# NetKAT—A Formal System for the Verification of Networks

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OASIS seminar
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# NetKAT papers

Carolyn Jane Anderson, Nate Foster, Arjun Guha, Jean-Baptiste Jeannin, Dexter Kozen, Cole Schlesinger, and David Walker, NetKAT: Semantic Foundations for Networks. POPL 14.

Nate Foster, Dexter Kozen, Matthew Milano, Alexandra Silva, and Laure Thompson, A Coalgebraic Decision Procedure for NetKAT. POPL 15.

# Networking

"The last bastion of mainframe computing" [Hamilton 2009]

- Modern computers
  - implemented with commodity hardware
  - programmed using general-purpose languages, standard interfaces
- Networks
  - built and programmed the same way since the 1970s
  - low-level, special-purpose devices implemented on custom hardware
  - routers and switches that do little besides maintaining routing tables and forwarding packets
  - configured locally using proprietary interfaces
  - network configuration ("tuning") largely a black art

# Networking

- Difficult to implement end-to-end routing policies and optimizations that require a global perspective
- Difficult to extend with new functionality
- Effectively impossible to reason precisely about behavior

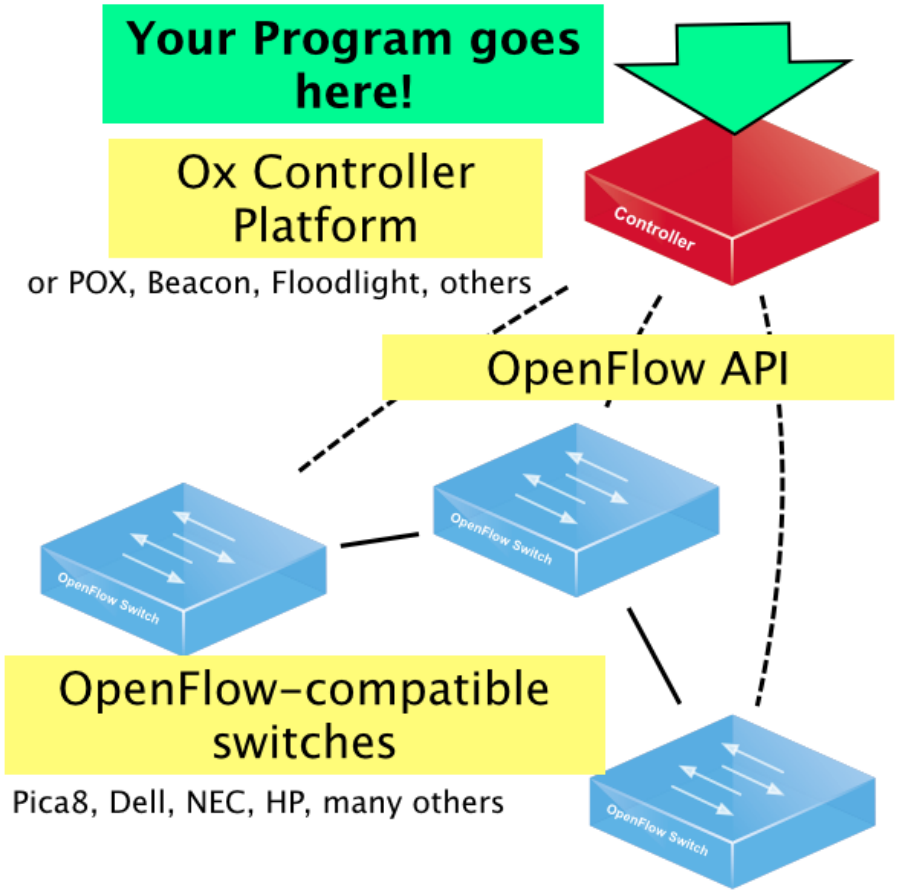
# Software Defined Networks (SDN)

## Main idea behind SDN

A general-purpose controller manages a collection of programmable switches

- controller can monitor and respond to network events
  - new connections from hosts
  - topology changes
  - shifts in traffic load
- controller can reprogram the switches on the fly
  - adjust routing tables
  - change packet filtering policies

# SDN Network Architecture



# Software Defined Networks (SDN)

Controller has a global view of the network

Enables a wide variety of applications:

- standard applications
  - shortest-path routing
  - traffic monitoring
  - access control
- more sophisticated applications
  - load balancing
  - intrusion detection
  - fault tolerance

# Software Defined Networks (SDN)

> *"In the SDN architecture, the control and data planes are decoupled, network intelligence and state are logically centralized, and the underlying network infrastructure is abstracted from the applications. As a result, enterprises and carriers gain unprecedented programmability, automation, and network control, enabling them to build highly scalable, flexible networks that readily adapt to changing business needs."*

—Open Networking Foundation, *Software-Defined Networking: The New Norm for Networks*, 2012

# OpenFlow

A first step: the OpenFlow API [McKeown & al., SIGCOMM 08]

- specifies capabilities and behavior of switch hardware
- a language for manipulating network configurations
- very low-level: easy for hardware to implement, difficult for humans to write and reason about

But...

- is platform independent
- provides an open standard that any vendor can implement

# A Major Trend in Industry

Deutsche Telekom

facebook

Goldman Sachs

verizon

Google

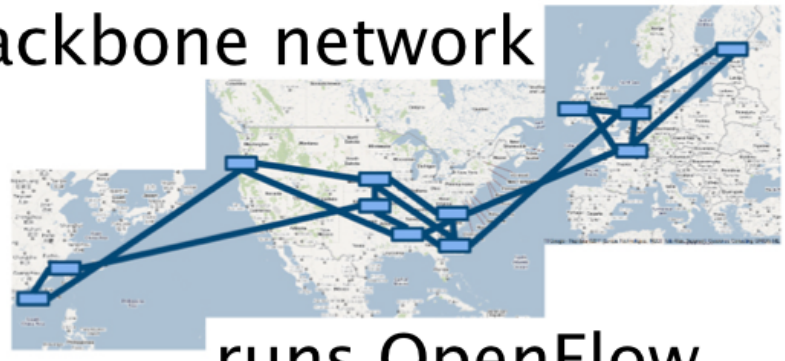
Microsoft

NTT Communications

YAHOO!

Google

Backbone network



runs OpenFlow

nicira

Bought by VMware for $1.2B

# Network Programming Languages & Analysis Tools

## Goals:

- raise the level of abstraction above hardware-based APIs (OpenFlow)
- make it easier to build sophisticated and reliable SDN applications and reason about them

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- Formally Verifiable Networking [Wang & al., HotNets 09]
- FlowChecker [Al-Shaer & Saeed Al-Haj, SafeConfig 10]
- Anteater [Mai & al., SIGCOMM 11]
- Nettle [Voellmy & Hudak, PADL 11]
- Header Space Analysis [Kazemian & al., NSDI 12]
- Frenetic [Foster & al., ICFP 11] [Reitblatt & al., SIGCOMM 12]
- NetCore [Guha & al., PLDI 13] [Monsanto & al., POPL 12]
- Pyretic [Monsanto & al., NSDI 13]
- VeriFlow [Khurshid & al., NSDI 13]
- Participatory networking [Ferguson & al., SIGCOMM 13]
- Maple [Voellmy & al., SIGCOMM 13]

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# NetKAT

Simple programming language/logic, expressive enough for basic properties.

## Reachability

- Can host $A$ communicate with host $B$? Can every host communicate with every other host?

## Security

- Does all untrusted traffic pass through the intrusion detection system located at $C$?
- Are non-SSH packets forwarded? Are SSH packets dropped?

## Loop detection

- Is it possible for a packet to be forwarded around a cycle in the network?

## Policy equivalence

- Given the network topology, are policies $p$ and $q$ equivalent?

# NetKAT [Anderson & al. 14]

NetKAT

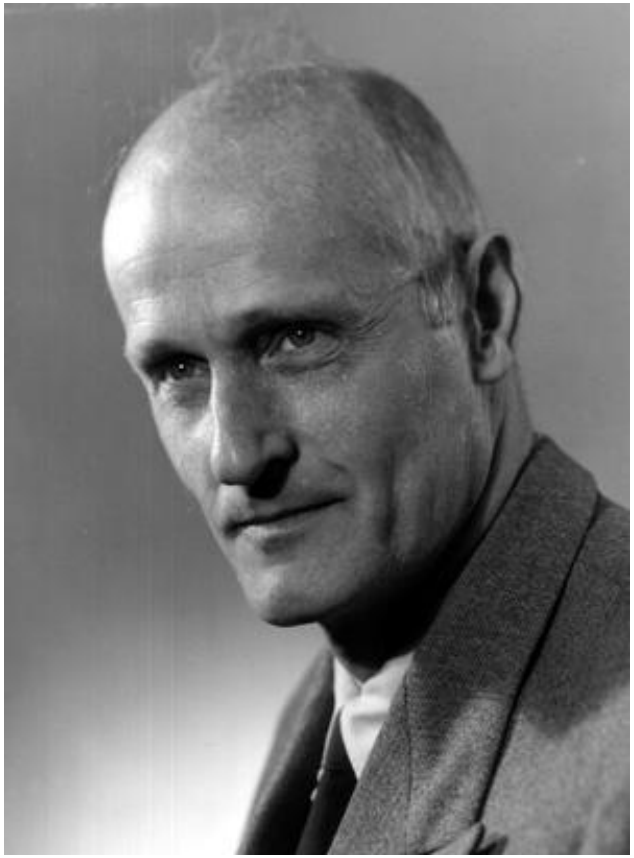
=

Kleene algebra with tests (KAT)

+

additional specialized constructs particular to network topology and packet switching

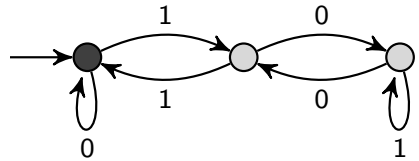
# Kleene Algebra (KA)



Stephen Cole Kleene
(1909–1994)

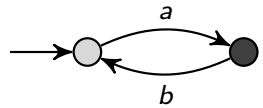
$(0 + 1(01^*0)^*1)^*$

{multiples of 3 in binary}




$(ab)^*a = a(ba)^*$

$\{a, aba, ababa, \ldots\}$




$(a + b)^* = a^*(ba^*)^*$

{all strings over $\{a, b\}$}

# Foundations of the Algebraic Theory

John Horton Conway
(1937–)

J. H. Conway. *Regular Algebra and Finite Machines*. Chapman and Hall, London, 1971.

# Axioms of KA

## Idempotent Semiring Axioms

$$p + (q + r) = (p + q) + r \qquad p(qr) = (pq)r$$
$$p + q = q + p \qquad 1p = p1 = p$$
$$p + 0 = p \qquad p0 = 0p = 0$$
$$p + p = p$$
$$p(q + r) = pq + pr \qquad a \leq b \overset{\triangle}{\iff} a + b = b$$
$$(p + q)r = pr + qr$$

## Axioms for $^*$

$$1 + pp^* \leq p^* \qquad q + px \leq x \;\Rightarrow\; p^*q \leq x$$
$$1 + p^*p \leq p^* \qquad q + xp \leq x \;\Rightarrow\; qp^* \leq x$$

# Standard Model

## Regular sets of strings over $\Sigma$

$$
\begin{aligned}
A + B &= A \cup B \\
AB &= \{xy \mid x \in A,\ y \in B\} \\
A^* &= \bigcup_{n \geq 0} A^n = A^0 \cup A^1 \cup A^2 \cup \cdots \\
1 &= \{\varepsilon\} \\
0 &= \varnothing
\end{aligned}
$$

This is the free KA on generators $\Sigma$

# Deciding KA

- PSPACE-complete [(1 + Stock)Meyer 74]
  - automata-based decision procedure
  - nondeterministically guess a string in $L(M_1) \oplus L(M_2)$, simulate the two automata
  - convert to deterministic using Savitch's theorem
  - inefficient—$\Omega(n^2)$ space, exponential time best-case
- coalgebraic decision procedures [Silva 10, Bonchi & Pous 12]
  - bisimulation-based
  - uses Brzozowski/Antimirov derivatives
  - Hopcroft–Karp union-find data structure, up-to techniques
  - implementation in OCaml
  - linear space, practical

# Kleene Algebra with Tests (KAT)

$(K, B, +, \cdot, ^*, ^-, 0, 1), \quad B \subseteq K$

- $(K, +, \cdot, ^*, 0, 1)$ is a Kleene algebra
- $(B, +, \cdot, ^-, 0, 1)$ is a Boolean algebra
- $(B, +, \cdot, 0, 1)$ is a subalgebra of $(K, +, \cdot, 0, 1)$

- $p, q, r, \ldots$ range over $K$
- $a, b, c, \ldots$ range over $B$

# Modeling While Programs

$$
\begin{aligned}
p; q &\triangleq pq \\
\textbf{if } b \textbf{ then } p \textbf{ else } q &\triangleq bp + \overline{b}q \\
\textbf{while } b \textbf{ do } p &\triangleq (bp)^* \overline{b}
\end{aligned}
$$

# KAT Results

## Deductive Completeness and Complexity

- deductively complete over language, relational, and trace models
- subsumes propositional Hoare logic (PHL)
- decidable in PSPACE

## Applications

- protocol verification
- static analysis and abstract interpretation
- verification of compiler optimizations

# NetKAT

# NetKAT

- a packet $\pi$ is an assignment of constant values $n$ to fields $x$
- a packet history is a nonempty sequence of packets
  $\pi_1 :: \pi_2 :: \cdots :: \pi_k$
- the head packet is $\pi_1$

## NetKAT

- assignments $x \leftarrow n$
  assign constant value $n$ to field $x$ in the head packet
- tests $x = n$
  if value of field $x$ in the head packet is $n$, then pass, else drop
- dup
  duplicate the head packet

# NetKAT

## Example

$$sw = 6 \,;\, pt = 88 \,;\, dest \leftarrow 10.0.0.1 \,;\, pt \leftarrow 50$$

"For all packets incoming on port 88 of switch 6, set the destination IP address to 10.0.0.1 and send the packet out on port 50."

# NetKAT Axioms

$$x \leftarrow n \,;\, y \leftarrow m \;\equiv\; y \leftarrow m \,;\, x \leftarrow n \quad (x \neq y)$$

assignments to distinct fields may be done in either order

---

$$x \leftarrow n \,;\, y = m \;\equiv\; y = m \,;\, x \leftarrow n \quad (x \neq y)$$

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an assignment to a field does not affect a different field

---

$$x = n \,;\, \mathsf{dup} \;\equiv\; \mathsf{dup} \,;\, x = n$$

field values are preserved in a duplicated packet

---

$$x \leftarrow n \;\equiv\; x \leftarrow n \,;\, x = n$$

an assignment causes the field to have that value

---

$$x = n \,;\, x \leftarrow n \;\equiv\; x = n$$

an assignment of a value that the field already has is redundant

---

$$x \leftarrow n \,;\, x \leftarrow m \;\equiv\; x \leftarrow m$$

a second assignment to the same field overrides the first

---

$$x = n \,;\, x = m \;\equiv\; 0 \quad (n \neq m) \qquad\qquad \left(\sum_n x = n\right) \;\equiv\; 1$$

every field has exactly one value

# Standard Model

Standard model of NetKAT is a packet-forwarding model

$$[\![e]\!] : H \to 2^H$$

where $H = \{\text{packet histories}\}$

$$\begin{aligned}
[\![x \leftarrow n]\!](\pi_1 :: \sigma) &\triangleq \{\pi_1[n/x] :: \sigma\} \\
[\![x = n]\!](\pi_1 :: \sigma) &\triangleq \begin{cases} \{\pi_1 :: \sigma\} & \text{if } \pi_1(x) = n \\ \varnothing & \text{if } \pi_1(x) \neq n \end{cases} \\
[\![\mathsf{dup}]\!](\pi_1 :: \sigma) &\triangleq \{\pi_1 :: \pi_1 :: \sigma\}
\end{aligned}$$

# Standard Model

$$
\begin{aligned}
[\![p + q]\!](\sigma) &\triangleq [\![p]\!](\sigma) \cup [\![q]\!](\sigma) \\
[\![p\,;q]\!](\sigma) &\triangleq \bigcup_{\tau \in [\![p]\!](\sigma)} [\![q]\!](\tau) \\
[\![p^*]\!](\sigma) &\triangleq \bigcup_{n} [\![p^n]\!](\sigma) \\
[\![1]\!](\sigma) &\triangleq [\![\mathsf{pass}]\!](\sigma) = \{\sigma\} \\
[\![0]\!](\sigma) &\triangleq [\![\mathsf{drop}]\!](\sigma) = \varnothing
\end{aligned}
$$

# Example

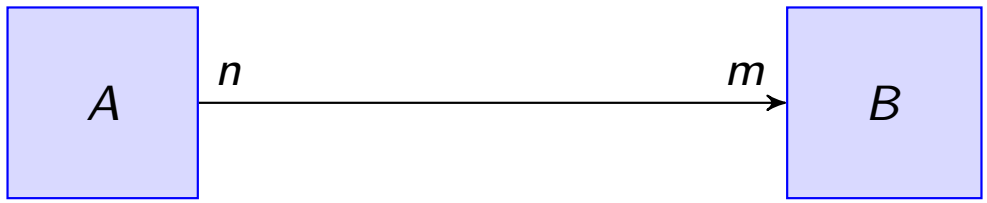
## Reachability

- Can host $A$ communicate with host $B$? Can every host communicate with every other host?

# Encoding Network Topology

## Modeling Links

$$sw = A \,;\, pt = n \,;\, sw \leftarrow B \,;\, pt \leftarrow m$$



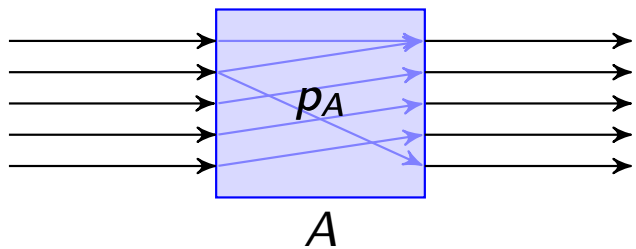

- filters out all packets not located at the source end of the link
- updates switch and port fields to the location of the target end
- this captures the effect of sending the packet across the link
- network topology is expressed as a sum of link expressions

# Switch Policies

Switch behavior for switch $A$ is specified by a NetKAT term

$$sw = A \,;\, p_A$$

where $p_A$ specifies what to do with packets entering switch $A$




Example

$$pt = n \,;\, dest = a \,;\, dest \leftarrow b \,;\, (pt \leftarrow m + pt \leftarrow k)$$

Incoming packets on port $n$ with destination $a \Rightarrow$ modify destination to $b$ and send out on ports $m$ and $k$

Switch policy $p_A$ is the sum of all such behaviors for $A$

# Putting It Together

Let

- $t$ = sum of all link expressions
- $p$ = sum of all switch policies

Then

- $pt$ = one step of the network
- each switch processes its packets, then sends them along links to the next switch
- $(pt)^*$ = the multistep behavior of the network in which the single-step behavior is iterated

# Reachability

To check if any packet can travel from $A$ to $B$ given the topology and the switch policies, ask whether

$$sw = A \,;\, t(pt)^* \,;\, sw = B \quad \not\equiv \quad 0 \ (drop).$$

- prefix $sw = A$ filters out packets not at $A$
- suffix $sw = B$ filters out packets not at $B$

# Other Applications

- forwarding loops
- traffic isolation
- access control
- correctness of a compiler that maps a NetKAT expression to a set of individual flow tables that can be deployed on the switches

# Results

## Soundness and Completeness [Anderson et al. 14]

- $\vdash p = q$ if and only if $[\![p]\!] = [\![q]\!]$

## Decision Procedure [Foster et al. 15]

- NetKAT coalgebra
- Efficient bisimulation-based decision procedure
- Implementation in OCaml
- Deployed in the Frenetic suite of network management tools

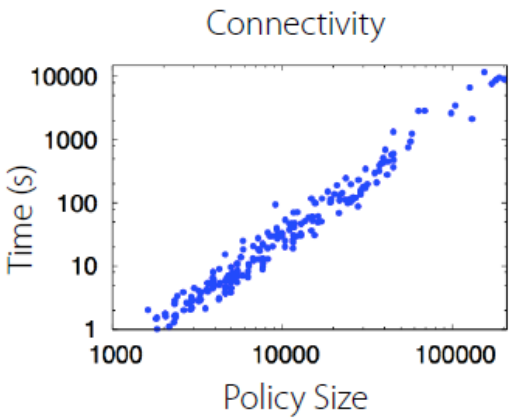
# A Bisimulation-Based Algorithm

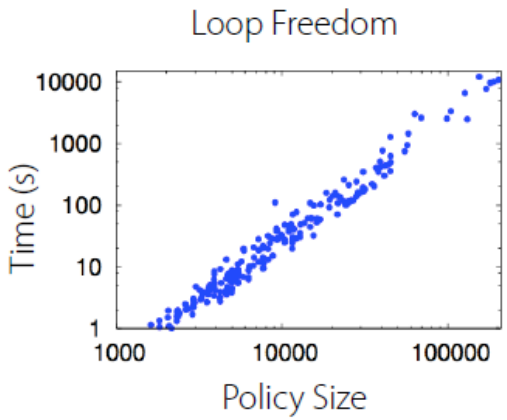
To check $e_1 = e_2$, convert to automata, check bisimilarity

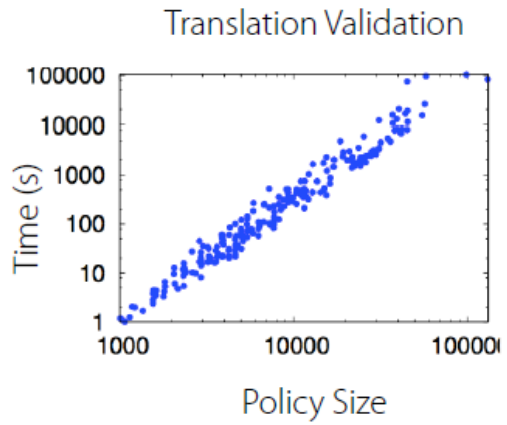
- exploits a sparse matrix representation
- Hopcroft-Karp union-find data structure to represent bisimilarity classes
- BDDs to represent tests (new — based on Pous, POPL 15)
- algorithm is competitive with state of the art

# A Bisimulation-Based Algorithm [Foster & al. 15]

- Topology Zoo
  - 261 real-world network topologies;
  - Use shortest path forwarding as network program;
  - Results:



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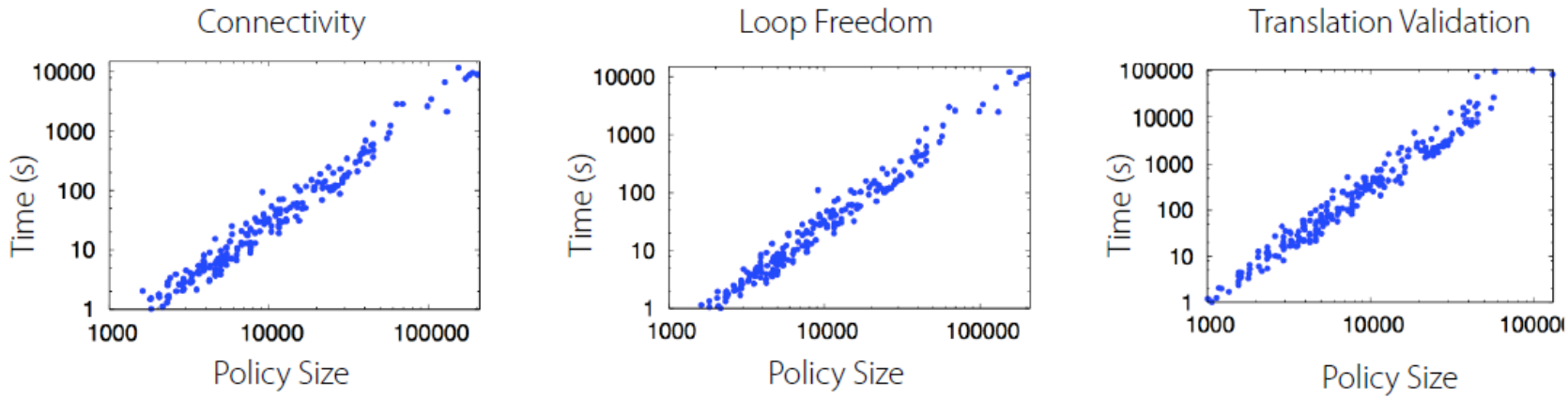


- Stanford Campus Network
  - Use actual router configurations
  - Results: Point to point reachability in 0.67s (vs 13s for HSA)

# Probabilistic NetKAT

- How much congestion is there?
- Is the network resilient under failure?
- Reducing costs without compromising reliability

# Probabilistic NetKAT

- How much congestion is there?
- Is the network resilient under failure?
- Reducing costs without compromising reliability

- Modular extension of NetKAT with probabilistic constructs
- Compositional semantics
- Compiler, Decision procedures, ...

Compositional quantitative reasoning $\rightsquigarrow$ fully realize the vision of SDN

# Conclusion

- Programming languages have a key role to play in emerging platforms for managing software-defined networks
- NetKAT is a high-level language for programming and reasoning about network behavior in the SDN paradigm
  - based on sound mathematical principles
  - formal denotational semantics, complete deductive system
  - efficient bisimulation-based decision procedure
- Future work:
  - further optimizations to reduce state space
  - probabilistic semantics
  - generating proof artifacts
  - refinement calculus
  - concurrent/distributed NetKAT

For papers and code, please visit:
http://frenetic-lang.org/

Thanks!