Universität Stuttgart

Institute of Parallel and
Distributed Systems (IPVS)

Universitätsstraße 38
D-70569 Stuttgart

Tutorial: Software-defined Networking

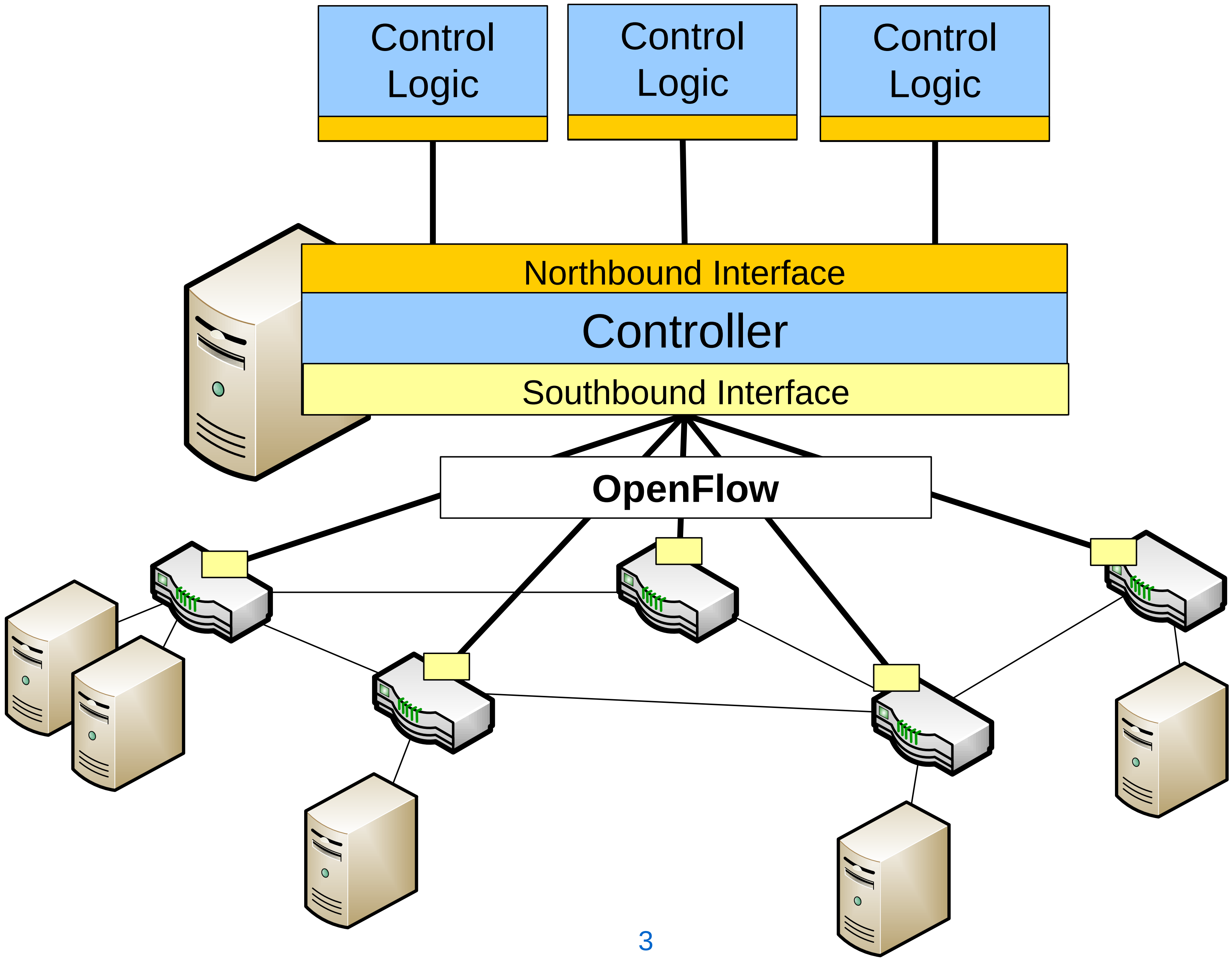
Part 2: Southbound Interface: OpenFlow Protocol

Frank Dürr

Overview

- The OpenFlow Protocol
- Proactive and Reactive Routing

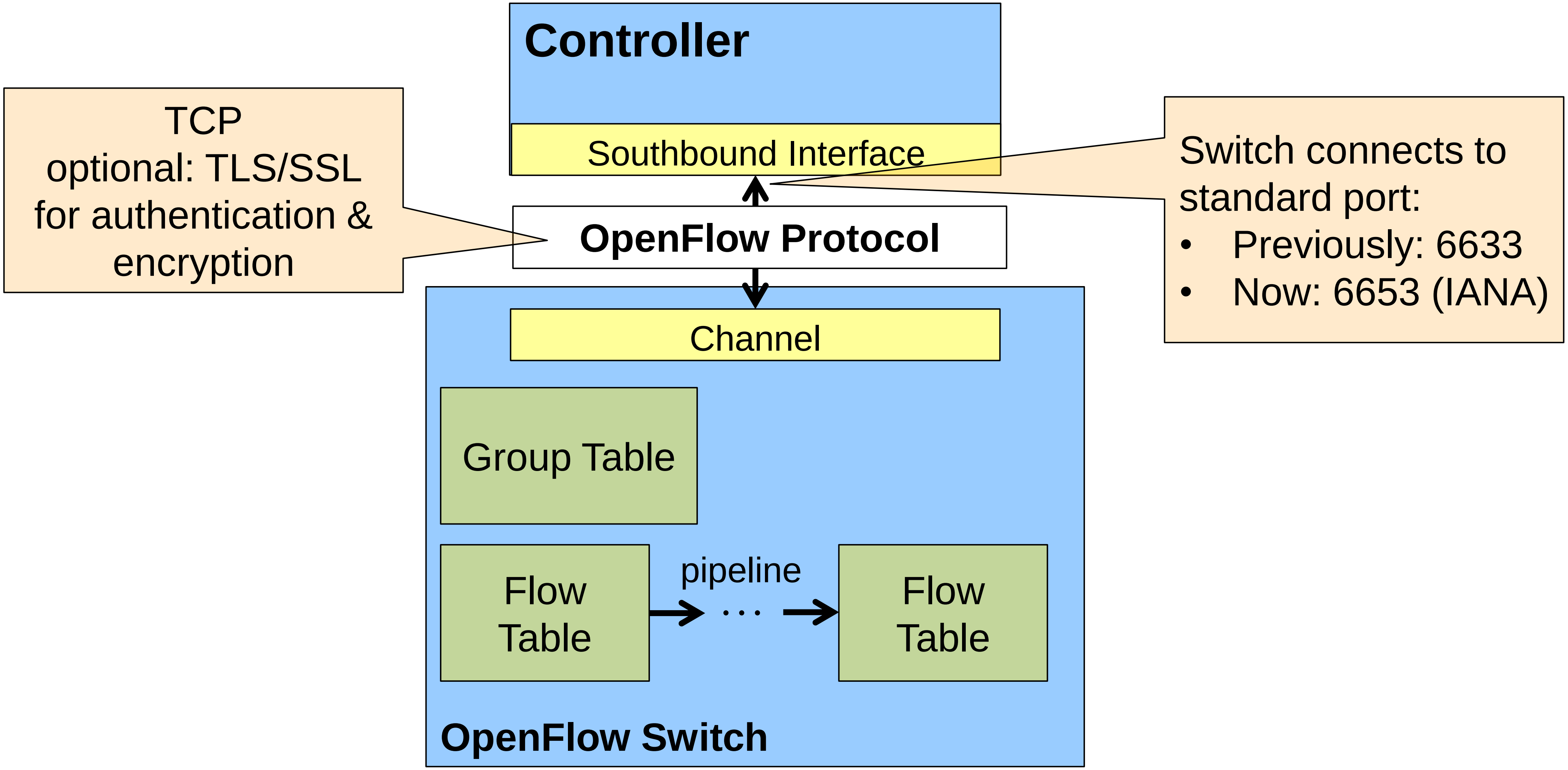
Southbound Interface: The OpenFlow Protocol



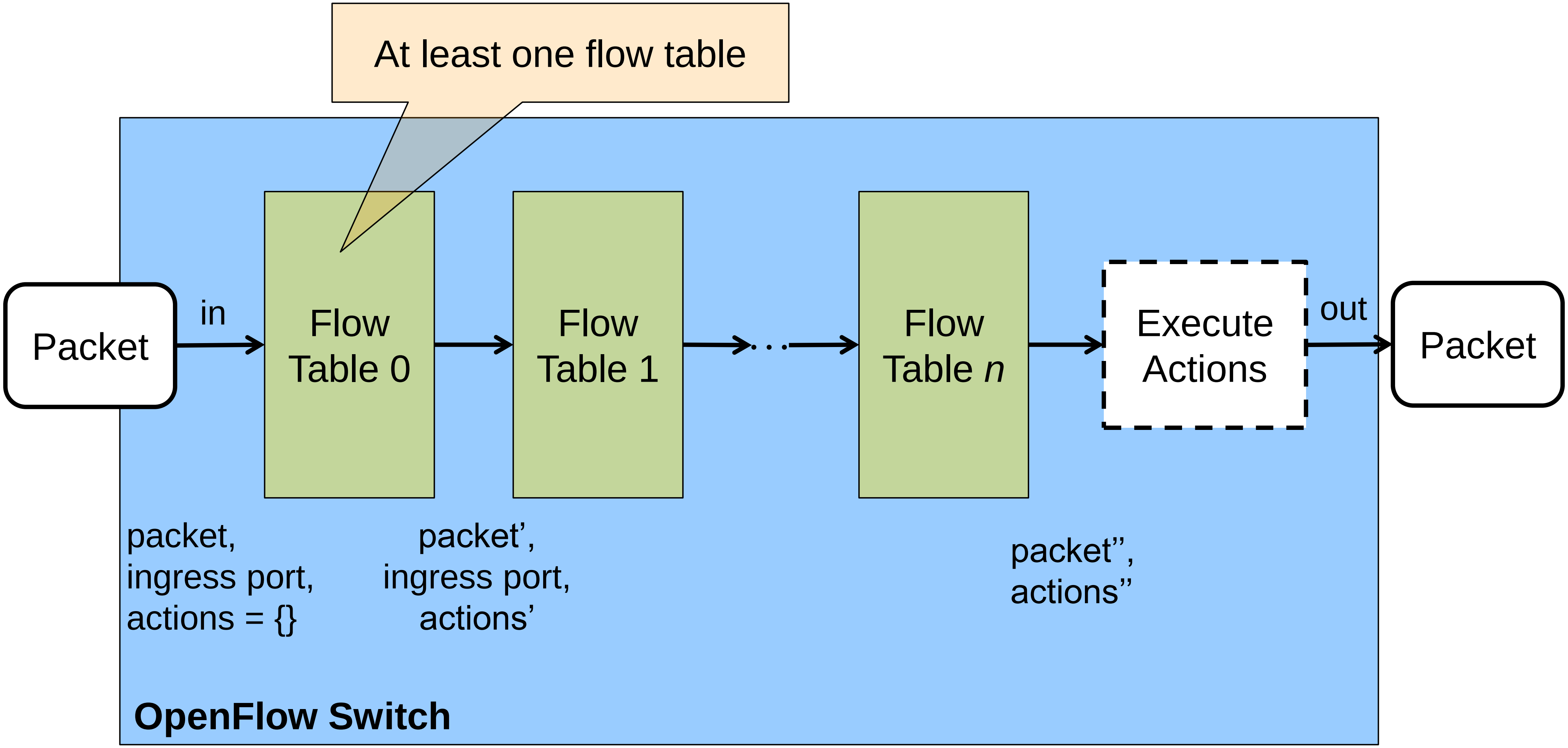
The OpenFlow Protocol: Overview

- OpenFlow de facto standard for southbound interface
- Defined by Open Networking Foundation
  - Major vendors (Cisco, IBM, NEC, HP, Alcatel-Lucent, VMware, …)
- Interface to a single switch
  - No aspects of control plane distribution defined
- Basic functionality
  - Modification of flow tables (adding, removing, modifying entries)
  - Injecting packets
  - Events for receiving packets (reactive routing)
  - Querying traffic statistics (counters)

Architecture of an OpenFlow System



The Way of a Packet through a Switch



Flow Tables & Flow Entries

- **Flow tables** consist of a list of flow entries
- **Flow entry (slightly simplified):**
  - *Match field:* Defines matching packets
  - *Priority:* Precedence if multiple entries match
  - *Counters:* Counts matches
  - *Instructions:*
    - Modification and forwarding of packet
  - *Timeouts:* Removes entry after a certain (idle) time

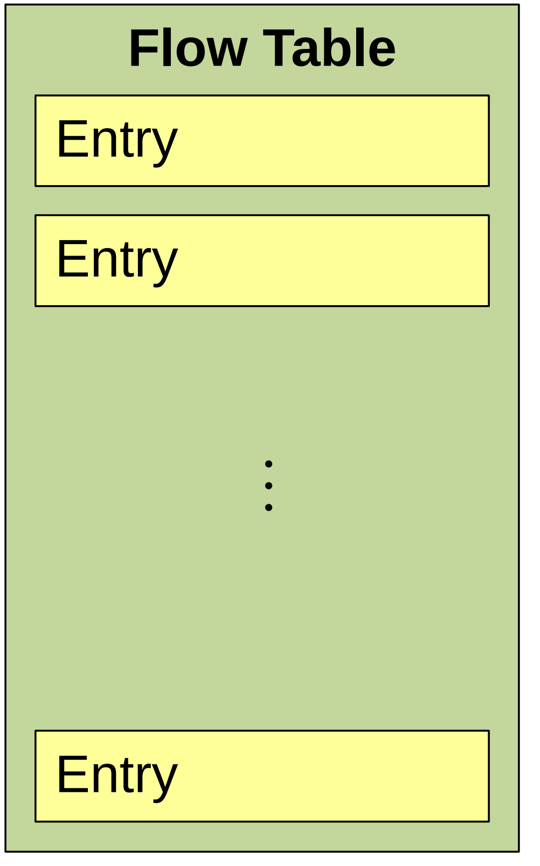
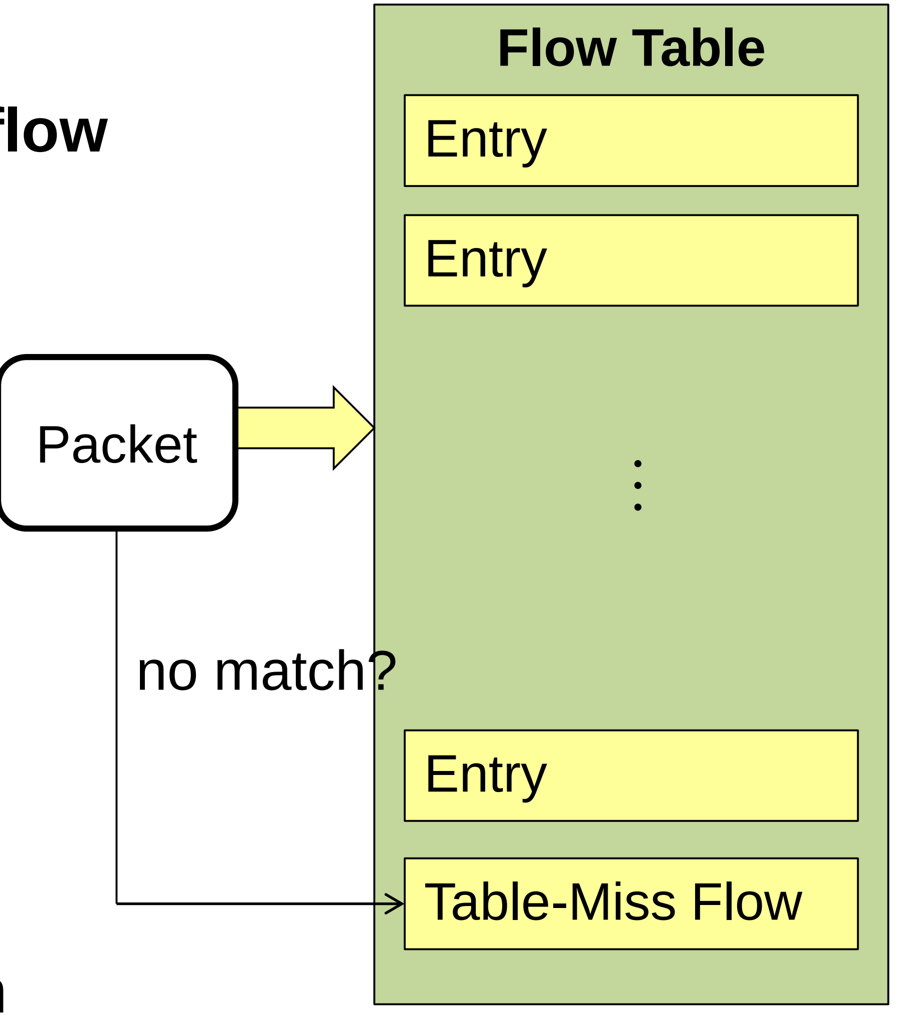


Table Misses

Important for dynamic routing

- Each table supports a **table-miss flow entry**
  - Lowest priority
  - Matches all packets
- Possible actions (at least):
  - Drop
  - **Send to controller**
- If no table-miss entry is defined
  - Drop packet (default in OF1.3)
  - Or define another default action



Match Fields

Subset of L2-4 header fields

- 10 tuple (must be supported)
  - For more (optional) fields please see OF standard
- Note: hardware switches might only support hardware-accelerated matching on some combinations!
  - Rest goes the “slow path“

Ingress Port			
Ether Src	Ether Dst	VLAN ID	Ether Type
IP SRC	IP DST	IP PROTO	
TCP/UDP SRC PORT	TCP/UDP SRC PORT		

Ether Type:

- Specifies layer 3 protocol
- E.g, 0x0800 = IPv4

IP PROTO:

- Specifies layer 4 protocol
- E.g, 6 = TCP, 17 = UDP

Wildcard Matching (1)

- Not all fields need to be specified: Wildcard *
  - Matches any value
- For IP addresses, bitmasks can be specified (CIDR)
  - Example: Subnet mask of IPv4 address 192.168.1.1/24 (netmask 255.255.255.0)

In Port	Eth Src	Eth Dst	Eth Type	VLAN ID	IP SRC	IP DST	IP Proto	Src Port	Dst Port
*	*	*	0x0800 (IPv4)	*	*	10.2.3.4	6 (TCP)	*	80
2	*	*	*	42	*	*	*	*	*
*	*	*	0x0800 (IPv4)	*	*	10.1.2.3	*	*	*

IPv4 traffic to a certain machine (e.g., result of a routing algorithm)

Traffic of a certain VLAN from a certain port

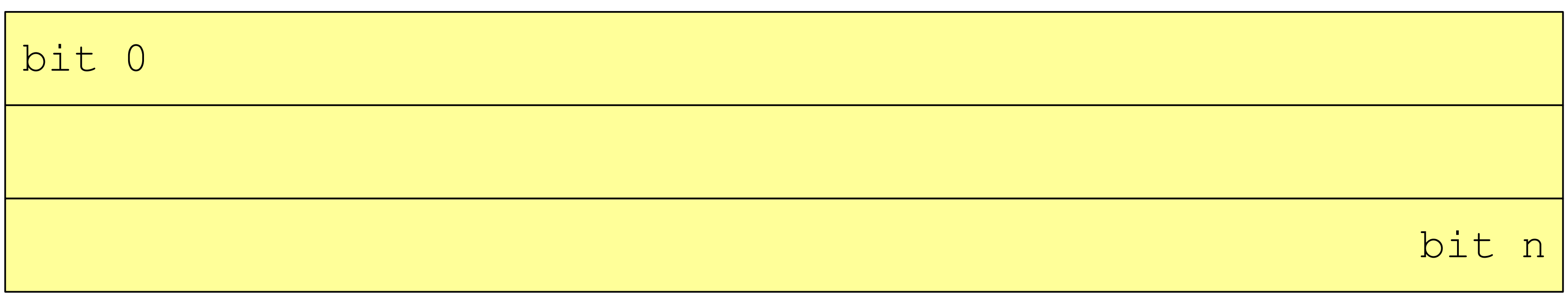
All traffic to a certain web server (port 80)

Wildcard Matching (2)

- Hardware switches can perform very fast matching using Content Addressable Memory (CAM)
  - Parallel matching of all entries in one clock cycle (micro-seconds)
- Two types of CAM
  - Binary CAM (BCAM): ordinary bits 0, 1
    - Good for exact match
  - Ternary CAM (TCAM): ordinary bits + wildcard (don‘t care) 0,1, *
    - Implementation of longest prefix match on IP addresses
- Drawbacks: Consumes significant energy, silicon space
  - Limited memory size in switches
    (hundreds to hundred thousand entries)
  - Remember the day of the 512k problem!

A Thought about Flexibility

- OpenFlow specification tailored to specific protocols
  - IP, TCP, UDP, ICMP, ARP, …
  - Did not support IPv6 in version 1.0!
- Again: Stuck with standard protocols
  - Practical trade-off: existing hardware switches can be easily modified to support OpenFlow
- Theoretically, we could just assume a big bit field and bit mask
  - Fields could be freely defined



Actions

- **Output:** output packet on the specified port
- **TTL modifications**
  - Decrement TTL, copy TTL outwards/inwards
- **Push and pop tags**
  - Add or remove VLAN/MPLS/PBB (MAC-in-MAC) tags to/from the packet
- **Set header fields**
  - Example: IP- or MAC-address re-writing
- **Group actions**
  - Example: Multicast

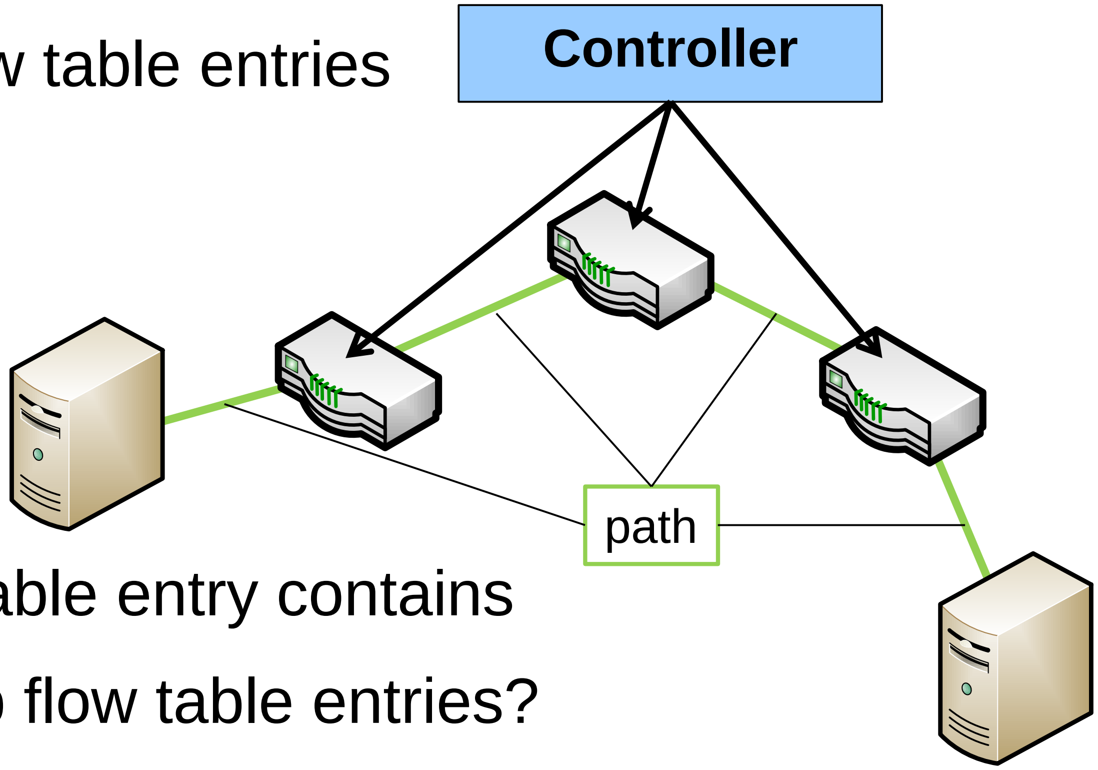
Order of execution of actions is well-defined by action type

Instructions

- Write actions
  - Adds given actions to the action set
  - Overwrites actions of the same type
- Go to table with given id
  - Hybrid switches can also go to the “normal“ table
- Apply specific actions immediately
  - Modify packet before going to next table
- Clear action set
- Meter id: send packet to a given meter (e.g. rate limitation)

Proactive vs Reactive Routing

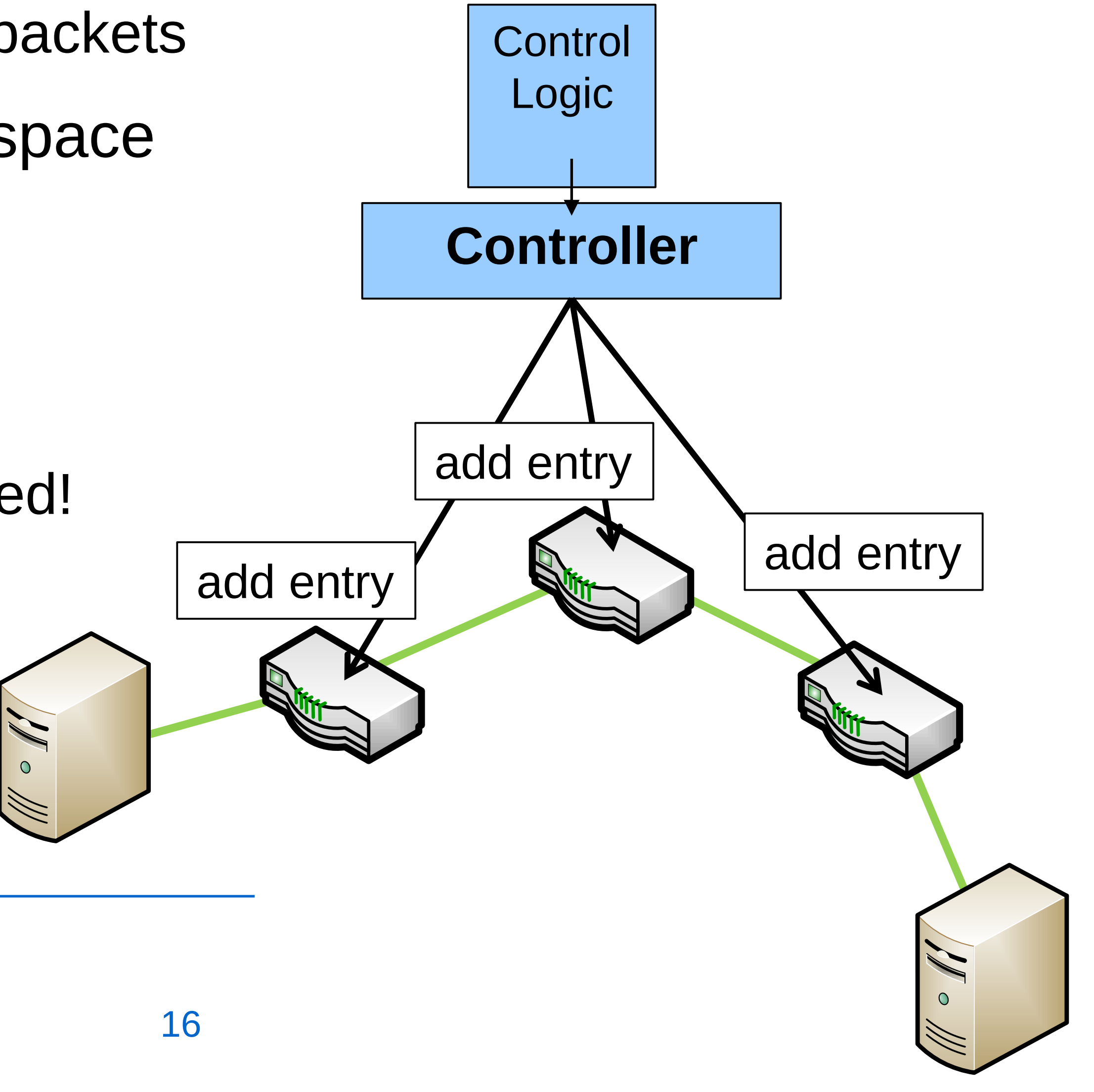
- Routes defined by a set of flow table entries
  - Along the path of packets



- So far, we know *what* a flow table entry contains
- Question now: *When* to set up flow table entries?
- Two options:
  - Proactively: before the flow starts
  - Reactively: as soon as the flow starts

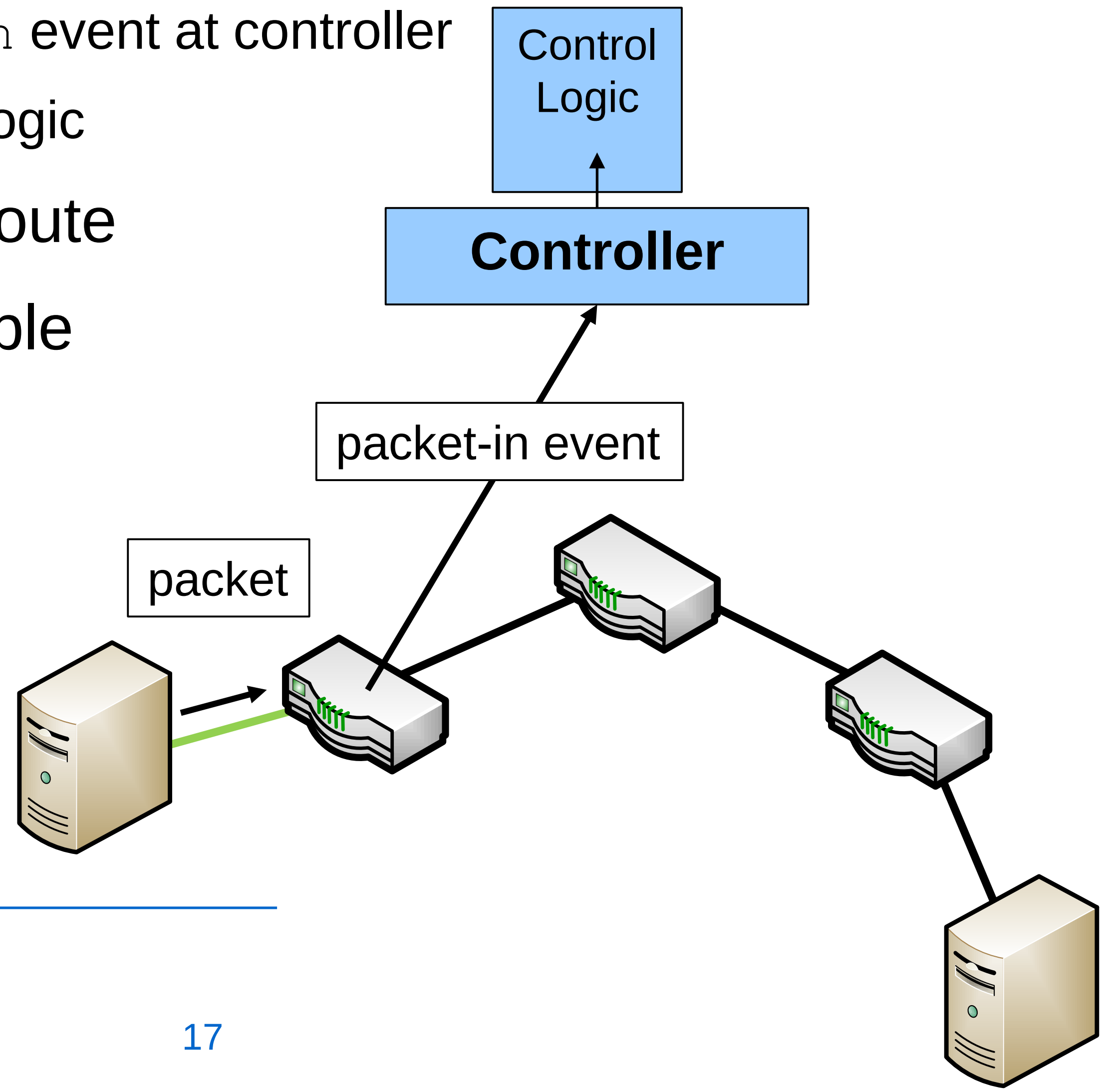
Proactive Routing

- Controller proactively “pushes“ flow table entries onto switches
- Advantage: Reduces controller load
  - No reactive handling of packets
- Disadvantage: Occupies space in flow table of switch
  - Even without traffic
  - Remember:
    Size of flow table is limited!



Reactive Routing (1)

- Switch receives a packet without matching flow table entry
  - Switch redirects packet to controller
    - Open flow `packet_in` event at controller
    - Forwarded to control logic
- Control logic calculates route
- Controller installs flow table entries along path
  - Further packets of flow don‘t involve controller again



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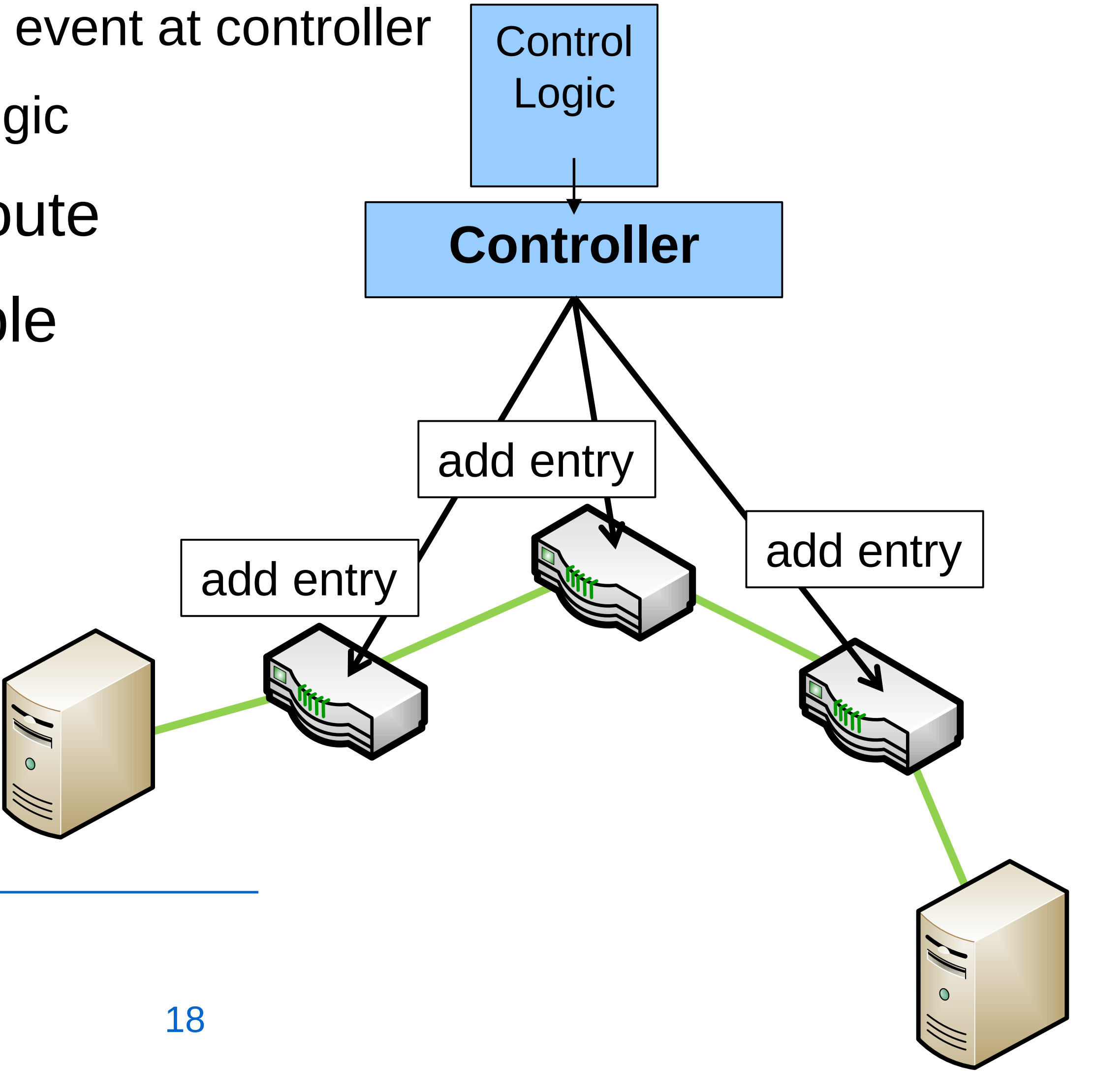

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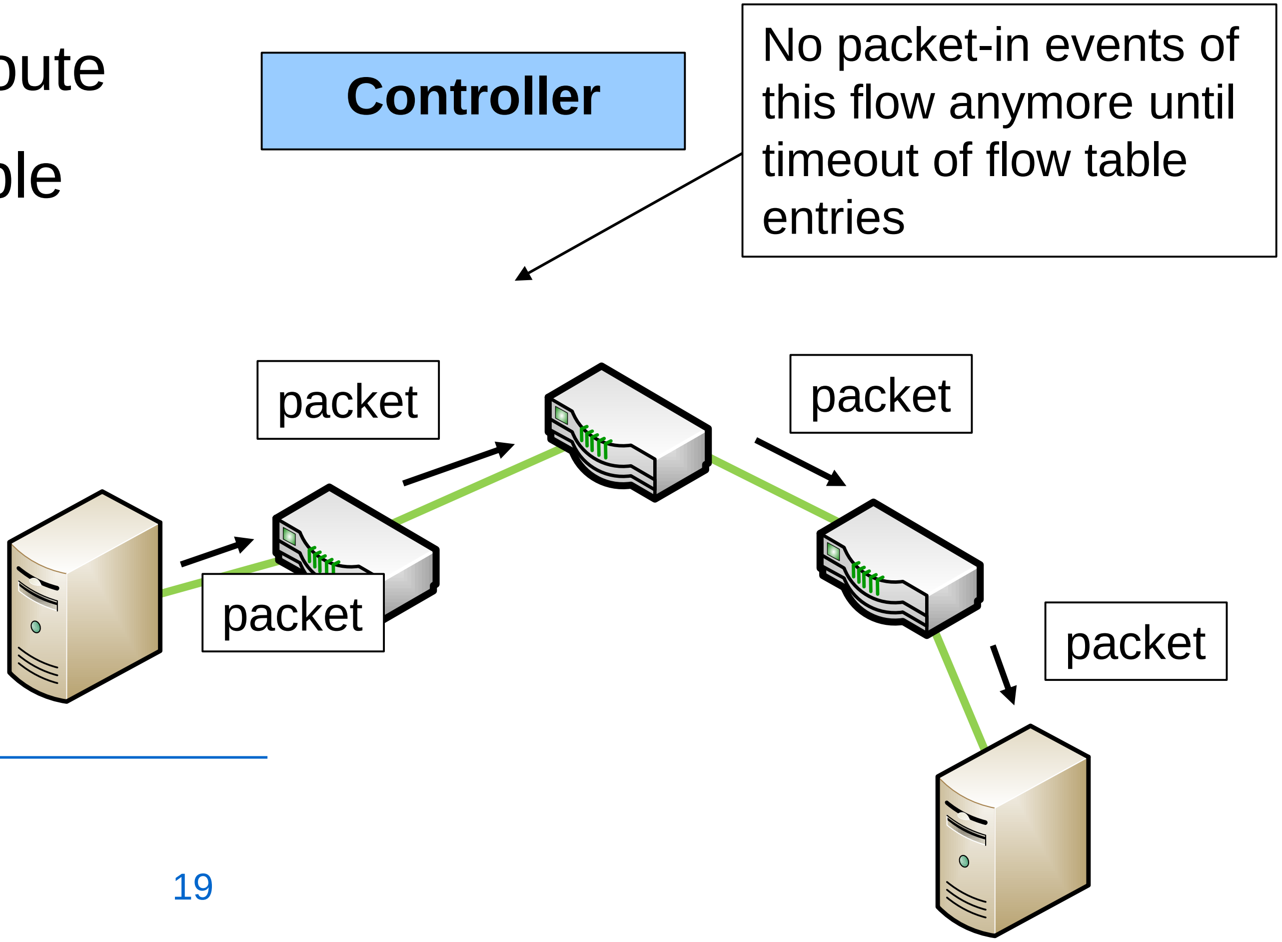

Reactive Routing (2)

- Advantage: Saves flow table space
- Disadvantage: Puts load onto controller and control network
  - Not such a big problem for TCP
    - Sender blocked until connection setup is done
  - Beware: Connection-less UDP can send at full rate immediately (without warning)!

Required Information for Routing

Dynamic routing requires knowledge of network status

- Network topology (nodes and links):
  - Switches and hosts
  - Links between switches (from switch port to switch port)
  - Links between hosts and switches (connection host to switch port)
  - Bandwidth of links
- Traffic statistics
  - Number of packets or bytes
  - Number of dropped packets, receive/transmit errors, etc.
  - Per flow (entry), link/port, group, etc.

Network Topology

- Discovery of network topology not covered by OpenFlow
- Controller implements standard protocols
  - Logical Link Layer Discovery Protocol (LLDP)
  - ARP handling for host discovery
- Controller exposes discovered information to control logic
  - See northbound interface discussion

Traffic Statistics

- OpenFlow switches implement **counters**
- Controller can **query counters** using OpenFlow messages:
  - Flow Statistics (OFPMP_FLOW, OFPMP_AGGREGATE)
  - Port Statistics (OFPMP_PORT_STATS)
  - Table Statistics (OFPMP_TABLE)
  - Queue Statistics (OFPMP_QUEUE)
  - Group Statistics (OFPMP_GROUP)
  - Meter Statistics (OFPMT_METER)

Counters

Counter	Bits	
Per Flow Table		
Reference Count (active entries)	32	*Required*
Packet Lookups	64	*Optional*
Packet Matches	64	*Optional*
Per Flow Entry		
Received Packets	64	*Optional*
Received Bytes	64	*Optional*
Duration (seconds)	32	*Required*
Duration (nanoseconds)	32	*Optional*
Per Port		
Received Packets	64	*Required*
Transmitted Packets	64	*Required*
Received Bytes	64	*Optional*
Transmitted Bytes	64	*Optional*
Receive Drops	64	*Optional*
Transmit Drops	64	*Optional*
Receive Errors	64	*Optional*
Transmit Errors	64	*Optional*
Receive Frame Alignment Errors	64	*Optional*
Receive Overrun Errors	64	*Optional*
Receive CRC Errors	64	*Optional*
Collisions	64	*Optional*
Duration (seconds)	32	*Required*
Duration (nanoseconds)	32	*Optional*

Per Queue		
Transmit Packets	64	*Required*
Transmit Bytes	64	*Optional*
Transmit Overrun Errors	64	*Optional*
Duration (seconds)	32	*Required*
Duration (nanoseconds)	32	*Optional*
Per Group		
Reference Count (flow entries)	32	*Optional*
Packet Count	64	*Optional*
Byte Count	64	*Optional*
Duration (seconds)	32	*Required*
Duration (nanoseconds)	32	*Optional*
Per Group Bucket		
Packet Count	64	*Optional*
Byte Count	64	*Optional*
Per Meter		
Flow Count	32	*Optional*
Input Packet Count	64	*Optional*
Input Byte Count	64	*Optional*
Duration (seconds)	32	*Required*
Duration (nanoseconds)	32	*Optional*
Per Meter Band		
In Band Packet Count	64	*Optional*
In Band Byte Count	64	*Optional*

Summary

- OpenFlow basics
  - Standard protocol between switch and controller (southbound)
  - Flow tables: pipeline processing
  - Flow table entries: match fields, instructions, actions
- Reactive and proactive flow table setup

Questions?