# Network Management and Software-Defined Networking (SDN)

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# Goal for today

- Provide the “why” of software-defined networking
  - Some history
  - Some gossip
  - ***And an exercise in architectural thinking***

- Not much of the “what”
  - but enough that some of you will want to know more

# Software-Defined Networking: *Caveats and Context*

# Caveats

- I cofounded a startup (Nicira) that worked on SDN
  - My views may be biased
  - I have no financial interest in the outcome, just ego
- SDN is not a revolutionary technology…
  - …just a way of organizing network functionality
- But that's all the Internet architecture is….
  - The Internet architecture isn't clever, but it is deeply wise
  - We know SDN isn't clever, but we hope it is wise….

# Context

- *Where did SDN come from?*
- *And what is the state of networking as a field?*
- **Keep context in mind as you learn about SDN…**

# Where did SDN come from?

- ~2004: Research on new management paradigms
  - RCP, 4D [Princeton, CMU,….]
  - SANE, Ethane [Stanford/Berkeley]
  - Industrial efforts with similar flavor (not published)
- 2008: Software-Defined Networking (SDN)
  - NOX Network Operating System [Nicira]
  - OpenFlow switch interface [Stanford/Nicira]
- 2011: Open Networking Foundation
  - **Board**: Google,Yahoo,Verizon,DT,Msft, Fbook,NTT,GS
  - **Members**: Cisco, Juniper, HP, Dell, Broadcom, IBM,…..

# Current Status of SDN

- SDN widely accepted as "**future of networking**"
  - More than 100 members in ONF (almost "everyone")
  - Commercialized, in production use (few places)
    - E.g., controls Google's WAN; NTT moving to deploy
- An insane level of SDN hype, and backlash…
  - SDN doesn't work miracles, merely makes things easier
- But the real question is: *why the rapid adoption?*

# The Field of Networking…

- Research built a great artifact: Internet
  - Mostly unrelated to academic research which came later
- CS networking now largely the study of the Internet
- Also interesting research in wireless, optical
  - Much of it is EE research into underlying technologies
  - Some wireless research (such at Katabi at MIT) broader
- But we failed to create an academic discipline

# Building an Artifact, Not a Discipline

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

- Networking:
  - Teach big bag of protocols
  - Notoriously difficult to manage
  - Evolves very slowly

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

# We are left with two key questions

- *Why the rapid adoption of SDN?*
  - What problem is it solving?
- *Why is networking behind other fields in CS?*
  - What is missing in the field?
- The answers are related, but will unfold slowly

# Network Management

# 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?

# Isolation

- L2 bcast protocols often used for discovery
  - Useful, unscalable, invasive
- Want multiple logical LANs on a physical network
  - Retain usefulness, cope with scaling, provide isolation
- 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>
  - If not port 80, drop
  - If source address = X, 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 and load
  - Compute appropriate MPLS/OSPF state
  - Send to network

# Network management has many goals

- Achieving these goals is job of the control plane…
- …which currently involves many mechanisms
- **Globally distributed:** routing algorithms
- **Manual/scripted configuration:** ACLs, VLANs
- **Centralized computation:** Traffic engineering

# Bottom Line

- Many different control plane mechanisms
- Each designed from scratch for their intended goal
- Encompassing a wide variety of implementations
  - Distributed, manual, centralized,…
- **Network control plane is a complicated mess!**

# How Did We Get Into This Mess?

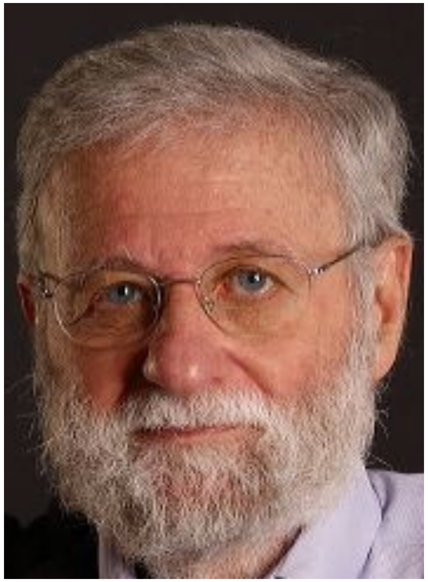
# How Have We Managed To Survive?

- 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!**

# A Simple Story About Complexity….

- ~1985: Don Norman visits Xerox PARC
  - Talks about user interfaces and stick shifts



# What Was His Point?

- 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

# What Is ***My*** Point?

- 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*
  - *By providing elegant conceptual formulations*
- This is why networking has weak foundation
  - We are ***still*** building the artifact, not the discipline

# Have answered one of our questions

- The reason networking is not a discipline is because it has not sought to extract simplicity
  - Other fields, such as OS, DB, etc, have
  - Those fields are more mature

- Extracting simplicity is also how you generalize to larger, more complicated systems
  - So it has practical advantages as well….

# Forcing people to make the transition

- We are really good at mastering complexity
  - And it has worked for us for decades, why change?

- How do you make people change?
  - Make them cry!

- A personal story about algebra and complexity
  - School problems:

    $3x + 2y = 8 \qquad x + y = 3$

  - My father's problems:

    $327x + 26y = 8757 \qquad 45x + 57y = 7776$

# Making Network Operators Cry…

# Step 1: Large datacenters

- 100,000s machines; 10,000s switches
- This is pushing the limits of what we can handle….

# Step 2: Multiple tenancy

- Large datacenters can host many customers
- Each customer gets their own logical network
  - Customer should be able to set policies on this network
  - ACLs, VLANs, etc.
- If there are 1000 customers, that adds 3 oom
  - Where oom = orders of magnitude
- This goes *way* beyond what we can handle

# Network Operators Are Now Weeping…

- They have been beaten by complexity
- The era of ad hoc control mechanisms is over
- We need a simpler, more systematic design
- ***So how do you "extract simplicity"?***

# 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…**

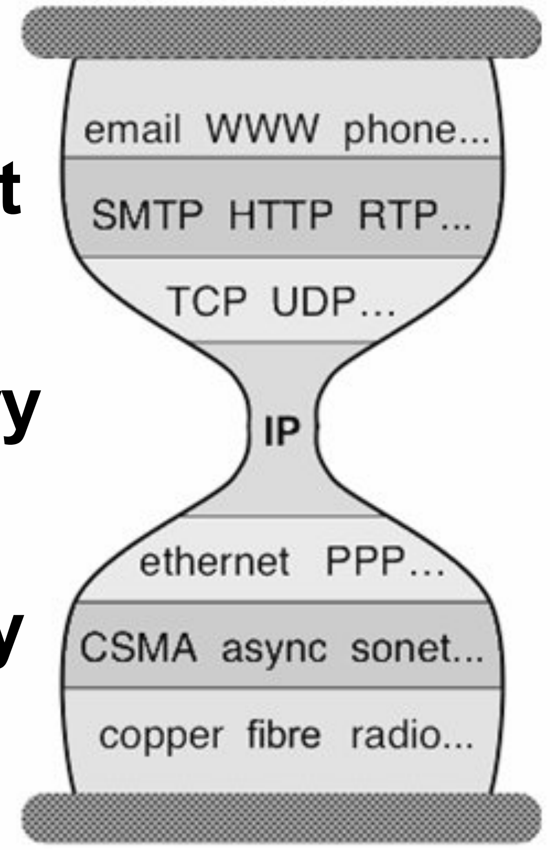
**Best-effort global packet delivery**

**…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

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

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

# 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!

# 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, 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 interchangable

# 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”

# Software Defined Network (SDN)

# Traditional Control Mechanisms

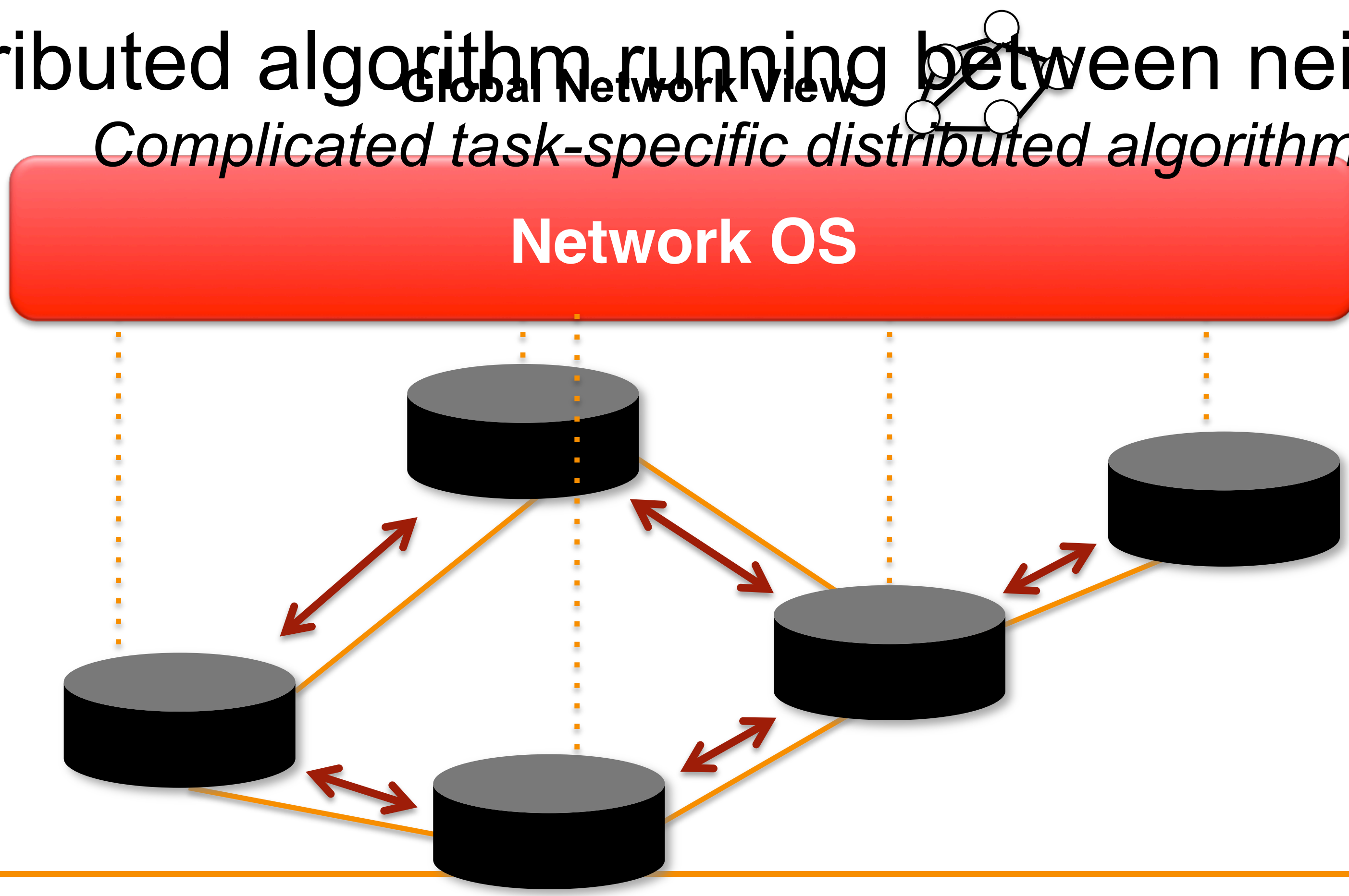
**routing, access control, etc.**

**Control Program**

Distributed algorithm running between neighbors

**Global Network View**

*Complicated task-specific distributed algorithm*



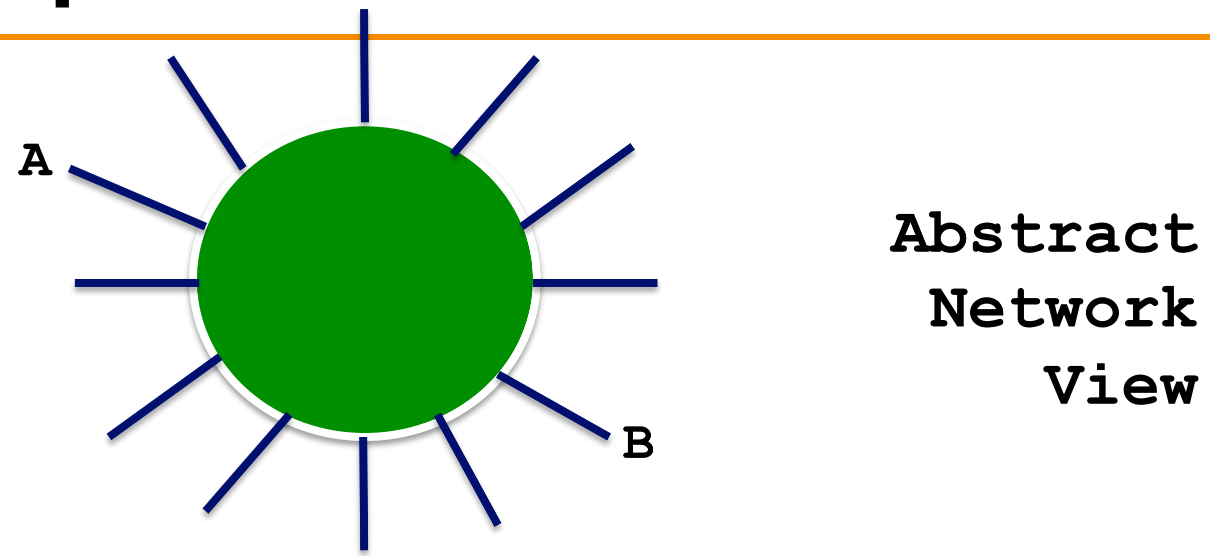
# Major Change in Paradigm

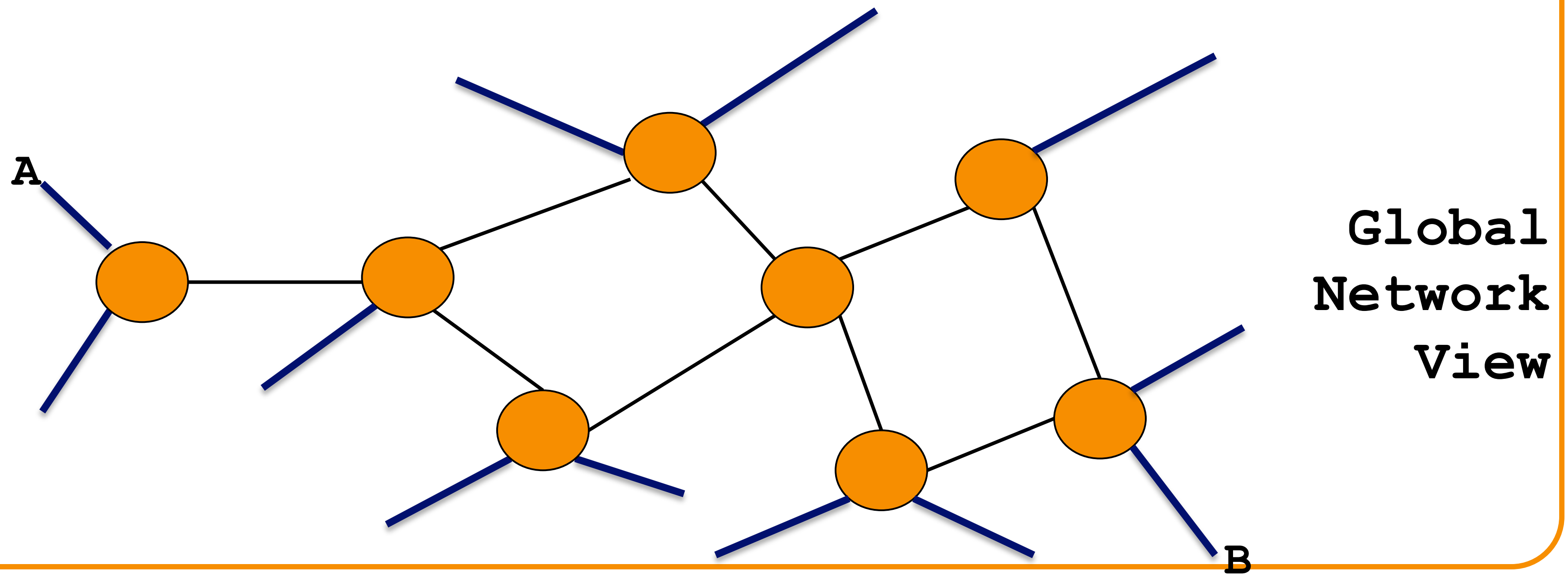
- Control program: **Configuration = Function(view)**
- Control mechanism now program using NOS API
- Not a distributed protocol, just a graph algorithm

# Abs#3: Specification Abstraction

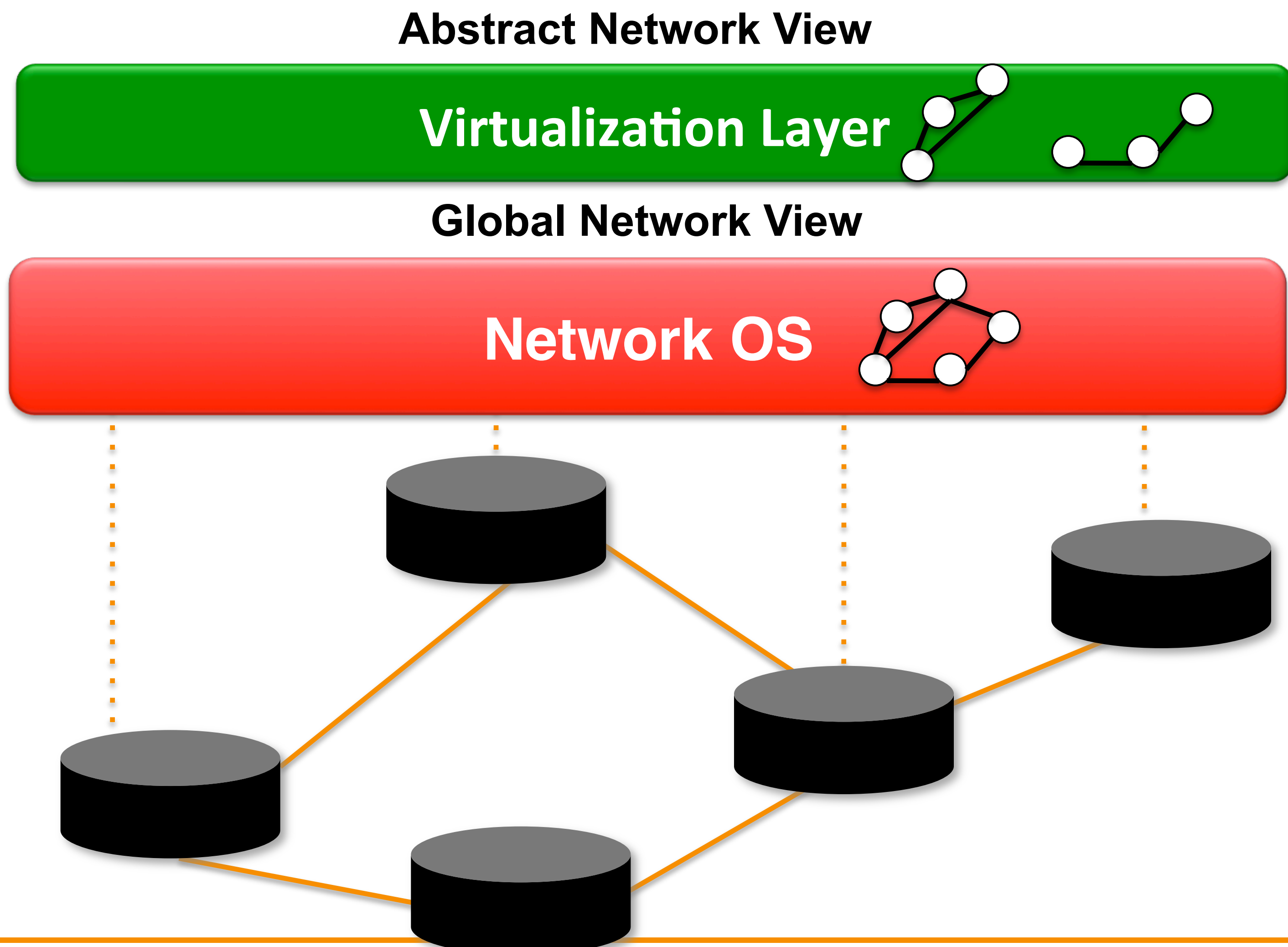
- Control mechanism expresses desired behavior
  - Whether it be isolation, access control, or QoS
- It should not be responsible for ***implementing*** that behavior on physical network infrastructure
  - Requires configuring the forwarding tables in each switch
- Proposed abstraction: **abstract view** of network
  - Abstract view models only enough detail to *specify goals*
  - Will depend on task semantics

# Simple Example: Access Control



# Software Defined Network



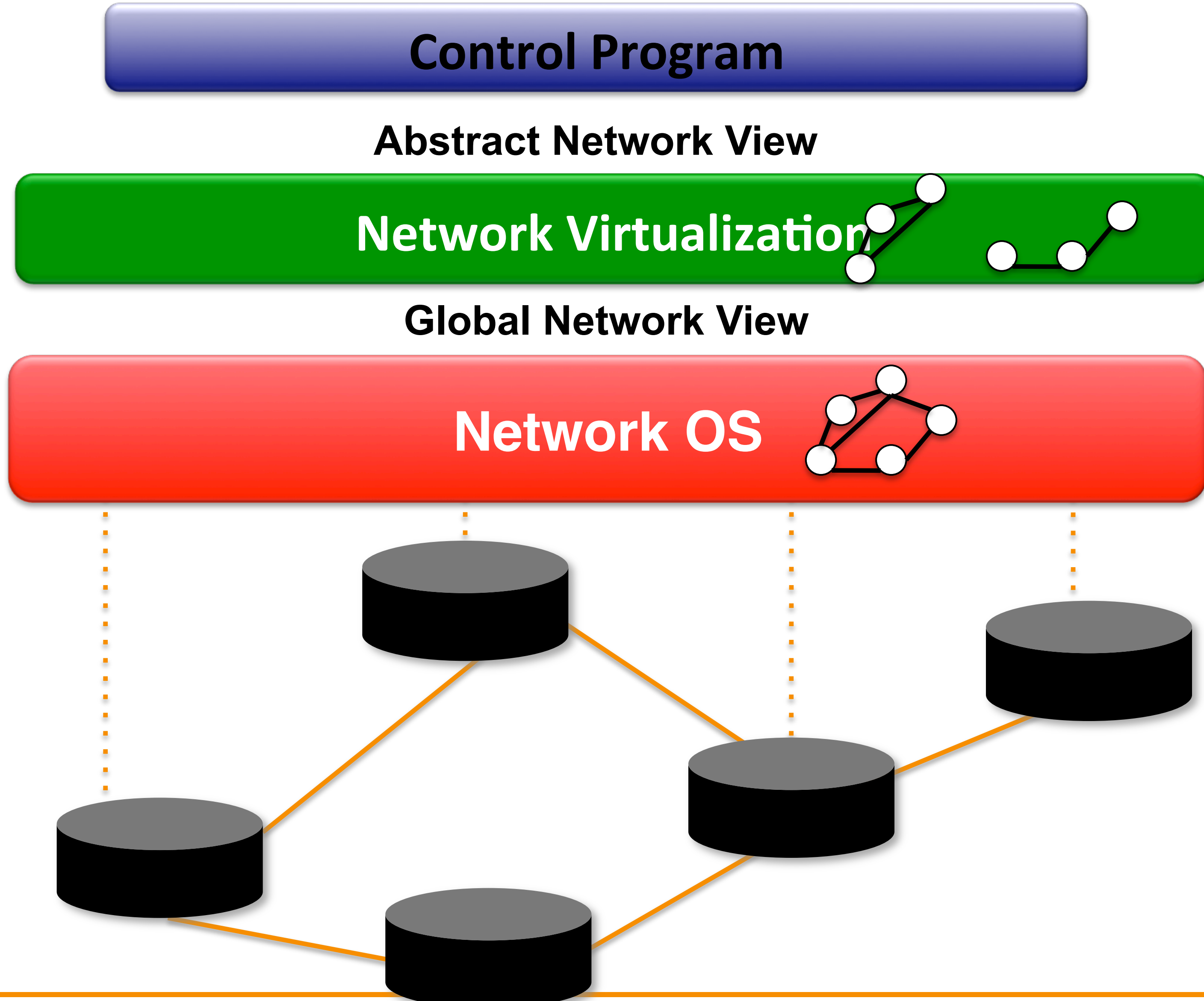
# Clean Separation of Concerns

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

- **VirtualizationLayer:** 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 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

# Why Does SDN Scale?

| | | |
|---|---|---|
| 0 - 10/s | Modification of Control Program | Strong Consistency |
| $10^1 – 10^3$/s | Per Network Event | Eventual Consistency |
| $10^3 – 10^6$/s | Per Flow | No Consistency |
| $10^6 – 10^8$/s | Per Packet | No Consistency |

# What This Really Means

# Routing Application

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

# Access Control Application

- 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)

# Common Questions about SDN

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- Is SDN incrementally deployable?
- Can SDN be extended to the WAN?
- Can you troubleshoot an SDN network?
- Is OpenFlow the right fwding abstraction?

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**Questions?**