CSC 2229 – Software-Defined Networking

Handout # 6: Programming Software-Defined Networks

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Some slides courtesy of J. Rexford (Princeton), N. Foster (Cornell) and N. Feamster (Georgia Tech), all used with permission.

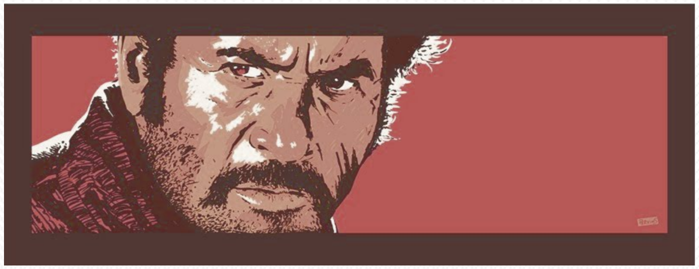
Announcements

- Final project proposal
  - Due: Friday, January 31st (5PM)
- In class presentations
  - Volunteer?
- Today:
  - Programming software-defined networks
  - Final project ideas

Programming SDNs

- The Good
  - Network-wide visibility
  - Direct control over the switches
  - Simple data-plane abstraction

- The Bad
  - Low-level programming interface
  - Functionality tied to hardware
  - Explicit resource control



- The Ugly
  - Non-modular, non-compositional
  - Challenging distributed programming

Programming OpenFlow is Not Easy

- OpenFlow and NOX make it *possible* to implement exciting new network services
  - Unfortunately, they do not make it *easy*.
- Combining different applications is not straightforward
- OpenFlow provides a very low-level abstraction
- We have a two-tier architecture
- Network of switches is susceptible to race conditions

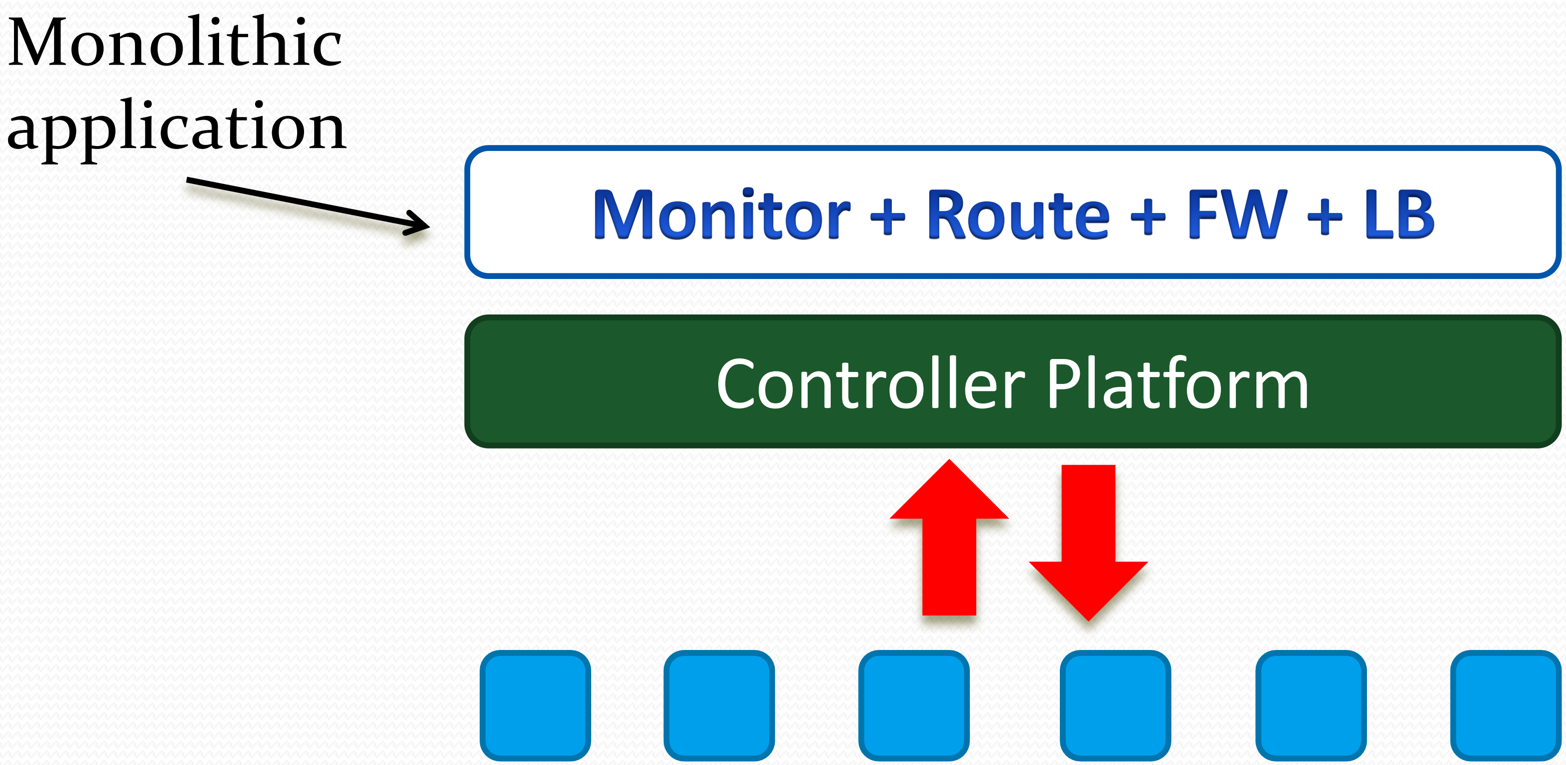
Problem 1: Anti-Modularity

- Combining different applications is challenging

- **Example**: monitor + route + firewall + load balancing
  - How these applications will work together?
  - How are messages from switches delivered to these applications
    How are messages from these apps aggregated to be sent to switches?
  - Do OpenFlow and NOX provide a way for each app to perform its job without impacting other apps?

- **Question**: How can we combine these applications?

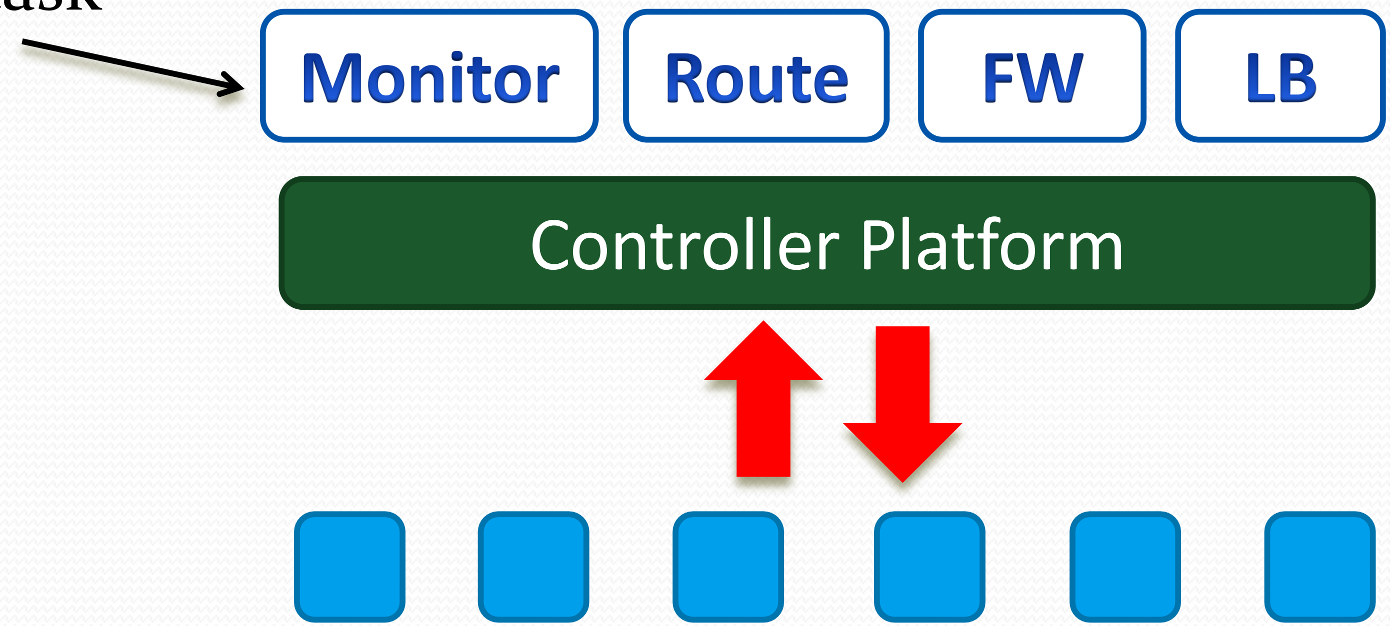
Combining Many Networking Tasks



Hard to program, test, debug, reuse, port, …

Modular Controller Applications

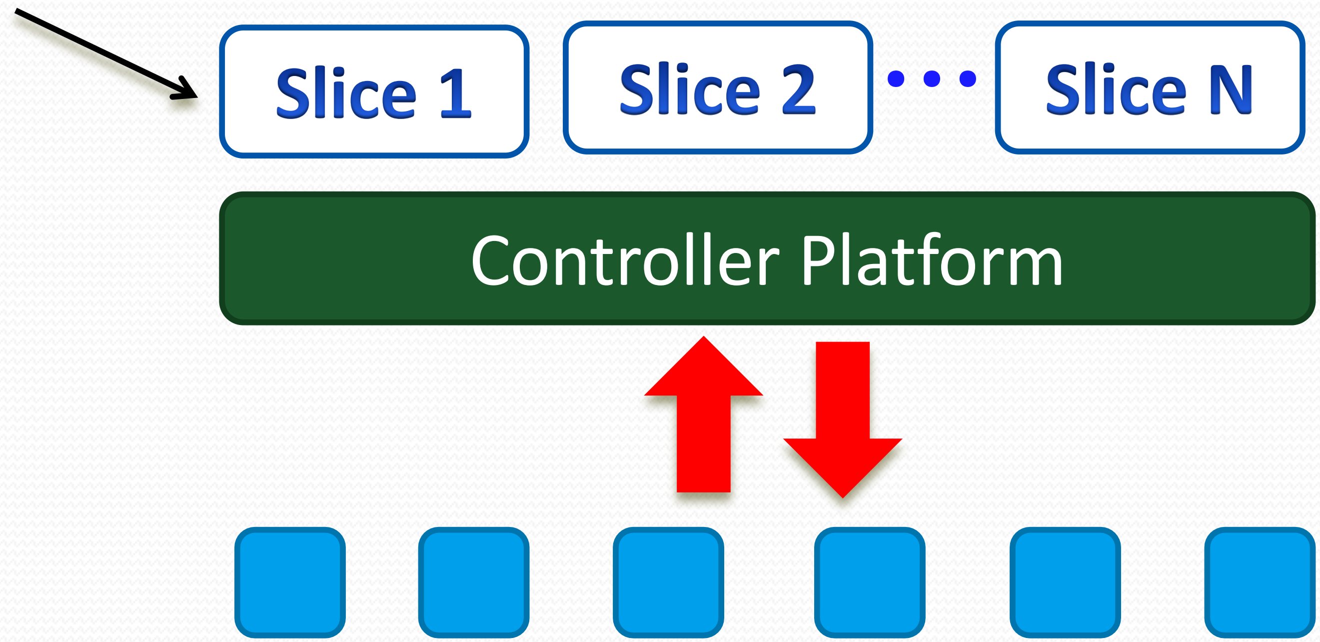
A module for
each task



Easier to program, test, and debug
Greater reusability and portability

Beyond Multi-Tenancy

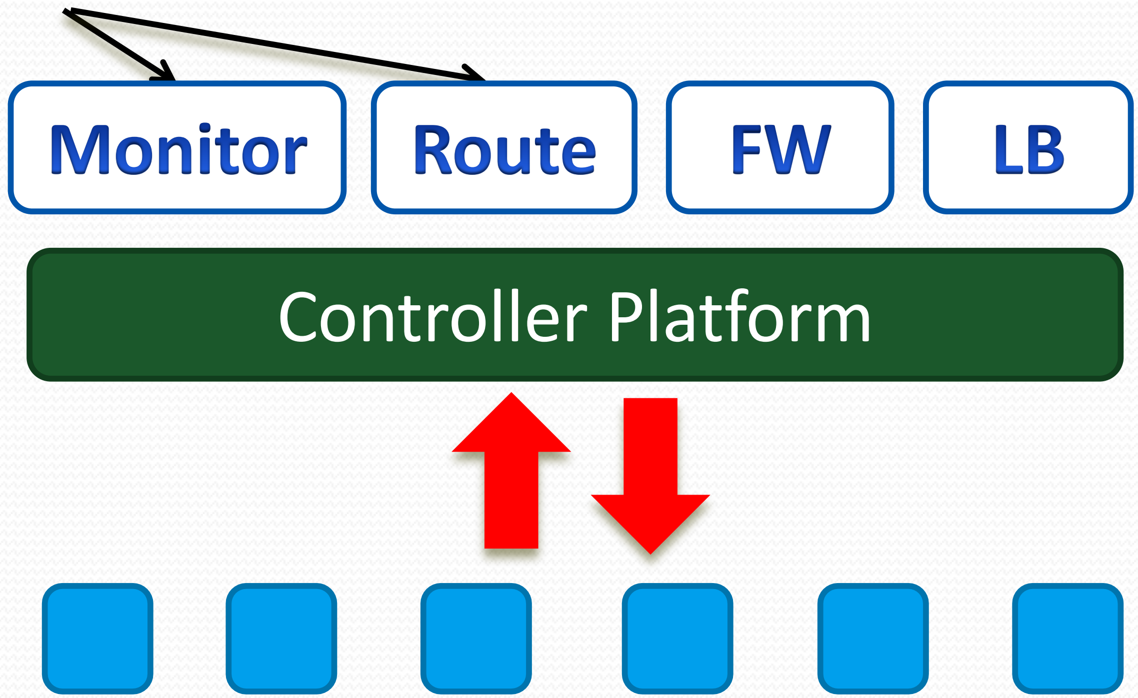
Each module controls a *different* portion of the traffic



Relatively easy to partition *rule space*, *link bandwidth*, and *network events* across modules

Modules Affect the *Same* Traffic

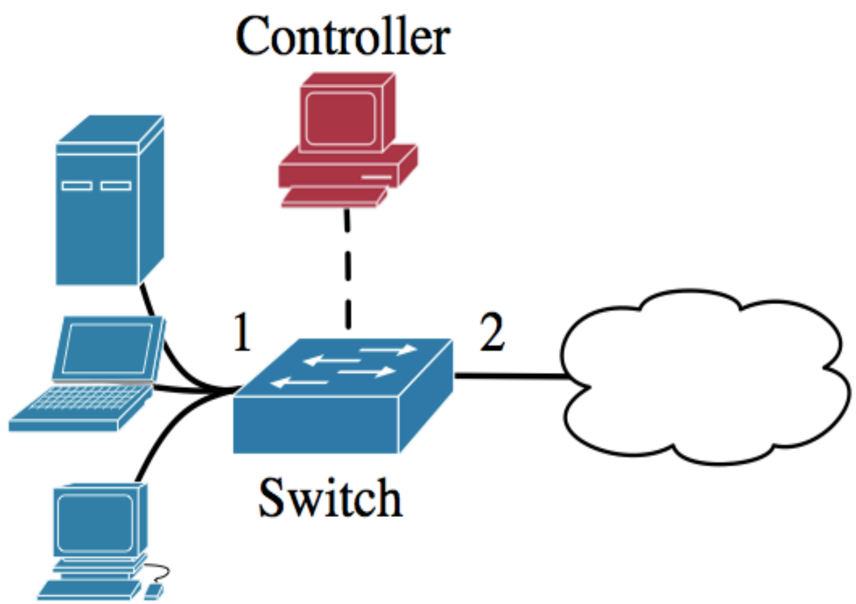
Each module *partially* specifies the handling of the traffic



How to combine modules into a complete application?

Anti-Modularity Example

- Consider a simple network



- Want to add two applications
- Simple repeater
  - Port 1 → Port 2
  - Port 2 → Port 1
- Web monitor
  - Packet and byte counts
  - Incoming web traffic

NOX Events and Commands

Events:

- **switch_join(switch)**: triggered when switch joins the network
- **stats_in(switch , xid , pattern , packets , bytes)**, triggered when *switch* returns the *packets* and *bytes* counters in response to a request for statistics about rules contained in *pattern*

Commands:

- **install(switch, pattern, priority, timeout, actions):** installs a rule in the flow table of *switch*
- **query_stats(switch, pattern)**: issues a request for statistics from all rules contained in *pattern* on *switch*

Anti-Modularity Example

Repeater

```
def switch_join(switch):
  repeater(switch)

def repeater(switch):
  pat1 = {in_port:1}
  pat2 = {in_port:2}
  install(switch,pat1,DEFAULT,None,[output(2)])
  install(switch,pat2,DEFAULT,None,[output(1)])
```

Web Monitor

```
def monitor(switch):
  pat = {in_port:2,tp_src:80}
  install(switch, pat, DEFAULT, None, [])
  query_stats(switch, pat)

def stats_in(switch, xid, pattern, packets, bytes):
  print bytes
  sleep(30)
  query_stats(switch, pattern)
```

Anti-Modularity Example

Repeater

```
def switch_join(switch):
  repeater(switch)

def repeater(switch):
  pat1 = {in_port:1}
  pat2 = {in_port:2}
  install(switch,pat1,DEFAULT,None,[output(2)])
  install(switch,pat2,DEFAULT,None,[output(1)])
```

Web Monitor

```
def monitor(switch):
  pat = {in_port:2,tp_src:80}
  install(switch, pat, DEFAULT, None, [])
  query_stats(switch, pat)

def stats_in(switch, xid, pattern, packets, bytes):
  print bytes
  sleep(30)
  query_stats(switch, pattern)
```

Repeater/Monitor

```
def switch_join(switch)
  repeater_monitor(switch)

def repeater_monitor(switch):
  pat1 = {in_port:1}
  pat2 = {in_port:2}
  pat2web = {in_port:2, tp_src:80}
  Install(switch, pat1, DEFAULT, None, [output(2)])
  install(switch, pat2web, HIGH, None, [output(1)])
  install(switch, pat2, DEFAULT, None, [output(1)])
  query_stats(switch, pat2web)

def stats_in(switch, xid, pattern, packets, bytes):
  print bytes
  sleep(30)
  query_stats(switch, pattern)
```

blue = from repeater
red = from web monitor
green = from neither

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- Network of switches is susceptible to race conditions

Problem 2: Low-Level API

- OpenFlow is a low-level programming interface
  - Derived from the features of the switch hardware
  - Rather than ease of use
- Programmer must describe *low-level details* that do not affect the *overall behavior* of the program
- Example: to implement simple set difference we require
  - Multiple rules
  - Priorities
  - All need to be managed by the programmer
- Focusing on the big picture not easy

Low-Level API Example

- Extend the repeater and monitoring
  - Monitor all incoming web traffic *except* traffic destined to 10.0.0.9 (on internal network)
- We need to express a logical "difference" of patterns
  - OpenFlow can only express positive constraints

```
def repeater_monitor_noserver(switch):
  pat1 = {in_port:1}
  pat2 = {in_port:2}
  pat2web = {in_port:2,tp_src:80}
  pat2srv = {in_port:2,nw_dst:10.0.0.9,tp_src:80}
  install(switch,pat1,DEFAULT,None,[output(2)])
  install(switch,pat2srv,HIGH,None,[output(1)])
  install(switch,pat2web,MEDIUM,None,[output(1)])
  install(switch,pat2,DEFAULT,None,[output(1)])
  query_stats(switch,pat2web)
```

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Problem 3: Two-Tiered System

- Control program manages networks by
  - Installing/uninstalling switch-level rules

- Programmer needs to specify communication patterns between controller and switches
  - Deal with tricky concurrency issues

- Controller does not have full visibility
  - Sees only packets that the switches do not know how to handle.
  - Previously installed rules
    - Reduce the load on the controller
    - Make it difficult to reason

- **Detour**: proactive vs. reactive rule installation

Two-Tiered Programming Example

- Extending the original repeater
  - Monitor the total amount of incoming traffic
  - By destination host

- Cannot install all of the rules we need in advance
  - Address of each host is unknown *a priori*

- The controller must dynamically install rules for the packets seen at run time

Two-Tiered Programming Example

```
def repeater_monitor_hosts(switch):
  pat = {in_port:1}
  install(switch,pat,DEFAULT,None,[output(2)])
def packet_in(switch,inport,packet):
  if inport == 2:
     mac = dstmac(packet)
     pat = {in_port:2,dl_dst:mac}
     install(switch,pat,DEFAULT,None,[output(1)])
     query_stats(switch,pat)
```

- Two programs depended on each other
- Complex concurrency issues can arise
- Reading/understanding the code is difficult
- Details are sources of significant distraction

Programming OpenFlow is Not Easy

- OpenFlow and NOX now make it *possible* to implement exciting new network services
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- OpenFlow provides a very low-level abstraction

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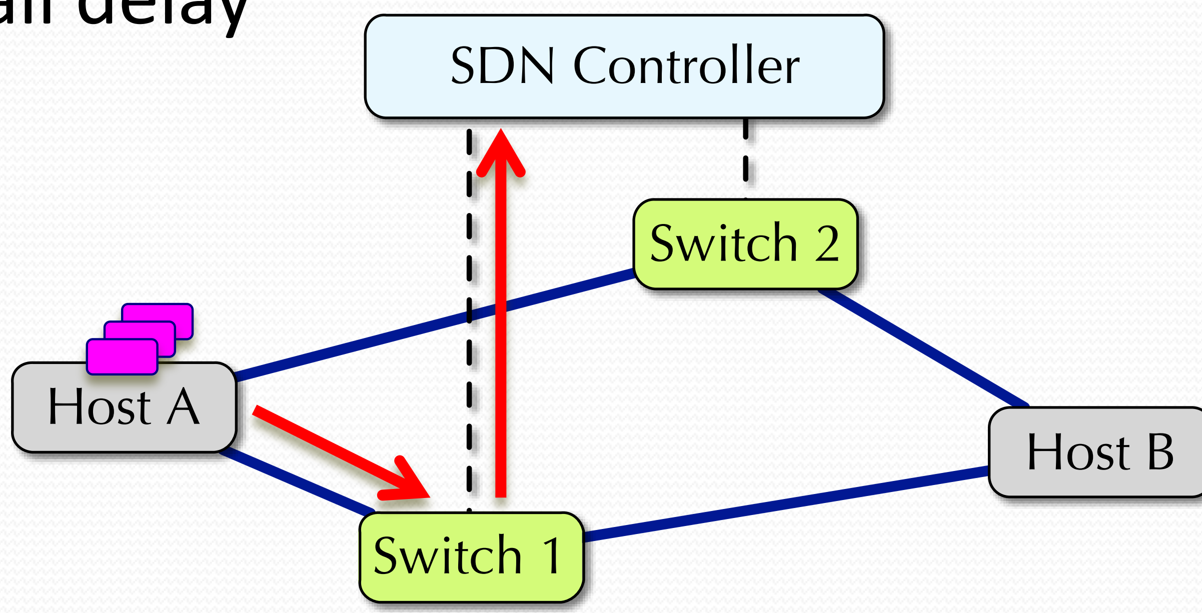
Problem 4: Race Conditions

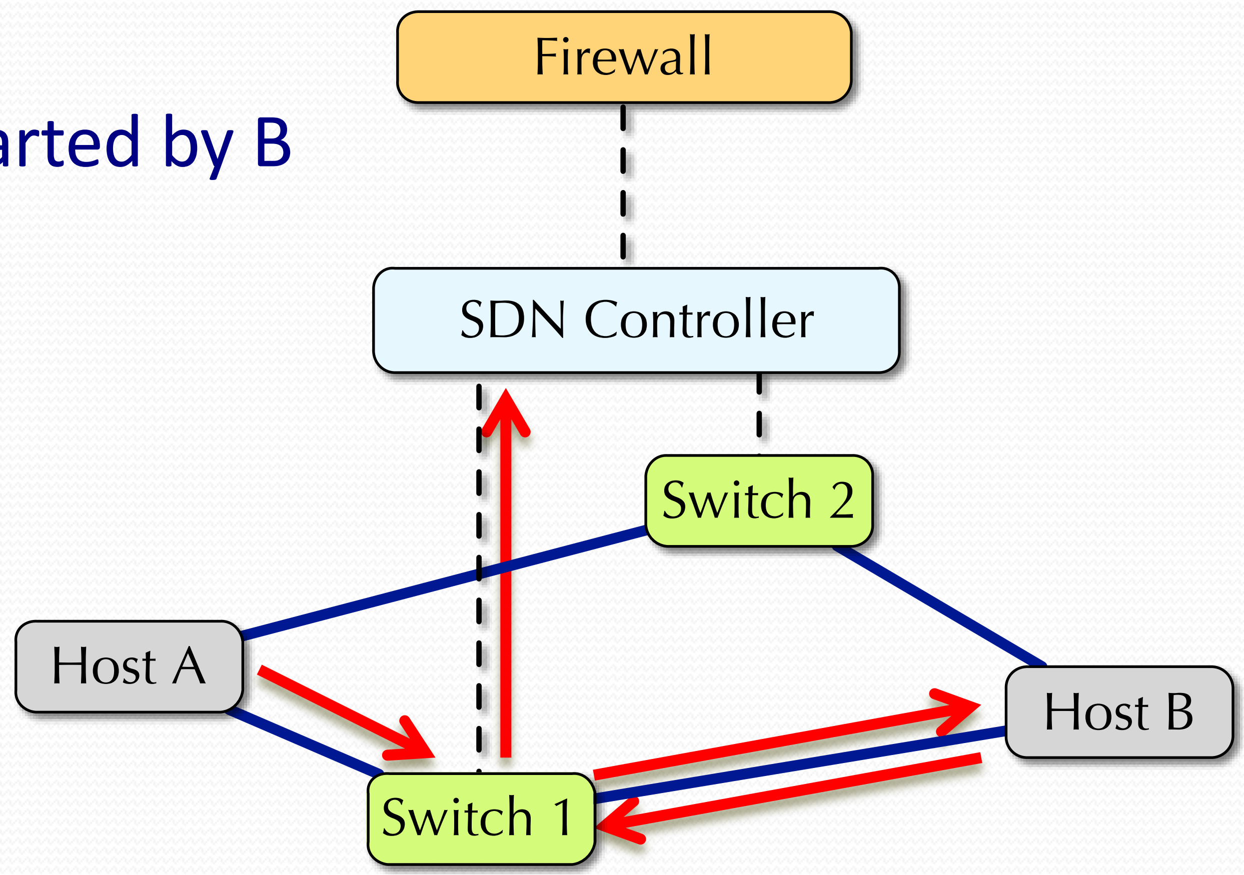
- Race conditions can cause complications
  - We have a distributed system
    - Of switches
    - And controllers

- Example 1: rule install delay
  - One new flow
  - Multiple packets



Race Conditions Example

- Example 2: firewall application
  - Running on multiple switches
  - Allow A initiate a flow to B
    - Two way
  - But, block flows started by B



Race Conditions Example

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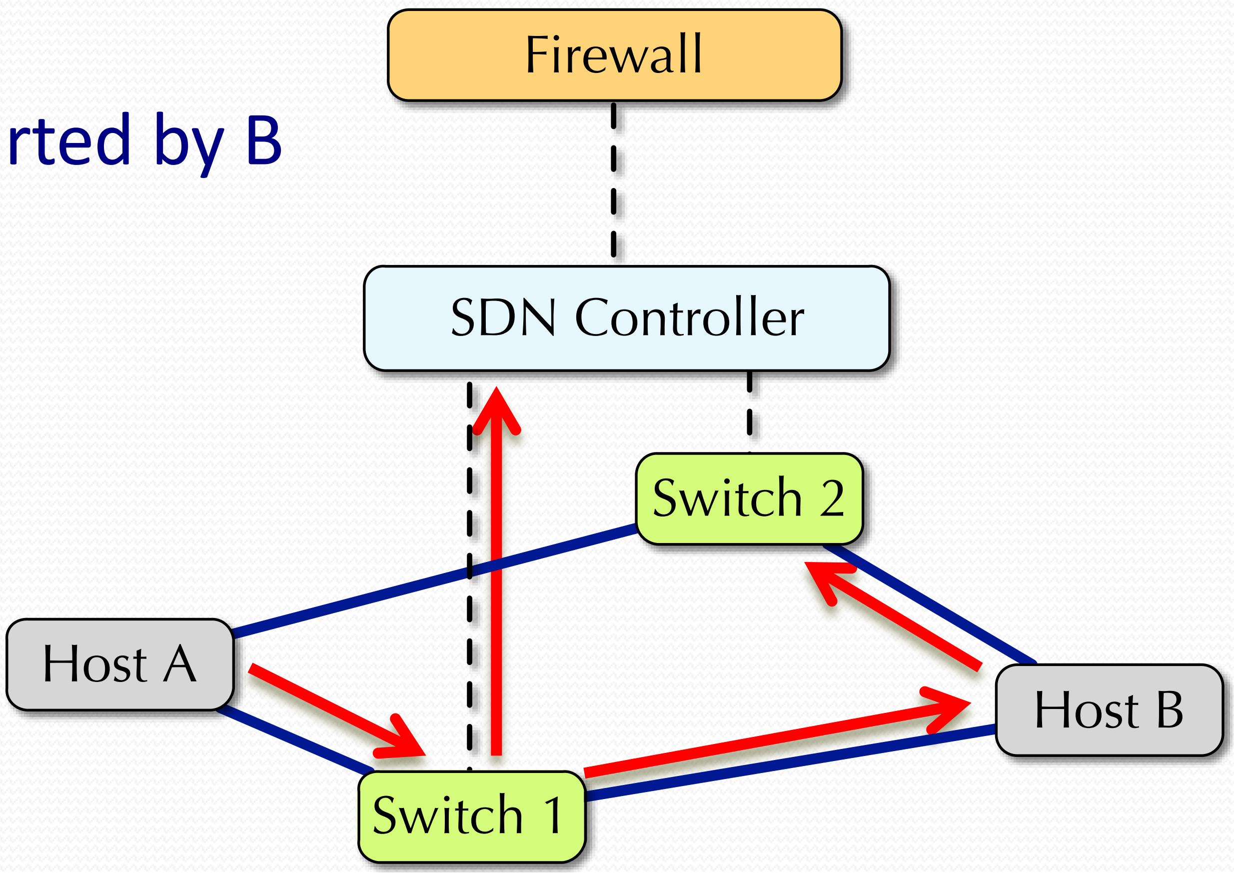
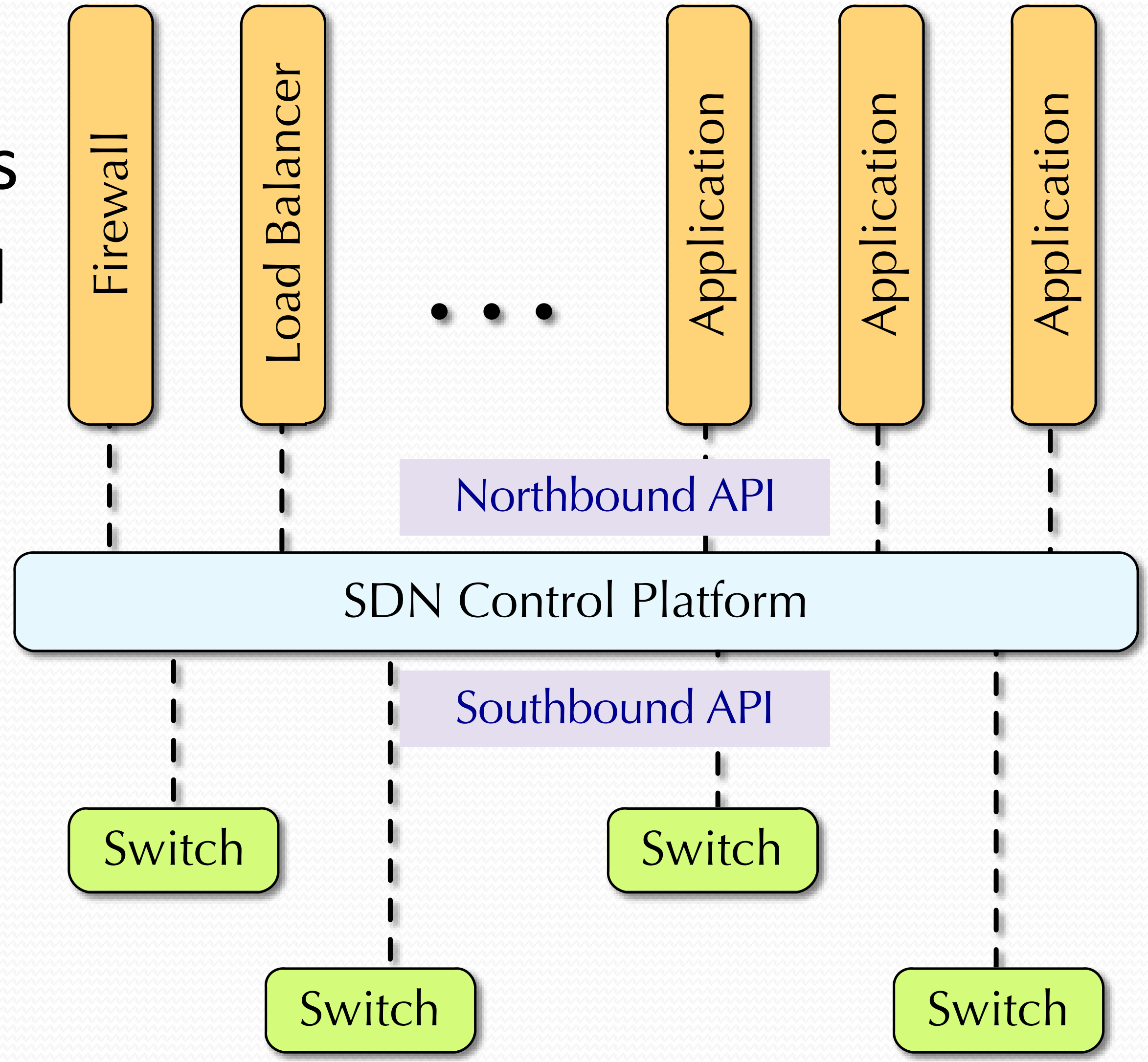


Northbound API

- Programming abstraction for applications
- Hides low-level details
- Helps orchestrate and combine applications



- Example uses
  - Path computation
  - Loop avoidance
  - Routing
  - Security

Who Will Use the Northbound API?

- Service providers
- Sophisticated network operators
  - Or, enthusiastic network administrators
- Vendors
- Researchers
- Or anyone who wants to add new capabilities to their network

Benefits of the Northbound API

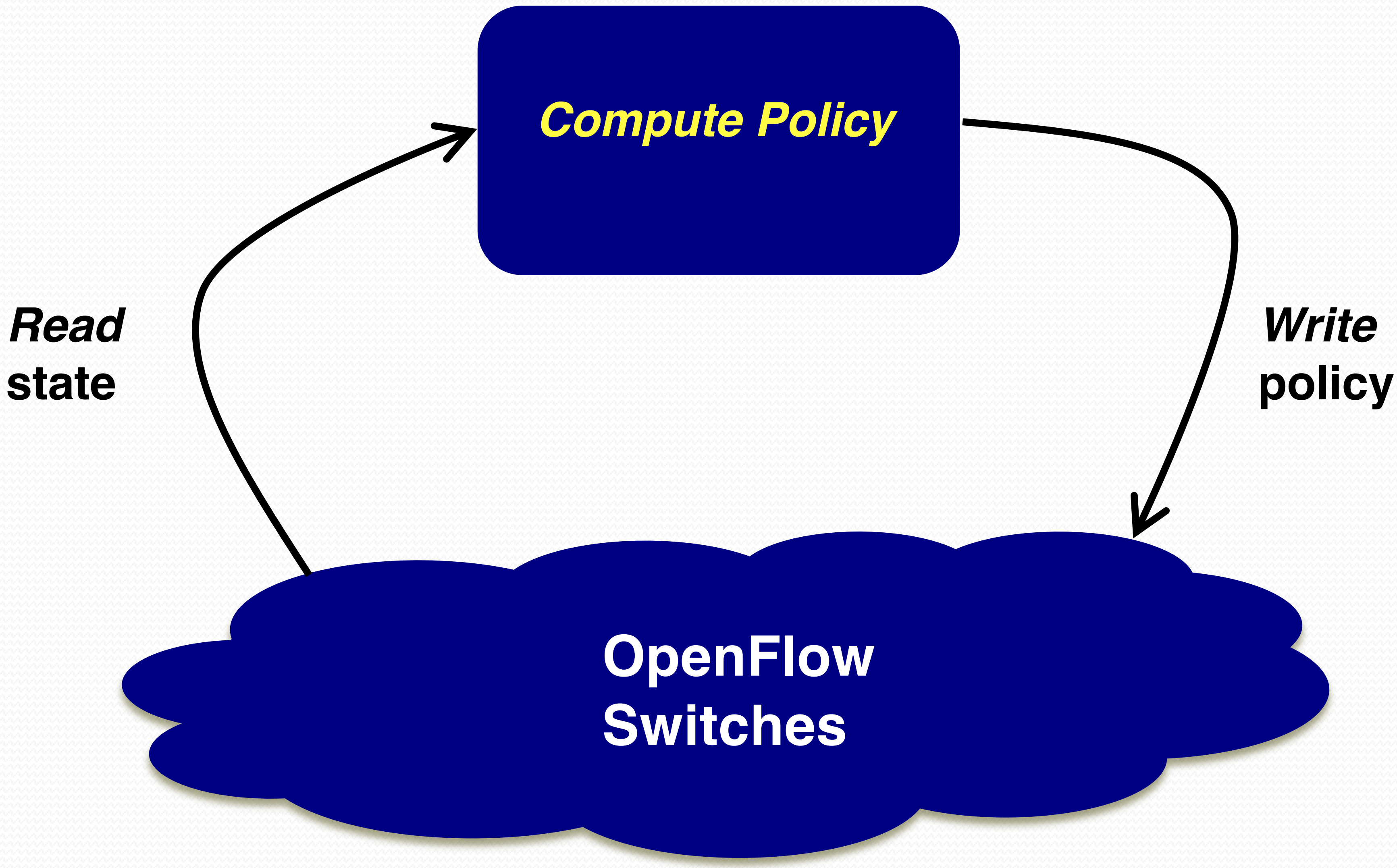
- Vendor independence
- Ability to quickly modify or customize control applications through simple programming

- Example applications:
  - Large virtual switch
  - Security applications
  - Resource management and control
  - Middlebox integration

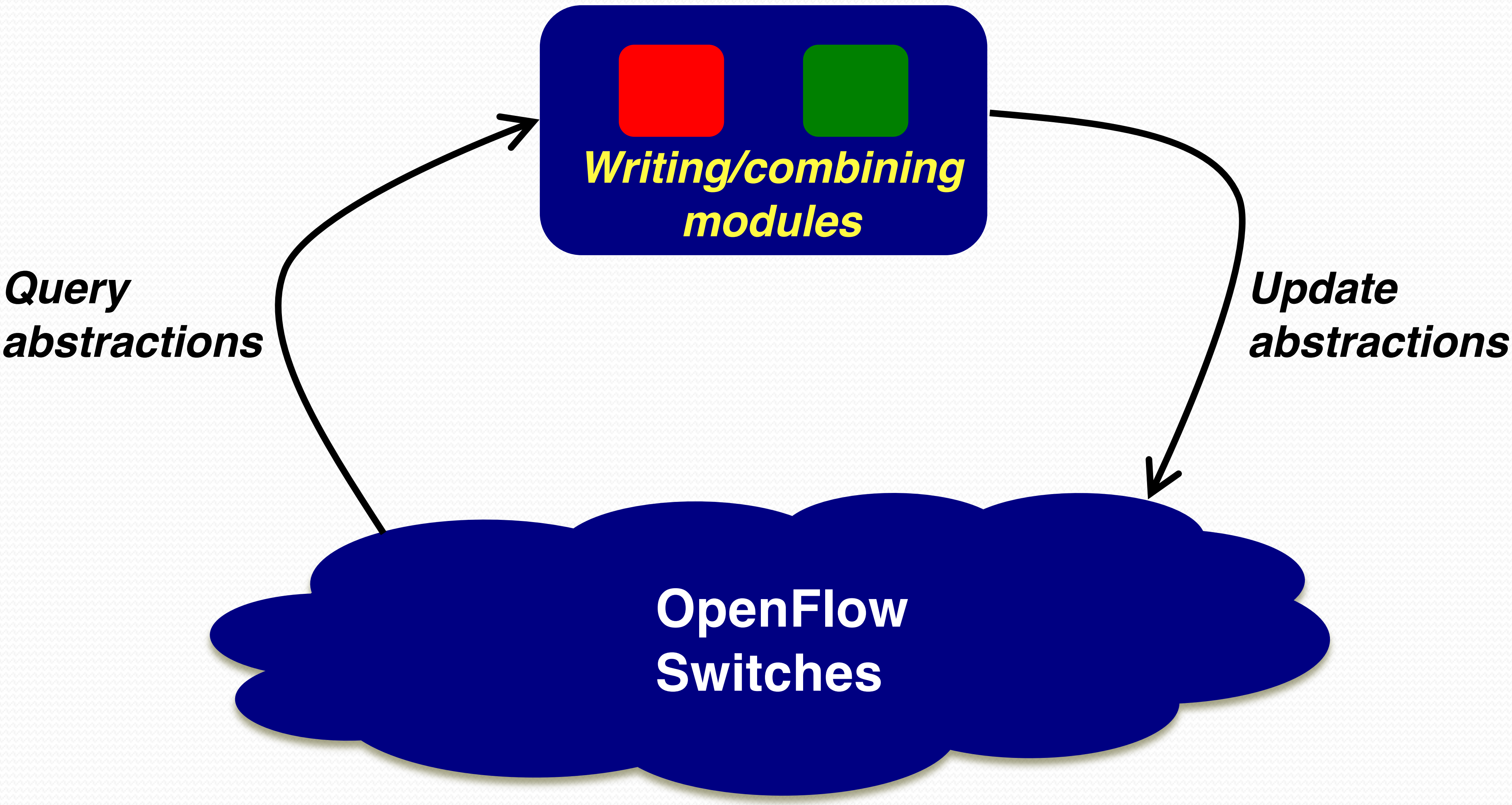
Frenetic Language

- *Declarative Design*
  - W*hat the programmer* might want
  - Rather than *how the hardware* implements it.
- *Modular Design*
  - Primitives have *limited network-wide effects* and semantics
  - Independent of the context in which they are used.
- *Single-tier Programming*
  - *See-every-packet abstraction*
- *Race-free Semantics*
  - Automatic race detection and packet suppression
- *Cost control*
  - Core query logic can be executed on network switches

Network Control Loop



Language-Based Abstractions



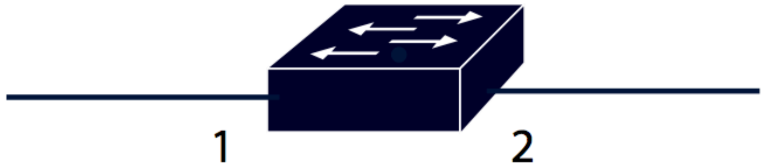
Frenetic Language

- Abstractions for querying network state
  - An integrated query language
    - Select, filter, group, sample sets of packets or statistics
    - Designed so that computation can occur on data plane
- Abstractions for specifying a forwarding policy
  - A functional stream processing library (based on FRP)
    - Generate streams of network policies
    - Transform, split, merge, filter policies and other streams
- Implementation
  - A collection of Python libraries on top of NOX

Frenetic Queries

$$
\begin{array}{lrl}
\textit{Queries} & q ::= & \texttt{Select}(a)\ \ast \\
 & & \texttt{Where}(\mathit{fp})\ \ast \\
 & & \texttt{GroupBy}([qh_1, \ldots, qh_n])\ \ast \\
 & & \texttt{SplitWhen}([qh_1, \ldots, qh_n])\ \ast \\
 & & \texttt{Every}(n)\ \ast \\
 & & \texttt{Limit}(n) \\
\textit{Aggregates} & a ::= & \texttt{packets} \mid \texttt{sizes} \mid \texttt{counts} \\
\textit{Headers} & qh ::= & \texttt{inport} \mid \texttt{srcmac} \mid \texttt{dstmac} \mid \texttt{ethtype} \mid \\
 & & \texttt{vlan} \mid \texttt{srcip} \mid \texttt{dstip} \mid \texttt{protocol} \mid \\
 & & \texttt{srcport} \mid \texttt{dstport} \mid \texttt{switch} \\
\textit{Patterns} & fp ::= & \texttt{true\_fp}() \mid qh\texttt{\_fp}(n) \mid \\
 & & \texttt{and\_fp}([\mathit{fp}_1, \ldots, \mathit{fp}_n]) \mid \\
 & & \texttt{or\_fp}([\mathit{fp}_1, \ldots, \mathit{fp}_n]) \mid \\
 & & \texttt{diff\_fp}(\mathit{fp}_1, \mathit{fp}_2) \mid \texttt{not\_fp}(\mathit{fp})
\end{array}
$$

Frenetic Queries



Goal: measure total web traffic on port 2, every 30 seconds

```
def web_query():
  return (Select(sizes) *
          Where(inport_fp(2) & srcport_fp(80)) *
          Every(30))
```

Key Property: query semantics is independent of other program parts

Policy in OpenFlow

- Defining "policy" is complicated
  - All rules in all switches
  - Packet-in handlers
  - Polling of counters
- Programming "policy" is error-prone
  - Duplication between rules and handlers
  - Frequent changes in policy (e.g., flowmods)
  - Policy changes affect packets in flight

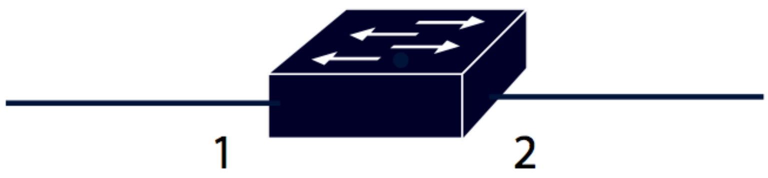
Frenetic Forwarding Policies

- **Rules** are created using the Rule Constructor, which takes a *pattern* and a list of *actions* as arguments
- **Network policies** associate rules with switches
  - Dictionaries mapping switches to list of rules
- **Policy events** are infinite, time-indexed streams of values, just like the events generated from queries
  - Programs control the installation of policies in a network *over time* by generating ***policy events***
- **Listeners** are event consumers
  - Print: send to console
  - Send: transfer packet to switch and apply actions
  - Register: apply network wide policy

Power of Policy as a Function

- Composition
  - Parallel: `Monitor + Route`
  - Sequential: `Firewall >> Route`
- `A >> (B + C) >> D`
- `(A >> P) + (B >> P)  (A + B)>>P`

Frenetic Forwarding Policies



Goal: implement a repeater switch

```
rules = [Rule(inport_fp(1), [forward(2)]),
         Rule(inport_fp(2), [forward(1)])]
```

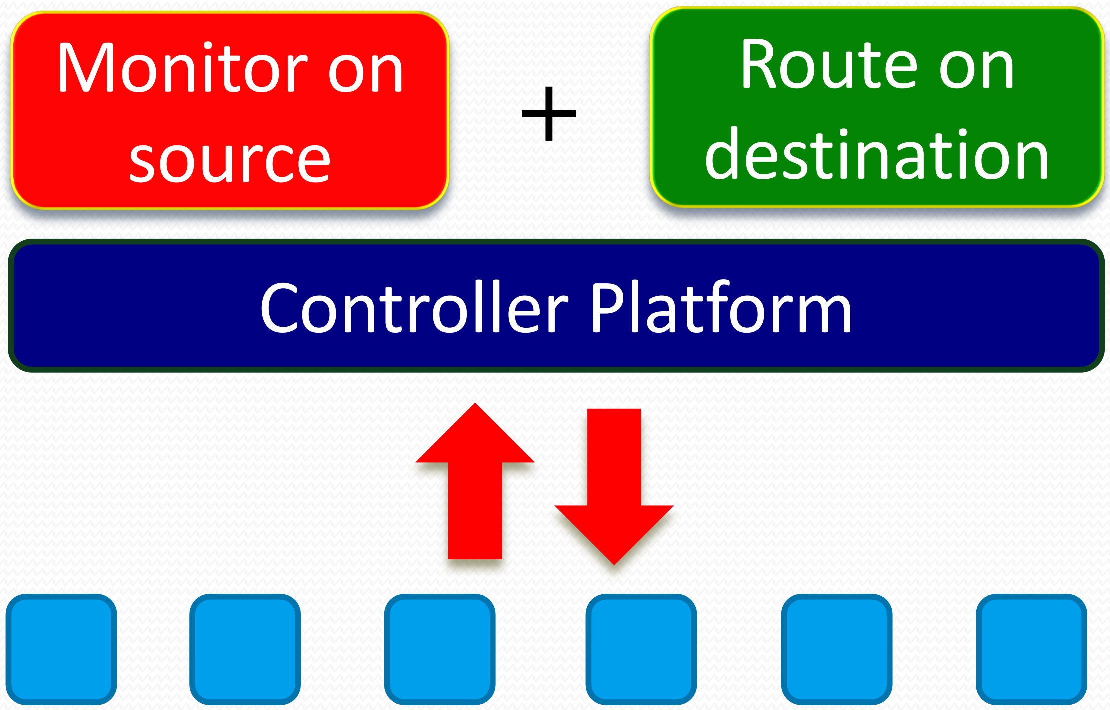
```
def repeater():
  return (SwitchJoin() >> Lift(lambda switch: {switch:rules}))
```

Key Property: Policy semantics independent of other queries/policies

Parallel Composition

srcip = 5.6.7.8 → count

dstip = 1.2.3.4 → fwd(1)
dstip = 3.4.5.6 → fwd(2)



Parallel Composition

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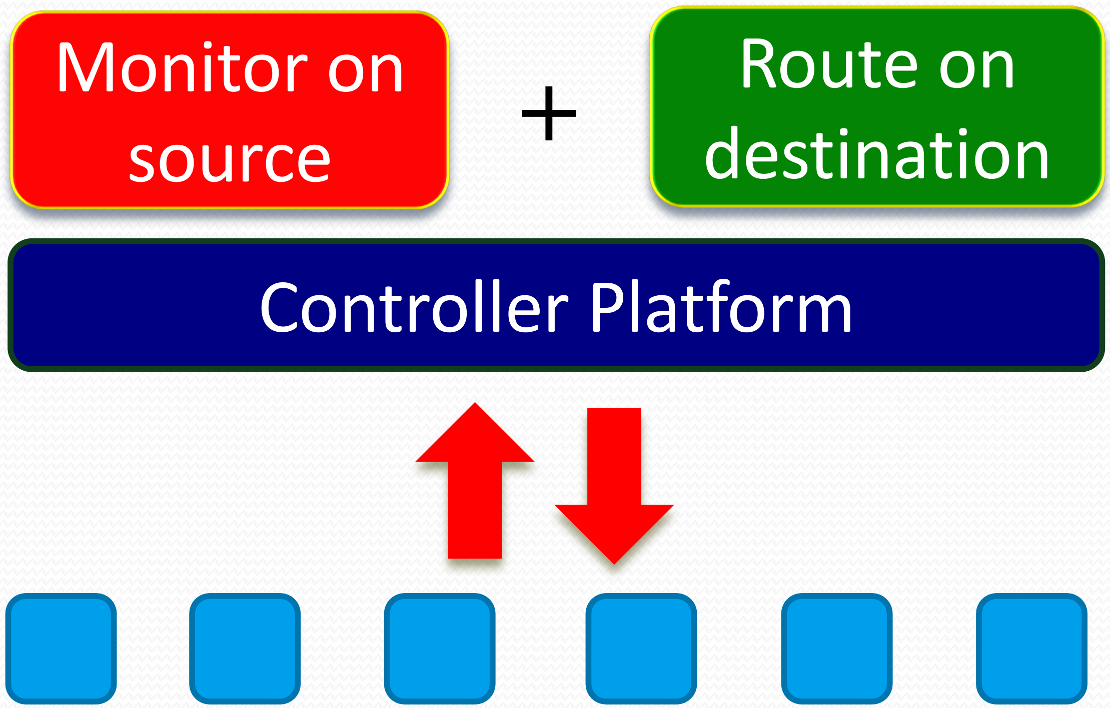
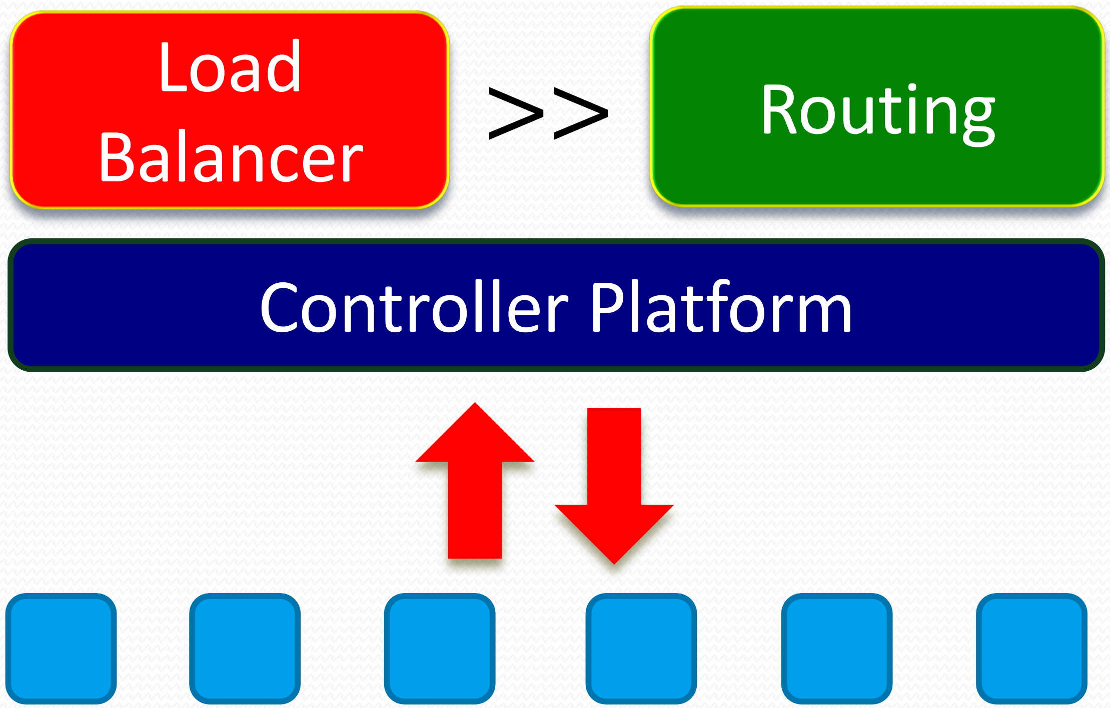


srcip = 5.6.7.8, dstip = 1.2.3.4 → fwd(1), count
srcip = 5.6.7.8, dstip = 3.4.5.6 → fwd(2), count
srcip = 5.6.7.8 → count
dstip = 1.2.3.4 → fwd(1)
dstip = 3.4.5.6 → fwd(2)

Sequential Composition

srcip = 0*, dstip=1.2.3.4 → dstip=10.0.0.1
srcip = 1*, dstip=1.2.3.4 → dstip=10.0.0.2

dstip = 10.0.0.1 → fwd(1)
dstip = 10.0.0.2 → fwd(2)



Sequential Composition

srcip = 0*, dstip=1.2.3.4 → dstip=10.0.0.1
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dstip = 10.0.0.1 → fwd(1)
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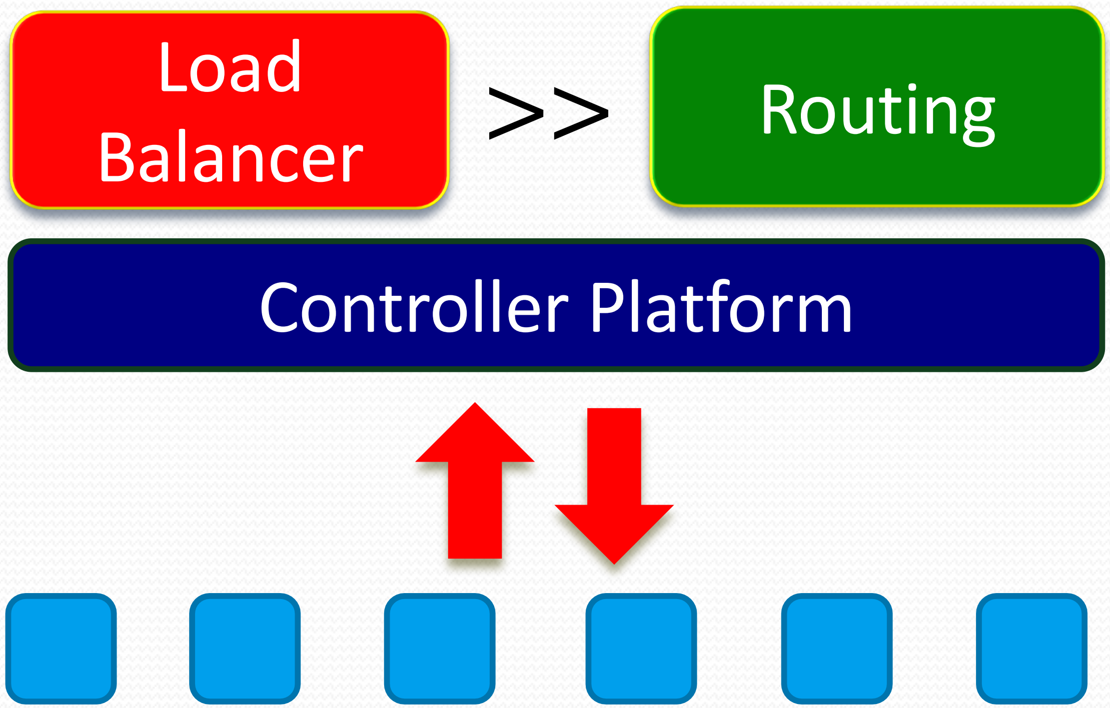
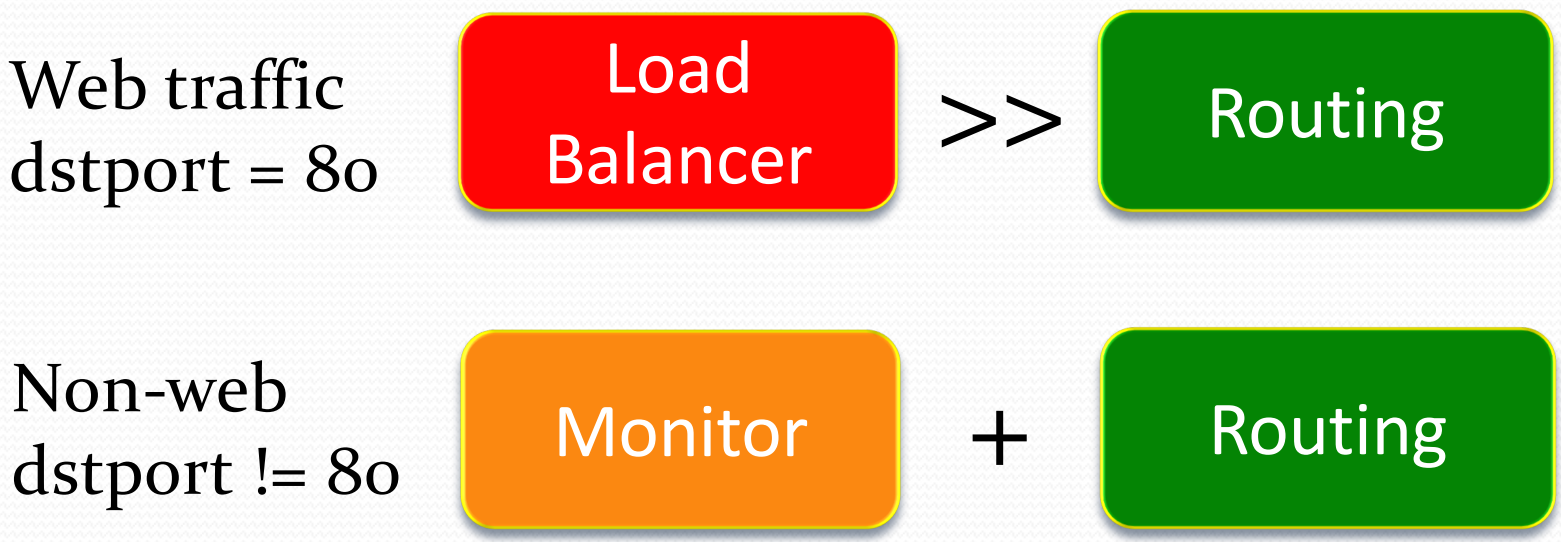


srcip = 0*, dstip = 1.2.3.4 → dstip = 10.0.0.1, fwd(1)
srcip = 1*, dstip = 1.2.3.4 → dstip = 10.0.0.2, fwd(2)

Dividing the Traffic Over Modules

- Predicates
  - Specify which traffic traverses which modules
  - Based on input port and packet-header fields



Program Composition

Goal: implement both web monitoring and repeater

```
def host_query():
  return (Select(counts) *
          Where(inport_fp(1) *
          GroupBy([srcmac]) *
          Every(60))

def secure(host_policy_stream): ...
```

```
def main():
  web_query() >> Print()
  secure(Merge(host_query(), repeater())) >> Register()
```

Key Property: queries and policies compose

Frenetic Runtime System

High-level Language

- Integrated query language
- Effective support for composition and reuse

Run-time System

- Interprets queries, policies
- Installs rules
- Tracks stats
- Handles asynchronous events