Software Defined Networking (SDN)

Andrea Bianco
andrea.bianco@polito.it
http://www.telematica.polito.it/

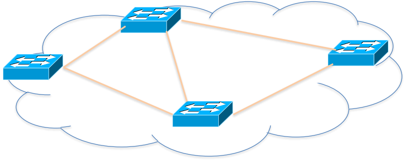
Outline

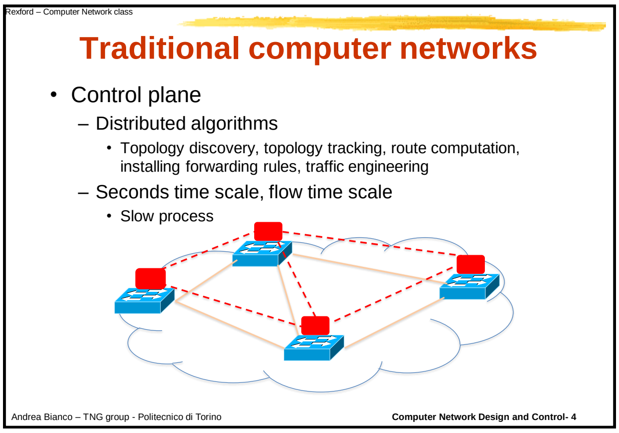
- SDN
  - Motivations and definitions
  - Centralized architecture
  - Flow based forwarding
- Openflow protocol
- Advances
  - Distributed controllers
  - Stateful switches

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





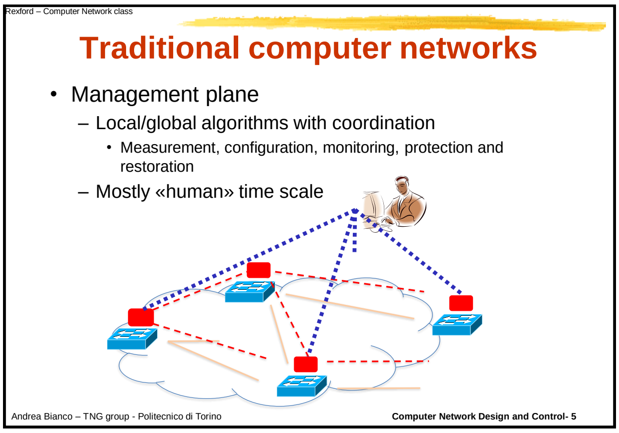
Rexford – Computer Network class

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

Andrea Bianco – TNG group - Politecnico di Torino

Computer Network Design and Control- 4



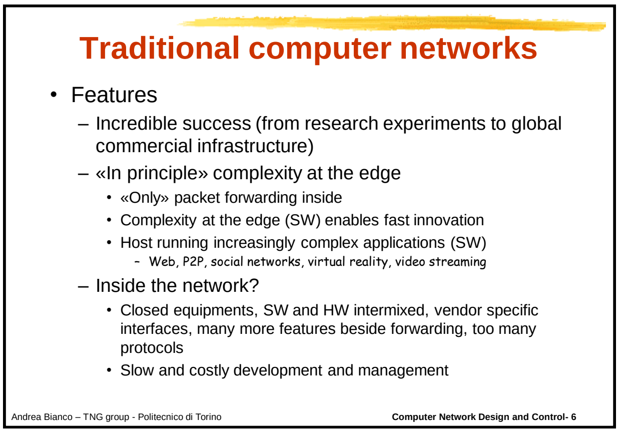
Rexford – Computer Network class

Traditional computer networks

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

Andrea Bianco – TNG group - Politecnico di Torino

Computer Network Design and Control- 5

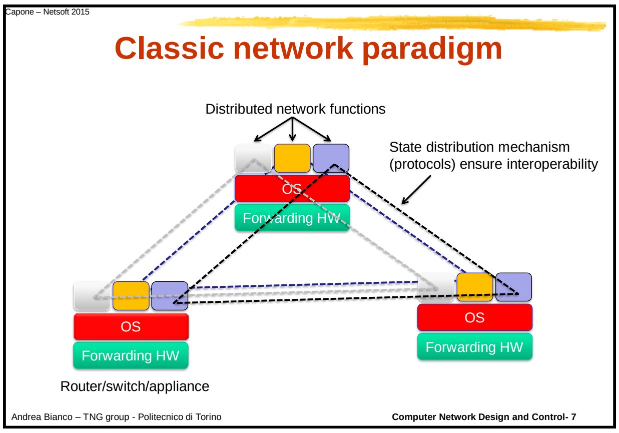


Traditional computer networks

- 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

Andrea Bianco – TNG group - Politecnico di Torino

Computer Network Design and Control- 6



Capone – Netsoft 2015

Classic network paradigm

Distributed network functions

State distribution mechanism (protocols) ensure interoperability

OS

Forwarding HW

OS

Forwarding HW

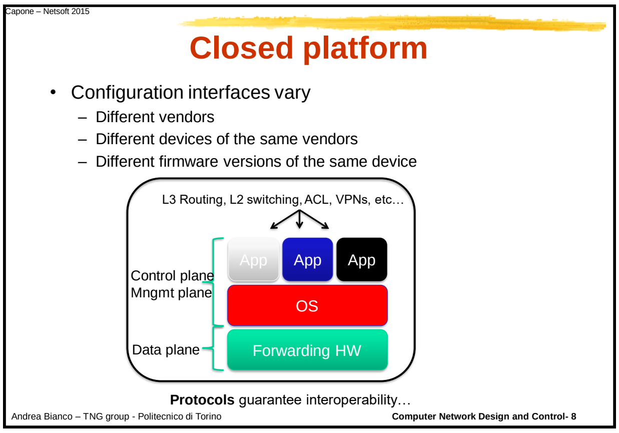
OS

Forwarding HW

Router/switch/appliance

Andrea Bianco – TNG group - Politecnico di Torino

Computer Network Design and Control- 7



Capone – Netsoft 2015

Closed platform

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

L3 Routing, L2 switching, ACL, VPNs, etc…

Control plane
Mngmt plane

App App App

OS

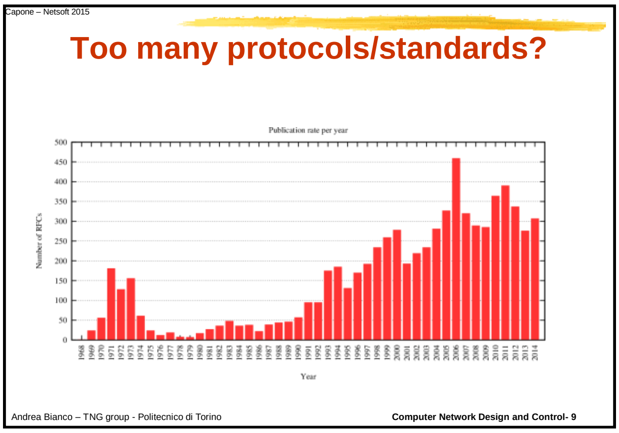
Data plane

Forwarding HW

Protocols guarantee interoperability…

Andrea Bianco – TNG group - Politecnico di Torino

Computer Network Design and Control- 8

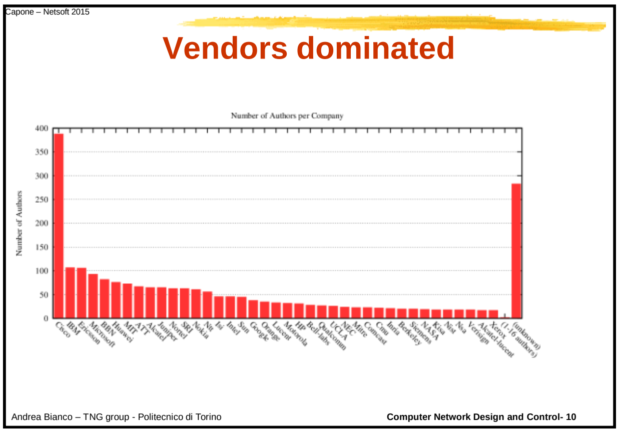


Capone – Netsoft 2015

Too many protocols/standards?

Andrea Bianco – TNG group - Politecnico di Torino

Computer Network Design and Control- 9

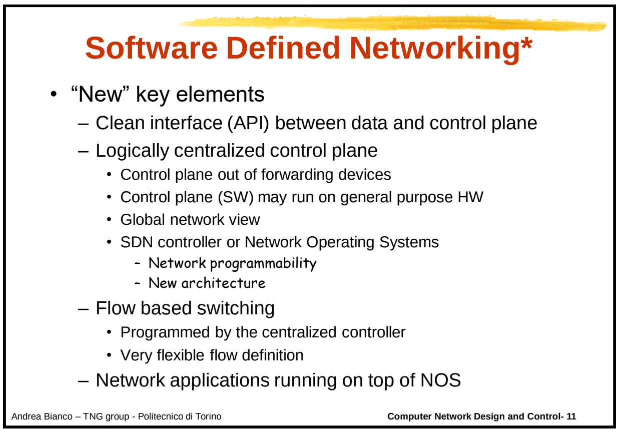


Capone – Netsoft 2015

Vendors dominated

Andrea Bianco – TNG group - Politecnico di Torino

Computer Network Design and Control- 10

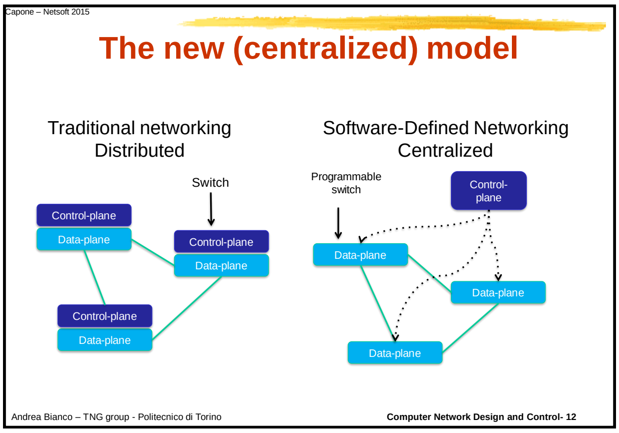


Software Defined Networking*

- "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

Andrea Bianco – TNG group - Politecnico di Torino

Computer Network Design and Control- 11



Capone – Netsoft 2015

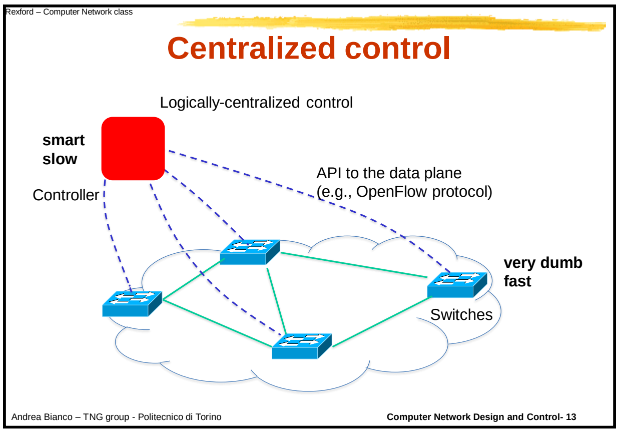
The new (centralized) model

Traditional networking
Distributed

Software-Defined Networking
Centralized

Andrea Bianco – TNG group - Politecnico di Torino

Computer Network Design and Control- 12



Rexford – Computer Network class

Centralized control

Logically-centralized control

smart
slow

Controller

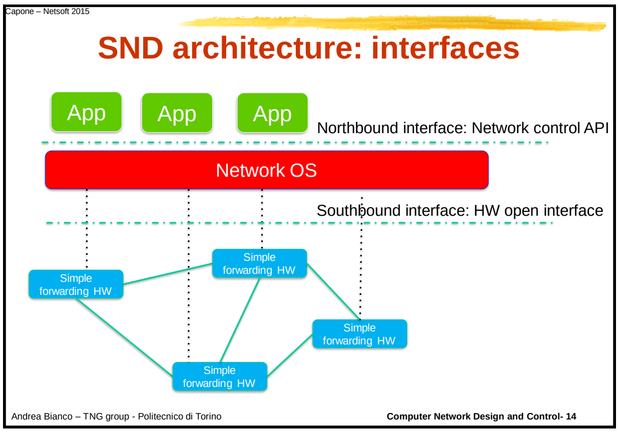
API to the data plane
(e.g., OpenFlow protocol)

very dumb
fast

Switches

Andrea Bianco – TNG group - Politecnico di Torino

Computer Network Design and Control- 13



Capone – Netsoft 2015

SND architecture: interfaces

App

App

App

Northbound interface: Network control API

Network OS

Southbound interface: HW open interface

Simple forwarding HW

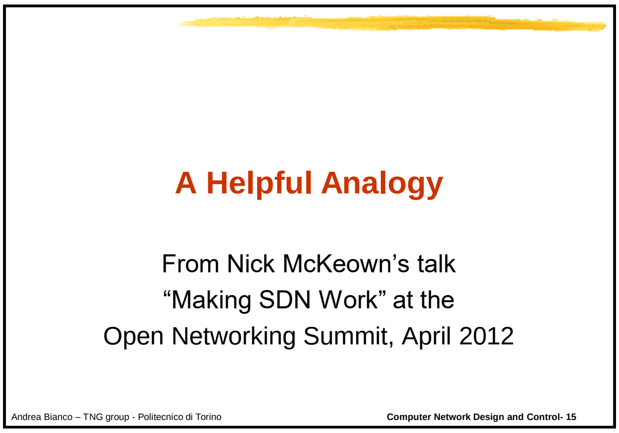
Simple forwarding HW

Simple forwarding HW

Simple forwarding HW

Andrea Bianco – TNG group - Politecnico di Torino

Computer Network Design and Control- 14

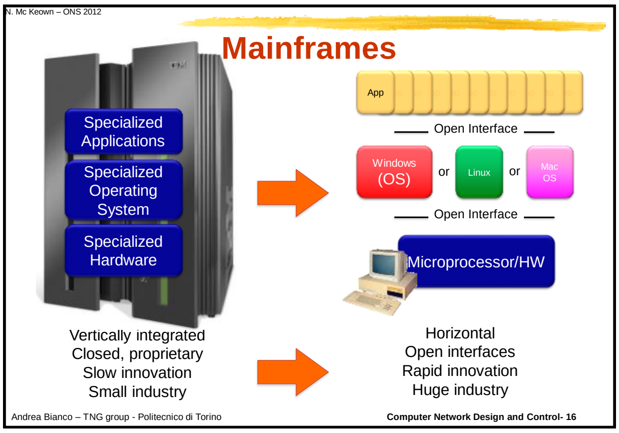


A Helpful Analogy

From Nick McKeown’s talk
“Making SDN Work” at the
Open Networking Summit, April 2012

Andrea Bianco – TNG group - Politecnico di Torino

Computer Network Design and Control- 15



N. Mc Keown – ONS 2012

Mainframes

Specialized Applications

Specialized Operating System

Specialized Hardware

App

Open Interface

Windows (OS) or Linux or Mac OS

Open Interface

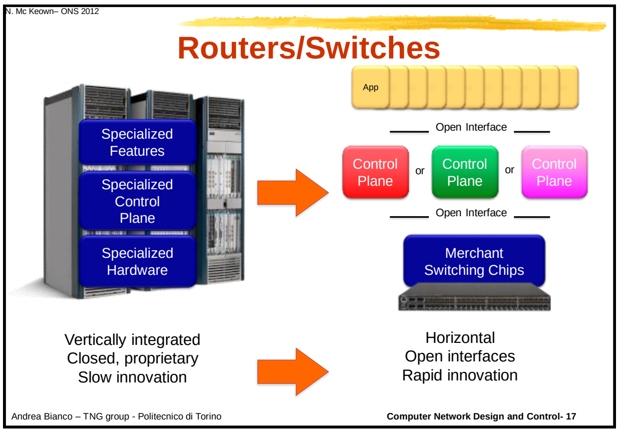
Microprocessor/HW

Vertically integrated
Closed, proprietary
Slow innovation
Small industry

Horizontal
Open interfaces
Rapid innovation
Huge industry

Andrea Bianco – TNG group - Politecnico di Torino

Computer Network Design and Control- 16



N. Mc Keown– ONS 2012

Routers/Switches

Specialized Features

Specialized Control Plane

Specialized Hardware

App

Open Interface

Control Plane or Control Plane or Control Plane

Open Interface

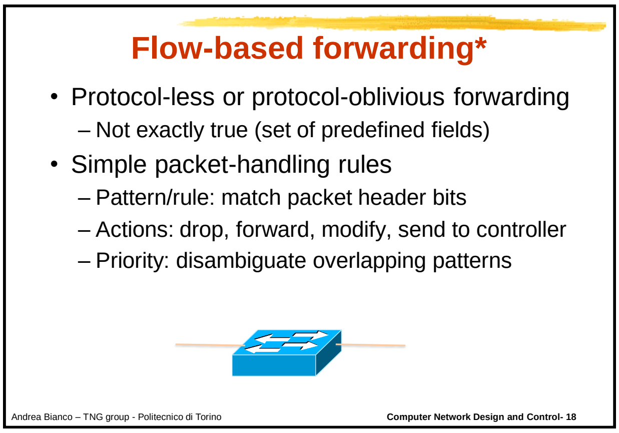
Merchant Switching Chips

Vertically integrated
Closed, proprietary
Slow innovation

Horizontal
Open interfaces
Rapid innovation

Andrea Bianco – TNG group - Politecnico di Torino

Computer Network Design and Control- 17

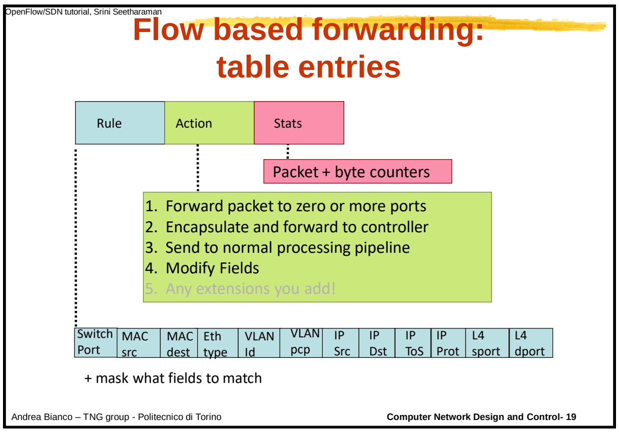


Flow-based forwarding*

- 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

Andrea Bianco – TNG group - Politecnico di Torino

Computer Network Design and Control- 18



OpenFlow/SDN tutorial, Srini Seetharaman

Flow based forwarding: table entries

Rule	Action	Stats

Packet + byte counters

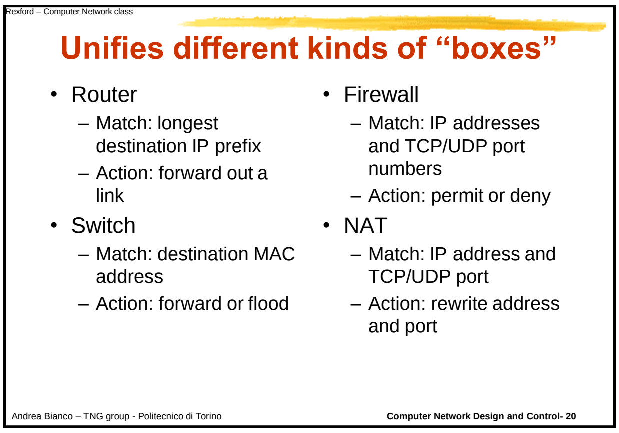
1. Forward packet to zero or more ports
2. Encapsulate and forward to controller
3. Send to normal processing pipeline
4. Modify Fields
5. Any extensions you add!

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

Andrea Bianco – TNG group - Politecnico di Torino

Computer Network Design and Control- 19



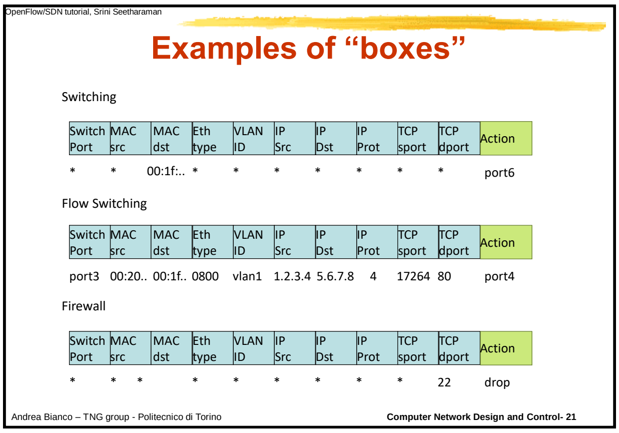
Rexford – Computer Network class

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

Andrea Bianco – TNG group - Politecnico di Torino

Computer Network Design and Control- 20



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

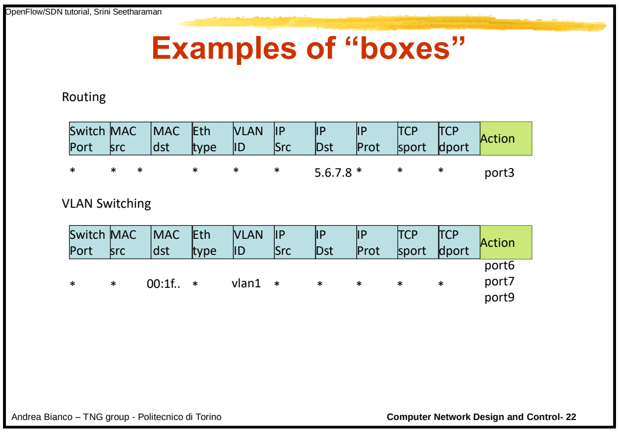
Switch Port	MAC src	MAC dst	Eth type	VLAN ID	IP Src	IP Dst	IP Prot	TCP sport	TCP dport	Action
port3	00:20..	00:1f..	0800	vlan1	1.2.3.4	5.6.7.8	4	17264	80	port4

Firewall

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

Andrea Bianco – TNG group - Politecnico di Torino

Computer Network Design and Control- 21



OpenFlow/SDN tutorial, Srini Seetharaman

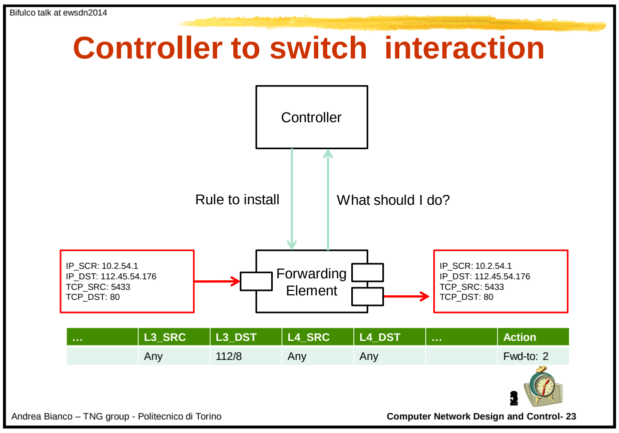
Examples of “boxes”

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



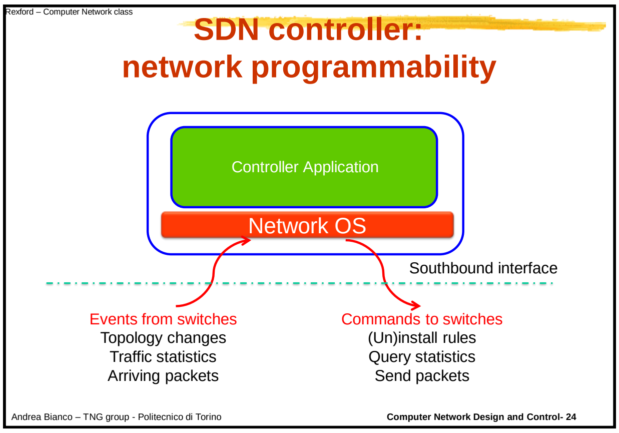
Bifulco talk at ewsdn2014

Controller to switch interaction

IP_SCR: 10.2.54.1
IP_DST: 112.45.54.176
TCP_SRC: 5433
TCP_DST: 80

IP_SCR: 10.2.54.1
IP_DST: 112.45.54.176
TCP_SRC: 5433
TCP_DST: 80

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

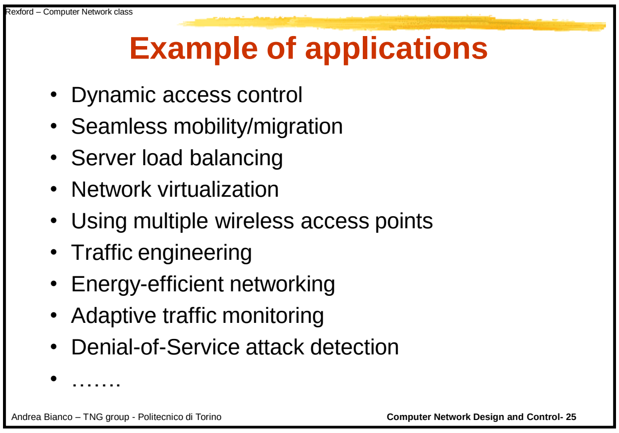


Rexford – Computer Network class

SDN controller: network programmability

Events from switches
Topology changes
Traffic statistics
Arriving packets

Commands to switches
(Un)install rules
Query statistics
Send packets



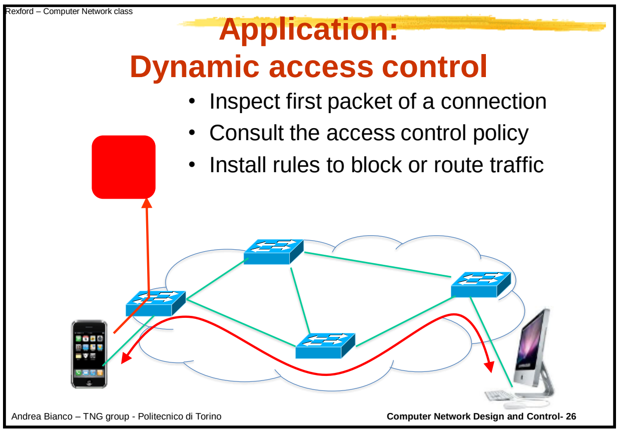
Rexford – Computer Network class

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
- …….

Andrea Bianco – TNG group - Politecnico di Torino

Computer Network Design and Control- 25



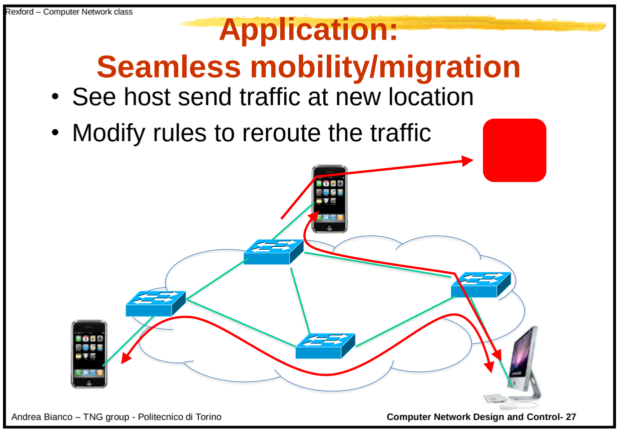
Rexford – Computer Network class

Application: Dynamic access control

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

Andrea Bianco – TNG group - Politecnico di Torino

Computer Network Design and Control- 26



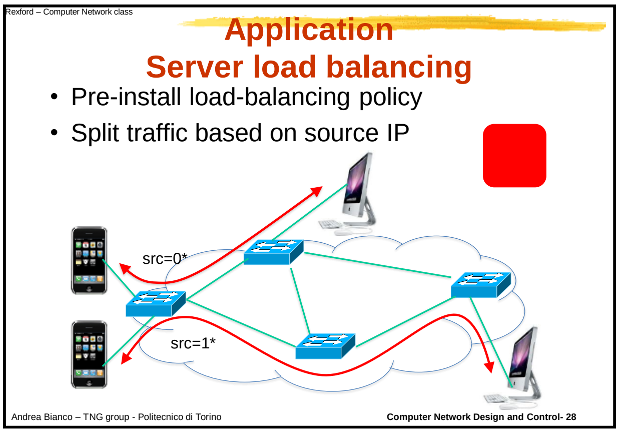
Rexford – Computer Network class

Application: Seamless mobility/migration

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

Andrea Bianco – TNG group - Politecnico di Torino

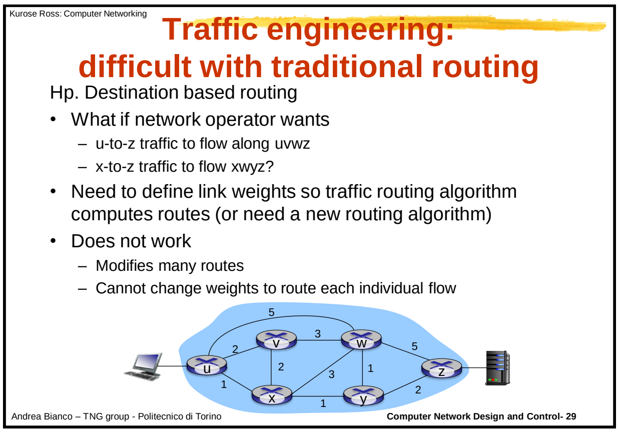
Computer Network Design and Control- 27



Rexford – Computer Network class

Application
Server load balancing

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

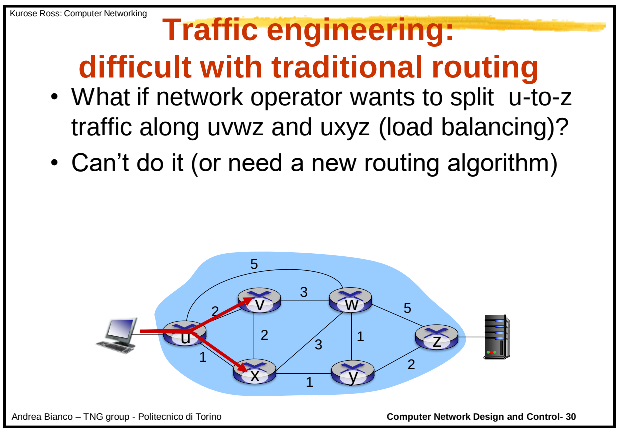


Kurose Ross: Computer Networking

Traffic engineering:
difficult with traditional routing

Hp. Destination based routing

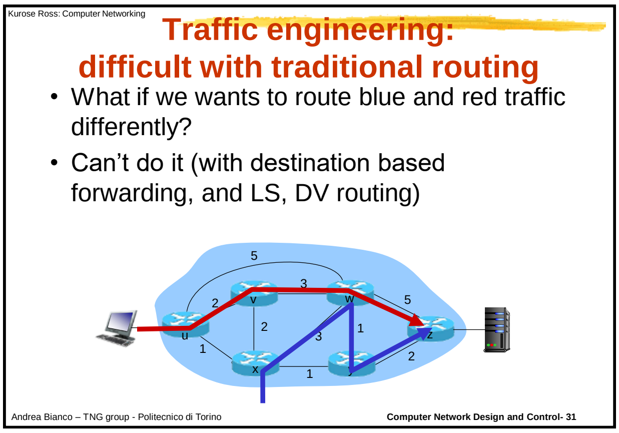
- What if network operator wants
  - u-to-z traffic to flow along uvwz
  - x-to-z traffic to flow xwyz?
- Need to define link weights so traffic routing algorithm computes routes (or need a new routing algorithm)
- Does not work
  - Modifies many routes
  - Cannot change weights to route each individual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


Kurose Ross: Computer Networking

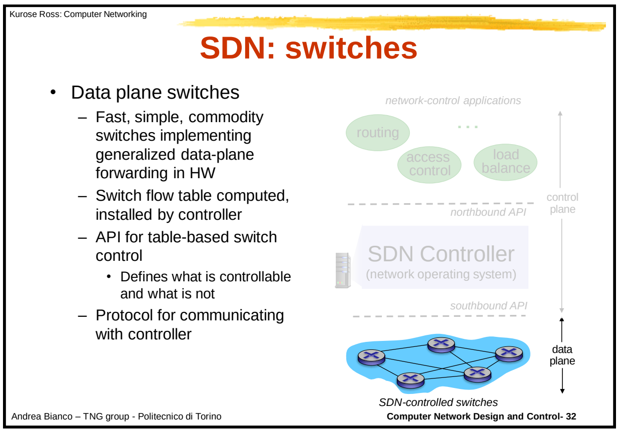
Traffic engineering: difficult with traditional routing

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

5
3
2
v
w
5
u
2
3
1
z
1
2
x
y
1

Andrea Bianco – TNG group - Politecnico di Torino

Computer Network Design and Control- 31


Kurose Ross: Computer Networking

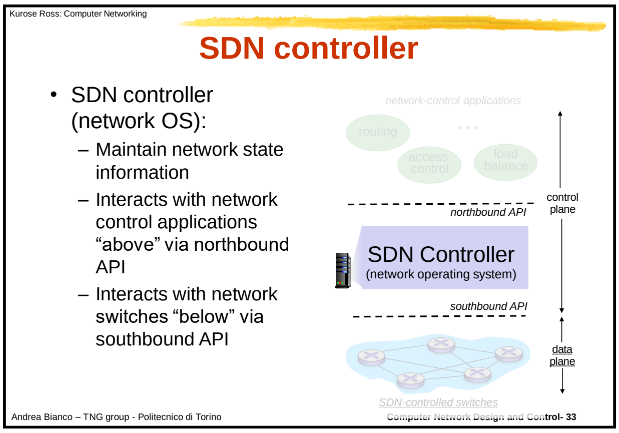
SDN: switches

- 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

network-control applications
routing
. . .
access control
load balance
northbound API
control plane
SDN Controller
(network operating system)
southbound API
data plane
SDN-controlled switches

Andrea Bianco – TNG group - Politecnico di Torino

Computer Network Design and Control- 32


Kurose Ross: Computer Networking

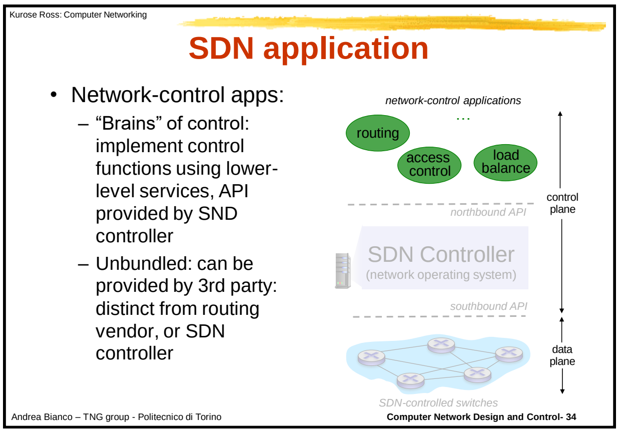
SDN controller

- 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

network-control applications
routing
. . .
access control
load balance
northbound API
control plane
SDN Controller
(network operating system)
southbound API
data plane
SDN-controlled switches

Andrea Bianco – TNG group - Politecnico di Torino

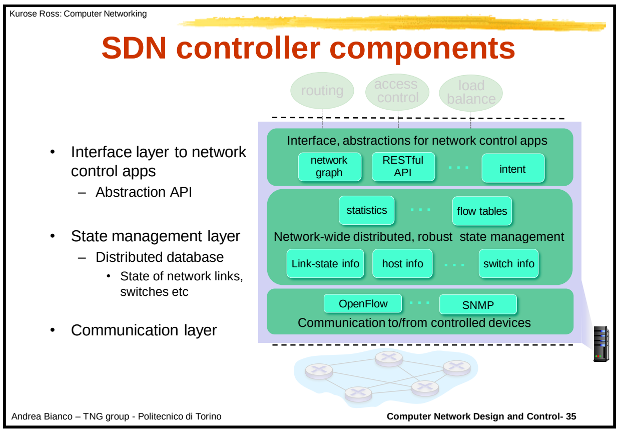
Computer Network Design and Control- 33



Kurose Ross: Computer Networking

SDN application

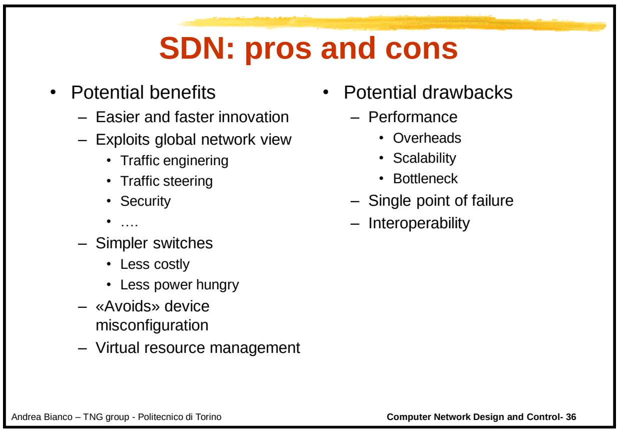
- Network-control apps:
  - “Brains” of control: implement control functions using lower-level services, API provided by SND controller
  - Unbundled: can be provided by 3rd party: distinct from routing vendor, or SDN controller



Kurose Ross: Computer Networking

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

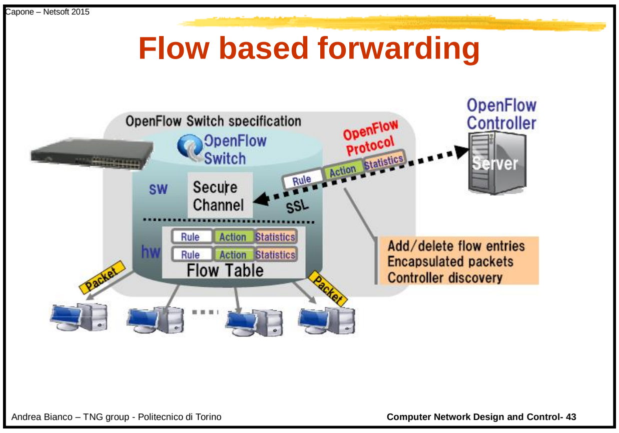
- Reactive
  - Flow table empty at boot
  - First packet of a flow sent to the controller
  - Controller inserts flow entries
  - Dynamic network

  - 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

Andrea Bianco
andrea.bianco@polito.it
http://www.telematica.polito.it/

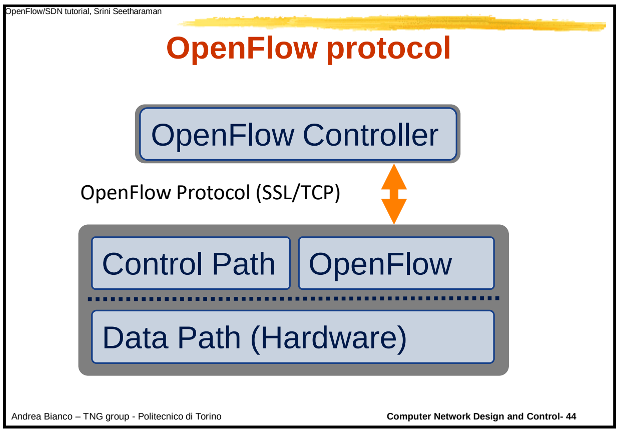


Capone – Netsoft 2015

Flow based forwarding

Andrea Bianco – TNG group - Politecnico di Torino

Computer Network Design and Control- 43

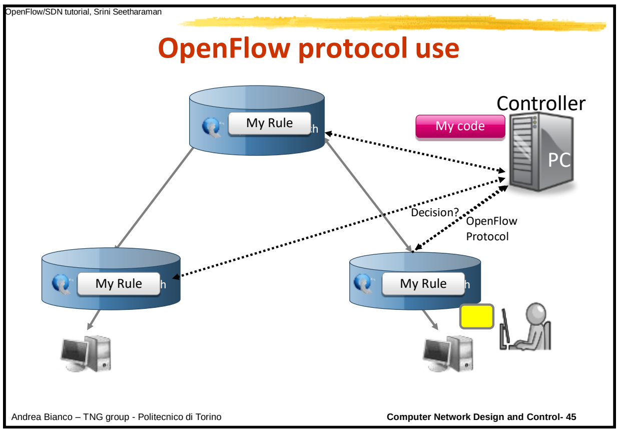


OpenFlow/SDN tutorial, Srini Seetharaman

OpenFlow protocol

Andrea Bianco – TNG group - Politecnico di Torino

Computer Network Design and Control- 44

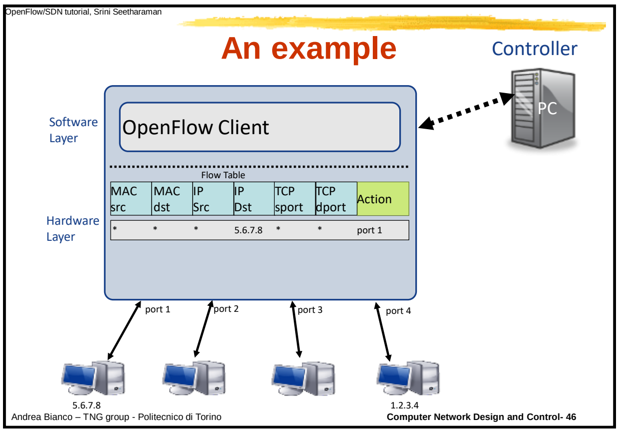


OpenFlow/SDN tutorial, Srini Seetharaman

OpenFlow protocol use

Andrea Bianco – TNG group - Politecnico di Torino

Computer Network Design and Control- 45



OpenFlow/SDN tutorial, Srini Seetharaman

An example

Controller

PC

Software Layer

OpenFlow Client

Hardware Layer

Flow Table

MAC src	MAC dst	IP Src	IP Dst	TCP sport	TCP dport	Action
*	*	*	5.6.7.8	*	*	port 1

port 1

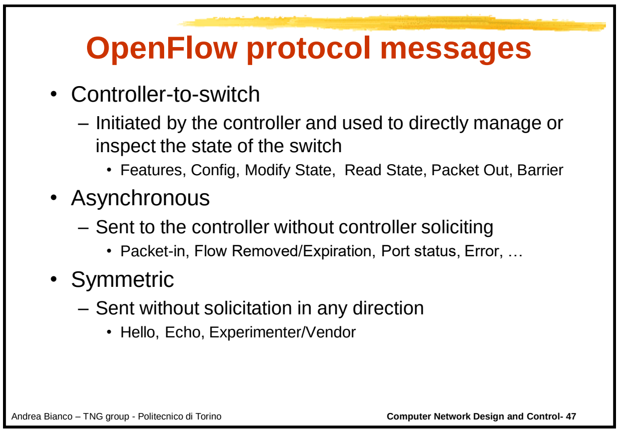
port 2

port 3

port 4

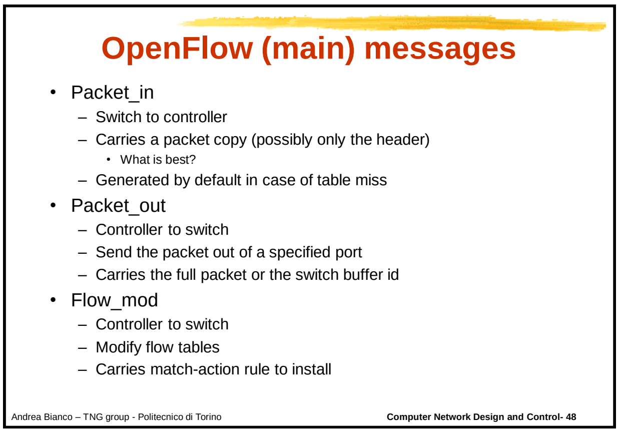
5.6.7.8

1.2.3.4



OpenFlow protocol messages

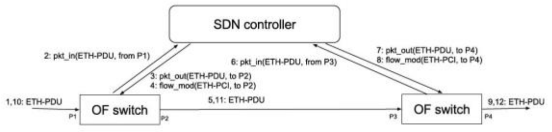
- Controller-to-switch
  - Initiated by the controller and used to directly manage or inspect the state of the switch
    - Features, Config, Modify State, Read State, Packet Out, Barrier
- Asynchronous
  - Sent to the controller without controller soliciting
    - Packet-in, Flow Removed/Expiration,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



OpenFlow (main) messages

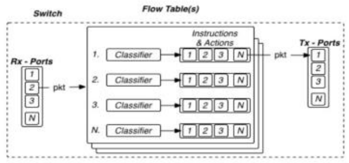
- Packet_in
  - Switch to controller
  - Carries a packet copy (possibly only the header)
    - What is best?
  - Generated by default in case of table miss
- Packet_out
  - Controller to switch
  - Send the packet out of a specified port
  - Carries the full packet or the switch buffer id
- Flow_mod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

OpenFlow example


SDN controller
2: pkt_in(ETH-PDU, from P1)
3: pkt_out(ETH-PDU, to P2)
4: flow_mod(ETH-PCI, to P2)
6: pkt_in(ETH-PDU, from P3)
7: pkt_out(ETH-PDU, to P4)
8: flow_mod(ETH-PCI, to P4)
1,10: ETH-PDU
OF switch
P1
P2
5,11: ETH-PDU
P3
OF switch
P4
9,12: ETH-PDU

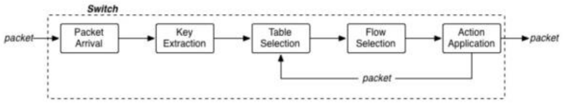
Packet processing

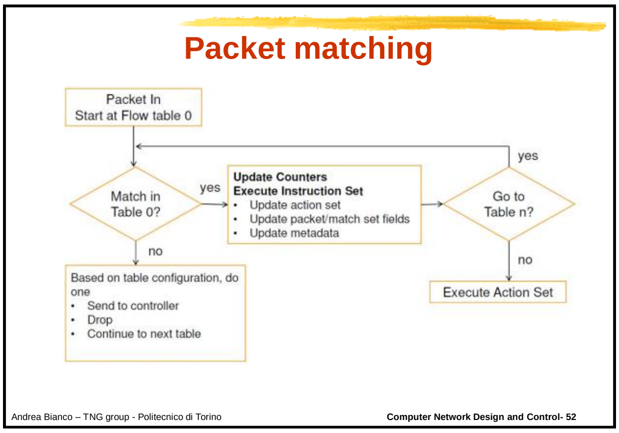
- Packets arrive and leave through ports
- Packets are matched to flow in flow tables using classifiers
- Flows contain set of instructions and actions applied to each packet in the match



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

Packet In
Start at Flow table 0

Match in Table 0?

yes

Update Counters
Execute Instruction Set
- Update action set
- Update packet/match set fields
- Update metadata

Go to Table n?

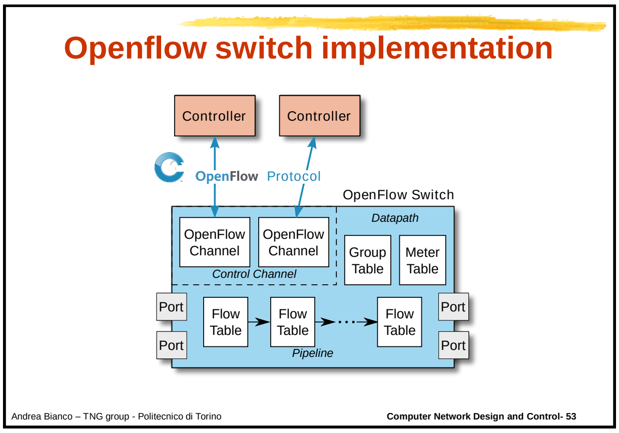
yes

no

Execute Action Set

no

Based on table configuration, do one
- Send to controller
- Drop
- Continue to next table



Openflow switch implementation

Controller

Controller

OpenFlow Protocol

OpenFlow Switch

Datapath

OpenFlow Channel

OpenFlow Channel

Control Channel

Group Table

Meter Table

Port

Port

Flow Table

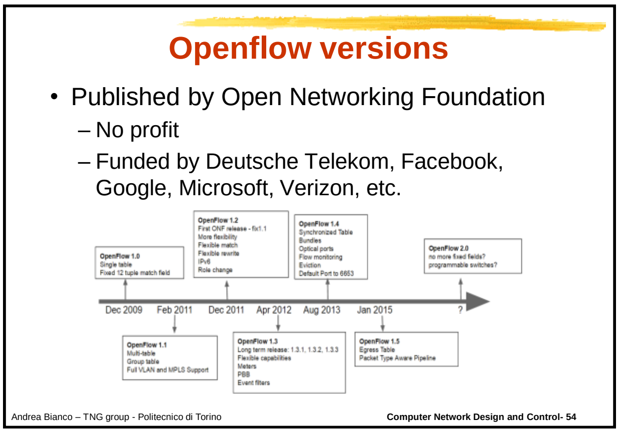
Flow Table

Flow Table

Port

Port

Pipeline



Openflow versions

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

OpenFlow 1.0
Single table
Fixed 12 tuple match field

OpenFlow 1.2
First ONF release - fix1.1
More flexibility
Flexible match
Flexible rewrite
IPv6
Role change

OpenFlow 1.4
Synchronized Table
Bundles
Optical ports
Flow monitoring
Eviction
Default Port to 6653

OpenFlow 2.0
no more fixed fields?
programmable switches?

Dec 2009 Feb 2011 Dec 2011 Apr 2012 Aug 2013 Jan 2015 ?

OpenFlow 1.1
Multi-table
Group table
Full VLAN and MPLS Support

OpenFlow 1.3
Long term release: 1.3.1, 1.3.2, 1.3.3
Flexible capabilities
Meters
PBB
Event filters

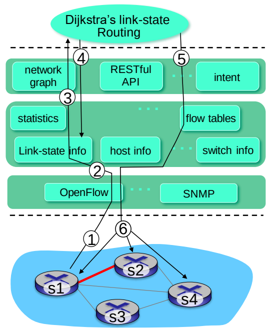
OpenFlow 1.5
Egress Table
Packet Type Aware Pipeline

SDN architecture in action

Andrea Bianco
andrea.bianco@polito.it
http://www.telematica.polito.it/

From Kurose Ross: Computer Networking

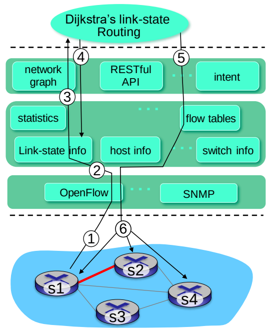
An example



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



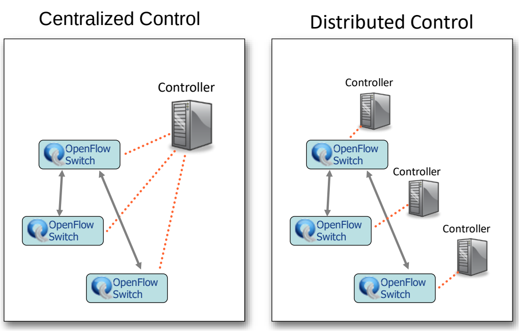
5. Link state routing app interacts with flow-table-computation component in SDN controller, which computes new flow tables needed
6. Controller uses OpenFlow to install new tables in switches that need updating

Distributed controllers

Andrea Bianco
andrea.bianco@polito.it
http://www.telematica.polito.it/

Srini Seetharaman, OpenFlow/SDN tutorial

Centralized vs Distributed Control



Why distributed/multiple controllers?

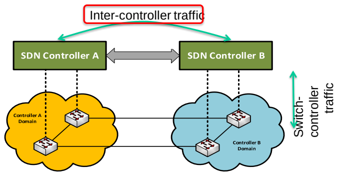
- To enhance resilience to failures
  - Controller failures can be managed
  - Still to deal with failures in data and control plane
- To solve scalability issues
  - Faster controllers
    - Limited scaling
  - More proactive rules to reduce number of requests
    - Limited flexibility
  - Multiple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

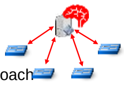


Stateful data plane

Andrea Bianco
andrea.bianco@polito.it
http://www.telematica.polito.it/

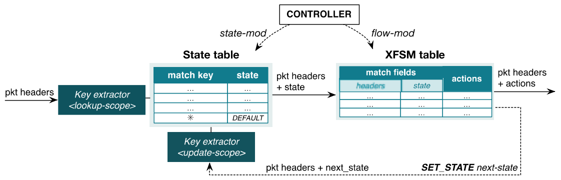
Stateful SDN dataplane

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



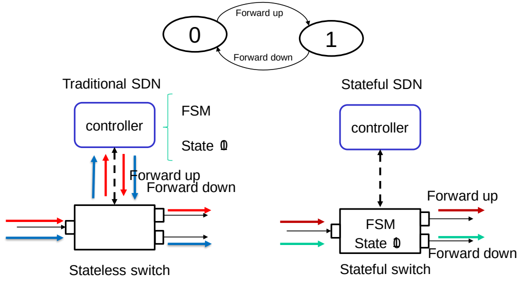
- Stateful approach: OpenState, OpenPacketProcessor (OPP), P4
  - Permit some level of stateful processing (e.g., finite state machines) within switches
    - OpenState adds a state table (IF state A THEN IF state B THEN)
    - OpenPacketProcessor: state defined with multiple variables, counters,
  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

Hardware implementation



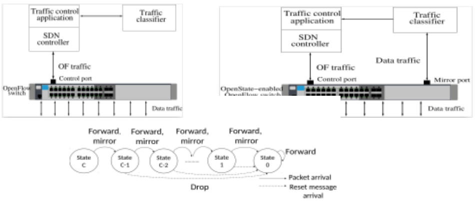
Toy example

- 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



Andrea Bianco – TNG group - Politecnico di Torino

Computer Network Design and Control- 67

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

Andrea Bianco – TNG group - Politecnico di Torino

Computer Network Design and Control- 68