify Field: E.g., add/remove VLAN tags, ToS bits, Change TTL

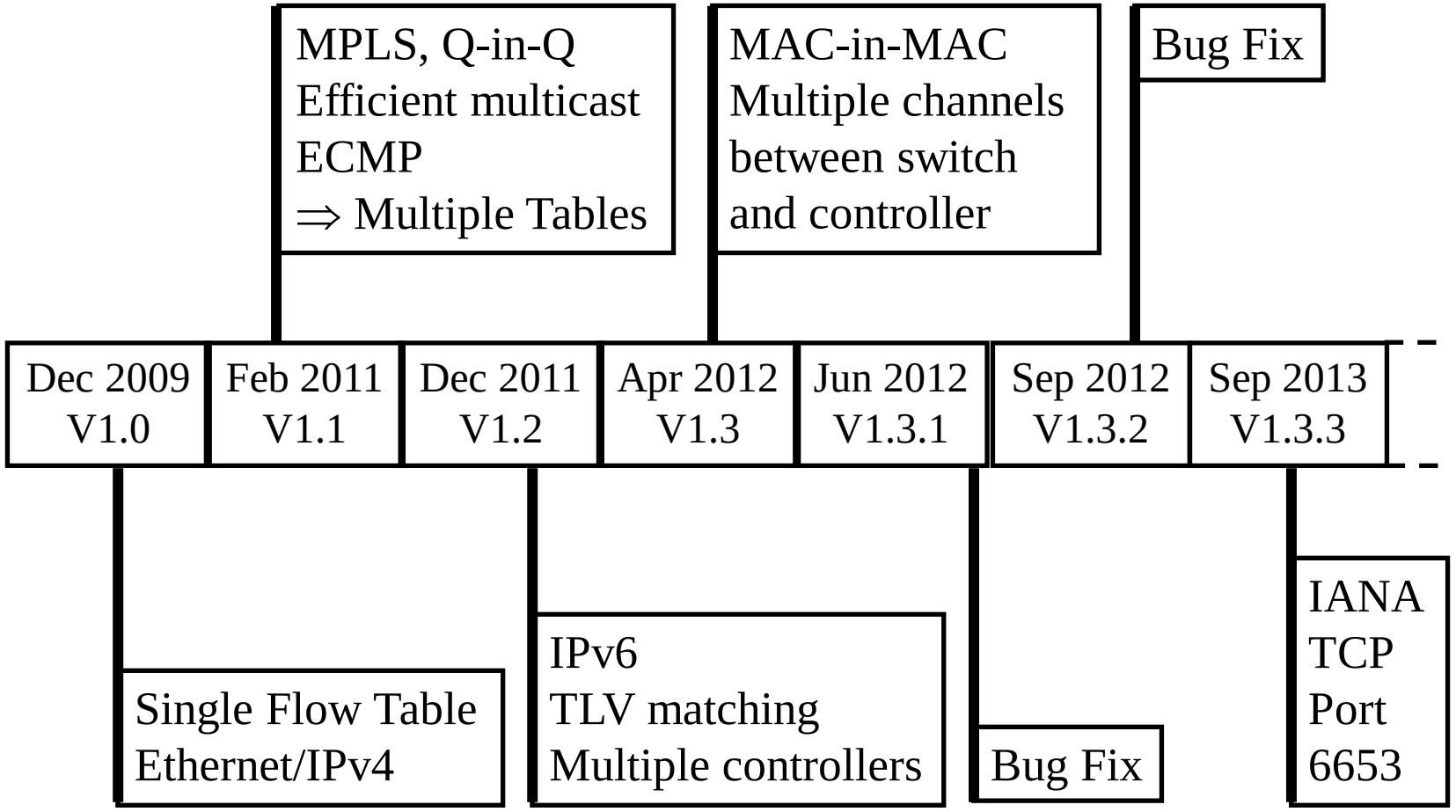
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Actions (Cont)

- Masking allows matching only selected fields, e.g., Dest. IP, Dest. MAC, etc.
- If a header matches an entry, corresponding actions are performed, and counters are updated
- If no header matches, the packet is queued, and the header is sent to the controller, which sends a new rule. Subsequent packets of the flow are handled by this rule.
- Secure Channel: Between the controller and the switch using TLS
- Modern switches already implement flow tables, typically using Ternary Content Addressable Memories (TCAMs)
- A controller can change the forwarding rules if a client moves
  $\Rightarrow$ Packets for mobile clients are forwarded correctly
- A controller can send flow table entries beforehand (**Proactive**) or Send them on demand (**Reactive**). OpenFlow allows both models.

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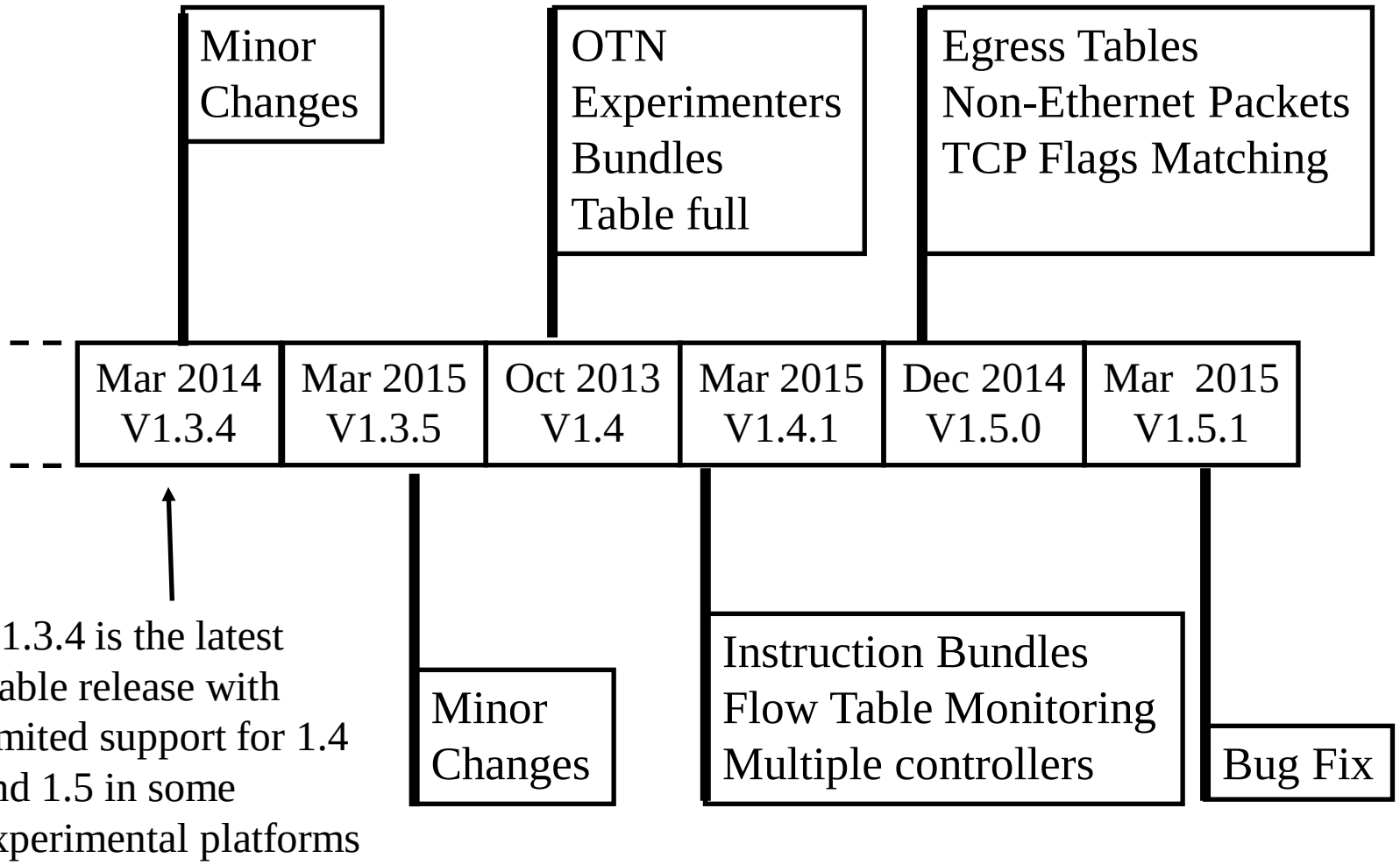
OpenFlow Evolution Summary



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OpenFlow Evolution Summary (Cont)

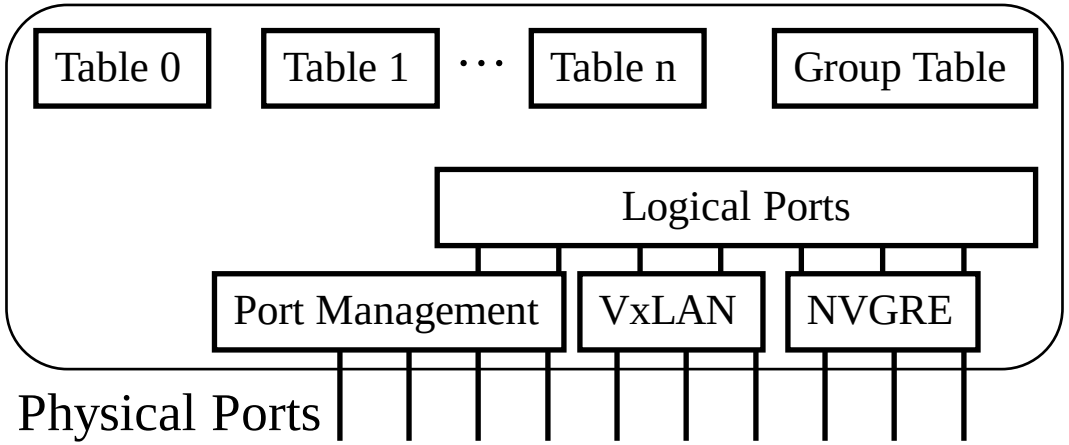


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Implementation Issues

- 40+ matching fields in a flow
- Multiple tables, each with a large number of flow entries
- Instructions and actions for each table
- Need VXLAN, NVGRE, etc. support
- For an extensive network, flow-level programming can take a long time
- Can't keep adding header fields ⇒ Move to P4 programming



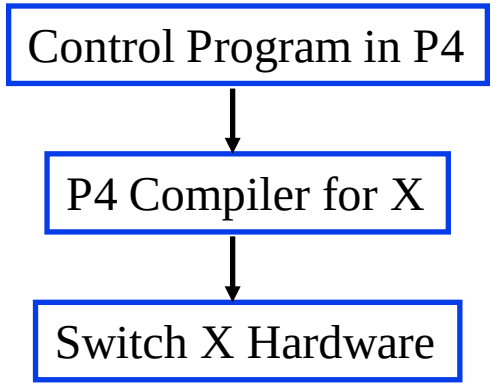
Ref: R. Oshana and S. Addepalli, "Networking Trends- Software Defined Networking, Network Virtualization and Cloud Orchestration," Asia Power Arch. Conf, Oct 2012, https://www.power.org/wp-content/uploads/2012/10/13.-FSL-SDN-Openflow-and-Cloud-computing-UPD_Rob-Oshana.pdf

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P4 Language

- **P**rogramming **P**rotocol-Independent **P**acket **P**rocessors
- **Protocol-Independent**: Produces forwarding instructions for any L2-L5 protocol
- **Target Independent**: Programmers write one program that can run on many different hardware ⇒ A hw specific compiler translates the program to instructions for that hardware
  - Similar to how C program can run on any hardware
- **Reconfigurability**: Can change the program w/o changing the hardware



Ref: P. Bosshart, et al., "P4: Programming Protocol-Independent Packet Processors," Computer Communication Review, ACM SIGCOMM, July 2014, 8 pp., http://www.sigcomm.org/node/3503

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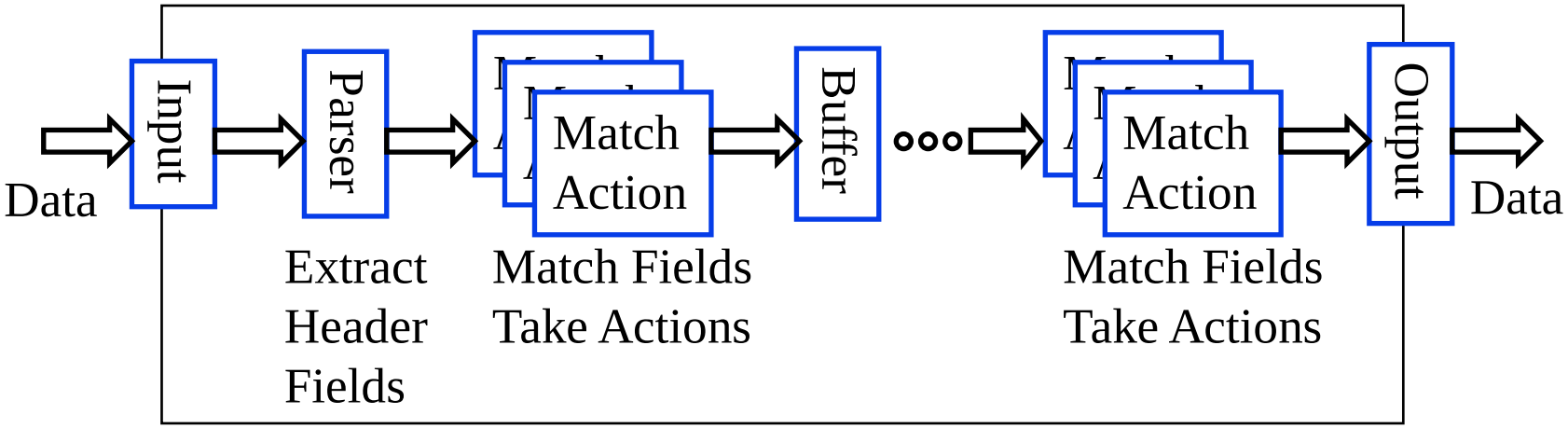
- What does "Protocol-Independent" mean in practice?

It is not specific to OpenFlow or any other competing protocol.

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P4 Switch Design

- Packet parser: How to extract header fields, their names, and types
  - OpenFlow assumed a fixed parser and needed a new version for each new field
- Can do tables, match, and Actions (similar to OpenFlow)
- But allows more general handling routines
- Maintained by "P4 Language Consortium"



Ref: https://p4.org/specifications/

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End of part 1

Open vSwitch

- Open Source Virtual Switch
- Nicira Concept
- It can run as a stand-alone hypervisor switch or as a distributed switch across multiple physical servers
- Default switch in XenServer 6.0, Xen Cloud Platform, and supported in Proxmox VE, VirtualBox, Xen KVM
- Integrated into many cloud management systems, including OpenStack, openQRM, OpenNebula, and oVirt
- Distributed with Ubuntu, Debian, and Fedora Linux. Also FreeBSD
- Intel has an accelerated version of Open vSwitch in its own Data Plane Development Kit (**DPDK**)

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Ref: http://openvswitch.org/

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Open vSwitch Features

- Link Aggregation Control Protocol (LACP)
- IEEE 802.1Q VLAN
- IEEE 802.1ag Connectivity Fault Management (CFM)
- Bidirectional Forwarding Detection (BFD) to detect link faults (RFC 5880)
- IEEE 802.1D-1998 Spanning Tree Protocol (STP)
- Per-VM traffic policing
- OpenFlow
- Multi-table forwarding pipeline
- IPv6
- GRE, VXLAN, IPSec tunneling
- Kernel and user-space forwarding engine options

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OVSDB

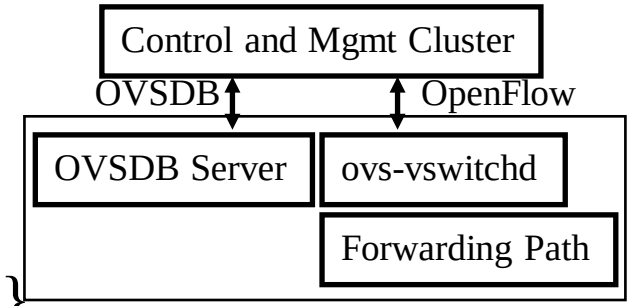
- Open vSwitch Database Management Protocol (OVSDB)
- Monitoring capability using publish-subscribe mechanisms
- Stores both provisioning and operational state
- Java Script Object Notation (JSON) is used for schema format and JSON-RPC over TCP for wire protocol (RFC 4627)

  <database-schema>

  "name": <id>

  "version": <version>

  "tables": {<id>: <table-schema>,…}



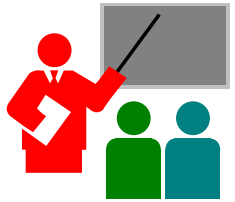
- RPC Methods: List databases, Get Schema, Update, Lock, …
- Open vSwitch project includes open-source OVSDB client and server implementations

Ref: B. Pfaff and B. Davie, "The Open vSwitch Database Management Protocol," IETF RFC 7047m December 2013, https://tools.ietf.org/pdf/rfc7047

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Summary



1. Four planes of Networking: Data, Control, Management, Service
2. OpenFlow separates the control plane and moves it to a central controller ⇒ Simplifies the forwarding element
3. Switches match incoming packets with flow entries in a table and handle them as instructed. The controller supplies the flow tables and other instructions.
4. OpenFlow was extended to IPv4, MPLS, IPv6, and Optical Networks. P4 was developed to handle extensibility.
5. Many hardware and software-based switches, including Open vSwitch

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Reading List

Any one book:

- T. Nadeau and K. Gray, “SDN,” O’Reilly, 2013, 384 pp, ISBN:978-1-449-34230-2B (Safari Book)
- 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).
- Kingston Smiler. S, "OpenFlow Cookbook," Packt Publishing, April 2015, 292 pp., ISBN:978-1-78398-795-5 (Safari Book).
- P. Bosshart et al., “P4: Programming Protocol-Independent Packet Processors,” Computer Communication Review, ACM SIGCOMM, July 2014, 8 pp., http://www.sigcomm.org/node/3503

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References

- N. McKeown et al., ``OpenFlow: Enabling Innovation in Campus Networks," ACM SIGCOMM CCR, Vol. 38, No. 2, April 2008, pp. 69-74.
- ONF, “The OpenFlow Timeline,” http://openflownetworks.com/of_timeline.php
- Open Data Center Alliance Usage Model: Software Defined Networking Rev 1.0,” http://www.opendatacenteralliance.org/docs/Software_Defined_Networking_Master_Usage_Model_Rev1.0.pdf
- R. Oshana and S. Addepalli, “Networking Trends- Software Defined Networking, Network Virtualization and Cloud Orchestration,” Asia Power Arch. Conf, Oct 2012, https://www.power.org/wp-content/uploads/2012/10/13.-FSL-SDN-Openflow-and-Cloud-computing-UPD_Rob-Oshana.pdf
- ONF, **Technical Library** (includes all OpenFlow, OF-Config, and other specifications), https://www.opennetworking.org/sdn-resources/technical-library

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References (Cont)

- http://www.openvswitch.org/
- http://www.projectfloodlight.org/indigo/
- http://flowforwarding.github.io/LINC-Switch/
- http://github.com/CPqD/openflow-openwrt
- http://cpqd.github.io/ofsoftswitch13/
- http://sourceforge.net/projects/xorplus

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Wikipedia Links

- http://en.wikipedia.org/wiki/OpenFlow
- http://en.wikipedia.org/wiki/Software-defined_networking
- http://en.wikipedia.org/wiki/Network_Functions_Virtualization
- http://en.wikipedia.org/wiki/Forwarding_plane
- https://en.wikipedia.org/wiki/P4_(programming_language)

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Wikipedia Links (Optional)

- http://en.wikipedia.org/wiki/NetFlow
- http://en.wikipedia.org/wiki/IP_Flow_Information_Export
- http://en.wikipedia.org/wiki/SFlow
- http://en.wikipedia.org/wiki/Northbound_interface
- http://en.wikipedia.org/wiki/Big_Switch_Networks
- http://en.wikipedia.org/wiki/Open_Data_Center_Alliance
- http://en.wikipedia.org/wiki/Virtual_Extensible_LAN
- http://en.wikipedia.org/wiki/Optical_Transport_Network
- http://en.wikipedia.org/wiki/Automatically_switched_optical_network
- http://en.wikipedia.org/wiki/Wavelength-division_multiplexing
- http://en.wikipedia.org/wiki/IEEE_802.1ad
- http://en.wikipedia.org/wiki/Transport_Layer_Security
- http://en.wikipedia.org/wiki/OpenStack
- http://en.wikipedia.org/wiki/IPv6_packet
- http://en.wikipedia.org/wiki/ICMPv6
- http://en.wikipedia.org/wiki/Multiprotocol_Label_Switching

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Acronyms

ACL	Access Control List
API	Application Programming Interface
ARP	Address Resolution Protocol
ASICs	Application Specific Integrated Circuit
BFD	Bidirectional Forwarding Detection
BUM	Broadcast, Unknown, and Multicast
CFM	Connectivity Fault Management
CPU	Central Processing Unit
DFCA	Dynamic Frequency Channel Allocation
DSCP	Differentiated Service Control Point
ECMP	Equal Cost Multipath
ESP	Encrypted Security Payload
FCAPS	Fault, Configuration, Accounting, Performance and Security
GRE	Generic Routing Encapsulation
ICMP	Internet Control Message Protocol
ID	Identifier

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Acronyms (Cont)

IDS	Intrusion Detection System
IEEE	Institution of Electrical and Electronic Engineers
IETF	Internet Engineering Task Force
IGMP	Internet Group Multicast Protocol
IP	Internet Protocol
IPFIX	IP Flow Information Export Protocol
IPSec	IP Security
IPv4	Internet Protocol version 4
IPv6	Internet Protocol version 6
JSON	Java Script Object Notation
KVM	Kernel-based Virtual Machine
LACP	Link Aggregation Control Protocol
LLDP	Link Layer Discovery Protocol
MAC	Media Access Control
MAN	Metropolitan Area Network
MPLS	Multiprotocol Label Switching

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Acronyms (Cont)

NFV	Network Function Virtualization
NVGRE	Network Virtualization using Generic Routing Encapsulation
OF	OpenFlow
ONF	Open Networking Foundation
openQRM	Open Qlusters Resource Manager
OpenWRT	Open WRT54G (Linksys product name) software
OSPF	Open Shortest Path First
OTN	Optical Transport Network
OVSDB	Open vSwitch Database
P4	Programming Protocol-Independent Packet Processors
PIM-SM	Protocol Independent Multicast - Sparse Mode
PIM	Protocol Independent Multicast
QoS	Quality of Service
RAN	Radio area networks
RFC	Request for Comments
RIP	IGMP, IPv6, PIM-SM
RIP	Routing Information Protocol

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Acronyms (Cont)

- RPC Remote Procedure Call
- RSPAN Remote Switch Port Analyzer
- SDN Software Defined Network
- SPAN Switch Port Analyzer
- SSL Secure Socket Layer
- STP Spanning Tree Protocol
- TCAM Ternary Content Addressable Memory
- TCP Transmission Control Protocol
- TLS Transport Level Security
- TLV Type-Length-Value
- ToS Type of Service
- TTL Time to Live
- TTP Table Typing Patterns
- UDP User Datagram Protocol
- VLAN Virtual Local Area Network
- VM Virtual Machine
- VxLAN Virtual Extensible Local Area Network
- WG Working Group

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http://www.cse.wustl.edu/~jain/cse5700-25/m_10ofl.htm

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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

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