

Event-Driven Network Programming



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Abstract

Software-defined networking (SDN) programs must simultaneously describe static forwarding behavior and dynamic updates in response to events. Event-driven updates are critical to get right, but difficult to implement correctly due to the high degree of concurrency in networks. Existing SDN platforms offer weak guarantees that can break application invariants, leading to problems such as dropped packets, degraded performance, security violations, etc. This paper introduces *event-driven consistent updates* that are guaranteed to preserve well-defined behaviors when transitioning between configurations in response to events. We propose *network event structures* (NESs) to model constraints on updates, such as which events can be enabled simultaneously and causal dependencies between events. We define an extension of the NetKAT language with mutable state, give semantics to stateful programs using NESs, and discuss provably-correct strategies for implementing NESs in SDNs. Finally, we evaluate our approach empirically, demonstrating that it gives well-defined consistency guarantees while avoiding expensive synchronization and packet buffering.

Categories and Subject Descriptors C.2.3 [Computer-communication Networks]: Network Operations—Network Management; D.3.2 [Programming Languages]: Language Classifications—Specialized application languages; D.3.4 [Programming Languages]: Processors—Compilers

Keywords network update, consistent update, event structure, software-defined networking, SDN, NetKAT

1. Introduction

Software-defined networking (SDN) allows network behavior to be specified using logically-centralized programs that

execute on general-purpose machines. These programs react to events such as topology changes, traffic statistics, receipt of packets, etc. by modifying sets of forwarding rules installed on switches. SDN programs can implement a wide range of advanced network functionality including fine-grained access control [8], network virtualization [22], traffic engineering [15, 16], and many others.

Although the basic SDN model is simple, building sophisticated applications is challenging in practice. Programmers must keep track of numerous low-level details such as encoding configurations into prioritized forwarding rules, processing concurrent events, managing asynchronous events, dealing with unexpected failures, etc. To address these challenges, a number of domain-specific network programming languages have been proposed [2, 10, 19, 21, 29, 31, 36, 37]. The details of these languages vary, but they all offer higher-level abstractions for specifying behavior (e.g., using mathematical functions, boolean predicates, relational operators, etc.), and rely on a compiler and run-time system to generate and manage the underlying network state.

Unfortunately, the languages that have been proposed so far lack critical features that are needed to implement dynamic, event-driven applications. Static languages such as NetKAT [2] offer rich constructs for describing network configurations, but lack features for responding to events and maintaining internal state. Instead, programmers must write a stateful program in a general-purpose language that generates a stream of NetKAT programs. Dynamic languages such as FlowLog and Kinetic [21, 31] offer stateful programming models, but they do not specify how the network behaves while it is being reconfigured in response to state changes. Abstractions such as consistent updates provide strong guarantees during periods of reconfiguration [26, 33], but current realizations are limited to properties involving a single packet (or set of related packets, such as a unidirectional flow). To implement *correct* dynamic SDN applications today, the most effective option is often to use low-level APIs, forgoing the benefits of higher-level languages entirely.

Example: Stateful Firewall. To illustrate the challenges that arise when implementing dynamic applications, consider a topology where an internal host H_1 is connected to switch s_1 , an external host H_4 is connected to a switch s_4 , and switches s_1 and s_4 are connected to each other (see Fig-

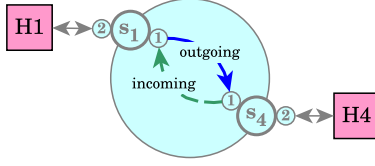


Figure 1: Topology for simple Stateful Firewall.

ure 1). Suppose we wish to implement a stateful firewall: at all times, host H_1 is allowed to send packets to host H_4 , but H_4 should only be allowed to send packets to H_1 if H_1 previously initiated a connection. Implementing even this simple application turns out to be difficult, because it involves coordinating behavior across multiple devices and packets. The basic idea is that upon receiving a packet from H_1 at s_4 , the program will need to issue a command to install a forwarding rule on s_4 allowing traffic to flow from H_4 back to H_1 . There are two straightforward (but incorrect) implementation strategies on current SDN controllers.

1. The outgoing request from H_1 is diverted to the controller, which sets up flow tables for the incoming path and also forwards the packet(s) to H_4 . Reconfiguring flow tables takes time, so H_4 's response will likely be processed by the default drop rule. Even worse, if the response is the SYN-ACK in a TCP handshake, normal retransmission mechanisms will not help—the client will have to wait for a timeout and initiate another TCP connection. In practice, this greatly increases the latency of setting up a connection, and potentially wreaks havoc on application performance.
2. The outgoing request is buffered at the controller, which sets up the flow tables for the incoming path but waits until the rules are installed before forwarding the packet(s). This avoids the problem in (1), but places extra load on the controller and also implements the firewall incorrectly, since incoming traffic is allowed before the outgoing request is delivered. Leaving the network unprotected (even briefly) can be exploited by a malicious attacker.

Thus, while it is tempting to think that reliability mechanisms built into protocols such as TCP already prevent (or at least reduce) these types of errors, this is not the case. While it is true that some applications can tolerate long latencies, dropped packets, and weak consistency, problems with updates *do* lead to serious problems in practice. As another example, consider an intrusion detection system that monitors suspicious traffic—inadvertently dropping or allowing even a few packets due to a reconfiguration would weaken the protection it provides. The root of these problems is that *existing SDN frameworks do not provide strong guarantees during periods of transition between configurations in response to events*. An eventual guarantee is not strong enough to implement the stateful firewall correctly, and even a consistent update [33] would not suffice, since consistent updates only dictate what must happen to individual packets.

Existing Approaches. Experienced network operators may be able to use existing tools/methods to correctly implement event-driven configuration changes. However, as seen above, this requires thinking carefully about the potential interleavings of events and updates, delegating atomic operations to the controller (incurring a performance hit), etc.

As mentioned, there are stateful programming systems that attempt to make this process easier for the programmer, but update strategies in these systems either offer no consistency guarantees during dynamic updates, rely on expensive processing via the controller, and/or require the programmer to craft an update protocol by hand. In this paper, we group these approaches together, using the term *uncoordinated update* to describe their lack of support for coordinating local updates in a way that ensures global consistency.

Event-Driven Consistent Update. We propose a new semantic correctness condition with clear guarantees about updates triggered by events. This enables specification of how the network should behave during updates, and enables precise formal reasoning about stateful network programs.

An *event-driven consistent update* is denoted as a triple $C_i \xrightarrow{e} C_f$, where C_i and C_f are the initial and final configurations respectively, and e is an event. Intuitively, these configurations describe the forwarding behaviors of the network before/after the update, while the event describes a phenomenon, such as the receipt of a packet at a particular switch, that triggers the update itself. Semantically, an event-triggered consistent update ensures that for each packet:

1. *the packet is forwarded consistently*, i.e. it must be processed entirely by a *single configuration* C_i or C_f , and
2. *the update does not happen too early*, meaning that if every switch traversed by the packet has *not* heard about the event, then the packet must be processed by C_i , and
3. *the update does not happen too late*, meaning that if every switch traversed by the packet *has* heard about the event, then the packet must be processed by C_f .

The first criterion requires that updates are consistent, which is analogous to a condition proposed previously by Reitblatt et al. [33]. However, a consistent update alone would not provide the necessary guarantees for the stateful firewall example, as it applies only to a single packet, and not to multiple packets in a bidirectional flow. The last two criteria relate the packet-processing behavior on each switch to the events it has “heard about.” Note that these criteria leave substantial flexibility for implementations: packets that do not satisfy the second or third condition can be processed by either the preceding or following configuration. It remains to define what it means for a switch s to have “heard about” an event e that occurred at switch t (assuming $s \neq t$). We use a causal model and say that s hears about e when a packet, which was processed by t after e occurred, is received at s . This can be formalized using a “happens-before” relation.

Returning to the stateful firewall, it is not hard to see that the guarantees offered by event-driven consistent updates are

sufficient to ensure correctness of the overall application. Consider an update $C_i \xrightarrow{e} C_f$. In C_i , H_1 can send packets to H_4 , but not vice-versa. In C_f , additionally H_4 can send packets to H_1 . The event e is the arrival at s_4 of a packet from H_1 to H_4 . Before e occurs, can H_4 send a packet to H_1 , as is possible in C_f ? No, since *none* of the switches along the necessary path have heard about the event. Now, imagine that the event e occurs, and H_4 wants to send a packet to H_1 afterwards. Can s_4 drop the new packet, as it would have done in the initial configuration C_i ? No, because the *only* switch the packet would traverse is s_4 , and s_4 has heard about the event, meaning that the only possible correct implementation should process this new packet in C_f .

Event-Driven Transition Systems. To specify event-driven network programs, we use labeled transition systems called *event-driven transition systems* (ETSs). In an ETS, each node is annotated with a network configuration and each edge is annotated with an event. For example, the stateful firewall application would be described as a two-state ETS, one state representing the initial configuration before H_1 has sent a packet to H_4 , and another representing the configuration after this communication has occurred. There would be a transition between the states corresponding to receipt of a packet from H_1 to H_4 at s_4 . This model is similar to the finite state machines used in Kinetic [21] and FAST [30]. However, whereas Kinetic uses uncoordinated updates, we impose additional constraints on our ETSs which allow them to be implemented *correctly* with respect to our consistency property. For example, we extend event-triggered consistent updates to *sequences*, requiring each sequence of transitions in the ETS to satisfy the property. For simplicity, in this paper, we focus on finite state systems and events corresponding to *packet delivery*. However, these are not fundamental assumptions—our design extends naturally to other notions of events, as well as infinite-state systems.

Network Event Structures. The key challenge in implementing event-driven network programs stems from the fact that at any time, the switches may have different views of the global set of events that have occurred. Hence, for a given ETS, several different updates may be enabled at a particular moment of time, and we need a way to resolve conflicts. We turn to the well-studied model of event structures [38], which allows us to constrain transitions in two ways: (1) *causal dependency*, which requires that an event e_1 happens before another event e_2 may occur, and (2) *compatibility*, which forbids sets of events that are in some sense incompatible with each other from occurring in the same execution. We present an extension called *network event structure* (NES), and show how an ETS can be encoded as an NES.

Locality. While event-driven consistent updates require immediate responses to *local* events (as in the firewall), they do not require immediate reactions to events “at a distance.” This is achieved by two aspects of our definitions.

The first defining aspect of our locality requirements involves the happens-before (“heard-about”) relation in event-driven consistent update. For example, the receipt of a packet in New York can not immediately affect the behavior of switches in London. Intuitively, this makes sense: requiring “immediate” reaction to remote events would force synchronization between switches and buffering of packets, leading to unacceptable performance penalties. Event-driven consistent update only requires the switches in London to react *after* they have heard about the event in New York.

The second defining aspect of our locality requirements involves the compatibility constraints in NESs. Suppose that New York sends packets to London and Paris, but the program requires transitioning to a different global state based on who received a packet first. Clearly, it would be impossible to implement this behavior without significant coordination. However, suppose New York and Philadelphia are sending packets to London, and the program requires transitioning to a different global state based on whose packet was received first in London. This behavior is easily implementable since the choice is local to London. We use NESs to rule out non-local incompatible events—specifically, we require that incompatible events must occur at the same switch.

Our approach gives consistency guarantees even when an event occurs at a switch different from the one that will be updated. The change will not happen “atomically” with the event that triggered it, but (a) every packet is processed by a single configuration, and (b) the configuration change occurs as dictated by event-driven consistent update (happens-before) requirements. We show that these requirements can be implemented with minimal performance penalty.

Locality issues are an instance of the tension between *consistency* and *availability* in distributed systems, which motivates existing SDN languages to favor availability (avoiding expensive synchronization and packet buffering) over consistency (offering strong guarantees when state changes). We demonstrate that it is possible to provide the same level of availability as existing systems, while providing a natural consistency condition that is powerful enough to build many applications. We also show that weakening the locality requirement forces us to weaken availability.

Overall, we present a new abstraction based on (i) a notion of causal consistency requiring that events are propagated between nodes, (ii) per-packet consistency governing how packets are forwarded through the network, and (iii) locality requirements. We believe this is a powerful combination that is a natural fit for building many applications.

Implementing Network Programs. NESs also provide a natural formalism for guiding an implementation technique for stateful programs. Intuitively, we need switches that can record the set of events that have been seen locally, make decisions based on those events, and transmit events to other switches. Fortunately, in the networking industry there is a trend toward more programmable data planes: mutable state

is already supported in most switch ASICs (e.g. MAC learning tables) and is also being exposed to SDN programmers in next-generation platforms such as OpenState [5] and P4 [6]. Using these features, we can implement an NES as follows.

1. Encode the sets of events contained in the NES as flat tags that can be carried by packets and tested on switches.
2. Compile the configurations contained in the NES to a collection of forwarding tables.
3. Add “guards” to each configuration’s forwarding rules to explicitly test for the tag enabling the configuration.
4. Add rules to “stamp” incoming packets with tags corresponding to the current set of events.
5. Add rules to “learn” which events have happened by reading tags on incoming packets and adding the tags in the local state to outgoing packets, as required to implement the happens-before relation.

In this paper, we prove that a system implemented in this way *correctly* implements an NES.

Evaluation. To evaluate our design, we built a prototype of the system described in this paper.[†] We have used this to build a number of event-driven network applications: (a) a stateful firewall, which we have already described; (b) a learning switch that floods packets going to unknown hosts along a spanning tree, but uses point-to-point forwarding for packets going to known hosts; (c) an authentication system that initially blocks incoming traffic, but allows hosts to gain access to the internal network by sending packet probes to a predefined sequence of ports; (d) a bandwidth cap that disables access to an external network after seeing a certain number of packets; and (e) an intrusion detection system that allows all traffic until seeing a sequence of internal hosts being contacted in a suspicious order. We have also built a synthetic application that forwards packets around a ring topology, to evaluate update scalability. We developed these applications in an extended version of NetKAT which we call *Stateful NetKAT*. Our experiments show that our implementation technique provides competitive performance on several important metrics while ensuring important consistency properties. We draw several conclusions. (1) Event-driven consistent update allow programmers to easily write real-world network applications and get the correct behavior, whereas approaches relying only on uncoordinated consistency guarantees do not. (2) The performance overhead of maintaining state and manipulating tags (measured in bandwidth) is within 6% of an implementation that uses only uncoordinated update. (3) There is an optimization that exploits common structure in rules across states to reduce the number of rules installed on switches. In our experiments, a basic heuristic version of this optimization resulted in a 32-37% reduction in the number of rules required on average.

Summary. Our main contributions are as follows.

- We propose a new semantic correctness condition for dynamic network programs called *event-driven consistent update* that balances the need for immediate response with the need to avoid costly synchronization and buffering of packets. Our consistency property generalizes the guarantees offered by consistent updates, and is as strong as possible without sacrificing availability.
- We propose *network event structures* to capture causal dependencies and compatibility between events, and show how to implement these using SDN functionality.
- We describe a compiler based on a stateful extension of NetKAT, and present optimizations that reduce the overhead of implementing such stateful programs.
- We conduct experiments showing that our approach gives well-defined consistency guarantees, while avoiding expensive synchronization and packet buffering.

The rest of this paper is structured as follows: §2 formalizes event-driven consistent updates; §3 defines event transition systems, network event structures, and Stateful NetKAT; §4 describes our implementation; and §5 presents experiments. We discuss related/future work in §6-7, and conclude in §8.

2. Event-Driven Network Behavior

This section presents our new consistency model for stateful network programs: *event-driven consistent update*.

Preliminaries. A *packet* pkt is a record of fields $\{f_1; f_2; \dots; f_n\}$, where fields f represent properties such as source and destination address, protocol type, etc. The (numeric) values of fields are accessed via the notation $pkt.f$, and field updates are denoted $pkt[f \leftarrow n]$. A *switch* sw is a node in the network with one or more *ports* pt . A *host* is a switch that can be a source or a sink of packets. A *location* l is a switch-port pair $n:m$. Locations may be connected by (unidirectional) physical links (l_{src}, l_{dst}) in the topology.

Packet forwarding is dictated by a *network configuration* C . A *located packet* $lp = (pkt, sw, pt)$ is a tuple consisting of a packet and a location $sw:pt$. We model C as a relation on located packets: if $C(lp, lp')$, then the network maps lp to lp' , possibly changing its location and rewriting some of its fields. Since C is a relation, it allows multiple output packets to be generated from a single input. In a real network, the configuration only forwards packets between ports within each individual switch, but for convenience, we assume that our C also captures link behavior (forwarding between switches), i.e. $C((pkt, n_1, m_1), (pkt, n_2, m_2))$ holds for each link $(n_1:m_1, n_2:m_2)$. We refer to a sequence of located packets that starts at a host and can be produced by C as a *packet trace*, using $Traces(C)$ to denote the set of all such packet traces. We let $\mathcal{C}$ be the set of all configurations.

Consider a tuple $ntr = (lp_0 lp_1 \dots, T)$, where the first component is a sequence of located packets, and each $t \in T$ is an increasing sequence of indices corresponding to located packets in the sequence. We call such a tuple a *network trace* if and only if the following conditions hold:

[†] The PLDI 2016 Artifact Evaluation Committee (AEC) found that our prototype system “met or exceeded expectations.”

1. for each lp_j , we have $j \in t$ for some $t \in T$, and
2. for each $t = (k_0 k_1 \dots) \in T$, lp_{k_0} is at a host, and $\exists C \in \mathcal{C}$ such that $C(lp_{k_i}, lp_{k_{i+1}})$ holds for all i , and
3. if we consider the graph G with nodes $\{k : (\exists t \in T : k \in t)\}$ and edges $\{(k_i, k_{i+1}) : (\exists t \in T : t = k_0 k_1 \dots k_i k_{i+1} \dots)\}$, then G is a family of *trees* rooted at $K = \{k_0 : (\exists t \in T : t = k_0 \dots)\}$.

We will use $ntr \downarrow k$ to denote the set $\{t \in T : k \in t\}$, and when $t = (k_0 k_1 \dots) \in T$, we can use similar notation $ntr \downarrow t$ to denote the packet trace $lp_{k_0} lp_{k_1} \dots$. Intuitively, we have defined a network trace to be an interleaving of these packet traces (the packet traces form the family of *trees* because, as previously mentioned, the configuration allows multiple output packets from a single input packet). Ultimately, we will introduce a consistency definition that dictates which interleavings of packet traces are correct.

We now define how the network changes its configuration in response to events. An *event* e is a tuple $(\varphi, sw, pt)_{eid}$, where eid is an (optional) event identifier and φ is a first-order formula over fields. Events model the arrival of a packet satisfying φ (denoted $pkt \models \varphi$) at location $sw:pt$. Note that we could have other types of events—anything that a switch can detect could be an event—but for simplicity, we focus on packet events. We say that a located packet $lp = (pkt, sw', pt')$ *matches* an event $e = (\varphi, sw, pt)$ (denoted by $lp \models e$) if and only if $sw = sw' \wedge pt = pt' \wedge pkt \models \varphi$.

Definition 1 (Happens-before relation $\prec_{ntr}$). *Given a network trace $ntr = (lp_0 lp_1 \dots, T)$, the happens-before relation $\prec_{ntr}$ is the least partial order on located packets that*

- *respects the total order induced by ntr at switches, i.e., $\forall i, j : lp_i \prec lp_j \Leftarrow i < j \wedge lp_i = (pkt, sw, pt) \wedge lp_j = (pkt', sw, pt')$, and*
- *respects the total order induced by ntr for each packet, i.e., $\forall i, j : lp_i \prec lp_j \Leftarrow i < j \wedge \exists t \in T : i \in t \wedge j \in t$.*

Event-Driven Consistent Update. In Section 1, we informally defined an event-driven consistent update as a triple $C_i \xrightarrow{e} C_f$ consisting of an initial configuration C_i , event e , and final configuration C_f . Here, we formalize that definition in a way that describes *sequences* of events and configurations (in the single-event case, this formal definition is equivalent to the informal one). We denote an *event-driven consistent update* as a pair $(U, \mathcal{E})$, where U is a sequence $C_0 \xrightarrow{e_0} C_1 \xrightarrow{e_1} \dots \xrightarrow{e_n} C_{n+1}$, and $\{e_0, \dots, e_n\} \subseteq \mathcal{E}$.

Let $ntr = (lp_0 lp_1 \dots, T)$ be a network trace. Given an event-driven consistent update $(U, \mathcal{E})$, we need the indices where the events from U first occurred. Specifically, we wish to find the sequence $k_0, \dots, k_n$ where lp_j does not match any $e \in \mathcal{E}$ for any $j > k_n$, and the following properties hold for all $0 \leq i \leq n$ (assuming $k_{(-1)} = -1$ for convenience):

- $k_i > k_{i-1}$, and
- lp_{k_i} matches e_i , and for all j , if $k_{i-1} < j < k_i$ then lp_j does not match e_i (i.e., k_i is the first occurrence of e_i after the index k_{i-1}), and

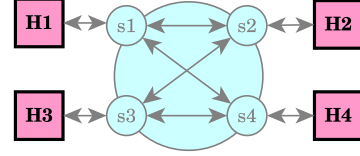


Figure 2: Example topology with four switches and hosts.

- $\exists t \in ntr \downarrow k_i$ such that t is in $Traces(C_i)$ (intuitively, the event e_i can be triggered only by a packet processed in the immediately preceding configuration).

If such a sequence exists, it is unique, and we denote it by $FO(ntr, U)$, shorthand for “first occurrences.”

Definition 2 (Event-driven consistent update correctness). *A network trace $ntr = (lp_0 lp_1 \dots, T)$ is correct with respect to an event-driven consistent update $U = C_0 \xrightarrow{e_0} C_1 \xrightarrow{e_1} \dots \xrightarrow{e_n} C_{n+1}$, if $FO(ntr, U) = k_0, \dots, k_n$ exists, and for all $0 \leq i \leq n$, the following holds for each packet trace $ntr \downarrow t = lp'_0 lp'_1 \dots$ where $t \in T$:*

- *$ntr \downarrow t$ is in $Traces(C)$ for some $C \in \{C_0, \dots, C_{n+1}\}$ (packet is processed entirely by one configuration), and*
- *if $\forall j : lp'_j \prec lp_{k_i}$, then $ntr \downarrow t$ is in $Traces(C)$ for some $C \in \{C_0, \dots, C_i\}$ (the packet is processed entirely in a preceding configuration), and*
- *if $\forall j : lp_{k_i} \prec lp'_j$, then $ntr \downarrow t$ is in $Traces(C)$ for some $C \in \{C_{i+1}, \dots, C_{n+1}\}$ (the packet is processed entirely in a following configuration).*

To illustrate, consider Figure 2. We describe an update $C_i \xrightarrow{e} C_f$. In the initial configuration C_i , the host H_1 can send packets to H_2 , but not vice-versa. In the final configuration C_f , traffic from H_2 to H_1 is allowed. Event e models the arrival to s_4 of a packet from H_1 (imagine s_4 is part of a distributed firewall). Assume that e occurs, and immediately afterwards, H_2 wants to send a packet to s_1 . Can s_2 drop the packet (as it would do in configuration C_i)? Event-driven consistent updates allow this, as otherwise we would require s_2 to react immediately to the event at s_4 , which would be an example of action at a distance. Formally, the occurrence of e is not in a happens-before relation with the arrival of the new packet to s_2 . On the other hand, if e.g. s_4 forwards some packets to s_1 and s_2 before the new packet from H_2 arrives, s_1 and s_2 would be required to change their configurations, and the packet would be allowed to reach H_1 .

Network Event Structures. As we have seen, event-driven consistent updates specify how the network should behave during a sequence of updates triggered by events, but additionally, we want the ability to capture constraints between the events themselves. For example, we might wish to say that e_2 can only happen after e_1 has occurred, or that e_2 and e_3 cannot both occur in the same network trace.

To model such constraints, we turn to the *event structures* model introduced by Winskel [38]. Intuitively, an event structure endows a set of events $\mathcal{E}$ with (a) a *consistency*

predicate (*con*) specifying which events are allowed to occur in the same sequence, and (b) an *enabling relation* ($\vdash$) specifying a (partial) order in which events can occur. This is formalized in the following definition (note that we use $\subseteq_{fin}$ to mean “finite subset,” and $\mathcal{P}_{fin}(X) = \{Y : Y \subseteq_{fin} \mathcal{P}(X)\}$).

Definition 3 (Event structure). *An event structure is a tuple $(\mathcal{E}, con, \vdash)$ where:*

- $\mathcal{E}$ is a set of events,
- $con : (\mathcal{P}_{fin}(\mathcal{E}) \rightarrow \text{Boolean})$ is a consistency predicate that satisfies $con(X) \wedge Y \subseteq X \implies con(Y)$,
- $\vdash : (\mathcal{P}(\mathcal{E}) \times \mathcal{E} \rightarrow \text{Boolean})$ is an enabling relation that satisfies $(X \vdash e) \wedge X \subseteq Y \implies (Y \vdash e)$.

An event structure can be seen as defining a transition system whose states are subsets of $\mathcal{E}$ that are consistent and reachable via the enabling relation. We refer to such a subset as an *event-set* (called “configuration” in [38]).

Definition 4 (Event-set of an event structure). *Given an event structure $N = (\mathcal{E}, con, \vdash)$, an event-set of N is any subset $X \subseteq \mathcal{E}$ which is: (a) consistent: $\forall Y \subseteq_{fin} X, con(Y)$ holds, and (b) reachable via the enabling relation: for each $e \in X$, there exists $e_0, e_1, \dots, e_n \in X$ where $e_n = e$ and $\emptyset \vdash \{e_0\}$ and $\{e_0, \dots, e_{i-1}\} \vdash e_i$ for all $1 \leq i \leq n$.*

We want to be able to specify which network configuration should be active at each event-set of the event structure. Thus, we need the following extension of event structures.

Definition 5 (Network event structure (NES)). *A network event structure is a tuple $(\mathcal{E}, con, \vdash, g)$ where $(\mathcal{E}, con, \vdash)$ is an event structure, and $g : (\mathcal{P}(\mathcal{E}) \rightarrow \mathcal{C})$ maps each event-set of the event structure to a network configuration.*

Correct Network Traces. We now define what it means for a network trace *ntr* to be *correct* with respect to an NES $N = (\mathcal{E}, con, \vdash, g)$. We begin by constructing a sequence S of events that is allowed by N . A sequence $S = e_0 e_1 \dots e_n$ is *allowed by N* , if $\emptyset \vdash \{e_0\} \wedge con(\{e_0\})$, and $\forall 1 \leq i \leq n : (\{e_0, e_1, \dots, e_{i-1}\} \vdash e_i \wedge con(\{e_0, e_1, \dots, e_i\}))$.

Intuitively, we say that *ntr* is correct if there is a sequence of events allowed by N which would cause *ntr* to satisfy the event-driven consistent update condition.

Definition 6 (Correct network trace). *Let S be the set of all sequences allowed by N . Formally, a network trace $ntr = (lp_0 lp_1 \dots, T)$ is correct with respect to N if*

- no lp_j matches any $e \in \mathcal{E}$, and for all packet traces $ntr \downarrow t$ where $t \in T$, we have $ntr \downarrow t$ is in $\text{Traces}(g(\emptyset))$, or
- there exists some $e_0 e_1 \dots e_n \in S$ such that *ntr* is correct with respect to event-driven consistent update $(g(\emptyset) \xrightarrow{e_0} g(\{e_0\}) \xrightarrow{e_1} \dots \xrightarrow{e_n} g(\{e_0, \dots, e_n\}), \mathcal{E})$.

Locality Restrictions for Incompatible Events. We now show how NESs can be used to impose reasonable locality restrictions. A set of events E is called *inconsistent* if and only if $con(E)$ does not hold. We use the term *minimally-inconsistent* to describe inconsistent sets where

all proper subsets are not inconsistent. An NES N is called *locally-determined* if and only if for each of its minimally-inconsistent sets E , all events in E happen at the same switch (i.e., $\exists sw \forall e_i \in E : e_i = (\varphi_i, sw, pt_i)$). To illustrate the need for the locally-determined property, let us consider the following two programs, P_1 and P_2 .

- **Program P_1 :** Recall that two events are inconsistent if either of them can happen, but both cannot happen in the same execution. Consider the topology shown in Figure 2 and suppose this program requires that H_2 and H_4 can both receive packets from H_1 , but only the first one to receive a packet is allowed to respond. There will be two events e_1 and e_2 , with e_1 the arrival of a packet from H_1 at s_2 , and e_2 the arrival of a packet from H_1 at s_4 . These events are always enabled, but the set $\{e_1, e_2\}$ is not consistent, i.e. $con(\{e_1, e_2\})$ does not hold. This models the fact that at most one of the events can take effect. These events happen at different switches—making sure that *at most one* of the events takes effect would necessitate information to be propagated instantaneously “at a distance.” In implementations, this would require using inefficient mechanisms (synchronization and/or packet buffering). Our locality restriction is a clean condition which ensures that the NES is efficiently implementable.
- **Program P_2 :** Consider a different program where H_2 can send traffic to one of the two hosts H_1, H_3 that sends it a packet first. The two events (a packet from H_1 arriving at s_2 , and a packet from H_3 arriving at s_2) are still inconsistent, but inconsistency does not cause problems in this case, because both events happen at the same switch (the switch can determine which one was first).

In contrast to our approach, an uncoordinated update approach improperly handles locality issues, mainly because it does not guarantee *when* the configuration change occurs. Consider the program P_1 again, and consider the (likely) scenario where events e_1 and e_2 happen nearly simultaneously. In an uncoordinated approach, this could result in switch s_2 hearing about e_1, e_2 (in that order), and s_4 hearing about e_2, e_1 (in that order), meaning the two switches would have conflicting ideas of which event was “first” (i.e. the switches would be in conflicting states, and this conflict cannot be resolved). In our implementation, we would require e_1 and e_2 to occur at the same switch, guaranteeing that we never see such a conflicting mix of states.

Strengthening Consistency. We now show that strengthening the consistency conditions imposed by NESs would lead to lower availability, as it would lead to the need for expensive synchronization, packet buffering, etc. First, we will try to remove the locally-determined condition, and second, we will try to obtain a strengthened consistency condition. The proof of the following theorem is an adaptation of the proof of the CAP theorem [7], as presented in [13]. The idea is that in asynchronous network communication, a switch might need to wait arbitrarily long to hear about an event.

Lemma 1. *In general, it is impossible to implement an NES that does not have the locally-determined condition while guaranteeing that switches process each packet within an a priori given time bound.*

Proof Sketch. Consider a simple NES, with event sets $\emptyset$, $\{e_1\}$, $\{e_2\}$, and where $\{e_1\}$ and $\{e_2\}$ are both enabled from $\emptyset$. Assume that $\text{con}(\{e_1, e_2\})$ does not hold, and that e_1 can happen at switch A and e_2 can happen at switch B (i.e., the locally-determined condition does not hold).

Because the communication is asynchronous, there is no a priori bound on how long the communication between switches can take. When a packet p that matches e_2 arrives at the switch B , the switch must distinguish the following two cases: (#1) event e_1 has occurred at A (and thus p does not cause e_2), or (#2) event e_1 has not occurred at A (and thus p causes e_2). No matter how long B waits, it cannot distinguish these two cases, and hence, when a packet that matches e_2 arrives to B , the switch B cannot correctly decide whether to continue as if e_2 has happened. It has the choice to either eventually decide (and risk the wrong decision), or to buffer the packet that matches e_2 . $\square$

We now ask whether we can strengthen the event-driven consistent update definition. We define *strong update* as an update $C_1 \xrightarrow{e} C_2$ such that immediately after e occurred, the network processes all incoming packets in C_2 . We obtain the following lemma by the same reasoning as the previous one.

Lemma 2. *In general, it is impossible to implement strong updates and guarantee that switches process each packet within an a priori given time bound.*

Proof Sketch. Let A be the switch where e can happen, and let B be a switch on which the configurations C_1, C_2 differ. For A and B , the same argument as in the previous lemma shows that B must either risk the wrong decision on whether to process packets using C_1 or C_2 , or buffer packets. $\square$

3. Programming with Events

The correctness condition we described in the previous section offers useful application-level guarantees to network programmers. At a high level, the programmer is freed from thinking about interleavings of packets/events and responses to events (configuration updates). She can think in terms of our consistency model—each packet is processed in a single configuration, and packets entering “after” an event will be processed in the new configuration (similar to causal consistency). An important consequence is that the response to an event is immediate with respect to a given flow if the event is handled at that flow’s ingress switch.

With this consistency model in mind, programmers can proceed by specifying the desired event-driven program behavior using network event structures. This section introduces an intuitive method for building NESs using simple transition systems where nodes correspond to configurations

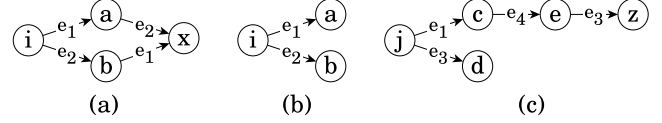


Figure 3: Event-driven transition systems.

and edges correspond to events. We also present a network programming language based on NetKAT that provides a compact notation for specifying both the transition system and the configurations at the nodes.

3.1 Event-Driven Transition Systems

Definition 7 (Event-driven Transition System). *An event-driven transition system (ETS) is a graph (V, D, v_0) , in which V is a set of vertices, each labeled by a configuration; $D \subseteq V \times V$ is a set of edges, each labeled by an event e ; and v_0 is the initial vertex.*

Consider the ETSs shown in Figure 3 (a-b). In (a), the two events are intuitively *compatible*—they can happen in any order, so we obtain a correct execution if both happen in different parts of the network, and different switches can have a different view of the order in which they happened. In (b), the two events are intuitively *incompatible*—only one of them can happen in any particular execution. Therefore, even if they happen nearly simultaneously, only one of them should take an effect. To implement this, we require the locality restriction—we need to check whether the two events happen at the same switch. We thus need to distinguish between ETSs such as (a) and (b) in Figure 3, to determine where locality restrictions must be imposed in the conversion from an ETS to an NES.

From ETSs to NESs. To convert an ETS to an NES, we first form the event sets (Definition 4) and then construct the enabling relation and consistency predicate. Given an ETS T , consider the set $W(T)$ of sequences of events in T from the initial node to any vertex (including the empty sequence). For each sequence $p \in W(T)$, let $E(p)$ be the set of events collected along the sequence. The set $F(T) = \{E(p) \mid p \in W(T)\}$ is our candidate collection of event sets. We now define conditions under which $F(T)$ gives rise to an NES.

1. We require that each set E in $F(T)$ must correspond to exactly one network configuration. This holds if all paths in $W(T)$ corresponding to E end at states labeled with the same configuration.
2. We require that $F(T)$ is *finite-complete*, i.e. for any sets $E_1, E_2, \dots, E_n$ where each $E_i \in F(T)$, if there is a set $E' \in F(T)$ which contains every E_i (an upper bound for the sets E_i), then the set $E_{lub} = \cup_i E_i$ (the least upper bound for the E_i) must also be in $F(T)$. For example, consider the ETS in Figure 3(c), which violates this condition since the event-sets $E_1 = \{e_1\}$ and $E_2 = \{e_3\}$ are both subsets of $\{e_1, e_4, e_3\}$, but there is no event-set of the form $E_1 \cup E_2 = \{e_1, e_3\}$.

In [38], such a collection $F(T)$ is called a *family of configurations*. Our condition (2) is condition (i) in Theorem 1.1.9 in [38] (conditions (ii)-(iii) are satisfied by construction).

Given an ETS T , it is not difficult to confirm the above conditions statically. They can be checked using straightforward graph algorithms, and any problematic vertices or edges in T can be indicated to the programmer. The development of *efficient* checking algorithms is left for future work.

We build the *con* and $\vdash$ relations of an NES from the family $F(T)$, using Theorem 1.1.12. of [38]. Specifically, predicate *con* can be defined by declaring all sets in $F(T)$ as consistent, and for $\vdash$, we take the smallest relation satisfying the constraints $\emptyset \vdash e \iff \{e\} \in F(T)$ and $X' \vdash e \iff (X' \in \text{con}) \wedge ((X' \cup \{e\}) \in F(T) \vee (\exists X \subseteq X' : X \vdash e))$.

After obtaining an NES, deciding whether it satisfies the locality restriction is easy: we check whether the NES is locally determined (see Section 2), verifying for each minimally-inconsistent set that the locality restriction holds. Again, we leave the *efficiency* of this check for future work.

Loops in ETSs. If there are loops in the ETS T , the previous definition needs to be slightly modified, because we need to “rename” events encountered multiple times in the same execution. This gives rise to an NES where each event-set is finite, but the NES itself might be infinite (and thus can only be computed lazily). If we have the ability to store and communicate unbounded (but finite) event-sets in the network runtime, then no modifications are needed to handle infinite NESs in the implementation (which is described in Section 4). Otherwise, there are various correct overapproximations we could use, such as computing the strongly-connected components (SCCs) of the ETS, enforcing the locality restriction on events in each (non-singleton) SCC, and requiring the implementation to attach timestamps on occurrences of events in those SCCs. For simplicity of the presentation, we will consider only loop-free ETSs in this paper.

3.2 Stateful NetKAT

NetKAT [2] is a domain-specific language for specifying network behavior. It has semantics based on Kleene Algebra with Tests (KAT), and a sound and complete equational theory that enables formal reasoning about programs. Operationally, a NetKAT program behaves as a function which takes as input a single packet, and uses tests, field-assignments, sequencing, and union to produce a set of “histories” corresponding to the packet’s traces.

Standard NetKAT does not support mutable *state*. Each packet is processed in isolation using the function described by the program. In other words, we can use a standard NetKAT program for specifying individual network configurations, but not event-driven configuration changes. We describe a stateful variant of NetKAT which allows us to compactly specify a *collection* of network configurations, as well as the event-driven relationships between them (i.e. an ETS). This variant preserves the existing equational theory of the

$f \in \text{Field}$ (packet field name)
 $n \in \mathbb{N}$ (numeric value)
 $x ::= f \mid \mathbf{pt}$ (modifiable field)
 $a, b ::= \mathbf{true} \mid \mathbf{false} \mid x = n \mid \mathbf{sw} = n \mid \mathbf{state}(n) = n$ (test)
 $\mid a \vee b \mid a \wedge b \mid \neg a$
 $p, q ::= a \mid x \leftarrow n \mid p + q \mid p ; q \mid p^*$ (command)
 $\mid (n:n) \rightarrow (n:n) \mid (n:n) \rightarrow (n:n) \rightarrow \langle \mathbf{state}(n) \leftarrow n \rangle$

Figure 4: Stateful NetKAT: syntax.

$$\begin{aligned}
 \llbracket \mathbf{state}(m) = n \rrbracket_{\vec{k}} &\triangleq \begin{cases} \llbracket \mathbf{true} \rrbracket_{\vec{k}} & \text{if } \vec{k}(m) = n \\ \llbracket \mathbf{false} \rrbracket_{\vec{k}} & \text{otherwise} \end{cases} \\
 \llbracket (a:b) \rightarrow (c:d) \rightarrow \langle \mathbf{state}(m) \leftarrow n \rangle \rrbracket_{\vec{k}} &\triangleq \llbracket (a:b) \rightarrow (c:d) \rrbracket_{\vec{k}}
 \end{aligned}$$

Figure 5: Stateful NetKAT: extracting NetKAT Program (state $\vec{k}$).

individual static configurations (though it is not a KAT itself), but also allows packets to affect processing of future packets via assignments to (and tests of) a global *state*. The syntax of Stateful NetKAT is shown in Figure 4. A Stateful NetKAT program is a *command*, which can be:

- a *test*, which is a formula over packet header fields (there are special fields **sw** and **pt** which test the switch- and port-location of the packet respectively),
- a *field assignment* $x \leftarrow n$, which modifies the (numeric) value stored in a packet’s field,
- a *union* of commands $p + q$, which unions together the packet-processing behavior of commands p and q ,
- a *command sequence* $p ; q$, which runs packet-processing program q on the result of p ,
- an *iteration* p^* , which is equivalent to $\mathbf{true} + p + (p ; p) + (p ; p ; p) + \dots$,
- or a *link definition* $(n_1:m_1) \rightarrow (n_2:m_2)$, which forwards a packet from port m_1 at switch n_1 across a physical link to port m_2 at switch n_2 .

The functionality described above is also provided by standard NetKAT [35]. The key distinguishing feature of our *Stateful NetKAT* is a special global vector-valued variable called **state**, which allows the programmer to represent a collection of NetKAT programs. The function shown in Figure 5 gives the standard NetKAT program $\llbracket p \rrbracket_{\vec{k}}$ corresponding to each value $\vec{k}$ of the state vector (for conciseness, we only show the non-trivial cases). We can use the NetKAT compiler [35] to generate forwarding tables (i.e. configurations) corresponding to these, which we denote $C(\llbracket p \rrbracket_{\vec{k}})$.

3.3 Converting Stateful NetKAT Programs to ETSs

Now that we have the $\llbracket \cdot \rrbracket_{\vec{k}}$ function to extract the static configurations (NetKAT programs) corresponding to the vertices of an ETS, we define another function $\llbracket \cdot \rrbracket_{\vec{k}}$, which produces the event-edges (Figure 6). This collects (using parameter φ) the conjunction of all tests seen up to a given

$\begin{aligned} \llbracket f \ominus n \rrbracket_{\vec{k}} \varphi &\triangleq (\{\}, \{\varphi \wedge f \ominus n\}) \\ \llbracket \text{sw} \ominus n \rrbracket_{\vec{k}} \varphi &\triangleq \llbracket \text{true} \rrbracket_{\vec{k}} \varphi \\ \llbracket \text{port} \ominus n \rrbracket_{\vec{k}} \varphi &\triangleq \llbracket \text{true} \rrbracket_{\vec{k}} \varphi \\ \llbracket \text{state}(m) \ominus n \rrbracket_{\vec{k}} \varphi &\triangleq \begin{cases} \llbracket \text{true} \rrbracket_{\vec{k}} \varphi & \text{if } \vec{k}(m) \ominus n \\ \llbracket \text{false} \rrbracket_{\vec{k}} \varphi & \text{otherwise} \end{cases} \\ \llbracket f \leftarrow n \rrbracket_{\vec{k}} \varphi &\triangleq (\{\}, \{\exists f : \varphi \wedge f = n\}) \\ \llbracket p + q \rrbracket_{\vec{k}} \varphi &\triangleq (\llbracket p \rrbracket_{\vec{k}} \varphi) \sqcup (\llbracket q \rrbracket_{\vec{k}} \varphi) \\ \llbracket p ; q \rrbracket_{\vec{k}} \varphi &\triangleq (\llbracket p \rrbracket_{\vec{k}} \blacksquare \llbracket q \rrbracket_{\vec{k}}) \varphi \\ \llbracket p^* \rrbracket_{\vec{k}} \varphi &\triangleq \bigsqcup_j F_p^j(\varphi, \vec{k}) \end{aligned}$	$\begin{aligned} \llbracket a \wedge b \rrbracket_{\vec{k}} \varphi &\triangleq \llbracket a ; b \rrbracket_{\vec{k}} \varphi \\ \llbracket a \vee b \rrbracket_{\vec{k}} \varphi &\triangleq \llbracket a + b \rrbracket_{\vec{k}} \varphi \\ \llbracket \text{true} \rrbracket_{\vec{k}} \varphi &\triangleq (\{\}, \{\varphi\}) \\ \llbracket \text{false} \rrbracket_{\vec{k}} \varphi &\triangleq (\{\}, \{\}) \\ \llbracket \neg \text{true} \rrbracket_{\vec{k}} \varphi &\triangleq \llbracket \text{false} \rrbracket_{\vec{k}} \varphi \\ \llbracket \neg \text{false} \rrbracket_{\vec{k}} \varphi &\triangleq \llbracket \text{true} \rrbracket_{\vec{k}} \varphi \\ \llbracket \neg(v \ominus n) \rrbracket_{\vec{k}} \varphi &\triangleq \llbracket v \oplus n \rrbracket_{\vec{k}} \varphi \\ \llbracket \neg \neg a \rrbracket_{\vec{k}} \varphi &\triangleq \llbracket a \rrbracket_{\vec{k}} \varphi \\ \llbracket \neg(a \wedge b) \rrbracket_{\vec{k}} \varphi &\triangleq \llbracket \neg a \vee \neg b \rrbracket_{\vec{k}} \varphi \\ \llbracket \neg(a \vee b) \rrbracket_{\vec{k}} \varphi &\triangleq \llbracket \neg a \wedge \neg b \rrbracket_{\vec{k}} \varphi \end{aligned}$
$\begin{aligned} \llbracket (s_1:p_1) \rightarrow (s_2:p_2) \rrbracket_{\vec{k}} \varphi &\triangleq (\{\}, \{\varphi\}) \\ \llbracket (s_1:p_1) \rightarrow (s_2:p_2) \rightarrow \langle \text{state}(m) \leftarrow n \rangle \rrbracket_{\vec{k}} \varphi &\triangleq (\{\vec{k}, (\varphi, s_2, p_2), \vec{k}[m \mapsto n]\}, \{\varphi\}) \end{aligned}$	

Figure 6: Stateful NetKAT: extracting event-edges from state $\vec{k}$.

program location, and records a corresponding event-edge when a state assignment command is encountered. The function returns a tuple (D, P) , where D is a set of event-edges, and P is a set of updated conjunctions of tests. In the figure, the $\sqcup$ operator denotes pointwise union of tuples, i.e. $(A_1, B_1, \dots) \sqcup (A_2, B_2, \dots) = (A_1 \cup A_2, B_1 \cup B_2, \dots)$. The $\blacksquare$ operator denotes (pointwise) Kleisli composition, i.e. $(f \blacksquare g) \triangleq \bigsqcup \{g y : y \in f x\}$, and function F is as follows.

$$\begin{aligned} F_p^0(\varphi, \vec{k}) &\triangleq (\{\}, \{\varphi\}) \\ F_p^{j+1}(\varphi, \vec{k}) &\triangleq (\llbracket p \rrbracket_{\vec{k}} \blacksquare F_p^j) \varphi \end{aligned}$$

The symbol variable $\ominus$ is either equality “=” or inequality “ $\neq$ ”, and $\oplus$ is the opposite symbol with respect to $\ominus$. Given any conjunction φ and a header field f , the formula $(\exists f : \varphi)$ strips all predicates of the form $(f \ominus n)$ from φ .

Using fst to denote obtaining the first element of a tuple, we can now produce the event-driven transition system for a Stateful NetKAT program p with the initial state $\vec{k}_0$:

$$\begin{aligned} ETS(p) &\triangleq (V, D, v_0) \\ \text{where } V &\triangleq \bigcup_{\vec{k}} \{(\vec{k}, C(\llbracket p \rrbracket_{\vec{k}}))\} \\ \text{and } D &\triangleq \text{fst}(\bigcup_{\vec{k}} (\llbracket p \rrbracket_{\vec{k}} \text{true})) \\ \text{and } v_0 &\triangleq (\vec{k}_0, C(\llbracket p \rrbracket_{\vec{k}_0})) \end{aligned}$$

4. Implementing Event-Driven Programs

Next, we show one method of implementing NESs in a real SDN, and we prove that this approach is correct—i.e., all traces followed by actual packets in the network are correct with respect to Definition 6 in Section 2. At a high level, the basic idea of our implementation strategy can be understood as follows. We assume that the switches in the network provide mutable state that can be read and written as packets are processed. Given an NES, we assign a tag to each event-set and compile to a collection of configurations whose rules are “guarded” by the appropriate tags. We then add logic that (i) updates the mutable state to record local events, (ii) stamps incoming packets with the tag for the current event-

set upon ingress, and (iii) reads the tags carried by packets, and updates the event-set at subsequent switches.

4.1 Implementation Building Blocks

Static Configurations. The NES contains a set of network configurations that need to be installed as flow tables on switches. In addition, we must be able to transition to a new configuration in response to a local event. We do this *proactively*, installing all of the needed rules on switches in advance, with each rule guarded by its configuration’s ID. This has a disadvantage of being less efficient in terms of rule-space usage, but an advantage of allowing quick configuration changes. In Section 5.3, we discuss an approach for addressing the space-usage issue by sharing rules between configurations. Our implementation strategy encodes each event-set in the NES as an integer, so a single unused packet header field (or single register on switches) can be used. This keeps the overhead low, even for very large programs.

Stateful Switches. Emerging data-plane languages such as P4 [6] and OpenState [5] are beginning to feature advanced functionality such as customizable parsing, stateful memories, etc. We assume that our switches support (1) modifying a local register (e.g. an integer on a switch) appropriately upon receipt of a packet, and (2) making packet forwarding decisions based on the value of a register. This allows each switch to maintain a local view of the global state. Specifically, the register records the set of events the device knows have occurred. At any time, the device can receive a packet (from the controller or another device) informing it of new event occurrences, which are “unioned” into the local register (by performing a table lookup based on integer values). Currently, P4 data planes support this type of functionality.

We also assume that the switch atomically processes each packet in the order in which it was received. Such “atomic” switch operations are proposed by the “Packet Transactions” P4 extension [34]. Because the P4 switch platform is attracting considerable attention (even spawning its own highly-

Switch ID	n	$\in \mathbb{N}$	Packet	pkt	$::= \{f_1; \dots; f_k; C; digest\}$	Configuration	C	$::= \{(lp, lp), \dots\}$
Port ID	m	$\in \mathbb{N}$	Located Packet	lp	$::= (pkt, l)$	Enabling Rel.	$\vdash$	$::= \{(E, e), \dots\}$
Host ID	h	$\in \mathbb{N}$	Queue Map	qm	$::= \{n \mapsto pkts, \dots\}$	Consist. Pred.	con	$::= \{E, \dots\}$
Location	l	$::= n : m$	Link	lk	$::= (l, l)$	Config. Map	g	$::= \{E \mapsto C, \dots\}$
			Links	L	$::= \{lk, \dots\}$	Switch	sw	$::= (n, qm, E, qm)$
			Event	e	$::= (\varphi, l)$	Queue, Control.	Q, R	$::= E$
			Event-set	E	$::= \{e, \dots\}$	Switches	S	$::= \{sw, \dots\}$

$(h, n:m) \in L \quad S = S' \cup \{(n, qm[m \mapsto pkts], E, qm_2)\}$			$(n:m, h) \in L \quad S = S' \cup \{(n, q_1, E, qm[m \mapsto pkt::pkts])\}$		
$(Q, R, S) \rightarrow (Q, R, S' \cup \{(n, qm[m \mapsto pkts @ [pkt[C \leftarrow g(E)]]], E, qm_2)\})$			$(Q, R, S) \rightarrow (Q, R, S' \cup \{(n, q_1, E, qm[m \mapsto pkts])\})$		
			IN		
			OUT		
			$E' = \{e : (E \cup pkt.digest) \vdash e \wedge con(E \cup pkt.digest \cup \{e\}) \wedge (pkt, n:m) \models e\}$ $\{lp : pkt.C((pkt, n:m), lp)\} = \{(pkt_1, n:m_1), \dots\} \quad S = S' \cup \{(n, qm[m \mapsto pkt::pkts], E, qm_2[m_1 \mapsto pkts_1, \dots])\}$		
			SWITCH		
			$(Q, R, S) \rightarrow (Q \cup E', R, S' \cup \{(n, qm[m \mapsto pkts], E \cup E' \cup pkt.digest, qm_2[m_1 \mapsto pkts_1 @ [pkt_1[digest \leftarrow pkt_1.digest \cup E \cup E']], \dots)])$		
			LINK		
			$(n_1:m_1, n_2:m_2) \in L \quad S = S' \cup \{(n_1, qm_1, E_1, qm_2[m_1 \mapsto pkt::pkts]), (n_2, qm_3[m_2 \mapsto pkts'], E_2, qm_4)\}$ $(Q, R, S) \rightarrow (Q, R, S' \cup \{(n_1, qm_1, E_1, qm_2[m_1 \mapsto pkts]), (n_2, qm_3[m_2 \mapsto pkts' @ [pkt]], E_2, qm_4)\})$		
			CTRLRECV		
			CTRLSEND		
			$Q = Q' \cup \{e\} \quad (Q, R, S) \rightarrow (Q', R \cup \{e\}, S)$ $R = R' \cup \{e\} \quad S = S' \cup \{(n, qm, E, qm_2)\} \quad (Q, R, S) \rightarrow (Q, R, S' \cup \{(n, qm, E \cup \{e\}, qm_2)\})$		

Figure 7: Implemented program semantics.

attended workshop), we feel that our assumptions are realistic for the current state-of-the-art in regards to switches.

Packet Processing. Each packet entering the network is admitted from a host to a port on an edge switch. The configuration ID j corresponding to the device's view of the global state is assigned to the packet's *version number* field. The packet will be processed only by j -guarded rules throughout its lifetime. Packets also carry a *digest* encoding the set of events the packet has heard about so far (i.e. the packet's view of the global state). If the packet passes through a device which has heard about additional events, the packet's digest is updated accordingly. Similarly, if the packet's digest contains events not yet heard about by the device, the latter adds them to its view of the state. When a packet triggers an event, that event is immediately added to the packet's digest, as well as to the state of the device where the event was detected. The controller is then notified about the event. Optionally (as an optimization), the controller can periodically broadcast its view of the global state to all switches, in order to speed up dissemination of the state.

4.2 Operational Model

We formalize the above via operational semantics for the global behavior of the network as it executes an NES. Each state in Figure 7 has the form (Q, R, S) , with a controller queue Q , a controller R , and set of switches S . Both the controller queue and controller are a set of events, and initially, $R=Q=\emptyset$. Each switch $s \in S$ is a tuple $(n, qm_{in}, E, qm_{out})$, where n is the switch ID, qm_{in}, qm_{out} are the input/output queue maps (mapping port IDs to packet queues). Map updates are denoted $qm[m \mapsto pkts]$. The event-set E represents a switch's view of what events have occurred. A packet's digest is denoted $pkt.digest$, and the configuration

corresponding to its version number is denoted $pkt.C$. The rules in Figure 7 can be summarized as follows.

- IN/OUT: move a packet between a host and edge port.
- SWITCH: process a packet by first adding new events from the packet's digest to the local state, then checking if the packet's arrival matches an event e enabled by the NES and updating the state and packet digest if so, and finally updating the digest with other local events.
- LINK: move a packet across a physical link.
- CTRLRECV: bring an event from the controller queue into the controller.
- CTRLSEND: update the local state of the switches.

4.3 Correctness of the Implementation

We now prove the correctness of our implementation. Formally, we show that the operational semantics generates correct traces, as defined in Section 2.

Lemma 3 (Global Consistency). *Given a locally-determined network event structure N , for an execution of the implementation $(Q_1, R_1, S_1)(Q_2, R_2, S_2) \dots (Q_m, R_m, S_m)$, the event-set $Q_i \cup R_i$ is consistent for all $1 \leq i \leq m$.*

Proof Sketch. We first show that if an *inconsistent* set Y where $|Y| > 1$ satisfies the locality restriction (i.e. all of its events are handled at the same switch), then $Y \subseteq R_i \cup Q_i$ is not possible for any i (the SWITCH rule ensures that multiple events from Y could not have been sent to the controller).

We proceed by induction over m , the trace length, noting that the base case $Q_0 \cup R_0 = \emptyset$ is consistent. Assume that the implementation adds an e (via SWITCH) to some consistent event-set $Q_m \cup R_m$, producing an inconsistent set. We look at the minimally-inconsistent set $Y \subseteq (Q_m \cup R_m \cup \{e\})$, and notice that the locality restriction requires all events in Y to

be detected at the same switch, so by the previous paragraph, we must have $|Y| \leq 1$. This generates a contradiction, since it would mean that either $Y = \{e_0\}$ or $Y \subseteq Q_m \cup R_m$, either of which would make Y consistent. $\square$

Traces of the Implementation. Note that we can readily produce the network trace (Section 2) that corresponds to an implementation trace, since a single packet pkt is processed at each step of Figure 7. We now present the main result of this section—executions of the implementation correspond to correct network traces (Definition 6).

Theorem 1 (Implementation Correctness). *For an NES N , and an execution $(Q_1, R_1, S_1)(Q_2, R_2, S_2) \cdots (Q_m, R_m, S_m)$ of the implementation, the corresponding network trace ntr is correct with respect to N .*

Proof Sketch. The proof is by induction over the length m of the execution. In the induction step, we show that (1) the SWITCH rule can only produce consistent event-sets (this follows directly from Lemma 3), and (2) when the IN rule tags a packet pkt based on the local event-set E , that E consists of exactly the events that happened before pkt arrived (as ordered by the happens-before relation). $\square$

5. Implementation and Evaluation

We built a full-featured prototype implementation in OCaml.

- We implemented the compiler described in Section 3. This tool accepts a Stateful NetKAT program, and produces the corresponding NES, with a standard NetKAT program representing the configuration at each node. We interface with Frenetic’s NetKAT compiler to produce flow-table rules for each of these NetKAT programs.
- We modified the OpenFlow 1.0 reference implementation to support the custom switch/controller needed to realize the runtime described in Section 4.
- We built tools to automatically generate custom Mininet scripts to bring up the programmer-specified network topology, using switches/controller running the compiled NES. We can then realistically simulate the whole system using real network traffic.

Research Questions. To evaluate our approach, we wanted to obtain answers to the following questions.

1. How useful is our approach? Does it allow programmers to easily write real-world network programs, and get the behavior they want?
2. What is the performance of our tools (compiler, etc.)?
3. How much does our correctness guarantee help? For instance, how do the running network programs compare with uncoordinated event-driven strategies?
4. How efficient are the implementations generated by our approach? For instance, what about message overhead? State-change convergence time? Number of rules used?

We address #1-3 through case studies on real-world programming examples, and #4 through quantitative perfor-

mance measurements on simple automatically-generated programs. For the experiments, we assume that the programmer has first confirmed that the program satisfies the conditions allowing proper compilation to an NES, and we assume that the ETS has no loops. Our tool could be modified to perform these checks via basic algorithms operating on the ETS, but they have not yet been implemented in the current prototype (as mentioned in Section 3.1, developing efficient algorithms for these checks is left for future work). Our experimental platform was an Ubuntu machine with 20GB RAM and a quad-core Intel i5-4570 CPU (3.2 GHz).

To choose a representative set of realistic examples, we first studied the examples addressed in other recent stateful network programming approaches, such as SNAP [3], FlowLog [31], Kinetic [21], NetEgg [39], and FAST [30], and categorized them into three main groups:

- **Protocols/Security:** accessing streaming media across subnets, ARP proxy, **firewall with authentication**, FTP monitoring, **MAC learning**, **stateful firewall**, TCP re-assembly, Virtual Machine (VM) provisioning.
- **Measurement/Performance:** heavy hitter detection, **bandwidth cap management (uCap)**, connection affinity in load balancing, counting domains sharing the same IP address, counting IP addresses under the same domain, elephant flows detection, link failure recovery, load balancing, network information base (NIB), QoS in multimedia streaming, rate limiting, sampling based on flow size, Snort flowbits, super spreader detection, tracking flow-size distributions.
- **Monitoring/Filtering:** application detection, DNS amplification mitigation, DNS TTL change tracking, DNS tunnel detection, **intrusion detection system (IDS)**, optimistic ACK attack detection, phishing/spam detection, selective packet dropping, sidejack attack detection, stolen laptop detection, SYN flood detection, UDP flood mitigation, walled garden.

As we will see in the following section, our current prototype system is best suited for writing programs such as the ones in the *Protocols/Security* category, since some of the *Measurement/Performance* programs require timers and/or integer counters, and some of the *Monitoring/Filtering* programs require complex pattern matching of (and table lookups based on) sequences of packets—functionality which we do not (yet) natively support. Thus, we have selected three examples from the first category, and one from each of the latter two, corresponding to the boldface applications in the list. We believe that these applications are representative of the basic types of behaviors seen in the other listed applications.

5.1 Case Studies

In the first set of experiments, we compare *correct* behavior (produced by our implementation strategy) with that of an *uncoordinated* update strategy. We simulate an uncoordinated strategy in the following way: events are sent to the controller, which pushes updates to the switches (in an un-

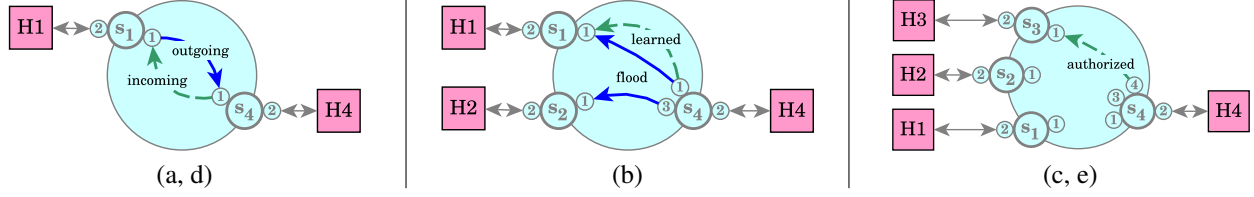


Figure 8: Topologies: (a) Firewall, (b) Learning Switch, (c) Authentication, (d) Bandwidth Cap, (e) Intrusion Detection System.

```

(a)
pt=2 ∧ ip_dst=H4; pt←1; (state=[0];
(1:1)→(4:1)→(state←[1]) + state≠[0];
(1:1)→(4:1); pt←2
+ pt=2 ∧ ip_dst=H1; state=[1]; pt←1;
(4:1)→(1:1); pt←2

(b)
pt=2 ∧ ip_dst=H1; (pt←1; (4:1)→(1:1) +
state=[0]; pt←3; (4:3)→(2:1)); pt←2
+ pt=2 ∧ ip_dst=H4; pt←1; (1:1)→(4:1)→(
state←[1]); pt←2
+ pt=2; pt←1; (2:1)→(4:3); pt←2

(c)
state=[0] ∧ pt=2 ∧ ip_dst=H1; pt←1;
(4:1)→(1:1)→(state←[1]); pt←2
+ state=[1] ∧ pt=2 ∧ ip_dst=H2; pt←3;
(4:3)→(2:1)→(state←[2]); pt←2
+ state=[2] ∧ pt=2 ∧ ip_dst=H3; pt←4;
(4:4)→(3:1); pt←2
+ pt=2; pt←1; ((1:1)→(4:1) + (2:1)→(4:3) +
(3:1)→(4:4)); pt←2

(d)
pt=2 ∧ ip_dst=H4;
pt←1; (
state=[0]; (1:1)→(4:1)→(state←[1])
+ state=[1]; (1:1)→(4:1)→(state←[2])
+ state=[2]; (1:1)→(4:1)→(state←[3])
); pt←2
+ state=[10]; (1:1)→(4:1)→(state←[11])
+ state=[11]; (1:1)→(4:1)
); pt←2
+ pt=2 ∧ ip_dst=H1; state≠[11]; pt←1;
(4:1)→(1:1); pt←2

(e)
pt=2 ∧ ip_dst=H1; pt←1; (state=[0];
(4:1)→(1:1)→(state←[1]) + state≠[0];
(4:1)→(1:1); pt←2
+ pt=2 ∧ ip_dst=H2; pt←3; (state=[1];
(4:3)→(2:1)→(state←[2]) + state≠[1];
(4:3)→(2:1); pt←2
+ pt=2 ∧ ip_dst=H3; pt←4; state≠[2];
(4:4)→(3:1); pt←2
+ pt=2; pt←1; ((1:1)→(4:1) + (2:1)→(4:3) +
(3:1)→(4:4)); pt←2

```

Figure 9: Programs: (a) Firewall, (b) Learning Switch, (c) Authentication, (d) Bandwidth Cap, (e) Intrusion Detection System.

predictable order) after a few-seconds time delay. We believe this delay is reasonable because heavily using the controller and frequently updating switches can lead to delays between operations of several seconds in practice (e.g. [17] reports up to 10s for a single switch update).

To show that problems still arise for smaller delays, in the firewall experiment described next, we varied the time delay in the uncoordinated strategy between 0ms and 5000ms (in increments of 100ms), running the experiment 10 times

for each. We then plotted the total number of incorrectly-dropped packets with respect to delay. The results are shown in Figure 10. Note that even with a very small delay, the uncoordinated strategy still always drops at least one packet.

Stateful Firewall. The example in Figures 8-9(a) is a simplified stateful firewall. It always allows “outgoing” traffic (from H1 to H4), but only allows “incoming” traffic (from H4 to H1) after the outside network has been contacted, i.e. “outgoing” traffic has been forwarded to H4.

Program p corresponds to configurations $C_{[0]} = \llbracket p \rrbracket_{[0]}$ and $C_{[1]} = \llbracket p \rrbracket_{[1]}$. In the former, only outgoing traffic is allowed, and in the latter, both outgoing and incoming are allowed. The ETS has the form $\{\langle [0] \rangle \xrightarrow{(dst=H4, 4:1)} \langle [1] \rangle\}$. The NES has the form $\{E_0=\emptyset \rightarrow E_1=\{(dst=H4, 4:1)\}\}$, where the g is given by $g(E_0) = C_{[0]}$, $g(E_1) = C_{[1]}$.

The Stateful Firewall example took 0.013s to compile, and produced a total of 18 flow-table rules. In Figure 11(a), we show that the running firewall has the expected behavior. We first try to ping H1 from H4 (the “H4-H1”/red points), which fails. Then we ping H4 from H1 (the “H1-H4”/orange points), which succeeds. Again we try H4-H1, and now this succeeds, since the event-triggered state change occurred.

For the uncoordinated strategy, Figure 11(b) shows that some of the H1-H4 pings get dropped (i.e. H1 does not hear back from H4), meaning the state change did not behave as if it was caused immediately upon arrival of a packet at S4.

Learning Switch. The example in Figures 8-9(b) is a simple learning switch. Traffic from H4 to H1 is flooded (sent to both H1 and H2), until H4 receives a packet from H1, at

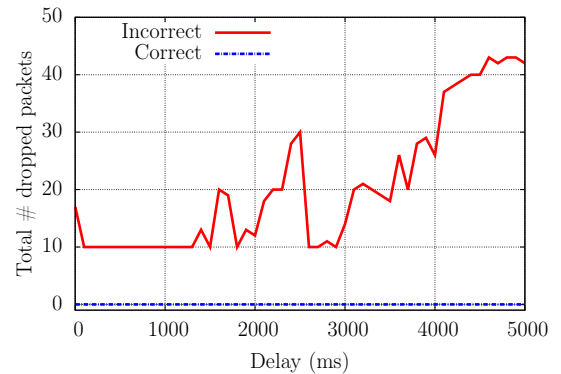


Figure 10: Stateful Firewall: impact of delay.

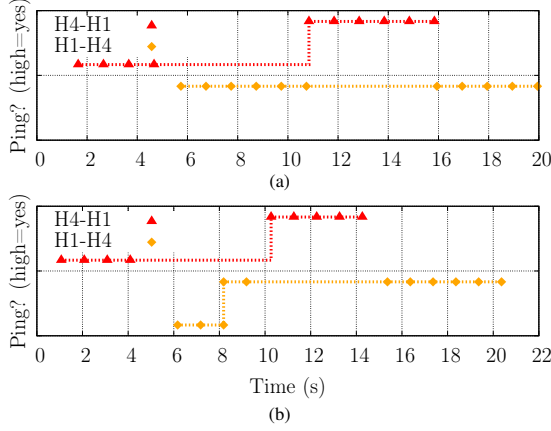


Figure 11: Stateful Firewall: (a) correct vs. (b) incorrect.

which point it “learns” the address of H1, and future traffic from H4 to H1 is sent only to H1.

This program p corresponds to two configurations $C_{[0]} = \llbracket p \rrbracket_{[0]}$ and $C_{[1]} = \llbracket p \rrbracket_{[1]}$. In the former, flooding occurs from H4, and in the latter, packets from H4 are forwarded directly to H1. The ETS has the form $\{\langle [0] \rangle \xrightarrow{(dst=H4, 4:1)} \langle [1] \rangle\}$. The NES has the form $\{E_0=\emptyset \rightarrow E_1=\{(dst=H4, 4:1)\}\}$, where the g is given by $g(E_0) = C_{[0]}$, $g(E_1) = C_{[1]}$.

This only allows learning for a single host (H1), but we could easily add learning for H2 by using a different index in the vector-valued *state* field: we could replace **state** in Figure 9(b) with **state**(0), and union the program (using the NetKAT “+” operator) with another instance of Figure 9(b) which learns for H2 and uses **state**(1).

The Learning Switch example took 0.015s to compile, and produced a total of 43 flow-table rules. We again compare the behavior of our correct implementation with that of an implementation which uses an uncoordinated update strategy. We first ping H1 from H4. Expected behavior is shown in Figure 12(a), where the first packet is flooded to both H1 and H2, but then H4 hears a reply from H1, causing

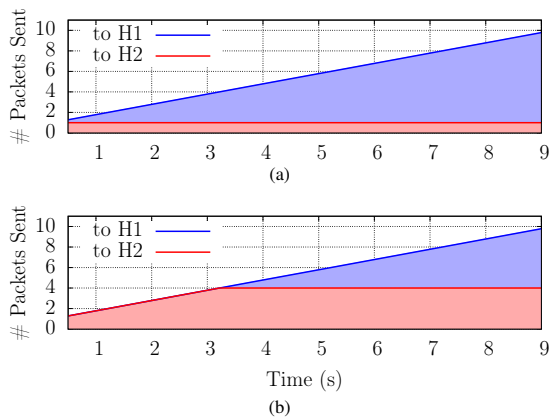


Figure 12: Learning Switch: (a) correct vs. (b) incorrect.

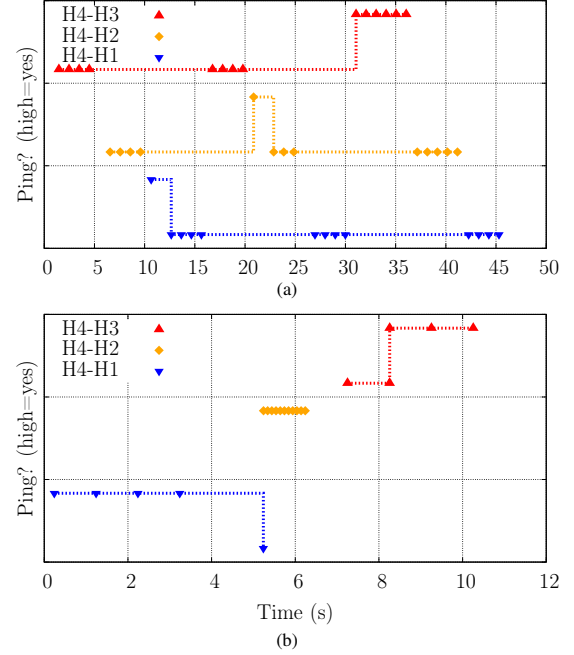


Figure 13: Authentication: (a) correct vs. (b) incorrect.

the state change (i.e. learning H1’s address), and all subsequent packets are sent only to H1. In Figure 12(b), however, since the state change can be delayed, multiple packets are sent to H2, even after H4 has seen a reply from H1.

Authentication. In this example, shown in Figures 8-9(c), the untrusted host H4 wishes to contact H3, but can only do so after contacting H1 and then H2, in that order.

This program p corresponds to three configurations: $C_{[0]} = \llbracket p \rrbracket_{[0]}$ in which only H4-H1 traffic is enabled, $C_{[1]} = \llbracket p \rrbracket_{[1]}$ in which only H4-H2 traffic is enabled, and $C_{[2]} = \llbracket p \rrbracket_{[2]}$ which finally allows H4 to communicate with H3. The ETS has the form $\{\langle [0] \rangle \xrightarrow{(dst=H1, 1:1)} \langle [1] \rangle \xrightarrow{(dst=H2, 2:1)} \langle [2] \rangle\}$. The NES has the form $\{E_0=\emptyset \rightarrow E_1=\{(dst=H1, 1:1)\} \rightarrow E_2=\{(dst=H1, 1:1), (dst=H2, 2:1)\}\}$, where the g function is given by $g(E_0) = C_{[0]}$, $g(E_1) = C_{[1]}$, $g(E_2) = C_{[2]}$.

The Authentication example took 0.017s to compile, and produced a total of 72 flow-table rules. In Figure 13(a) we demonstrate the correct behavior of the program, by first trying (and failing) to ping H3 and H2 from H4, then successfully pinging H1, again failing to ping H3 (and H1), and finally succeeding in pinging H3. The incorrect (uncoordinated) implementation in Figure 13(b) allows an incorrect behavior where we can successfully ping H1 and then H2, but then fail to ping H3 (at least temporarily).

Bandwidth Cap. The Figure 8-9(d) example is a simplified bandwidth cap implementation. It allows “outgoing” traffic (H1-H4), but only until the limit of n packets has been reached, at which point the service provider replies with a

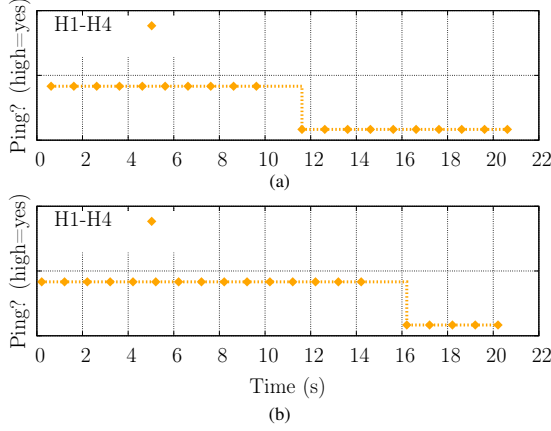


Figure 14: Bandwidth Cap: (a) correct vs. (b) incorrect.

notification message, and disallows the “incoming” path. In this experiment, we use a bandwidth cap of $n = 10$ packets.

Program p corresponds to configurations $C_{[0]} = \llbracket p \rrbracket_{[0]}$, $\dots$, $C_{[n]} = \llbracket p \rrbracket_{[n]}$, which all allow incoming/outgoing traffic, and a configuration $C_{[n+1]} = \llbracket p \rrbracket_{[n+1]}$ which disallows the incoming traffic. The ETS has the form $\{\langle [0] \rangle \xrightarrow{(dst=H4, 4:1)} \langle [1] \rangle \xrightarrow{(dst=H4, 4:1)} \dots \xrightarrow{(dst=H4, 4:1)} \langle [n+1] \rangle\}$. The NES has the form $\{E_0 = \emptyset \rightarrow E_1 = \{(dst=H4, 4:1)\} \rightarrow \dots \rightarrow E_{n+1} = \{(dst=H4, 4:1)_0, \dots, (dst=H4, 4:1)_n\}\}$, where the g is given by $g(E_0) = C_{[0]}, \dots, g(E_{n+1}) = C_{[n+1]}$. Note that the subscripts on events in the NES event-sets (e.g. the ones in E_{n+1}) indicate “renamed” copies of the same event (as described in Section 3.1).

The Bandwidth Cap example took 0.023s to compile, and produced a total of 158 flow-table rules. In Figure 14(a), we show that the running example has the expected behavior. We send pings from H1 to H4, of which exactly 10 succeed, meaning we have reached the bandwidth cap. Using the uncoordinated update strategy in Figure 14(b), we again send pings from H1 to H4, but in this case, 15 are successful, exceeding the bandwidth cap.

Intrusion Detection System. In this example, shown in Figures 8-9(e), the external host H4 is initially free to communicate with the internal hosts H1, H2, and H3. However, if H4 begins engaging in some type of suspicious activity (in this case, beginning to scan through the hosts, e.g. contacting H1 and then H2, in that order), the activity is thwarted (in this case, by cutting off access to H3).

This program p corresponds to three configurations: $C_{[0]} = \llbracket p \rrbracket_{[0]}$ and $C_{[1]} = \llbracket p \rrbracket_{[1]}$, in which all traffic is enabled, and $C_{[2]} = \llbracket p \rrbracket_{[2]}$ in which H4-H3 communication is disabled. The ETS has the form $\{\langle [0] \rangle \xrightarrow{(dst=H1, 1:1)} \langle [1] \rangle \xrightarrow{(dst=H2, 2:1)} \langle [2] \rangle\}$. The NES has the form $\{E_0 = \emptyset \rightarrow E_1 = \{(dst=H1, 1:1)\} \rightarrow E_2 = \{(dst=H1, 1:1), (dst=H2, 2:1)\}\}$, where the g function is given by $g(E_0) = C_{[0]}$, $g(E_1) = C_{[1]}$, $g(E_2) = C_{[2]}$.

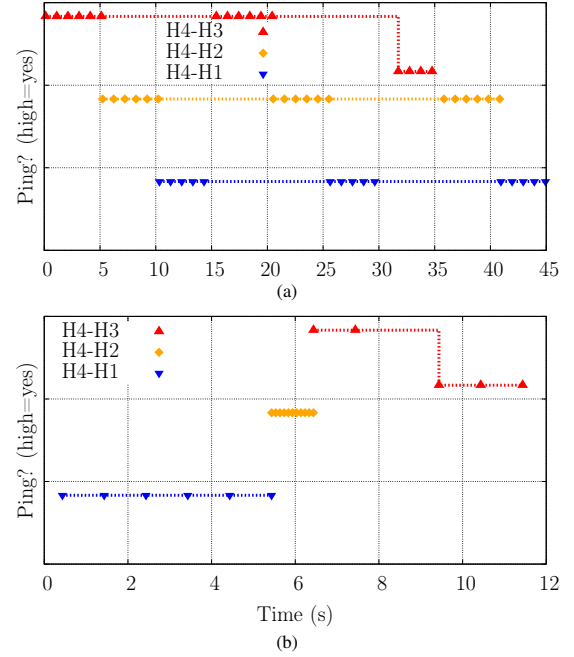


Figure 15: Intrusion Detection System: (a) correct vs. (b) incorrect.

This IDS example took 0.021s to compile and produced 152 flow-table rules. In Figure 15(a), we demonstrate the correct behavior of the program, by first successfully pinging H3, H2, H1, H3, H2, H1 (in that order) from H4. This results in a situation where we have contacted H1 and then H2, causing the third attempt to contact H3 to be blocked (H4-H3 pings dropped). The incorrect (uncoordinated) implementation in Figure 15(b) allows a faulty behavior where we can successfully ping H1 and then H2 (in that order), but subsequent H4-H3 traffic is still enabled temporarily.

5.2 Quantitative Results

In this experiment, we automatically generated some event-driven programs which specify that two hosts H1 and H2 are connected to opposite sides of a ring of switches. Initially, traffic is forwarded clockwise, but when a specific switch detects a (packet) event, the configuration changes to forward counterclockwise. We increased the “diameter” of the ring (distance from H1 to H2) up to 8, as shown in Figure 16, and performed the following two experiments.

1. We used `iperf` to measure H1-H2 TCP/UDP bandwidth, and compared the performance of our running event-driven program, versus that of the initial (static) configuration of the program running on un-modified OpenFlow 1.0 reference switches/controller. Figure 16(a) shows that our performance (solid line) is very close to the performance of a system which does not do packet tagging, event detection, etc. (dashed line)—we see around 6% performance degradation on average (note that the solid and dashed lines almost coincide).

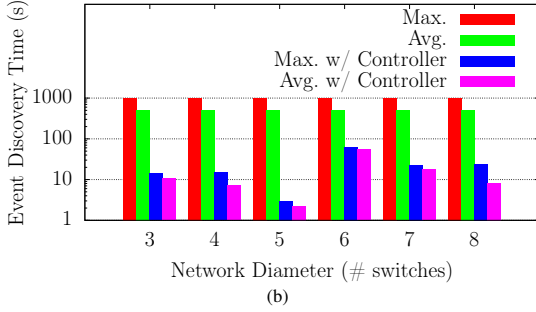
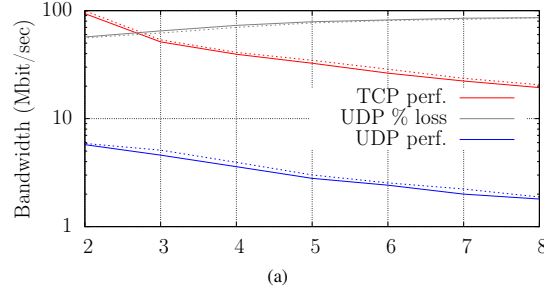


Figure 16: Circular Example: (a) bandwidth (solid line is ours, dotted line is reference implementation) and (b) convergence.

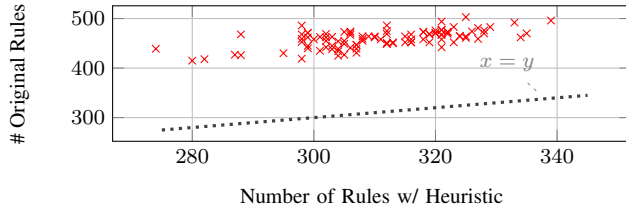


Figure 17: Heuristic: reducing the number of rules.

2. We measured maximum and average time needed for a switch to learn about the event. The “Max.” and “Avg.” bars in Figure 16(b) are these numbers when the controller does not assist in disseminating events (i.e. only the packet digest is used), and the other columns are the maximum and average when the controller does so.

5.3 Optimizations

When a configuration change occurs, the old and new configurations are often similar, differing only in a subset of flow-table rules. Tables are commonly stored in TCAM memory on switches, which is limited/costly, so it is undesirable to store duplicate rules. As mentioned in Section 4.1, each of our rules is guarded by its configuration’s numeric ID. If the same rule occurs in several configurations having IDs with the same (binary) high-order bits, intuitively we can reduce space usage by keeping a single copy of the rule, and guarding it with a configuration ID having the shared high-order bits, and *wildcarded* low-order bits. For example, if rule r is used in two different configurations having IDs 2 (binary 10) and 3 (binary 11), we can wildcard the lowest bit ($1*$), and keep a single rule $(1*)r$ having this wildcarded guard, in-

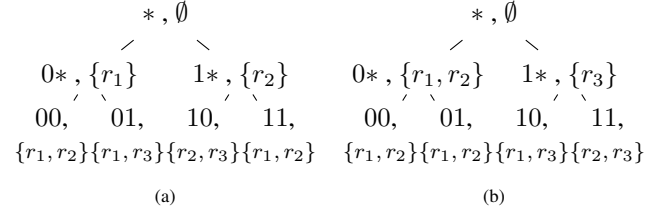


Figure 18: Heuristic: two different tries for the same configurations.

stead of two copies of r , with the “10” and “11” guards. Ideally, we would like to (re)assign numeric IDs to the configurations, such that maximal sharing of this form is achieved.

We formalize the problem as follows. Assume there is a set of all possible rules $\mathcal{R}$. A configuration C is a subset of these rules $C \subseteq \mathcal{R}$. Assume there are k bits in a configuration ID. Without loss of generality we assume there are exactly 2^k configurations (if there are fewer, we can add dummy configurations, each containing all rules in $\mathcal{R}$). For a given set of configurations, we construct a *trie* having all of the configurations at the leaves. This trie is a complete binary tree in which every node is marked with (1) a wildcarded mask that represents the configuration IDs of its children, and (2) the intersection of the rule-sets of its children.

Consider configurations $C_0 = \{r_1, r_2\}$, $C_1 = \{r_1, r_3\}$, $C_2 = \{r_2, r_3\}$, $C_3 = \{r_1, r_2\}$. Figure 18 shows two different assignments of configurations to the leaves of tries. The number of rules for trie (a) is 6: $(0*)r_1$, $(00)r_2$, $(01)r_3$, $(1*)r_2$, $(10)r_3$, $(11)r_1$. The number of rules for trie (b) is 5: $(0*)r_1$, $(0*)r_2$, $(1*)r_3$, $(10)r_1$, $(11)r_2$. Intuitively, this is because the trie (b) has larger sets in the interior. Our polynomial heuristic follows that basic intuition: it constructs the trie from the leaves up, at each level pairing nodes in a way that maximizes the sum of the cardinalities of their sets. This does not always produce the global maximum rule sharing, but we find that it produces good results in practice.

As indicated by the Figure 17 result (64 randomly-generated configurations w/ 20 rules), on average, rule savings was about 32% of the original number of rules. We also ran this on the previously-discussed Firewall, Learning Switch, Authentication, Bandwidth Cap, and IDS examples, and got rule reductions of $18 \rightarrow 16$, $43 \rightarrow 27$, $72 \rightarrow 46$, $158 \rightarrow 101$, and $152 \rightarrow 133$ respectively.

6. Related Work

Network Updates, Verification, and Synthesis. We already briefly mentioned an early approach known as consistent updates [33]. This work was followed by update techniques that respect other correctness properties [25] [17] [40] [26]. These approaches for expressing and verifying correctness of network updates work in terms of *individual* packets.

In event-driven network programs, it is necessary to check properties which describe interactions between *multiple* packets. There are several works which seek to perform

network updates in the context of multi-packet properties [12] [23]. There are also proposals for synthesizing SDN controller programs from multi-packet examples [39] and from first-order specifications [32]. Lopes et al. presented techniques for verifying reachability in stateful network programs [24], using a variant of Datalog. This is a complimentary approach which could be used as a basis for verifying reachability properties of our stateful programs.

Network Programming Languages. Network programs can often be constructed using high-level languages. The Frenetic project [10] [27] [11] allows higher-level specification of network policies. Other related projects like Merlin [36] and NetKAT [35] [4] provide high-level languages/tools to compile such programs to network configurations. Works such as Maple [37] and FlowLog [31] seek to address the *dynamic* aspect of network programming.

None of these systems and languages provide both (1) event-based constructs, and (2) strong semantic guarantees about consistency during updates, while our framework enables both. Concurrently with this paper, an approach called SNAP [3] was developed, which enables event-driven programming, and allows the programmer to ensure consistency via an *atomic* language construct. Their approach offers a more expressive language than our Stateful NetKAT, but in our approach, we enable correct-by-construction event-based behavior and provide a dynamic correctness property, showing (formally) that is strong enough for easy reasoning, yet flexible enough to enable efficient implementations. We also prove the correctness of our implementation technique.

Routing. The consistency/availability trade-off is of interest in routing outside the SDN context as well. In [18], a solution called consensus routing is presented, based on a notion of causality between *triggers* (related to our events). However, the solution is different in many aspects, e.g. it allows a transient phase without safety guarantees.

High-Level Network Functionality. Some recent work has proposed building powerful high-level features into the network itself, such as fabrics [9], intents [1], and other virtualization functionality [22]. Pyretic [28] and projects built on top of it such as PyResonance [20], SDX [14], and Kinetic [21] provide high-level operations on which network programs can be built. These projects do not guarantee consistency during updates, and thus could be profitably combined with an approach such as ours.

7. Discussion and Future Work

Generality of Our Approach. The event-driven SDN update problem considered in this paper is an instance of a more general distributed-systems programming problem, namely *how to write correct and efficient programs for distributed systems*. We provide a PL approach (consistency property, programming language, and compiler/runtime) which ensures that the programmer need not reason about

interleavings of events and updates for each application, and we show that our consistency model and implementation technique work well in the context of SDN programs, but we do not believe they are limited to that specific arena. Our approach could also possibly be extended to other distributed systems in which availability is prioritized, and consistency can be relaxed in a well-defined way, as in our event-driven consistent updates. Example domains include wireless sensor networks or other message-passing systems where the nodes have basic stateful functionality.

Future Work. There are several directions for future work which could address limitations of our current system.

1. We assume that the set of (potential) hosts is known in advance, and use this information to generate corresponding flow tables for each switch. This may not be the right choice in settings where hosts join/leave. Our approach could be extended to represent hosts *symbolically*.
2. We currently store all configurations on the switches, so that they are immediately available during updates. Our optimizations allow this to be done in a space-efficient way, but there may be situations when it would be better for the controller to reactively push new configurations to switches. This is an interesting problem due to interleavings of events and controller commands.
3. It would be interesting to consider formal reasoning and automated verification for Stateful NetKAT.
4. We provide a solution to the problem of performing multiple updates, and the dynamic implementations we produce are meant to “run” in the network indefinitely. However, there may be ways to update the running dynamic program itself in some consistent way.

8. Conclusion

This paper presents a full framework for correct event-driven programming. Our approach provides a way of rigorously defining correct event-driven behavior without the need for specifying logical formulas. We detail a programming language and compiler which allow the user to write high-level network programs and produce correct and efficient SDN implementations, and we demonstrate the benefits of our approach using real-world examples. This paper considers the challenging problem of distributing an event-based stateful network program, and solves it in a principled way.

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References

- [1] ONOS Intent Framework. 2014. URL <https://wiki.onosproject.org/x/XgAZ>.
- [2] C. J. Anderson, N. Foster, A. Guha, J.-B. Jeannin, D. Kozen, C. Schlesinger, and D. Walker. NetKAT: Semantic Foundations for Networks. *POPL*, 2014.
- [3] M. T. Arashloo, Y. Koral, M. Greenberg, J. Rexford, and D. Walker. SNAP: Stateful Network-Wide Abstractions for Packet Processing. 2015.
- [4] R. Beckett, M. Greenberg, and D. Walker. Temporal NetKAT. *PLVNET*, 2015.
- [5] G. Bianchi, M. Bonola, A. Capone, and C. Cascone. OpenState: Programming Platform-independent Stateful Openflow Applications Inside the Switch. *ACM SIGCOMM CCR*, 2014.
- [6] P. Bosshart, D. Daly, G. Gibb, M. Izzard, N. McKeown, J. Rexford, C. Schlesinger, D. Talayco, A. Vahdat, G. Varghese, et al. P4: Programming Protocol-independent Packet Processors. *ACM SIGCOMM CCR*, 2014.
- [7] E. Brewer. Towards robust distributed systems (abstract). *PODC*, page 7, 2000.
- [8] M. Casado, M. J. Freedman, J. Pettit, J. Luo, N. McKeown, and S. Shenker. Ethane: Taking Control of the Enterprise. *SIGCOMM*, 2007.
- [9] M. Casado, T. Koponen, S. Shenker, and A. Tootoonchian. Fabric: A Retrospective on Evolving SDN. *HotSDN*, 2012.
- [10] N. Foster, R. Harrison, M. J. Freedman, C. Monsanto, J. Rexford, A. Story, and D. Walker. Frenetic: A Network Programming Language. *ICFP*, 2011.
- [11] N. Foster, A. Guha, M. Reitblatt, A. Story, M. J. Freedman, N. P. Katta, C. Monsanto, J. Reich, J. Rexford, C. Schlesinger, et al. Languages for Software-Defined Networks. *Communications Magazine, IEEE*, 51(2):128–134, 2013.
- [12] S. Ghorbani and B. Godfrey. Towards Correct Network Virtualization. *HotSDN*, 2014.
- [13] S. Gilbert and N. Lynch. Perspectives on the CAP Theorem. *IEEE Computer*, 45(2):30–36, 2012.
- [14] A. Gupta, L. Vanbever, M. Shahbaz, S. P. Donovan, B. Schlinker, N. Feamster, J. Rexford, S. Shenker, R. Clark, and E. Katz-Bassett. SDX: A Software Defined Internet Exchange. *SIGCOMM*, 2014.
- [15] C.-Y. Hong, S. Kandula, R. Mahajan, M. Zhang, V. Gill, M. Nanduri, and R. Wattenhofer. Achieving High Utilization with Software-driven WAN. *SIGCOMM*, 2013.
- [16] S. Jain et al. B4: Experience with a Globally-Deployed Software Defined WAN. *SIGCOMM*, 2013.
- [17] X. Jin, H. H. Liu, R. Gandhi, S. Kandula, R. Mahajan, M. Zhang, J. Rexford, and R. Wattenhofer. Dynamic Scheduling of Network Updates. *SIGCOMM*, 2014.
- [18] J. John, E. Katz-Bassett, A. Krishnamurthy, T. Anderson, and A. Venkataramani. Consensus Routing: The Internet as a Distributed System. *NSDI*, 2008.
- [19] N. Kang, Z. Liu, J. Rexford, and D. Walker. Optimizing the One Big Switch Abstraction in Software-Defined Networks. *CoNEXT*, 2013.
- [20] H. Kim, A. Gupta, M. Shahbaz, J. Reich, N. Feamster, and R. Clark. Simpler Network Configuration with State-Based Network Policies. Technical report, Georgia Tech, 2013.
- [21] H. Kim, J. Reich, A. Gupta, M. Shahbaz, N. Feamster, and R. Clark. Kinetic: Verifiable Dynamic Network Control. *NSDI*, 2015.
- [22] T. Koponen, K. Amidon, P. Baland, M. Casado, A. Chanda, B. Fulton, I. Ganichev, J. Gross, N. Gude, P. Ingram, et al. Network Virtualization in Multi-tenant Datacenters. *NSDI'14*.
- [23] W. Liu, R. B. Bobba, S. Mohan, and R. H. Campbell. Inter-Flow Consistency: Novel SDN Update Abstraction for Supporting Inter-Flow Constraints. *NDSS*, 2015.
- [24] N. P. Lopes, N. Bjørner, P. Godefroid, K. Jayaraman, and G. Varghese. Checking Beliefs in Dynamic Networks. *NSDI*, 2015.
- [25] A. Ludwig, M. Rost, D. Foucard, and S. Schmid. Good Network Updates for Bad Packets: Waypoint Enforcement Beyond Destination-based Routing Policies. *HotNets*, 2014.
- [26] J. McClurg, H. Hojjat, P. Cerny, and N. Foster. Efficient Synthesis of Network Updates. *PLDI*, 2015.
- [27] C. Monsanto, N. Foster, R. Harrison, and D. Walker. A Compiler and Run-time System for Network Programming Languages. *POPL*, 2012.
- [28] C. Monsanto, J. Reich, N. Foster, J. Rexford, and D. Walker. Composing Software Defined Networks. *NSDI*, 2013.
- [29] M. Moshref, M. Yu, A. B. Sharma, and R. Govindan. Scalable Rule Management for Data Centers. *NSDI*, 2013.
- [30] M. Moshref, A. Bhargava, A. Gupta, M. Yu, and R. Govindan. Flow-level State Transition as a New Switch Primitive for SDN. 2014.
- [31] T. Nelson, A. D. Ferguson, M. Scheer, and S. Krishnamurthi. Tierless Programming and Reasoning for Software-Defined Networks. *NSDI*, 2014.
- [32] O. Padon, N. Immerman, A. Karbyshev, O. Lahav, M. Sagiv, and S. Shoham. Decentralizing SDN Policies. *POPL*, 2015.
- [33] M. Reitblatt, N. Foster, J. Rexford, C. Schlesinger, and D. Walker. Abstractions for Network Update. *SIGCOMM'12*.
- [34] A. Sivaraman, M. Budiu, A. Cheung, C. Kim, S. Licking, G. Varghese, H. Balakrishnan, M. Alizadeh, and N. McKeown. Packet Transactions: A Programming Model for Data-Plane Algorithms at Hardware Speed. 2015.
- [35] S. Smolka, S. Eliopoulos, N. Foster, and A. Guha. A Fast Compiler for NetKAT. *ICFP*, 2015.
- [36] R. Soulé, S. Basu, P. J. Marandi, F. Pedone, R. Kleinberg, E. G. Sirer, and N. Foster. Merlin: A Language for Provisioning Network Resources. *CoNEXT*, 2014.
- [37] A. Voellmy, J. Wang, Y. R. Yang, B. Ford, and P. Hudak. Maple: Simplifying SDN Programming Using Algorithmic Policies. *SIGCOMM*, 2013.
- [38] G. Winskel. *Event Structures*. Springer, 1987.
- [39] Y. Yuan, D. Lin, R. Alur, and B. T. Loo. Scenario-based Programming for SDN Policies. *CoNEXT*, 2015.
- [40] W. Zhou, D. Jin, J. Croft, M. Caesar, and P. B. Godfrey. Enforcing Generalized Consistency Properties in Software-Defined Networks. *NSDI*, 2015.