CS452/552
Software Defined Networking

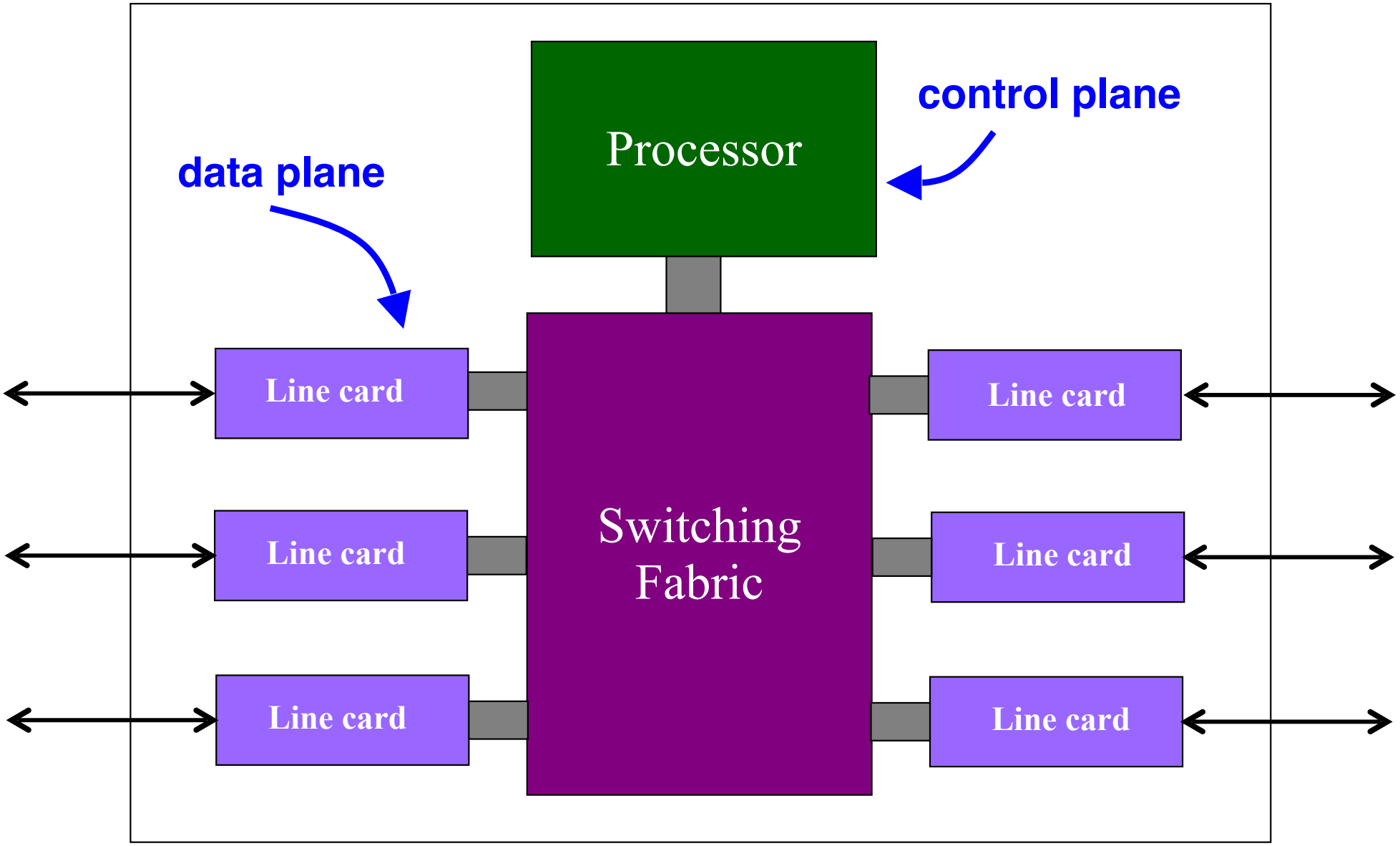
Based on slides by J. Rexford @ Princeton & N. Mckeown @ Stanford & S. Shenker @ Berkeley & P. Gill @ Umass

Data, Control, and Management Planes

Timescales

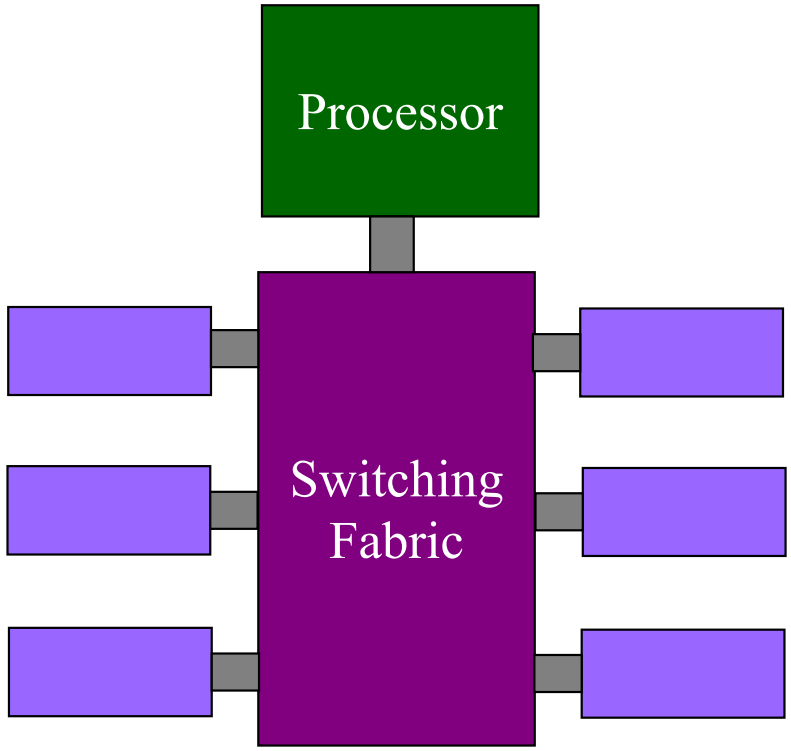
	Data	Control	Management
Time-scale	Packet (nsec)	Event (10 msec to sec)	Human (min to hours)
Tasks	Forwarding, buffering, filtering, scheduling	Routing, circuit set-up	Analysis, configuration
Location	Line-card hardware	Router software	Humans or scripts

Data and Control Planes



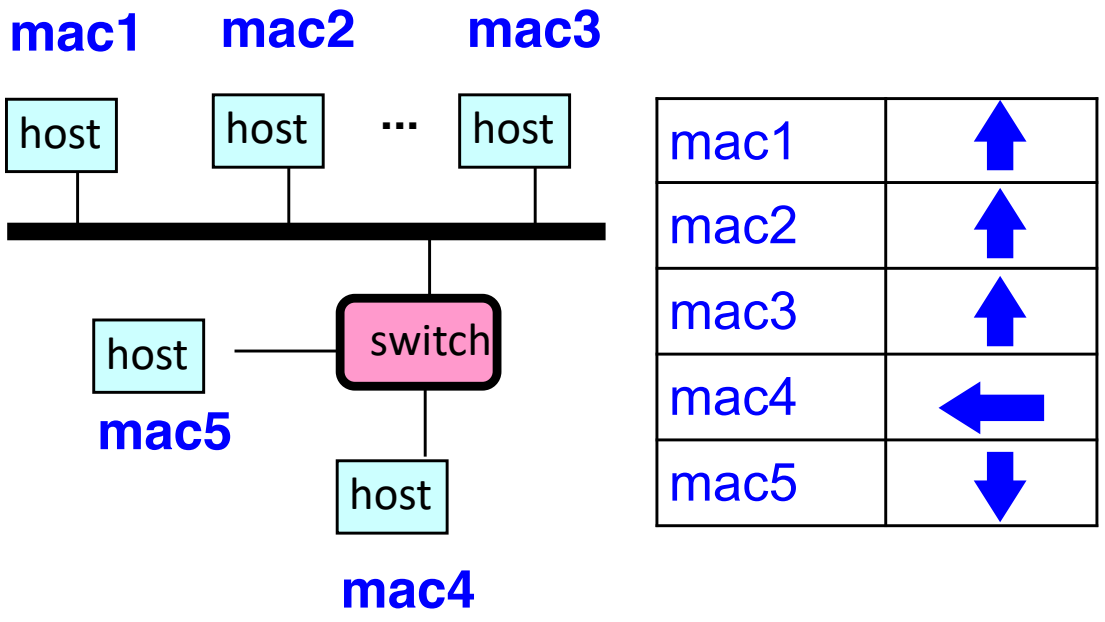
Data Plane

- Streaming algorithms on packets
  - Matching on some bits
  - Perform some actions
- Wide range of functionality
  - Forwarding
  - Access control
  - Mapping header fields
  - Traffic monitoring
  - Buffering and marking
  - Shaping and scheduling
  - Deep packet inspection



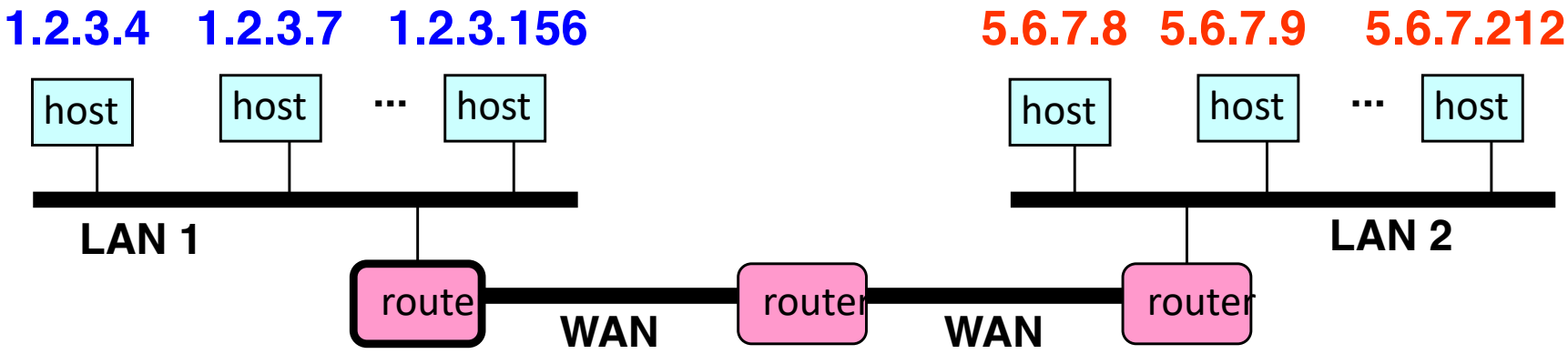
Switch: Match on Destination MAC

- MAC addresses are location independent
  - Assigned by the vendor of the interface card
  - Cannot be aggregated across hosts in LAN



Router: Match on IP Prefix

- IP addresses grouped into common subnets
  - Allocated by ICANN, regional registries, ISPs, and within individual organizations
  - Variable-length prefix identified by a mask length



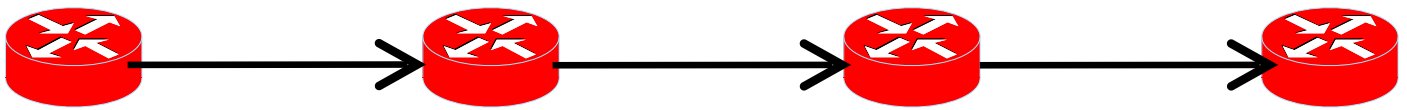
1.2.3.0/24	←
5.6.7.0/24	→

forwarding table

Prefixes may be nested. Routers identify the *longest matching* prefix.

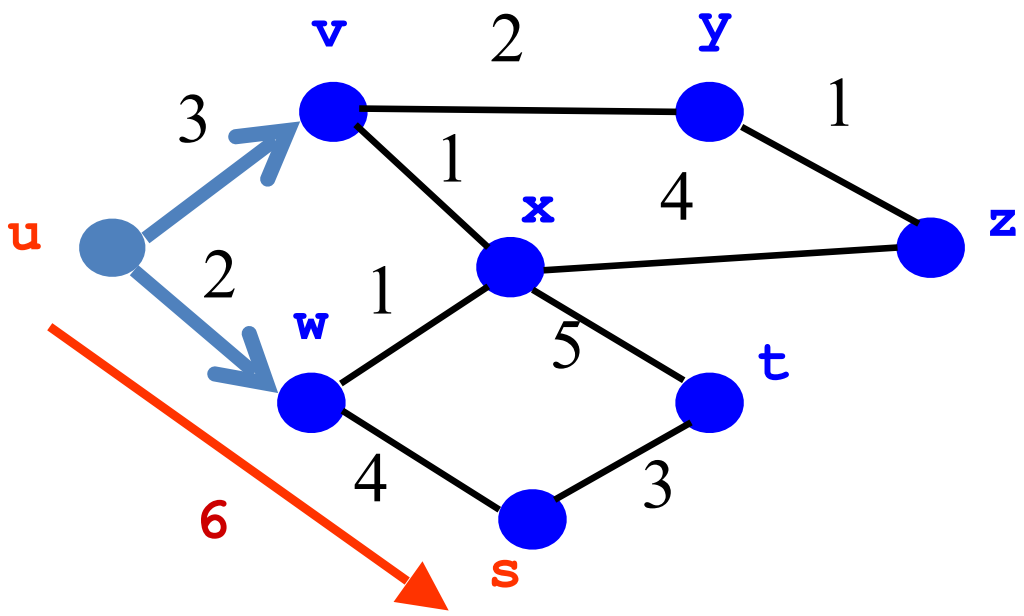
Forwarding vs. Routing

- Forwarding: data plane
  - Directing a data packet to an outgoing link
  - Individual router *using* a forwarding table
- Routing: control plane
  - Computing paths the packets will follow
  - Routers talking amongst themselves
  - Individual router ***creating*** a forwarding table



Routing Example: Shortest-Path Routing

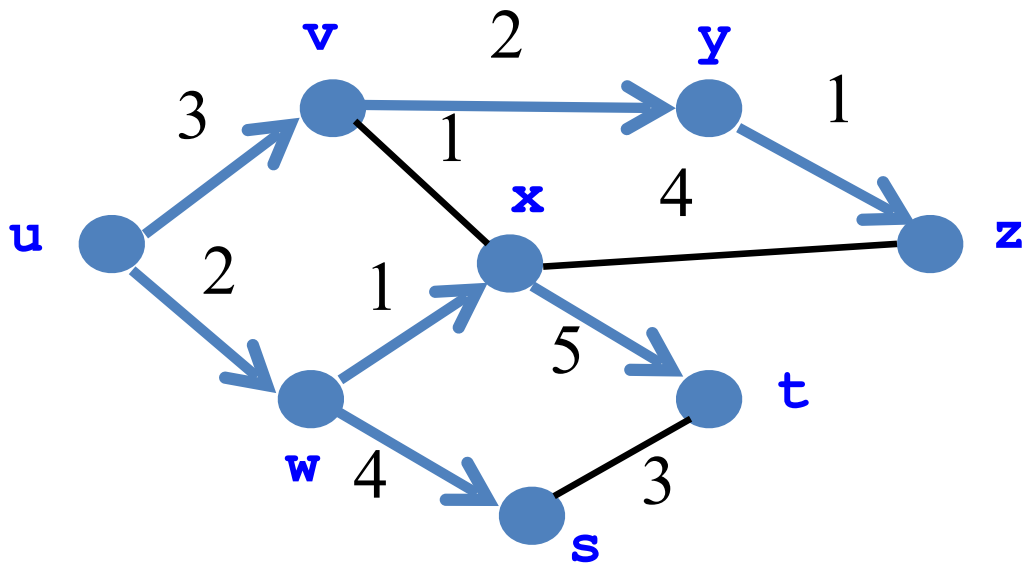
- Compute: *path costs* to all nodes
  - From a source u to all other nodes
  - Cost of the path through each link
  - Next hop along least-cost path to s



Dest	link
v	(u,v)
w	(u,w)
x	(u,w)
y	(u,v)
z	(u,v)
s	(u,w)
t	(u,w)

Distributed Control Plane

- Link-state routing: OSPF, IS-IS
  - Flood the entire topology to all nodes
  - Each node computes shortest paths
  - Dijkstra's algorithm



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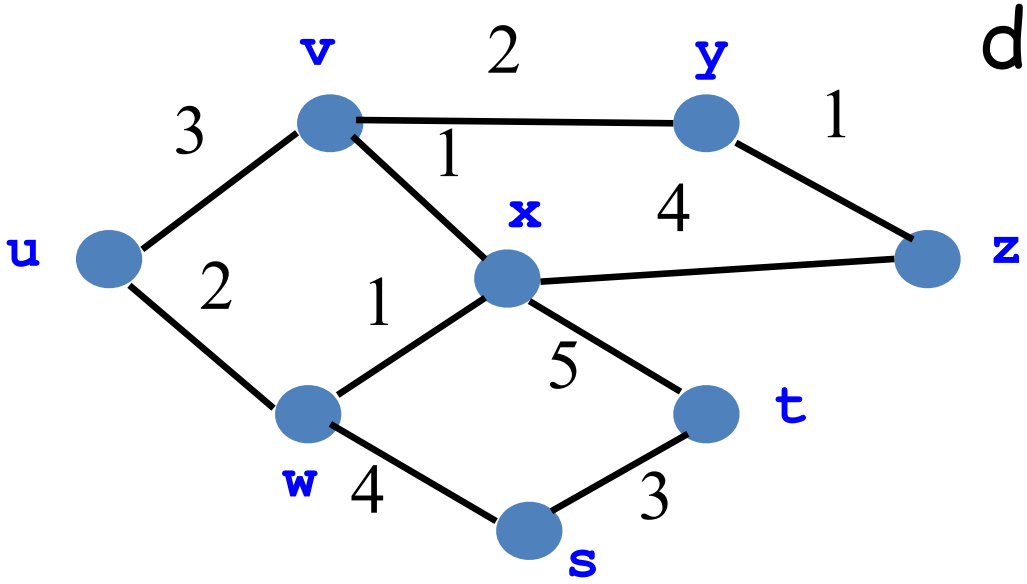
Distributed Control Plane

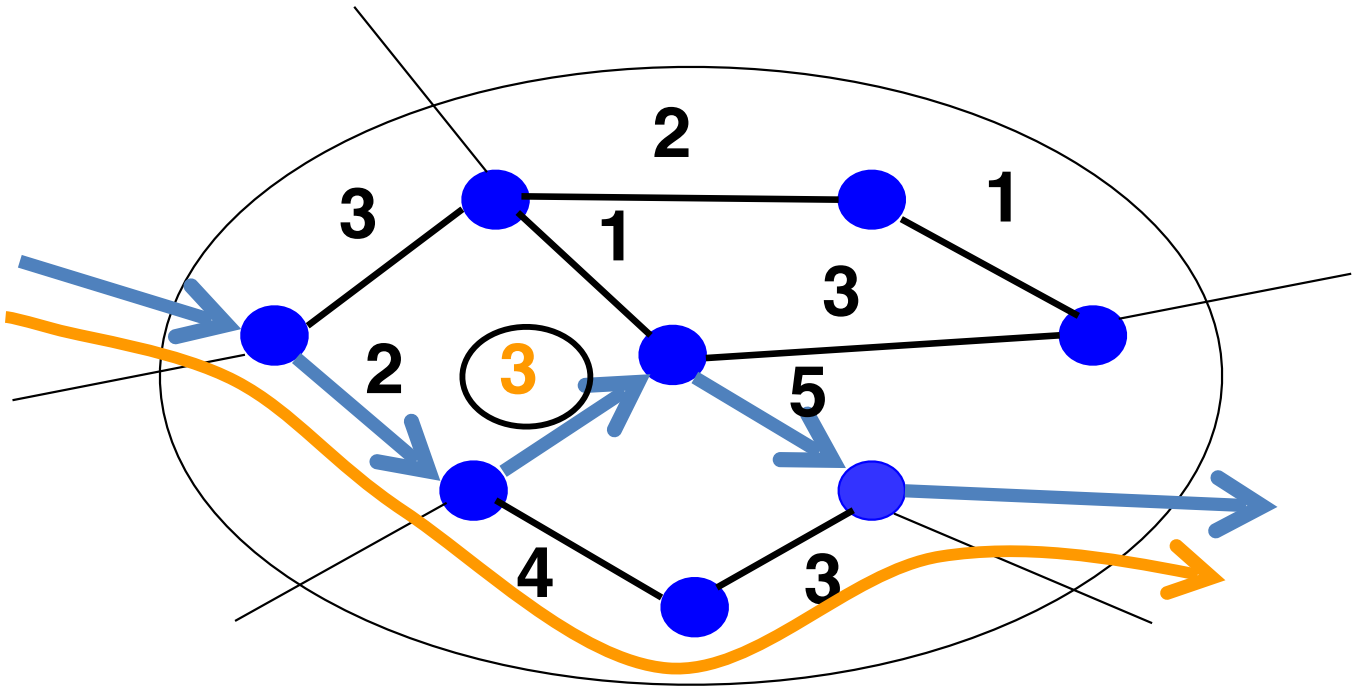
- Distance-vector routing: RIP, EIGRP
  - Each node computes path cost
  - … based on each neighbors' path cost
  - Bellman-Ford algorithm



$$d_u(z) = \min\{c(u,v) + d_v(z), \; c(u,w) + d_w(z)\}$$

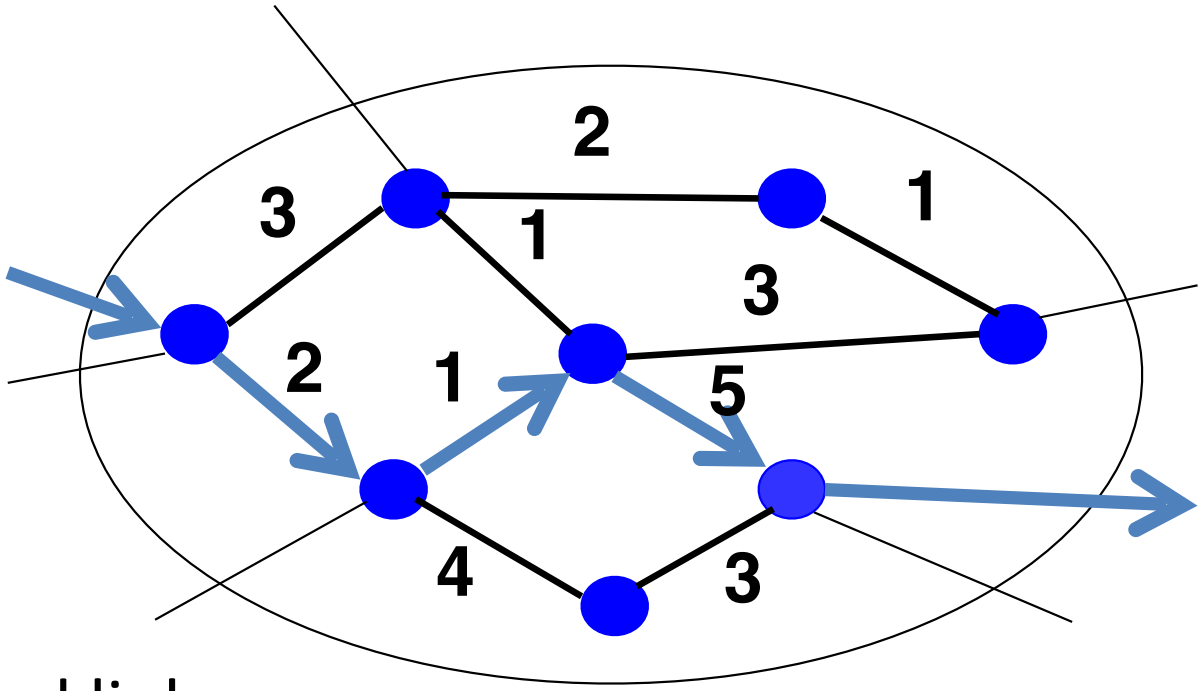
Traffic Engineering Problem

- Management plane: setting the weights
  - Inversely proportional to link capacity?
  - Proportional to propagation delay?
  - Network-wide optimization based on traffic?



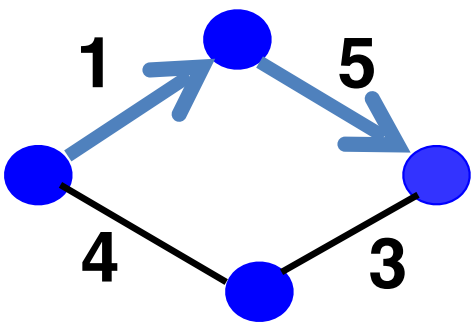
Traffic Engineering: Optimization

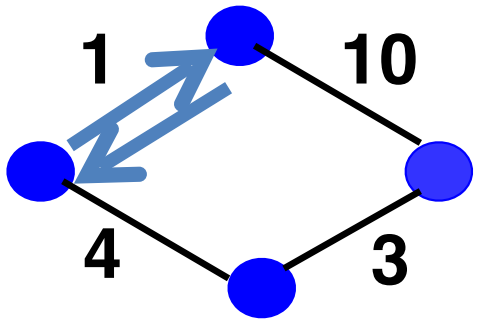
- Inputs
  - Network topology
  - Link capacities
  - Traffic matrix
- Output
  - Link weights
- Objective
  - Minimize max-utilized link
  - Or, minimize a sum of link congestion
  - Or, maximize QoS for highest paying customers
  - Or, something else

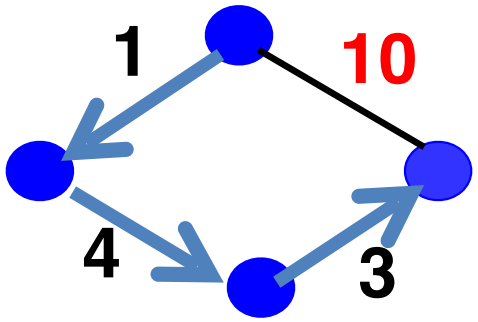


Transient Routing Disruptions

- Topology changes
  - Link weight change
  - Node/link failure or recovery
- Routing convergence
  - Nodes temporarily disagree how to route
  - Leading to transient loops and blackholes







Management Plane Challenges

- Indirect control
  - Changing weights instead of paths
  - Complex optimization problem
- Uncoordinated control
  - Cannot control which router updates first
- Interacting protocols and mechanisms
  - Routing and forwarding
  - Naming and addressing
  - Access control
  - Quality of service
  - …

Software Defined Networking (high level view)

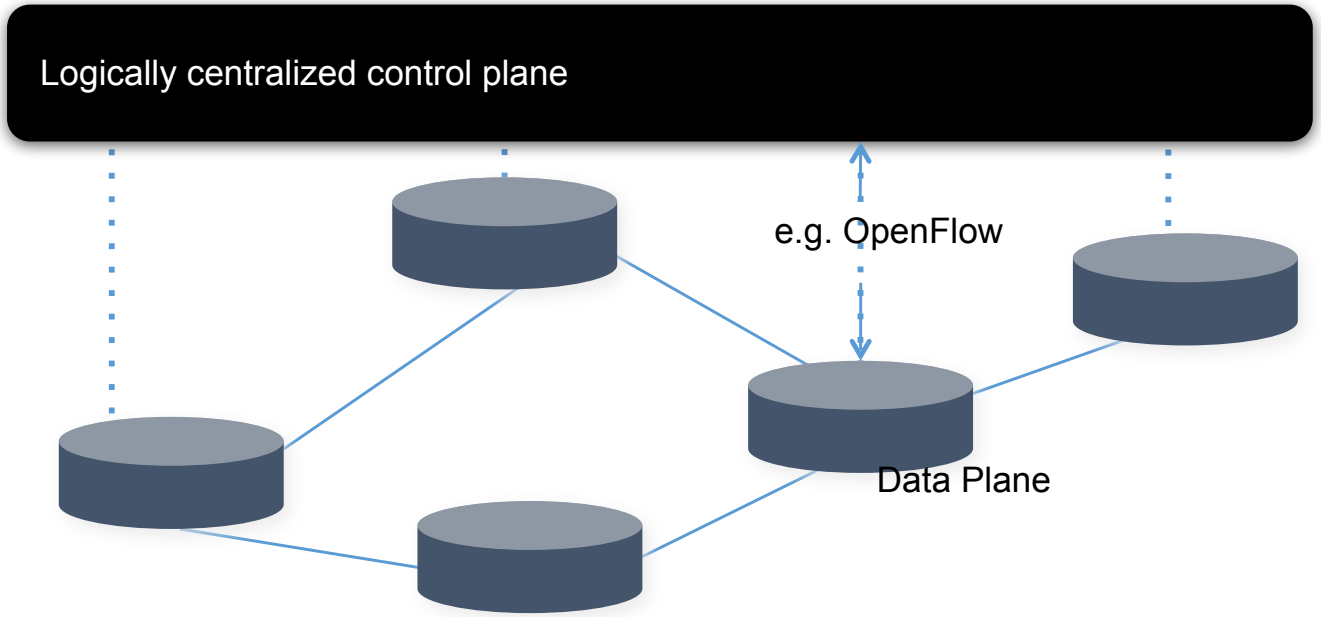
Virtualization of networks

Virtualization of resources: a powerful abstraction in systems engineering:

- computing examples: virtual memory, virtual devices
  - Virtual machines: e.g., java, vmware
  - IBM VM os from 1960's/70's
- layering of abstractions
  - don't sweat the details of the lower layer, only deal with lower layers abstractly

What is SDN?

- SDN (software-defined networking) is the separation of control and data planes
  - The separation allows control topology to be independent of physical network topology



Why SDN?

Great talk by Scott Shenker

http://www.youtube.com/watch?v=WVs7Pc99S7w

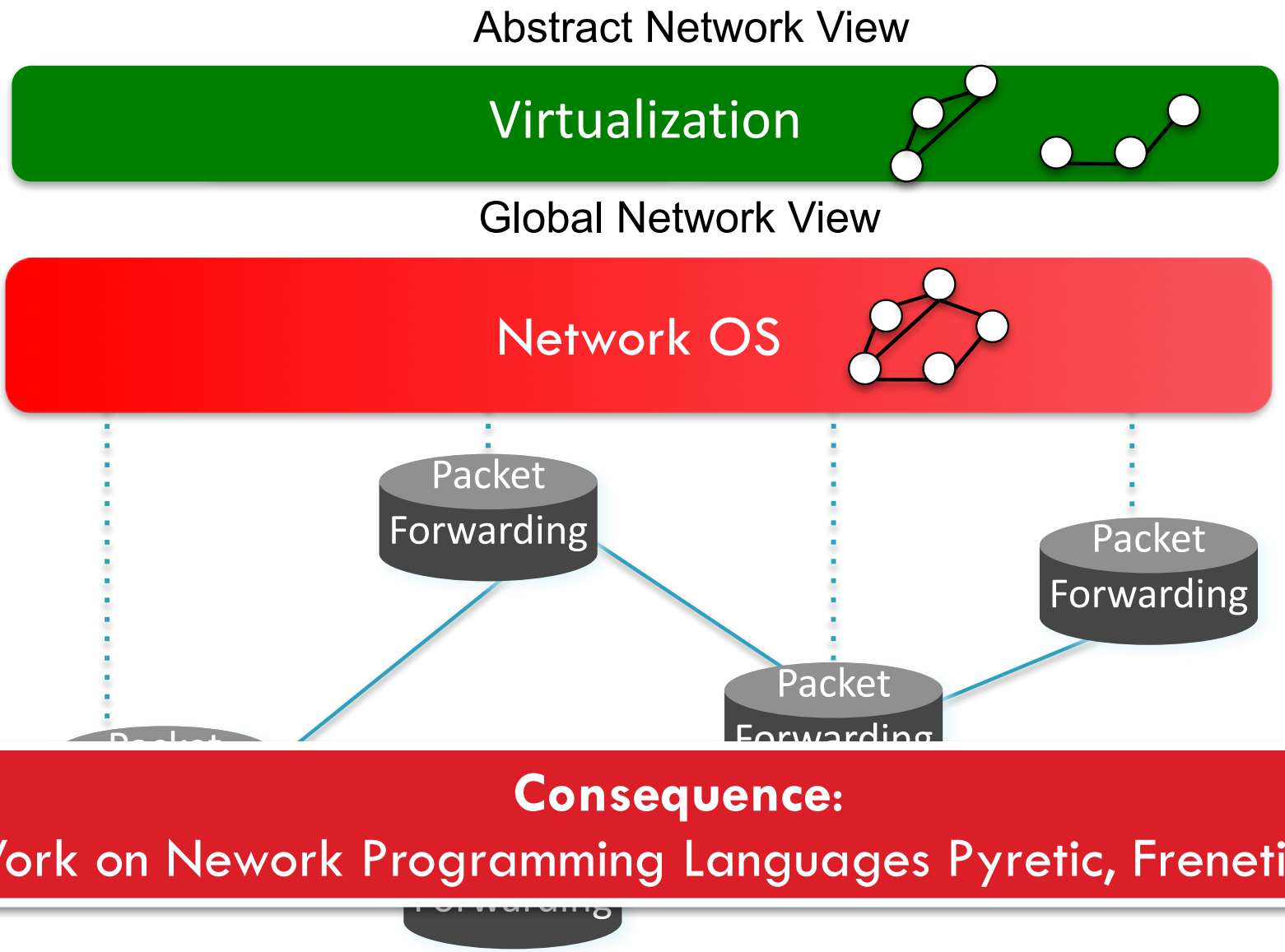
Networking and Lack of Abstractions

- Lack of abstractions
- Inability to express intent
- Unpredictable outcome from complex distributed algorithms
- Interactions among protocols (e.g. IGP & EGP)
- Can’t manage a device unless it’s properly configured
  - bootstrap issue – control & management plane dependent on correct data plane
  - Fragility, risk of change
- Glacial pace of innovation

By comparison: Programming

- Machine languages: no abstractions
  - Had to deal with low-level details
- Higher-level languages: OS and other abstractions
  - File system, virtual memory, abstract data types, ...
- Modern languages: even more abstractions
  - Object orientation, garbage collection,…

Software Defined Network (SDN)



Consequence:
Work on Nework Programming Languages Pyretic, Frenetic etc.

Recap: Timescales

	Data	Control	Management
Time-scale	Packet (nsec)	Event (10 msec to sec)	Human (min to hours)
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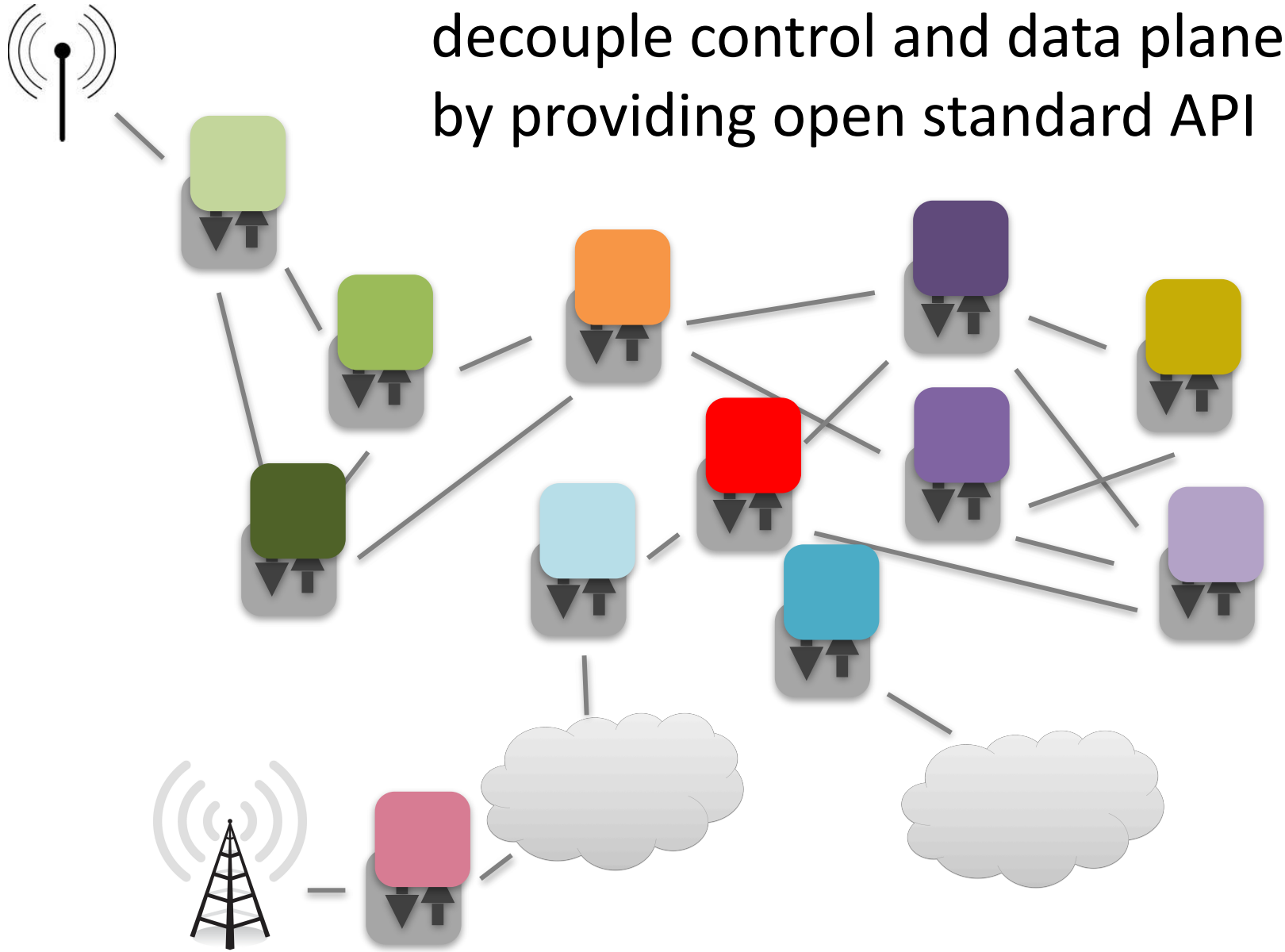
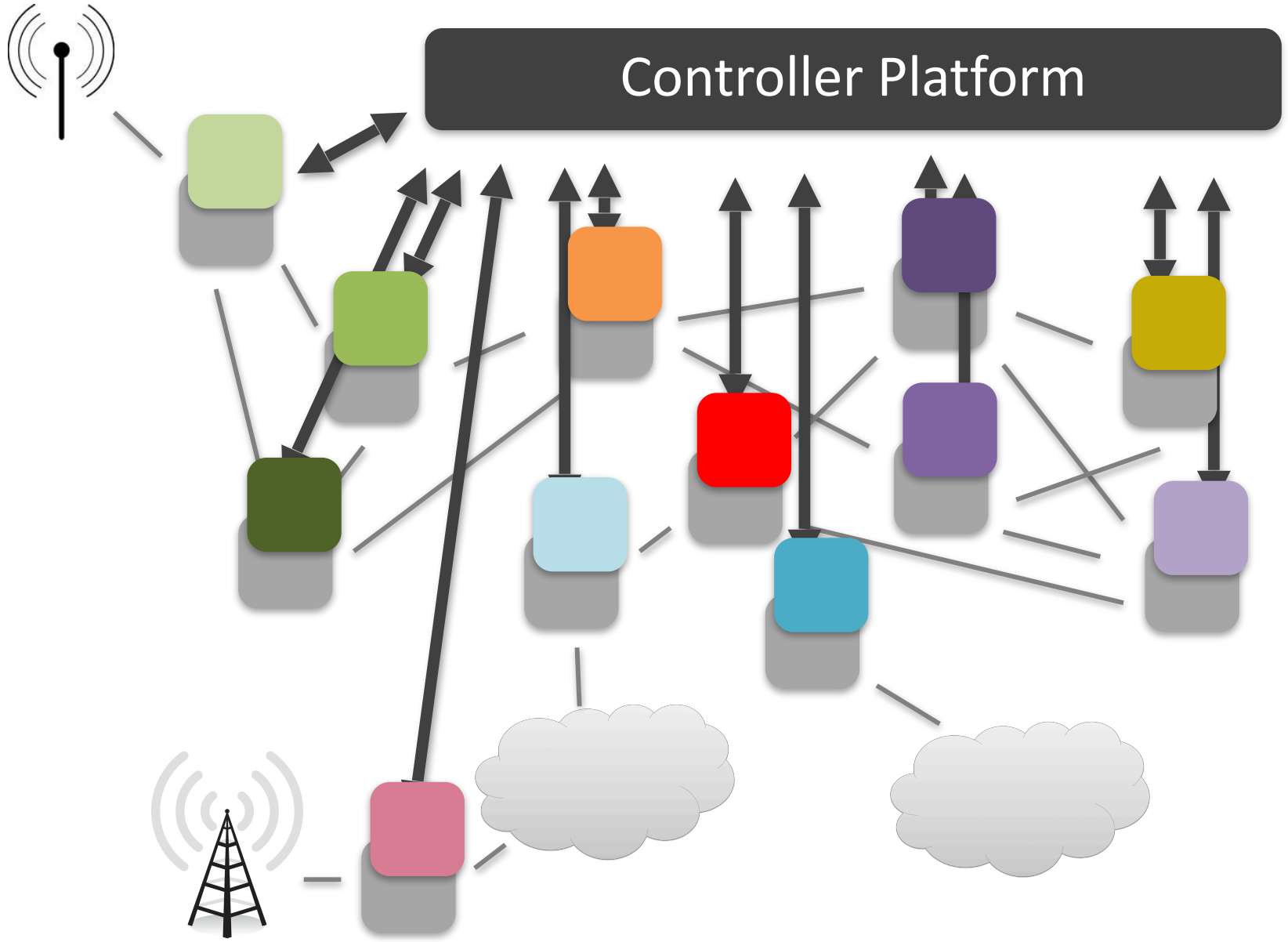
Control/Data Separation

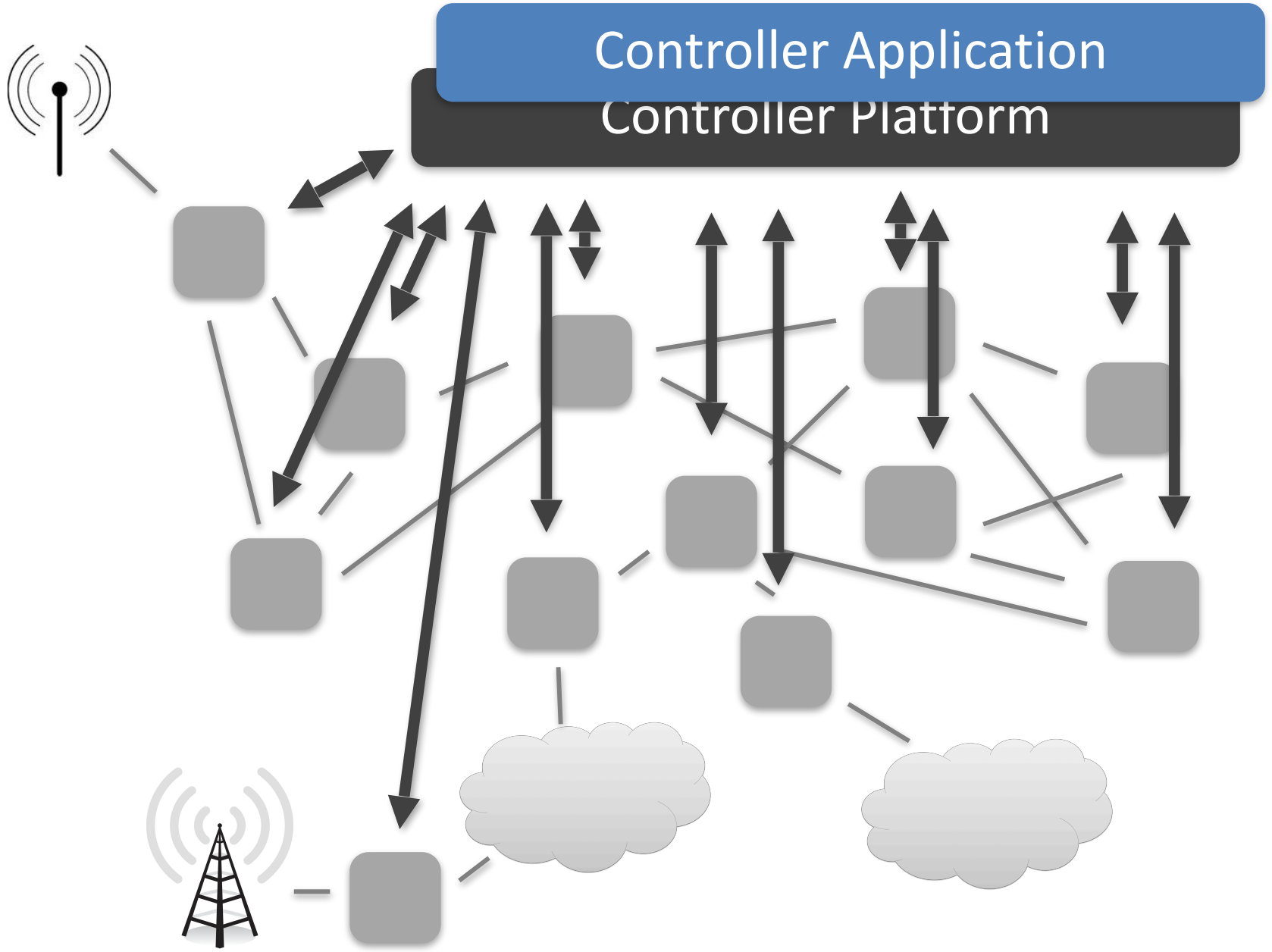
decouple control and data planes
by providing open standard API



Logically Centralized Controller



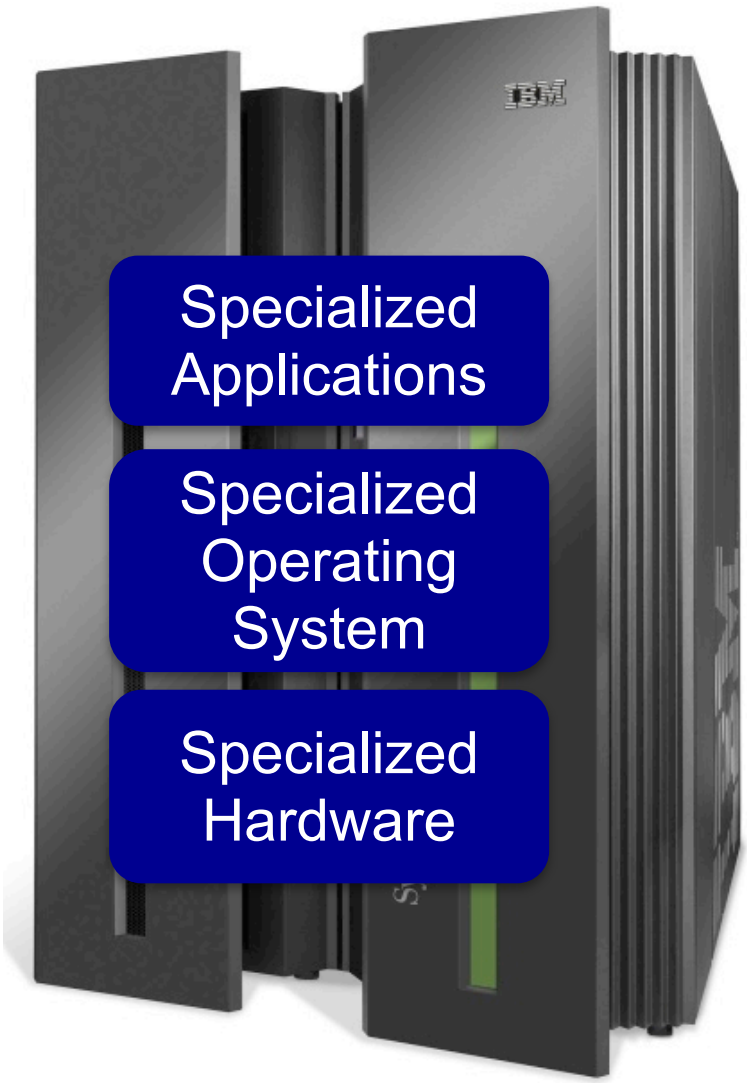
Transition from thinking of Protocols to Applications



Key SDN Insights

- Centralizing the control plane enables more powerful abstractions
  - E.g. X and Y should be able to communicate
  - Express intent network-wide
- Distributed systems techniques to make central control scalable and fault tolerant
- Central control means a single API for the network, rather than an API per box
- Networks provisioned by software, not humans
- Disaggregation → innovation
- Network-wide intent → better security

Computing Evolution



Vertically integrated
Closed, proprietary
Slow innovation
Small industry

App

Open Interface

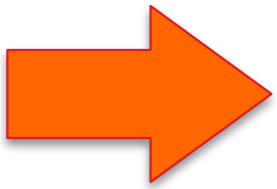
Windows (OS) or Linux or Mac OS

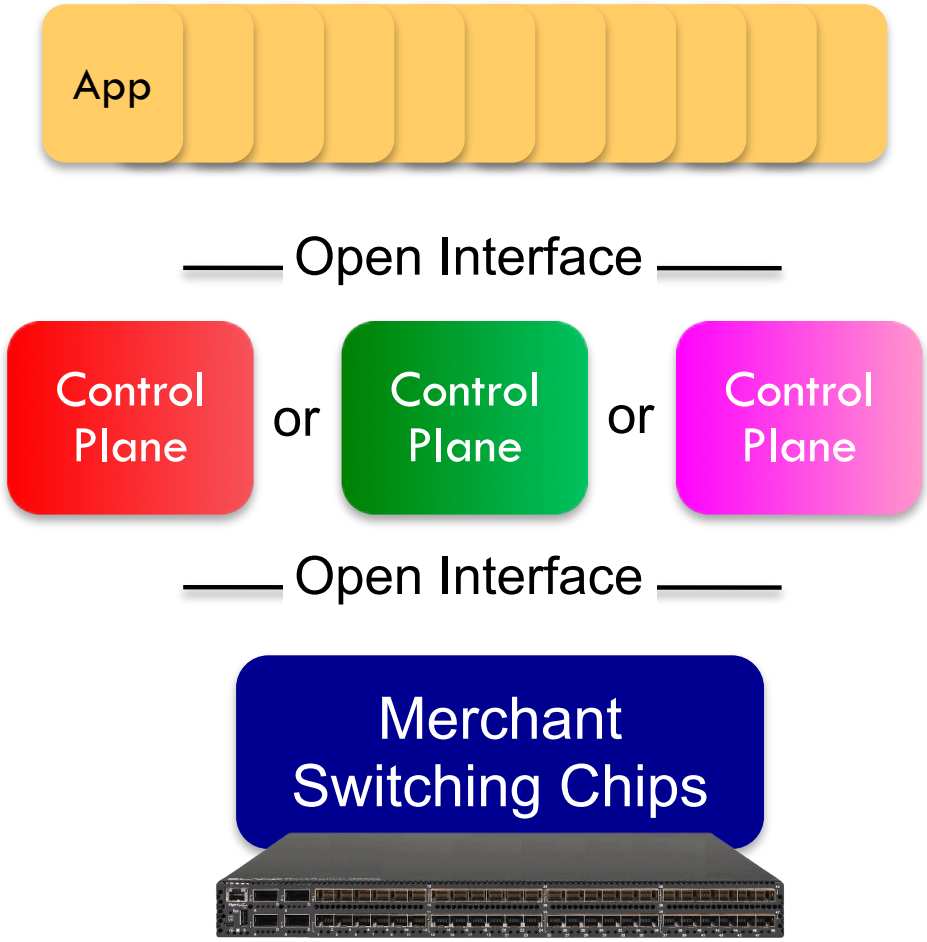
Open Interface

Microprocessor

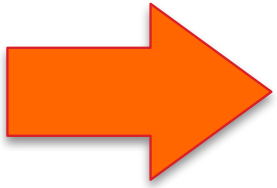
Horizontal
Open interfaces
Rapid innovation
Huge industry

Networking Evolution



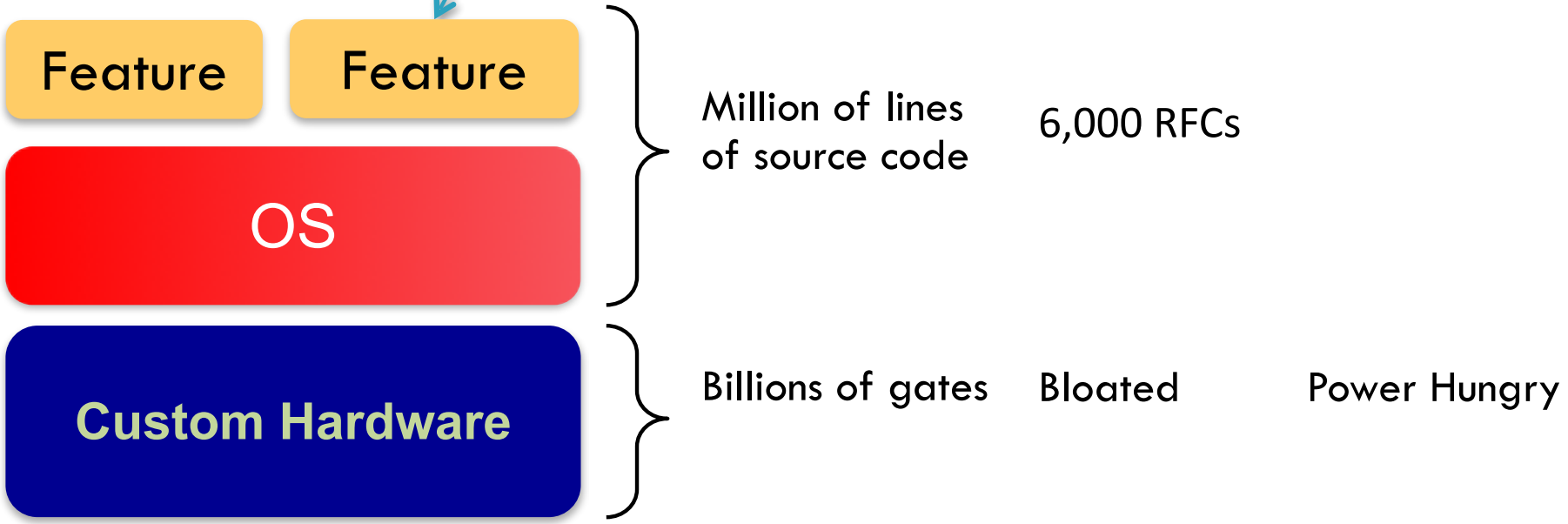


Vertically integrated
Closed, proprietary
Slow innovation



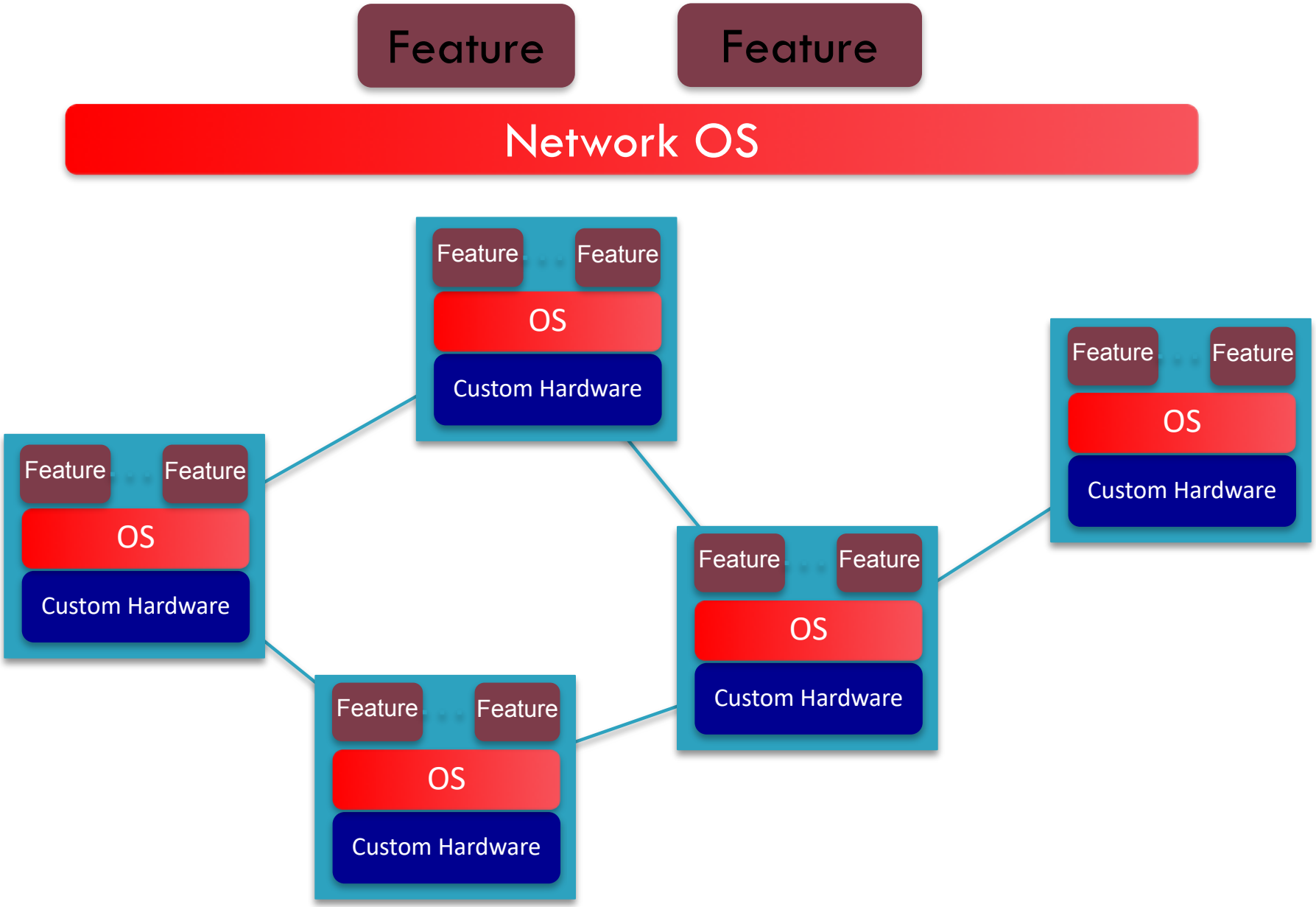
Horizontal
Open interfaces
Rapid innovation

Routing, management, mobility management, access control, VPNs, …

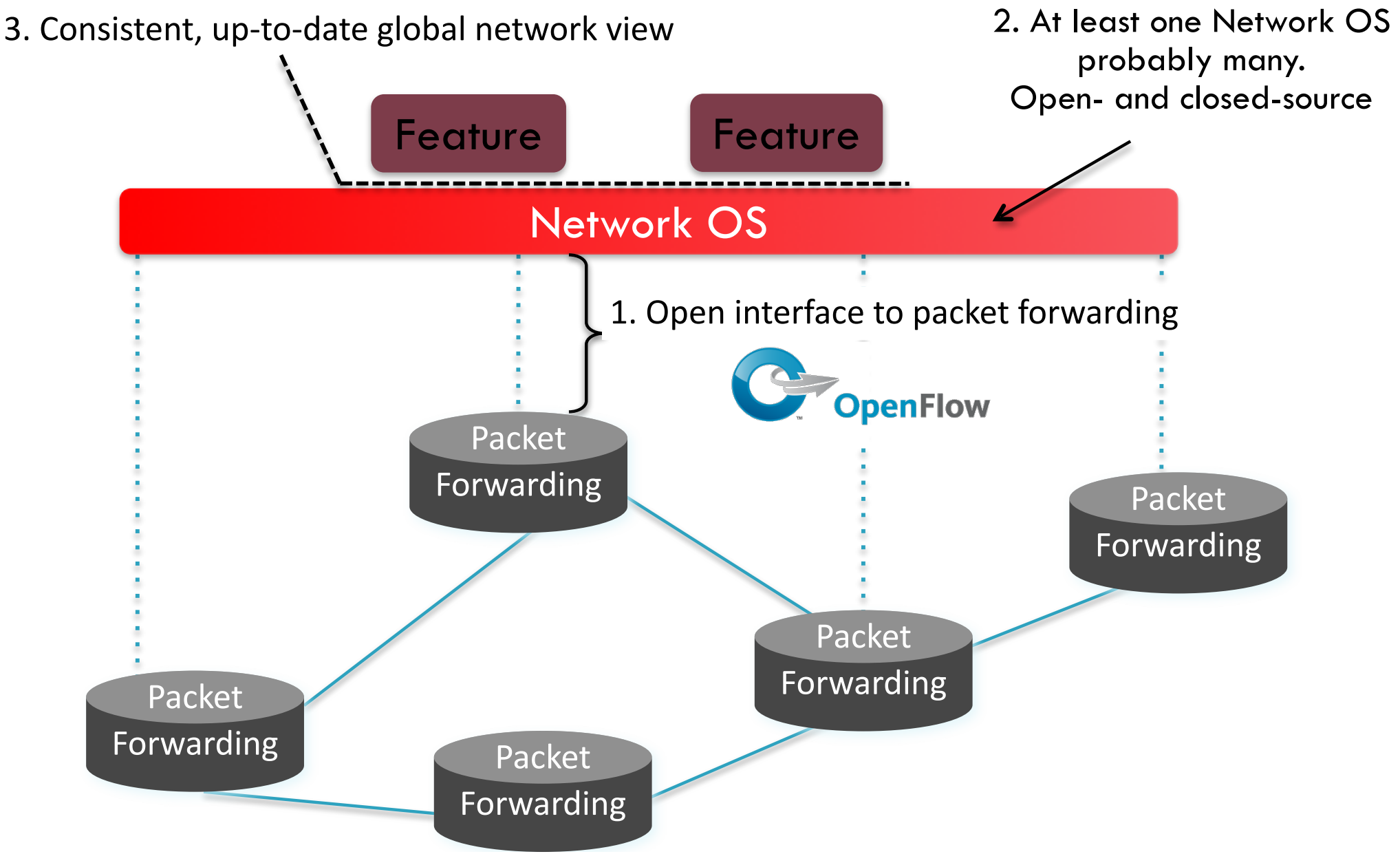


- Vertically integrated, complex, closed, proprietary
- Networking industry with “mainframe” mind-set

The network is changing



Software Defined Network (SDN)



Network OS

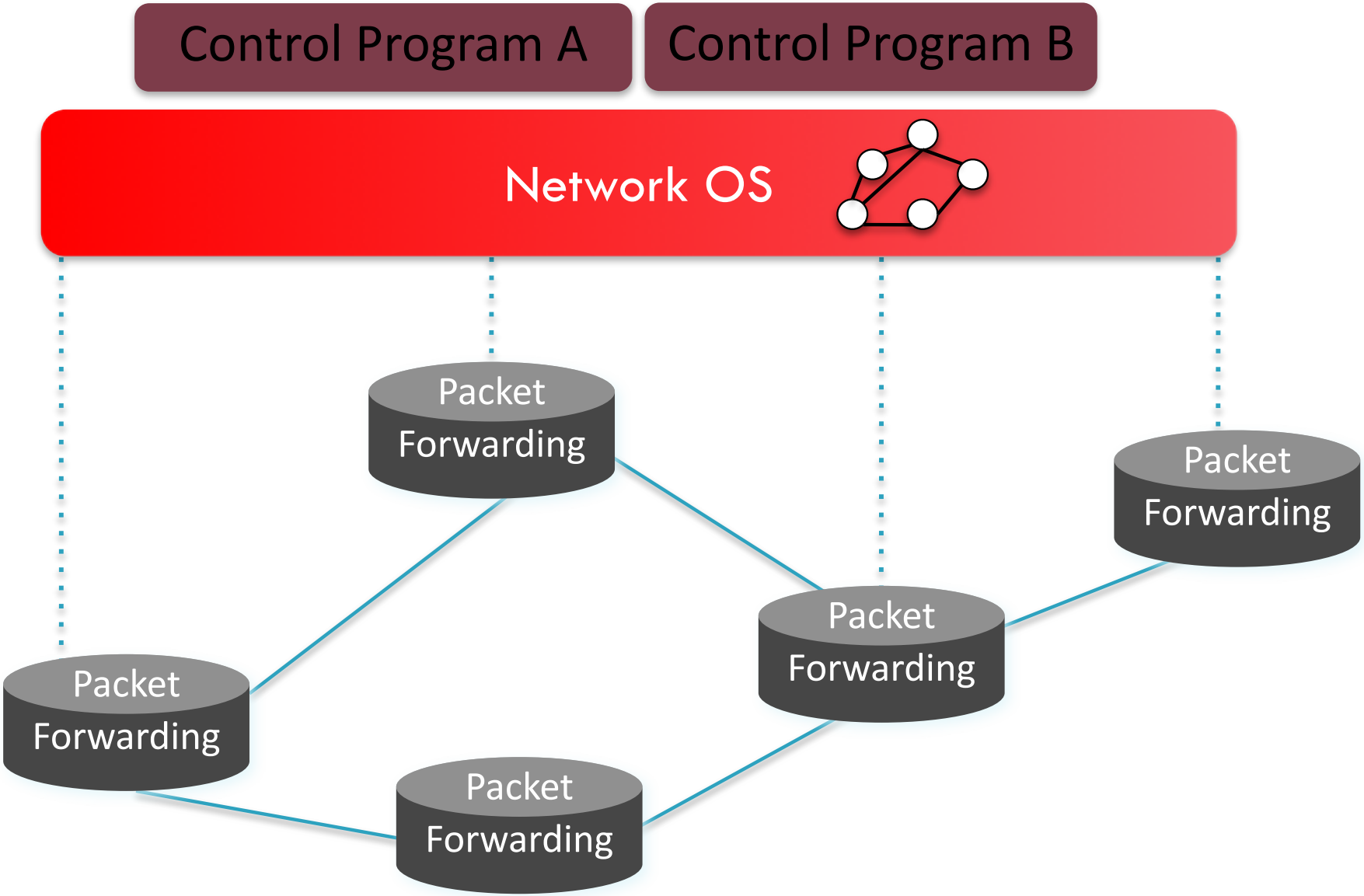
Network OS: distributed system that creates a consistent, up-to-date network view

- Runs on servers (controllers) in the network
- NOX, ONIX, Trema, Beacon, Maestro, … + more

Uses forwarding abstraction to:

- Get state information **from** forwarding elements
- Give control directives **to** forwarding elements

Software Defined Network (SDN)



Control Program

- Control program operates on view of network
  - **Input**: global network view (graph/database)
  - **Output**: configuration of each network device

- Control program is not a distributed system
  - Abstraction hides details of distributed state

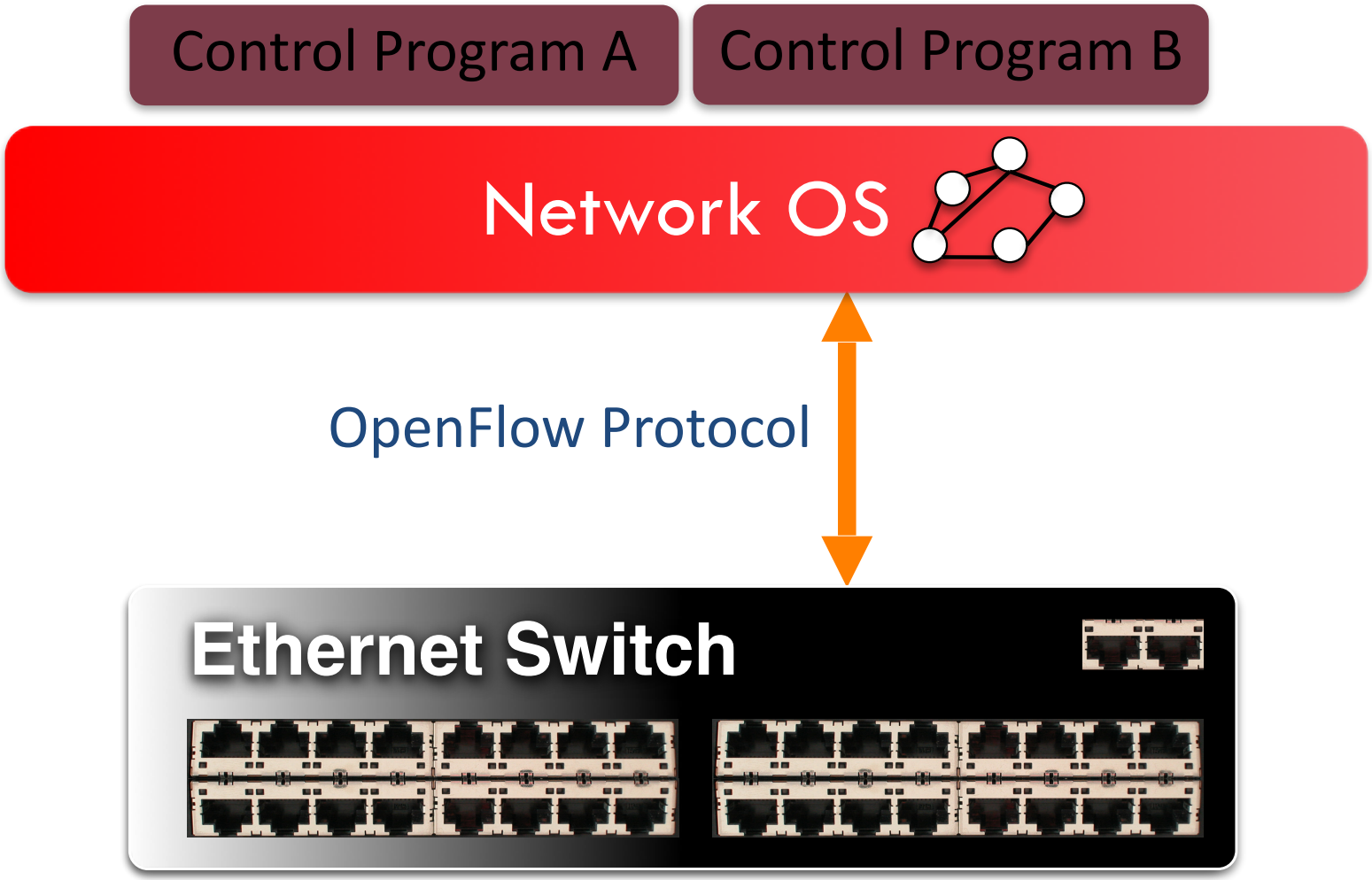
Forwarding Abstraction

Purpose: Abstract away forwarding hardware

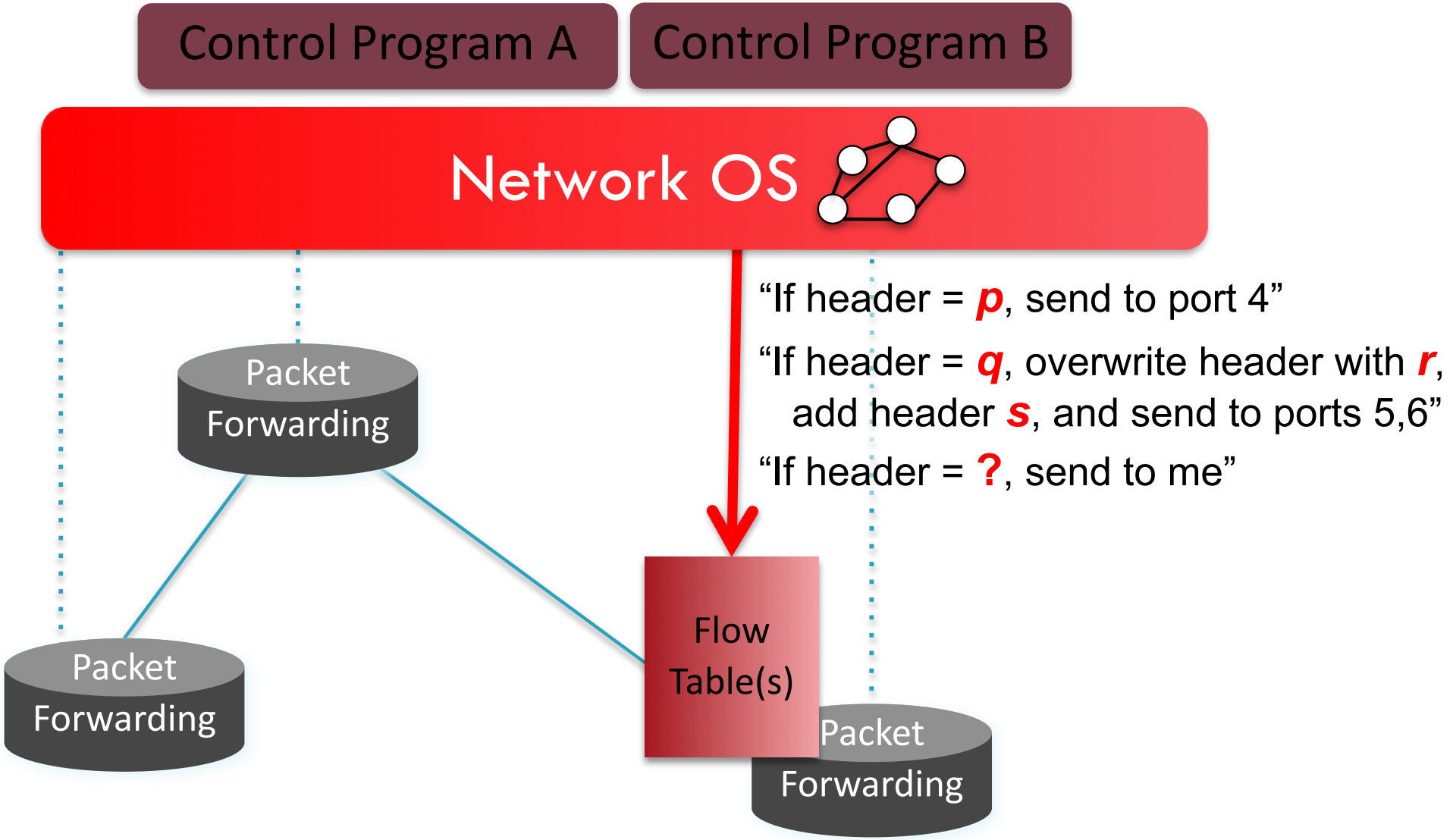
- Flexible
  - Behavior specified by control plane
  - Built from basic set of forwarding primitives
- Minimal
  - Streamlined for speed and low-power
  - Control program not vendor-specific

- OpenFlow is an example of such an abstraction

OpenFlow Basics

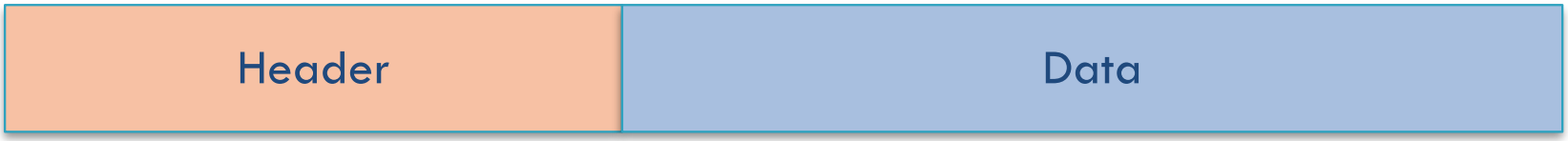


OpenFlow Basics



Plumbing Primitives

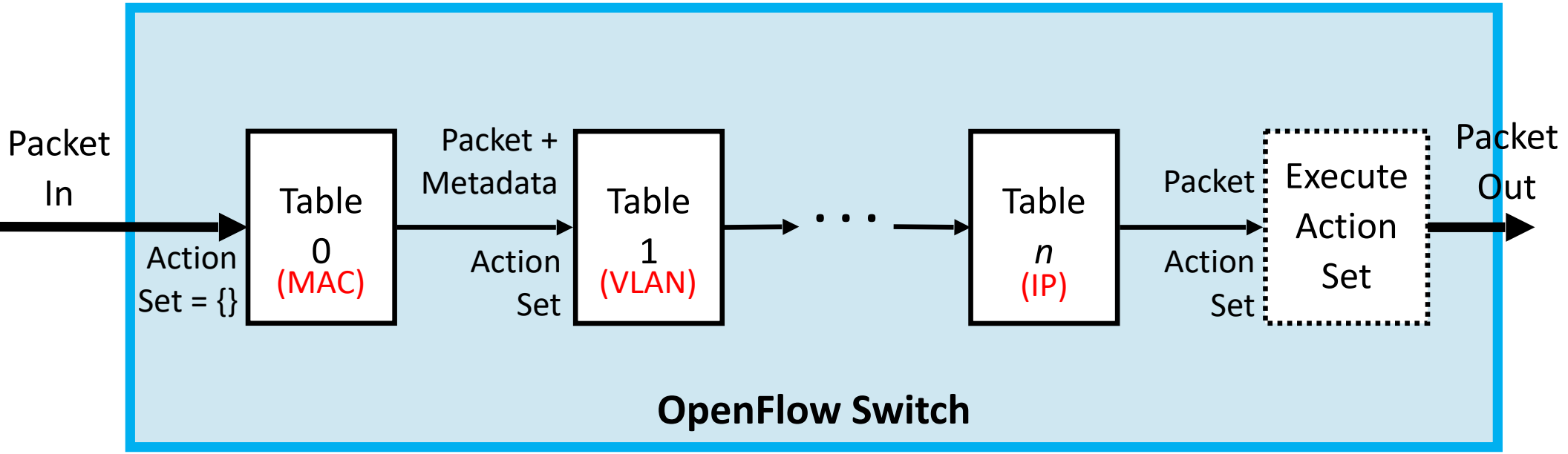
- Primitive is *<Match, Action>*
- ***Match*** arbitrary bits in headers:

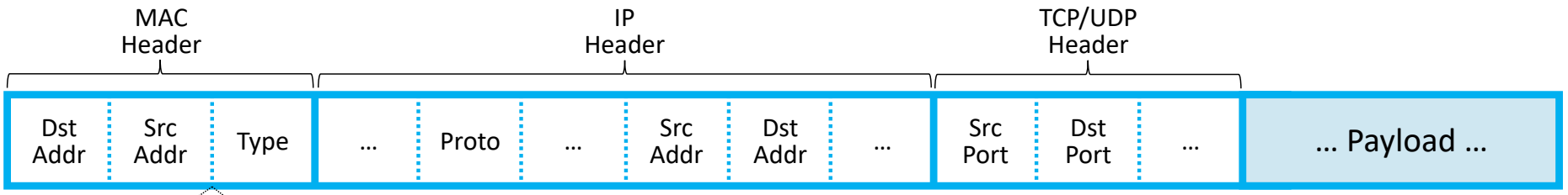


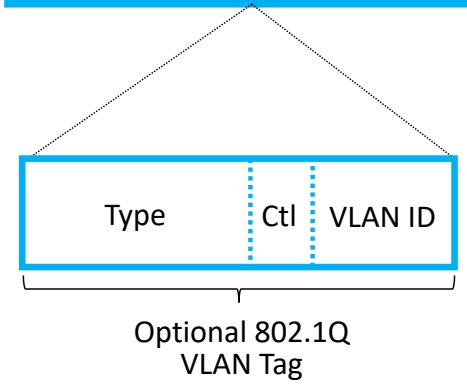
Match: 1000x01xx0101001x

  - Match on any header, or new header
  - Allows any flow granularity
- ***Action***
  - Forward to port(s), drop, send to controller
  - Overwrite header with mask, push or pop
  - Forward at specific bit-rate

OpenFlow-style Data Plane



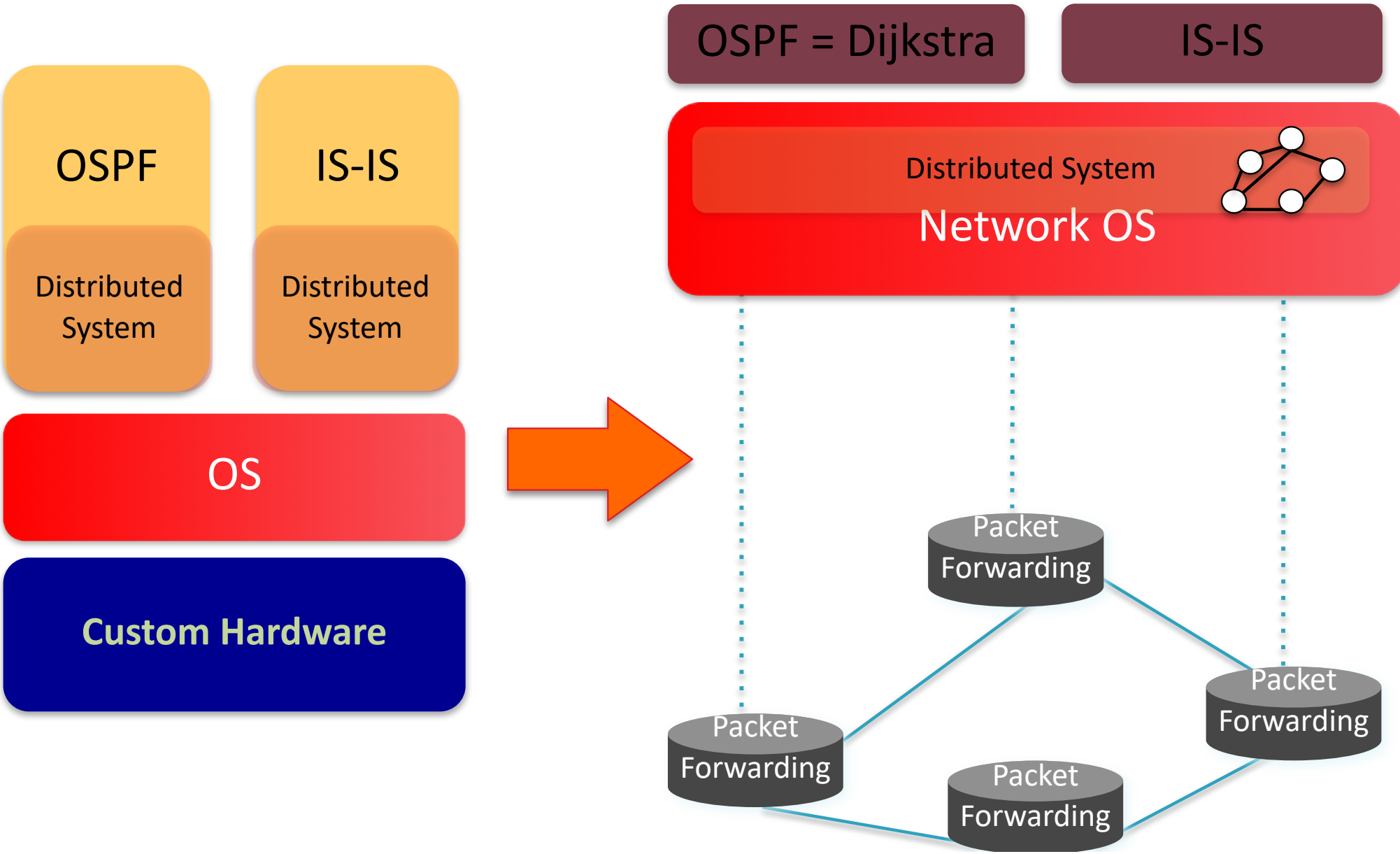




Example 1: OSPF and Dijkstra

- OSPF
  - RFC 2328: **245 pages**
- Distributed System
  - Builds consistent, up-to-date map of the network: **101 pages**
- Dijkstra's Algorithm
  - Operates on map: **4 pages**

Example


OSPF
IS-IS
Distributed System
Distributed System
OS
Custom Hardware
OSPF = Dijkstra
IS-IS
Distributed System
Network OS
Packet Forwarding
Packet Forwarding
Packet Forwarding
Packet Forwarding

Open Networking Foundation (ONF)

New non-profit standards organization (Mar 2011)

Defining standards for SDN, starting with OpenFlow

Board of Directors

- Google, Facebook, Microsoft, Yahoo, DT, Verizon

39 Member Companies

- Cisco, VMware, IBM, Juniper, HP, Broadcom, Citrix, NTT, Intel, Ericsson, Dell, Huawei, …

http://www.OpenNetworkingFoundation.org

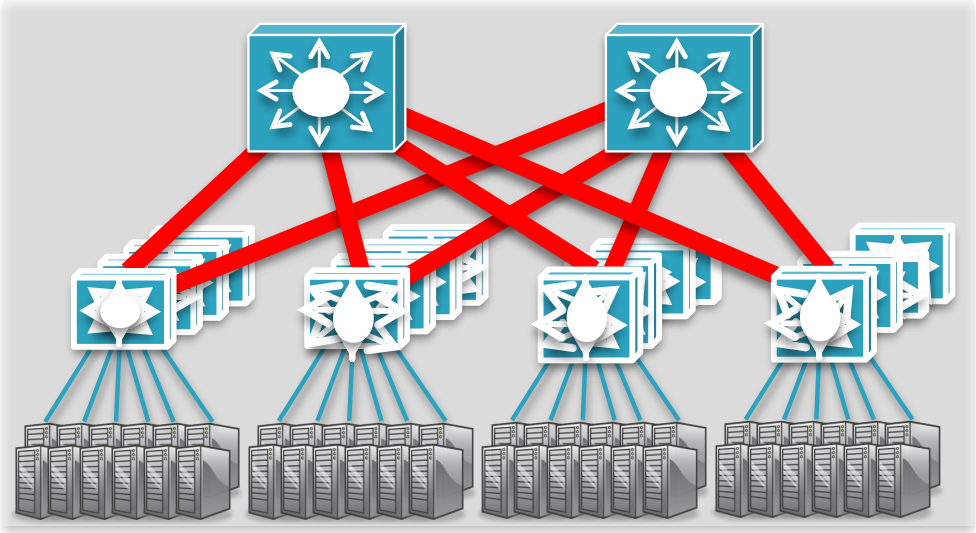
Telco Operators

- Global IP traffic growing 40-50% per year
- End-customer monthly bill remains unchanged
- Therefore, CAPEX and OPEX need to reduce 40-50% per Gb/s per year
- But in practice, reduces by ~20% per year

SDN enables industry to reduce OPEX and CAPEX

…and to create new differentiating services

Example: New Data Center



Cost

200,000 servers

Fanout of 20 ➔ 10,000 switches

$5k vendor switch = $50M

$1k commodity switch = $10M

Savings in 10 data centers = $400M

Control

More flexible control

Tailor network for services

Quickly improve and innovate

Summary

- Networks becoming
  - More programmatic
  - Defined by owners and operators, not vendors
  - Faster changing, to meet operator needs
  - Lower opex, capex and power
- Abstractions
  - Shield programmers from complexity
  - Make behavior more provable