Machine-Verified Network Controllers

Nate Foster
Cornell University

frenetic

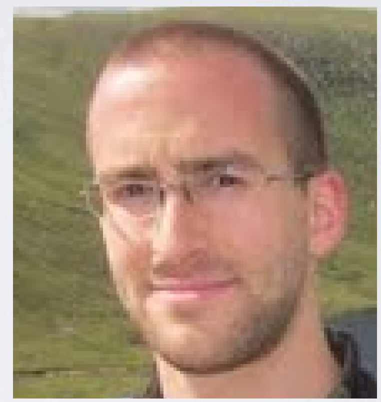
Proof Assistants

Coq

Proof Assistants

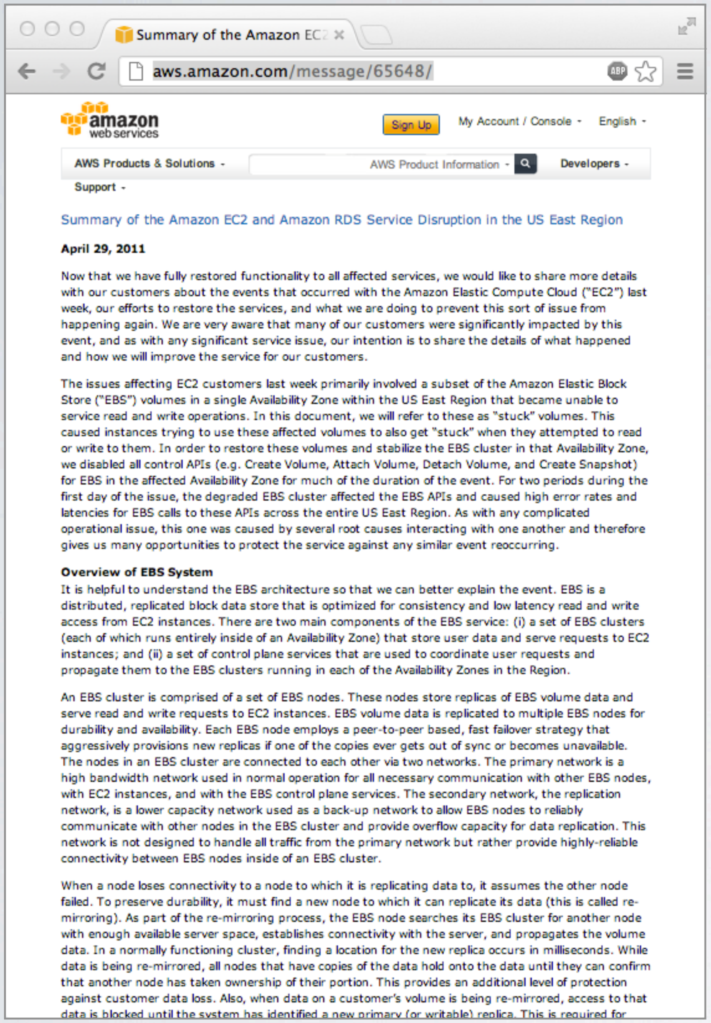
Coq

Arjun Guha
Postdoc → UMass



Mark Reitblatt
PhD student

Networks in Practice



Summary of the Amazon EC2

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Summary of the Amazon EC2 and Amazon RDS Service Disruption in the US East Region

April 29, 2011

Now that we have fully restored functionality to all affected services, we would like to share more details with our customers about the events that occurred with the Amazon Elastic Compute Cloud ("EC2") last week, our efforts to restore the services, and what we are doing to prevent this sort of issue from happening again. We are very aware that many of our customers were significantly impacted by this event, and as with any significant service issue, our intention is to share the details of what happened and how we will improve the service for our customers.

The issues affecting EC2 customers last week primarily involved a subset of the Amazon Elastic Block Store ("EBS") volumes in a single Availability Zone within the US East Region that became unable to service read and write operations. In this document, we will refer to these as "stuck" volumes. This caused instances trying to use these affected volumes to also get "stuck" when they attempted to read or write to them. In order to restore these volumes and stabilize the EBS cluster in that Availability Zone, we disabled all control APIs (e.g. Create Volume, Attach Volume, Detach Volume, and Create Snapshot) for EBS in the affected Availability Zone for much of the duration of the event. For two periods during the first day of the issue, the degraded EBS cluster affected the EBS APIs and caused high error rates and latencies for EBS calls to these APIs across the entire US East Region. As with any complicated operational issue, this one was caused by several root causes interacting with one another and therefore gives us many opportunities to protect the service against any similar event reoccurring.

Overview of EBS System

It is helpful to understand the EBS architecture so that we can better explain the event. EBS is a distributed, replicated block data store that is optimized for consistency and low latency read and write access from EC2 instances. There are two main components of the EBS service: (i) a set of EBS clusters (each of which runs entirely inside of an Availability Zone) that store user data and serve requests to EC2 instances; and (ii) a set of control plane services that are used to coordinate user requests and propagate them to the EBS clusters running in each of the Availability Zones in the Region.

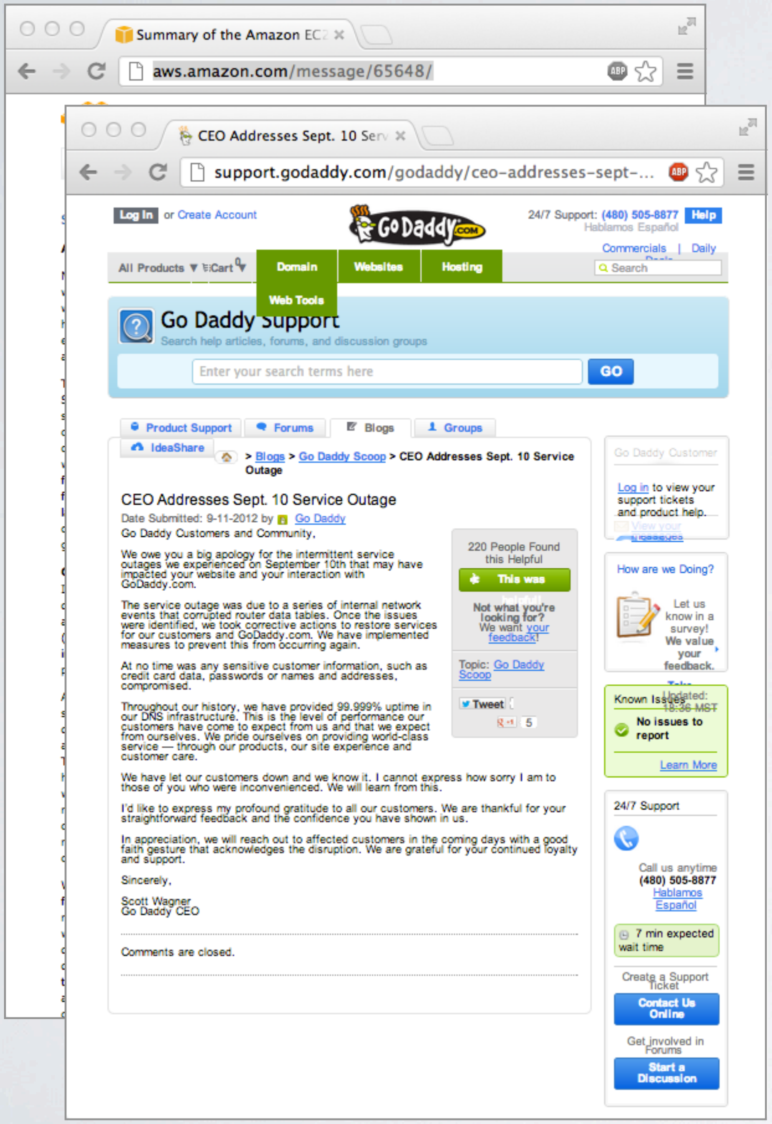
An EBS cluster is comprised of a set of EBS nodes. These nodes store replicas of EBS volume data and serve read and write requests to EC2 instances. EBS volume data is replicated to multiple EBS nodes for durability and availability. Each EBS node employs a peer-to-peer based, fast failover strategy that aggressively provisions new replicas if one of the copies ever gets out of sync or becomes unavailable. The nodes in an EBS cluster are connected to each other via two networks. The primary network is a high bandwidth network used in normal operation for all necessary communication with other EBS nodes, with EC2 instances, and with the EBS control plane services. The secondary network, the replication network, is a lower capacity network used as a back-up network to allow EBS nodes to reliably communicate with other nodes in the EBS cluster and provide overflow capacity for data replication. This network is not designed to handle all traffic from the primary network but rather provide highly-reliable connectivity between EBS nodes inside of an EBS cluster.

When a node loses connectivity to a node to which it is replicating data to, it assumes the other node failed. To preserve durability, it must find a new node to which it can replicate its data (this is called re-mirroring). As part of the re-mirroring process, the EBS node searches its EBS cluster for another node with enough available server space, establishes connectivity with the server, and propagates the volume data. In a normally functioning cluster, finding a location for the new replica occurs in milliseconds. While data is being re-mirrored, all nodes that have copies of the data hold onto the data until they can confirm that another node has taken ownership of their portion. This provides an additional level of protection against customer data loss. Also, when data on a customer's volume is being re-mirrored, access to that data is blocked until the system has identified a new primary (or writable) replica. This is required for

"The trigger for this event was a network configuration change"

—Amazon

Networks in Practice



Summary of the Amazon EC

aws.amazon.com/message/65648/

CEO Addresses Sept. 10 Serv

support.godaddy.com/godaddy/ceo-addresses-sept-...

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> Blogs > Go Daddy Scoop > CEO Addresses Sept. 10 Service Outage

CEO Addresses Sept. 10 Service Outage

Date Submitted: 9-11-2012 by Go Daddy

Go Daddy Customers and Community,

We owe you a big apology for the intermittent service outages we experienced on September 10th that may have impacted your website and your interaction with GoDaddy.com.

The service outage was due to a series of internal network events that corrupted router data tables. Once the issues were identified, we took corrective actions to restore services for our customers and GoDaddy.com. We have implemented measures to prevent this from occurring again.

At no time was any sensitive customer information, such as credit card data, passwords or names and addresses, compromised.

Throughout our history, we have provided 99.999% uptime in our DNS infrastructure. This is the level of performance our customers have come to expect from us and that we expect from ourselves. We pride ourselves on providing world-class service — through our products, our site experience and customer care.

We have let our customers down and we know it. I cannot express how sorry I am to those of you who were inconvenienced. We will learn from this.

I'd like to express my profound gratitude to all our customers. We are thankful for your straightforward feedback and the confidence you have shown in us.

In appreciation, we will reach out to affected customers in the coming days with a good faith gesture that acknowledges the disruption. We are grateful for your continued loyalty and support.

Sincerely,

Scott Wagner
Go Daddy CEO

Comments are closed.

220 People Found this Helpful

Not what you're looking for? We want your feedback!

Topic: Go Daddy Scoop

Known Issues

No issues to report

24/7 Support

Call us anytime (480) 505-8877

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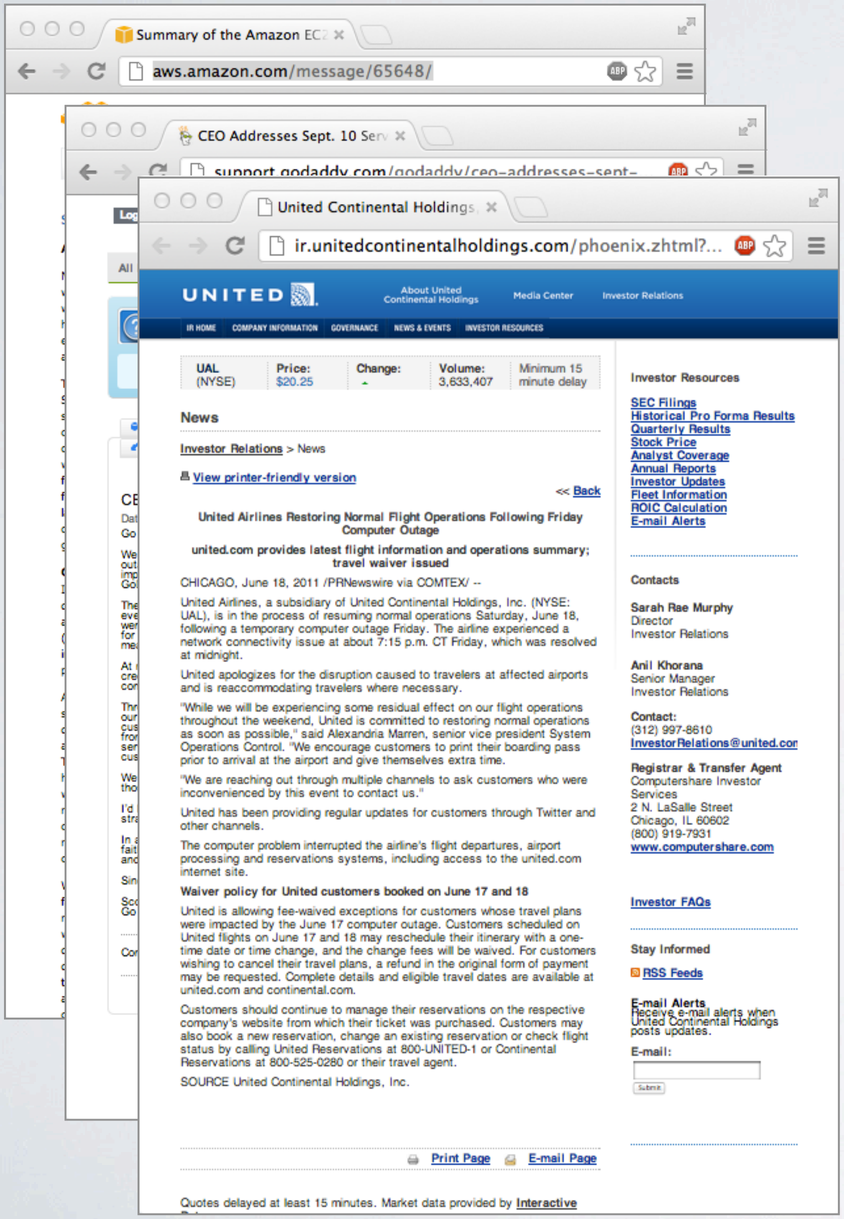
Start a Discussion

"The service outage was due to a series of internal network events that corrupted router data tables"

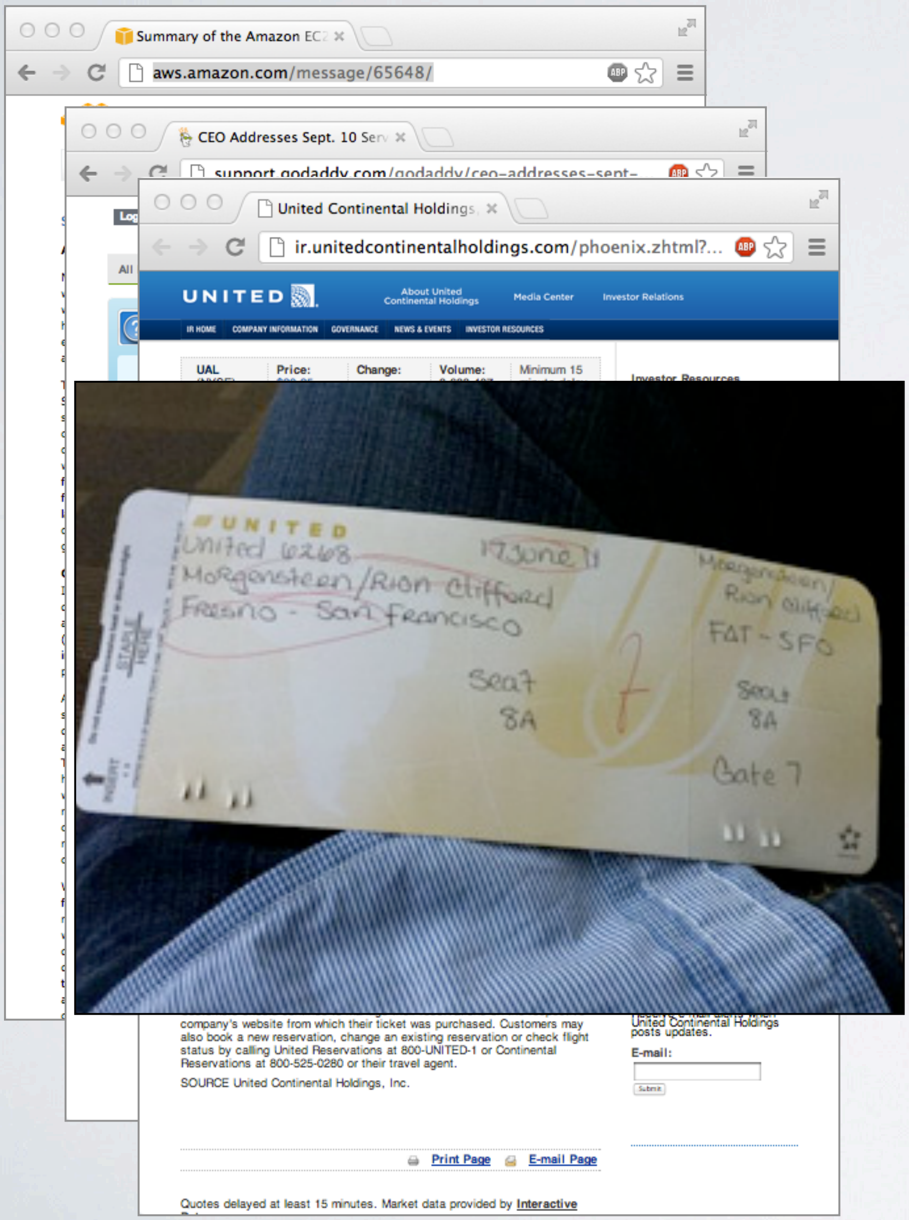
—GoDaddy

Networks in Practice



"The airline experienced a network connectivity issue..."
—United Airlines

Networks in Practice



"The airline experienced a network connectivity issue..."

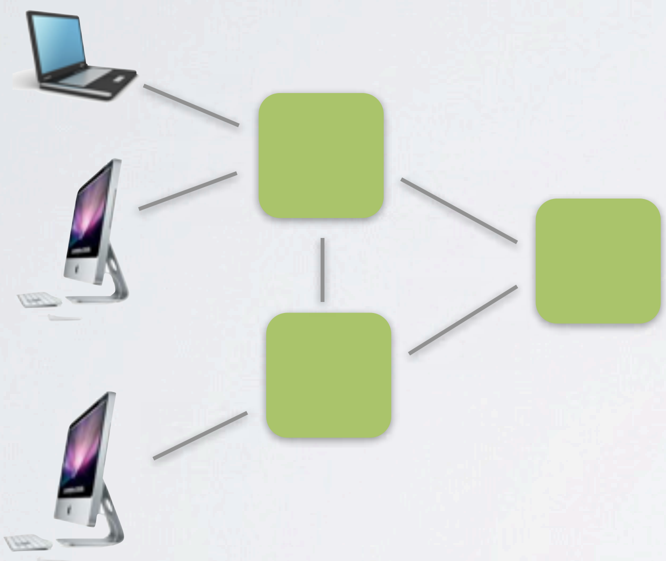
—United Airlines

Networks in Practice

There are hosts...

Networks in Practice

Connected by switches...



Networks in Practice

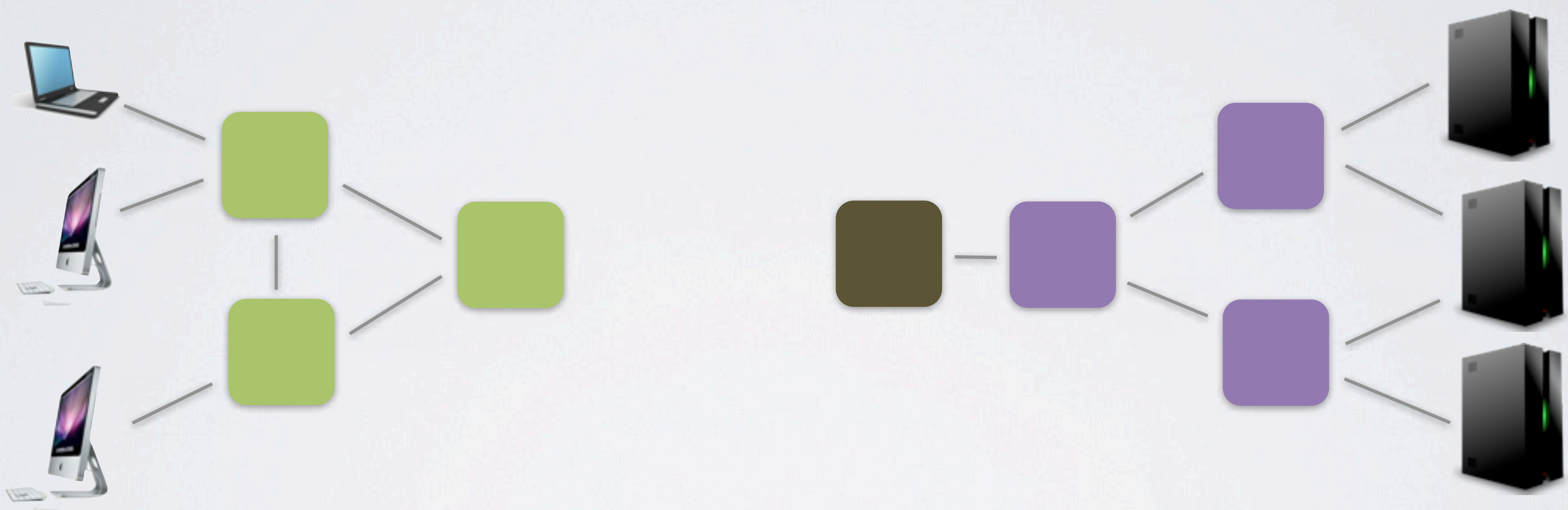
There are also servers...

Networks in Practice

Connected by routers...

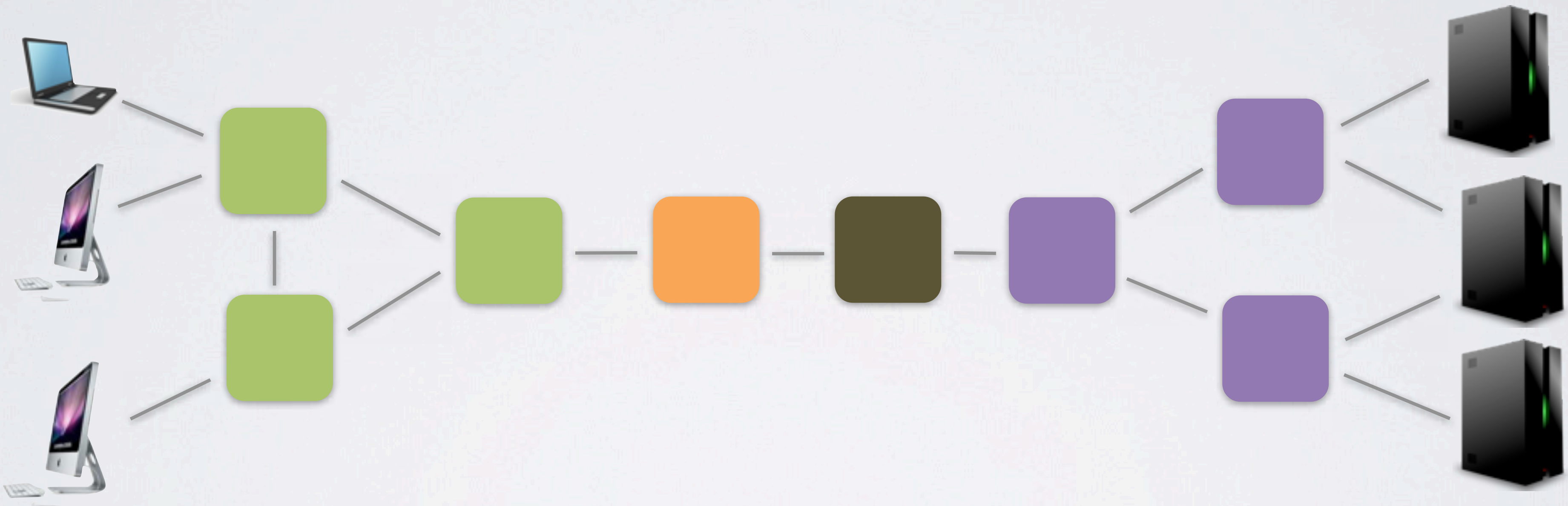
Networks in Practice

And a load balancer...



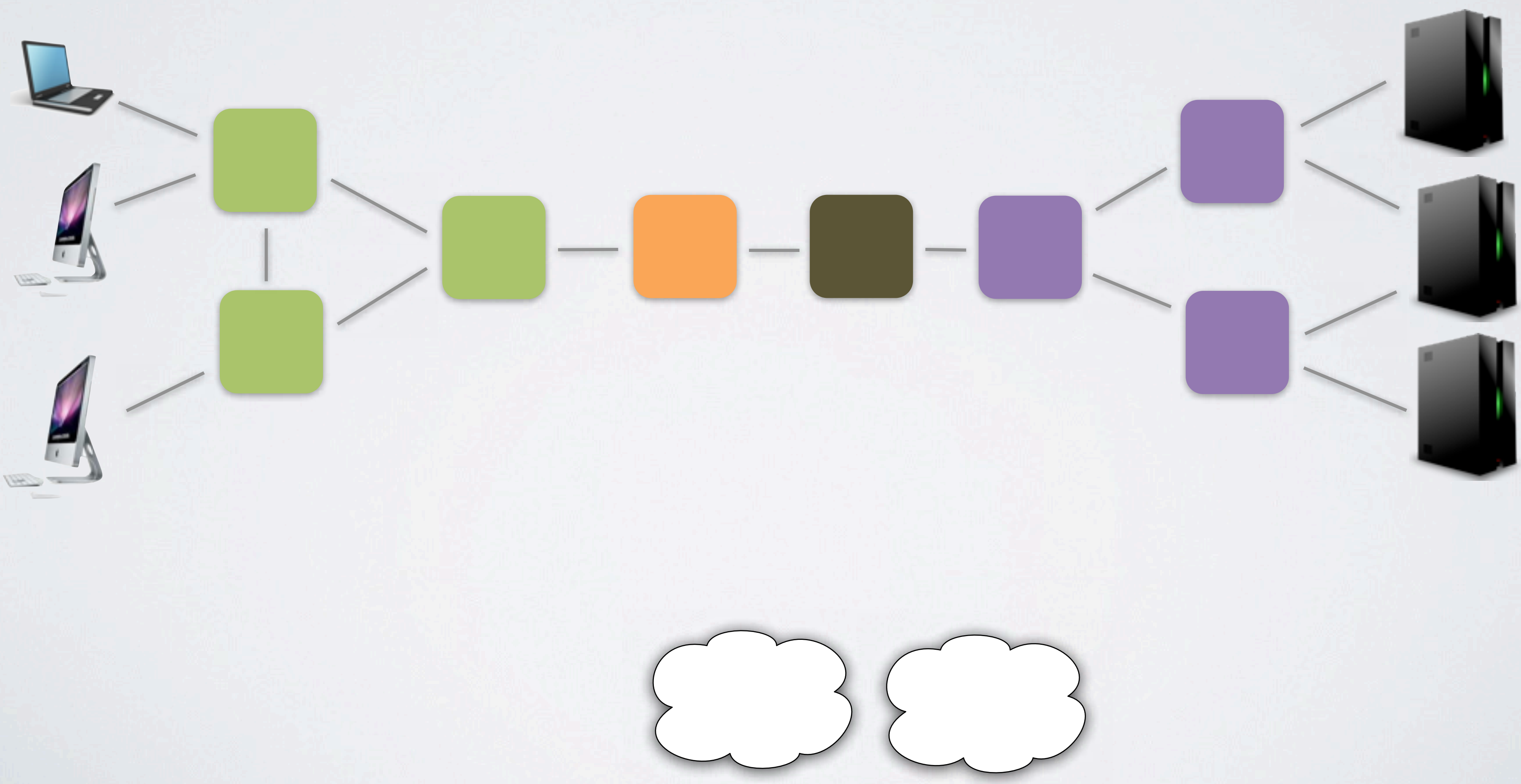
Networks in Practice

And a gateway router...



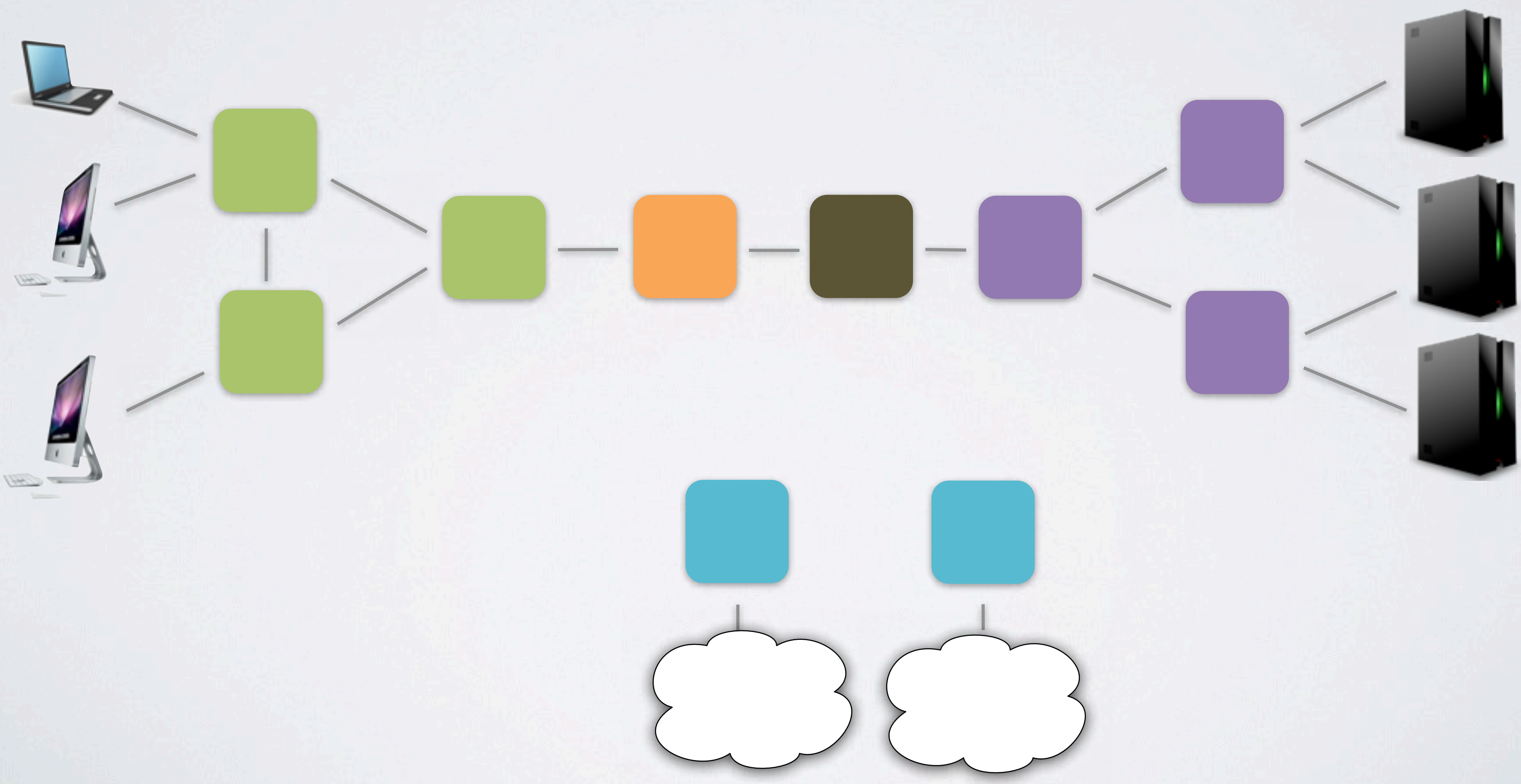
Networks in Practice

There are other ISPs...



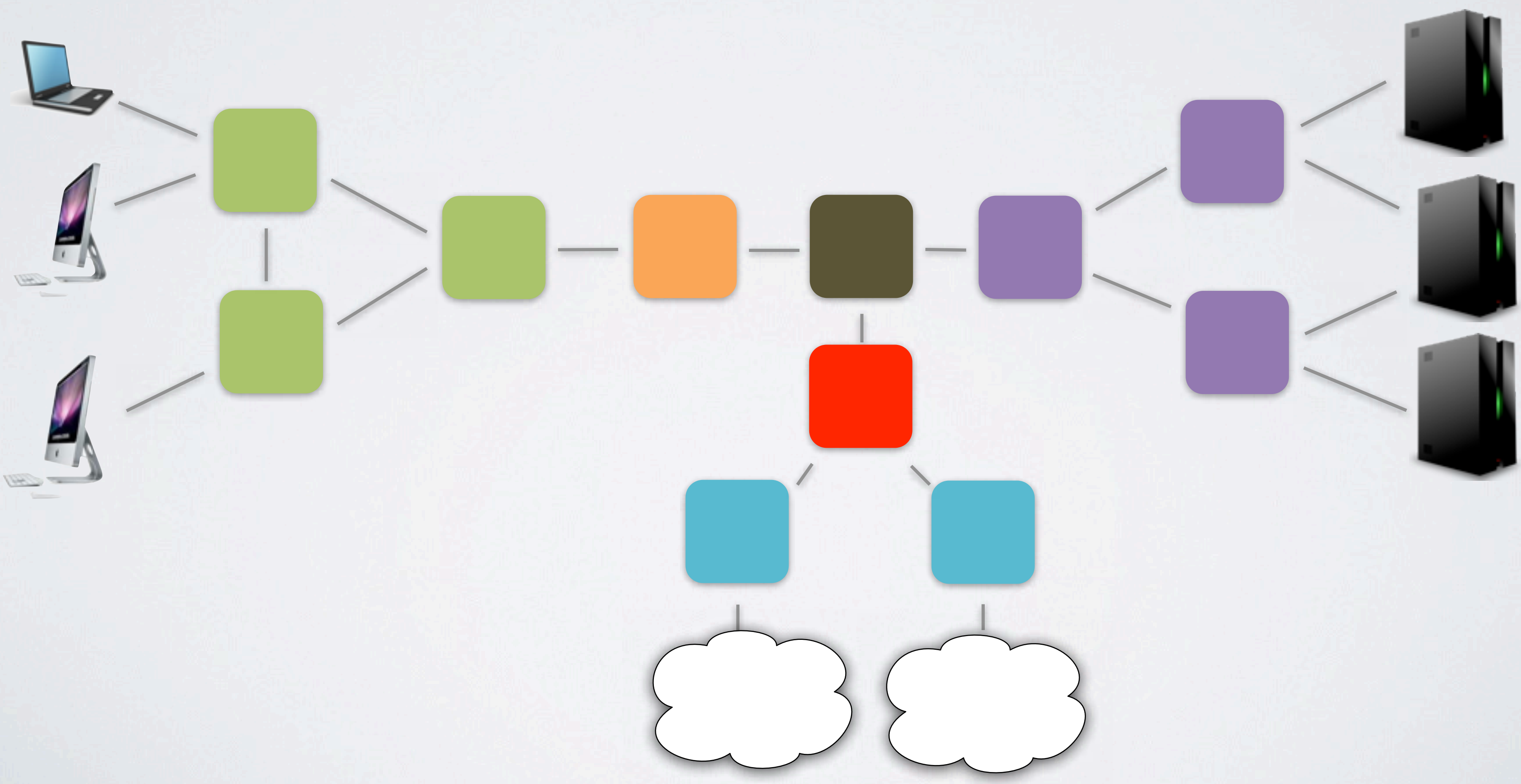
Networks in Practice

So we need to run BGP...



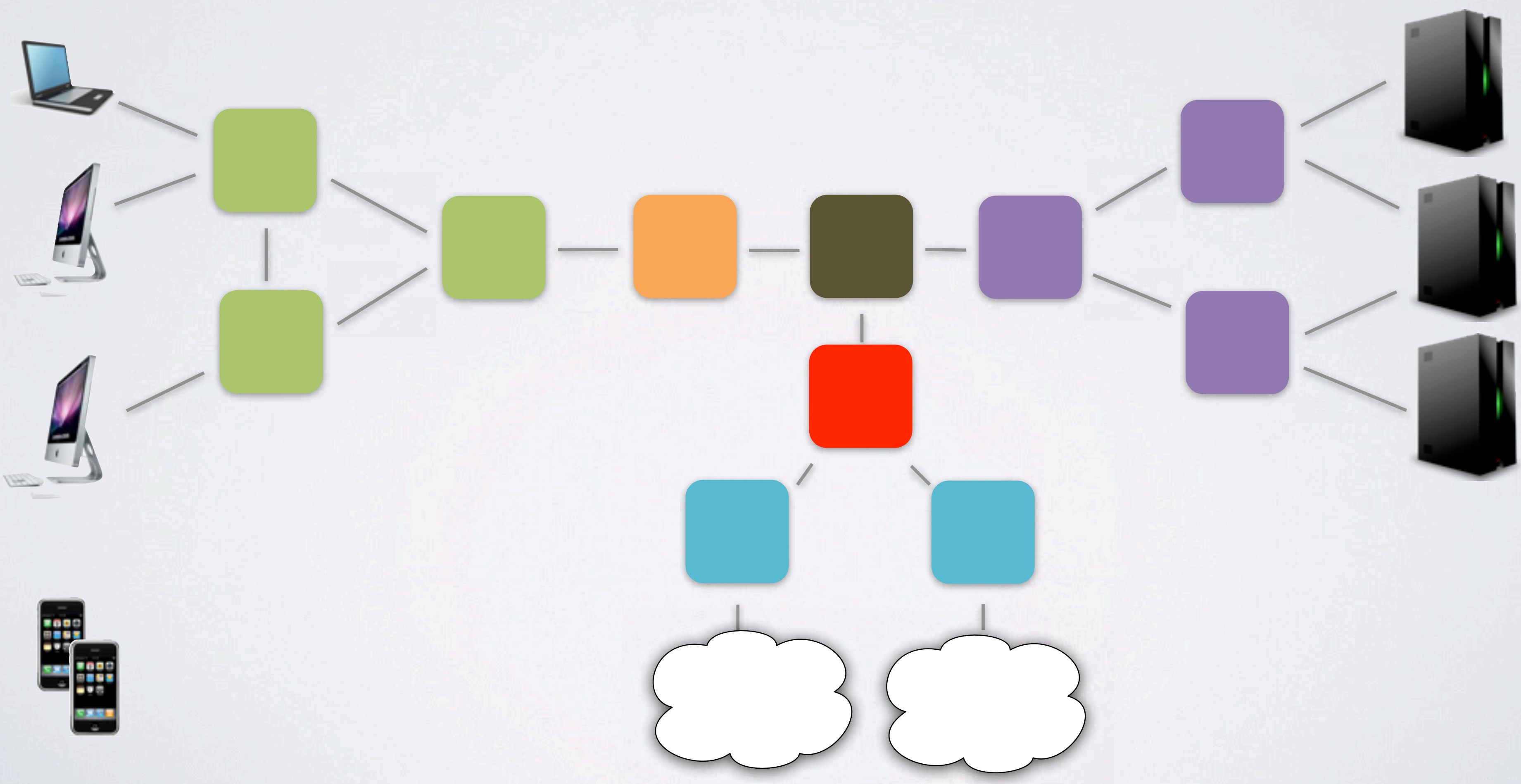
Networks in Practice

And we need a firewall to filter incoming traffic...



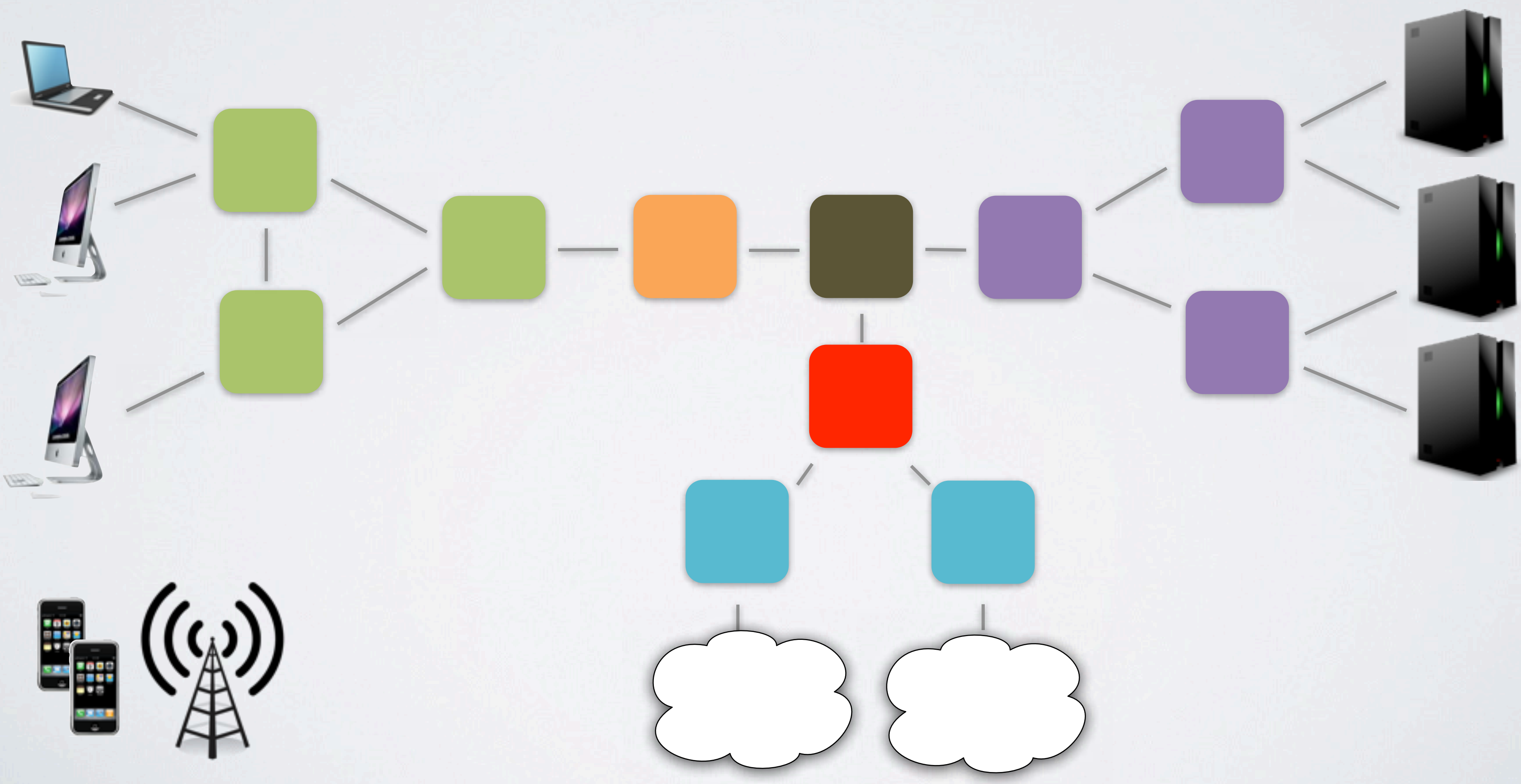
Networks in Practice

There are also wireless hosts...



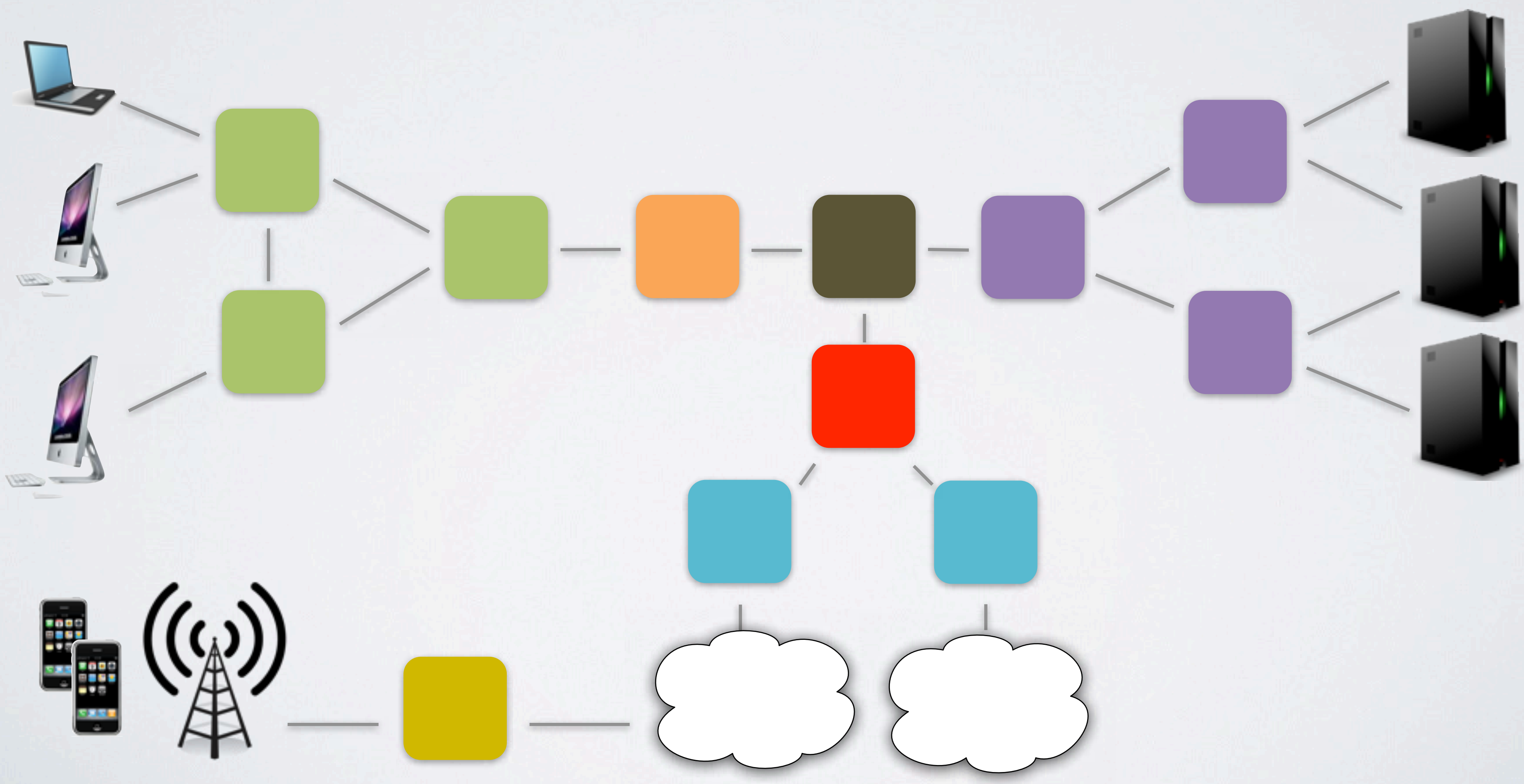
Networks in Practice

So we need wireless gateways...



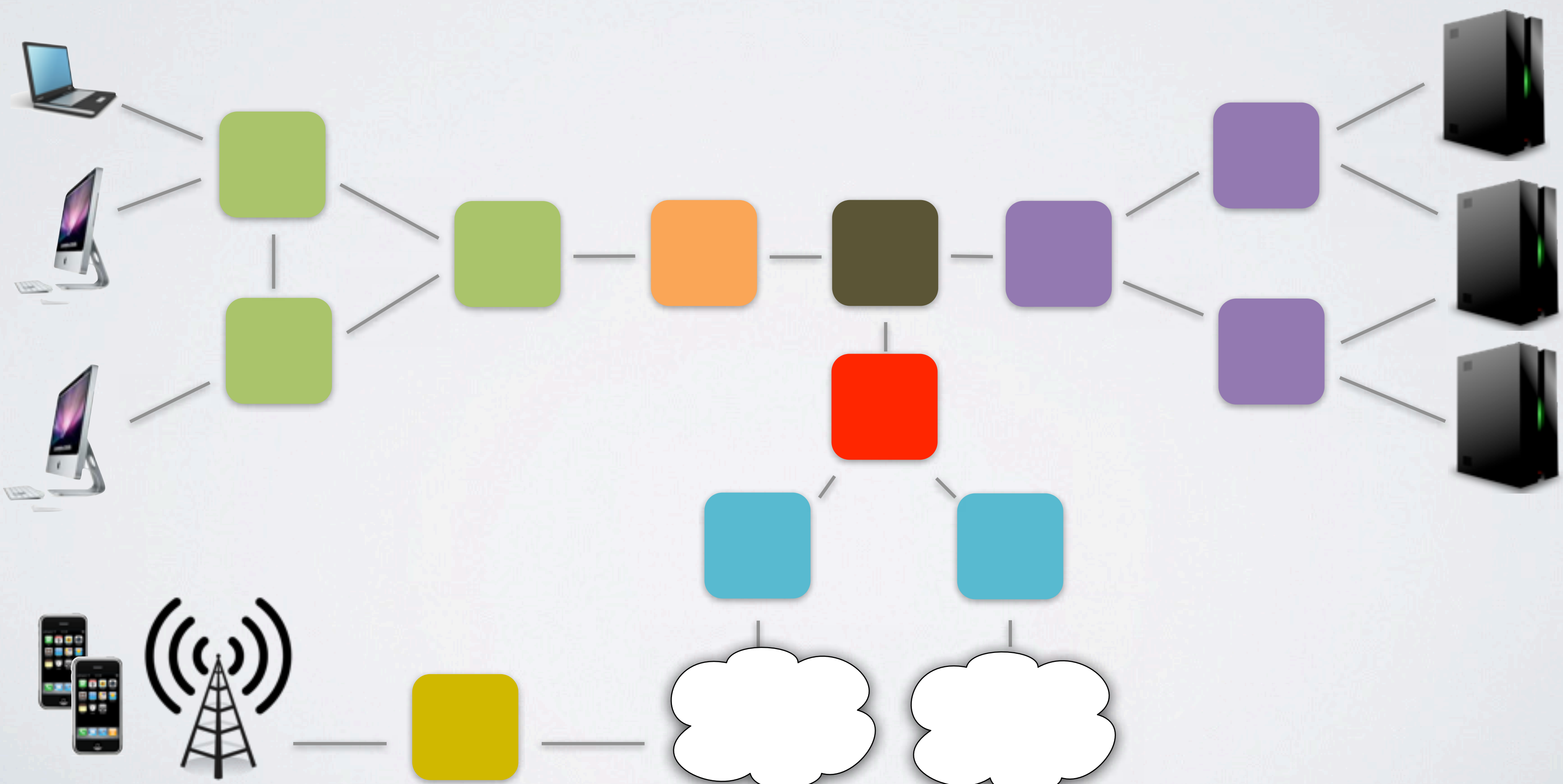
Networks in Practice

And yet more middleboxes for lawful intercept...



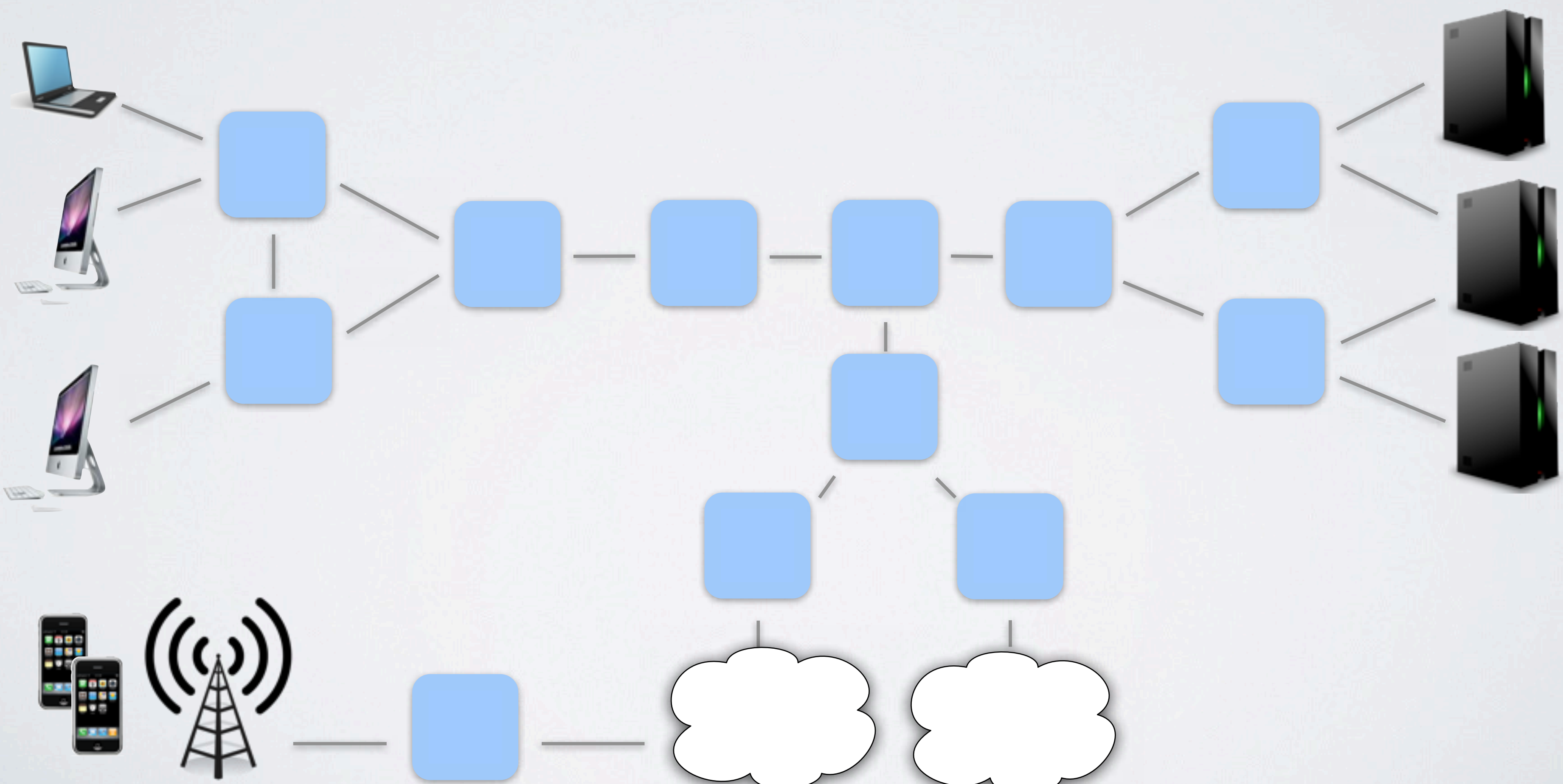
Networks in Practice

Each color represents a different set of control plane protocols and algorithms... this is



Software-Defined Networking

A clean-slate architecture that standardizes features and decouples forwarding from



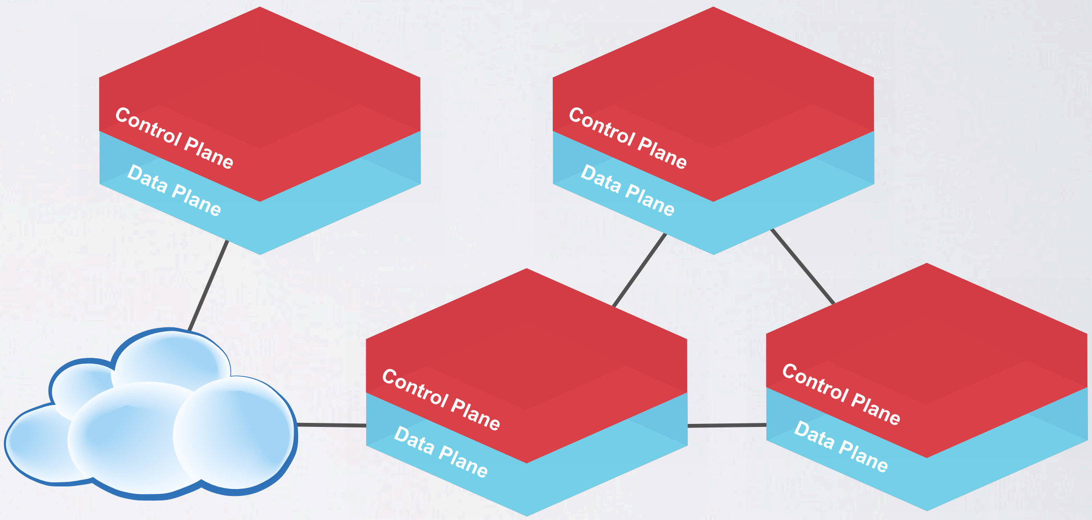
Software-Defined Networking

Essential ingredients

- Decouple control and data planes
- Logically-centralized control

Enables

- Novel functionality
- Formal reasoning



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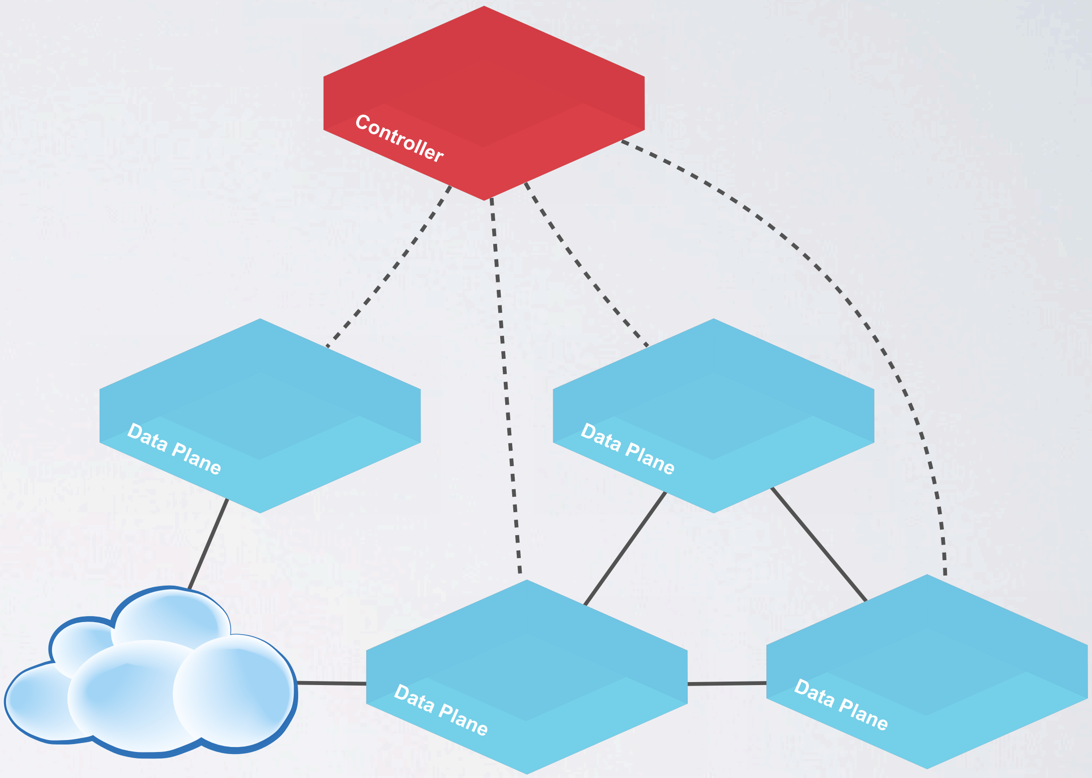

Existing Tools

There is a cottage industry in SDN configuration-checking tools...

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- FlowChecker [SafeConfig '10]

FlowChecker: Configuration Analysis and Verification of Federated OpenFlow Infrastructures

Ehab Al-Shaer and Saeed Al-Haj
Department of Software and Information Systems
University of North Carolina at Charlotte
{ealshaer, salhaj}@uncc.edu

ABSTRACT

It is difficult to build a real network to test novel experiments. OpenFlow makes it easier for researchers to run their own experiments by providing a virtual slice and configuration on real networks. Multiple users can share the same network by assigning a different slice for each one. Users are given the responsibility to maintain and use their own slice by writing rules in a FlowTable. Misconfiguration problems can arise when a user writes conflicting rules for single FlowTable or even within a path of multiple OpenFlow switches that need multiple FlowTables to be maintained at the same time.

In this work, we describe a tool, FlowChecker, to identify any intra-switch misconfiguration within a single FlowTable. We also describe the inter-switch or inter-federated inconsistencies in a path of OpenFlow switches across the same or different OpenFlow infrastructures. FlowChecker encodes FlowTables configuration using Binary Decision Diagrams and then uses the model checker technique to model the inter-connected network of OpenFlow switches.

Categories and Subject Descriptors

C.2.3 [**Computer-Communication Networks**]: Network Operations—*Network management*

General Terms

Security, Verification

Keywords

OpenFlow, configuration verification, access control, automated analysis, binary decision diagrams

1. INTRODUCTION

OpenFlow is an innovative architecture that provides an open programmable platform for network access control [17]. By separating the data and control plans, users can use the OpenFlow centralized controllers to install filters (match, count and action) in the OpenFlow switches and control the global data processing in the network. Currently, OpenFlow control supports the following actions: forward, drop, encapsulate, encrypt, limit, and classify/enqueue for QoS. The platform is also extensible to support more actions. The controller running new protocols or algorithms might insert, modify, or remove filters in the switches in order to enforce network-wide policies or properties (e.g., guests should access the internet only through a proxy) [17]. Thus, it is assumed that the integrated behavior of the installed filters will globally implement these policies. However, the following conflicts become apparent: (1) the semantic gap between the controller platform (e.g., NOX [13]) and the filter tables in the data processing units, (2) the distribution of access control that supports aggregate flows (wildcards) and many different actions, (3) the ability of sharing one controller by different users, and (4) the ability of using multiple controllers in the same domain. These conflicts together increase the potential of intra-federated (single domain) OpenFlow configuration conflicts. In addition, as two or more OpenFlow infrastructures communicate with each other, potential inter-federated conflicts may appear due to inconsistency in the controller or switch configuration. This may result in invalidation of end-to-end policy enforcement.

Due to these reasons, a correct enforcement of the controller policies might be questionable without the support of formal automated configuration verification tools. This work attempts to address these problems by (1) encoding OpenFlow configuration using Binary Decision Diagrams (BDDs) considering the priority-based matching semantic, various actions, the existence of multiple controllers and multiple users, (2) modeling the global behavior of the OpenFlow network based on FlowTables over single or multiple federated infrastructures in a single state machine, and (3) providing a generic property-based verification interface using BDD-based symbolic model checking and temporal logic. The presented system, called FlowChecker, can be used by administrators/users for (1) verifying the consistency of different switches and controllers across different OpenFlow federated infrastructures, (2) validating the correctness of the configuration synthesis generated by a new implemented protocols, and (3) debugging reachability and security problems. FlowChecker can also be used to conduct "what-if" analysis to study the impact of the new protocols or algorithms on the network by simply changing the state in the FlowTables and then analyzing the effect.

The development of FlowChecker leverages our previous

SafeConfig'10, October 4, 2010, Chicago, Illinois, USA.

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FlowChecker: Configuration Analysis and Verification of Federated OpenFlow Infrastructures

Debugging the Data Plane with Anteater

A NICE Way to Test OpenFlow Applications

Marco Canini*, Daniele Venzano*, Peter Perešíni*, Dejan Kostić*, and Jennifer Rexford†

*EPFL †Princeton University

Abstract

The emergence of OpenFlow-capable switches enables exciting new network functionality, at the risk of programming errors that make communication less reliable. The centralized programming model, where a single controller program manages the network, seems to reduce the likelihood of bugs. However, the system is inherently distributed and asynchronous, with events happening at different switches and end hosts, and inevitable delays affecting communication with the controller. In this paper, we present efficient, systematic techniques for testing unmodified controller programs. Our NICE tool applies model checking to explore the state space of the entire system—the controller, the switches, and the hosts. Scalability is the main challenge, given the diversity of data packets, the large system state, and the many possible event orderings. To address this, we propose a novel way to augment model checking with symbolic execution of event handlers (to identify representative packets that exercise code paths on the controller). We also present a simplified OpenFlow switch model (to reduce the state space), and effective strategies for generating event interleavings likely to uncover bugs. Our prototype tests Python applications on the popular NOX platform. In testing three real applications—a MAC-learning switch, in-network server load balancing, and energy-efficient traffic engineering—we uncover eleven bugs.

1 Introduction

While lowering the barrier for introducing new functionality into the network, Software Defined Networking (SDN) also raises the risks of software faults (or *bugs*). Even today's networking software—written and extensively tested by equipment vendors, and constrained (at least somewhat) by the protocol standardization process—can have bugs that trigger Internet-wide outages [1,2]. In contrast, programmable networks will offer a much wider range of functionality, through software created by a diverse collection of network operators and third-party developers. The ultimate success of SDN, and enabling technologies like OpenFlow [3], depends on having effective ways to test applications in pursuit of achieving high reliability. In this paper, we present NICE, a tool that efficiently uncovers bugs in OpenFlow programs, through a combination of model checking and symbolic execution. Building on our position paper [4] that argues for automating the testing of OpenFlow applications, we introduce several new contributions summarized in Section 1.3.

1.1 Bugs in OpenFlow Applications

An OpenFlow network consists of a distributed collection of switches managed by a program running on a logically-centralized controller, as illustrated in Figure 1. Each switch has a flow table that stores a list of rules for processing packets. Each rule consists of a pattern (matching on packet header fields) and actions (such as forwarding, dropping, flooding, or modifying the packets, or sending them to the controller). A pattern can require an "exact match" on all relevant header fields (*i.e.*, a *microflow* rule), or have "don't care" bits in some fields (*i.e.*, a *wildcard* rule). For each rule, the switch maintains traffic counters that measure the bytes and packets processed so far. When a packet arrives, a switch selects the highest-priority matching rule, updates the counters, and performs the specified action(s). If no rule matches, the switch sends the packet header to the controller and awaits a response on what actions to take. Switches also send event messages, such as a "join" upon joining the network, or "port change" when links go up or down.

The OpenFlow controller (un)installs rules in the switches, reads traffic statistics, and responds to events. For each event, the controller program defines a handler, which may install rules or issue requests for traffic statistics. Many OpenFlow applications[1] are written on the NOX controller platform [5], which offers an OpenFlow

[1] In this paper, we use the terms "OpenFlow application" and "controller program" interchangeably.

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There is a cottage industry in SDN configuration-checking tools...

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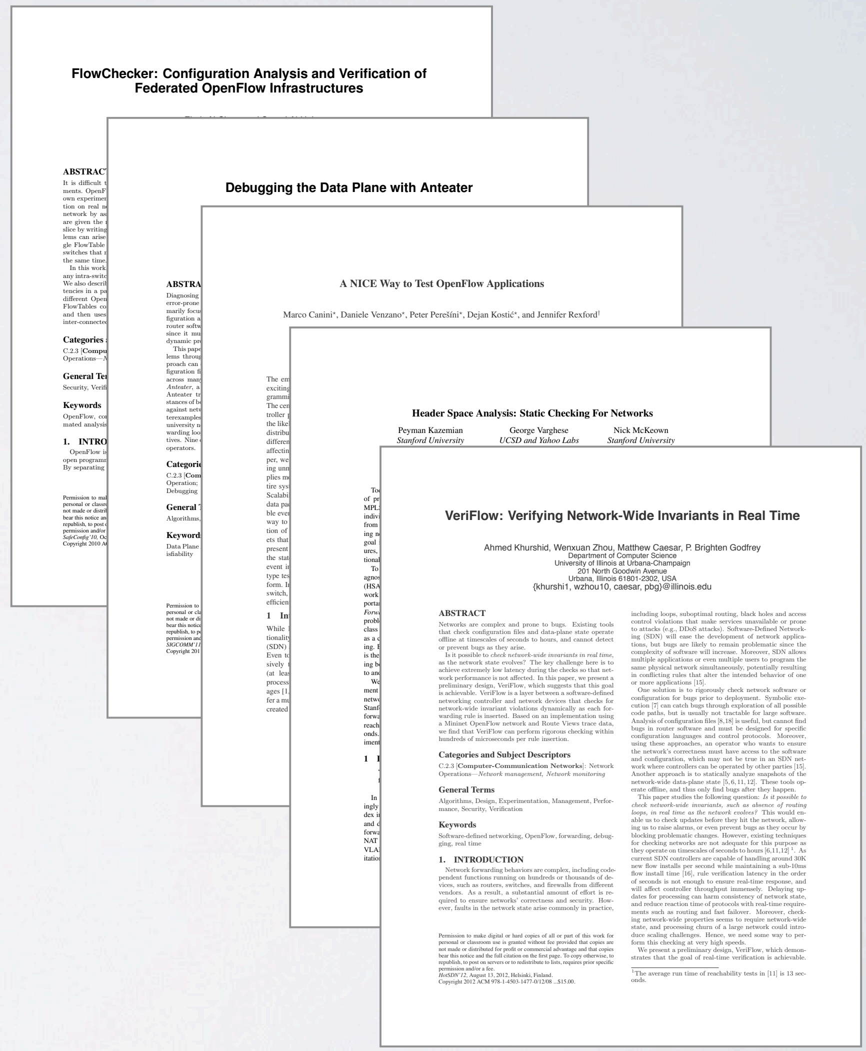
- VeriFlow [HotSDN '12]
- and many others...



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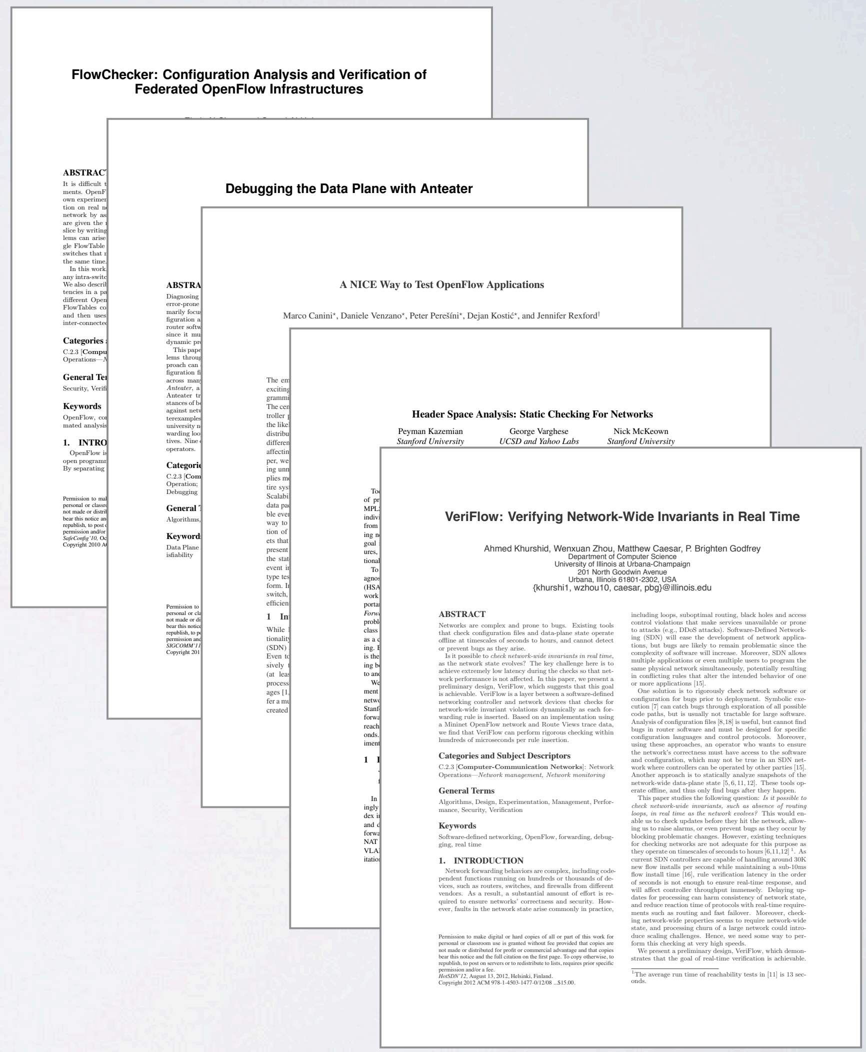


These are all great tools!

But they are expensive to run, and each builds on a custom (typically ad hoc) foundation

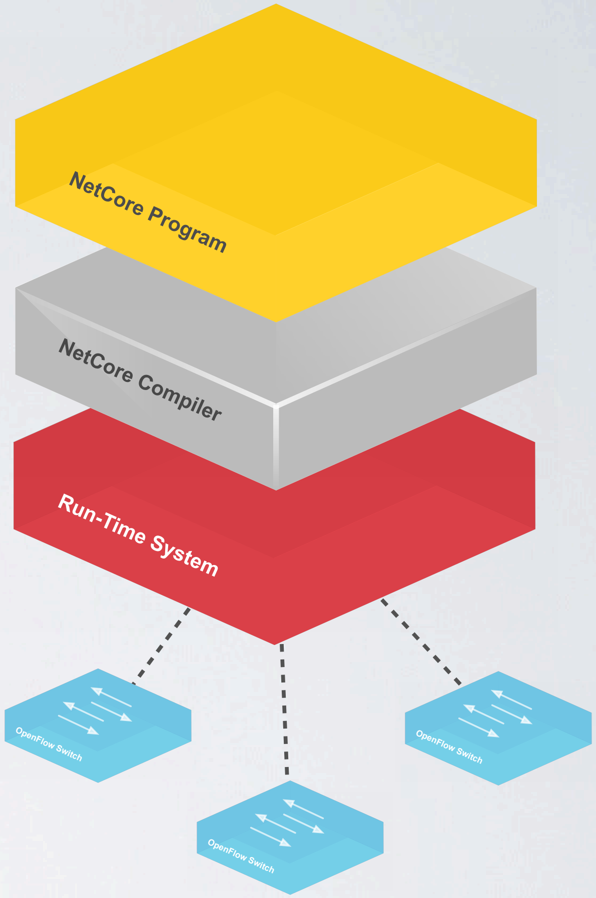
Machine-Verified Controllers

Vision

- Develop programs in a high-level language
- Reason at a high level of abstraction
- Use a compiler and run-time system to generate low-level control messages
- Machine-verified proofs of correctness

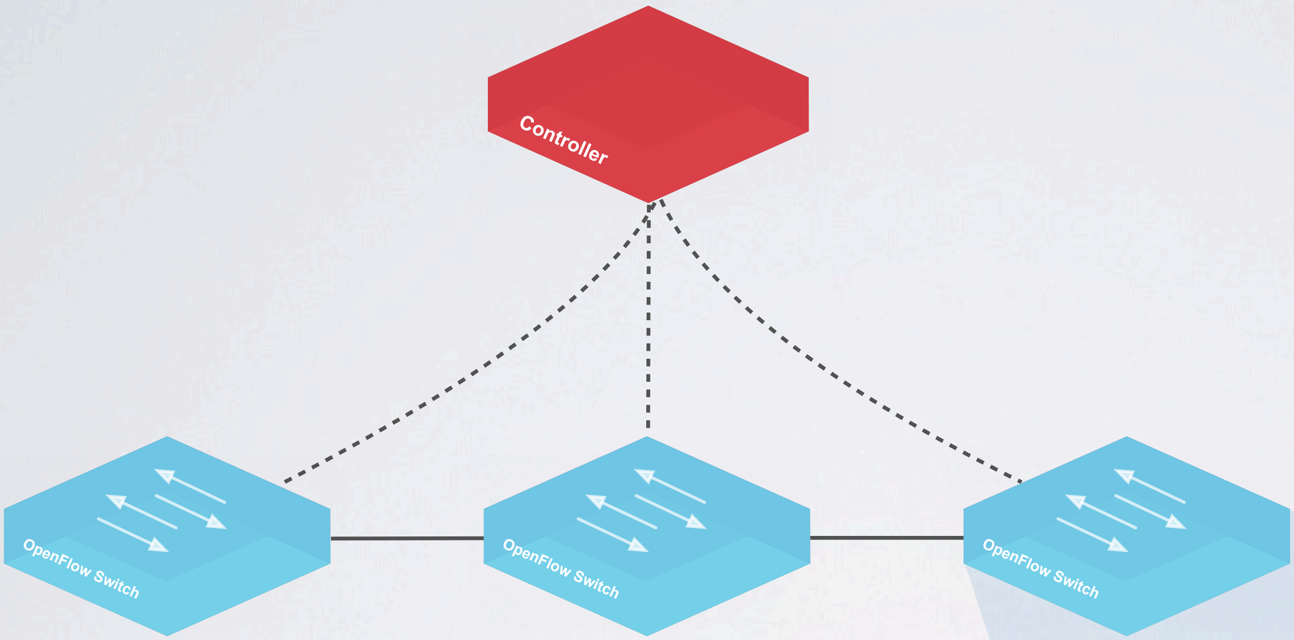
Contributions

- NetCore compiler + optimizer
- Featherweight OpenFlow model
- General framework for establishing run-time system correctness



OVERVIEW

OpenFlow Switches



Forwarding Table: prioritized list of rules

Rule: pattern, actions, and counters

Pattern: prefix match on headers

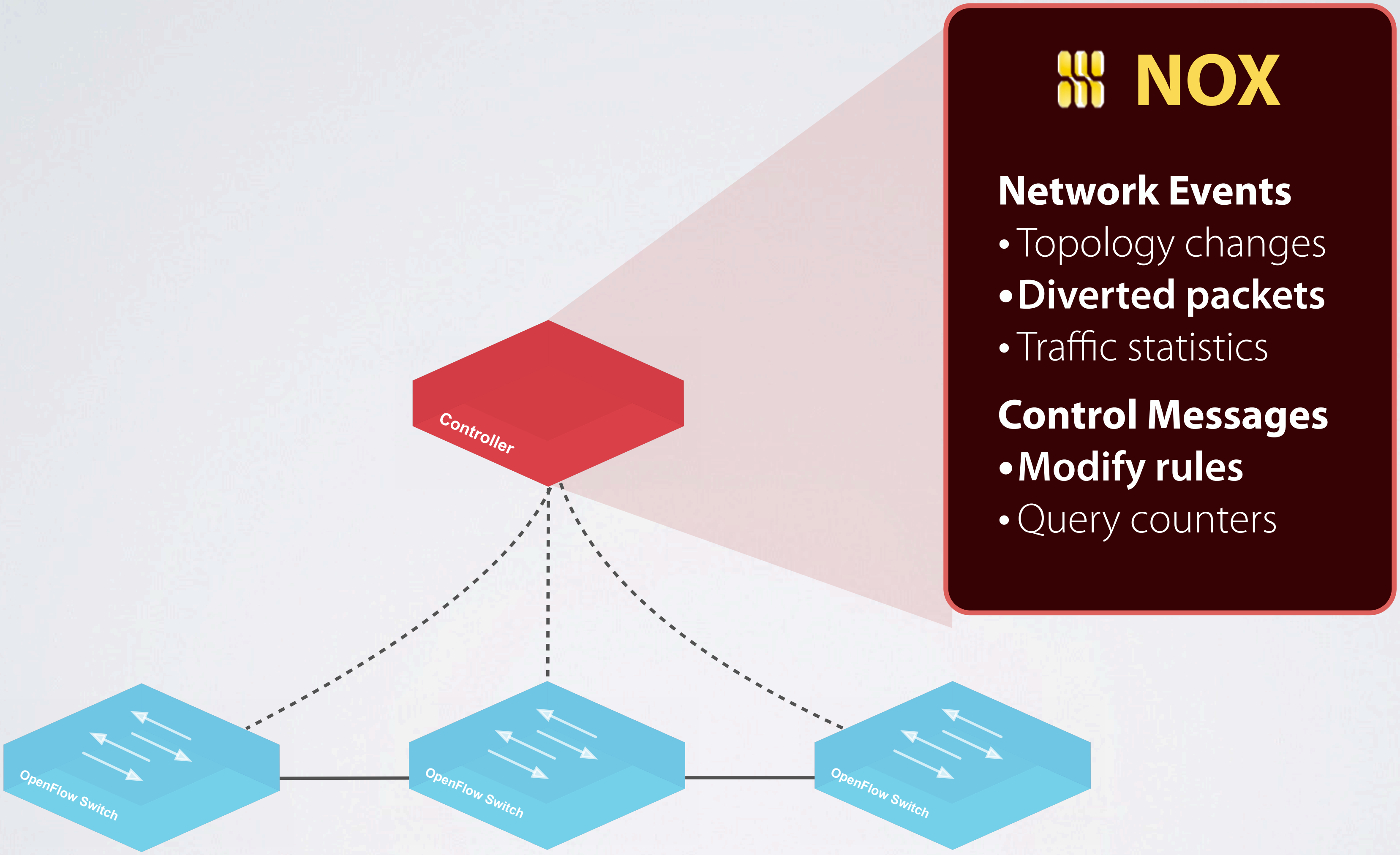
Action: forward or modify

Counters: total bytes and packets processed

OpenFlow

Pattern	Action	Bytes	Packets
1010	Drop	200	10
010*	Forward(2)	100	4
011*	Controller	0	0

Priority


NOX
Network Events
• Topology changes
• Diverted packets
• Traffic statistics
Control Messages
• Modify rules
• Query counters
Controller
OpenFlow Switch
OpenFlow Switch
OpenFlow Switch

Issue #1: Switch-Level Errors

What happens if...

- The controller misses a keep-alive message?
- The controller sends a malformed message?
  - Bad output port
  - Too many actions
  - Inconsistent actions
  - Unsupported actions
- The switches runs out of space for rules?

Any of these can lead to essentially arbitrary behavior

Issue #2: Malformed Patterns

What happens if the controller sends the following message to a switch?

```
FlowMod AddFlow { match = { srcIPAddress = 10.0.1.*”, ... },
                  actions = [ flood ], ... }
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...but it actually installs a rule that floods *all* traffic

Why? Switches *silently* ignore IP fields unless the Ethernet frame type is IP!

Issue #3: Message Reordering

What happens if the controller sends the following pair of OpenFlow messages to a switch in sequence?

```
FlowMod AddFlow { match = { ethFrameType = ethTypeIP,
                            srcIPAddress =
"10.0.1.99", ... },
                  priority = 1,
                  actions = [ ] }
FlowMod AddFlow { match = { ethFrameType = ethTypeIP,
                            srcIPAddress = "10.0.1.*", ... },
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```

The intention is to encode a negation...

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```
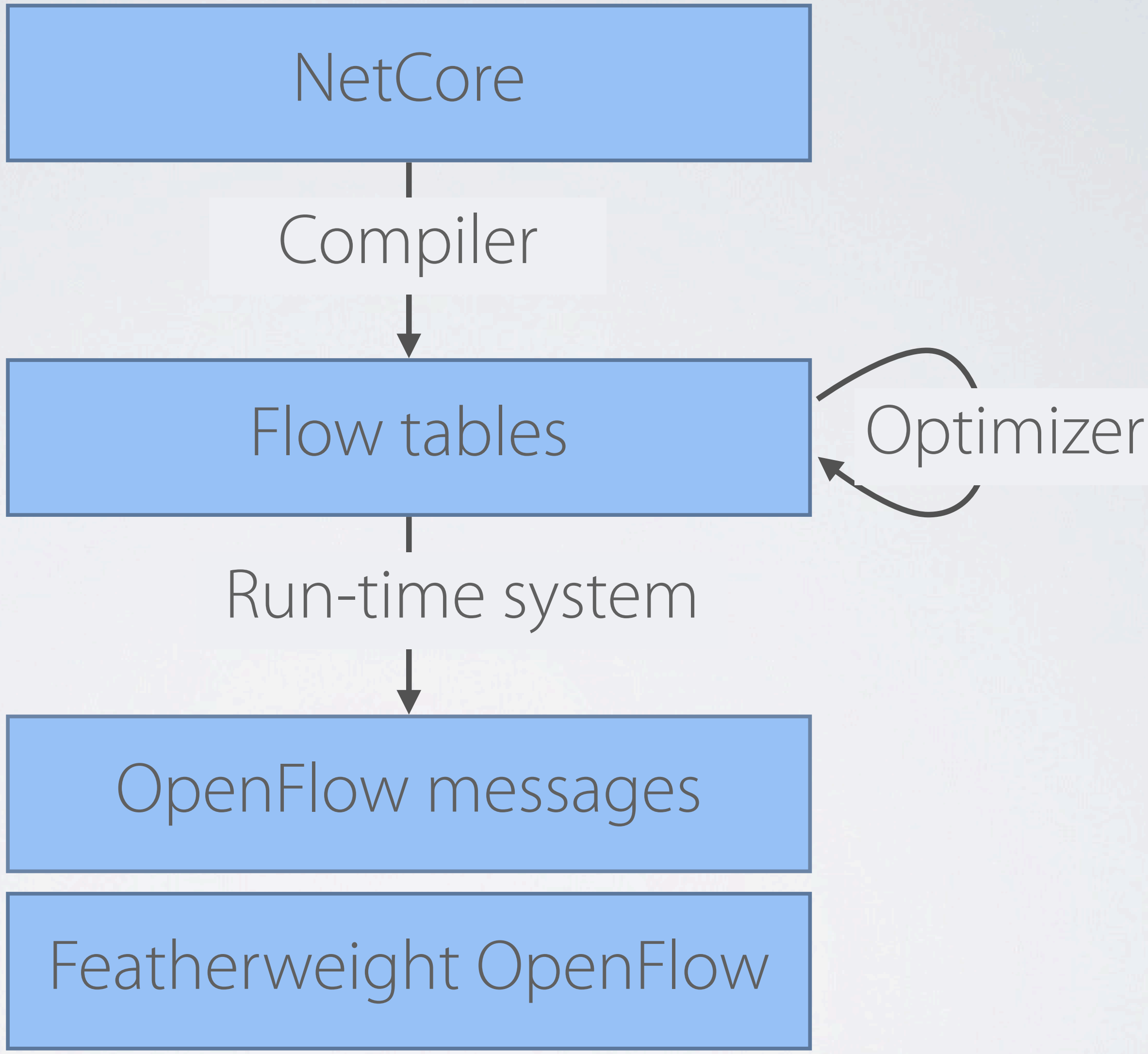
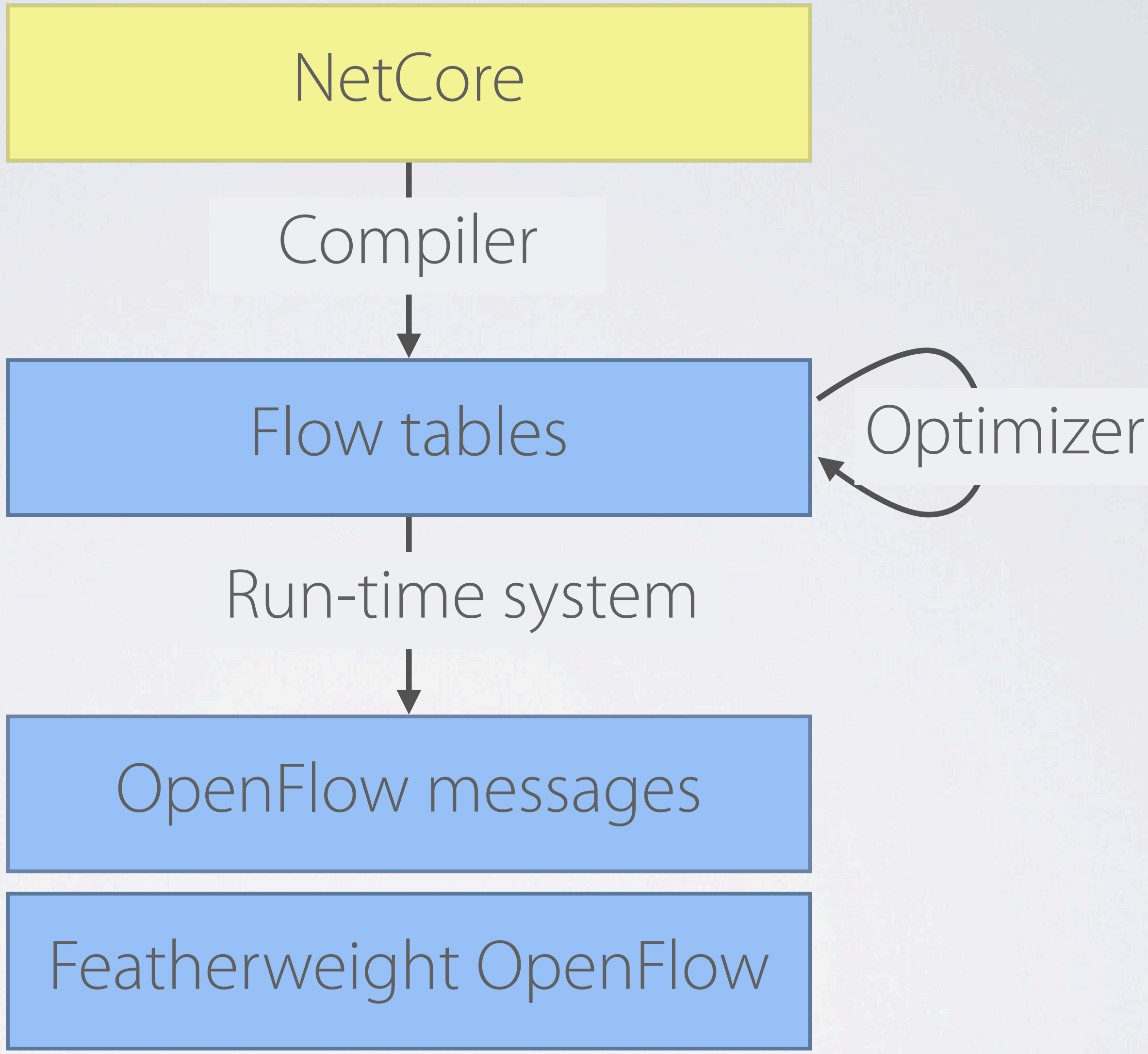

The intention is to encode a negation...

...but the switch may process these in either order!

MACHINE-VERIFIED CONTROLLERS


NetCore
Compiler
Flow tables
Optimizer
Run-time system
OpenFlow messages
Featherweight OpenFlow


NetCore
Compiler
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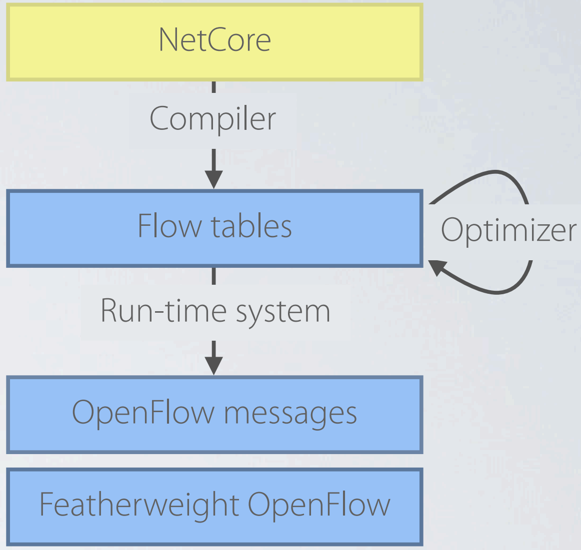
OpenFlow messages
Featherweight OpenFlow

NetCore [POPL '12]



Syntax

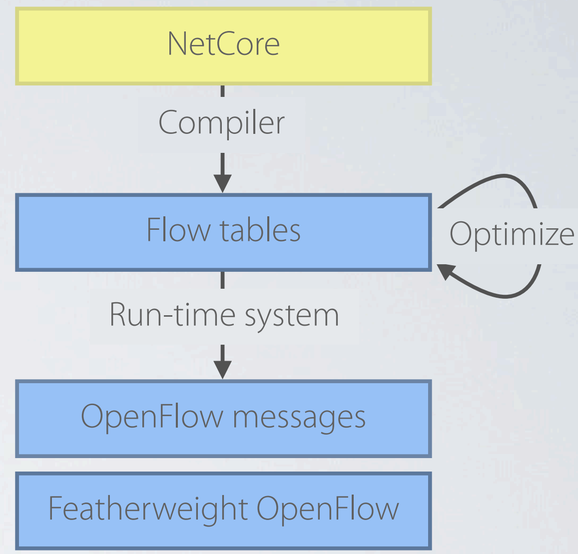
```
Inductive pred : Type :=                    (* Predicates *)
  | OnSwitch : Switch -> pred
  | IngressPort : Port -> pred
  | DlSrc : EthernetAddress -> pred
  | DlDst : EthernetAddress -> pred
  | DlVlan : option VLAN -> pred
  | ...
  | And : pred -> pred -> pred
  | Or : pred -> pred -> pred
  | Not : pred -> pred
  | All : pred
  | None : pred.

Inductive PseudoPort : Type :=              (* Psuedo Ports *)
  | PhysicalPort : Port -> PseudoPort
  | AllPorts : PseudoPort.

Inductive act : Type :=                     (* Actions *)
  | FwdMod : Mod -> PseudoPort -> act

Inductive pol : Type :=                     (* Policies *)
  | Policy : pred -> list act -> pol
  | Union : pol -> pol -> pol
  | Restrict : pol -> pred -> pol.
```

NetCore

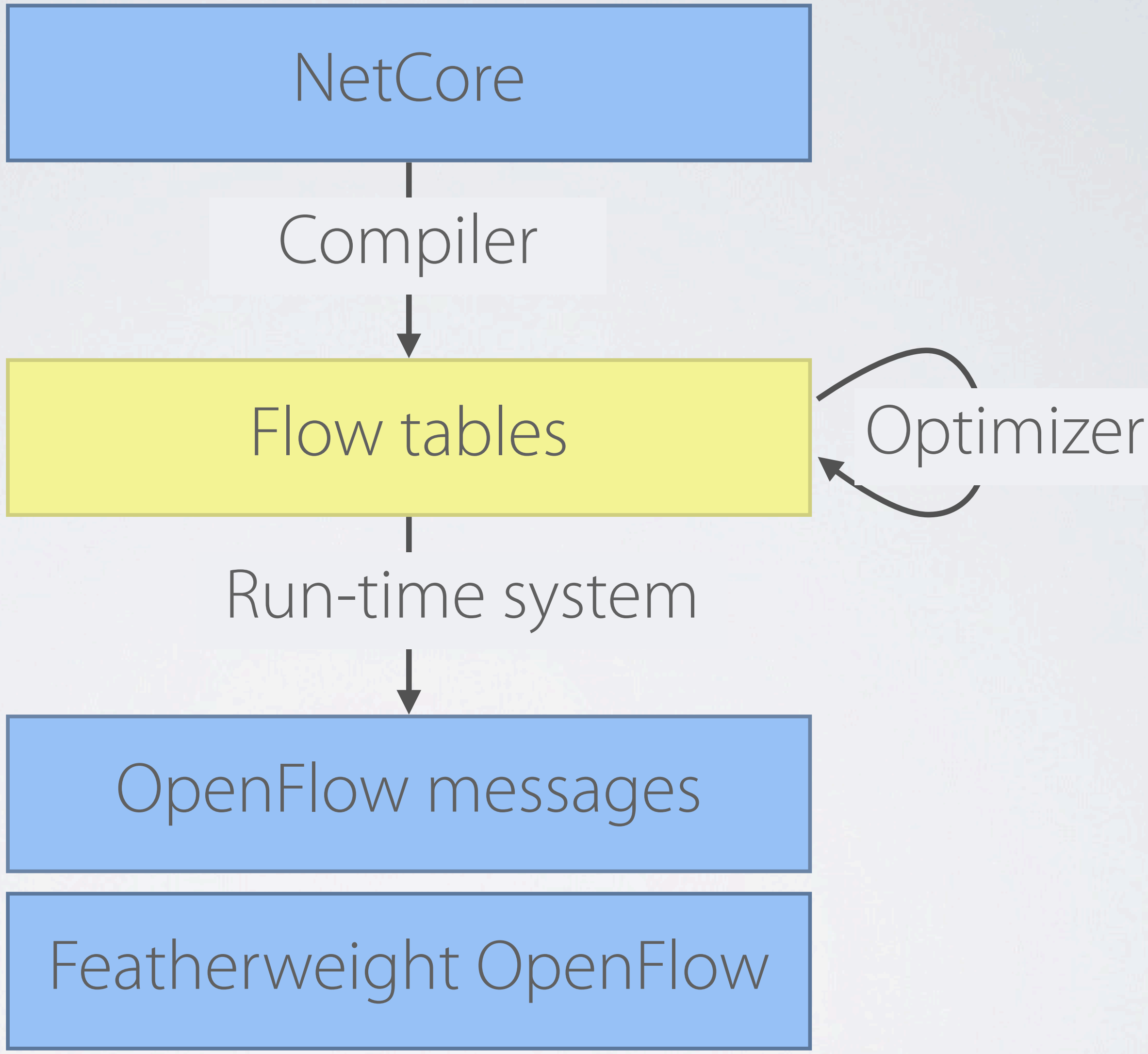
[POPL '12]

Semantics

$$\frac{\begin{array}{c} lp = (sw, pt, pk) \\ lps_{out} = pol(sw, pt, pk) \\ S = \{\!|(T(sw, pt_{out}), pk) \mid (pt_{out}, pk) \in lps_{out}|\!\} \end{array}}{\{\!|lp|\!\} \uplus \{\!|lp_1 \cdots lp_n|\!\} \xrightarrow{lp} S \uplus \{\!|lp_1 \cdots lp_n|\!\}}$$



- Models hop-by-hop forwarding behavior of the network
- Abstracts away from the underlying distributed system
- Makes it easy to reason about network-wide properties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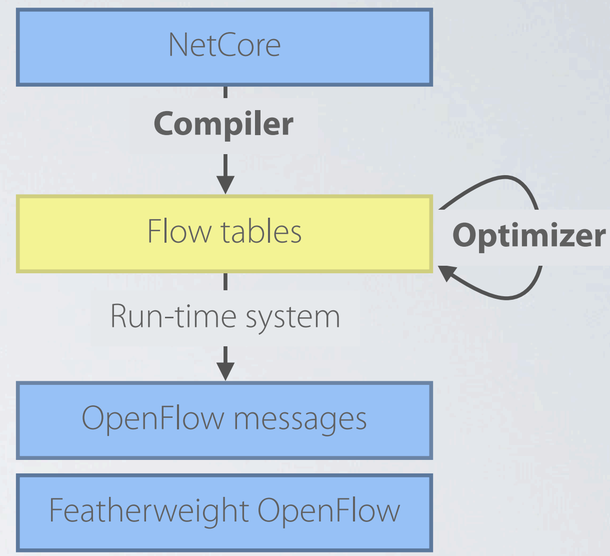
NetCore to Flow Tables



Example

Priority	Pattern	Action
65534	**inPort** = 2, **dlSrc** = dc:ba:65:43:21	**Fwd** 2
65533	**inPort** = 2	**Fwd** 3

NetCore compiler

- Key operation: flow table intersection
- Must restrict to “valid” patterns

Optimizer

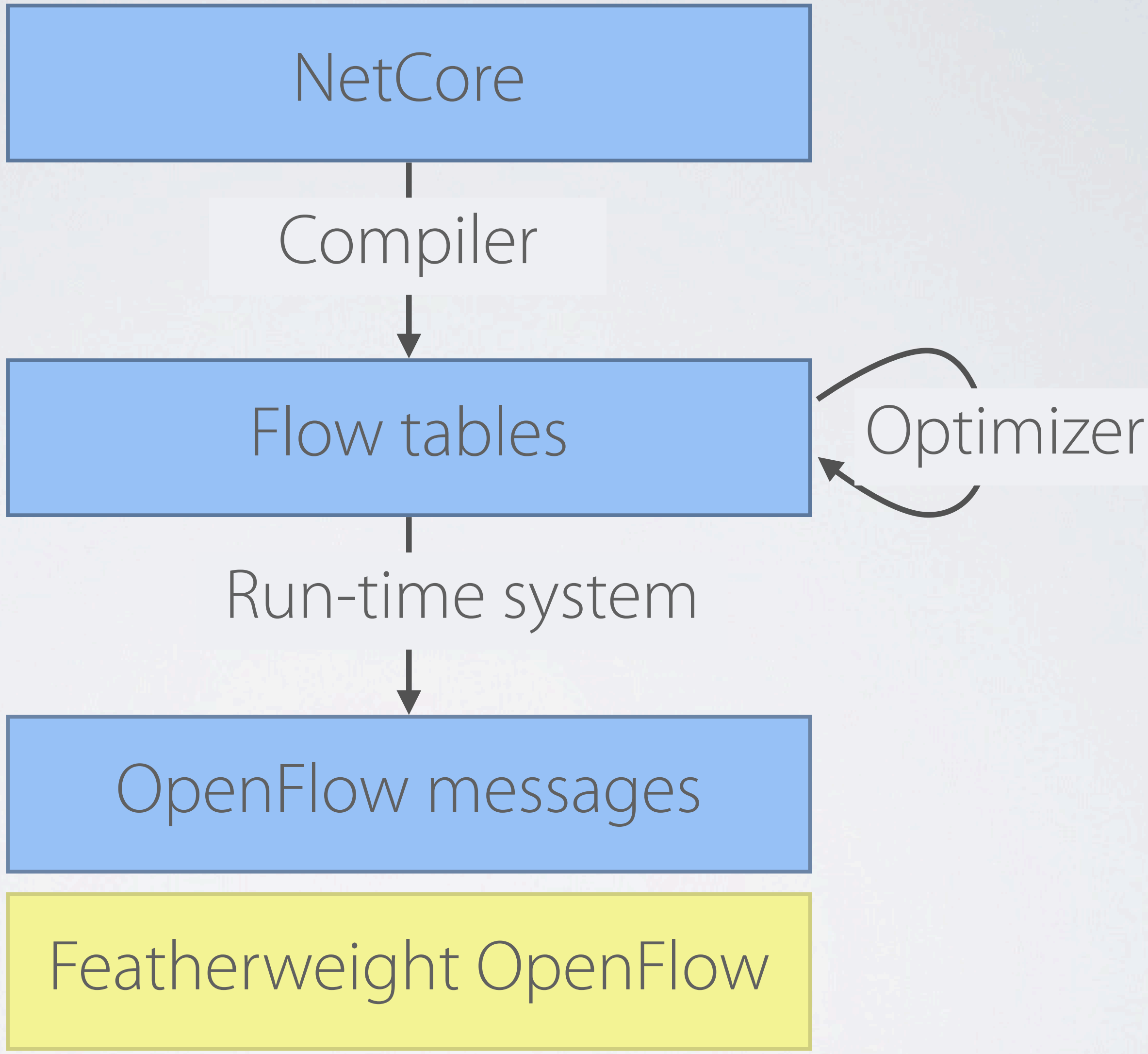
- Optimizer prunes (many) redundant rules
- Based on simple algebra of operations

Correctness Theorem

NetCore ~ FlowTable

Valid Patterns

```
Inductive ValidPattern : Pattern -> Prop :=
   | SupportedIPPatternValid : forall dlSrc dlDst dlVlan dlVlanPcp nwSrc nwDst nwTos
                               tpSrc tpDst inPort nwProto,
     In nwProto SupportedL4Protos ->
     ValidPattern (MkPattern dlSrc dlDst (WildcardExact Const_0x800)
                               dlVlan dlVlanPcp
                               nwSrc nwDst (WildcardExact nwProto)
                               nwTos tpSrc tpDst inPort)
   | UnsupportedIPPatternValid : forall dlSrc dlDst dlVlan dlVlanPcp nwSrc nwDst nwTos
                                   inPort nwProto,
     ~ In nwProto SupportedL4Protos ->
     ValidPattern (MkPattern dlSrc dlDst (WildcardExact Const_0x800)
                               dlVlan dlVlanPcp
                               nwSrc nwDst (WildcardExact nwProto)
                               nwTos WildcardAll WildcardAll inPort)
   | ARPPacketValid : forall dlSrc dlDst dlVlan dlVlanPcp nwSrc nwDst inPort,
     ValidPattern (MkPattern dlSrc dlDst (WildcardExact Const_0x806)
                               dlVlan dlVlanPcp
                               nwSrc nwDst WildcardAll
                               WildcardAll WildcardAll WildcardAll inPort)
   | UnknownDlTypPatternValid : forall dlSrc dlDst dlTyp dlVlan dlVlanPcp inPort,
     ValidPattern (MkPattern dlSrc dlDst dlTyp
                               dlVlan dlVlanPcp
                               WildcardAll WildcardAll WildcardAll
                               WildcardAll WildcardAll WildcardAll inPort)
   | EmptyPatternValid :
     ValidPattern Pattern_empty.
```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OpenFlow Specification

42 pages...

...of informal English text

...and C struct definitions

Featherweight OpenFlow

Syntax

Devices	Switch	S	$::= \mathbb{S}(sw, pts, RT, inp.outp, inm, out$
	Controller	C	$::= \mathbb{C}(\sigma, f_{in}, f_{out})$
	Link	L	$::= \mathbb{L}(loc_{src}, pks, loc_{dst})$
	OpenFlow Link to Controller	M	$::= \mathbb{M}(sw, SMS, CMS)$
Packets and Locations	Packet	pk	$::= abstract$
	Switch ID	sw	$\in \mathbb{N}$
	Port ID	pt	$\in \mathbb{N}$
	Location	loc	$\in sw \times pt$
	Located Packet	lp	$\in loc \times pk$
Controller Components	Controller state	σ	$::= abstract$
	Controller input relation	f_{in}	$\in sw \times CM \times \sigma \rightsquigarrow \sigma$
	Controller output relation	f_{out}	$\in \sigma \rightsquigarrow sw \times SM \times \sigma$
Switch Components	Rule table	RT	$::= abstract$
	Rule table Interpretation	$[\![RT]\!]$	$\in lp \to \{\!\mid lp_1 \cdots lp_n \mid\!\} \times \{\!\mid CM_1 \cdots C$
	Rule table modifier	ΔRT	$::= abstract$
	Rule table modifier interpretation	apply	$\in \Delta RT \to RT \to \Delta RT$
	Ports on switch	pts	$\in \{pt_1 \cdots pt_n\}$
	Consumed packets	inp	$\in \{\!\mid lp_1 \cdots lp_n \mid\!\}$
	Produced packets	$outp$	$\in \{\!\mid lp_1 \cdots lp_n \mid\!\}$
	Messages from controller	inm	$\in \{\!\mid SM_1 \cdots SM_n \mid\!\}$
	Messages to controller	$outm$	$\in \{\!\mid CM_1 \cdots CM_n \mid\!\}$
Link Components	Endpoints	loc_{src}, loc_{dst}	$\in loc$ where $loc_{src} \neq loc_{dst}$
	Packets from loc_{src} to loc_{dst}	pks	$\in [pk_1 \cdots pk_n]$
Controller Link	Message queue from controller	SMS	$\in [SM_1 \cdots SM_n]$
	Message queue to controller	CMS	$\in [CM_1 \cdots CM_n]$
Abstract OpenFlow Protocol	Message from controller	SM	$::= \mathbf{FlowMod}\ \Delta RT \mid \mathbf{PktOut}\ pt\ p$
	Message to controller	CM	$::= \mathbf{PktIn}\ pt\ pk \mid \mathbf{BarrierReply}\ n$

Semantics

$$\frac{(outp', outm') = [\![RT]\!](lp)}{\mathbb{S}(sw, pts, RT, \{\!\mid lp \mid\!\} \uplus inp, outp, inm, outm) \xrightarrow{lp} \mathbb{S}(sw, pts, RT, inp, outp' \uplus outp, inm, outm' \uplus outm)}\ (\textsc{Pkt-Process})$$

$$\frac{}{\begin{array}{ll} & \mathbb{S}(sw, pts, RT, inp, \{\!\mid (sw, pt, pk) \mid\!\} \uplus outp, inm, outm) \mid \mathbb{L}((sw, pt), pks, loc') \\ \longrightarrow & \mathbb{S}(sw, pts, RT, inp, outp, inm, outm) \mid \mathbb{L}((sw, pt), [pk] +\!\!+ pks, loc') \end{array}}\ (\textsc{Send-Wire})$$

$$\frac{}{\begin{array}{ll} & \mathbb{L}(loc, pks +\!\!+ [pk], (sw, pt)) \mid \mathbb{S}(sw, pts, RT, inp, outp, inm, outm) \\ \xrightarrow{(sw,pt,pk)} & \mathbb{L}(loc, pks, (sw, pt)) \mid \mathbb{S}(sw, pts, RT, \{\!\mid (sw, pt, pk) \mid\!\} \uplus inp, outp, inm, outm) \end{array}}\ (\textsc{Recv-Wire})$$

$$\frac{RT' = \mathrm{apply}(\Delta RT, RT)}{\mathbb{S}(sw, pts, RT, inp, outp, \{\!\mid \mathbf{FlowMod}\ \Delta RT \mid\!\} \uplus inm, outm) \longrightarrow \mathbb{S}(sw, pts, RT', inp, outp, inm, outm)}\ (\textsc{Switch-FlowMod})$$

$$\frac{pt \in pts}{\mathbb{S}(sw, pts, RT, inp, outp, \{\!\mid \mathbf{PktOut}\ pt\ pk \mid\!\} \uplus inm, outm) \longrightarrow \mathbb{S}(sw, pts, RT, inp, \{\!\mid (sw, pt, pk) \mid\!\} \uplus outp, inm, outm)}\ (\textsc{Switch-PktOut})$$

$$\frac{f_{out}(\sigma) \rightsquigarrow (sw, SM, \sigma')}{\mathbb{C}(\sigma, f_{in}, f_{out}) \mid \mathbb{M}(sw, SMS, CMS) \longrightarrow \mathbb{C}(\sigma', f_{in}, f_{out}) \mid \mathbb{M}(sw, [SM] +\!\!+ SMS, CMS)}\ (\textsc{Ctrl-Send})$$

$$\frac{f_{in}(sw, \sigma, CM) \rightsquigarrow \sigma'}{\mathbb{C}(\sigma, f_{in}, f_{out}) \mid \mathbb{M}(sw, SMS, CMS +\!\!+ [CM]) \longrightarrow \mathbb{C}(\sigma', f_{in}, f_{out}) \mid \mathbb{M}(sw, SMS, CMS)}\ (\textsc{Ctrl-Recv})$$

$$\frac{SM \neq \mathbf{BarrierRequest}\ n}{\begin{array}{ll} & \mathbb{M}(sw, SMS +\!\!+ [SM], CMS) \mid \mathbb{S}(sw, pts, RT, inp, outp, inm, outm) \\ \longrightarrow & \mathbb{M}(sw, SMS, CMS) \mid \mathbb{S}(sw, pts, RT, inp, outp, \{\!\mid SM \mid\!\} \uplus inm, outm) \end{array}}\ (\textsc{Switch-Recv-Ctrl})$$

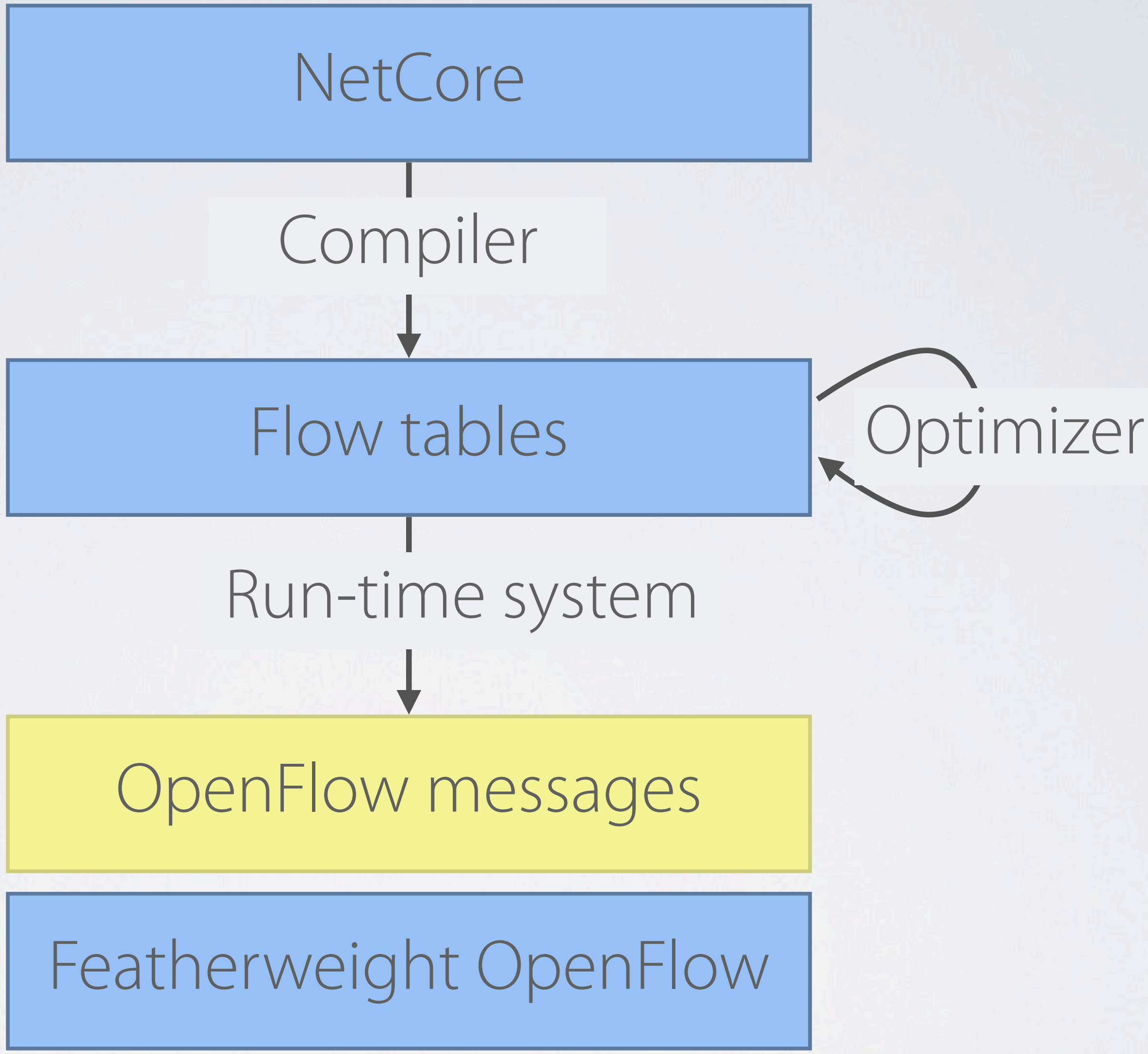
$$\frac{}{\begin{array}{ll} & \mathbb{M}(sw, SMS +\!\!+ [\mathbf{BarrierRequest}\ n], CMS) \mid \mathbb{S}(sw, pts, RT, inp, outp, \emptyset, outm) \\ \longrightarrow & \mathbb{M}(sw, SMS, CMS) \mid \mathbb{S}(sw, pts, RT, inp, outp, \emptyset, \{\!\mid \mathbf{BarrierReply}\ n \mid\!\} \uplus outm) \end{array}}\ (\textsc{Switch-Recv-Barrier})$$

$$\frac{}{\begin{array}{ll} & \mathbb{S}(sw, pts, RT, inp, outp, inm, \{\!\mid CM \mid\!\} \uplus outm) \mid \mathbb{M}(sw, SMS, CMS) \\ \longrightarrow & \mathbb{S}(sw, pts, RT, inp, outp, inm, outm) \mid \mathbb{M}(sw, SMS, [CM] +\!\!+ CMS) \end{array}}\ (\textsc{Switch-Send-Ctrl})$$

Key judgments:

- Controller in: $(sw, CM, \sigma) \rightsquigarrow \sigma'$
- Controller out: $\sigma \rightsquigarrow (sw, SM, \sigma')$
- Network step: $M \rightarrow M'$

Models *all* essential asynchrony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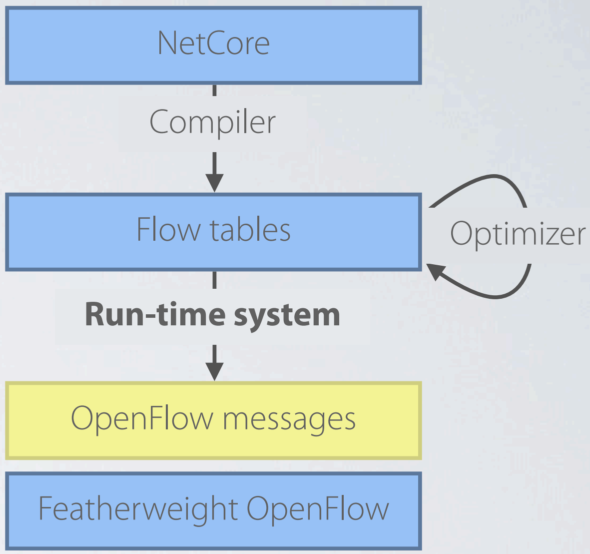
Run-Time System



Invariants

- Maintain a sound approximation of overall flow table each switch
- Eventually process all diverted packets

Theorem

FlowTable ≈ Featherweight OpenFlow

Run-time instances

- Trivial: processes all packets on controller
- Proactive: installs rules, falls back to Trivial when out of space
- Full: like Proactive, but also installs exact-match rules

Safe Wires

```
Inductive SafeWire : SF -> SF -> SF -> list CM -> Prop :=
| SafeWire_nil : forall lb ub,
    extends ub lb ->
    SafeWire lb ub lb nil
| SafeWire_cons_FlowMod : forall lb ub sf sft lst,
    SafeWire lb ub sf lst ->
    extends ub (apply_SFT sft sf) ->
    SafeWire lb ub (apply_SFT sft sf) (FlowMod sft :: lst)
| SafeWire_cons_PktOut : forall lb ub sf pt pk lst,
    SafeWire lb ub sf lst ->
    SafeWire lb ub sf (PktOut pt pk :: lst)
| SafeWire_cons_BarrierRequest : forall lb ub sf n lst,
    SafeWire lb sf lst ->
    SafeWire lb ub sf (BarrierRequest n :: lst).
```

Implementation

Source

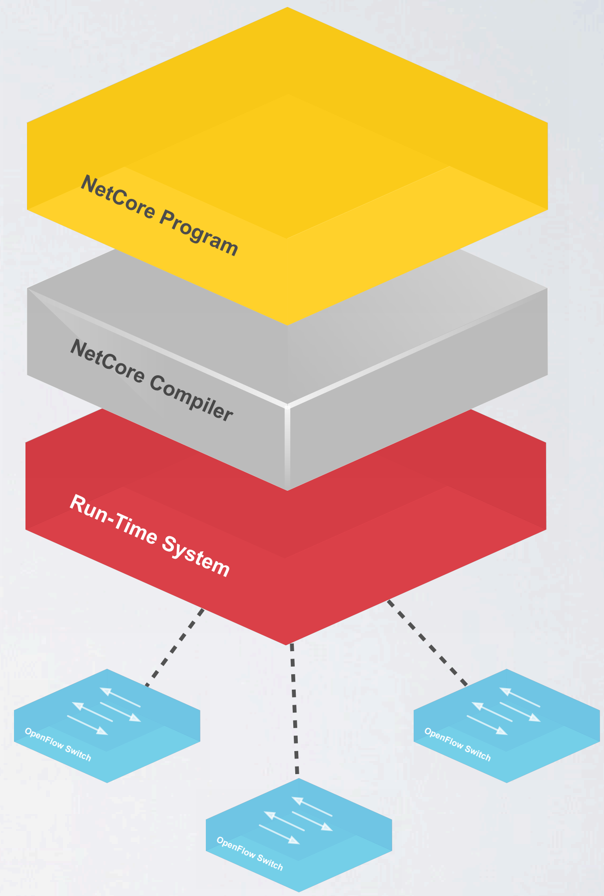
- ~8,000 lines of Coq
- ~1,500 lines of Haskell

Components

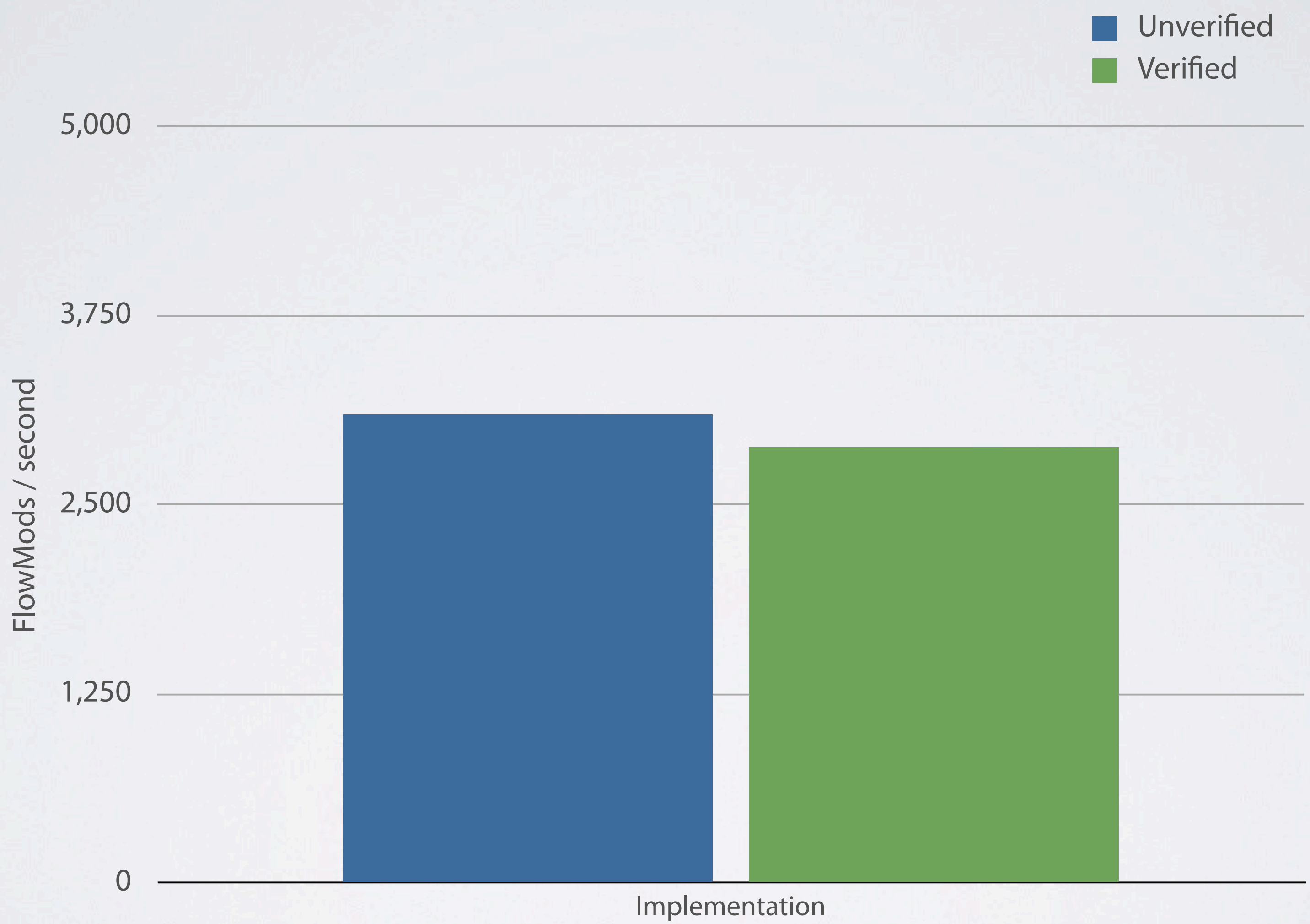
- NetCore compiler and optimizer
- Flow tables
- Featherweight OpenFlow
- Run-time system instances
- Proofs of correctness

Status

- Extracts to Haskell source code
- Compiles against Nettle libraries
- Running on "production" traffic in the lab



Performance



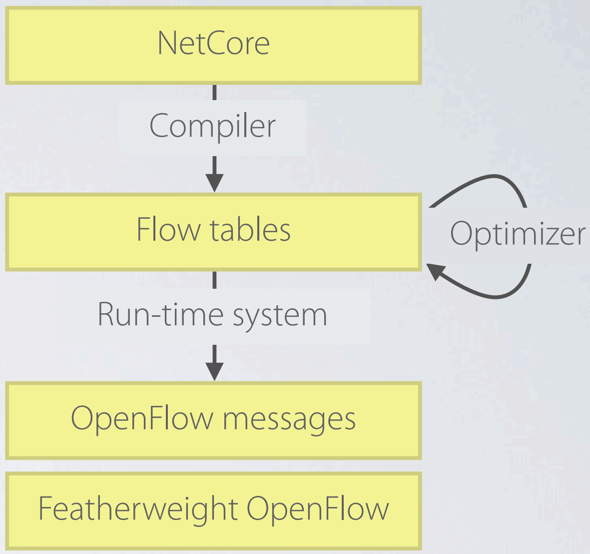
Conclusion

Networks are critical infrastructure...

...developed using 1970s-era techniques

Software-defined networks are an architecture that could be used to put networks on a solid foundation

Machine-verified controllers based on NetCore a first step in this direction



A Grand Collaboration: Languages + Networking

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- Shrutarshi Basu (PhD)
- Nate Foster (Faculty)
- **Arjun Guha** (Postdoc)
- Stephen Gutz (Undergrad)
- **Mark Reitblatt** (PhD)
- Robert Soulé (Postdoc)
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- Cole Schlesinger (PhD)
- Dave Walker (Faculty)
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