Inferring Models of Concurrent Systems from Logs of their Behavior with CSight

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ABSTRACT

Concurrent systems are notoriously difficult to debug and understand. A common way of gaining insight into system behavior is to inspect execution logs and documentation. Unfortunately, manual inspection of logs is an arduous process, and documentation is often incomplete and out of sync with the implementation.

To provide developers with more insight into concurrent systems, we developed CSight. CSight mines logs of a system's executions to infer a concise and accurate model of that system's behavior, in the form of a communicating finite state machine (CFSM).

Engineers can use the inferred CFSM model to understand complex behavior, detect anomalies, debug, and increase confidence in the correctness of their implementations. CSight's only requirement is that the logged events have vector timestamps. We provide a tool that automatically adds vector timestamps to system logs. Our tool prototypes are available at http://synoptic.googlecode.com/.

This paper presents algorithms for inferring CFSM models from traces of concurrent systems, proves them correct, provides an implementation, and evaluates the implementation in two ways: by running it on logs from three different networked systems and via a user study that focused on bug finding. Our evaluation finds that CSight infers accurate models that can help developers find bugs.

1. INTRODUCTION

When a system behaves in an unexpected manner, or when a developer must make changes to legacy code, the developer faces the challenging task of understanding the system's behavior. To help with this task, developers often enable logging and analyze runtime logs. Unfortunately, the size and complexity of logs often exceed a human's ability to navigate and make sense of the captured data.

One promising approach to help developers is model inference. The goal of a model-inference algorithm is to convert a log of system executions into a model, typically a finite state machine, that accurately and concisely represents the system that generated the log. Numerous model-inference algorithms and tools exist to help debug, verify, and validate *sequential* programs [11, 43, 44, 10].

Unfortunately, this rich prior body of work is not directly applicable to distributed or concurrent systems. This is because a common assumption made in model inference is that the underlying set of executions is totally ordered — for every pair of events in an execution, one precedes the other. This assumption is crucial to the inference algorithms' correctness, and running them on logs that are not totally ordered results in inaccurate models. Unfortunately, this assumption does not hold for concurrent systems, such as networked systems, for which events at different nodes may occur without happens-before relationships [40]. Additionally, most model-inference algorithms infer finite state machine (FSM) models, which are inappropriate for modeling multi-process implementations.

This paper describes a new model-inference technique and a corresponding tool, called CSight (for "concurrency insight"), which infers a communicating finite state machine (CFSM) [14] model of the processes that generated the log. CSight can be applied to logs of distributed systems, protocol traces, traces of AJAX events in a web-browser, and other concurrent behavior traces. CSight models have multiple developer-oriented uses — for example, developers can inspect, query, and check CSight's models against their own mental model of the system to find bugs. These uses are the focus of our present work. However, we believe that CSight-generated models have numerous other applications, such as model-based testing of concurrent systems, and automated detection of anomalous behavior as systems are exposed to new workloads and environments.

This paper presents the following four contributions:

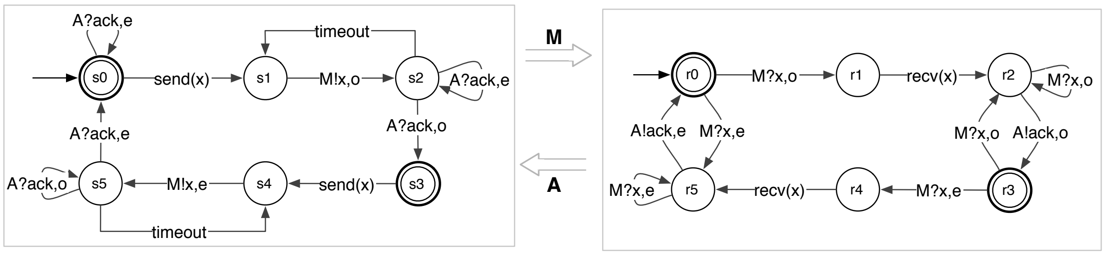
1. A novel model-inference algorithm to infer a CFSM model from a log of vector-timestamped concurrent executions (Section 3), and a corresponding tool called CSight.
2. A proof that the CFSM models generated by CSight are accurate, in the sense that they satisfy several key properties of the input log (Section 4).
3. A tool for automatically augmenting existing process-local logging mechanisms with vector-timestamping logic. This makes it easy to apply CSight to existing systems (Section 5).
4. A two-pronged evaluation of CSight (Section 6):
   - We applied CSight to logs of three systems — the stop-and-wait protocol, the opening/closing handshakes of TCP, and the replication strategy in the Voldemort [57] distributed hash table. CSight was effective for uncovering the true model for each of these systems.
   - We performed a user study with a class of 39 undergraduates to evaluate the efficacy of CFSM models in finding bugs. We found that CFSM models are just as useful in finding implementation bugs as time-space diagrams, a popular alternative for visualizing concurrent executions.

We start with an overview of the CSight algorithm (Section 2).

2. CSIGHT OVERVIEW

CSight's input is a log of observed system execution events, and its output is a model that describes the concurrent system that generated the log. An input log consists of *execution traces* of the system. A trace is a set of events, each of which has a vector timestamp [25, 46]. Vector time is a standard logical clock mechanism that provides

Sender	Receiver
1,0 send(x)	2,1 M?x,o
2,0 M!x,o	2,2 recv(x)
3,3 A?ack,o	2,3 A!ack,o
4,3 send(x)	5,4 M?x,e
5,3 M!x,e	5,5 recv(x)
6,6 A?ack,e	5,6 A!ack,e
7,6 send(x)	8,7 M?x,o
8,6 M!x,o	8,8 recv(x)
9,9 A?ack,o	8,9 A!ack,o
10,9 send(x)	11,10 M?x,e
11,9 M!x,e	11,11 recv(x)
12,12 A?ack,e	11,12 A!ack,e



(a) Input log **(b.1) Output model (Sender)** **(b.2) Output model (Receiver)**

Figure 1: Example input and output of CSight for the stop-and-wait protocol (SAW) [55]. (a) Example input log with a single trace of two processes running SAW. The two integers at the beginning of each event in the log are the event's vector clock timestamp. (b) The CSight-derived CFSM model of SAW, derived from a log with additional traces (not-shown), consisting of (b.1) the sender process model and (b.2) the receiver process model.
In SAW, the sender transmits messages to the receiver using channel `M`, and the receiver replies with acknowledgments through channel `A`. Notation `Q!x` means enqueue message `x` at tail of channel `Q`, and event `Q?x` means dequeue message `x` from the head of channel `Q`. The event `send(x)` is a down-call to send `x` at the sender, and `recv(x)` is an up-call at the receiver indicating that `x` was received. In the SAW implementation, `x` is a variable that stands for an arbitrary message string. CSight, however, treats the logged event instances, like "send(x)" and "timeout", as strings and does not interpret them. The `timeout` event at the sender triggers a message re-transmission after some internal timeout threshold is reached. The "alternating bit" is associated with each message and is appended to a message before it is sent. For example, the first (and every odd) message sent by the sender is represented as `x,o` (`o` for odd) while every even message sent by the sender is encoded as `x,e` (`e` for even).

a partial order of events in the system. Section 5 describes a tool that automatically adds vector time tracking to existing systems.

Figure 1(a) shows an example input log generated by two processes executing the stop-and-wait protocol [55]. In this protocol, a *sender* process communicates a sequence of messages to a *receiver* process over an unreliable channel. The receiver must acknowledge an outstanding message before the sender moves on to the next message. If a message is delayed or lost, the sender retransmits the message after a timeout.

Figure 1(b) shows CSight's output — a communicating finite state machine [14] (CFSM) model. A CFSM models multiple processes, or threads of execution, each of which is described by a finite state machine (FSM). In the standard CFSM formalism, processes communicate with one another via message passing over reliable FIFO channels. However, unreliable channels can be simulated by replacing each unreliable channel with a lossy "middlebox" FSM that non-deterministically chooses between forwarding and losing a message. The model in Figure 1(b) handles message loss, but the lossy middlebox is not shown in the diagram.

We use the CFSM formalism because it is similar to the widely known FSM formalism. CFSMs are well-established in the formal methods community, and we believe (and empirically verify in Section 6) that a CFSM is intuitive and sufficiently simple for developers to comprehend. For example, a single-process FSM in a CFSM can be inspected and understood without needing to understand the activity of other processes in the system.

CSight infers a CFSM (e.g., Figure 1(b)) by transforming the input log (e.g., Figure 1(a)) through a series of representations and analyses. Figure 2 details this process. The CSight process has three key stages:

Stage 1: temporal property mining. CSight mines temporal properties, or invariants, from the log (steps ① and ② in Figure 2). For example, for the log in Figure 1(a), CSight would mine the property "event instance string `send(x)` always precedes the event instance string `receive(x)`". Section 3.2 describes all the types of properties CSight mines. CSight uses these properties to judge the accuracy of the current model, as it refines the model to accurately describe the log.

Stage 2: create initial model. CSight uses the log to build a compact model (steps ③ and ④ in Figure 2). This model generalizes all the executions in the log, and it is inaccurate in that it admits executions that violate the properties mined from step one. To build this small model CSight assumes that whenever an event of a particular type executes, the system must be in a unique state associated with events of that type. For example, every time the log has a `send(x)` event, CSight assumes the system was in the exact same `send(x)` state. This creates an overly permissive but highly compact model.

Stage 3: refine the model. CSight gradually changes the initial compact model from stage 2 into a larger model that satisfies all of the mined properties from stage 1 (steps ⑤ and ⑥ in Figure 2). To accomplish this, CSight checks which of the mined properties are not satisfied by the present model. A property is not satisfied if the model allows an execution that violates the property. CSight checks properties with model checking, which either guarantees that the property is satisfied by all modeled executions, or finds a counter-example execution that violates the property. If a counter-example exists, CSight refines the model to eliminate that counter-example using the CEGAR approach [16]. CSight repeats the model-checking and refinement loop until all of the mined properties are satisfied, at which point it outputs the resulting model.

The next section formally describes the CSight process and details each of the steps in Figure 2.

3. FORMAL DESCRIPTION OF CSIGHT

In Section 4, we will prove three important properties about CSight's model-inference process:

- **Inferred model fits the input log.** The final model accepts all the observed traces in the input log (see Theorem 1).
- **Refinement always makes progress.** Every iteration of the refinement process (stage 3 in Section 2) makes progress toward satisfying all of the mined invariants (see Theorem 2).
- **Inferred model satisfies mined invariants.** Every trace accepted by the final model behaves like the observed traces; that is, every invariant that is true of the observed traces is also true of every accepted trace (see Theorem 3).

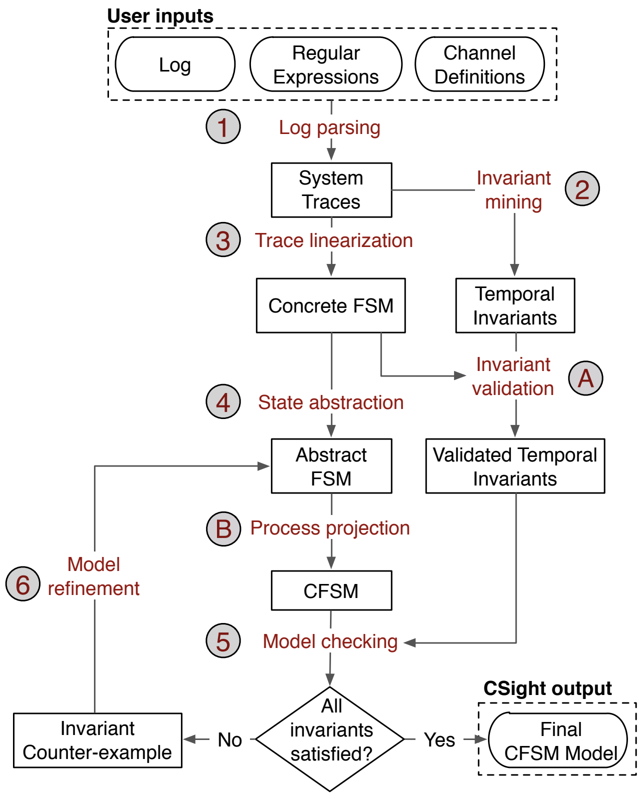


Figure 2: CSight process flow chart. Section 3 describes the numbered steps. Steps (A) and (B) are distinguished with letters as they do not appear in [8].

To enable proving these properties, we must first formalize the problem domain. A reader who wishes to only get an intuitive understanding of the approach can skim this section.

We start by defining CSight's inputs (Section 3.1) and the invariants that CSight mines (Section 3.2). Then, we specify how CSight converts a log into a concrete FSM (Section 3.3) and how CSight abstracts the concrete FSM into the initial abstract FSM (AFSM) (Section 3.4). Finally, we describe how CSight model-checks and refines the AFSM to satisfy the valid invariants, and how the AFSM is converted into a CFSM model (Section 3.5).

First, we describe the notation used in the rest of the paper. Given an n-tuple t, let $|t| = n$, and for all $1 \leq i \leq n$, let $t[i]$ refer to the i^{th} component of t; for $i > n$, let $t[i] = \varepsilon$. We write $t'' = t \cdot t'$ to denote concatenation of two tuples: t'' has length $|t| + |t'|$, and for all $1 \leq i \leq |t|$, $t''[i] = t[i]$ and for all $1 \leq i \leq |t'|]$, $t''[|t| + i] = t'[i]$. We call t a *prefix* of t'' iff $\exists t'$ such that $t'' = t \cdot t'$. The projection function π maps a tuple t and a set S to a tuple t' such that t' is generated from t by deleting all components of t that are not in S. Finally, we use the symbol $\hat{}$ to denote variables that represent abstract objects in the modeling process and to differentiate these from concrete features of the input log. For example, for a logged (concrete) event instance e the corresponding abstract event type is denoted as $\hat{e}$.

3.1 Expected log input

To use CSight, the user must provide an input *log*, a set of user-defined regular expressions, and a set of channel definitions (step (1) in Figure 2). The regular expressions determine which log lines are parsed (and which are ignored), what part of a line corresponds to a vector timestamp, and which local, send, or receive event the line represents. The channel definitions are used to associate send and receive events with inter-process channels.

Currently, CSight assumes that the input log contains only complete, non-erroneous executions. We plan to lift this assumption in our future work.

The rest of this section formally describes the structure of the input log. We assume that an input *log L* is produced by a system composed of h processes, indexed from 1 to h. The log contains multiple *system traces*, each of which represents a single concurrent execution of the system. A system trace consists of a set of event instances logged by different processes and a *happens-before* relation [40] (a strict partial ordering over event instances). For example, the log in Figure 1(a) contains a single system trace; in this trace the vector timestamps encode the partial order.

Definition 1 (System trace)**.** A *system trace* is the pair $S = \langle T, \prec \rangle$, where $T = \cup T_i$ is the union of a set of process traces (see Def. 2), one per process; and $\prec$ is the happens-before relation. This relation partially orders event instances at different processes and totally orders event instances (see Def. 3) in each process trace T_i according to their positions in the trace. That is, $\forall e_i = \langle \hat{e}, i, k \rangle \in T_i$, $e'_i = \langle \hat{e'}, i, k' \rangle \in T_i$, $e_i \prec e'_i \iff k < k'$.

S must satisfy three communication consistency constraints: (1) every sent message is received, (2) only sent messages are received, and (3) sent messages on the same channel must be received in FIFO order. The validity of the communication consistency constraints #1 and #3 depends on the underlying message passing protocol.[1]

We express the above three constraints with a bijection between message send and message receive event instances for every pair of processes. For all i, j, let $S_{ij} \subset T$ be the send events along channel c_{ij}, and let $R_{ij} \subset T$ be the receive events along channel c_{ij}. Then $\forall i, j, \exists$ a bijection $f : S_{ij} \to R_{ij}$, such that:

1. $f(s) = r \implies s \prec r$
2. $\forall s_1, s_2 \in S_{ij}, s_1 \prec s_2 \implies f(s_1) \prec f(s_2)$.

A system trace is composed of multiple process traces, and each process trace is the set of event instances generated by a specific process. We assume that each event instance is given a unique position k in a consecutive order, from 1 to the length of the trace.

Definition 2 (Process trace)**.** For the process i, a *process trace* is a set T_i of event instances, such that $\forall k \in [1, |T_i|]$, $\exists \langle \hat{e}, i, k \rangle \in T_i$, and $\langle \hat{e_1}, i, k_1 \rangle \in T_i$ and $\langle \hat{e_2}, i, k_2 \rangle \in T_i \implies k_1 = k_2$.

The execution of each process generates a sequence of event instances, each of which has an event type from a finite alphabet of process event types. These event types can be local events, message send events, or message receive events.

Definition 3 (Event instance)**.** For a process i, an *event instance* is a triple $e = \langle \hat{e}, i, k \rangle$, where $\hat{e}$ is the event type of e, and $k \geq 1$ is an integer that uniquely indicates the order (position) of the event instance, among all event instances generated by process i. When the value of k is not important, we denote this triplet as e_i.

Finally, we assume a fixed set of channels, each of which is used to connect one sender process to one receiver process. Each of the send and receive event types is associated with a channel.

Definition 4 (Channel)**.** A *channel* c_{ij} is identified by a pair of process indices (i, j), where $i \neq j$ and $i, j \in [1, h]$. Indices i and j denote the channel's *sender* and *receiver* process, respectively.

We use the standard notation `!` to denote send events, `?` to denote receive events, and use labels for channels. For example, in Figure 1, the event `M!x,e` is a send of message `x,e` on channel `M`.

[1] In this paper we focus on TCP, which satisfies both assumptions. Generally, TCP is used by the complex systems that CSight targets. Removing these assumptions is future work (see Section 8).

3.2 Invariant mining

CSight uses the log to mine a set of temporal invariants — linear temporal logic expressions — that relate events in the log (step 2 in Figure 2). These invariants (Def. 5) are true for all of the observed execution traces. CSight guarantees that the final inferred CFSM model satisfies all the mined invariants.

Definition 5 (Event invariant)**.** Let L be a log, and let $\hat{a}_i$ and $\hat{b_j}$ be two event types whose corresponding event instances, a_i and b_j, appear at least once in some system trace in L. Then, an *event invariant* is a property that relates $\hat{a}_i$ and $\hat{b_j}$ in one of the following three ways.

$\hat{a}_i \rightarrow \hat{b_j}$ **:** An event instance of type $\hat{a}$ at host i is **always followed by** an event instance of type $\hat{b}$ at host j. Formally: $\forall \langle T, \prec \rangle \in L, \forall a_i \in T, \exists b_j \in T, a_i \prec b_j$.

$\hat{a}_i \not\rightarrow \hat{b_j}$ **:** An event instance of type $\hat{a}$ at host i is **never followed by** an event instance of type $\hat{b}$ at host j. Formally: $\forall \langle T, \prec \rangle \in L, \forall a_i \in T, \nexists b_j \in T, a_i \prec b_j$.

$\hat{a}_i \leftarrow \hat{b_j}$ **:** An event instance of type $\hat{a}$ at host i **always precedes** an event instance of type $\hat{b}$ at host j. Formally: $\forall \langle T, \prec \rangle \in L, \forall b_j \in T, \exists a_i \in T, a_i \prec b_j$.

For example, one invariant of the stop-and-wait protocol model in Figure 1 is `M?m-0` $\rightarrow$ `A?a-0`. The invariant types and the corresponding mining algorithms are described in more detail in [9]. The above invariant types are also exactly the most frequently observed specification patterns formulated by Dwyer et al. [24] for serial systems.[2] In our experience, these invariants were sufficient for capturing key temporal properties of the systems that produced the logs we considered.

3.3 Deriving a concrete FSM

In step 3 of Figure 2, CSight creates a concrete FSM that accepts all possible linearizations of the partially ordered system traces in the log. The concrete FSM model closely fits the logged observations, but it is not a concise model. Later, we will show how CSight uses abstraction to make the concrete FSM concise.

3.3.1 Concrete state

To define a concrete FSM we need to introduce notions of state that describe the concrete observations in the log. For this, we will define process states, channel states, and system states.

Definition 6 (Local process state)**.** Each process begins execution in an initial state, q_i^ε, and after executing a sequence s of process i event instances, the process enters state q_i^s. More formally, let L_i be the set of process i traces in a log L, then the set of process i local states is Q_i:

$$Q_i = \{q_i^\varepsilon\} \bigcup \{q_i^s \mid \exists t \in L_i, s \text{ is a prefix of } t\}$$

We call q_i^s a *terminal* state for process i if and only if $s \in L_i$.

Now, we define the global process state and global channel state that together make up the system state.

Definition 7 (Global process state)**.** A *global* process state $q = \langle q_1, \ldots, q_h \rangle$ is a h-tuple that represents the state of all processes in the system. That is, $q \in Q = Q_1 \times \cdots \times Q_h$, with $q_i \in Q_i$ denoting a state at process i.

[2]Scope is constrained to a trace (i.e., global scope). The translation is not one-to-one: $\hat{a} \rightarrow \hat{b}$ is Dwyer et al.'s Existence pattern when $\hat{a}$ is the *start* event that precedes every trace, and is otherwise Dwyer et al.'s Response pattern. Another example is $\forall \hat{b}, \hat{a} \leftarrow \hat{b}$, which is Dwyer et al.'s Universality pattern.

A channel contains all sent messages not yet received. For each channel c_{ij}, a (possibly empty) finite set of *messages* M_{ij} are the only messages that can be *sent* and *received* on c_{ij}.

Definition 8 (Channel state)**.** The *channel state* w_{ij} of a channel c_{ij} is a tuple of variable length whose entries are messages that can be sent and received along c_{ij}. That is, $w_{ij} \in (M_{ij})^*$.

Definition 9 (Global channel state)**.** A *global channel state* w is a set of channel states for all channels in the system. More formally, $w = \{w_{ij} \mid w_{ij} \in (M_{ij})^*\}$. We reuse ε to also stand for a global channel state with all channels empty. Further, we denote the set of all possible global channel states M.

Finally, we represent the *system state* as a pair of global process state and global channel state, $\langle q, w \rangle \in Q \times M$.

3.3.2 Transitions

Next, we specify how a sequence of event instances impacts the state of the system. For this, we define a process transition function, δ_i, which maps a process i state and an event instance to a new state.

Definition 10 (Process transition function)**.** Let E_i be the set of all process i event instances in a log L and let L_i be the set of process i traces in L. Then, the *process transition function* for a process i is $\delta_i : Q_i \times E_i \rightarrow Q_i$, such that

- $\delta_i(q_i^s, e_i) = q_i^{s \cdot e_i} \iff \exists t \in L_i, (s \cdot e_i)$ is a prefix of t.

As an example that illustrates δ_i, assume that states are the natural numbers: $Q_i = \mathbb{N}$, and event instances E_i are totally ordered: $\exists g \colon E_i \rightarrow \mathbb{N}$. Then, we can define $\delta_i(q_i, e_i)$ as the number that is formed by concatenating q_i and $g(e_i)$.

Notice that δ_i has a distinguishing property — two local process states are different if they were generated by two distinct sequences of events. Or, more formally:

1. $e_i \neq f_i \iff \delta_i(q_i, e_i) \neq \delta_i(q_i, f_i)$
2. $q_i = q_i' \iff \delta_i(q_i, e_i) = \delta_i(q_i', e_i)$

3.3.3 The concrete FSM

CSight uses the system traces parsed from a log L to construct a *concrete FSM* $\mathcal{F}_L$ (step 3 in Figure 2). This FSM represents the observed, concrete executions of the whole system. Each state in the concrete FSM is a tuple of the individual process states and channel contents (for all processes and channels in the system). A channel's content is computed from the sequence of observed message sends and receives in the trace. Process states, however, must be inferred, and are assumed to be uniquely determined by the process history. In other words, for a specific sequence of events at a process, CSight creates a single unique *anonymous* process state. Figure 3 illustrates how the anonymous process states and the corresponding concrete FSM are derived from a set of input system traces.

A key property of $\mathcal{F}_L$ is that it accepts all linearizations of all traces in L, as well as all possible traces that are *stitchings* of different concrete traces that share identical concrete states.

Definition 11 (Concrete FSM)**.** Given a log L, a *concrete FSM* $\mathcal{F}_L$ for L is a tuple $\langle S, s_I, E, \Delta, S_T \rangle$.

- The states of $\mathcal{F}_L$ are system states: $S = Q \times M$
- There is a unique initial system state: $s_I = \langle [q_1^\varepsilon, \ldots, q_h^\varepsilon], \varepsilon \rangle$
- $E = \{e \mid \exists \langle T, \prec \rangle \in L, e \in T\}$
- The transition function Δ is the composition of the individual process transition functions, except that Δ also handles communication events.
  $\Delta : Q \times M \times E \rightarrow Q \times M$
  $\Delta(\langle q, w \rangle, e_i) = \langle q', w' \rangle$, where:

- $q'_i = \delta_i(q_i, e_i)$, and $q'_j = q_j$ if $j \neq i$.
- $$w'_{ij} = \begin{cases} w_{ij} \cdot m & e_i = c_{ij}!m \\ tail & e_i = c_{ij}?m,\ w_{ij} = m \cdot tail \\ \text{undefined} & e_i = c_{ij}?m,\ w_{ij}[1] \neq m \\ w_{ij} & \text{otherwise} \end{cases}$$

- The terminal states have empty channels, and each process is in a terminal state that was derived by executing all of the event instances for that process in some system trace in L. $S_T = \{\langle q, \varepsilon \rangle \mid \forall i, q_i \text{ is terminal}\}$

3.3.4 *Validating the mined invariants*

Although the invariants CSight mines (Section 3.2) are true of the input traces, in some cases it is not always possible to construct a concrete FSM model that satisfies the invariants and accepts all of the input traces. This situation is caused by the incompleteness of the log.

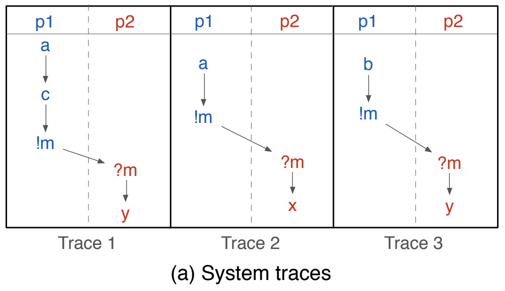
Consider Figure 3, which details the construction of a concrete FSM from three input system traces. The traces were generated by a system with two processes, p1 and p2, with a single channel from p1 to p2. The mined invariant $b_1 \not\to x_2$ is true of the log, but it is not valid in the concrete FSM. This situation arises due to incompleteness of the traces. This can be caused by insufficient executions ($b_1 \to x_2$ is possible but was not observed) or insufficient information in the trace (the m events that precede x_2 differ from those that precede y_2, in a way that is not recorded in the trace). In either case, the $b_1 \not\to x_2$ invariant is an undesirable false positive.

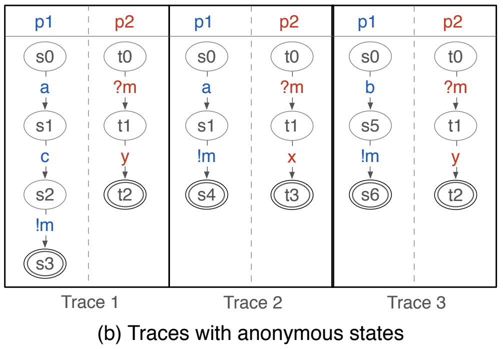
CSight detects and omits invariants of the above form by checking if the paths in the concrete FSM satisfy the mined invariants. We call this process *invariant validation* (step Ⓐ in Figure 2). Figure 3(b) shows the traces from Figure 3(a) with intermediate anonymous states — note that the state of process p2 after executing $?m$ is identical across *all* three traces. These anonymous local process states, along with concrete channel contents, are used to derive the concrete FSM (Figure 3(c)) corresponding to the above execution DAGs. This concrete FSM is checked for paths that violate the mined invariants, and these invariants are reported to the user and automatically omitted from the set of CSight steps that follow.

The output of this process is a set of *valid* invariants. Figure 4 details the `ValidateInvariants` procedure.

It is worth noting that invariant validation is necessary because of how CSight generates anonymous local process states: the local process state is completely determined by the set of executed *local* events (the assumption mentioned in Section 3.3). If a process state was determined not by just the local process events, but by the global history of events at all processes in the system then we would not need to perform invariant validation (all invariants would be satisfied in the concrete FSM). However, such an approach would lead to state explosion, as states would be differentiated to a very fine degree. An advantage of our design choice is that it mitigates the much more difficult problem of state explosion.

One concrete method by which an invalid invariant can be made valid is by refining the existing event types in the log based on remote events. For example, in the traces in Figure 4(a), if message m was differentiated into m_{ac}, m_a, and m_b then all of the mined invariants would be valid.





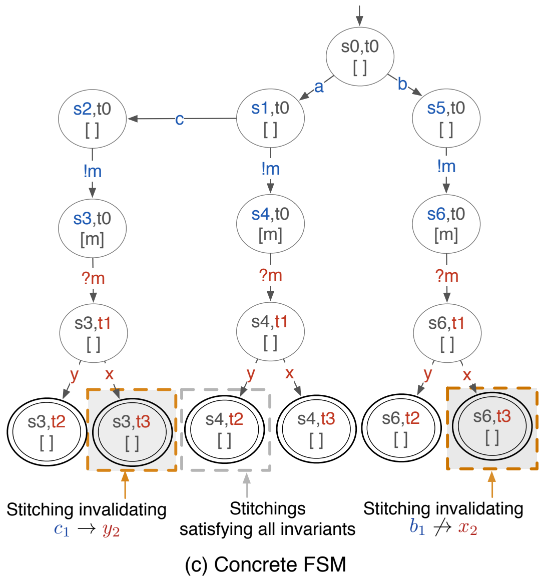


Figure 3: (a) System traces parsed from an input log with three traces, generated by two processes: p1 and p2. All messages flow from p1 to p2. Note that the system traces satisfy the invariants $c_1 \to y_2$ and $b_1 \not\to x_2$. (b) The traces from (a) with added per-process anonymous states. Note the reuse of states s0, s1, t0, t1, and t2. (c) Concrete FSM for the system traces in (a). The middle box highlights a stitching that satisfies all of the mined invariants. The two shaded boxes highlight stitchings that invalidate the $c_1 \to y_2$ and the $b_1 \not\to x_2$ invariants. During *invariant validation*, CSight model-checks the concrete FSM to identify and omit these invalid invariants from the refinement process.

3.4 Abstracting a concrete FSM

A concrete FSM is not concise — it is a DAG whose longest path is as long as the longest execution — and it is not sufficiently abstract. CSight generates a more concise *abstract FSM* model from the concrete FSM, using a process we call *state abstraction* (step ④ in Figure 2). As a reminder, we use the symbol ˆ to denote variables that represent abstract objects in the modeling process and to differentiate these from concrete features of the input log.

The concrete FSM $\mathcal{F}_L$ accepts all possible linearized sequences of event *instances* from executions in a log L. Let $\hat{\mathbf{P}}$ represent a partitioning of states in $\mathcal{F}_L$, that is a partitioning of $Q \times M$ (we

```
function ValidateInvariants($\mathcal{F}_L$, $Invs$):
    let $Invs' = Invs$
    foreach complete path $p$ in $\mathcal{F}_L$:
        foreach $inv \in Invs$:
            if ($p$ violates $inv$):
                $Invs' = Invs' \setminus \{inv\}$
    return $Invs'$
```

Figure 4: `ValidateInvariants` model-checks the mined invariants *Invs* in the concrete FSM $\mathcal{F}_L$ and returns a subset of invariants, $Invs' \subseteq Invs$, that are valid for $\mathcal{F}_L$. This procedure corresponds to step A in Figure 2.

use **bold font** to denote a set of sets)[3]. CSight's aim can now be defined as deriving an *abstract* FSM (AFSM) $\hat{\mathcal{A}}_L(\hat{\mathbf{P}})$ whose states are partitions in $\hat{\mathbf{P}}$ and that accepts sequences of *events* — rather than *event instances*. Transitions between states (partitions) in $\hat{\mathcal{A}}_L(\hat{\mathbf{P}})$ are generated through existential abstraction: there is a transition from $\hat{P}_1 \in \hat{\mathbf{P}}$ to $\hat{P}_2 \in \hat{\mathbf{P}}$ on event type $\hat{e}$ iff there are concrete states s_1 and s_2 such that $s_1 \in \hat{P}_1, s_2 \in \hat{P}_2$, and there is a transition from s_1 to s_2 on some event instance e, corresponding to $\hat{e}$. Note that $\hat{\mathcal{A}}_L(\hat{\mathbf{P}})$, like the concrete FSM $\mathcal{F}_L$, accepts all of the linearized event instance sequences. We now formally define $\hat{\mathcal{A}}_L(\hat{\mathbf{P}})$.

Definition 12 (Abstract FSM (AFSM))**.** For a log L, let $\mathcal{F}_L = \langle S, s_I, E, \Delta, S_T \rangle$ be the concrete FSM for L, and let $\hat{\mathbf{P}}$ be a partitioning of S. Then, an *abstraction of* $\mathcal{F}_L$, or an *abstract FSM* of L, is an FSM $\hat{\mathcal{A}}_L(\hat{\mathbf{P}}) = \langle \hat{\mathbf{P}}, \hat{\mathbf{P}}_I, \hat{E}, \hat{\Delta}, \hat{\mathbf{P}}_T \rangle$, where

- Initial states in $\hat{\mathcal{A}}_L(\hat{\mathbf{P}})$ are those partitions that contain the initial concrete state: $\hat{\mathbf{P}}_I = \{\hat{P} \in \hat{\mathbf{P}} \mid s_I \in \hat{P}\}$.
- Transitions in $\hat{\mathcal{A}}_L(\hat{\mathbf{P}})$ are event types that correspond to event instances in the concrete FSM: $\hat{E} = \{\hat{e} \mid \exists e, e \in E\}$.
- A transition between two partitions in $\hat{\mathcal{A}}_L(\hat{\mathbf{P}})$ exists if and only if there is a corresponding concrete transition between some two concrete states in the two partitions: $\hat{\Delta}(\hat{P}, \hat{e}) = \hat{P}' \iff \exists q \in \hat{P}, q' \in \hat{P}', e \in E, \Delta(q, e) = q'$.
- Terminal states in $\hat{\mathcal{A}}_L(\hat{\mathbf{P}})$ are those partitions that contain a terminal concrete state: $\hat{\mathbf{P}}_T = \{\hat{P} \in \hat{\mathbf{P}} \mid S_T \cap \hat{P} \neq \emptyset\}$.

An important feature of an AFSM is that it generalizes observed system states. A partition contains a finite number of observed system states, but through loops with transitions that modify channel state, an AFSM can generate arbitrarily long channel contents, leading to an arbitrarily large number of system states. We may not have observed these system states, but an AFSM model generalizes to predict that they are feasible.

CSight uses a first-k-in-channels partitioning strategy for generating an initial AFSM for a concrete FSM. This partitioning assigns two system states to the same partition if and only if the first-k message sequences in the channel states of the two states are identical. For example, suppose a system has two channels, c_{12} and c_{21}, and there are three concrete states: s_1, s_2, and s_3. Let $s.channels$ denote the channel contents for state s and suppose that $s_1.channels = \{c_{12} : [], c_{21} : [m]\}$, $s_2.channels = \{c_{12} : [], c_{21} : [m, m]\}$, and $s_3.channels = \{c_{12} : [l], c_{21} : [m]\}$. Then the first-1 contents of s_1 and s_2 are $\{c_{12} : [], c_{21} : [m]\}$ (the second m in $s_2.c_{21}$ is not included), while the first-1 contents of s_3 are $\{c_{12} : [l], c_{21} : [m]\}$. Therefore, in a first-1 partitioning strategy, s_1 and s_2 would map to the same partition, while s_3 would map to a different partition.

[3]We use ˆ for $\hat{\mathbf{P}}$ even though it is a partitioning of states in the *concrete* FSM because the partitions in this set represent states in the *abstract* FSM. This set links the concrete and abstract FSMs.

```
function AFSMtoCFSM(AFSM $\hat{\mathcal{A}}$):
    $\hat{\mathcal{A}} = \langle \hat{P}, P_I, E, \Delta, P_T \rangle$
    foreach $i \in [1, \ldots, h]$:
        // $\hat{\mathcal{A}}_i$ is $\hat{\mathcal{A}}$ with non pid $i$ events replaced with $\varepsilon$.
        let $\hat{\mathcal{A}}_i = (\hat{P}, P_I, E_i, \Delta_i, P_T)$, where
            $E_i = \{e_i \in E\}$, and
            $\Delta_i(q, \varepsilon) = q' \iff \Delta(q, e_j) = q', i \neq j$
            $\Delta_i(q, e_i) = q' \iff \Delta(q, e_i) = q'$
        let $F_i$ = eliminate−$\varepsilon$ ($\hat{\mathcal{A}}_i$)
    CFSM $\hat{C}_{\hat{\mathcal{A}}} = \langle F_i \rangle_{i=1}^{h}$
    return $\hat{C}_{\hat{\mathcal{A}}}$
```

Figure 5: `AFSMtoCFSM` translates an AFSM $\hat{\mathcal{A}}$ into a CFSM $\hat{C}_{\hat{\mathcal{A}}}$; `eliminate-ε` performs standard ε transition elimination [35]. This procedure corresponds to step B in Figure 2.

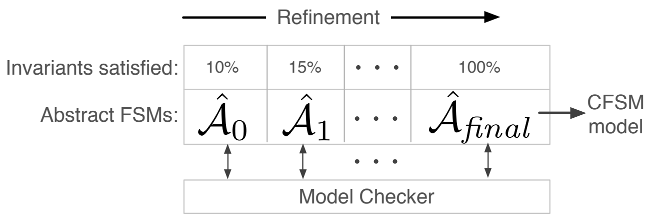


Figure 6: A high-level summary of the CSight refinement process (steps 5 and 6 in Figure 2). CSight starts with an initial abstract FSM, $\hat{\mathcal{A}}_0$, which is refined to a final abstract FSM, $\hat{\mathcal{A}}_{final}$. This final abstract FSM satisfies all of the mined invariants, and is converted into a CFSM that is returned as output.

Definition 13 (First-k partitioning)**.** Let S be a set of system states. $\hat{\mathbf{P}}_k$ is a first-k partitioning of S if $\forall \hat{P} \in \hat{\mathbf{P}}_k$, $\langle q, w \rangle, \langle q', w' \rangle \in \hat{P} \iff \forall c_{ij}, \forall g \in [1, k], w_{ij}[g] = w'_{ij}[g]$.

Finally, a CFSM is a set of per-process FSMs that communicate over FIFO channels. Channels are reliable, unidirectional, and have a single sender and receiver process. The alphabet of a process FSM includes process-local events, and inter-process communication (message *send* and message *receive*) events. We use the notation $c!m$ for a *send* event of message m on channel c, and the notation $c?m$ for a *receive* event of message m on channel c. Each channel has its own set of valid messages.

Definition 14 (Communicating FSM (CFSM))**.** A CFSM of h processes is a tuple of h process FSMs, $\langle F_1, F_2, \ldots, F_h \rangle$, and a set message sets $\mathcal{M}$ to indicate the message types that can be sent by one process and received at another. For each process i, its FSM is $\hat{F}_i = \langle \hat{Q}_i, \hat{I}_i, \hat{E}_i, \hat{\Delta}_i, \hat{T}_i \rangle$ and the message set M_i contains message types that can be sent from process i and received by some other process j, for all j. That is, $M_i = \cup_j M_{ij}$, where $c_{ij}?m \in \hat{E}_j \iff \exists i, m \in M_{ij}$ and $c_{ij}!m \in \hat{E}_i \iff \exists j, m \in M_{ij}$.

3.5 Model-checking and refining an AFSM

Figure 6 overviews, at a high level, the CSight model-checking and refinement process and Figure 7 lists an outline of the complete CSight algorithm. CSight uses the McScM [33] model checker to check if an invariant holds in the AFSM (step 5 in Figure 2). As McScM model-checks CFSMs and not AFSMs, to use McScM, CSight converts an AFSM into a CFSM. Further, as McScM reasons about state (un-)reachability, CSight encodes a temporal invariant in terms of states that can only be reached if the sequence of executed events violates the invariant. This encoding is described in

```
function CSight(Log $L, k$):
  let $Invs$ = ValidateInvariants(MineInvariants($L$))
  let $\mathcal{F}_L$ = concrete FSM for $L$
  let $\hat{\mathcal{A}}$ = AFSM for $\mathcal{F}_L$ with first-$k$ partitioning $\hat{\mathbf{P}}_k$
  let $\hat{C}_{\hat{\mathcal{A}}}$ = AFSMtoCFSM($\hat{\mathcal{A}}$)
  let $Invs$ = ValidateInvariants(MineInvariants($L$))
  foreach $Inv \in Invs$:
    while ($\hat{C}_{\hat{\mathcal{A}}}$ violates $Inv$):        // Call to model checker.
        let $\hat{p}$ = counter-example path for $Inv$ in $\hat{C}_{\hat{\mathcal{A}}}$
        // Translate events path $\hat{p}$ in $\hat{C}_{\hat{\mathcal{A}}}$ into $\hat{S}$, a list of
        // sets of paths in $\hat{\mathcal{A}}$, $|\hat{S}| = h$
        let $\hat{S}$ = CFSMPathToAFSMPath($p, \hat{C}_{\hat{\mathcal{A}}}$)
        $\hat{\mathcal{A}}$ = Refine($\hat{\mathcal{A}}, \hat{S}$)
        $\hat{C}_{\hat{\mathcal{A}}}$ = AFSMtoCFSM($\hat{\mathcal{A}}$)
  return $\hat{C}_{\hat{\mathcal{A}}}$
```

Figure 7: An outline of the CSight algorithm. Figure 5 details the `AFSMtoCFSM` procedure and Figure 9 details the `CFSMPathToAFSMPath` procedure. `MineInvariants` is described in [9] and Figure 4 details `ValidateInvariants`. The CSight implementation also handles model checker timeouts.

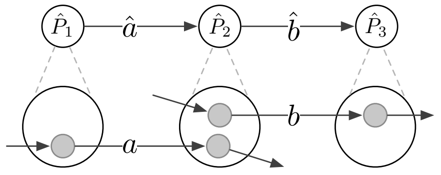


Figure 8: An AFSM path, $[\hat{a}, \hat{b}]$, that can be eliminated by refining (splitting) the abstract state $\hat{P}_2$, separating the two concrete states that generate the abstract path.

Appendix A.

An AFSM is an abstraction of concrete FSM. CSight's goal is to construct a communicating FSM (CFSM). An AFSM can be thought of as a cross product of the per-process FSM, and the CFSM can therefore be reconstructed from the AFSM. Figure 5 details the `AFSMtoCFSM` procedure for converting an AFSM into a CFSM to use McScM (step B in Figure 2). This procedure is also used to derive the final CFSM output in CSight.

Model-checking an invariant produces one of three cases:
(1) The invariant holds in the model. There is nothing more for CSight to do for this invariant.
(2) The invariant does not hold and McScM finds and reports a counter-example CFSM execution. A *CFSM execution* is a sequence of events that abides by CFSM semantics (e.g., a process can only receive a message if that message is at the head of the channel). A *counter-example* CFSM execution is a sequence of events that violates the invariant. In this case, CSight refines the AFSM to eliminate the counter-example (Section 3.5.1) and then re-model-checks this invariant in case another counter-example for it exists.
(3) McScM fails to terminate within a user-defined threshold (defaulted to 5 minutes). CSight then attempts to check a different invariant first before coming back to the invariant that timed out.[4]

If CSight resolves all invariants, it outputs the model. But, if McScM repeatedly times out on every invariant, then CSight terminates and does not output a model. We did not observe the latter case in our experiments.

[4]After refining the model to satisfy one invariant, a different, previously difficult-to-check invariant may become trivial to model-check.

```
function CFSMPathToAFSMPath($\hat{p}, \hat{C}_{\hat{\mathcal{A}}}$):
  // $\hat{p}$ is a complete events path in CFSM $\hat{C}_{\hat{\mathcal{A}}}$
  let AFSM $\hat{\mathcal{A}} = \langle \hat{\mathbf{P}}, \hat{\mathbf{P}}_I, \hat{E}, \hat{\Delta}, \hat{\mathbf{P}}_T \rangle$
  foreach $i \in [1, \dots, h]$:
    let $E_i$ = event types generated by process $i$
    let $\hat{S}_i = \{\hat{s} \mid \hat{s}$ an events path in $\hat{\mathcal{A}}$ from $\hat{P}_1$ to $\hat{P}_k$,
                 $\pi(\hat{s}, E_i) = \pi(\hat{p}, E_i), \hat{P}_1 \in \hat{\mathbf{P}}_I$,
                 $\exists \langle q, w \rangle \in \hat{P}_k, q_i$ terminal, and
                                $\forall j, w[ji] = \varepsilon\}$
  return $[\hat{S}_1, \dots, \hat{S}_h]$
```

Figure 9: `CFSMPathToAFSMPath` translates an events path $\hat{p}$ in a CFSM $\hat{C}_{\hat{\mathcal{A}}}$ into $\hat{S}$, a list of sets of paths in $\hat{\mathcal{A}}$. Each set in $\hat{S}$ maps to one event in $\hat{p}$.

3.5.1 *Refining an AFSM to satisfy invariants*

CSight uses counter-example guided abstraction refinement (CEGAR) [16] to eliminate a counter-example for an invariant (step 6 in Figure 2). Figure 8 illustrates how the concrete states from the log may generate a counter-example partitions path in the AFSM.

The McScM-generated invariant counter-example is a CFSM execution. Refining CFSM states to eliminate a counter-example is challenging because a single state in the concrete FSM can map to multiple states in the CFSM. Instead, CSight performs partition refinement in the AFSM. It does this by mapping the McScM-generated *CFSM counter-example* into an *AFSM counter-example*. Figure 9 describes this translation.

Note that the AFSM counter-example is a list of *sets* of AFSM paths, one set of AFSM paths for each process in the system. This is because the process-specific event subsequence of a CFSM execution maps to potentially multiple paths in the AFSM (due to the CFSM construction based on ε-transitions in Figure 5).

Once the AFSM counter-example is generated, CSight eliminates the CFSM counter-example by transforming the AFSM into a more concrete (or less abstract) AFSM. It does so using partition refinement (`Refine` in Figure 10). Given an AFSM counter-example, `Refine` identifies the set of partitions that stitch concrete observations, as in partition $\hat{P}_2$ in Figure 8. It then refines all partitions in a set that is smallest across all processes and returns the refined AFSM.

A refined AFSM is more concrete — closer to the the concrete FSM. The refined AFSM has more partition states, and each partition state contains fewer concrete system states.

Definition 15 (AFSM Refinement)**.** An AFSM $\hat{\mathcal{A}}_L(\hat{\mathbf{Q}})$ is a *refinement* of AFSM $\hat{\mathcal{A}}_L(\hat{\mathbf{P}})$ if $\forall \hat{Q} \in \hat{\mathbf{Q}}, \exists \hat{P} \in \hat{\mathbf{P}}, \hat{Q} \subseteq \hat{P}$, and

$$\bigcup_{\hat{Q} \in \hat{\mathbf{Q}}} \hat{Q} = \bigcup_{\hat{P} \in \hat{\mathbf{P}}} \hat{P}$$

Next, in Section 4, we prove three key properties of the CSight process.

4. FORMAL ANALYSIS

We now use the formalisms defined in the previous section to prove three results about the CSight model inference process: (1) the inferred model fits the input log, (2) the inferred model satisfies mined invariants, and (3) refinement always makes progress.

We begin with an observation: The concrete FSM $\mathcal{F}_L$ satisfies all mined, validated invariants. This is true by construction in `ValidateInvariants` in Figure 4.

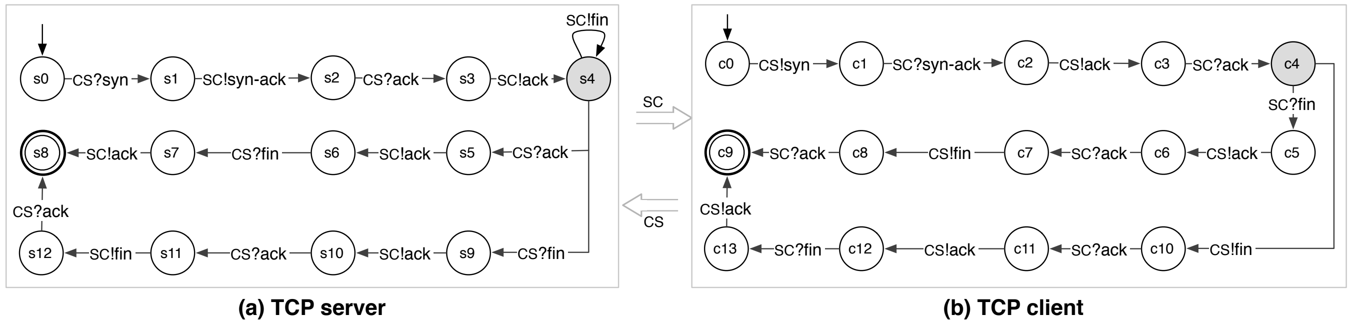


Figure 11: The inferred state machines for the (a) TCP server and (b) TCP client. The server communicates with the client over the `SC` channel, and the client communicates with the server over the `CS` channel. Shaded states represent the `connection-established` states.

```
function Refine(AFSM $\hat{\mathcal{A}}$, AFSM Event Paths $\hat{S}$):
    let $\langle \hat{\mathbf{P}}, \hat{\mathbf{P}}_I, \hat{E}, \hat{\Delta}, \hat{\mathbf{P}}_T \rangle = \hat{\mathcal{A}}$
    // $min$ is an index into $\hat{S}$, denoting a set of process paths
    // requiring the fewest number of refinements to eliminate.
    let $min = 0$
    foreach $i \in [1, \dots, h]$:
        foreach $\hat{s} \in \hat{S}[i]$:
            let $\hat{\Pi}$ = state sequence for $\hat{s}$ in $\hat{\mathcal{A}}$
            // Find stitching partitions, e.g., $\hat{P}_2$ in Fig. 8, by
            // traversing $\hat{\Pi}$ and recording partitions that can be
            // refined to eliminate $\hat{\Pi}$ from $\hat{\mathcal{A}}$.
            let $\widehat{Stitch}_{\hat{s}} = \{\hat{P} \mid \hat{P}$ is a stitching state in $\hat{\Pi}\}$
            if $\widehat{Stitch}_{\hat{s}}$ is empty:
                next $i$
        // Set of stitching partitions shared by those paths in $\hat{\mathcal{A}}$
        // that correspond to strings in $\hat{S}[i]$
        let $\widehat{Stitch}_i = \cap_{\hat{s} \in \hat{S}[i]} \widehat{Stitch}_{\hat{s}}$
        // $min$ is an index that tracks the smallest $\widehat{Stitch}_i$
        if $min = 0$ or $\left|\widehat{Stitch}_i\right| < \left|\widehat{Stitch}_{min}\right|$:
            $min = i$
    let $\hat{\mathbf{P}}' = \hat{\mathbf{P}}$ with all partitions in $\widehat{Stitch}_{min}$ refined to
            eliminate all paths in $\hat{S}[min]$
    // Derive $\hat{\mathbf{P}}'_I, \hat{\Delta}'$, and $\hat{\mathbf{P}}'_T$ from $\hat{\mathbf{P}}'$ as in Def. 12.
    let AFSM $\hat{\mathcal{A}}' = \langle \hat{\mathbf{P}}', \hat{\mathbf{P}}'_I, \hat{E}, \hat{\Delta}', \hat{\mathbf{P}}'_T \rangle$
    return $\hat{\mathcal{A}}'$
```

Figure 10: `Refine` removes an invariant counter-example from an AFSM. It refines one of the sets of process paths in $\hat{S}$, selecting the one that require the fewest refinements. Note that $\hat{S}$ is a list of sets of paths, one set per process.

Observation 1 (Concrete FSM satisfies mined, validated invariants)**.** Let L be a log, and let *Invs* be the set of invariants that are valid in $\mathcal{F}_L$. Then, $\forall Inv \in Invs$, $s \in Lang(\mathcal{F}_L)$, s satisfies *Inv*.

Theorem 1 (Inferred model fits the input log)**.** *For all logs L and integers k, `CSight`(L,k) returns a CFSM model that accepts all traces in L.*

Proof of Theorem 1. Let $\hat{C}_{\hat{\mathcal{A}}}$ be the model returned by `CSight`(L,k). By construction, $\hat{\mathcal{A}}$ accepts all of the traces in $\hat{C}_{\hat{\mathcal{A}}}$. Furthermore, $\hat{\mathcal{A}}$ is an abstract FSM for $\mathcal{F}_L$ — the concrete FSM of log L.

All abstract FSMs must at least accept the traces in the concrete FSM. Therefore, $\hat{\mathcal{A}}$ accepts all of the traces in $\mathcal{F}_L$. Since, $\mathcal{F}_L$ accepts all of the traces in L by construction, $\hat{\mathcal{A}}$ accepts the traces as well, and therefore $\hat{C}_{\hat{\mathcal{A}}}$ must also accept them. □

A key property of the `Refine` procedure in Figure 10 is that it eliminates a counter-example path from a CFSM. We prove this next.

Theorem 2 (Refinement progress: Refinement eliminates counter-examples)**.** *Let $\hat{p}$ be a CFSM counter-example path for invariant Inv in $\hat{C}_{\hat{\mathcal{A}}}$, let $\hat{S}$ = `CFSMPathToAFSMPath`$(\hat{p}, \hat{C}_{\hat{\mathcal{A}}})$, and let $\hat{\mathcal{A}}'$ = `Refine`$(\hat{\mathcal{A}}, \hat{S})$. Then, $\hat{p}$ is not a counter-example to Inv in $\hat{C}_{\hat{\mathcal{A}}'}$. That is, $\hat{p}$ is not a valid execution of $\hat{C}_{\hat{\mathcal{A}}'}$.*

Proof of Theorem 2. Proof by contradiction. Assume that $\hat{p}$ is a sequence of events that is a valid execution of $\hat{C}_{\hat{\mathcal{A}}'}$ and that $\hat{p}$ violates *Inv*. Consider an invocation of `Refine`$(\hat{\mathcal{A}}, \hat{S})$. `Refine` (Figure 10) uses a non-zero *min* value to compute $\hat{\mathbf{P}}'$ on line 19 and returns a CFSM $\hat{C}_{\hat{\mathcal{A}}'} = \langle \hat{F}_i \rangle_{i=1}^{h}$.

For $\hat{p}$ to be a valid execution in $\hat{C}_{\hat{\mathcal{A}}'}$, the sub-sequence of process i events $\hat{p}_i$, $\hat{p}_i = \pi(\hat{p}, \hat{E}_i)$, must be a valid execution in $\hat{F}_i$, for all i. The procedure `AFSMtoCFSM` (line 14 in Figure 7), detailed in Figure 5, constructs $\hat{F}_i$ to accept $\hat{p}_i$ iff there is a complete path $\hat{s}$ in $\hat{\mathcal{A}}'$, such that $\hat{p}_i = \pi(\hat{s}, \hat{E}_i)$. However, any such $\hat{s}$ must also be in $\widehat{Stitch}_{min}$, which is used to compute $\hat{\mathbf{P}}'$ in Figure 10. Therefore, after refining $\widehat{Stitch}_{min}$, $\hat{s}$ can no longer be a valid path in $\hat{\mathcal{A}}'$. Contradiction. □

Now, we prove that the `CSight` procedure in Figure 7 returns a CFSM model that satisfies all of the mined, validated invariants.

Theorem 3 (Inferred model satisfies mined invariants.)**.** *For a given log L, if `CSight` outputs a CFSM model then this model satisfies all of the mined, validated event invariants from $\mathcal{F}_L$.*

Proof of Theorem 3. For a log L with a total of n event instances, CSight can refine the initial abstract FSM for L, $\mathcal{A}_L(\hat{\mathbf{P}}_k)$, at most $n-1$ times. This is because after $n-1$ refinements, each partition in the abstract FSM must map to exactly one concrete state, and a singleton partition cannot be refined further.

Let $\hat{\mathcal{A}}$ be the abstract FSM after $n-1$ refinements of $\mathcal{A}_L(\hat{\mathbf{P}}_k)$. Because $\hat{\mathcal{A}}$ maps each event instance to a unique partition, it is indistinguishable from $\mathcal{F}_L$, the concrete FSM it abstracts. Therefore, $Lang(\hat{\mathcal{A}}) = Lang(\mathcal{F}_L)$. By Observation 1, $\mathcal{F}_L$ satisfies all validated invariants, therefore so does $\hat{\mathcal{A}}$.

Since CSight does not terminate until all the validated invariants are satisfied in the abstract FSM, it either returns $\hat{\mathcal{A}}$ after $n-1$ refinements, or it returns a smaller (and more abstract) $\hat{\mathcal{A}}'$. In both cases, the returned AFSM satisfies all of the validated invariants. □

5. LOGGING VECTOR TIMESTAMPS

CSight requires its input logs to be annotated with vector timestamps. Vector time is a logical clock mechanism to partially order events in a concurrent system [25, 46]. While some systems use this mechanism internally and could include vector timestamps in their logs, many do not. To ease using CSight with concurrent systems, we have built ShiVector[5], a tool to automatically compute and insert vector timestamps into Java system logs. ShiVector does not require modification of the system's source code, only recompilation with the ShiVector library added to the classpath.

ShiVector uses aspects (via AspectJ) to intercept socket-based network communication to piggy-back process vector timestamps on top of existing application-level protocols.[6] ShiVector also intercepts logging events to augment each logged event with a vector timestamp at the time that the event was logged. Thus, ShiVector automatically tracks and injects vector timestamps into concurrent systems' logs.

6. EXPERIMENTAL EVALUATION

The CSight prototype uses McScM for model checking and graphviz for model visualization. In all experiments we used a value of $k = 1$ for the first-k-in-channels partitioning strategy. We evaluated CSight on three sets of logs, produced by: a simulator of the stop-and-wait protocol; the TCP stack of OS X; and Voldemort [57], an open-source project that implements a distributed hash table [22] and is used in data centers at companies like LinkedIn. We also carried out a user study with a group of undergraduate students to evaluate the efficacy of CFSM models in finding bugs.

6.1 Stop-and-wait protocol

We applied CSight to traces from a simulator of the stop-and-wait protocol described in Section 2. We derived a diverse set of traces by varying message delays to produce different message interleavings. CSight mined a total of 66 valid invariants. The model CSight derived (Figure 1(b)) is identical to the true model of the stop-and-wait protocol. This experiment was a sanity check to verify that CSight performed as expected on this well-understood protocol, when faced with concurrency-induced non-determinism in interleavings.

6.2 TCP

The TCP protocol uses a three-phase opening handshake to establish a bi-directional communication channel between two end-points. It tears down and cleans up the connection using a four-phase closing handshake. The TCP state machine is complicated by the fact that packet delays and packet losses cause the end-points to timeout and re-transmit certain packets, which may in turn induce new messages. Our goal was to model common-case TCP behavior, so we did not explore these protocol corner cases.

We used netcat and dummynet [52] to generate TCP packet flow. We captured packets using tcpdump and then semi-manually annotated the log to include vector timestamps. A subset of the traces that involve only the the opening and closing TCP handshakes were fed into CSight.

For the captured TCP log, CSight identified 149 valid invariants, some of which are not true of the complete protocol (e.g., because the input traces did not contain certain packet retransmissions). The CSight-derived CFSM model is shown in Figure 11. The shaded states `s4` and `c4` represent the server and client `connection-established` states, which is reached when the two end-points have successfully set up the bi-directional channel. Transitions up to these two states model the opening handshake, while transitions after these states model the closing handshake. The closing handshake is split into a server-initiated tear-down sequence (middle row of states) and a client-initiated tear-down (bottom-most row of states).

The derived model is accurate except for the self-loop on state `s4` in Figure 11(a). This loop appears because `s4` represents both the `connection-established` state and the state after the server has initiated the closing handshake. This loop appears to contradict the `SC!fin` $\not\rightarrow$ `SC!fin` invariant, which *is* mined by CSight and is valid. However, the model checker only considers counter-examples that terminate. Note that if the loop at `s4` is traversed twice then the client will be unable to consume both server `fin` packet copies and will enter an unspecified reception error state and therefore not terminate. Such unspecified reception states are typically undesirable, as they can be confusing. The McScM model checker can be used to detect these states and further refinement will eliminate them. Implementing this elimination remains as part of future work.

Figure 11 also illustrates a key feature of CSight — the user decides (by specifying a set of line-matching regular expressions) what information in the log is relevant to the modeling task. Thus, for each use of CSight, the user decides on the trade-off between comprehensibility of the model (e.g., model size) and the amount of information lost/retained by the modeling process. For example, the TCP model in Figure 11 is simple to understand, but it omits TCP sequence numbers, data packets, and other details that were present in the input log.

6.3 Voldemort distributed hash table

Voldemort [57] implements a distributed hash table with a client API that has two main methods. `put(k,v)` associates the value `v` with the key `k`, and `get(k)` retrieves the current value associated with the key `k`. Voldemort is a *distributed system* as it provides scalability by partitioning the key space across multiple machines and achieves fault tolerance by replicating keys and values across multiple machines.

The Voldemort project has an extensive test suite. We used a subset of integration tests that exercise the synchronous replication protocol to generate a log of replication messages in a system with one client and two replicas. We logged messages generated by client calls to the synchronized versions of `put` and `get` and captured just the messages between the client and the two replicas.[7] Since Voldemort does not implement vector timestamps, we used ShiVector (described in Section 5) to produce a vector timestamped log.

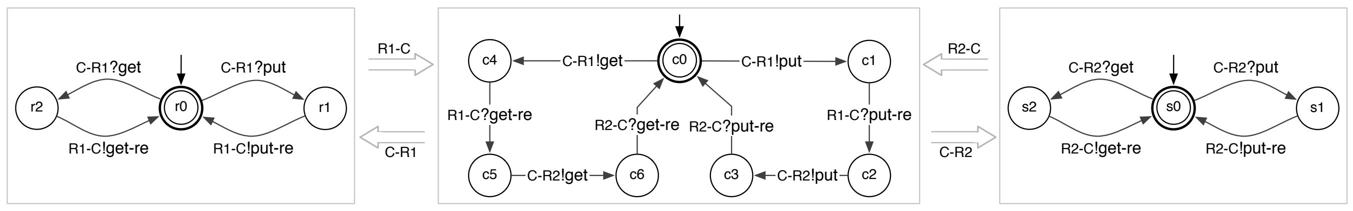
CSight mined 112 valid invariants and generated the model in Figure 12. This model contains a client FSM and two replica FSMs. As expected, the replica FSMs are identical. Synchronized Voldemort operations are serialized in a specific order, so the flow of messages for `put` as well as for `get` is identical — the client first executes the operation at replica 1 and then at replica 2.

We manually inspected Voldemort's replication code to confirm that the model in Figure 12 is accurate. This model provides a high-level overview of how replication messages flow in the system. However, as with the TCP protocol, the model also abstract away and omits numerous details, such as what happens when replicas fail. One feature of CSight is that it allows a developer to focus on those aspects of system behavior that are important to them. For example, by not exercising irrelevant system behavior in the first place, or by running CSight with regular expressions that ignore certain logged behavior in the log parsing stage of the process.

[5]https://bitbucket.org/bestchai/shivector/

[6]We plan to extend ShiVector to interpose on other kinds of inter-process communication.

[7]The replicas also communicate with each other to maintain key availability, but we excluded this communication from the log.



(a) Voldemort Replica 1 **(b) Voldemort client** **(c) Voldemort Replica 2**

Figure 12: (a,c) replica models and (b) client model for a three-node Voldemort cluster. "re" stands for "response".

6.4 User study

To determine whether CFSM models are useful in finding bugs, we designed and ran a user study. It is typical for developers to interpret distributed executions in the form of time-space diagrams. Therefore, we compared the efficacy of CFSM models against time-space diagrams in bug-finding tasks. Throughout the study and in the oral feedback session that followed, participants were not told the purpose of the study.

The study focused on two concurrent systems: the stop-and-wait protocol and Voldemort. We introduced a bug into each system — the sender in the stop-and-wait protocol failed to re-transmit packets on timeout, and the synchronized Voldemort client sent requests to all replicas concurrently, instead of blocking on acknowledgment from each replica. In our experience, both bugs are representative of real bugs faced by distributed system developers. The root cause of the stop-and-wait bug is not taking the right action on an event; the root cause of the Voldemort bug is performing an action at the wrong time. For each buggy system, we generated: (1) a set of representative time-space execution diagrams (8 for the stop-and-wait protocol and 6 for Voldemort), and (2) a CFSM model. Overall, we created four artifacts for the study — *tspace-saw* and *cfsm-saw* (time-space diagrams and CFSM model of the buggy stop-and-wait protocol), and *tspace-vol* and *cfsm-vol* (artifacts for buggy Voldemort).

The study consisted of an in-class, web-based assignment[8] in an undergraduate Introduction to Software Engineering class at the University of Massachusetts, Amherst. The 39 students who completed the assignment had, on average, 4.2 years of programming experience, and 76% of the students had never taken a networks course.

We considered two factors: the model factor (time-space diagrams vs. CFSM models), and the task factor (stop-and-wait vs. Voldemort). To account for learning effects, we used a within-participants mixed design across all 39 participants. We randomly assigned each student to one of four possible study sequences: ⟨*tspace-saw*, *cfsm-vol*⟩, ⟨*tspace-vol*, *cfsm-saw*⟩, ⟨*cfsm-saw*, *tspace-vol*⟩, ⟨*cfsm-vol*, *tspace-saw*⟩. We considered the two bugs to be independent — finding one bug in one artifact does not help in finding the other bug in a different artifact.

Each task consisted of two steps:

1. Each student completed a mini-tutorial on the appropriate diagram (time-space and CFSM, respectively). To verify their understanding, at the end of each tutorial, each student had to answer two basic questions correctly. They could resubmit their answers until both were correct.[9]

2. Each student was given a *correct*, written description of the system in English, along with either a set of time-space diagrams or a CFSM model. The student was asked to respond to a single open-ended question. For time-space diagrams (*tspace-saw*, *tspace-vol*) we asked: "List all of the time-space diagrams above that you think do not conform to the description of the system above. What made you choose these diagrams?" For the CFSM models (*cfsm-saw*, *cfsm-vol*) we asked: "How does the observed model differ from the intended system description?"

6.4.1 Results

Students found bugs approximately as well with the CFSM model as they did with the time-space diagrams that are developers' current preferred visualization. For the stop-and-wait protocol, students who were shown the CFSM were 72% successful in getting the right answer, while those who were shown the 8 time-space diagrams were 61% successful. For Voldemort, the success rate with the CFSM was 72% and the success rate with the 6 time-space diagrams was 86%.

Students found CFSMs just as useful (for completing the task) as the small collection of time-space diagrams. These results indicate that CFSM models can be used to effectively find bugs. Moreover, in practice, developers have to inspect neither 8 nor 6 executions of the system, but hundreds or thousands. The task of manually finding the anomalous time-space diagrams would be infeasible. The CFSM models, though, will remain roughly of the same size and complexity regardless of the number of executions. Therefore, we believe that our results on the utility of CFSMs over time-space diagrams are conservative, and CFSMs would perform even better in practice. Our study finds that they already perform as well as time-space diagrams tightly focused on the buggy behavior.

Students' oral feedback on the assignment reveals why many of them preferred the CFSM model. According to many students, time-space diagrams were difficult to follow, especially for long executions:

> "I found the time-space diagrams confusing. It was hard to tell what was happening when. The [CFSM] models were simpler and made it clear what state a system was in and I could keep track of that state." – student 1

> "Time-space diagrams were easy to follow for small time segments. For longer time segments, you got lost. The other [CFSM] models were better for longer time." – student 2

Students could compare a CFSM model to their own mental model, or the model they would draw after reading the system description:

> "I read the description and tried to recreate the [CFSM] model myself first. Then, I compared what I drew to the given diagram and found mistakes. Understanding those mistakes helped me understand the system a lot better." – student 3

Finally, students mentioned that CFSM models were easier to use because they did not explicitly model time:

> "For the [CFSM] models, I assumed no time delay in the network messages. It was harder to do in the time-space diagrams because you

[8] Available online: http://www.bestchai.net/papers/icse2014_csight_eval/

[9] The average time to complete either tutorial was 5 minutes. Students made, on average, 1.8 attempts to answer the tutorial questions correctly. These measures were similar when the time-space and the CFSM tutorials were considered separately.

cannot ignore the delay there. In CFSMs, you can ignore time at first, and then allow for it." – student 4

7. RELATED WORK

CFSMs can be inferred from manually-labeled message sequence charts [13]. In contrast, CSight automates the inference by relying on mined invariants. CFSMs inferred from executions can demonstrate system properties, such as absence of deadlocks and unspecified receptions [15, 56]. We found that CFSMs also provide a concise representation of complex concurrent system logs. Another potentially useful inferred model of concurrent systems is *class*-level specifications in the form of symbolic message sequence charts [39]. CSight can use these to merge identical process FSMs, such as the replica models in Figure 12(a,c).

In addition to inferring models, concurrent system logs can be used to detect anomalies [36, 45, 58], identify performance bugs [53, 54], and mine temporal system properties [9, 17, 60]. Our focus is on concurrency and on extracting a model that can aid understanding of more general system behavior. Our own work on mining temporal invariants of concurrent systems [9] is complementary to CSight, which needs to mine such invariants from execution logs. Probabilistic analysis of logs (measuring number, frequency, and regularity of event occurrences) can help discover concurrent system execution patterns, which can help the developer better understand and improve the design of concurrent systems [17]. Logs can also be used to mine message sequence charts [38], which describe the process interactions within a concurrent system.

The problem of finding a short sequence of refinements to produce a small abstract FSM that satisfies all of the valid invariants is NP-hard [16], and CSight's design finds an approximate solution. For logs of serial systems (totally ordered logs), the problem of automata inference from positive examples of executions is computable [12] but NP-complete [30, 5], and the FSA cannot be approximated by any polynomial-time algorithm [49]. Unlike CSight, prior work on model inference from totally ordered logs either excluded concurrency or captured a particular interleaving of concurrent events [2, 10, 7, 11, 18, 28, 44, 47, 50]. Tomte [1] and Synoptic [10] take a similar approach to CSight, using CEGAR [16] to refine models. Synoptic mines temporal invariants and infers FSM models from a log of sequential executions, while Tomte infers scalarset Mealy machines. CSight mirrors Synoptic's inference procedure but uses a different modeling formalism and algorithms, and works for concurrent systems that log concurrency as a partial order. We believe that modeling concurrency explicitly is crucial to understanding a concurrent system's behavior.

System models can also be inferred from developer-written specifications [4, 19, 21, 29, 31, 37]. Compared to CSight, these techniques require significantly more manual effort from the developer and are not suitable for legacy systems.

CSight relies on the McScM model checker [33, 32] for checking the validity of invariants in a CFSM model. A key property of McScM is that it verifies models with no a priori bound on channel size. However, this means that McScM is not guaranteed to terminate.

Currently, the scalability bottleneck in CSight is the McScM model checker [33, 32], whose runtime depends on model size and model complexity. To improve scalability, we plan to use the more efficient Spin model checker [34], though Spin is less precise on states with channels that contain many messages.

Aguilera et al. pioneered a popular black-box approach to debugging distributed systems [3]. In this approach, multiple observations of a distributed executions are used to infer causality, dependencies, and other important characteristics of the system. This approach was somewhat relaxed in later work to produce more informative and application specific results in Magpie [6] and later in X-Trace [26]. The focus of this prior work is on *data*, or request flow. In contrast, CSight generates CFSM models that model the partially ordered sequence of *events* executed by a concurrent system.

Runtime checking of concurrent systems can also aid debugging by monitoring user-defined system invariants or properties as the system executes. If a property is violated, reporting the incident to the user might identify a bug [51, 27, 42, 20]. Alternatively, the system could self-adapt by steering the system away from the violation [41, 23, 59, 48]. CSight could be used to first infer a model, and then check, at runtime, that the executions adhere to the model.

8. DISCUSSION

The vector timestamps tracked and logged by the ShiVector library (Section 5) may adversely affect system performance. However, as is typical for production systems, ShiVector can be enabled for a small fraction of the requests. As long as the collected traces are representative of typical system behavior, CSight's model, too, will be representative.

CSight's model construction cannot directly eliminate two kinds of error states [14] — unspecified reception and deadlock. Unspecified reception occurs when a process enters a state with a message *m* at the head of its channel, but has no reachable future state that receives *m*. A deadlocked system state occurs when no process can send a message and at least one process cannot reach a terminating state. Currently, CSight does not check if these error states are reachable in the final model. It is possible to extend CSight with such a check, for example, by using the McScM model checker, but the check would be computationally expensive.

CSight mines three types of invariants and ensures that the final model satisfies the valid invariants. For the invariants to be accurate, the log must have executions representative of all possible executions of the modeled system. While we found these invariant types to be sufficient to infer interesting models in practice, more extensive invariants can lead to more expressive models.

CSight works for system traces that satisfy certain communication constraints (Def. 1). For example, CSight cannot model unclean termination and assumes that each execution terminates with empty channels. However, in practice, system logs may not satisfy these constraints. In our future work we will extend CSight to handle terminal states with non-empty channels.

9. CONCLUSION

Concurrent systems are hard to implement, debug, and verify. To help with these tasks, we developed CSight, a tool that uses a partially ordered log of events to infer a concise and accurate communicating finite state machine model of the system. CSight's accuracy comes from its use of mined temporal properties that relate events in the log. Our tool prototypes are available for download at http://synoptic.googlecode.com/. By automatically mining a system model from logs, CSight has the potential to ease system understanding, debugging, and maintenance tasks.

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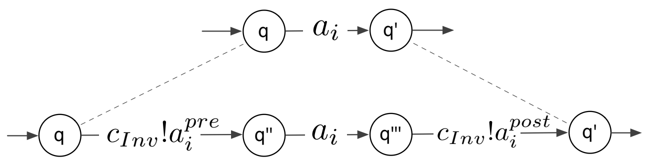

Figure 13: An edge in a CFSM (top) that is transformed to track a_i (bottom).

APPENDIX

A. CHECKING INVARIANTS WITH MCSCM

Model checking an event invariant (Section 3.2) in a CFSM (Section 3.4) is a three step process. First, the CFSM must be augmented with synthetic "tracking" transitions that record when an event type mentioned by the invariant is executed by the model checker. Second, the negation of the invariant must be encoded as a set of "bad states" of the CFSM. If the model checker finds an execution that can reach one of these states, it will emit the path, which is the counter-example path for the invariant. Finally, the counter-example path must be post-processed before it can be used. We now describe each of these steps in more detail.

A.1 Preparing a CFSM for model checking

Consider an event invariant *Inv*, such that $Inv = a_i \mathcal{T} b_j$, with $\mathcal{T} \in \{\rightarrow, \not\rightarrow, \leftarrow\}$. And, let $\mathcal{C}$ be a CFSM in which we want to check if *Inv* holds.

We modify $\mathcal{C}$ to produce a new CFSM model, $\mathcal{C}'$, which will be used as input to the McScM model checker. We transform $\mathcal{C}$ into $\mathcal{C}'$ in two ways — we convert local events into send events on a synthetic channel, and we add synthetic "tracking events" to track the execution of a_i and b_j event types.

Handling local events. The McScM model checker does not model local events (it only supports message send and receive events). We cannot omit local events from $\mathcal{C}'$, as we need to be able to unambiguously map an McScM counter-example path in $\mathcal{C}'$ to a path in $\mathcal{C}$. We therefore add a synthetic "local events" channel, c_{local}, and allow all processes to send messages on c_{local}. This channel is write-only — processes never receive on c_{local}. Finally, each process local event type, e_i, in $\mathcal{C}$ is translated into the event type $c_{local}!e_i$ in $\mathcal{C}'$. That is, we replace transitions of the form $\Delta_i(q, e_i) = q'$ with $\Delta_i(q, c_{local}!e_i) = q'$.

Tracking events necessary for checking Inv. Given a CFSM and a set of "bad states", the McScM model checker checks if there is an execution of the input CFSM that causes it to reach one of the bad states. A bad state is a kind of a *system state* (introduced in Section 3.3); it consists of a global process state and a global channel state. In McScM, the global channel state is expressed with regular expressions over channel contents.[10]

To check *Inv* with McScM, we therefore need to generate a set of system states of $\mathcal{C}'$, each of which encodes a violation of *Inv*. To generate this encoding for $Inv = a_i \mathcal{T} b_j$, we need to track when a_i or b_j occur. We do this with "tracking events", which track the occurrence of a_i and b_j as send events to a synthetic *Inv*-specific channel, c_{Inv}. This channel is used exclusively for checking *Inv*. As with the synthetic local events channel, all processes can send on c_{Inv}, and no process ever receives from this channel. Figure 13 illustrates this tracking. More formally, if Δ_i is the process i FSM transition function in $\mathcal{C}$, then we track a_i and b_j event types as follows:

1. Replace transitions of the form $\Delta_i(q, a_i) = q'$ with:
   - $\Delta_i(q, c_{Inv}!a_i^{pre}) = q''$
   - $\Delta_i(q'', a_i) = q'''$
   - $\Delta_i(q''', c_{Inv}!a_i^{post}) = q'$

   Where, q'', q''' are synthetic states with just the transitions above, and $c_{Inv}!a_i^{pre}$ and $c_{Inv}!a_i^{post}$ are synthetic event types that maintain a record of when a_i occurs as messages in c_{Inv}.
2. Similarly, to keep track of b_j, replace $\Delta_j(p, b_j) = p'$ with:
   - $\Delta_j(p, c_{Inv}!b_j^{pre}) = p''$
   - $\Delta_j(p'', b_j) = p'''$
   - $\Delta_j(p''', c_{Inv}!b_j^{post}) = p'$

Note that the first transformation retains the event a_i and the second transformation retains the event b_j. This is necessary as we want $\mathcal{C}'$ to have identical behavior to $\mathcal{C}$ (ignoring the added tracking events).

To see why we need to augment both a_i and b_j with a pre and a post event, consider other strategies, with less overhead (fewer synthetic events). For example, assume that $Inv = a_i \rightarrow b_j$ and we repaced transitions of the form $\Delta_i(q, a_i) = q'$ with $\Delta_i(q, c_{Inv}!a_i^{pre}) = q''$ and $\Delta_i(q'', a_i) = q'$; and we replaced transitions of the form $\Delta_j(p, b_j) = p'$ with $\Delta_j(p, c_{Inv}!b_j^{pre}) = p''$ and $\Delta_j(p'', b_j) = p'$.

Then, consider the following contents of c_{Inv}: $[a_i^{pre}, b_j^{pre}]$. These two tracking events imply one of three executions:

1. $c_{Inv}!a_i^{pre} \rightarrow a_i \rightarrow c_{Inv}!b_j^{pre} \rightarrow b_j$	*Inv* true
2. $c_{Inv}!a_i^{pre} \rightarrow c_{Inv}!b_j^{pre} \rightarrow a_i \rightarrow b_j$	*Inv* true
3. $c_{Inv}!a_i^{pre} \rightarrow c_{Inv}!b_j^{pre} \rightarrow b_j \rightarrow a_i$	*Inv* false

The above example indicates that the simpler strategy results in ambiguity — given the contents of channel c_{Inv} we cannot tell if *Inv* satisfies the execution that produced the tracing events in c_{Inv}. Likewise, we can show that other strategies that do not include all of the four pre and post events lead to ambiguity.

A.2 Expressing invariants as McScM bad states

To model check *Inv* in $\mathcal{C}'$ we need to construct bad states for *Inv*. Each such state needs to specify the states of all of the processes in the system and describe the contents of all channels in $\mathcal{C}'$ as regular expressions. First, we overview the McScM regular expression syntax for denoting channel contents:

• $a\,.\,b$	concatenation of a and b
• $a\hat{}*$	zero or more a
• $a\hat{}+$	one or more a
• $a \mid b$	either a or b
• ( )	grouping
• _	empty channel

Using the above syntax, we now define some basic patterns that we will reuse in specifying bad states.

- `ANY` $= (c_{Inv}!a_i^{pre} \mid c_{Inv}!a_i^{post} \mid c_{Inv}!b_i^{pre} \mid c_{Inv}!b_i^{post})\hat{}*$
  Accepts an arbitrary sequence of tracking events.
- `A` $= (c_{Inv}!a_i^{pre} \mid c_{Inv}!a_i^{post})$
  Implicitly accepts an a_i via the corresponding tracking events.
- `B` $= (c_{Inv}!b_i^{pre} \mid c_{Inv}!b_i^{post})$
  Implicitly accepts a b_j via the corresponding tracking events.

Now, let *Acc* be the set of all accepting global process states. That is, $Acc = \{a \mid a[i] \text{ accept state for process } i\}$. We will now form bad states based on the kinds of invariant we are checking. Note that we only specify the contents of c_{Inv} channel; the contents of all other channels are: (1) all system channels (non-invariant and non-local-event channels) are specified as being empty – "_", and (2) the local

[10]Therefore, an McScM bad state is, in fact, a *set* of system states, as defined in Section 3.3.

events channel is specified as containing an arbitrary sequence of local events.[11]

Now, we can specify the set of bad states B for each invariant type:

- $\mathcal{T} = \rightarrow$ $\quad B = \{\langle a, \texttt{ANY}\,.\,\texttt{A\^{}+}\rangle | a \in Acc\}$
- $\mathcal{T} = \not\rightarrow$ $\quad B = \{\langle a, \texttt{ANY}\,.\,\texttt{A}\,.\,\texttt{ANY}\,.\,\texttt{B}\,.\,\texttt{ANY}\rangle | a \in Acc\}$
- $\mathcal{T} = \leftarrow$ $\quad B = \{\langle a, \texttt{B\^{}+}\,.\,\texttt{ANY}\rangle | a \in Acc\}$

A.3 Post-processing the counter-example path

The invariant counter-example path returned by McScM for $\mathcal{C}'$ must be post-processed to derive a valid counter-example for $\mathcal{C}$. The path is transformed in two ways, that counter the transformations described in A.1: (1) remove all tracking events, and (2) replace events that are send events to the local channel, c_{local}, to be local events in $\mathcal{C}$.

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[11]This is $(e^1|\ldots|e^n)\hat{}*$, where e^i is a local event in $\mathcal{C}$.

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