CSCI-1680
Software-Defined Networking

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With content from Scott Shenker, Nick McKeown

SDN

- **For now: a new paradigm for network management**
- **SDN widely accepted as “future of networking”**
  - ~1000 engineers at latest Open Networking Summit
  - Commercialized, in production use
    - Controls Google’s WAN; Microsoft and Google cloud offerings
    - VMWare’s main networking product
    - Drives many OpenStack network deployments
  - *Strong acceptance in industry and academia*

- **An insane level of SDN hype, and backlash…**
  - Nicira bought by VMWare in 2012 for $1.2B
  - SDN doesn’t work miracles, merely makes things easier

- **If SDN is the solution, what is the problem?**

The Problem with Networking

- **So, what is the problem that justified such excitement?**
- **The management of networks**
  - Loosely, everything related to the *control plane*

- **The real problem: networking as a discipline is built on weak foundations**

Building an Artifact, Not a Discipline

- **Other fields in “systems”: OS, DB, etc.**
  - Teach basic principles
  - Are easily managed
  - Continue to evolve

- **Networking:**
  - Study of an artifact: the Internet
  - Teach (mostly) big bag of protocols
  - Notoriously difficult to manage
  - Evolves very slowly

- ***Networks are much more primitive and less understood than other computer systems***

What is Network Management?

- **Recall the two "planes"**
- **Data plane: forwarding packets**
  - Based on local forwarding state
- **Control plane: computing that forwarding state**
  - Involves coordination with rest of system
- **Broad definition of "network management":**
  - ***Everything having to do with the control plane***

Original goals for the control plane

- **Basic connectivity: route packets to destination**
  - Local state computed by routing protocols
  - Globally distributed algorithms
- **Interdomain policy: find policy-compliant paths**
  - Done by fully distributed BGP
- **For long time, these were the only relevant goals!**
  - What other goals are there in running a network?

Also

- Isolation
- Access Control
- Traffic Engineering
- …

Isolation

- **Want multiple LANs on single physical network**

- **Packets on LAN don't pass through routers**
  - But routers used to impose various controls (later)

- **Use VLANs (virtual LANs) tags in L2 headers**
  - Controls where broadcast packets go
  - Gives support for logical L2 networks
  - Routers connect these logical L2 networks

- **No universal method for setting VLAN state**

Access Control

- **Operators want to limit access to various hosts**
  - Don't let laptops access backend database machines

- **This can be imposed by routers using ACLs**
  - ACL: Access control list

- **Example entry in ACL: <header template; drop>**

Traffic Engineering

- **Want to avoid persistent overloads on links**
- **Choose routes to spread traffic load across links**
- **Two main methods:**
  - Setting up MPLS tunnels
  - Adjusting weights in OSPF
- **Often done with centralized computation**
  - Take snapshot of topology
  - Compute appropriate MPLS/OSPF state
  - Send to network

Control Plane Mechanisms

- **Many different control plane mechanisms**
- **Designed from scratch for specific goal**
- **Variety of implementations**
  - **Globally distributed:** routing algorithms
  - **Manual/scripted configuration:** ACLs, VLANs
  - **Centralized computation:** Traffic engineering
- **Network control plane is a complicated mess!**

How Have We Managed To Survive?

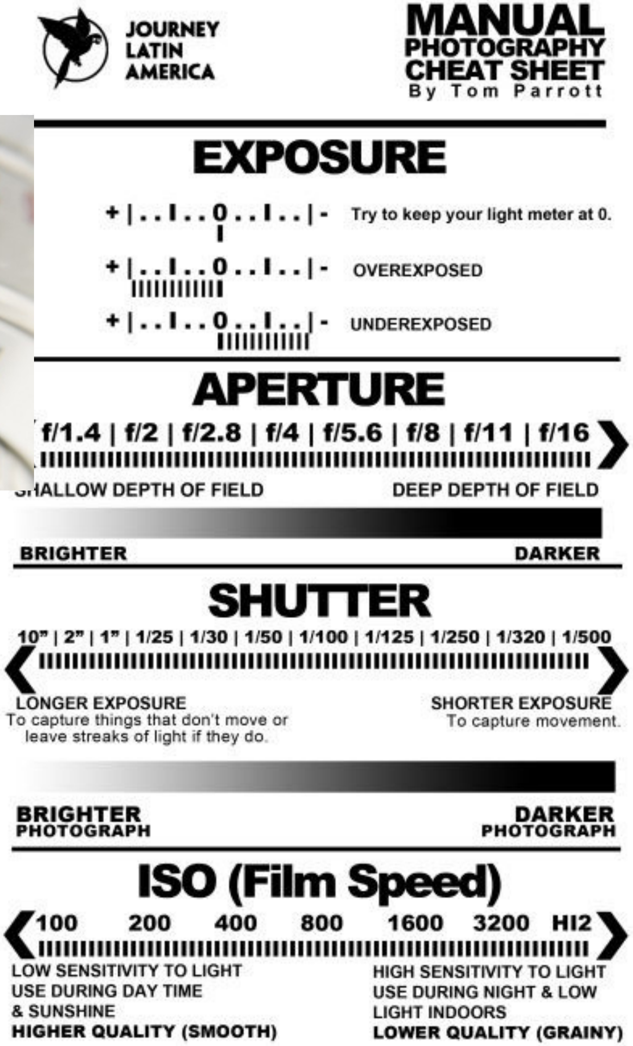
- **Net. admins miraculously master this complexity**
  - Understand all aspects of networks
  - Must keep myriad details in mind
- **This ability to master complexity is both a blessing**
  - **…and a curse!**

Mastering Complexity versus Extracting Simplicity

- **The ability to master complexity is valuable**
  - But not the same as the ability to **extract simplicity**

- **Each has its role:**
  - When first getting systems to work, *master complexity*
  - When making system easy to use, *extract simplicity*

- **You will never succeed in extracting simplicity**
  - If you don't recognize it is a different skill set than mastering complexity



JOURNEY LATIN AMERICA

MANUAL PHOTOGRAPHY CHEAT SHEET
By Tom Parrott

EXPOSURE

+|..I..0..I..|- Try to keep your light meter at 0.

+|..I..0..I..|- OVEREXPOSED

+|..I..0..I..|- UNDEREXPOSED

APERTURE

f/1.4 | f/2 | f/2.8 | f/4 | f/5.6 | f/8 | f/11 | f/16

SHALLOW DEPTH OF FIELD — DEEP DEPTH OF FIELD

BRIGHTER — DARKER

SHUTTER

10" | 2" | 1" | 1/25 | 1/30 | 1/50 | 1/100 | 1/125 | 1/250 | 1/320 | 1/500

LONGER EXPOSURE
To capture things that don't move or leave streaks of light if they do.

SHORTER EXPOSURE
To capture movement.

BRIGHTER PHOTOGRAPH — DARKER PHOTOGRAPH

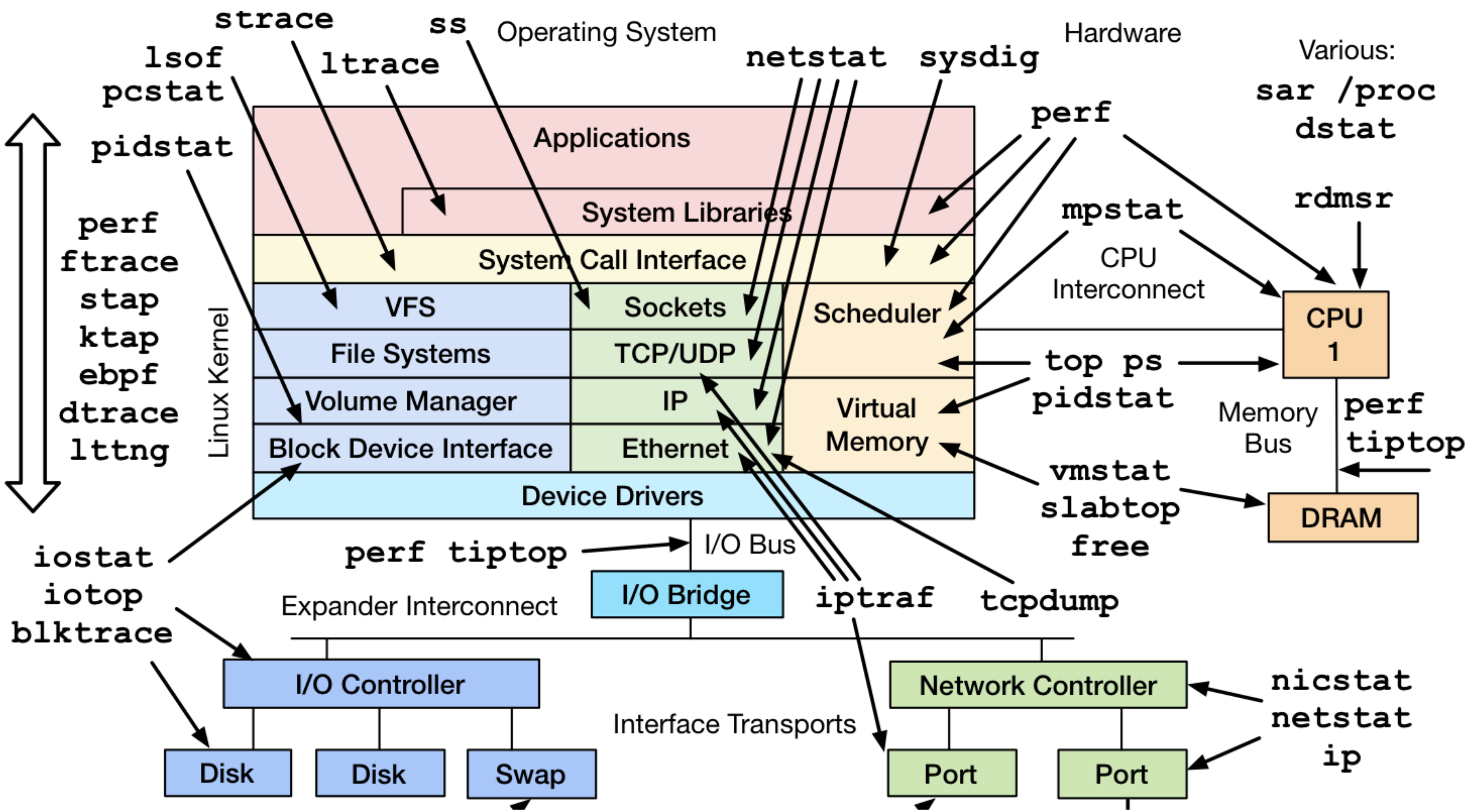
ISO (Film Speed)

100 200 400 800 1600 3200 HI2

LOW SENSITIVITY TO LIGHT
USE DURING DAY TIME
& SUNSHINE
HIGHER QUALITY (SMOOTH)

HIGH SENSITIVITY TO LIGHT
USE DURING NIGHT & LOW
LIGHT INDOORS
LOWER QUALITY (GRAINY)

Iphone photo by Sam Alive



Linux Observability tools by Brendan Gregg, brendangregg.com

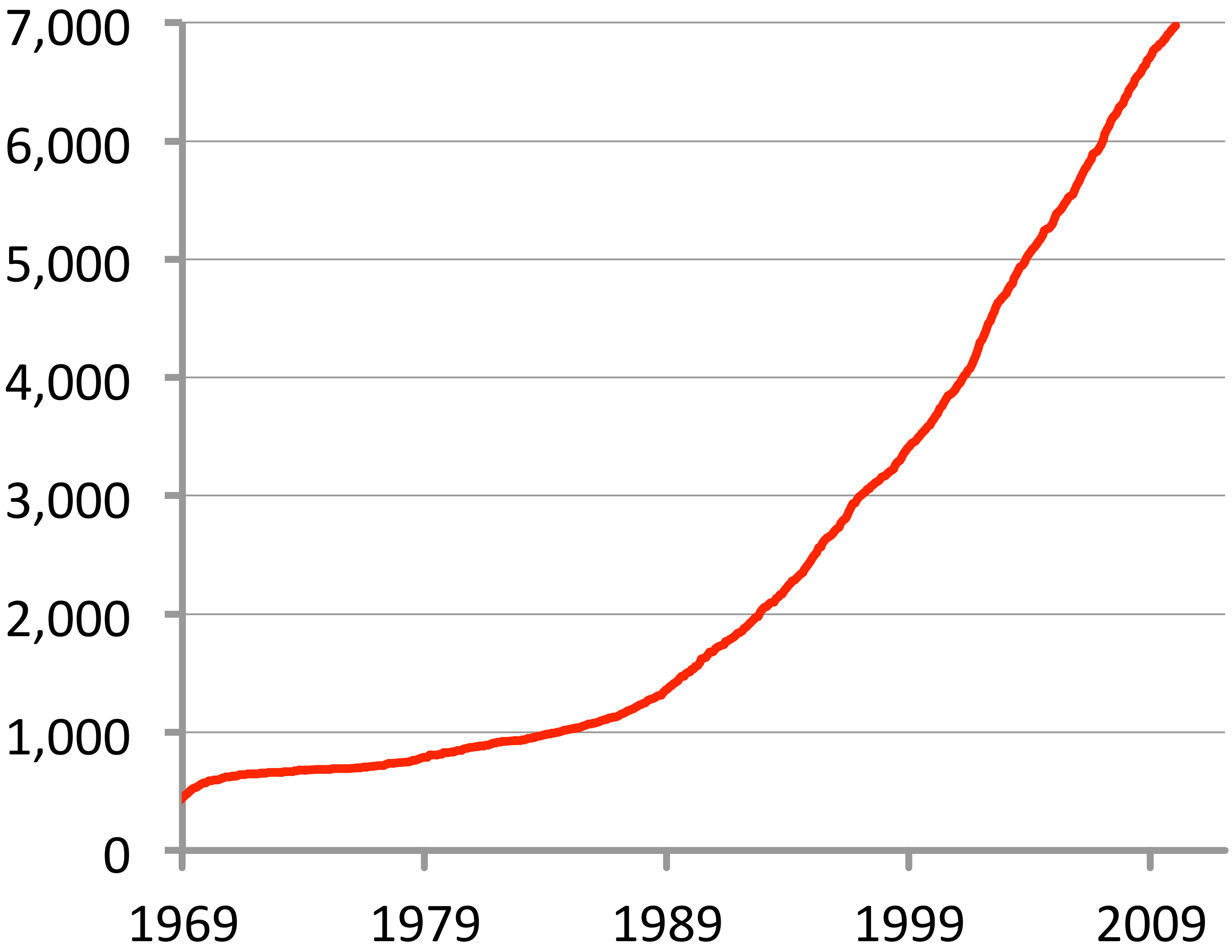
Mastering Complexity versus Extracting Simplicity

- **Networking has never made the distinction…**
  - And therefore has never made the transition from mastering complexity to extracting simplicity

- **Still focused on mastering complexity**
  - Networking "experts" are those that know all the details

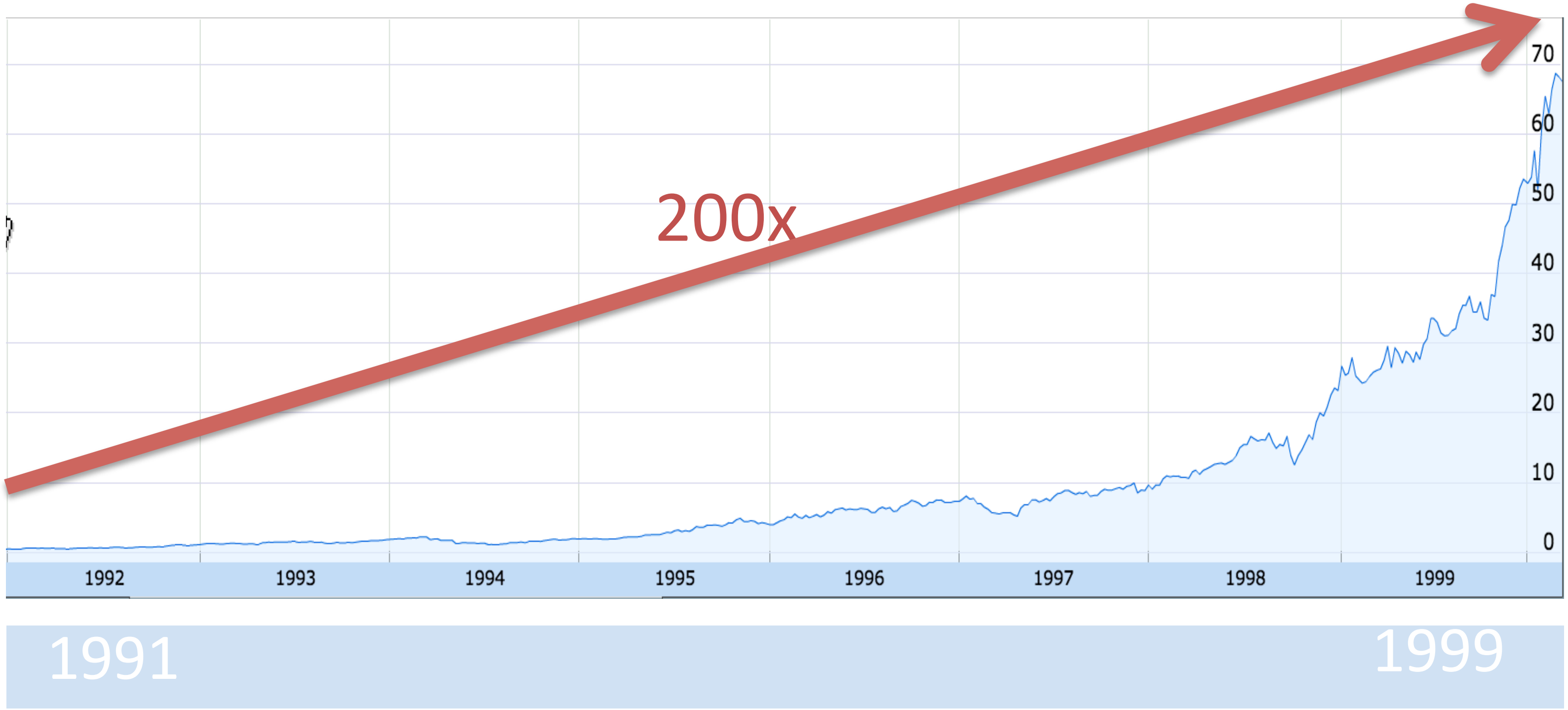
- ***Extracting simplicity lays intellectual foundations***
  - This is why networking has weak foundation
  - We are ***still*** building the artifact, not the discipline

Number of published Internet Standards



Graph from Nick McKeown

Cisco Stock Price



Google Fin

Why make the transition

- **Complexity has increased to “unmanageable” levels**
- **Consider datacenters:**
  - 100,000s machines, 10,000s switches
  - 1000s of customers
    - Each with their own logical networks: ACLs, VLANs, etc
- **Way beyond what we can handle**
  - Leads to brittle, ossified configurations
  - Probably inefficient too

An Example Transition: Programming

- **Machine languages: no abstractions**
  - Had to deal with low-level details
  - Mastering complexity was crucial

- **Higher-level languages: OS and other abstractions**
  - File system, virtual memory, abstract data types, ...

- **Modern languages: even more abstractions**
  - Object orientation, garbage collection,...

Abstractions key to extracting simplicity

"The Power of Abstraction"

"Modularity based on abstraction is the way things get done"

– Barbara Liskov

Abstractions → Interfaces → Modularity

What About Networking Abstractions?

- Consider the data and control planes separately
- Different tasks, so naturally different abstractions

Abstractions for Data Plane: Layers

Applications

…built on…

Reliable (or unreliable) transport

…built on…

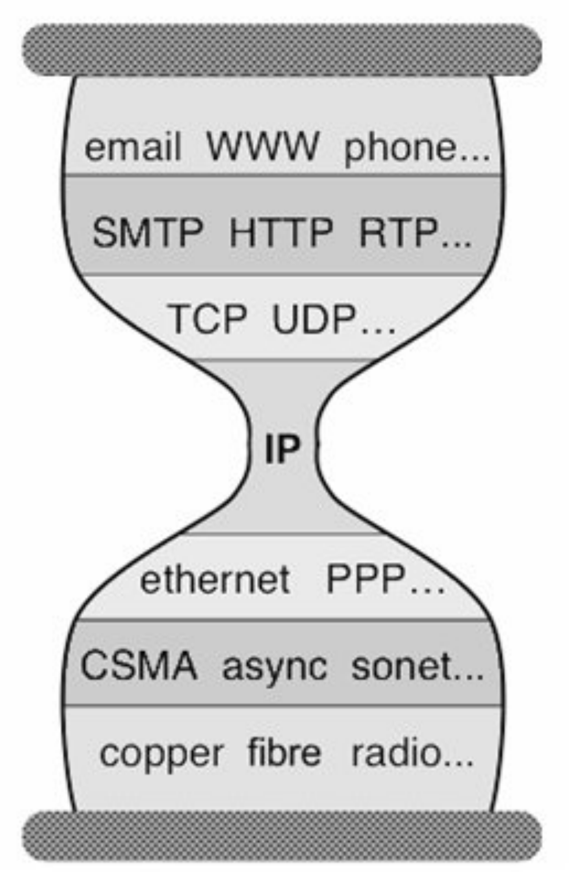
Best-effort global packet delivery

…built on…

Best-effort local packet delivery

…built on…

Physical transfer of bits



The Importance of Layering

- **Decomposed delivery into basic components**
- **Independent, compatible innovation at each layer**
  - Clean "separation of concerns"
  - Leaving each layer to solve a tractable problem
- **Responsible for the success of the Internet!**
  - Rich ecosystem of independent innovation

Control Plane Abstractions

?

(Too) Many Control Plane Mechanisms

- **Control Plane: mechanisms without abstraction**
  - *Too many mechanisms, not enough functionality*

- **Variety of goals, no modularity:**
  - **Routing:** distributed routing algorithms
  - **Isolation**: ACLs, VLANs, Firewalls,…
  - **Traffic engineering**: adjusting weights, MPLS,…

Finding Control Plane Abstractions

How do you find abstractions?

- You first decompose the problem….
- …and define abstractions for each subproblem
- So what is the control plane problem?

Task: Compute forwarding state:

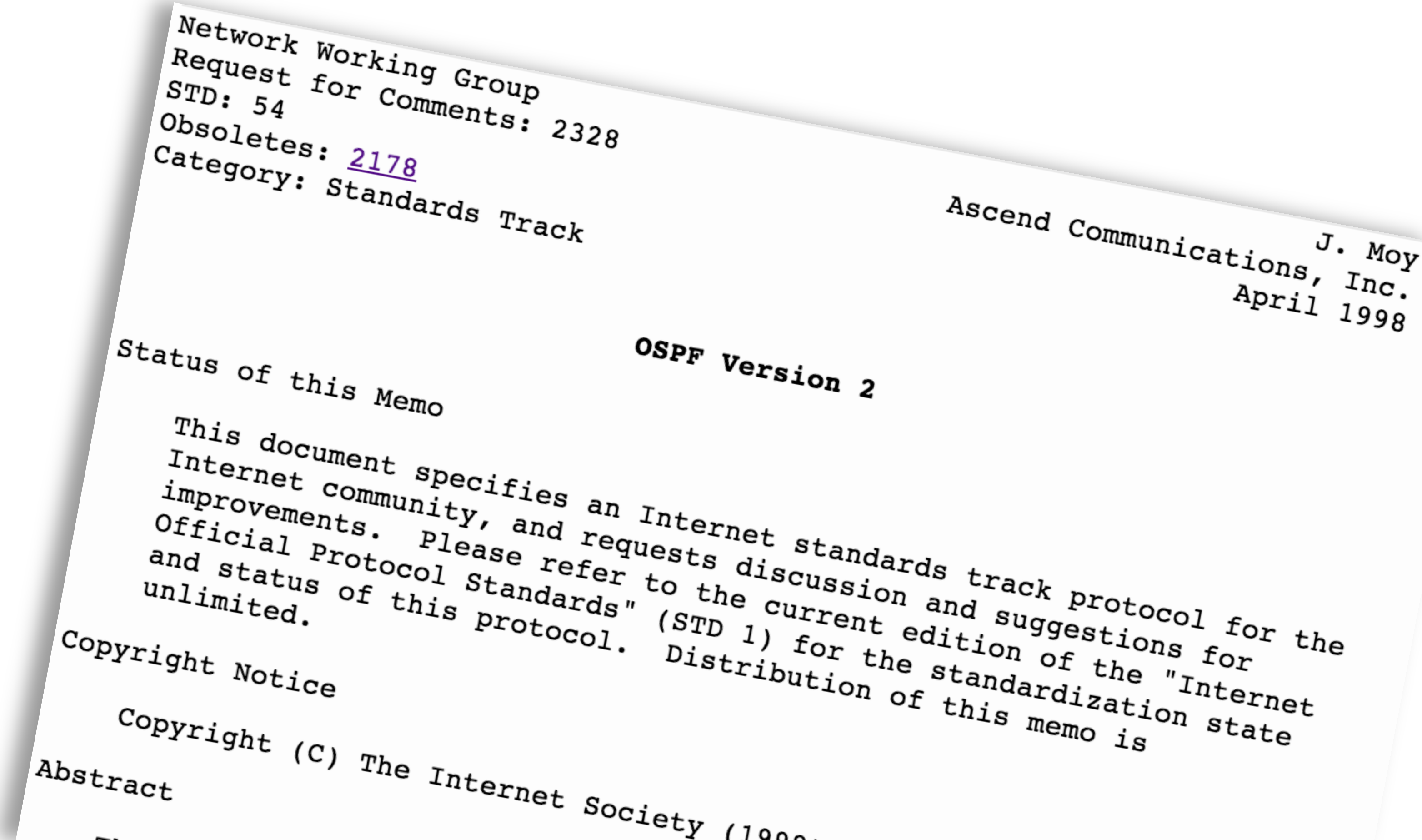
- **Consistent with low-level hardware/software**
  - Which might depend on particular vendor
- **Based on entire network topology**
  - Because many control decisions depend on topology
- **For all routers/switches in network**
  - Every router/switch needs forwarding state

Our current approach

- **Design one-off mechanisms that solve all three**
  - A sign of how much we love complexity
- **No other field would deal with such a problem!**
- **They would define abstractions for each subtask**
- **…and so should we!**

Example

- **OSPF:**
  - 5% for Djikstra's algorithm,
  - 95% to find and maintain the state of the network



```
Network Working Group                                          J. Moy
Request for Comments: 2328              Ascend Communications, Inc.
STD: 54                                                    April 1998
Obsoletes: 2178
Category: Standards Track

                          OSPF Version 2

Status of this Memo

   This document specifies an Internet standards track protocol for the
   Internet community, and requests discussion and suggestions for
   improvements.  Please refer to the current edition of the "Internet
   Official Protocol Standards" (STD 1) for the standardization state
   and status of this protocol.  Distribution of this memo is
   unlimited.

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Abstract
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Separate Concerns with Abstractions

1. **Be compatible with low-level hardware/software**

   Need an abstraction for general **forwarding model**

2. **Make decisions based on entire network**

   Need an abstraction for **network state**

3. **Compute configuration of each physical device**

   Need an abstraction that **simplifies configuration**

Abs#1: Forwarding Abstraction

- **Express intent independent of implementation**
  - Don't want to deal with proprietary HW and SW
- **OpenFlow is current proposal for forwarding**
  - Standardized interface to switch
  - Configuration in terms of flow entries:
    - <header fields, action>
- **Design details concern exact nature of:**
  - Header matching
  - Allowed actions

Two Important Facets to OpenFlow

- **Switches accept external control messages**
  - Not closed, proprietary boxes
- **Standardized flow entry format**
  - So switches are interchangeable

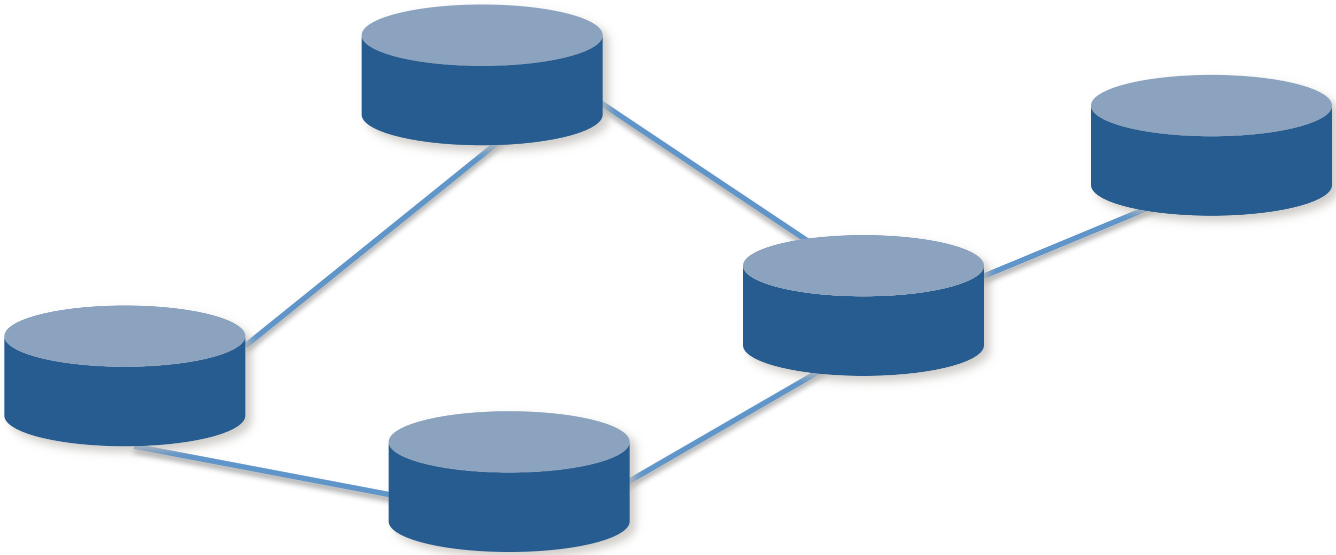
Abs#2: Network State Abstraction

- **Abstract away various distributed mechanisms**
- **Abstraction: global network view**
  - Annotated network graph provided through an API
- **Implementation: "Network Operating System"**
  - Runs on servers in network ("controllers")
  - Replicated for reliability
- **Information flows both ways**
  - Information *from* routers/switches to form "view"
  - Configurations *to* routers/switches to control forwarding

Network Operating System

- **Think of it as a centralized link-state algorithm**
- **Switches send connectivity info to controller**
- **Controller computes forwarding state**
  - Some control program that uses the topology as input
- **Controller sends forwarding state to switches**
- **Controller is replicated for resilience**
  - System is only “logically centralized”

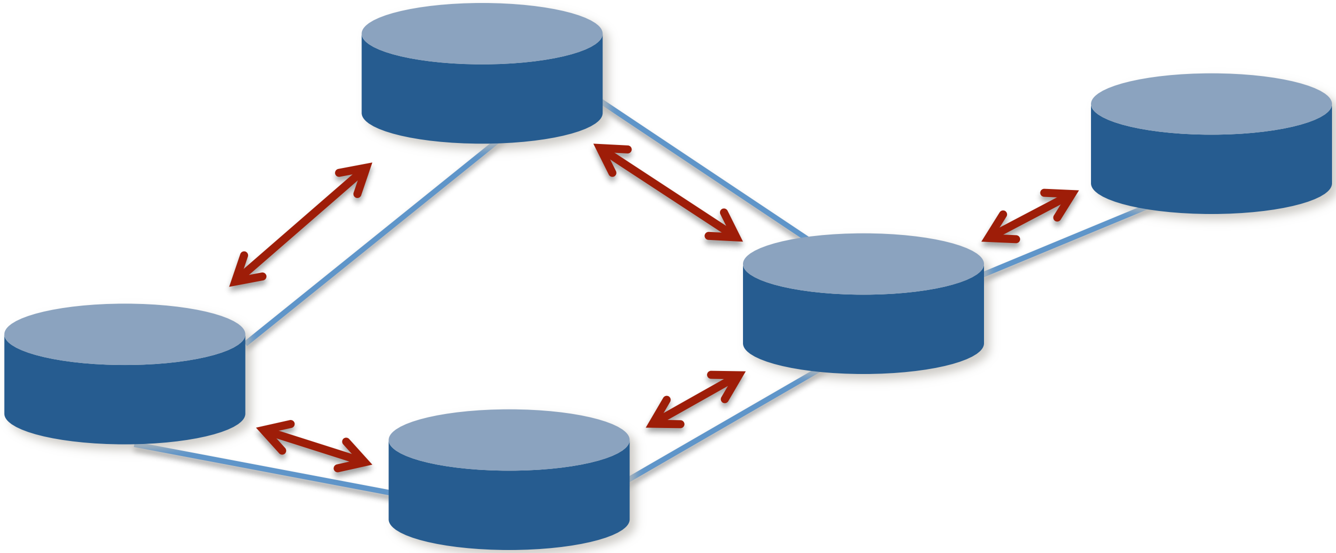
Network of Switches and/or Routers



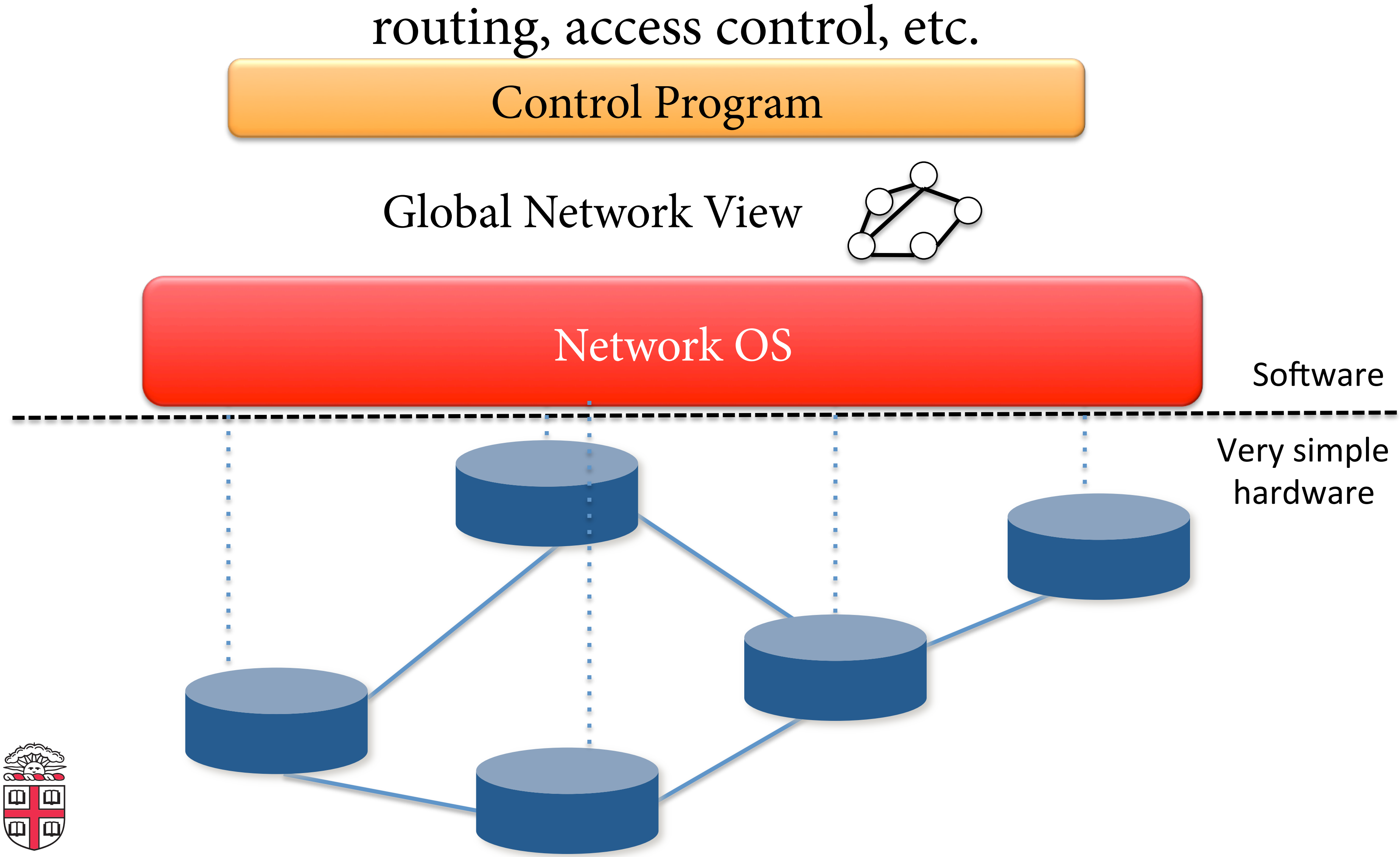
Traditional Control Mechanisms

Distributed algorithm running between neighbors

Complicated task-specific distributed algorithm



Software Defined Network (SDN)



routing, access control, etc.

Control Program

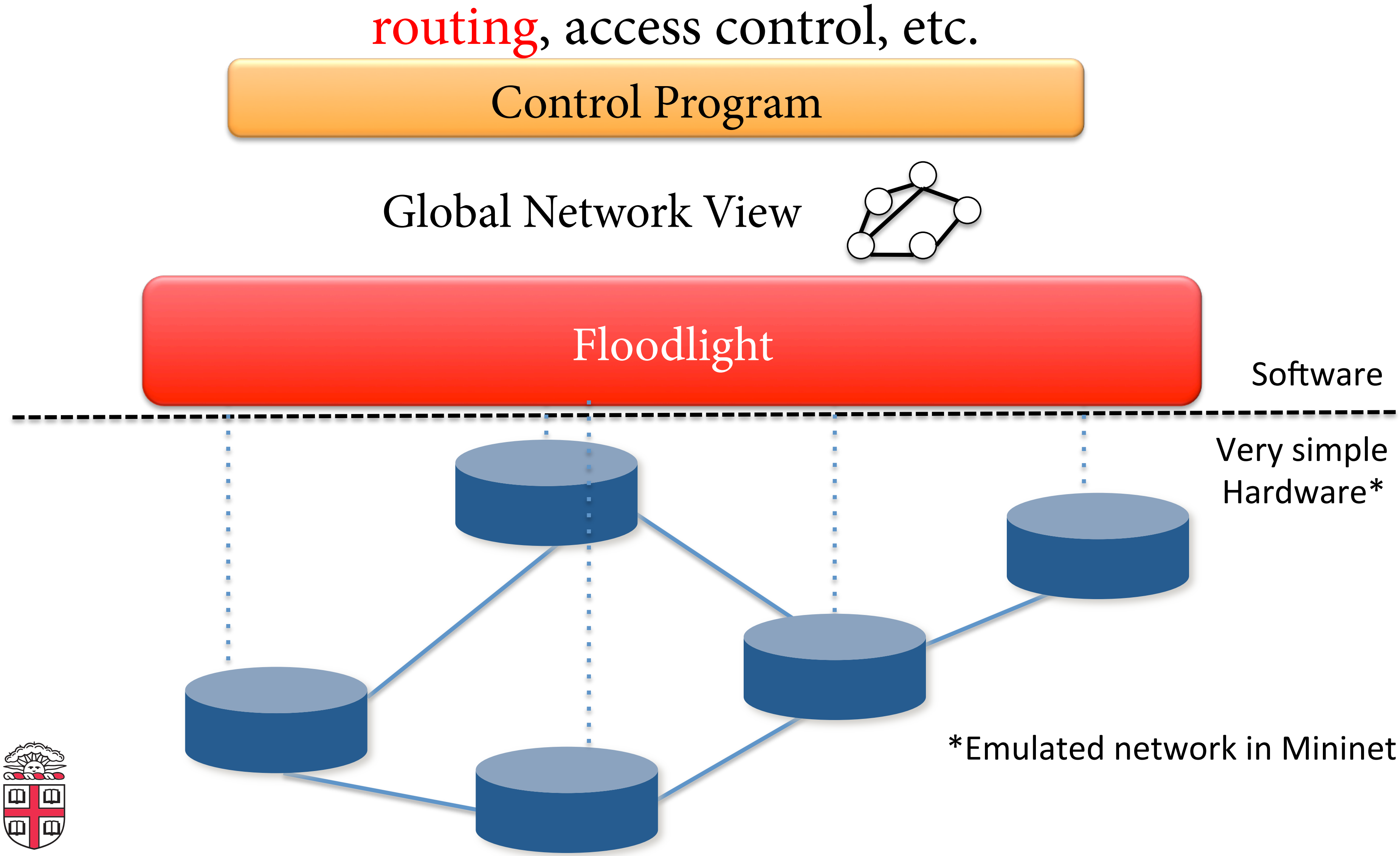
Global Network View

Network OS

Software

Very simple
hardware

Your final Project



routing, access control, etc.

Control Program

Global Network View

Floodlight

Software

Very simple
Hardware*

*Emulated network in Mininet

Major Change in Paradigm

- Control program:
  - Configuration = Function(view)

- Control mechanism now program using NOS API

- Not a distributed protocol, just a graph algorithm

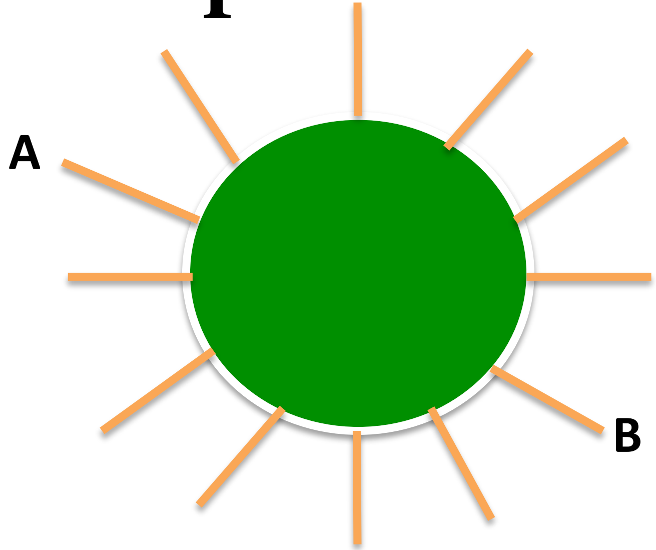
Abs#3: Specification Abstraction

- **Control mechanism expresses desired behavior**
  - Whether it be isolation, access control, or QoS

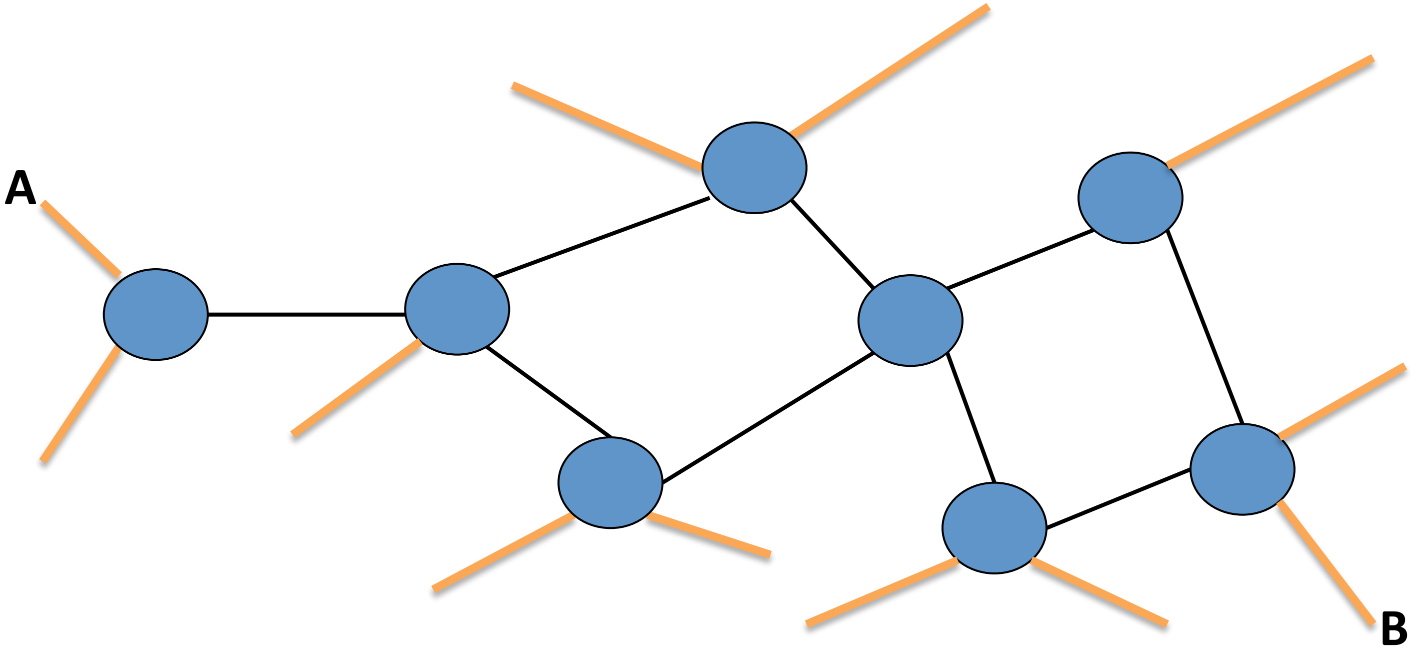
- **It should not be responsible for *implementing* that behavior on physical network infrastructure**
  - Requires configuring the forwarding tables in each switch

- **Proposed abstraction: abstract view of network**
  - Abstract view models only enough detail to *specify goals*
  - Will depend on task semantics

Simple Example: Access Control



Abstract Network View



Global Network View

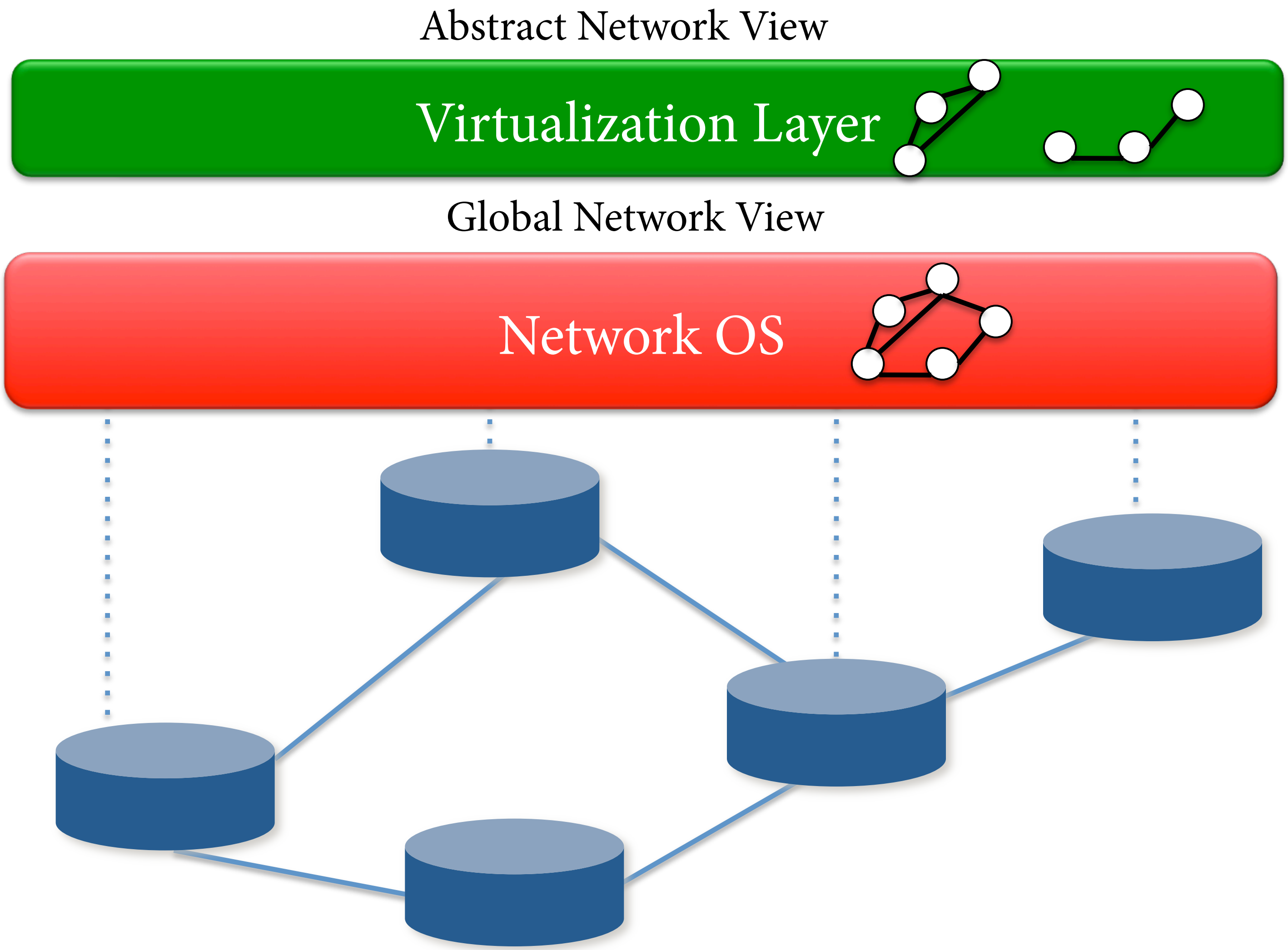
Routing

- Look at graph of network
- Compute routes
- Give to SDN platform, which passes on to switches

Access Control

- **Control program decides who can talk to who**
- **Pass this information to SDN platform**
- **Appropriate ACL flow entries are added to network**
  - In the right places (based on the topology)

Network Virtualization



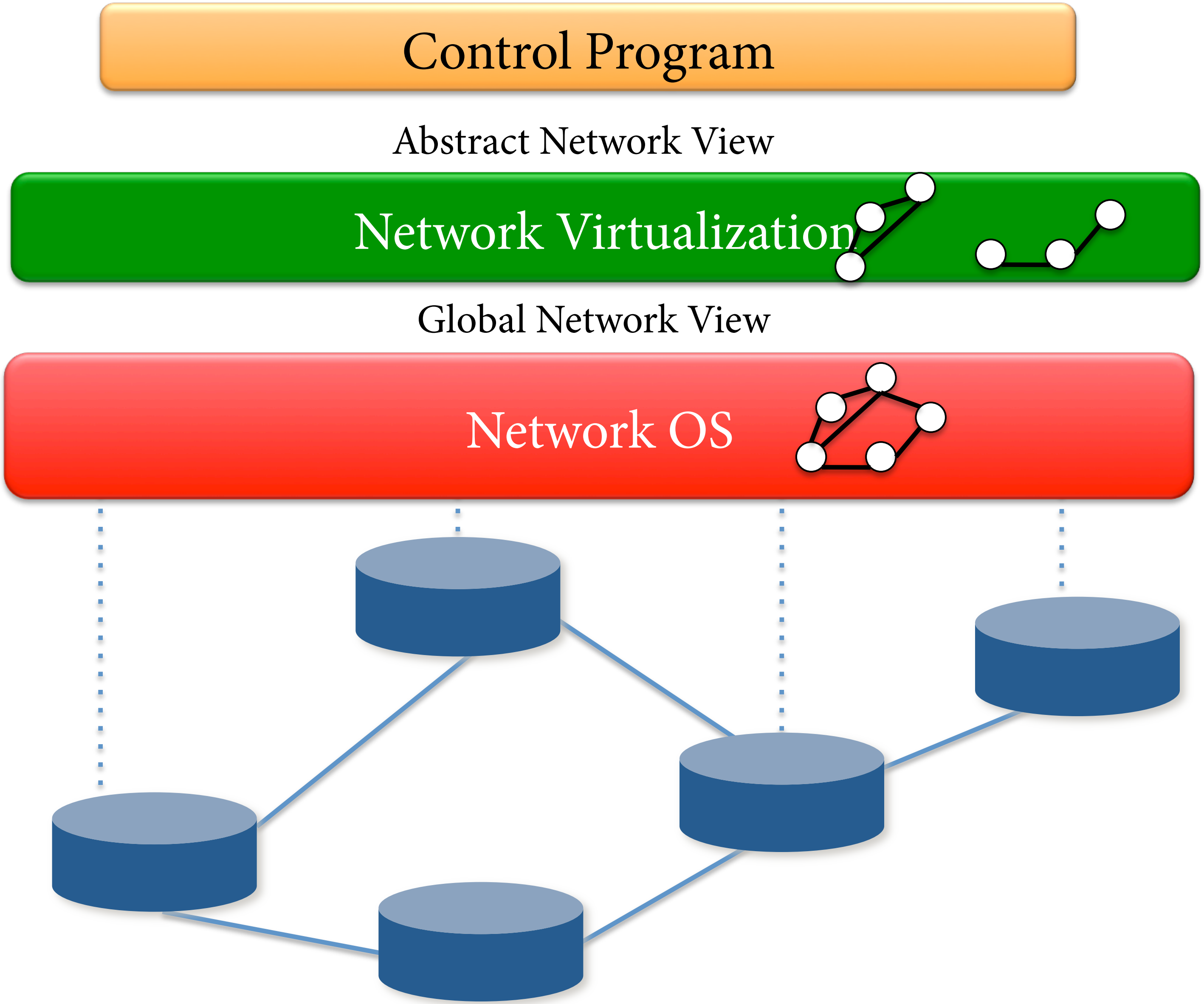
Clean Separation of Concerns

- **Control program: express goals on abstract view**
  - Driven by **Operator Requirements**

- **Virtualization Layer: abstract view ←→ global view**
  - Driven by **Specification Abstraction** for particular task

- **NOS: global view ←→ physical switches**
  - API: driven by **Network State Abstraction**
  - Switch interface: driven by **Forwarding Abstraction**

SDN: *Layers* for the Control Plane



Abstractions for Control Plane

Expression of Intent

…built on…

Abstract Network View

…built on…

Global Network View

…built on…

Physical Topology

Abstractions Don't Remove Complexity

- **NOS, Virtualization are complicated pieces of code**

- **SDN merely localizes the complexity:**
  - Simplifies interface for control program (user-specific)
  - Pushes complexity into ***reusable*** code (SDN platform)

- **This is the big payoff of SDN: modularity!**
  - The core distribution mechanisms can be reused
  - Control programs only deal with their specific function

- **Note that SDN separates control and data planes**
  - SDN platform does control plane, switches do data plane

What This Really Means

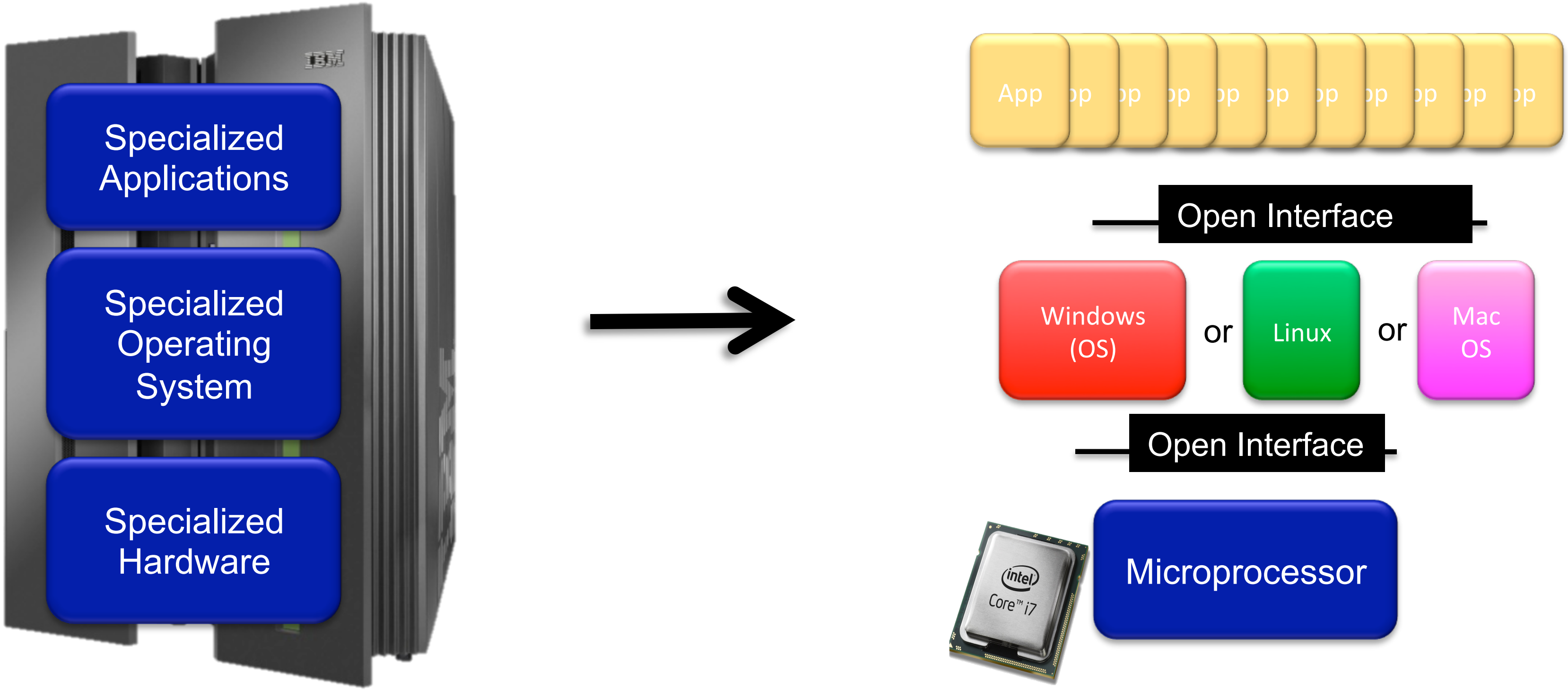
Separation of Control/Data Plane

- **Today, routers implement both**
  - They forward packets
  - And run the control plane software
- **SDN networks**
  - Data plane implemented by switches
    - Switches act on local forwarding state
  - Control plane implemented by controllers
    - All forwarding state computed by SDN platform
- **This is a technical change, with broad implications**

Changes

- **Less vendor lock-in**
  - Can buy HW/SF from different vendors
- **Changes are easier**
  - Can test components separately
    - *HW has to forward*
    - *Can simulate controller*
    - *Can do verification on logical policy*
  - Can change topology and policy independently
  - Can move from private net to cloud and back!
  - Greater rate of innovation

Computer Industry



Specialized Applications

Specialized Operating System

Specialized Hardware

App pp pp pp pp pp pp pp pp pp pp

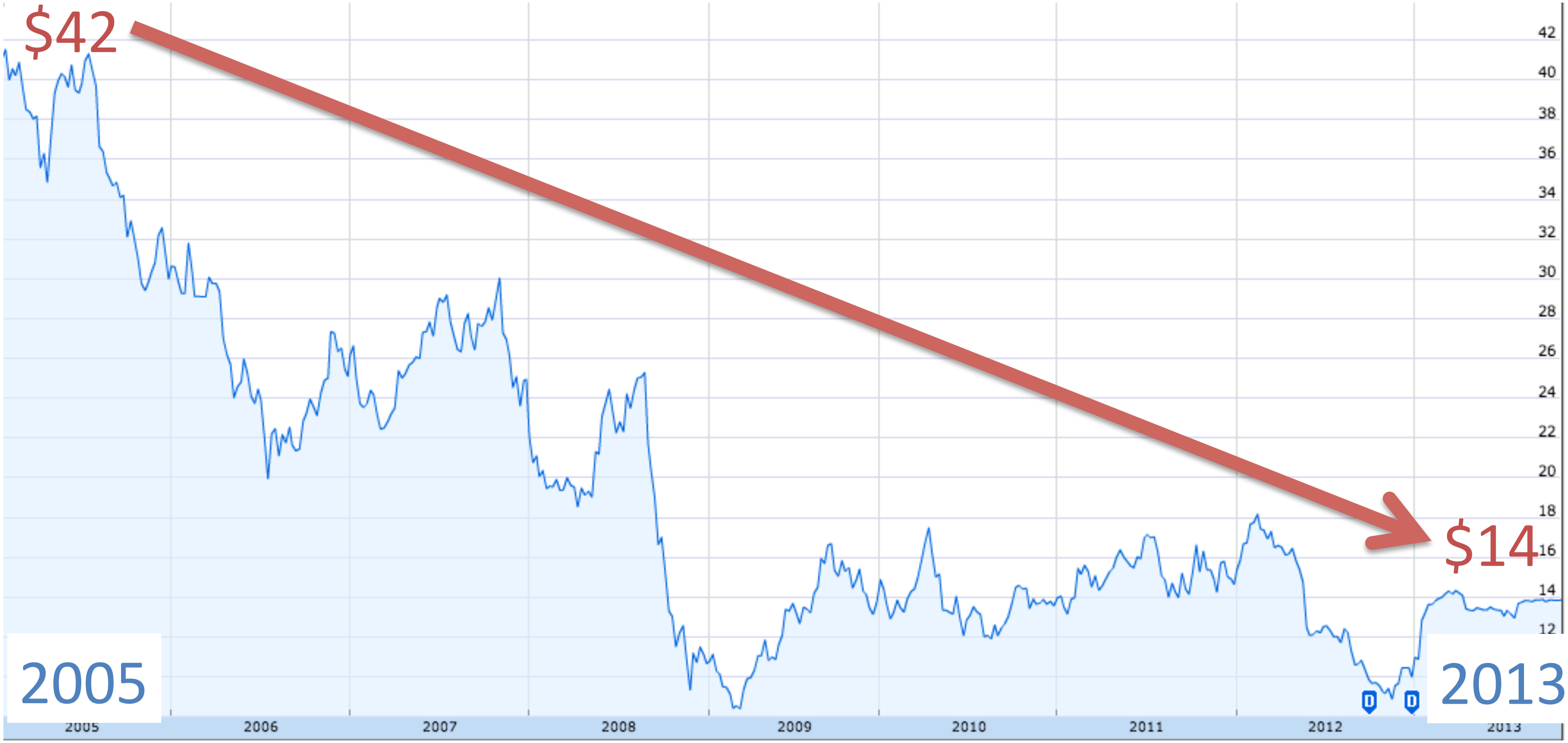
Open Interface

Windows (OS) or Linux or Mac OS

Open Interface

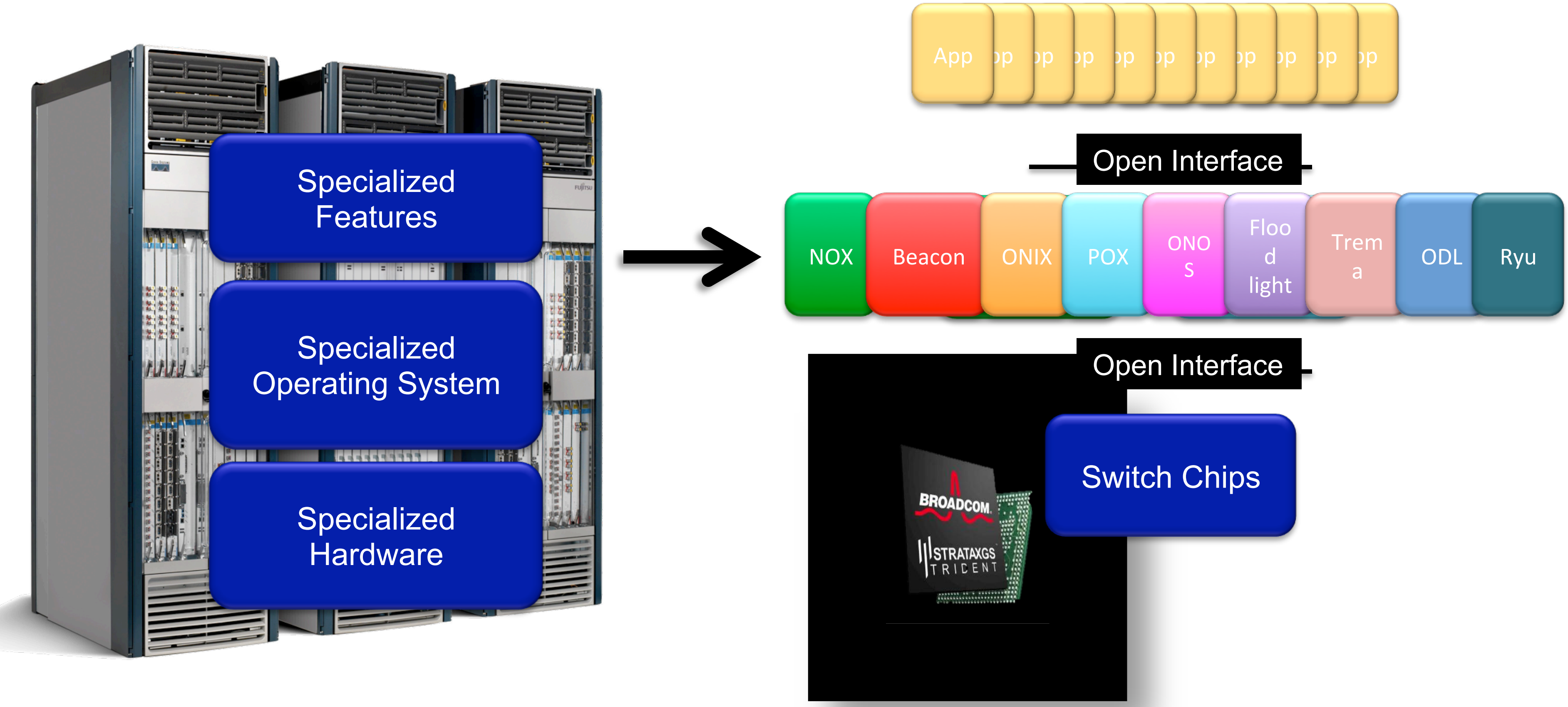
Microprocessor

Dell Stock Price



Google Finance

Networking Industry



Specialized Features

Specialized Operating System

Specialized Hardware

App pp pp pp pp pp pp pp pp pp pp

Open Interface

NOX

Beacon

ONIX

POX

ONOS

Floodlight

Trema

ODL

Ryu

Open Interface

Switch Chips

Current Status of SDN

- **SDN widely accepted as "future of networking"**
  - Commercial use inter-datacenter (Google), intra-datacenter (Microsoft)
  - Network virtualization is current killer app
    - VMWare's NSX, OpenStack network management
- **Insane level of SDN hype, and backlash…**
  - SDN doesn't work miracles, merely makes things easier
- **Open Networking Foundation (100+ members)**
  - **Board**: Google, Yahoo, Verizon, DT, Msoft, F'book, NTT
  - **Members**: Cisco, Juniper, HP, Dell, Broadcom, IBM,…
- **Watch out for upcoming chapters!**

To learn more…

- **Scott Shenker's talk "The Future of Networking, and the Past of Protocols"**
  - http://www.youtube.com/watch?v=YHeyuD89n1Y
  - Keynote at the 2011 Open Networking Summit
- **NEC SDN Reading List**
  - http://www.nec-labs.com/~lume/sdn-reading-list.html
- **The Road to SDN**
  - http://queue.acm.org/detail.cfm?id=2560327

OpenFlow

- **Simple API between switches and centralized controller**
- **Basic abstraction: flow match / action**
  - E.g., if a packet matches this IP dest, ETH protocol type, forward on port 3
  - If a packet matches ARP, send to controller
  - It a packet comes from evil IP address, drop