CS358 Computer Networks

Software defined networking

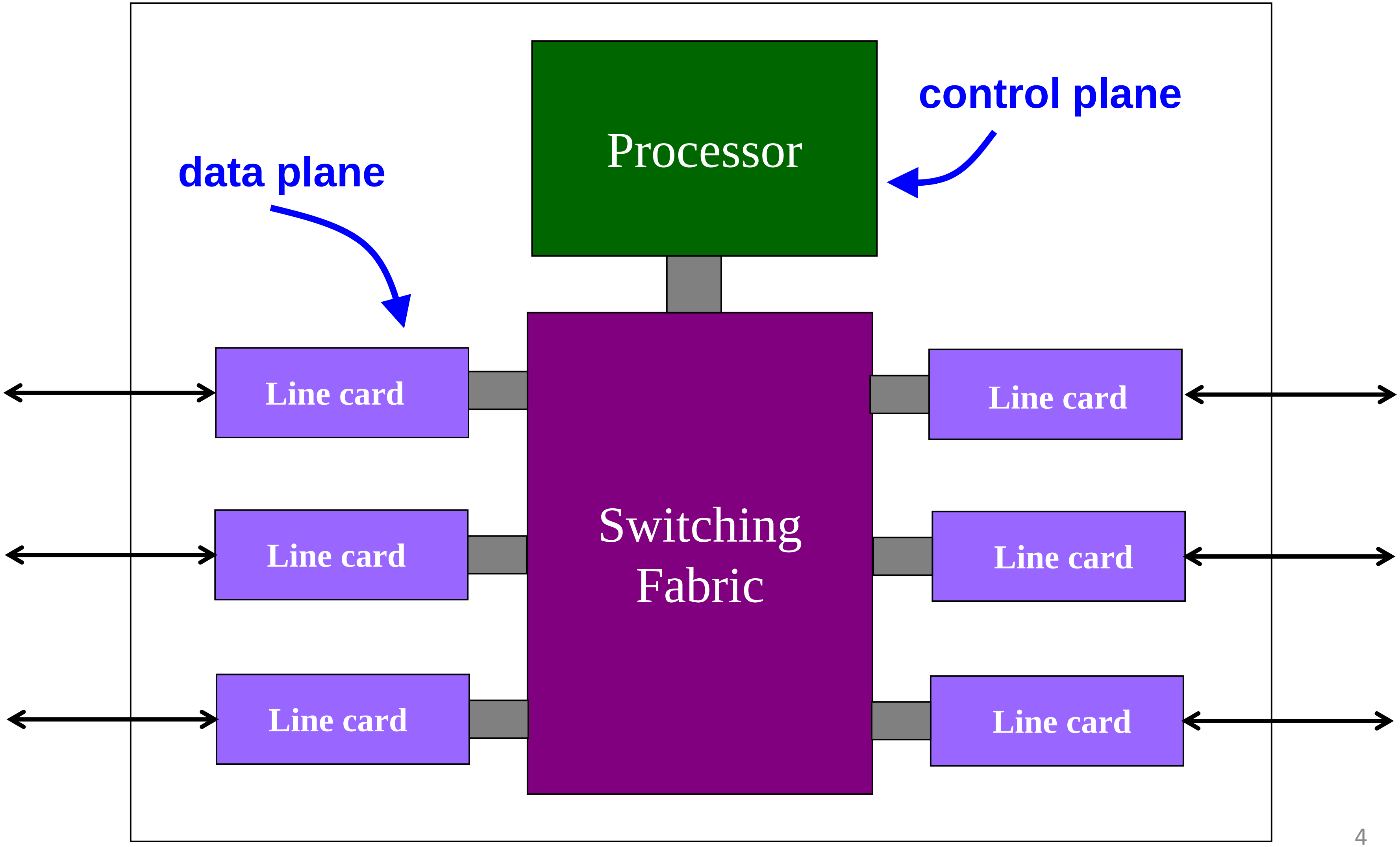
Based on slides by J. Rexford @ Princeton & N. Mckeown @ Stanford & S. Shenker @ Berkeley. Updated by P. Gill Fall 2014.

Data, Control, and Management Planes

Timescales

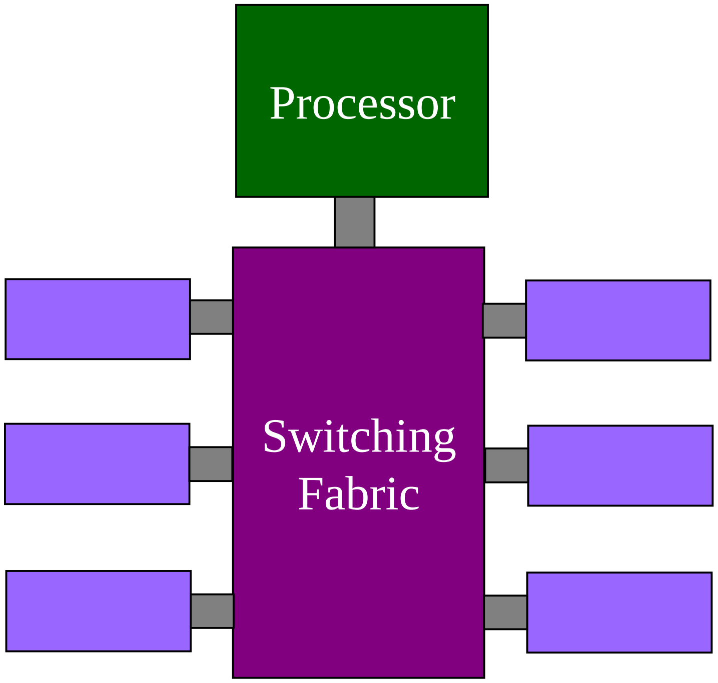
	Data	Control	Management
Time-scale	Packet (nsec)	Event (10 msec to sec)	Human (min to hours)
Tasks	Forwarding, buffering, filtering, scheduling	Routing, circuit set-up	Analysis, configuration
Location	Line-card hardware	Router software	Humans or scripts

Data and Control Planes



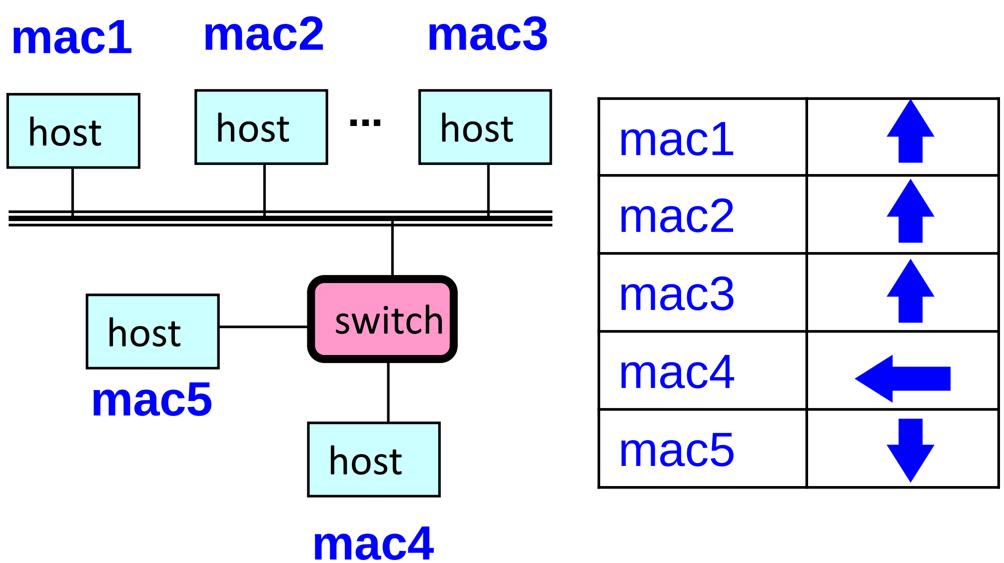
Data Plane

- 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



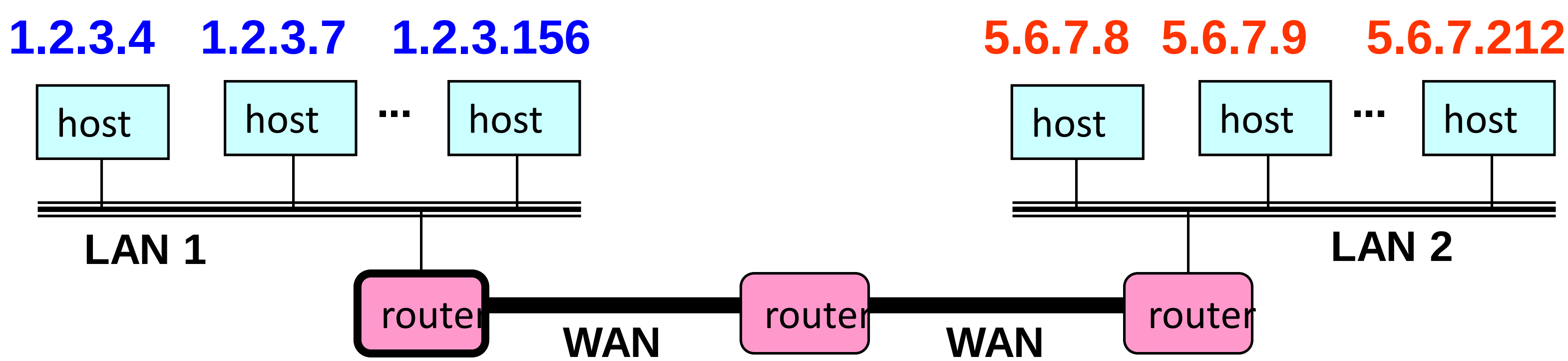
Switch: Match on Destination MAC

- 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

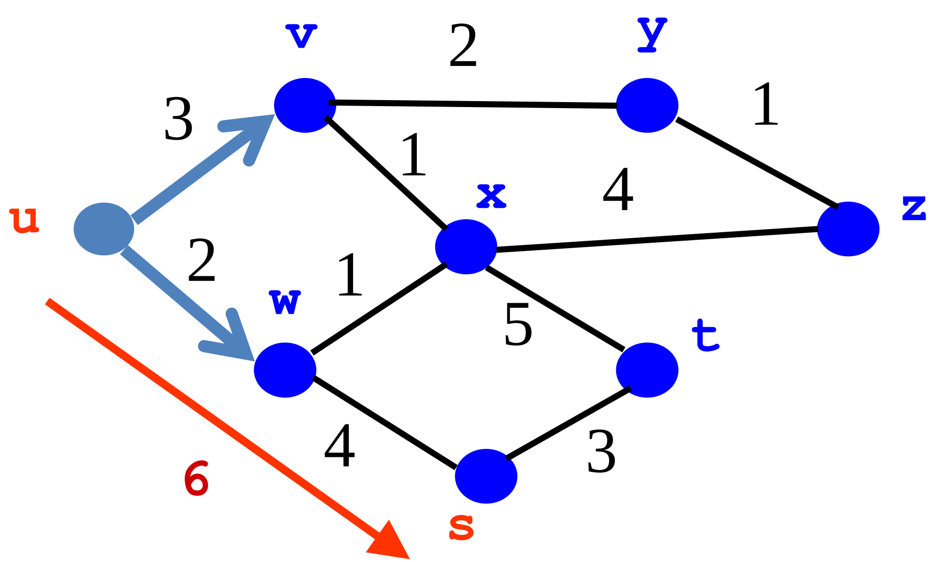
Prefixes may be nested. Routers identify the *longest matching* prefix.

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

Example: Shortest-Path Routing

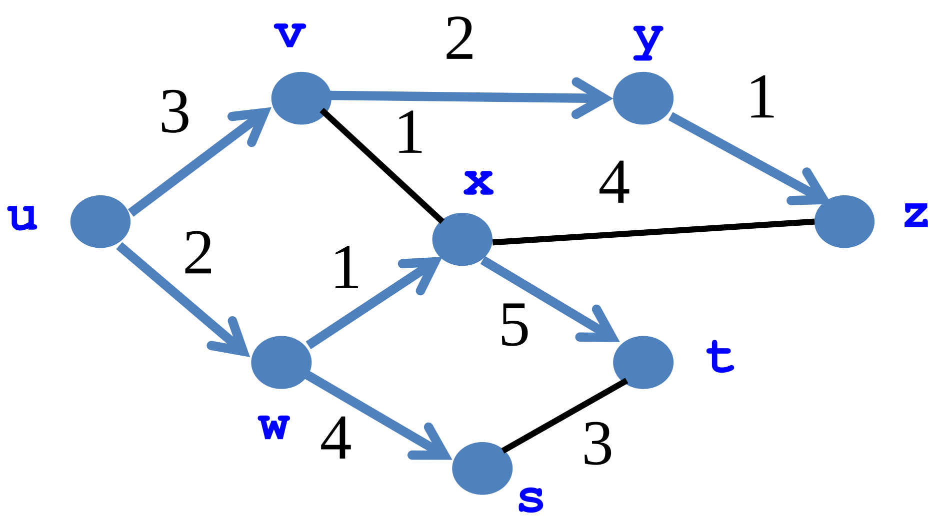
- Compute: *path costs* to all nodes
  - From a source u to all other nodes
  - Cost of the path through each link
  - Next hop along least-cost path to s



	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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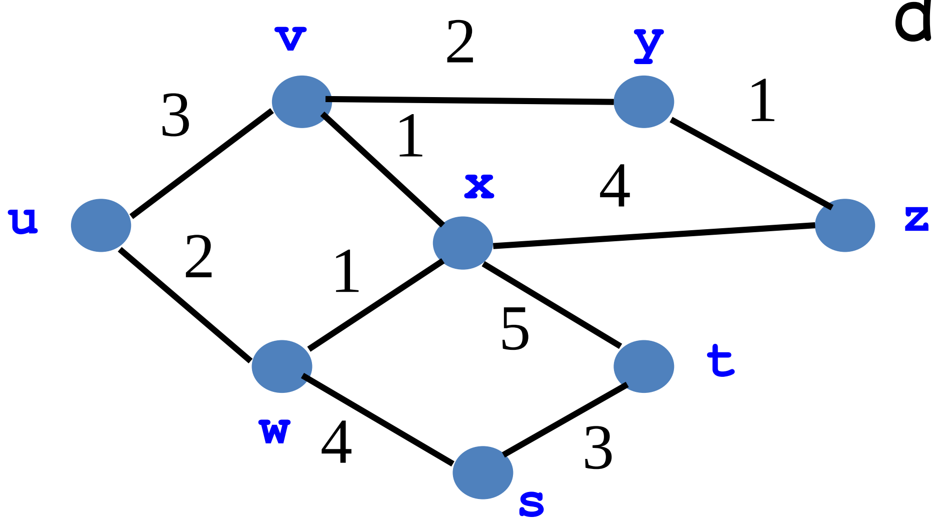
Distributed Control Plane

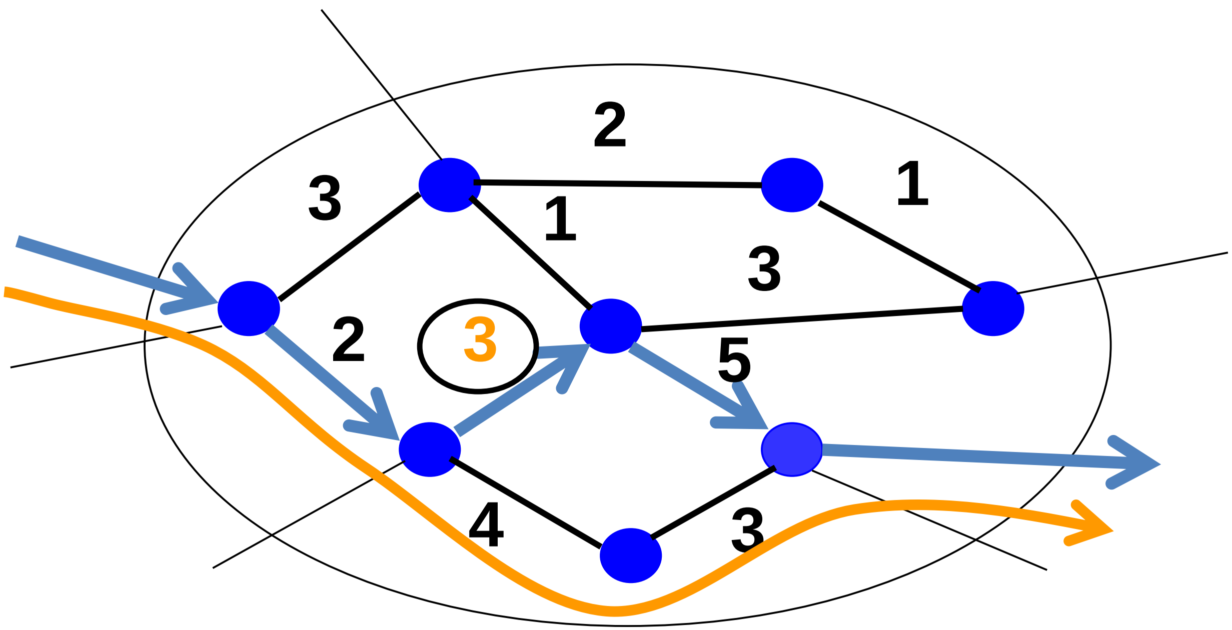
- Distance-vector routing: RIP, EIGRP
  - Each node computes path cost
  - … based on each neighbors' path cost
  - Bellman-Ford algorithm



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

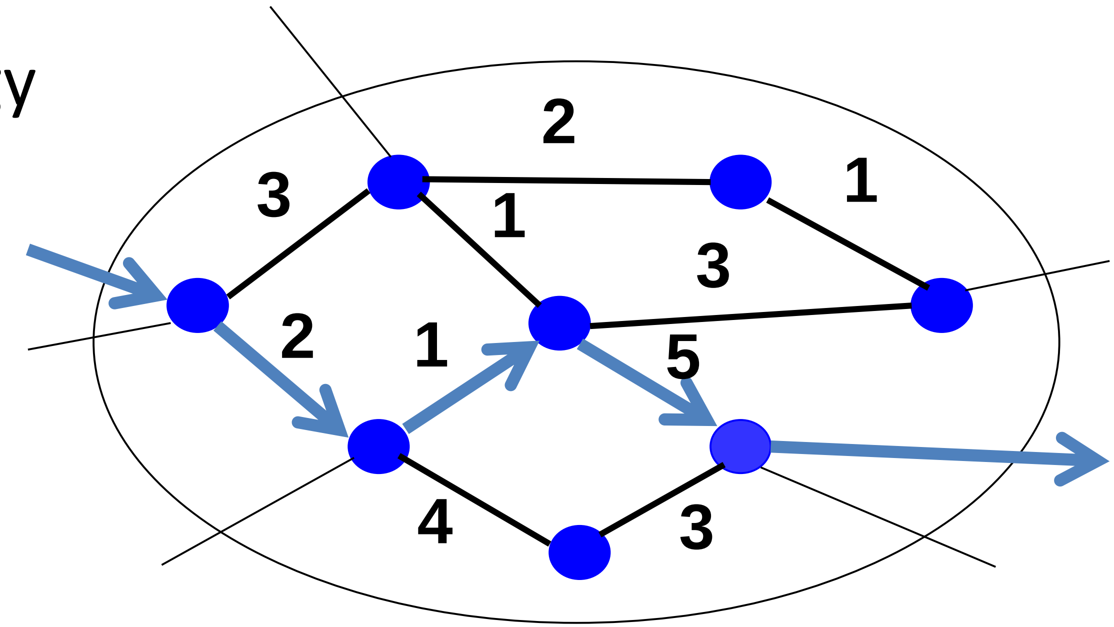
Traffic Engineering Problem

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



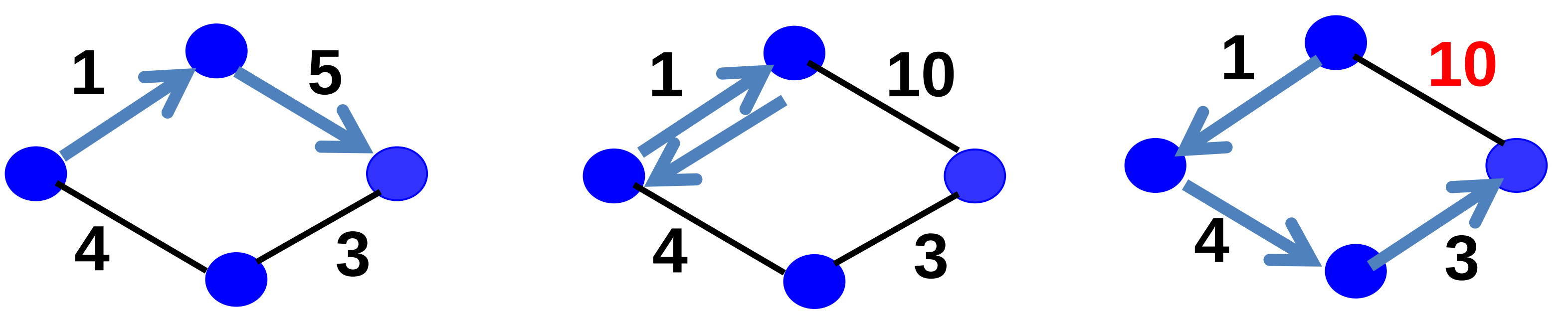
Traffic Engineering: Optimization

- Inputs
  - Network topology
  - Link capacities
  - Traffic matrix
- Output
  - Link weights
- Objective
  - Minimize max-utilized link
  - Or, minimize a sum of link congestion



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



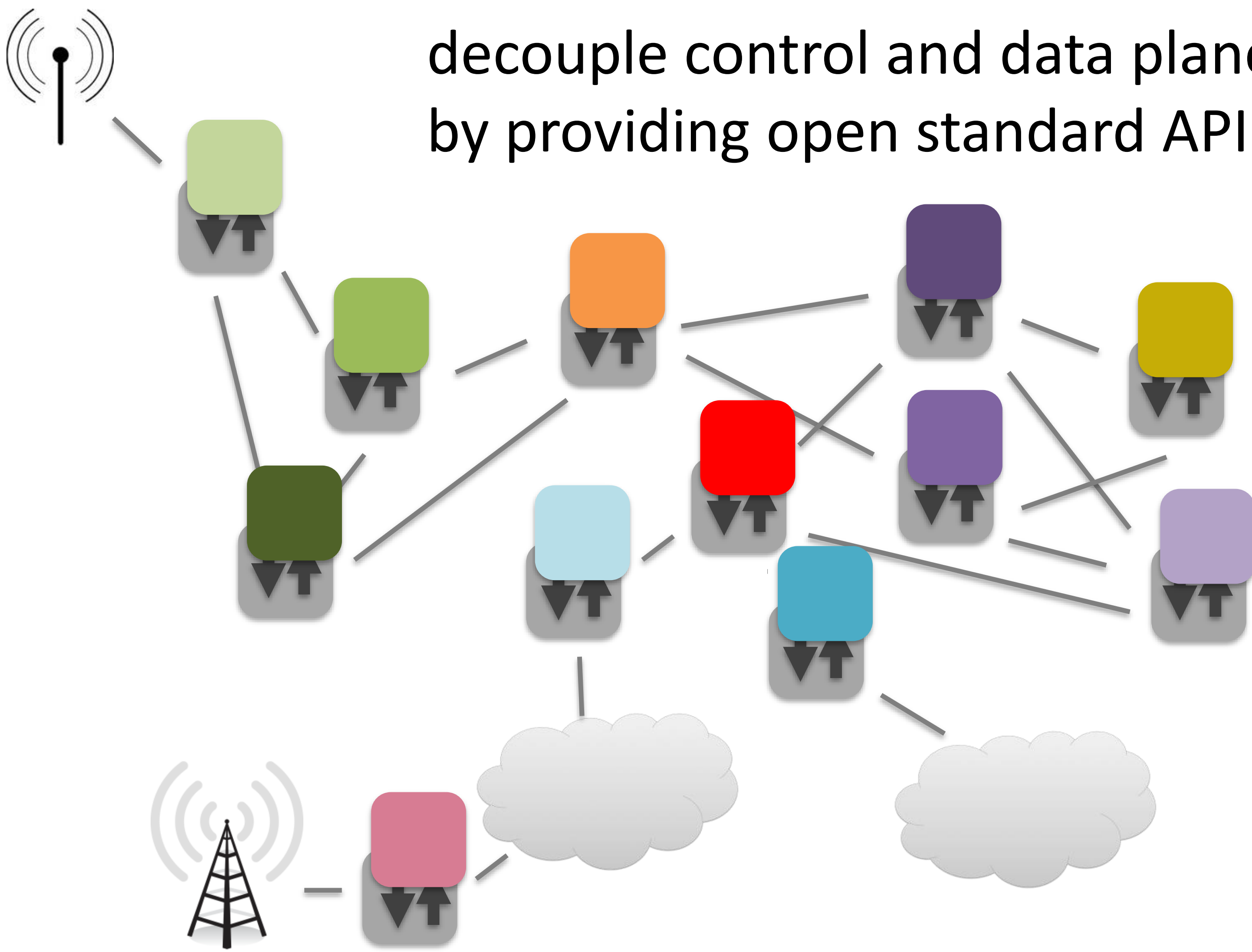
Management Plane Challenges

- 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
  - …

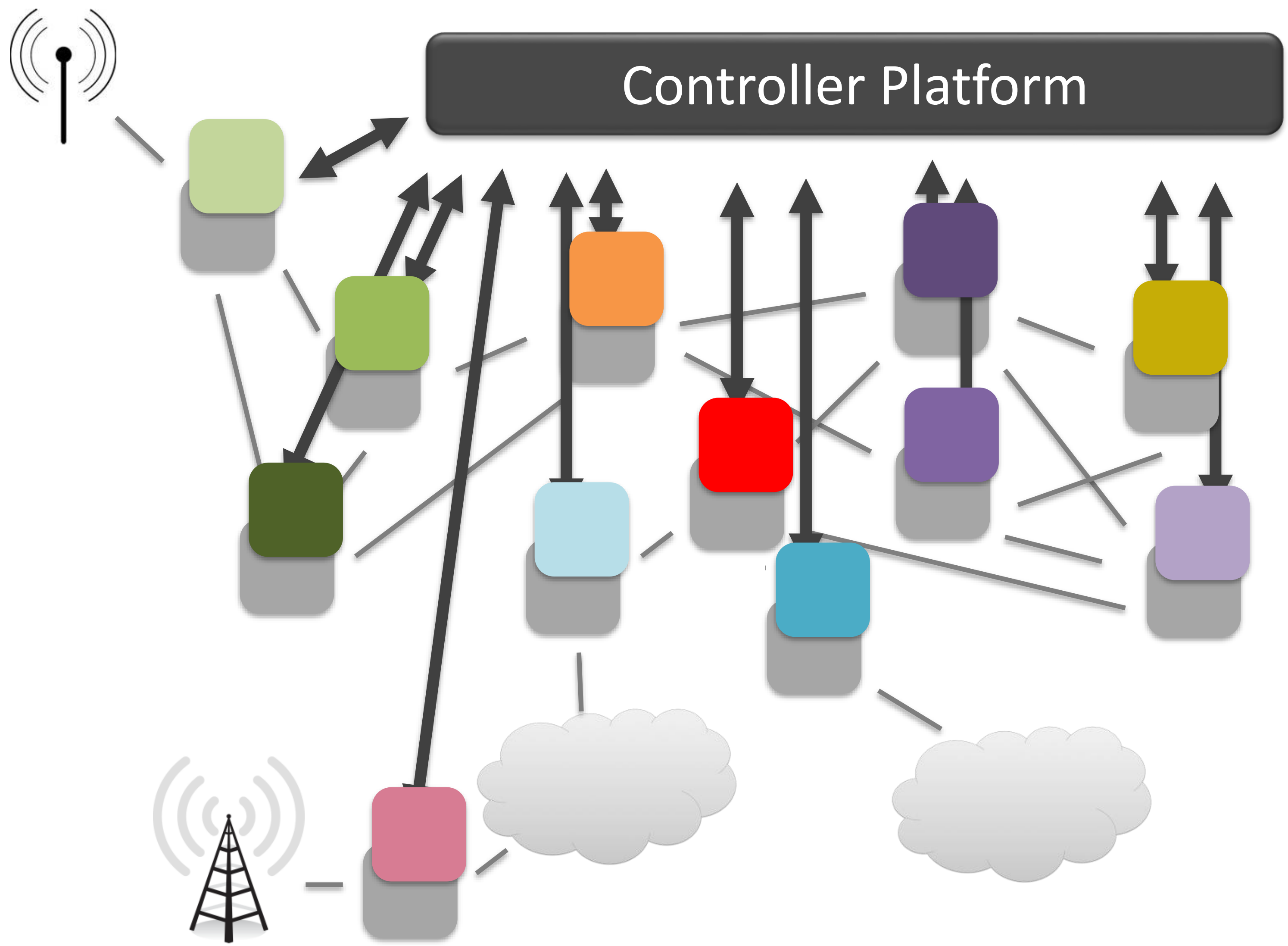
Software Defined Networking (high level view)

Control/Data Separation

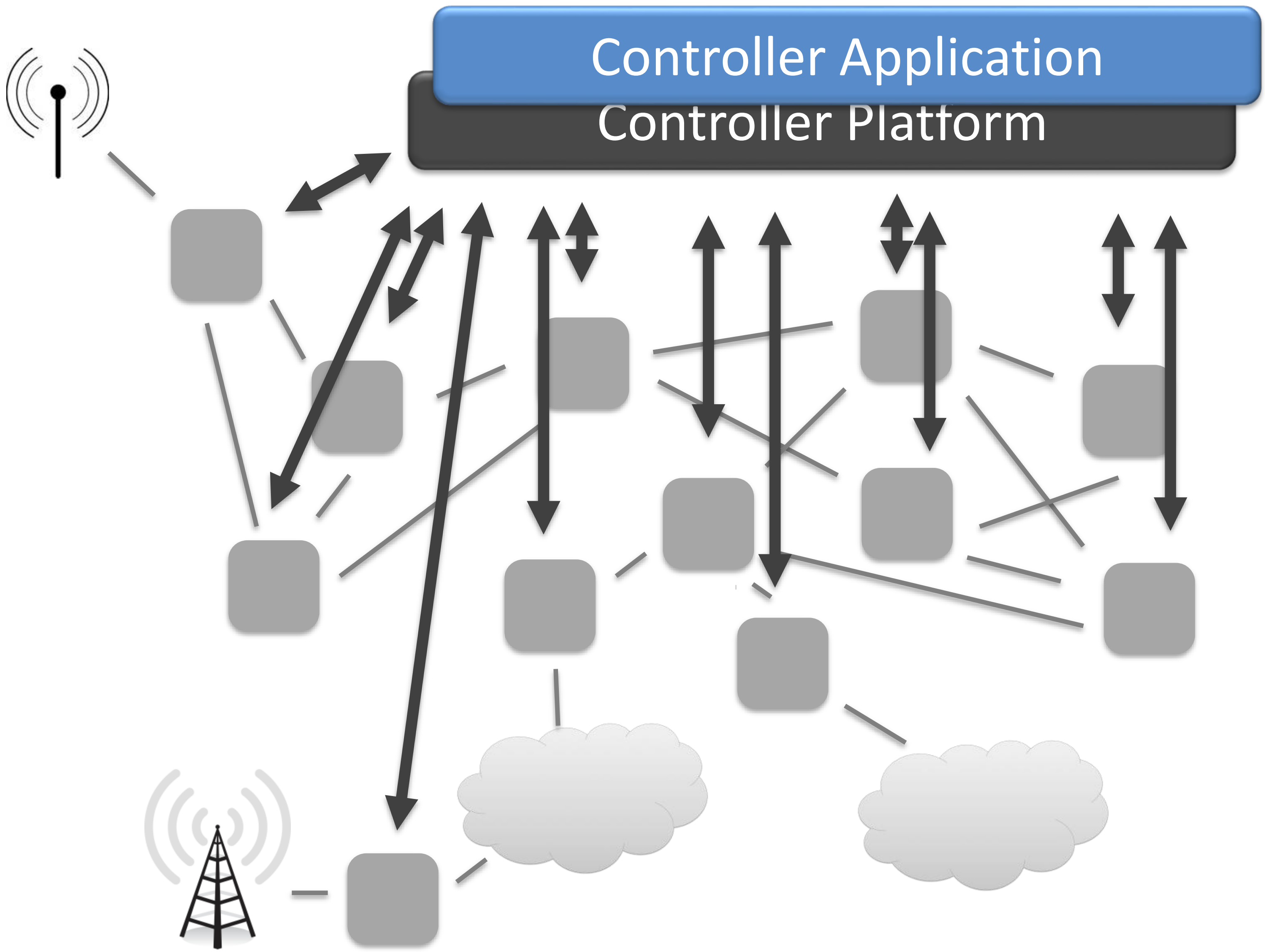
decouple control and data planes
by providing open standard API



(Logically) Centralized Controller

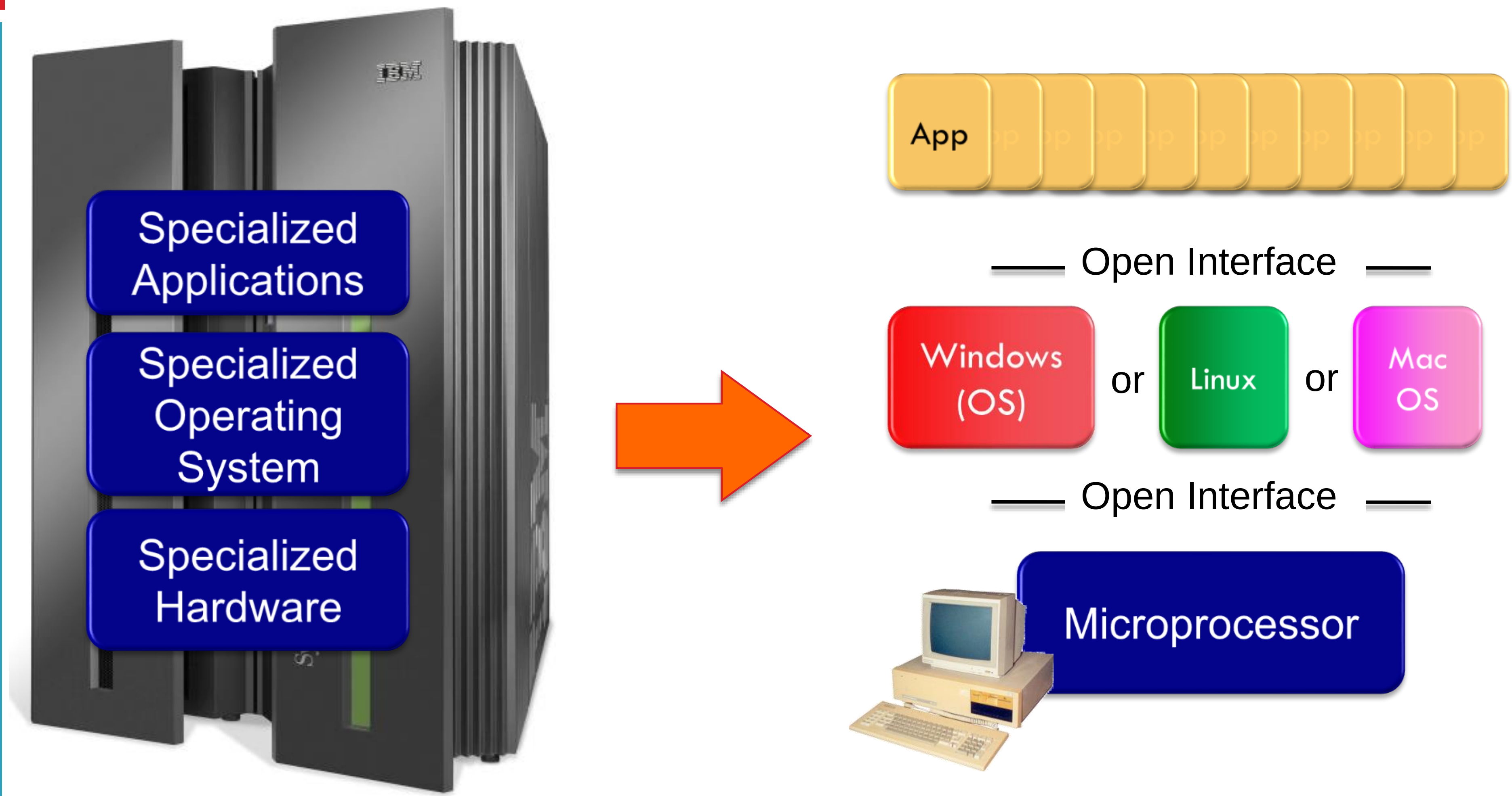


Protocols ➔ Applications



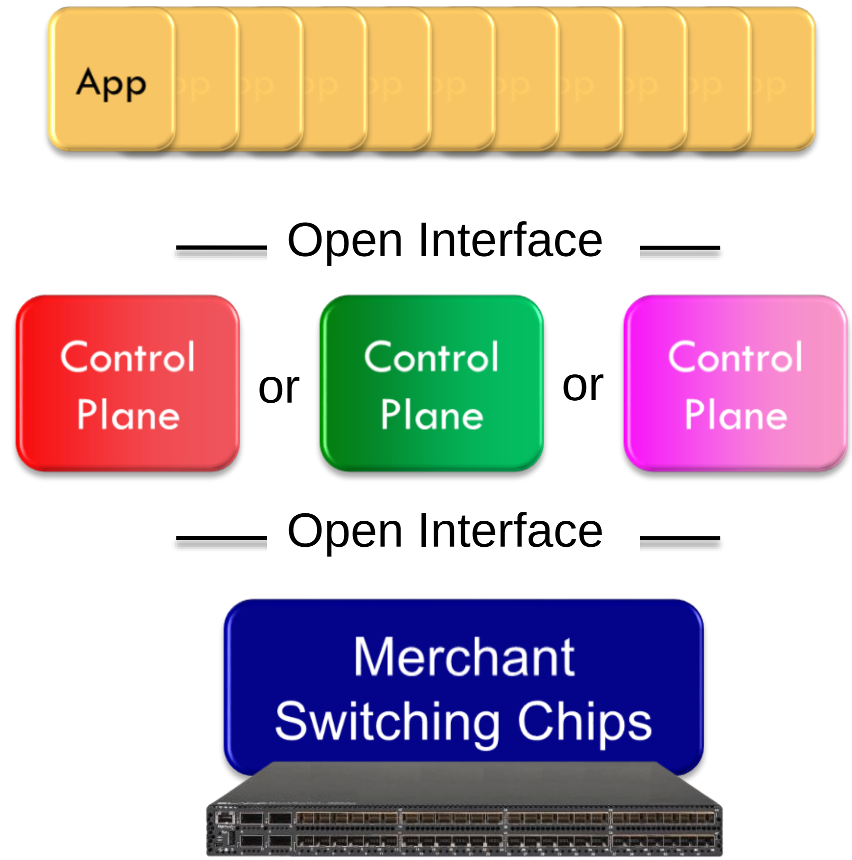
Outline

1. What are Software Defined Networks?
2. Why SDN?
3. The Consequences
   - For industry
   - For research
   - For standards and protocols



Vertically integrated
Closed, proprietary
Slow innovation
Small industry

Horizontal
Open interfaces
Rapid innovation
Huge industry



Vertically integrated
Closed, proprietary
Slow innovation

Horizontal
Open interfaces
Rapid innovation

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

Feature | Feature

OS

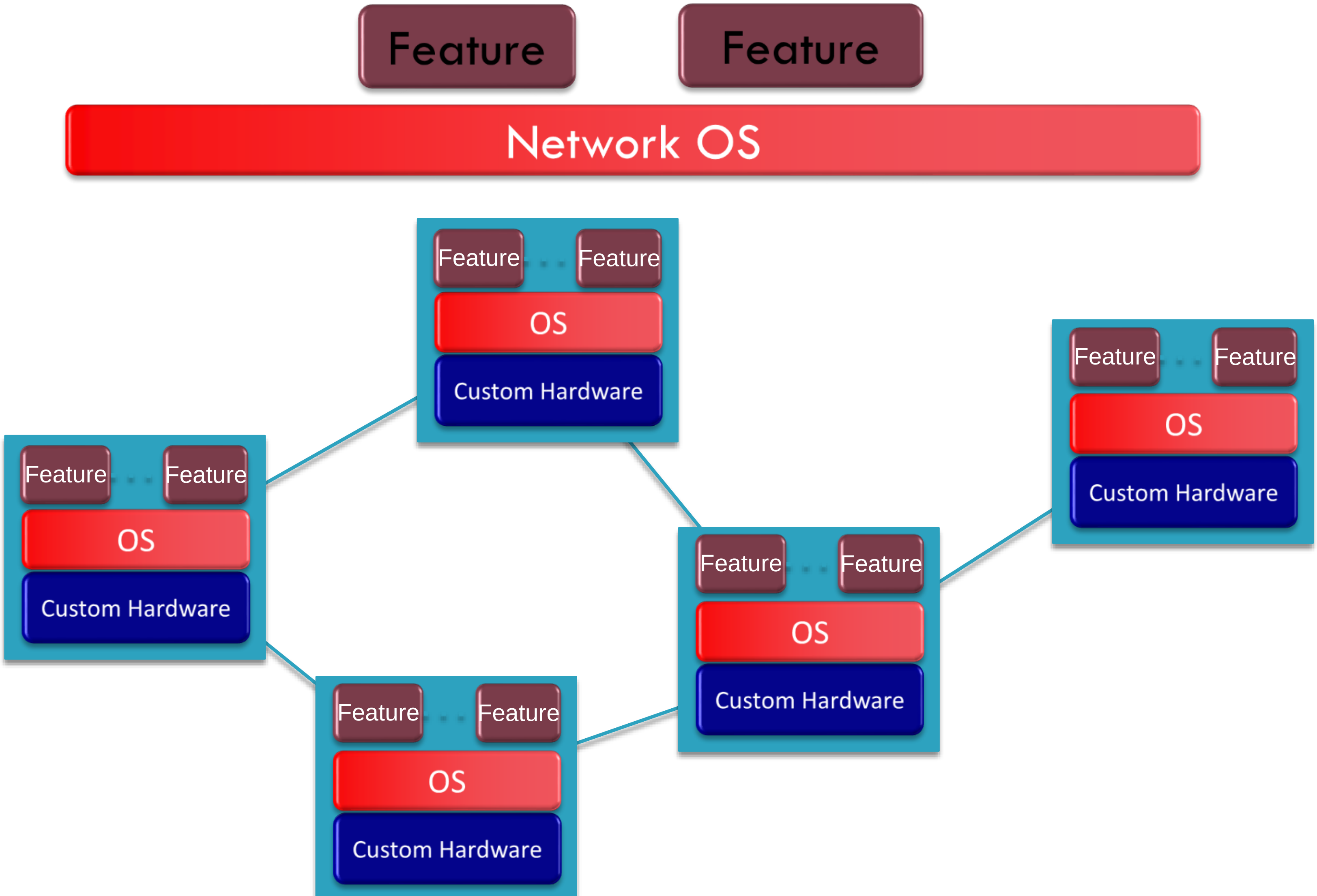
Custom Hardware

Million of lines of source code | 6,000 RFCs

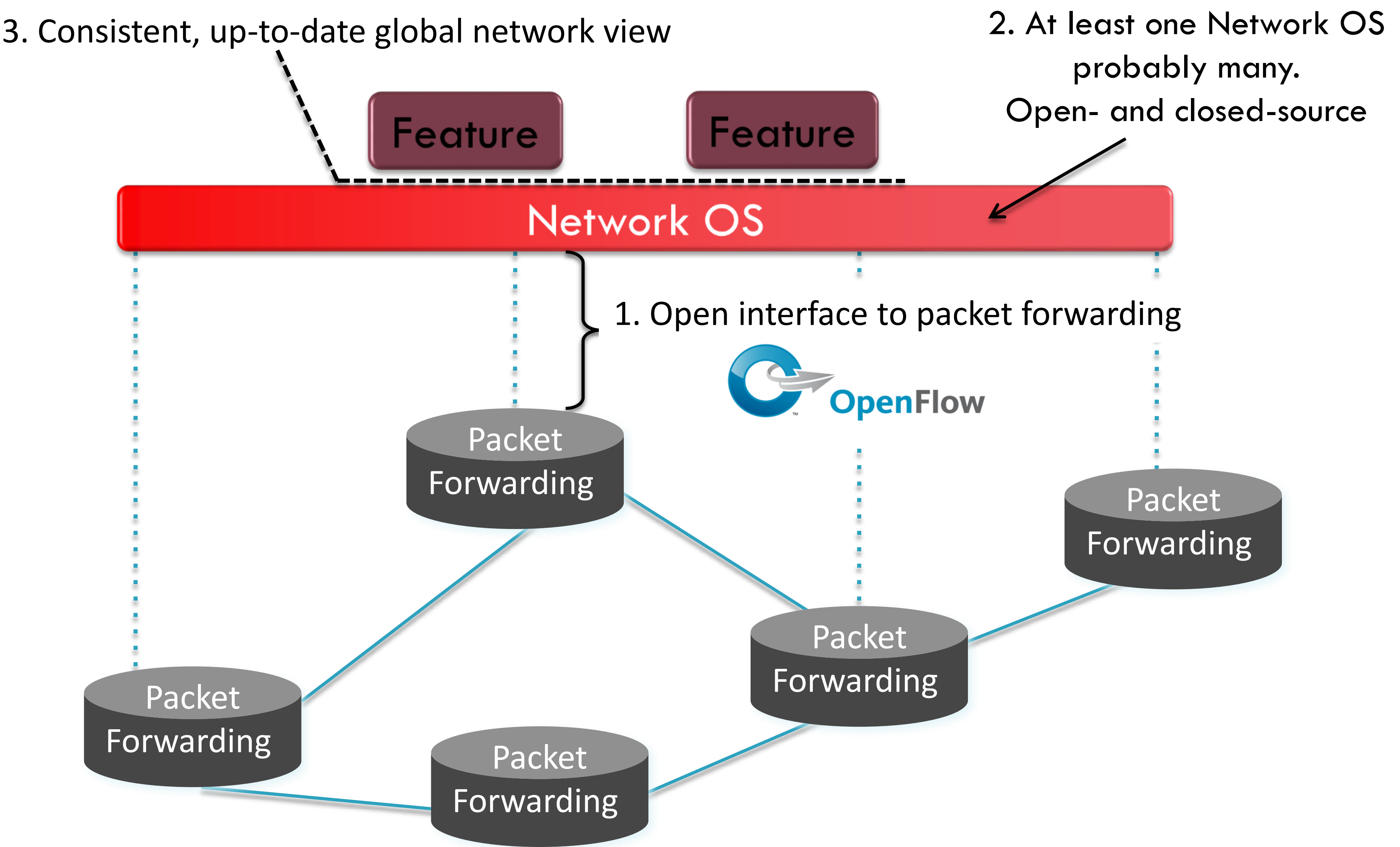
Billions of gates | Bloated | Power Hungry

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

The network is changing



Software Defined Network (SDN)



Network OS

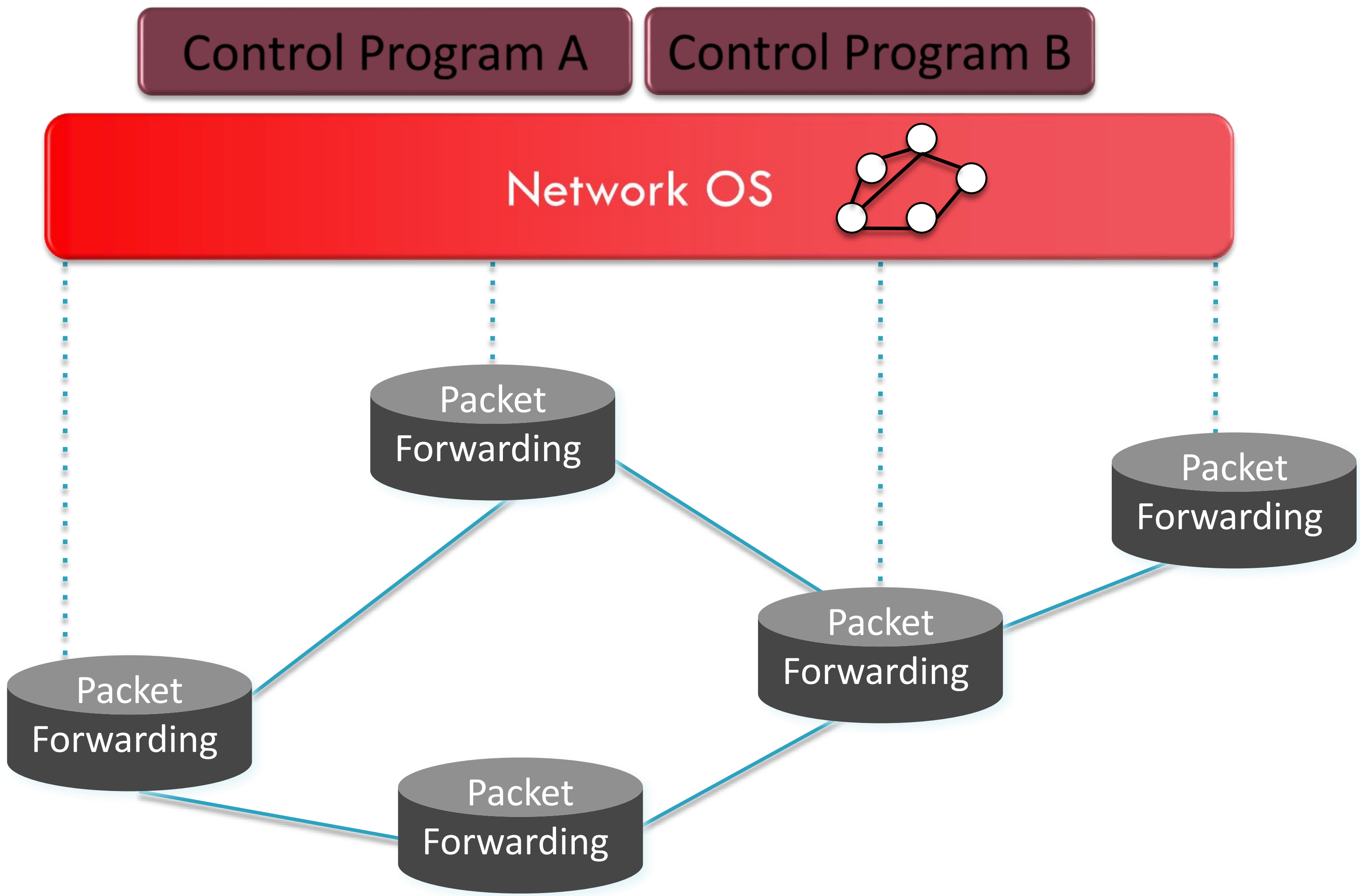
Network OS: distributed system that creates a consistent, up-to-date network view

- 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

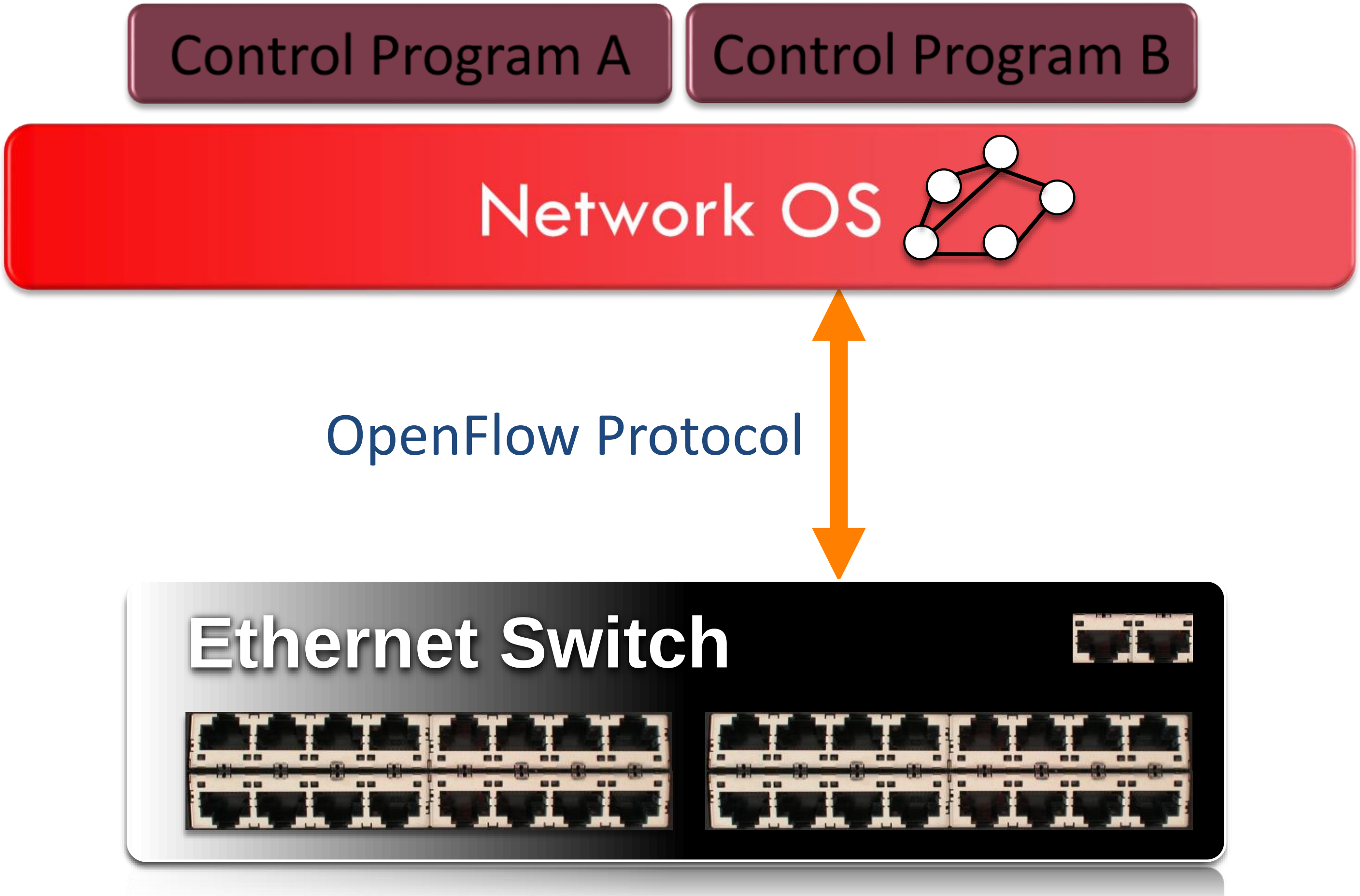
Forwarding Abstraction

Purpose: Abstract away forwarding hardware

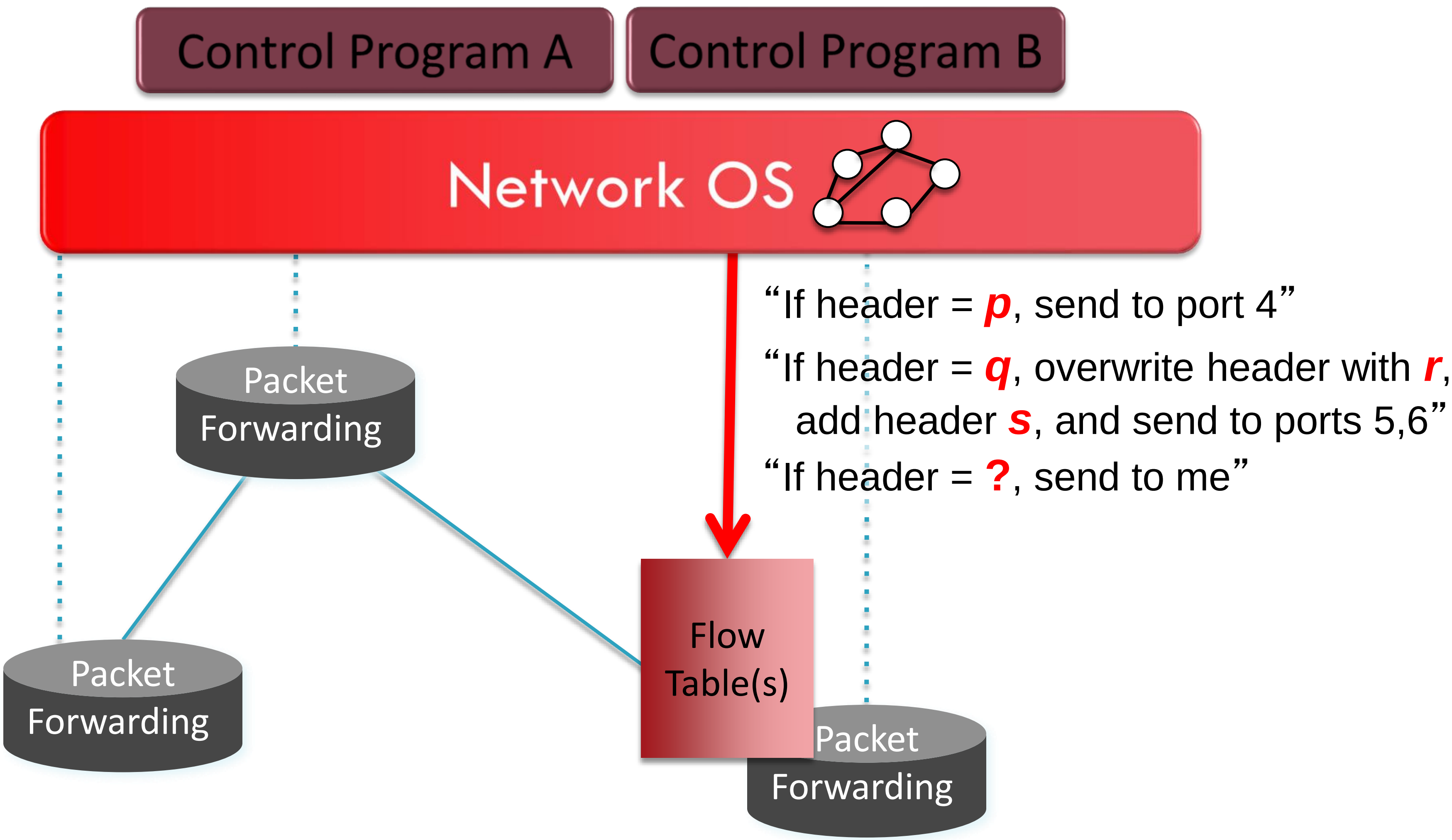
- Flexible
  - Behavior specified by control plane
  - Built from basic set of forwarding primitives
- Minimal
  - Streamlined for speed and low-power
  - Control program not vendor-specific

- 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

General Forwarding Abstraction

Small set of primitives
"Forwarding instruction set"

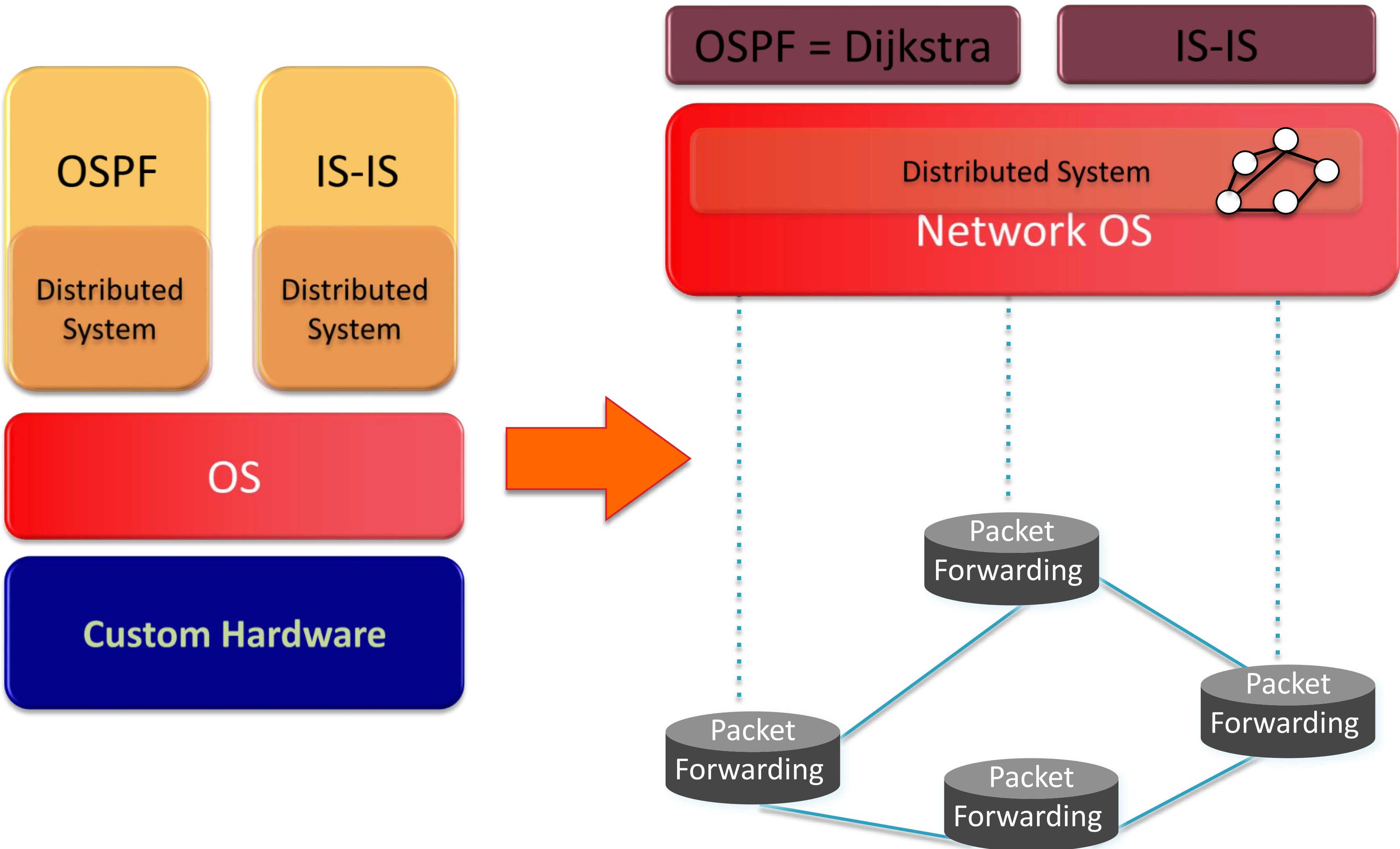
Protocol independent
Backward compatible

Switches, routers, WiFi APs,
basestations, TDM/WDM

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

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GREAT TALK BY SCOTT SHENKER

HTTP://WWW.YOUTUBE.COM/WATCH?V=WVS7PC99S7W

(Story summarized here)

Networking

- Networking is
  - “Intellectually Weak”
  - behind other fields
  - about the mastery of complexity

Good abstractions tame complexity

- Interfaces are instances of those abstractions

No abstraction => increasing complexity

- We are now at the complexity limit

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,...

Programming Analogy

- What if programmers had to:
  - Specify where each bit was stored
  - Explicitly deal with internal communication errors
  - Within a programming language with limited expressibility

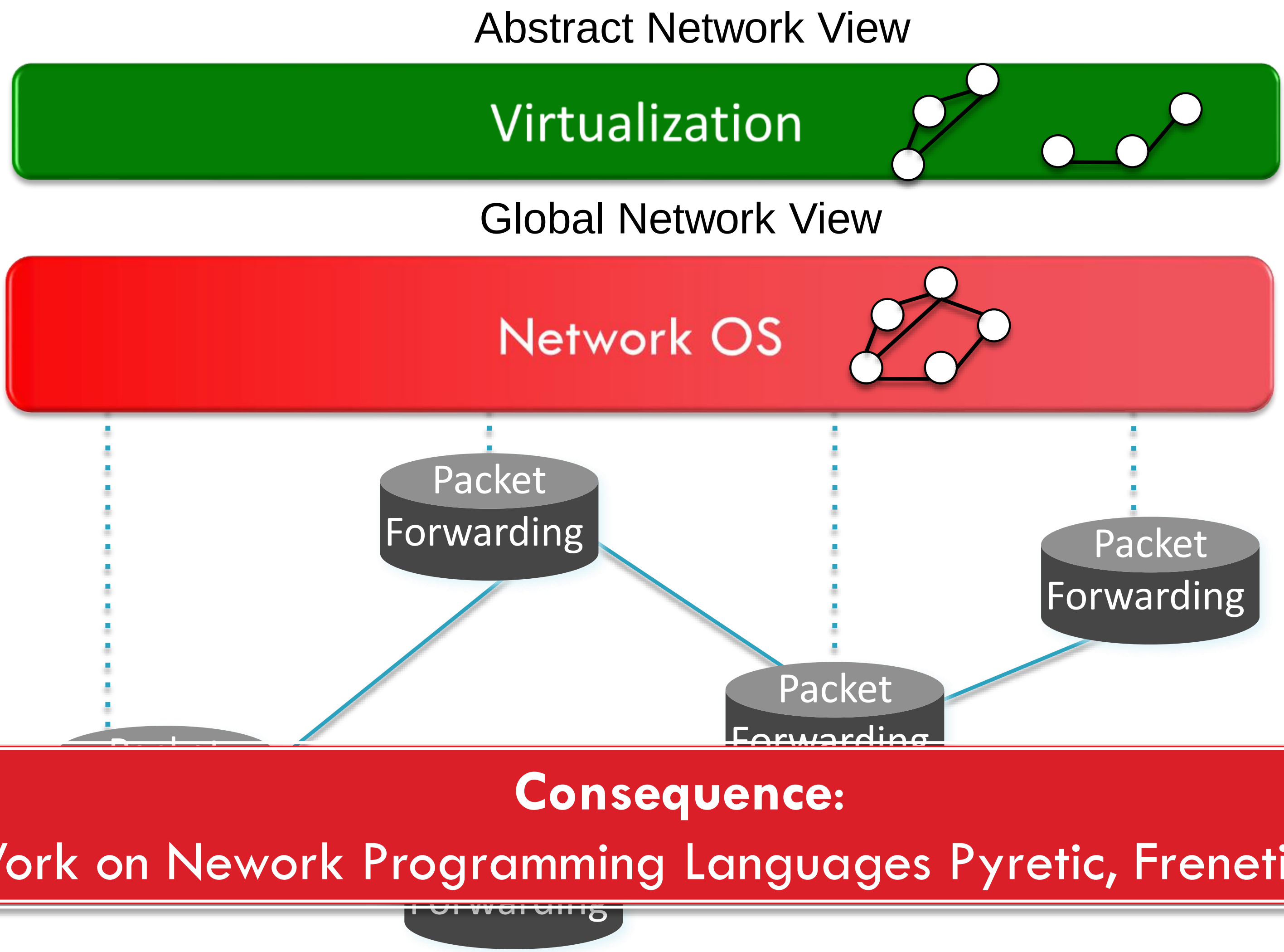
- Programmers would redefine problem by:
  - Defining higher level abstractions for memory
  - Building on reliable communication primitives
  - Using a more general language

Specification Abstraction

- Network OS eases implementation
  - E.g., Helps manage distributed state
- Next step is to ease specification
  - E.g., How do you specify what the system should do?

- Key goals
  - Provide abstract view of network map
  - Control program operates on abstract view
  - Develop means to simplify specification

Software Defined Network (SDN)



Consequence:

Work on Nework Programming Languages Pyretic, Frenetic etc.

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SDN in development

Domains

- Data centers
- Enterprise/campus
- Cellular backhaul
- Enterprise WiFi
- WANs

Products

- Switches, routers: About 15 vendors
- Software: About 6 vendors and startups

New startups (6 so far). Lots of hiring in networking.

Cellular industry

- Recently made transition to IP
- Billions of mobile users
- Need to securely extract payments and hold users accountable
- IP is bad at both, yet hard to change

SDN enables industry to customize their network

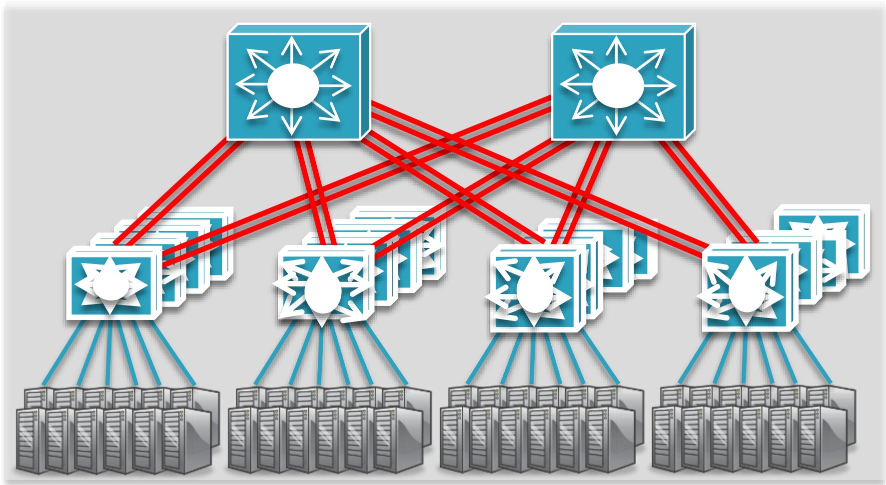
Telco Operators

- 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

Consequences for research

Ease of trying new ideas

- Existing tools: NOX, Beacon, switches, Mininet
- More rapid technology transfer
- GENI, Ofelia and many more

A stronger foundation to build upon

- Provable properties of forwarding
- New languages and specification tools

Consequences for standards

Standards will define the interfaces

The role of standards will change:

- Network owners will define network behavior
- Features will be adopted without standards

Programming world

- Good software is adopted, not standardized

Summary

- Networks becoming
  - More programmatic
  - Defined by owners and operators, not vendors
  - Faster changing, to meet operator needs
  - Lower opex, capex and power
- Abstractions
  - Will shield programmers from complexity
  - Make behavior more provable
  - Will take us places we can’t yet imagine

Administravia …

- Assignment 4 due December 13
- Internet in the News (10% of final grade)
  - Due next Monday Dec. 1 on Piazza
  - Reading/commenting on others' Internet in the News part of participation mark
  - Recent news: http://www.newsweek.com/china-could-shut-down-us-power-grid-cyber-attack-says-nsa-chief-286119
  - Lots of topics, pick something you find interesting
- No class Wednesday!
- Next Monday → Mobile networks!