Frenetic: A High-Level Language for OpenFlow Networks

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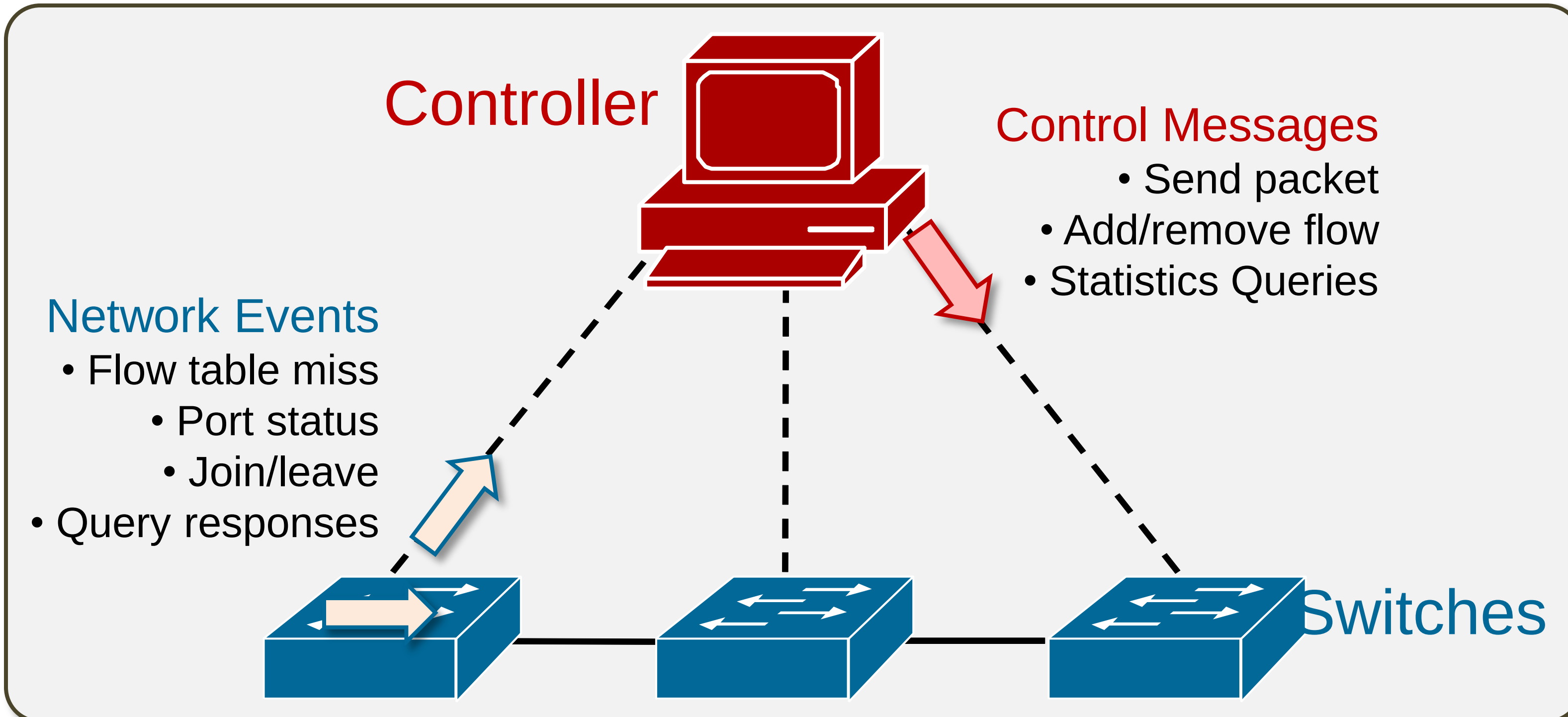
Background

- Chilling effect on innovation
  - Hardware and software are closed and proprietary
  - New requirements brought problems into sharp relief
- OpenFlow/NOX allowed us to take back the network
  - Direct access to dataplane hardware
  - Programmable control plane via open API
- OpenFlow/NOX made innovation possible, not easy
  - Low level interface mirrors hardware
  - Thin layer of abstraction
  - Few built-in features
- So let's give the network programmer some help…

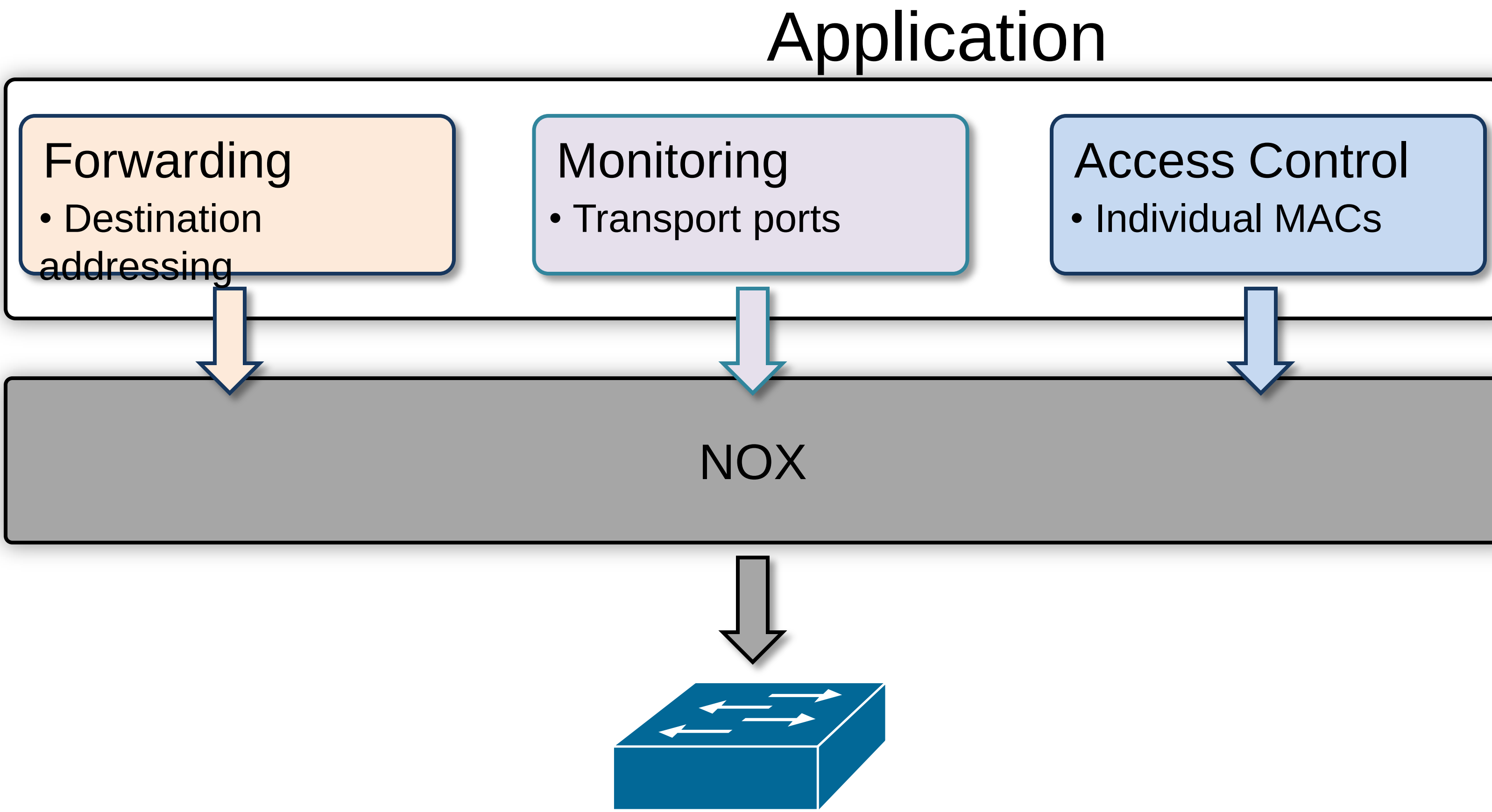
OpenFlow Architecture



OpenFlow Switch Flow Table

Priority	Pattern	Action	Counters
0-65535	Physical Port, Link Source/Destination/Type, VLAN, Network Source/Destination/Type, Transport Source/Destination	Forward Modify Drop	Bytes, Count

Programming Networks with NOX



In general, program modules do not *compose*

OpenFlow/NOX Difficulties

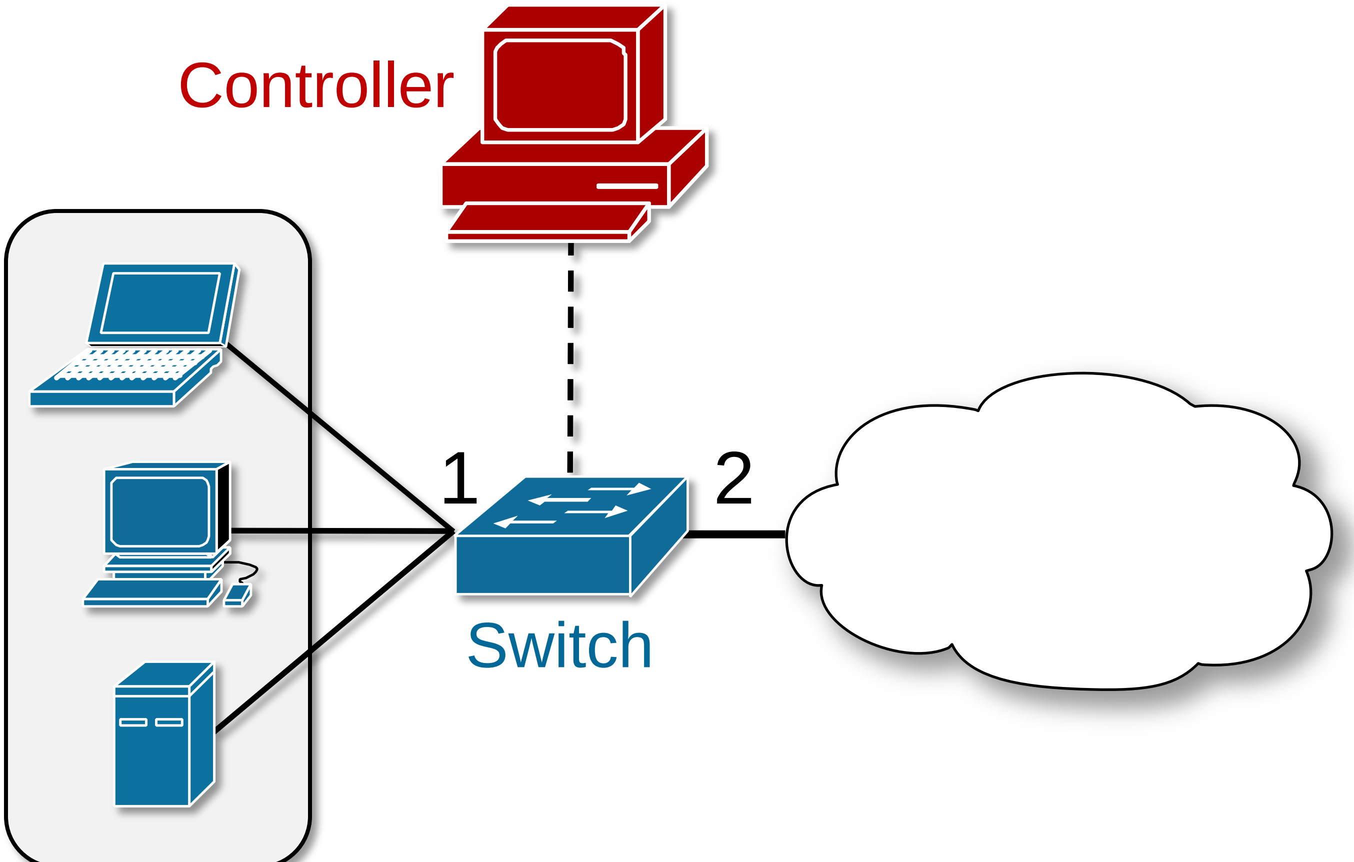
- Multiple task vs. independent modules
  - Routing, access control, traffic monitoring
  - Rules may be overlapping

- Low-level abstraction
  - No support for operations like union and intersection
  - Manual refactoring of rules to compose subprograms

- Split architecture
  - Between logic running on the switch and controller

- Asynchronous interactions
  - Between switch and controller
  - Various race conditions

Example

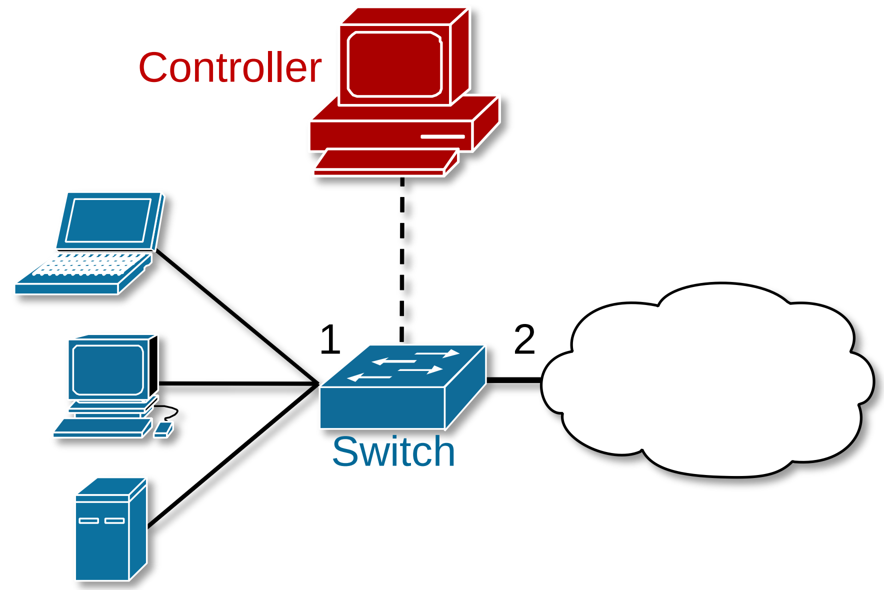


- Simple Network Repeater
  - Forward packets received on port 1 out 2; vice versa

Simple Repeater

NOX Program

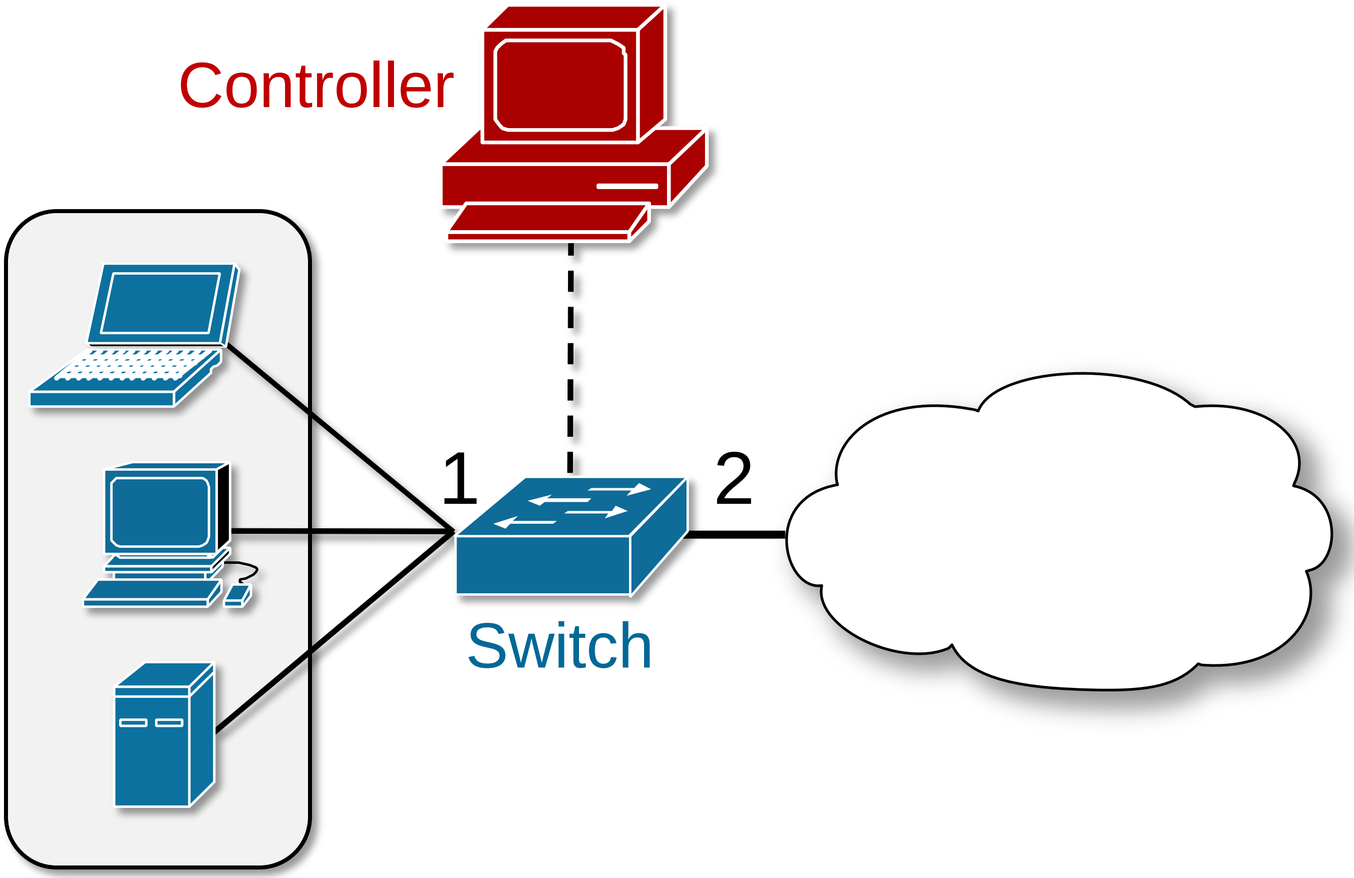
```
def simple_repeater():
  # Repeat Port 1 to Port 2
  p1 = {IN_PORT:1}
  a1 = [(OFPAT_OUTPUT, PORT_2)]
  install(switch, p1, HIGH, a1)

  # Repeat Port 2 to Port 1
  p2 = {IN_PORT:2}
  a2 = [(OFPAT_OUTPUT, PORT_1)]
  install(switch, p2, HIGH, a2)
```



Flow Table

Priority	Pattern	Action	Counters
HIGH	IN_PORT:1	OUTPUT:2	(0,0)
HIGH	IN_PORT:2	OUTPUT:1	(0,0)

Interactions between modules



- Simple Network Repeater with Host Monitoring
  - Forward packets received on port 1 out 2; vice versa
  - Monitor incoming HTTP traffic totals per host

Interactions between modules

```
# Repeat port 1 to 2
def port1_to_2():
  p1 = {IN_PORT:1}
  a1 = [(OFPAT_OUTPUT, PORT_2)]
  install(switch, p1, HIGH, a1)

# Callback to generate rules per host
def packet_in(switch, inport, pkt):
  p    = {DL_DST:dstmac(pkt)}
  pweb = {DL_DST:dstmac(pkt),
          DL_TYPE:IP,NW_PROTO:TCP,
          TP_SRC:80}
  a = [(OFPAT_OUTPUT, PORT_1)]
  install(switch, pweb, HIGH, a)
  install(switch, p, MEDIUM, a)

def main():
  register_callback(packet_in)
  port1_to_2()
```

```
def simple_repeater():
  # Port 1 to port 2
  p1 = {IN_PORT:1}
  a1 = [(OFPAT_OUTPUT, PORT_2)]
  install(switch, p1, HIGH, a1)

  # Port 2 to Port 1
  p2 = {IN_PORT:2}
  a2 = [(OFPAT_OUTPUT, PORT_1)]
  install(switch, p2, HIGH, a2)
```

Priority	Pattern	Action	Counters
HIGH	{IN_PORT:1}	OUTPUT:2	(0,0)
HIGH	{DL_DST:*mac*,DL_TYPE:IP_TYPE,NW_PROTO:TCP, TP_SRC:80}	OUTPUT:1	(0,0)
MEDIUM	{DL_DST:*mac*}	OUTPUT:1	(0,0)

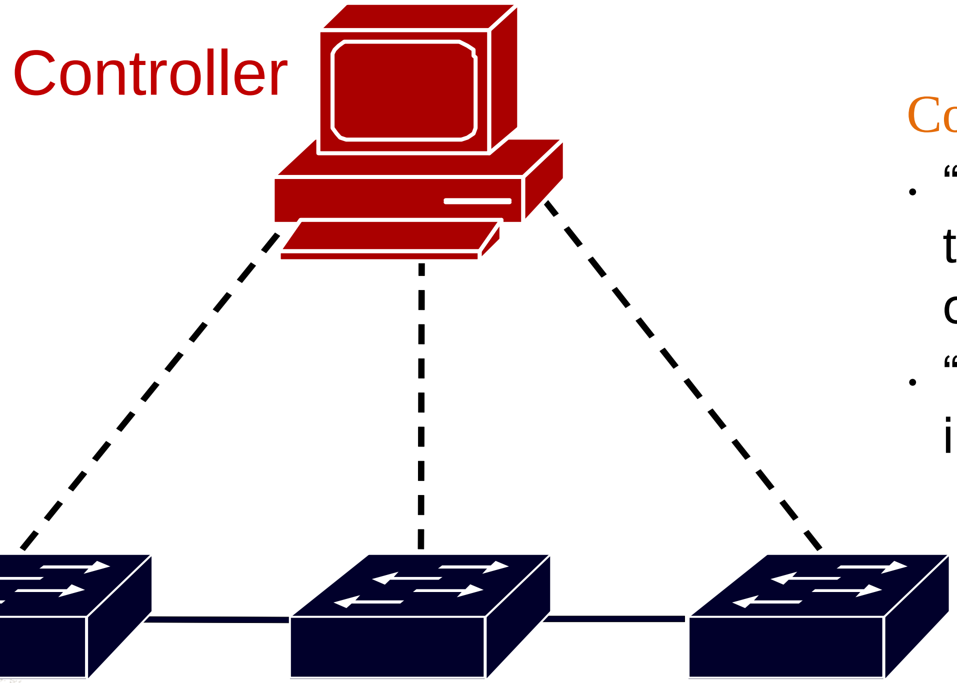
Low-level programming interface

Switch-level API:

- Derived from switch feature, rather than being designed for ease of use
- Multiple rules are manually adjusted with restrict priority

```
def repeater_monitor(switch):
  pat1 = {in_port:1}
  pat2 = {in_port:2}
  pat2web = {in_port:2,tp_src:80}
  install(switch,pat1,[output(2)],DEFAULT)
  install(switch,pat2web,[output(1)],HIGH)
  install(switch,pat2,[output(1)],DEFAULT)
  query_stats(switch,pat2web)

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)
```

Two-tiered Programming Model



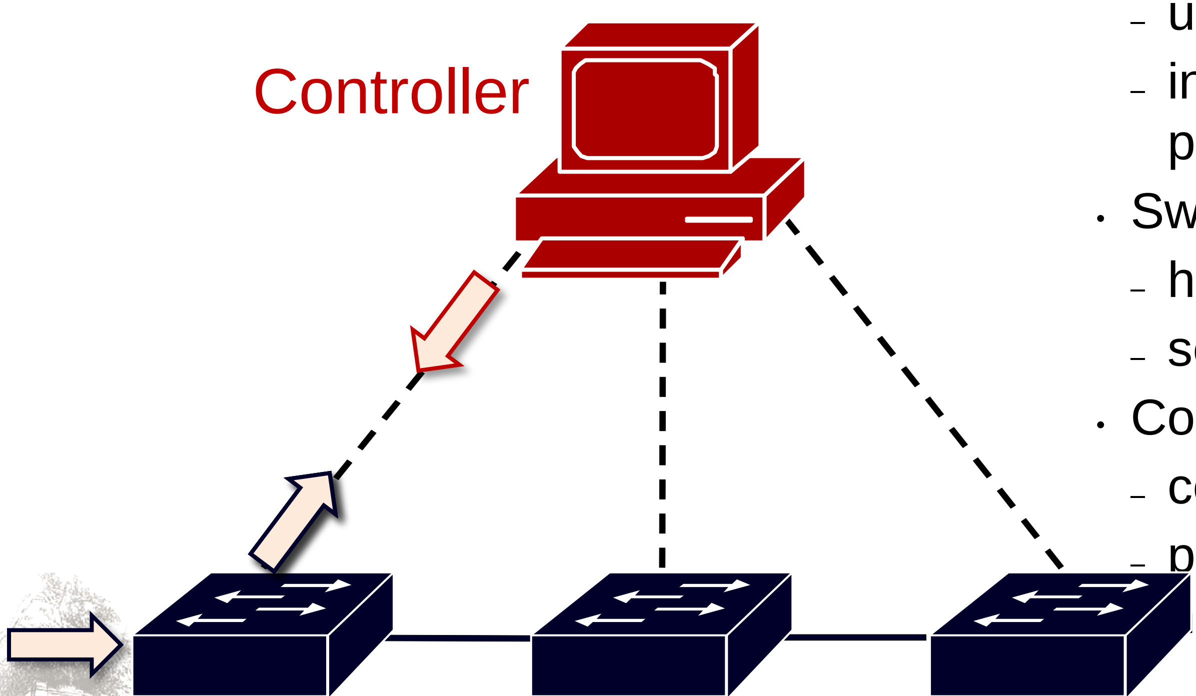
Tricky problem:

- Controller activity is driven by packets sent from switches
- Efficient applications install rules on switches to forward packets in hardware

Constant questions:

- "Is that packet going to come to the controller to trigger my computation?"
- "Or is it already being handled invisibly on the switch?"

Network Race Conditions



A challenging chain of events:

- Switch
  - sends packet to controller
- Controller
  - analyzes packet
  - updates its state
  - initiates installation of new packet-processing rules
- Switch
  - hasn’t received new rules
  - sends new packets to controller
- Controller
  - confused
  - packets in the same flow handled inconsistently

Problems – One Common Cause

- Problems:
  - Non-modular programming: Programs can't be divided into modules for monitoring and forwarding
  - Network race conditions: The controller sees more events (packets) than it anticipates
  - Two-tiered programming: Will the controller be able to see the appropriate events given the forward rules installed?

- One common cause:
  - No effective *abstractions* for *reading* network state

The Solution

- Separate network programming into two parts:
  - Abstractions for reading network state
    - Reads should have *no effect* on forwarding policy
    - Reads should be able to *see every packet*
  - Abstractions for specification of forwarding policy
    - Forwarding *policy* must be separated from *implementation mechanism*
- A natural decomposition that mirrors the two fundamental tasks of network management
  - Monitoring and forwarding

Key principles

- Declarative Design
  - Consider what the programmer might want
  - Rather than how the hardware implements it
- Modular Design
  - Limited network-wide effects primitives and semantics
  - Independently used in different contexts
- Single-tier Programming
  - Support see-every-packet abstration
  - Side-step many complexities of two-tiered model
- Race-free Semantics
  - Auto race detection
  - Packet suppression
- Cost Control
  - Gives programmers guidance concerning the costs
  - Query language is carefully defined

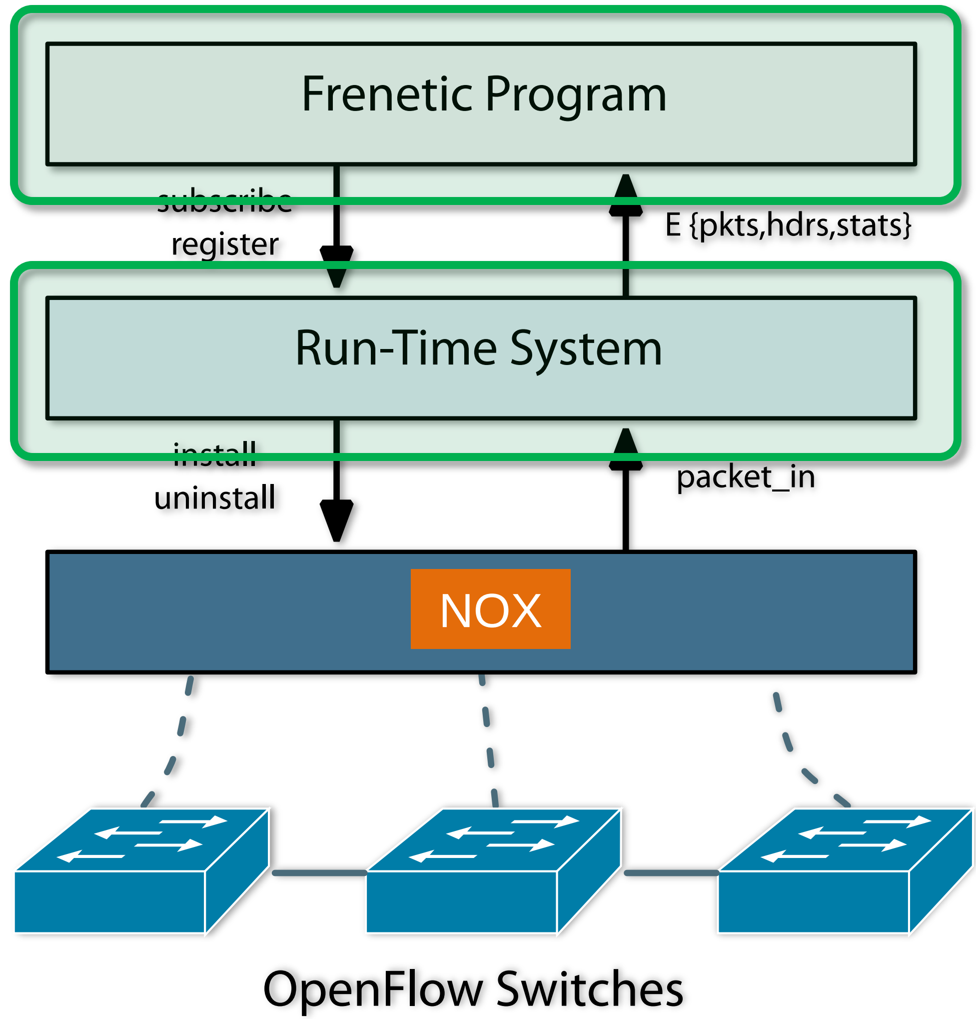
Frenetic

A High-level Language

- High-level patterns to describe flows
- Unified abstraction
- Composition

A Run-time System

- Handles module interactions
- Deals with asynchronous behavior



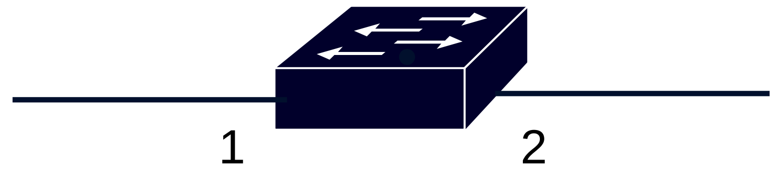
Frenetic Design

The Network Query Language

- Low-level rules on switches
- High-level abstraction for programmers
- Result is an event stream

$$
\begin{array}{lrl}
\textit{Queries} & q ::= & \texttt{Select}(a) \ \texttt{*} \\
 & & \texttt{Where}(fp) \ \texttt{*} \\
 & & \texttt{GroupBy}([qh_1, \ldots, qh_n]) \ \texttt{*} \\
 & & \texttt{SplitWhen}([qh_1, \ldots, qh_n]) \ \texttt{*} \\
 & & \texttt{Every}(n) \ \texttt{*} \\
 & & \texttt{Limit}(n) \\
\textit{Aggregates} & a ::= & \texttt{packets} \mid \texttt{sizes} \mid \texttt{counts} \\
\textit{Headers} & qh ::= & \texttt{inport} \mid \texttt{srcmac} \mid \texttt{dstmac} \mid \texttt{ethtype} \mid \\
 & & \texttt{vlan} \mid \texttt{srcip} \mid \texttt{dstip} \mid \texttt{protocol} \mid \\
 & & \texttt{srcport} \mid \texttt{dstport} \mid \texttt{switch} \\
\textit{Patterns} & fp ::= & \texttt{true\_fp}() \mid qh\texttt{\_fp}(n) \mid \\
 & & \texttt{and\_fp}([fp_1, \ldots, fp_n]) \mid \\
 & & \texttt{or\_fp}([fp_1, \ldots, fp_n]) \mid \\
 & & \texttt{diff\_fp}(fp_1, fp_2) \mid \texttt{not\_fp}(fp)
\end{array}
$$

Frenetic Queries



Goal: measure the total bytes of web traffic arriving on port 2, every 30 seconds

data to be returned from query (options: sizes, counts, packets)

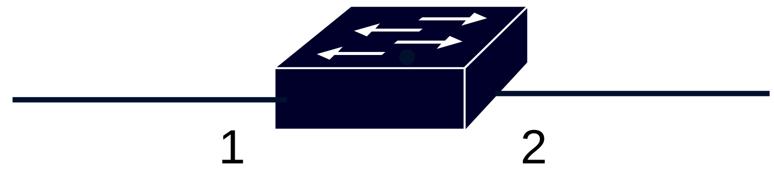
filter based on packet headers (web traffic in on port 2)

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

period: 30 seconds

Key Property: Query semantics independent of other program parts

Frenetic Queries

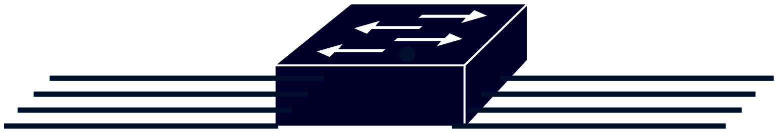


Goal: sum the number of packets, per host (ie: mac address), traveling through port 2, every minute

```
def host_query():
  return (Select  (counts)       *
          Where   (inport_fp(2)) *
          GroupBy ([srcmac])     *
          Every   (60))
```

categorize results by srcmac address

Frenetic Queries



Goal: report the hosts connected to each switch port; report a host each time it moves from one port to the next

get packets for analysis

```
def learning_query():
  return (Select    (packets)   *
          GroupBy   ([srcmac])  *
          SplitWhen ([inport])  *
          Limit     (1))
```

at most one packet per flow

categorize by srcmac

sub-categorize when the inport changes (the host moves)

Key Property: Query implementation handles network race conditions

Using Queries

- Query results, or other streams, are piped in to listeners

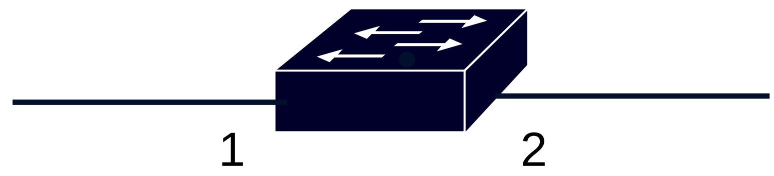
```
def web_query(): …
def host_query(): …
def learning_query(): …
```

```
def web_stats():
  web_query() >> Print()
```

```
def all_stats():
  Merge(web_query(), host_query()) >> Print()
```

Key Property: Queries compose

Frenetic Forwarding Policies



Goal: implement a repeater switch

rule actions

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

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

listen for switch joining the network

packet pattern (defined over headers)

```
def main():
  repeater() >> register()
```

construct repeater policy for that switch

register policy with run time

Key Property: Policy semantics independent of other queries/policies

Program Composition

Goal: implement both the stats monitor and the repeater

```
def main():
  repeater() >> register()
  all_stats()
```

Key Property: Queries and policies compose

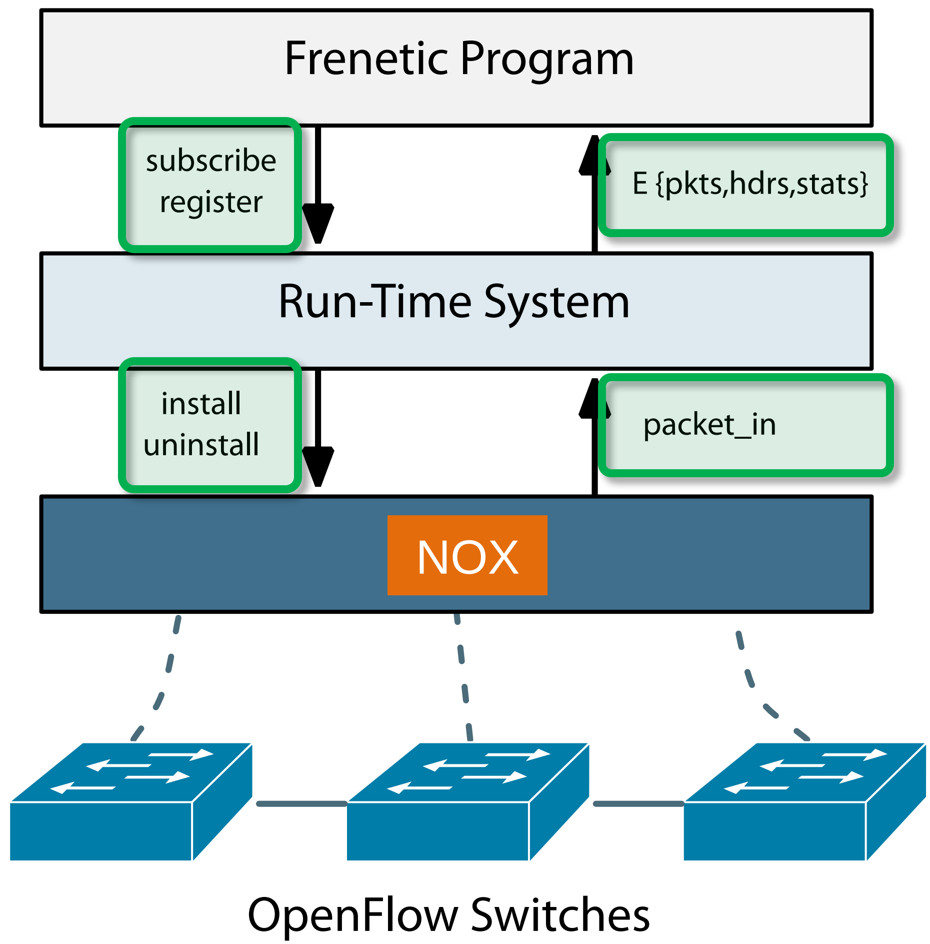
Frenetic Run-time System

Frenetic programs interact only with the run-time

- Programs create *subscribers*
- Programs *register* rules

Run-time handles the details

- Manages switch-level rules
- Handles NOX events
- Pushes values onto the appropriate event streams



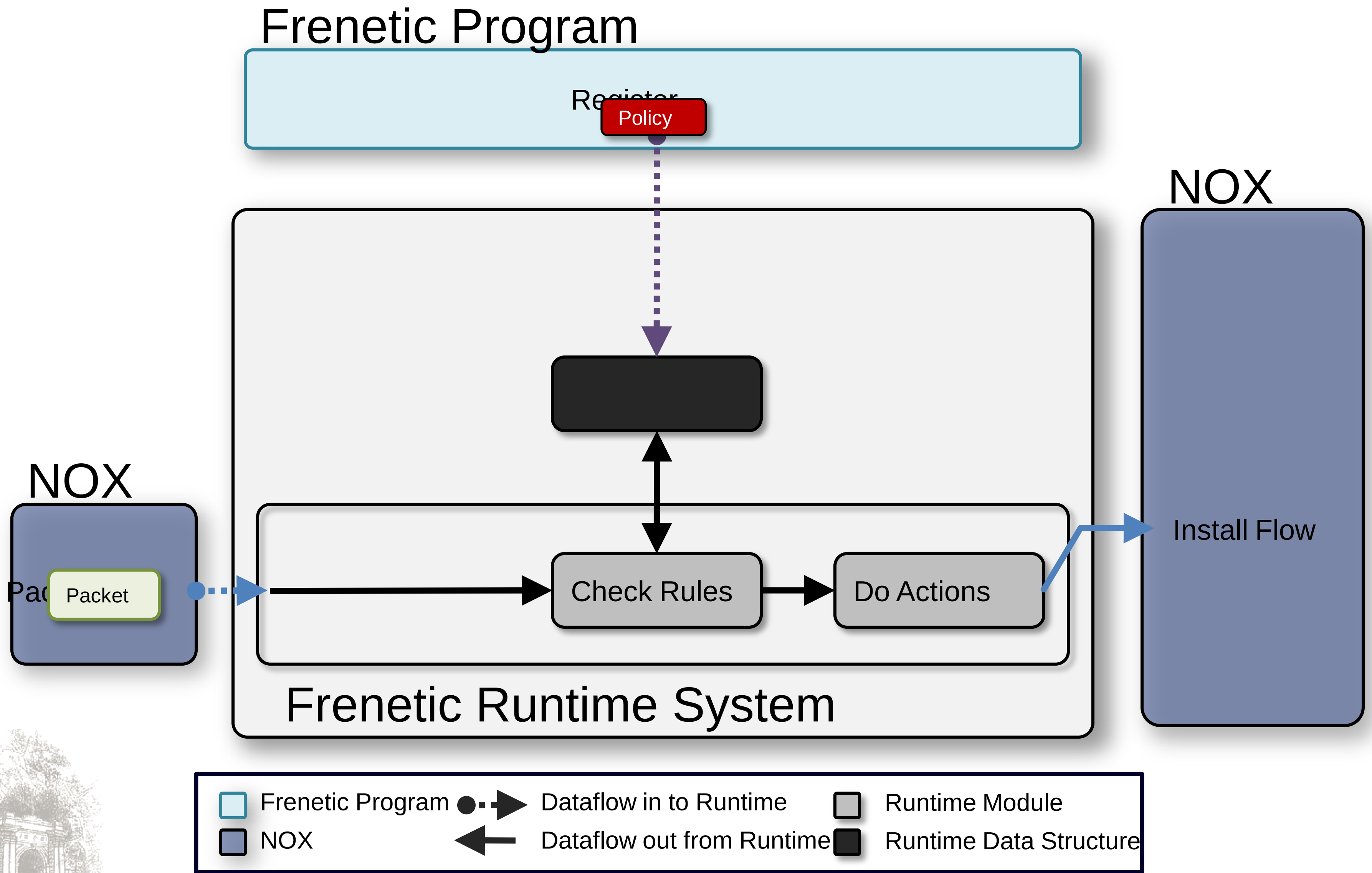
Implementation Options

- Rule Granularity
  - microflow (exact header match)
    - simpler; more rules generated
  - wildcard (multiple header match in single rule)
    - more complex; fewer rules (may be) generated
- Rule Installation
  - reactive (lazy)
    - first packet of each new flow goes to controller
  - proactive (eager)
    - new rules pushed to switches

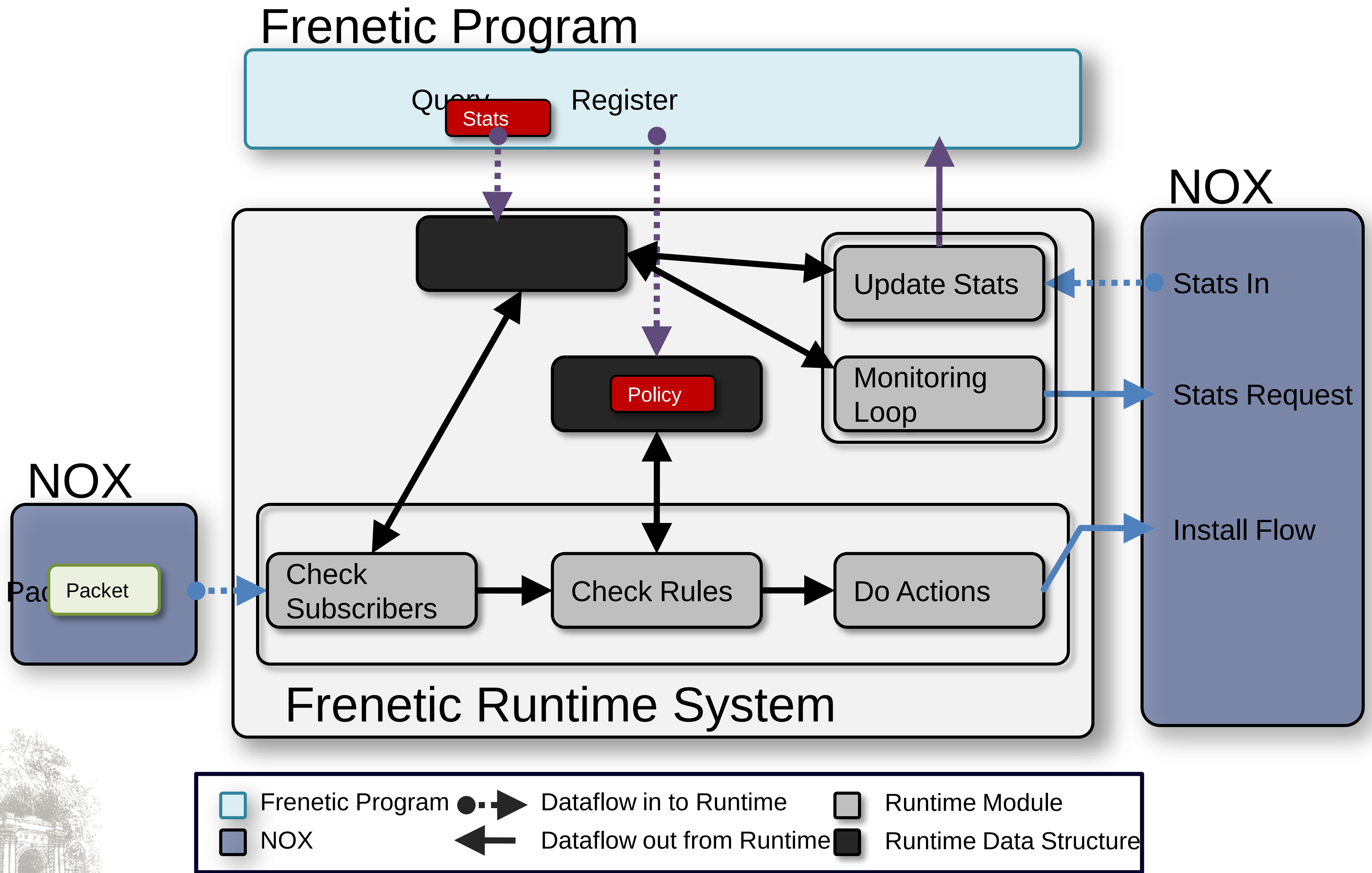
Frenetic 1.0

Frenetic 2.0

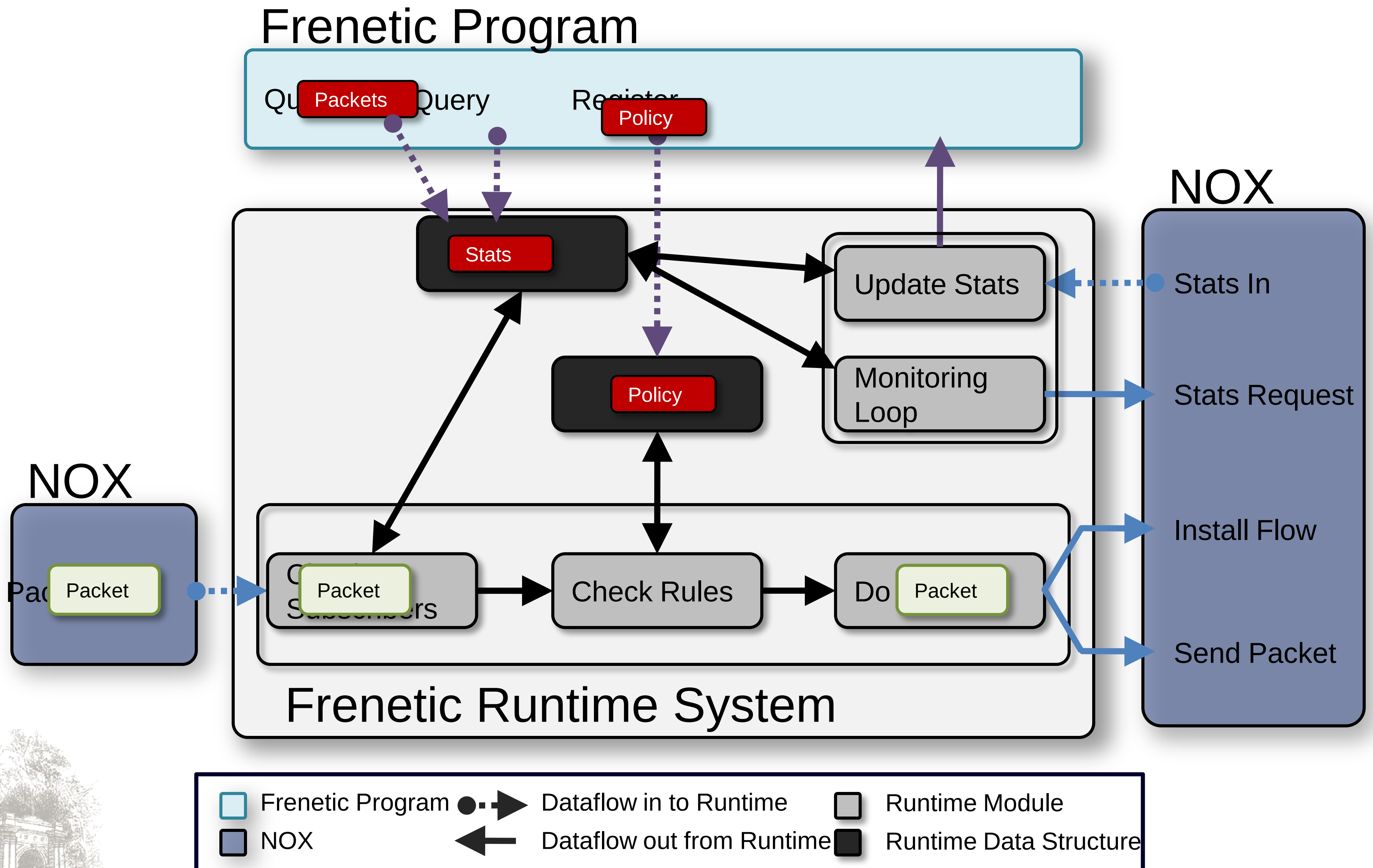
Run-time Activities



Run-time Activities



Run-time Activities



Evaluation

Metrics:

- Lines of code
- Traffic to controller
- Total trafic

Microbenchmarks:

- All-Pairs Connectivity
- Web Statistics
- Heavy Hitters

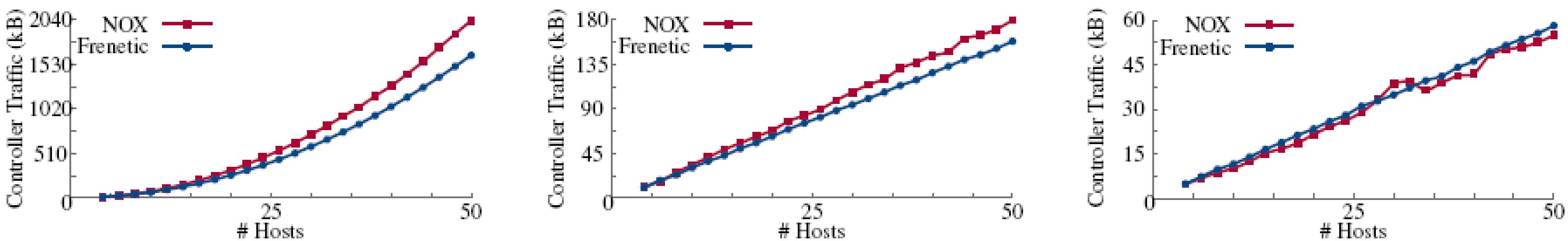
Forwarding Policy:

- Hub
- Learning Switch
- Loop-Free Learning Switch

Evaluation

		Connectivity			Heavy Hitters			Web Stats		
		HUB	*LSW*	*LFLSW*	*HUB*	*LSW*	*LFLSW*	*HUB*	*LSW*	*LFLSW*
NOX	Lines of Code	20	55	75	110	198		104	135	
	Controller Traffic (kB)	12.8	13.5	31.3	9.3	10.3	⋆	4.5	4811	⋆
	Aggregate Traffic (kB)	69.2	42.3	64.1	57.2	36.1		14.1	9.0	
Frenetic	Lines of Code	6	30	58	29	53	81	13	37	65
	Controller Traffic (kB)	9.1	12.0	12.4	11.1	10.6	10.9	4.5	5.1	5.8
	Aggregate Traffic (kB)	65.6	41.0	41.5	55.0	36.4	36.9	13.6	9.20	9.9

Table 1. Experimental results.



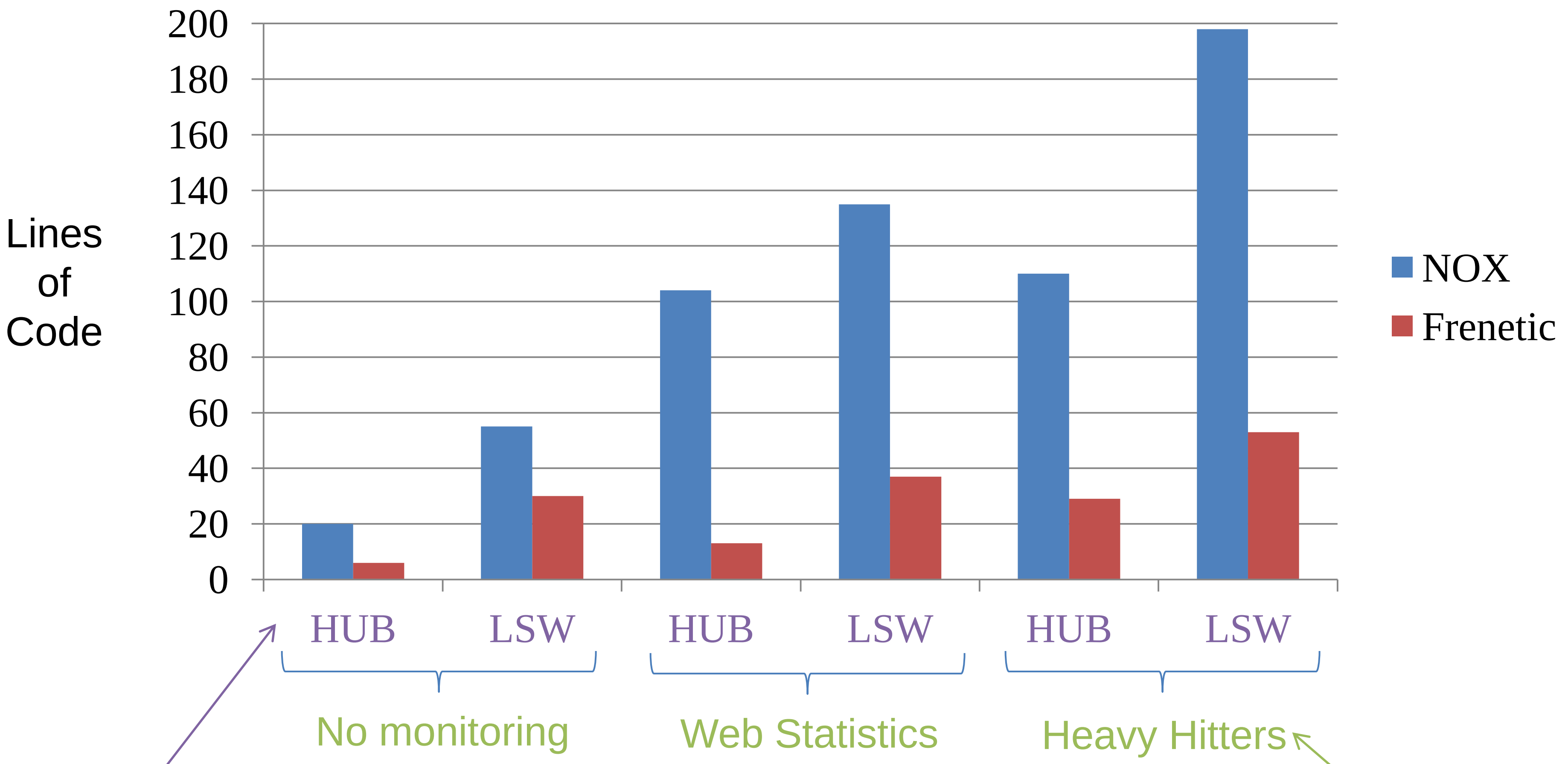
(a) All-Pairs Connectivity

(c) Heavy Hitters

(b) Web Statistics

Figure 9. Scalability experimental results.

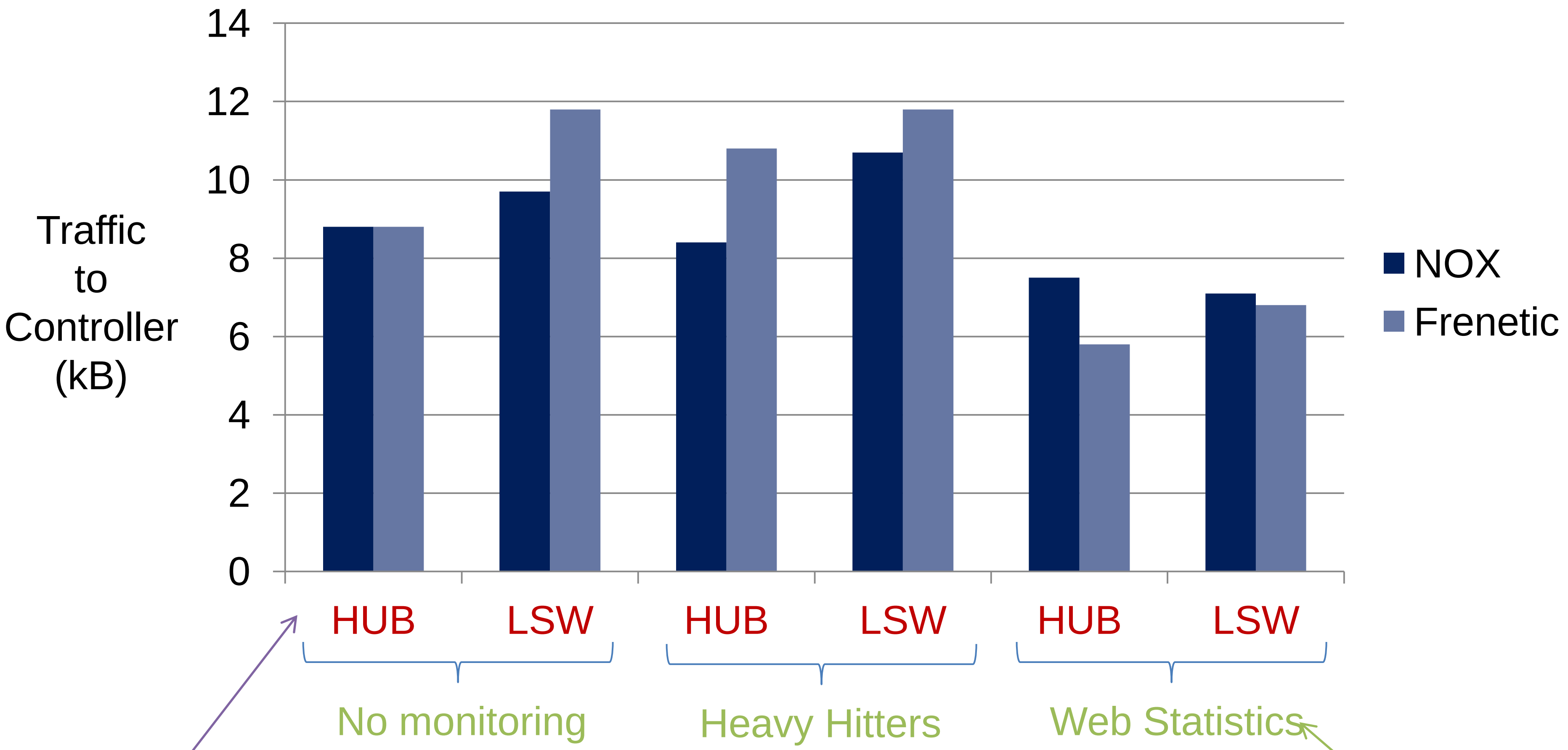
MicroBench: Lines of Code



Forwarding Policy:
HUB: Floods out other ports
LSW: Learning Switch

Monitoring Policy

MicroBench: Controller Traffic

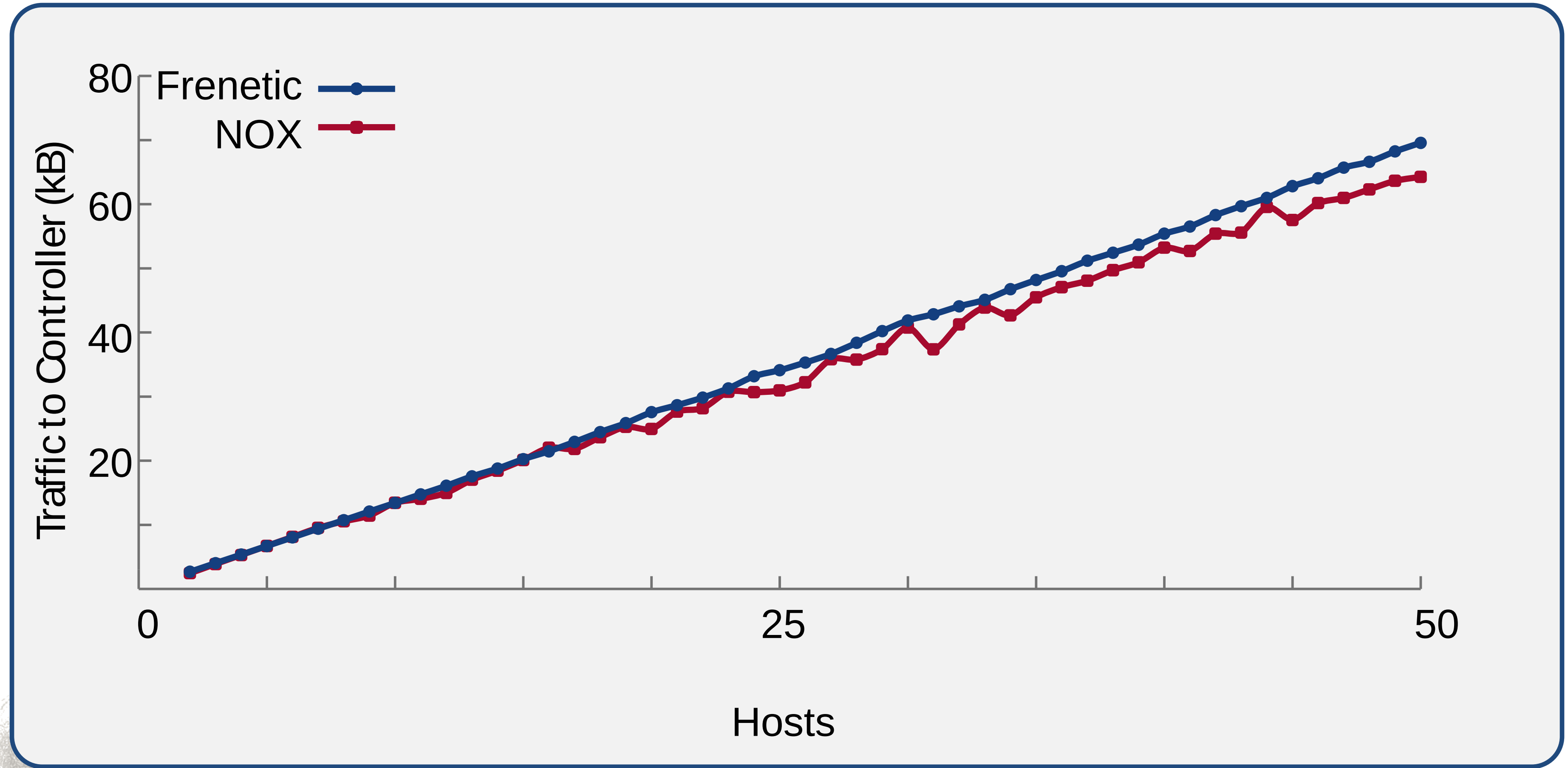


Forwarding Policy:
HUB: Floods out other ports
LSW: Learning Switch

Monitoring Policy

Frenetic Scalability

Frenetic scales to larger networks comparably with NOX



Ongoing and Future Work

- Surface Language
  - Current prototype is in Python – to ease transition
  - Would like a standalone language
- Optimizations
  - More programs can also be implemented efficiently
  - Would like a compiler to identify and rewrite optimizations
- Proactive Strategy
  - Current prototype is reactive, based on microflow rules
  - Would like to enable proactive, wildcard rule installation
- Network Wide Abstractions
  - Current prototype focuses only on a single switch
  - Need to expand to multiple switches

Acknowledgements

- Almost the whole content comes from authors' slides presented at PRESTO 2010, Microsoft Research 2011 and also their paper at ICFP 2011
- This slides is only for seminar use in NSLab
- For more information, please refer to the following links:
  - http://www.cs.princeton.edu/~jrex/papers/icfp11.pdf
  - http://www.cs.princeton.edu/~jrex/talks/presto11.pptx
  - http://www.cs.princeton.edu/~dpw/talks/frenetic-05-11.pptx

Discussion