Software Defined Networking (SDN)

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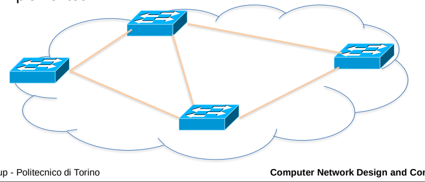
Outline

- SDN
  - Motivations and definitions
  - Centralized architecture
  - Flow based forwarding
- Openflow protocol
- Advances
  - Distributed controllers
  - Stateful switches

Rexford – Computer Network class

Traditional computer networks

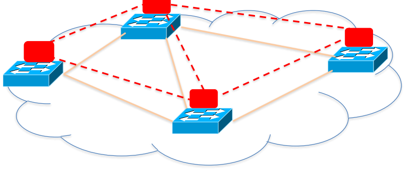
- Data plane
  - Local algorithms, dealing with packets
    - Forwarding, filtering, scheduling, buffering, marking, rate-limiting, measuring at the packet level
  - Packet transmission time scale
    - Very fast processing
    - Implemented in HW



Rexford – Computer Network class

Traditional computer networks

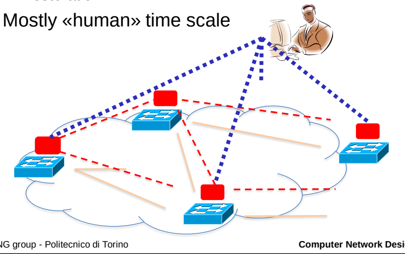
- Control plane
  - Distributed algorithms
    - Topology discovery, topology tracking, route computation, installing forwarding rules, traffic engineering
  - Seconds time scale, flow time scale
    - Slow process



Rexford – Computer Network class

Traditional computer networks

- Management plane
  - Local/global algorithms with coordination
    - Measurement, configuration, monitoring, protection and restoration
  - Mostly «human» time scale



Traditional computer networks

- Features
  - Incredible success (from research experiments to global commercial infrastructure)
  - «In principle» complexity at the edge
    - «Only» packet forwarding inside
    - Complexity at the edge (SW) enables fast innovation
    - Host running increasingly complex applications (SW)
      - Web, P2P, social networks, virtual reality, video streaming
  - Inside the network?
    - Closed equipments, SW and HW intermixed, vendor specific interfaces, many more features beside forwarding, too many protocols
    - Slow and costly development and management

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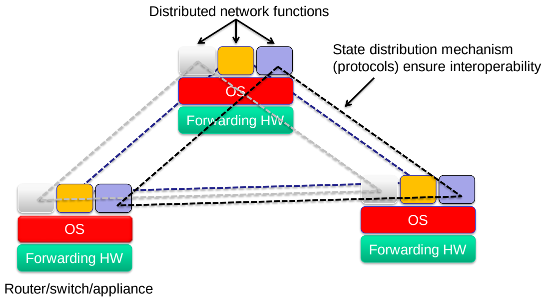
Classic network paradigm



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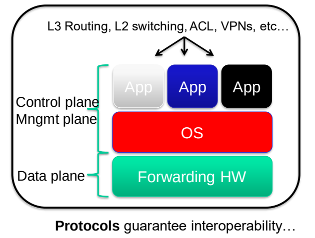
Closed platform

- Configuration interfaces vary
  - Different vendors
  - Different devices of the same vendors
  - Different firmware versions of the same device



Protocols guarantee interoperability…

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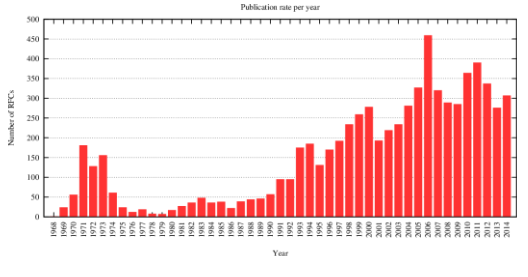
Too many protocols/standards?



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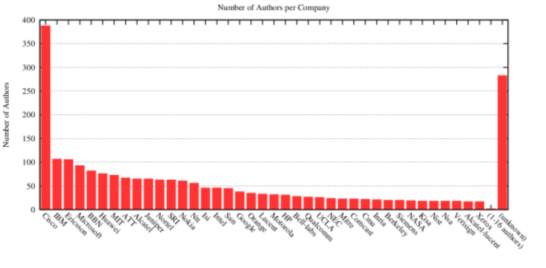
Vendors dominated



Software Defined Networking*

- "New" key elements
  - Clean interface (API) between data and control plane
  - Logically centralized control plane
    - Control plane out of forwarding devices
    - Control plane (SW) may run on general purpose HW
    - Global network view
    - SDN controller or Network Operating Systems
      - Network programmability
      - New architecture
  - Flow based switching
    - Programmed by the centralized controller
    - Very flexible flow definition
  - Network applications running on top of NOS

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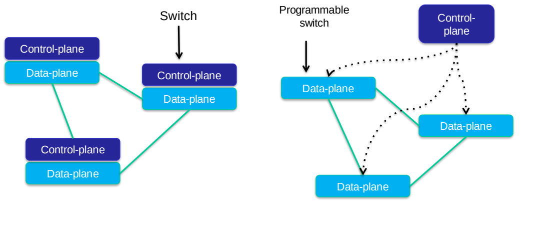
The new (centralized) model

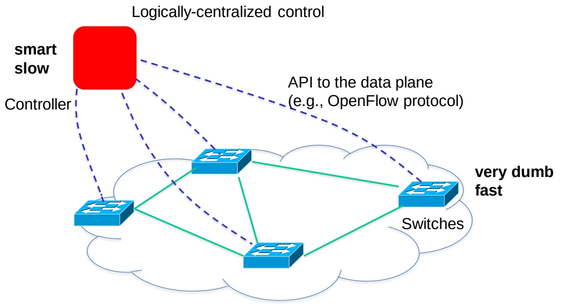
Traditional networking
Distributed

Software-Defined Networking
Centralized



Rexford – Computer Network class

Centralized control



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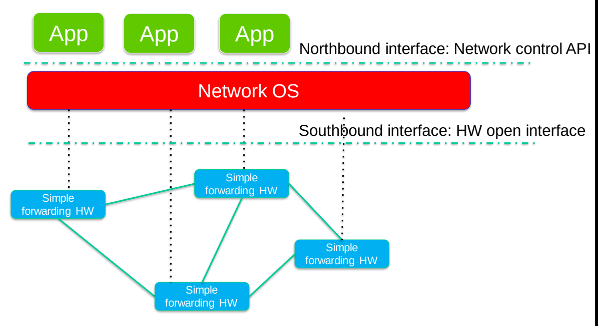
SND architecture: interfaces

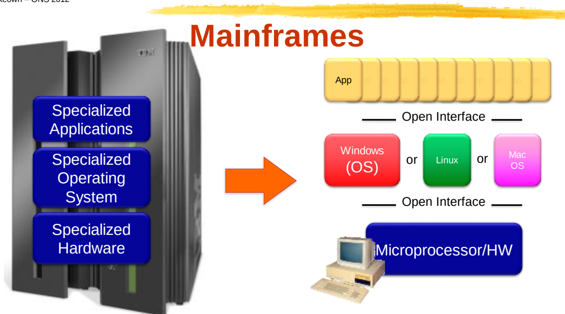


A Helpful Analogy

From Nick McKeown's talk
"Making SDN Work" at the
Open Networking Summit, April 2012

N. Mc Keown – ONS 2012

Mainframes

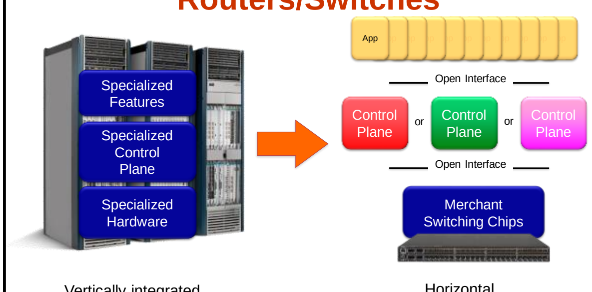


Vertically integrated
Closed, proprietary
Slow innovation
Small industry

Horizontal
Open interfaces
Rapid innovation
Huge industry

N. Mc Keown– ONS 2012

Routers/Switches

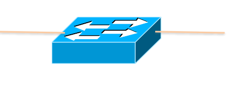


Vertically integrated
Closed, proprietary
Slow innovation

Horizontal
Open interfaces
Rapid innovation

Flow-based forwarding*

- Protocol-less or protocol-oblivious forwarding
  - Not exactly true (set of predefined fields)
- Simple packet-handling rules
  - Pattern/rule: match packet header bits
  - Actions: drop, forward, modify, send to controller
  - Priority: disambiguate overlapping patterns



OpenFlow/SDN tutorial, Srini Seetharaman

Flow based forwarding: table entries

Rule	Action	Stats

Stats: Packet + byte counters

Action:
1. Forward packet to zero or more ports
2. Encapsulate and forward to controller
3. Send to normal processing pipeline
4. Modify Fields
5. Any extensions you add!

Rule:

Switch Port	MAC src	MAC dest	Eth type	VLAN Id	VLAN pcp	IP Src	IP Dst	IP ToS	IP Prot	L4 sport	L4 dport

+ mask what fields to match

Rexford – Computer Network class

Unifies different kinds of “boxes”

- Router
  - Match: longest destination IP prefix
  - Action: forward out a link
- Switch
  - Match: destination MAC address
  - Action: forward or flood
- Firewall
  - Match: IP addresses and TCP/UDP port numbers
  - Action: permit or deny
- NAT
  - Match: IP address and TCP/UDP port
  - Action: rewrite address and port

OpenFlow/SDN tutorial, Srini Seetharaman

Examples of “boxes”

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	port4

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/SDN tutorial, Srini Seetharaman

Examples of “boxes”

Routing

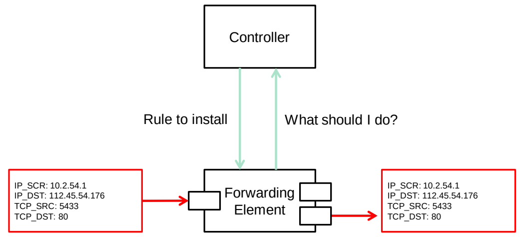
Switch Port	MAC src	MAC dst	Eth type	VLAN ID	IP Src	IP Dst	IP Prot	TCP sport	TCP dport	Action
*	*	*	*	*	*	5.6.7.8	*	*	*	port3

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

Bifulco talk at ewsdn2014

Controller to switch interaction



...	L3_SRC	L3_DST	L4_SRC	L4_DST	...	Action
	Any	112/8	Any	Any		Fwd-to: 2

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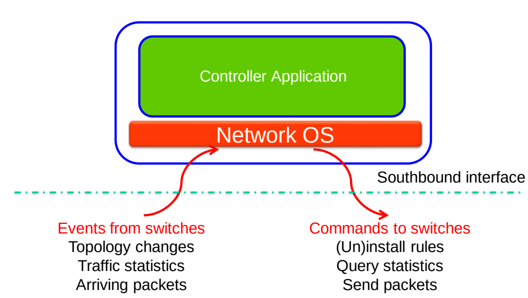
SDN controller: network programmability



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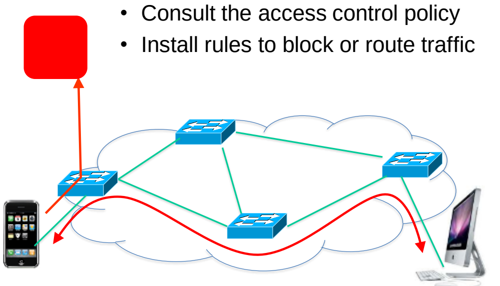
Example of applications

- Dynamic access control
- Seamless mobility/migration
- Server load balancing
- Network virtualization
- Using multiple wireless access points
- Traffic engineering
- Energy-efficient networking
- Adaptive traffic monitoring
- Denial-of-Service attack detection
- …….

Rexford – Computer Network class

Application: Dynamic access control

- Inspect first packet of a connection
- Consult the access control policy
- Install rules to block or route traffic



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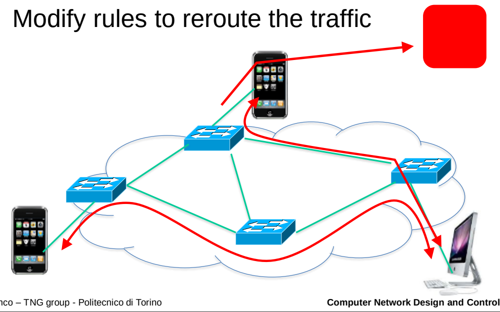
Application: Seamless mobility/migration

- See host send traffic at new location
- Modify rules to reroute the traffic



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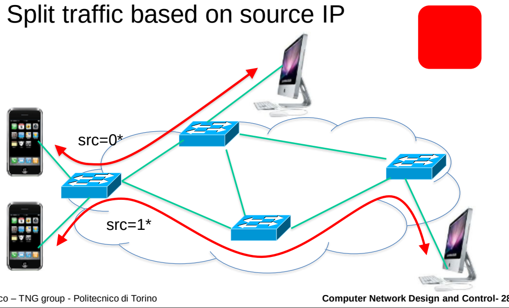
Application Server load balancing

- Pre-install load-balancing policy
- Split traffic based on source IP

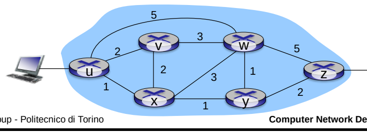


Kurose Ross: Computer Networking

Traffic engineering: difficult with traditional routing

Hp. Destination based routing

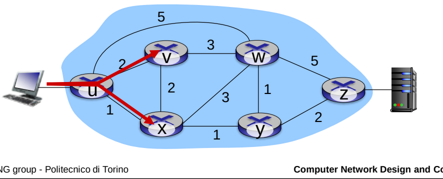
- What if network operator wants
  - u-to-z traffic to flow along uvwz
  - x-to-z traffic to flow xwyz?
- Need to define link weights so traffic routing algorithm computes routes (or need a new routing algorithm)
- Does not work
  - Modifies many routes
  - Cannot change weights to route each individual flow



Kurose Ross: Computer Networking

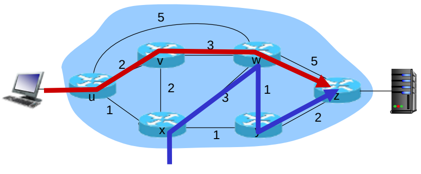
Traffic engineering: difficult with traditional routing

- What if network operator wants to split u-to-z traffic along uvwz and uxyz (load balancing)?
- Can't do it (or need a new routing algorithm)



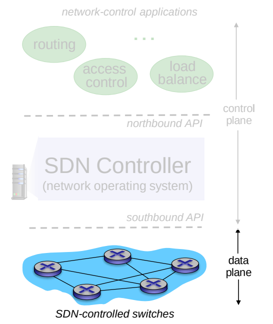
Traffic engineering: difficult with traditional routing

- What if we wants to route blue and red traffic differently?
- Can't do it (with destination based forwarding, and LS, DV routing)



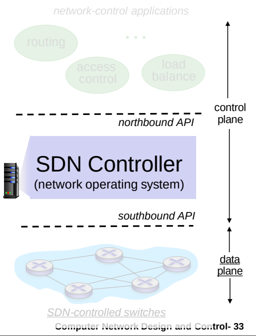
SDN: switches

- Data plane switches
  - Fast, simple, commodity switches implementing generalized data-plane forwarding in HW
  - Switch flow table computed, installed by controller
  - API for table-based switch control
    - Defines what is controllable and what is not
  - Protocol for communicating with controller



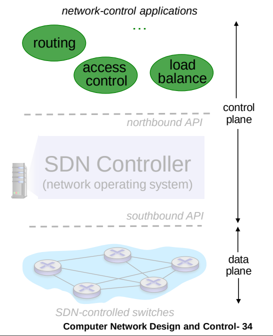
SDN controller

- SDN controller (network OS):
  - Maintain network state information
  - Interacts with network control applications "above" via northbound API
  - Interacts with network switches "below" via southbound API



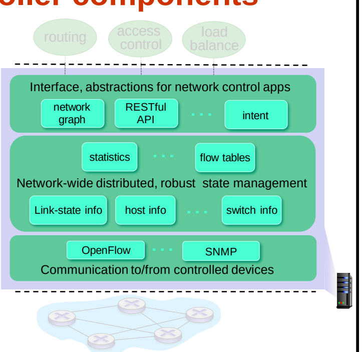
SDN application

- Network-control apps:
  - "Brains" of control: implement control functions using lower-level services, API provided by SND controller
  - Unbundled: can be provided by 3rd party: distinct from routing vendor, or SDN controller



SDN controller components

- Interface layer to network control apps
  - Abstraction API
- State management layer
  - Distributed database
    - State of network links, switches etc
- Communication layer



SDN: pros and cons

- Potential benefits
  - Easier and faster innovation
  - Exploits global network view
    - Traffic enginering
    - Traffic steering
    - Security
    - ….
  - Simpler switches
    - Less costly
    - Less power hungry
  - «Avoids» device misconfiguration
  - Virtual resource management
- Potential drawbacks
  - Performance
    - Overheads
    - Scalability
    - Bottleneck
  - Single point of failure
  - Interoperability

SDN where?

- Campus LAN
- Data center
- WAN (google) to interconnect data centers
- ISP?
- 5G networks

The role of the scenario

- Datacenter
  - Very large number of devices
    - Spatially collocated
  - Low and predictable delays between devices
  - Dedicated network for control
    - Out of band control traffic

- ISP/POP
  - Lower number of devices
    - Spatially distributed
  - High and unpredictable latencies
  - Control and data share the same resources
    - In band control traffic

Level of aggregation

- Flow Based
  - Every flow is individually set up by controller
  - Exact-match flow entries
  - Flow table contains one entry per flow
  - Suited for fine grain control, e.g. campus networks
- Group Based
  - One flow entry covers large groups of flows
  - Wildcard flow entries
  - Flow table contains one entry per category/group of flows
  - Suited for large number of flows, e.g. ISPs

Level of aggregation

- High aggregation level
  - Dealing with few large objects
  - Reduced occupation of forwarding table
  - Reduced signaling overhead and controller load
  - Coarse granularity in the control of flow Qos
    - A flow steering moves a large amount of traffic
  - Less elements to deal with for load balancing but more difficult to balance

Reactive vs. Proactive

- Reactive
  - Flow table empty at boot
  - First packet of a flow sent to the controller
  - Controller inserts flow entries
  - Dynamic network

  - Every flow incurs small (?) additional flow setup time
  - Large control traffic
  - Large load on the controller
  - Efficient use of flow table
  - If control connection lost, switch has limited utility
- Proactive
  - Controller pre-populates flow table in switch at boot
  - Zero additional flow setup time
  - Static network

  - Loss of control connection does not disrupt traffic
  - Essentially requires aggregated (wildcard) rules
    - Reduced table size

OpenFlow protocol

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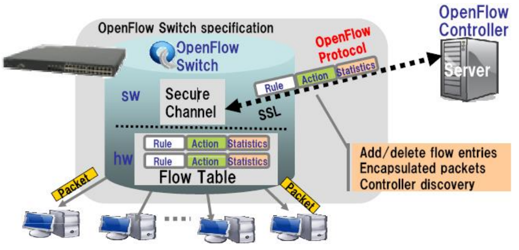
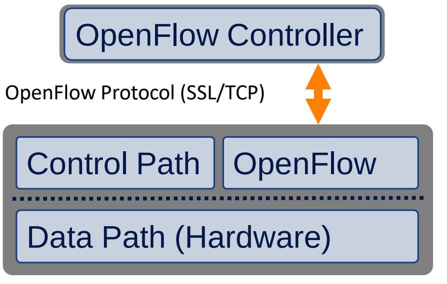
Flow based forwarding



OpenFlow/SDN tutorial, Srini Seetharaman

OpenFlow protocol



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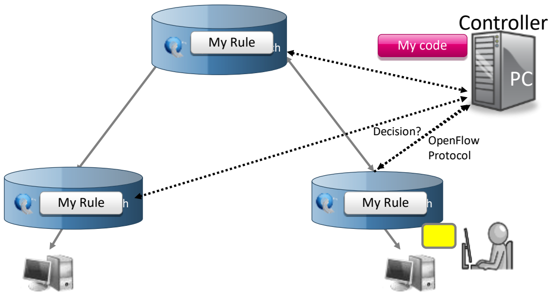
OpenFlow protocol use



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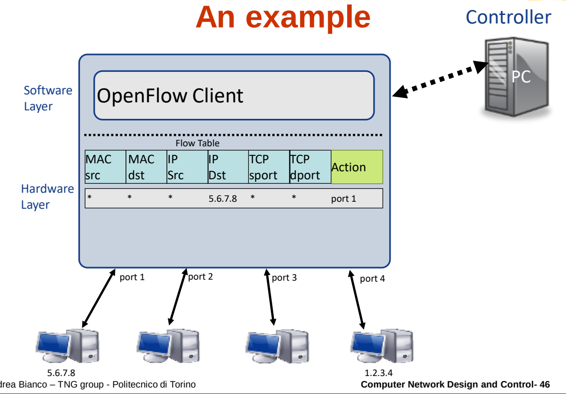
An example



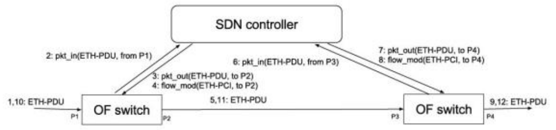
OpenFlow protocol messages

- Controller-to-switch
  - Initiated by the controller and used to directly manage or inspect the state of the switch
    - Features, Config, Modify State, Read State, Packet Out, Barrier
- Asynchronous
  - Sent to the controller without controller soliciting
    - Packet-in, Flow Removed/Expiration, Port status, Error, …
- Symmetric
  - Sent without solicitation in any direction
    - Hello, Echo, Experimenter/Vendor

OpenFlow (main) messages

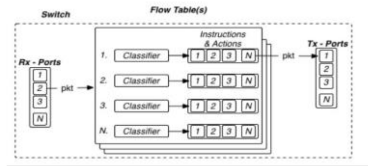
- Packet_in
  - Switch to controller
  - Carries a packet copy (possibly only the header)
    - What is best?
  - Generated by default in case of table miss
- Packet_out
  - Controller to switch
  - Send the packet out of a specified port
  - Carries the full packet or the switch buffer id
- Flow_mod
  - Controller to switch
  - Modify flow tables
  - Carries match-action rule to install

OpenFlow example



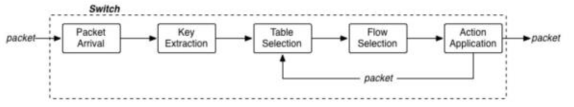
Packet processing

- Packets arrive and leave through ports
- Packets are matched to flow in flow tables using classifiers
- Flows contain set of instructions and actions applied to each packet in the match

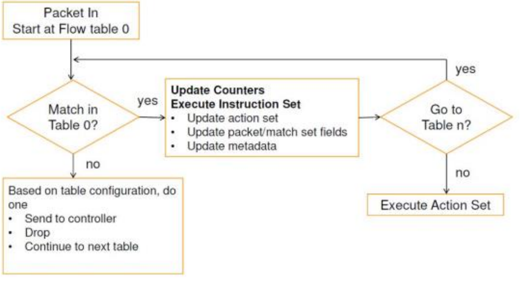


Packet lifecycle

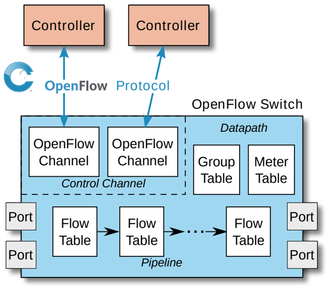
- On packet arrival a key is built
  - Metadata (arrival time, arrival port, memory location)
  - Fields in packet header
- Key is used to select a flow in the table
- Actions associated with the flow are applied
  - Drop, mutate, queue, forward, move to next table



Packet matching

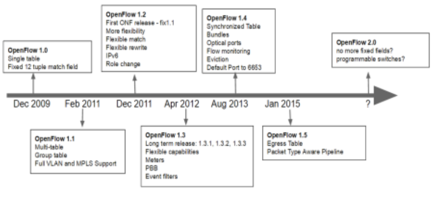


Openflow switch implementation



Openflow versions

- Published by Open Networking Foundation
  - No profit
  - Funded by Deutsche Telekom, Facebook, Google, Microsoft, Verizon, etc.



SDN architecture in action

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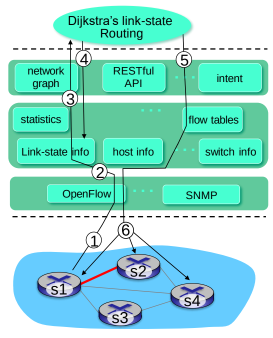
From Kurose Ross: Computer Networking

An example



① S1, experiencing link failure using OpenFlow port status message to notify controller

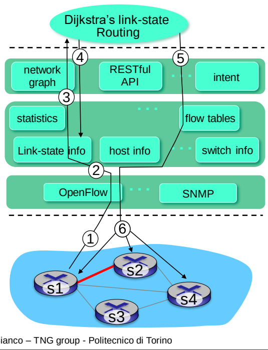
② SDN controller receives OpenFlow message, updates link status info

③ Dijkstra's routing algorithm application has previously registered to be called when ever link status changes. It is called.

④ Dijkstra's routing algorithm access network graph info, link state info in controller, computes new routes

From Kurose Ross: Computer Networking

An example



⑤ Link state routing app interacts with flow-table-computation component in SDN controller, which computes new flow tables needed

⑥ Controller uses OpenFlow to install new tables in switches that need updating

Distributed controllers

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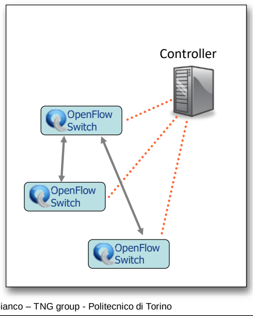
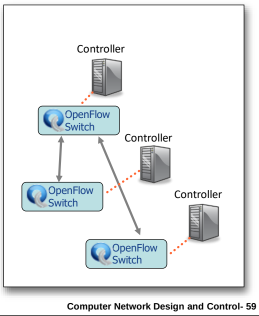
Srini Seetharaman, OpenFlow/SDN tutorial

Centralized vs Distributed Control

Centralized Control



Distributed Control



Why distributed/multiple controllers?

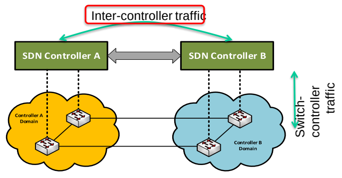
- To enhance resilience to failures
  - Controller failures can be managed
  - Still to deal with failures in data and control plane
- To solve scalability issues
  - Faster controllers
    - Limited scaling
  - More proactive rules to reduce number of requests
    - Limited flexibility
  - Multiple controllers
    - Permit load balancing to reduce processing load
    - Permit switch migration

Distributed controllers

- Virtual topology among controllers
  - to coordinate the operations of the controllers
  - peer, hierarchical, master/slave
- Network view maintenance
  - different levels of consistency (strong/weak) among the controllers
  - affects the reactivity
  - may lead to temporary rule conflicts

Control plane in distributed controllers

- Switch-controller (Sw-Ctr) traffic
  - Standardized
- Controller-controller (Ctr-Ctr) traffic (East-West-bound interfaces)
  - Proprietary
  - To get consistent view
  - May be non neglibile
  - Critical for reactivity



Stateful data plane

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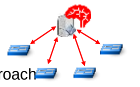
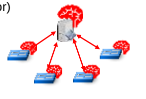
Stateful SDN dataplane

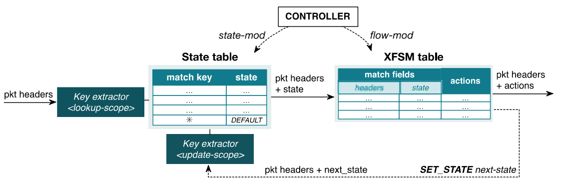
- Stateless approach (OpenFlow)
  - Stateless switches, all the states in the controller
  - Limited reactivity due to the (logically) centralized approach



- Stateful approach: OpenState, OpenPacketProcessor (OPP), P4
  - Permit some level of stateful processing (e.g., finite state machines) within switches
    - OpenState adds a state table (IF state A THEN IF state B THEN)
    - OpenPacketProcessor: state defined with multiple variables, counters,
    - P4 much more flexible (description language of HW behavior)
  - Enabled by new generation of hardware
    - 6.5Tbps Tofino chipset @ Barefoot Networks

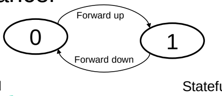


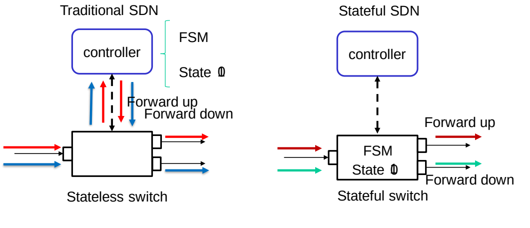
Hardware implementation



Toy example

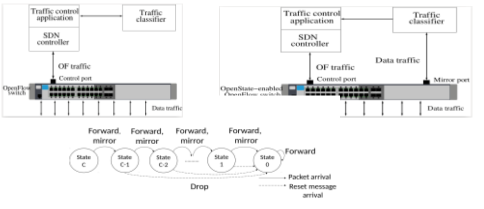
- Naive load balancer





Traffic classification

- Mirror a pre-defined number of packets to traffic classifier for each flow
- Interrupt the mirroring if the flow is identified



Stateful benefits

- Improve network reactivity
  - Simple local decisions at the switch
  - Reduced controller load
  - Reduced signaling overhead
- Permits to gracefully move functionalities
  - Balance central vs distributed control
- Not all switches need to be stateful
  - State positioning or distribution