A Fast Compiler For NetKAT

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Outline

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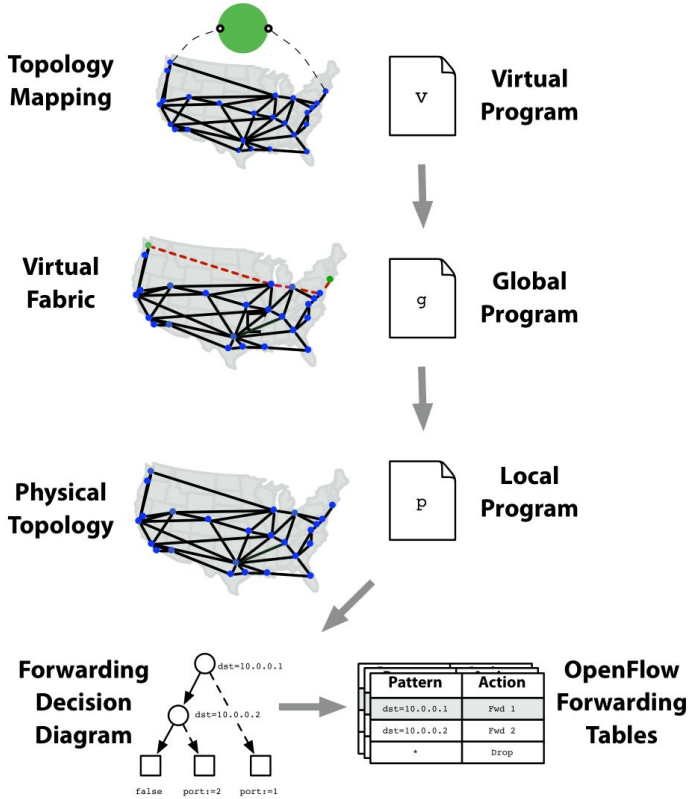
Network Programming

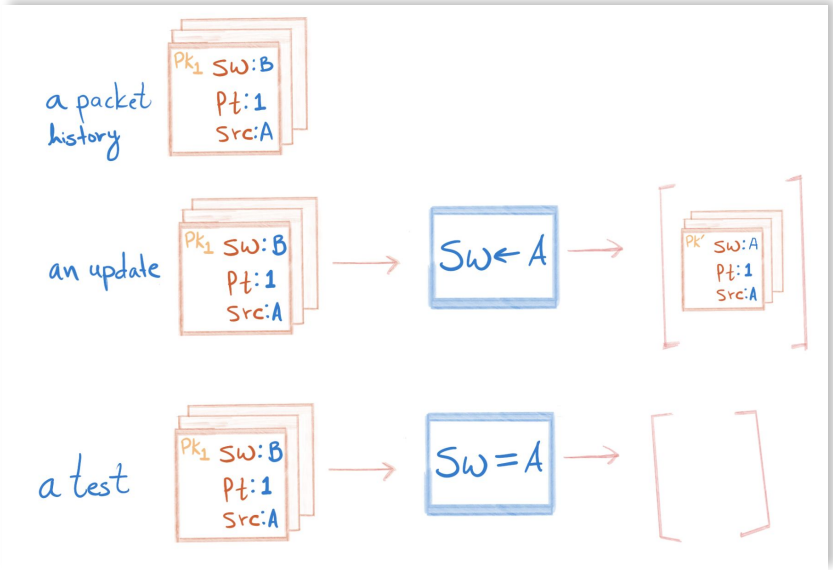
- Reprogrammable network switches enable software defined networking (SDN)
- High-level languages are used to express network design and properties
- The compiler translates the high-level language constructs to hardware-level table-based forwarding rules

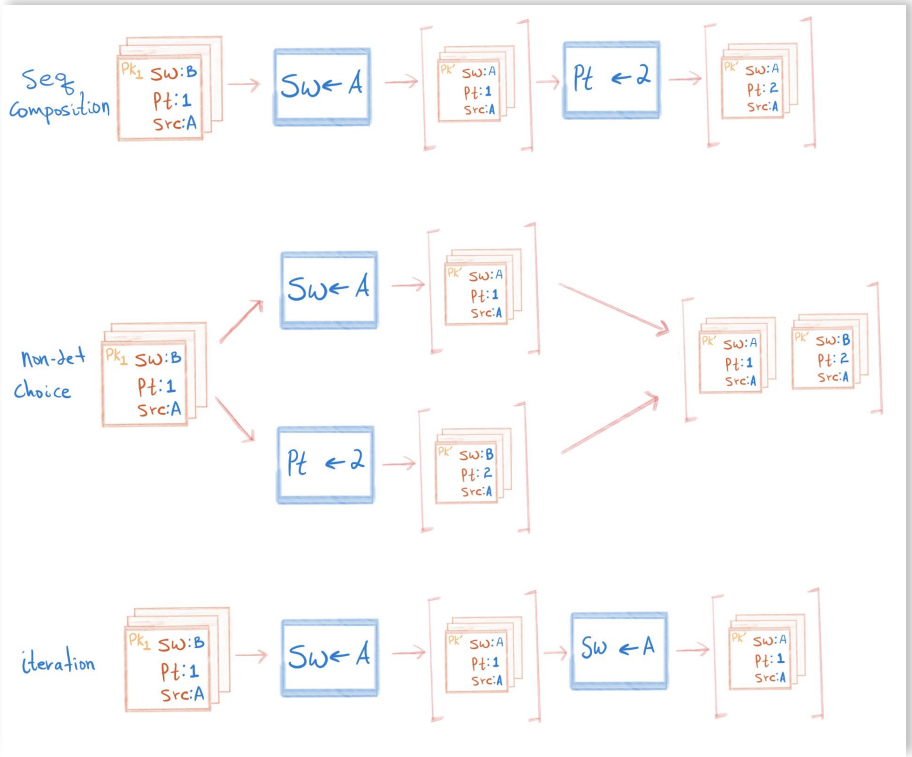
NetKAT: Yet Another Programming Language

- A Verification First language where formal verification is built into the language from the beginning
- Provides formal semantics for network programming based on Kleene Algebra with Tests (KAT)
- Verification is performed via a semi-automatic equational reasoning in the algebraic framework
- Can express both local (switch level) and global (across switches/topological) behaviors



NetKAT Semantics





Compiling NetKAT

- Global programs are hard to compile since they break switch boundaries
- The compiler must insert and maintain some state for global programs
- Local programs could be converted to forwarding tables easily but this approach is inefficient

Pattern	Action
⋆	pt←2

$pol_A \triangleq \mathsf{pt}{\leftarrow}2$

(a) An atomic modification

Pattern	Action
dst=A	*true*
⋆	*false*

$pol_B \triangleq \mathsf{dst}{=}\mathsf{A}$

(b) An atomic predicate

Pattern	Action
dst=A	pt←2
⋆	*false*

$pol_B \cdot pol_A$

(c) Forwarding to a single host

Pattern	Action
dst=A	pt←1
dst=B	pt←2
⋆	*false*

$pol_D \triangleq \mathsf{dst}{=}\mathsf{A} \cdot \mathsf{pt}{\leftarrow}1 + \mathsf{dst}{=}\mathsf{B} \cdot \mathsf{pt}{\leftarrow}2$

(d) Forwarding traffic to two hosts

Pattern	Action
dst=A	pt←3
proto=ssh	pt←3
⋆	*false*

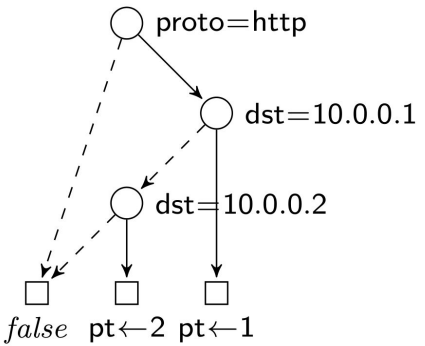
$pol_E \triangleq \begin{pmatrix} \mathsf{proto}{=}\mathsf{ssh} + \\ \mathsf{dst}{=}\mathsf{A} \end{pmatrix} \cdot \mathsf{pt}{\leftarrow}3$

(e) Monitoring SSH traffic and traffic to host A

The Local Compiler

- Forwarding Decision Diagrams (FDDs) are binary trees where the nodes are tests and the leaves are assignments
- Translate NetKAT programs to FDDs. This is sound (Theorem 1)
- The FDDs are in ordered and reduced form
- The order of the fields is reflected in the order of the rules in the table

proto = http * (dst = 10.0.0.1 * pt ← 1 + dst = 10.0.0.2 * pt ← 2)



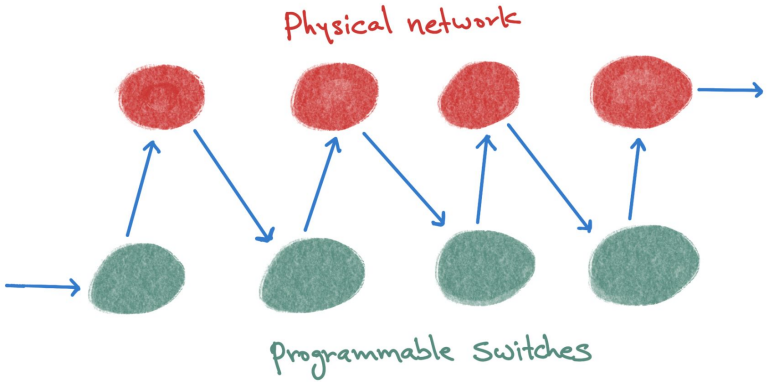
Pattern	Action
proto=http, dst=10.0.0.1	pt←1
proto=http, dst=10.0.0.2	pt←2
proto=http	*false*
⋆	*false*

The Global Compiler

- The NetKAT automaton is defined on guarded strings of form

$$pk_{in} * pk_1 * dup * pk_2 \ldots * pk_{out}$$

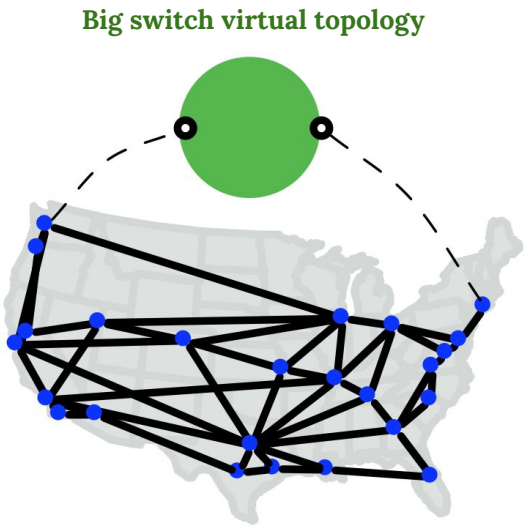
- A new PC field tracks the state of the automaton
- All NetKAT programs can be converted to a NetKAT automata. This is sound (Theorem 2)
- Textbook determinization and optimization techniques can be applied
- Take union of the FDDs of the local programs (green blobs in the NA) and treat it as a local program!



Extract the local programs from the global program and let the physical network provide the links between the switches

Virtualization

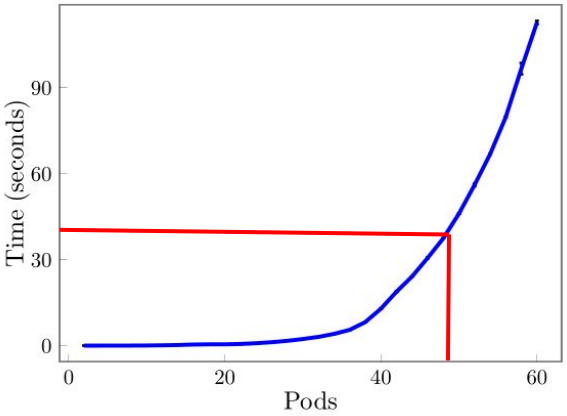
- Virtualization is an abstraction that allows programmers to write more concise programs
- Virtual programs are defined against a virtual topology decoupling the program from the physical topology
- Can target various physical topologies
- Can provide a simple form of traffic isolation at the program level
- The compiler now needs to lower the virtual program to a specific physical topology



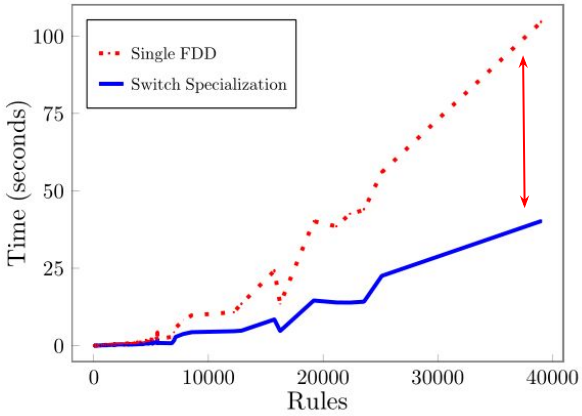
Virtualization

- The compiler gets
  - a relation R that maps Virtual Ports to Physical ports
  - a virtual topology
  - sets of in and out ports
- Packets are tracked across the virtual topology and the physical topology
- The fabric is a NetKAT program that updates the location of the packets in the physical topology when its location changes in the virtual topology (and vice versa)
- Challenge: keeping the two locations consistent!
- Solution: a game between V (the program) and F (the fabric). F attempts to keep up with V; if it can't, the physical topology can't implement the program
- There could be multiple fabrics, each optimizing for different variables (e.g. # of hops, # of links)

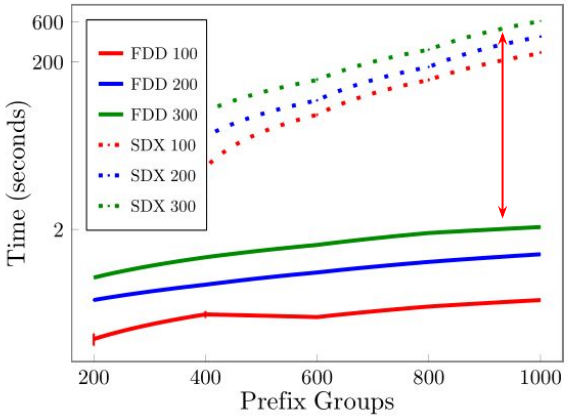
Experiments: Compilation Time for Local Compiler



(a) Routing on k-pod fat-trees.



(b) Destination-based routing on topology zoo.



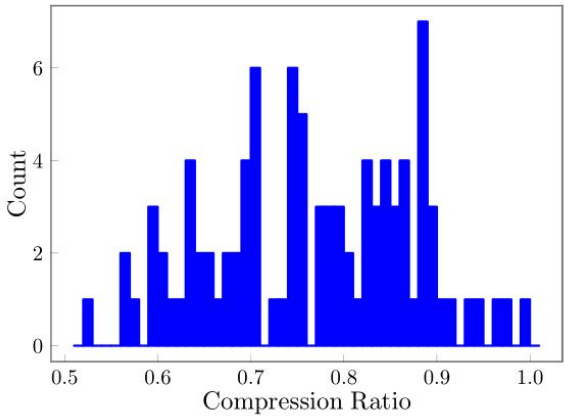
(c) Time needed to compile SDX benchmarks.

a) compilation time for a data-center size network is okay

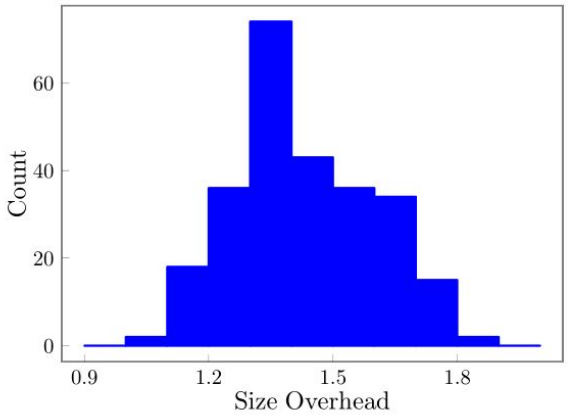
b) generating multiple small FDDs first helps

c) FDD ~10x better for the largest group (1k) and participants (300)

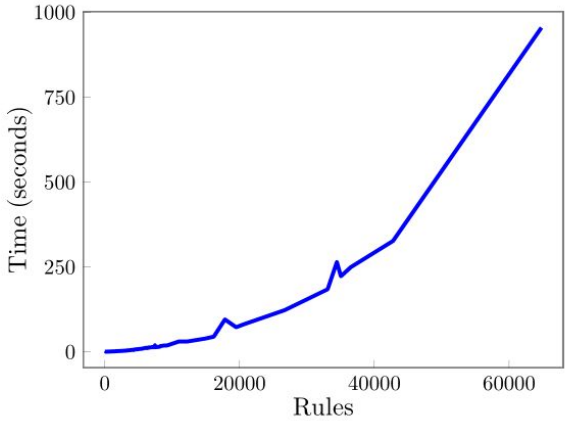
Experiments: Table Size and Time for Global Programs



(a) Compressing Classbench ACLs.



(b) Table size overhead for global programs.



(c) Compilation time for global programs.

a) 30% fewer rules on average (with simple optimizations)

b) Within 2x range of local tables (without minimizing the NetKAT automata)

c) Much slower than local compiler

Conclusion and Comments

- A compiler for the full NetKAT language with acceptable compilation time and table size overhead
- The concepts used (BDDs and finite automata) are well known and offer many optimizations/improvements directions for the compiler
- The formalism and syntax is awkward for FDDs since they need to inductively respect the ordering. Compare this to vanilla BDDs.
- Getting the ordering right is important for BDDs!
- GKAT (POPL'20) brings decision complexity to near-linear (compared to NetKAT's PSPACE) for a fragment of KAT. The automaton optimizations used here might not be needed if NetKAT moves to GKAT instead of full KAT.

Thank You!

Questions?

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