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1 Overview

An increasingly common trend in distributed computing is the mass execution of small homogeneous proceses. This pattern is prevalent in big data processing, and micro service based architectures. A key tenant of these processes is minimal or non existent state. This property is largely due to the complexities of designing massive systems which can coordinate stateful behavior. Here we propose a technique for analyzing the stateful behavior of thousands of homogeneous processes, over many executions. Our analysis composes the logs of all processes into a single aggregate state machine. This model is replicated in a runtime, and is used to simulate new executions which are checked for specificed safety and liveness properties. We propose two models for constructing aggregate state machines. First a theroretical model which generates no false positives, but is constrained to minimal systems. Second a pragmatic model for large systems which permits false positives. Our second model is paired with additional analysis which orders false positives by their likelyhood to be real safty violations.

2 Intro

Building large scale distributed systems is challenging. Rather than face the headaches of coordinating thounds of machines by hands, developers use frameworks which hide the complexity [4, 20, 16]. These frameworks sacrifice performance for generality and simplicity [15]. Recent work has demontrated that some tasks benfit greatly from the implementation of custom stateful agorithms [6]. Such performance gains are not feasable for the majority of developers, as the difficulty of checking the correctness of their systems remains high.

Static and dynamic analysis are common approches for building correct distributed systems. Languages such as TLA+ and COQ [12, 3] are usefully for specifying systems, and use model checkers to ensure that safty and liveness properties are not violated. These checkers require extreme ammounts of computation to check and the matenice of a fully flushed out specification, in addition to a complete implmenentation. and the gap between specification, and implementation still admit bugs. Dynamic model checking techniques check implementations by systematically exercising a system, or replaying known faults [17, 18]. While these approaches are less costly computationally, they represent a strict under aproximation of the systems behavour.

In this work we propose a dynamic analysis technique which uses logs to reach safty violating states not reached during execution. Our technique uses the logs generated from many executions of a system and composes an aggregate state machine of a single aggregate process, which summerizes all logged behaviour. A runtime enviornment replicates these machines, and systematically steps through state transitions. User specified safty and liveness conditions are checked during simulation. Violations, and their corresponding simulated traces are output to the user.

Our state machine aggregation algorithm builds on one fundemintal observation - If the logged state of any two processes match exactly, then their states are the same. Our state machines are built by finding all occurances of matching state from all processes on all executions, and overlaying their individual state machines. The same matching rule is applied to messages, and local events which trigger state transitions. Using exact state matching, distributed states not reached during exection can be observerd through simulation, further all viloations are real bugs.

Our exact state matching algorithm is the extension of theroretical literature [10]. While correct these conditions are rarely met in practice, for instance ip port combinations alone fragment an aggregate state machine into a sparse graph closely resembling traces themselvles. To apply our analysis in practice we extend our notion of exact state matching to relaxed state matching, where the logged states of proccesses represent the same state in our model if a subset of their states match exactly. This relaxation of state matching collapses the size of a state machine, but overaproximates state transitions, thereby permiting false positives.

We propose an additional analysis procedure to order violations flaged using relaxed state matchingm, by their lieklyhood to be real violations. Prior to simulation data invariants are collected on state traces on variables which do not exactly match. Transitions between states on non matching variables are aproximated using program synthesis. During simulation non matching variables are aproximated by applying opertations generated by the synthesized transition. Traces generated which violated the minimal number of invariants are reported to the user, as they are least likely to have diverged from the systems constrained behavour.

The rest of the paper is arraged as follows. Section 3 Defines our model of a distributed system, and FSM construction. Section 4 describes our system. Sections **??** outline a proposed evalutation, and timeline.

3 model

In the following section we describe our model of a distributed system, and state machine. We then further extend our state machine model to a relaxed version.

3.1 System Model

Execution: An execution of a distributed program is defined as a set of n processes $P_1, P_2, \ldots P_n$ all of which execute the same source code, with potentially different configurations.
Process State: The state s of any process P during an execution is the set of m variables v where $s = \{v_1, v_2, \ldots v_m\}$, including the program counter. All processes share a unique initial state s_0.
Event: The set of events E is a finite alphabet of events which can be generated by any process. Our model restricts events to 3 general types *Sending, Receiving, and Local*.
Event State: Event state C (channel state) is a set of 1 or more variable values associated with an event. The state of a sending or receiving event, is the set of all transmitted variables. The event state of a local event, is the prior state of the process P.
Trace: A trace T of process P_i is the sequence of k (State, Event) pairs $T_i = (s_0 : e_0), (s_1, : e_1), \ldots, (s_k, e_k)$.
Trace Matrix: A trace matrix M, is an n,m matrix in which index i,j is the trace generated by process j on execution i.

3.2 FSM Model

State Matching $\forall i, j \; s_i = s_j \iff \forall v \in s, v_{i,k} = v_{j,k}$.
Event Matching $\forall i, j \; e_i = e_j \iff \forall v \in s, v_{i,k} = v_{j,k} \wedge$ event Type $e_i ==$ eventType e_j.
Node A unique node n exists for all sets of matching states.
Edge A directed edge is defined as the triple (s_i, e, s_j). An edge exists between two nodes $n_k, n_l \iff \exists$ trace T which contains $(s_i : e_i), (s_{i+1} : e_{i+1})$. Two edges match if their states, and event match.

3.3 Relaxed FSM

Relaxed State Matching states s_i, s_j match $iff \exists rs \in s$ where rs_i matches rs_j and $|s| - |rs| \geq k$.
Relaxed Event Matching events e_i, e_j match $iff \exists re \in c$ where re_i matches re_j and $|e| - |re| \geq l$.

4 System

The following section describes our analysis system. The section is broken up into 3 section. First the translation of distributed logs to aggregated FSM is detail. Second state, and transition invariant detection are discussed, and operation generation. Finally we discuss our execution engine and fault detectors.

4.1 FSM Generation

Prior to execution, a system must be instrumented to log its state, and the state of sent and received messages. For this purpose we make use of the Dinv runtime environment. Dinv logs the state of individual processes during execution. Using automatic instrumentation, all in scope variables are written to a key-value store at the entrance and exit of each function. Upon executing a sending, receiving or local event, the contents of the key value store are persisted to disk (or aggregated to a central source) with a corresponding vector timestamp. Each write to disk corresponds to a trace pair (s_i, e_i). Post execution the logs of one or more executions are aggregated together for FSM generation.

Logging State Defining a distributed system by the state of each process, and the state of messages, is a fundamental distributed model for many algorithms.

Capturing all process, and message state is the fundamental backbone of distributed algorithms [13, 14]. Further, the reduction of distributed executions to communication events is a common method for reducing complexity while retaining essential information [7, 2, 9, 11, 8].
FMS Graph ConstructionFSM nodes are built by matching states. User configuration determines how matching is performed. By default **State Matching** is used to match states as it guarantees correctness [10]. Users may either specify a subset of named variables, variables for **Relaxed state matching**. Matching states are processed in linear

time by hashing and mapping variable states. Similarly edges are constructed using **Event Matching**. As above relaxed event matching is performed on a subset of user defined variables.

4.2 Invariant Detection, and operation inference

Using exact state matching the FMS generated from the aggregation of traces is a strict under representation of a systems behavior (TODO ▶*find a fundamental paper on dynamic analysis*◀), therefore all safety, and liveness violations are correct. In practice exact state matching results in a massive FSM with few inferred paths to traverse (as the likelihood of variables such as buffers, id's and ports matching is low). Relaxed state matching generates a smaller FSM with more paths to explore. However, matching on a subset of state allows false positives in both safety, and liveness detection. Here we present a novel technique for identifying safety and liveness conditions on relaxed state matching which orders violations by their likelihood of being false positives. This technique uses simulated values for variables which do not match, and invariant violations as a heuristic measure of divergence from the real system.

Each node n is composed of a set of matching states, $n = s_0, s_1, \ldots, s_n$. Some subset of variables in each matching state $s = v_0, v_1, \ldots, v_m$ match, while another subset of variables do not. The subset of variables which do not match form a sub trace which profiles their behavior. We use Daikon to detect data invariants which held during execution [5].

Edges connecting nodes are state transitions with an associated operation on the state. In the case of **State Matching** transitions between state, are equivalent to an assignment statement (ie if node n and n are constructed from exactly matching states, for any transition e between states $\forall i,\ v_i \ == v_i'$. **Relaxed State Matching** is more complicated, because many values may exist for any variable v in state n. A transition between two states may not be valid in the case of **Relaxed State Matching**, as the aggregate state is an over approximation of the systems observed behavior.

To reduce false positives when applying **Relaxed State Matching** the values of unmatched variables are simulated during runtime. If the trace produced by the runtime violates invariants detected from real executions, the probability of a violation being a false positive increases TODO ▶*this is a big claim, and one that will need to be backed up. If it is true it will be a research contribution.*◀ To simulate variable values, we synthesize operations using Z3, and input output examples from traces [19]. The state transitions inferred by Z3 are applied to variables during runtime. In cases where no operations could be inferred within a given timeout, a value is deterministicly chosen for relaxed variable.

4.3 Runtime

TODO ▶*Our*◀ runtime executes replicated versions of the inferred state machine. Each machine can send and receive messages to any other machine, and execute local events. The number of state machines to execute is a user defined parameter. More machines increase runtime, but may detect subtle bugs reliant on complicated multi machine state. Algorithm 1 overview our runtime engine.

Data: $Replication, Depth, Model, Conditions$
Result: Condition Violating Traces
while $Depth \geq 0$ **do**
  $eventQueue \leftarrow GenEvents(Model, Replication)$
  while $\neg eventQuene.Empty()$ **do**
    $ApplyEvent(eventQueue.Pop())$
    $CheckSafty(Conditions)$
    $CheckLiveness(Conditions)$
    $Recurse(Replication, Depth -$
    $-, Model, Conditions)$
  end
end

Algorithm 1: Runtime Algorithm

Initial all machines are set to an empty initial state $\perp$. All valid events are generated at the beginning of the main runtime loop. A valid event is the set of all outgoing edges of all the current state of all nodes. Each event is added to an event queue and is applied systematically. Three kinds of events can be applied at runtime.

- *Local Event* A local event transitions a single node from one state to another.
- *Send Event* A send event generates a message, which is placed on an outstanding message list
- *Receive Event* A receive event consumes a message. Two conditions exist for receiving messages, droppable, and undroppable. Droppable message can be consumed by any machine in any state, if no transition exists for the message, the state of the received machine does not change. Undroppable messages are only delivered to machines which are in a state with a transition corresponding to the message being received [18].

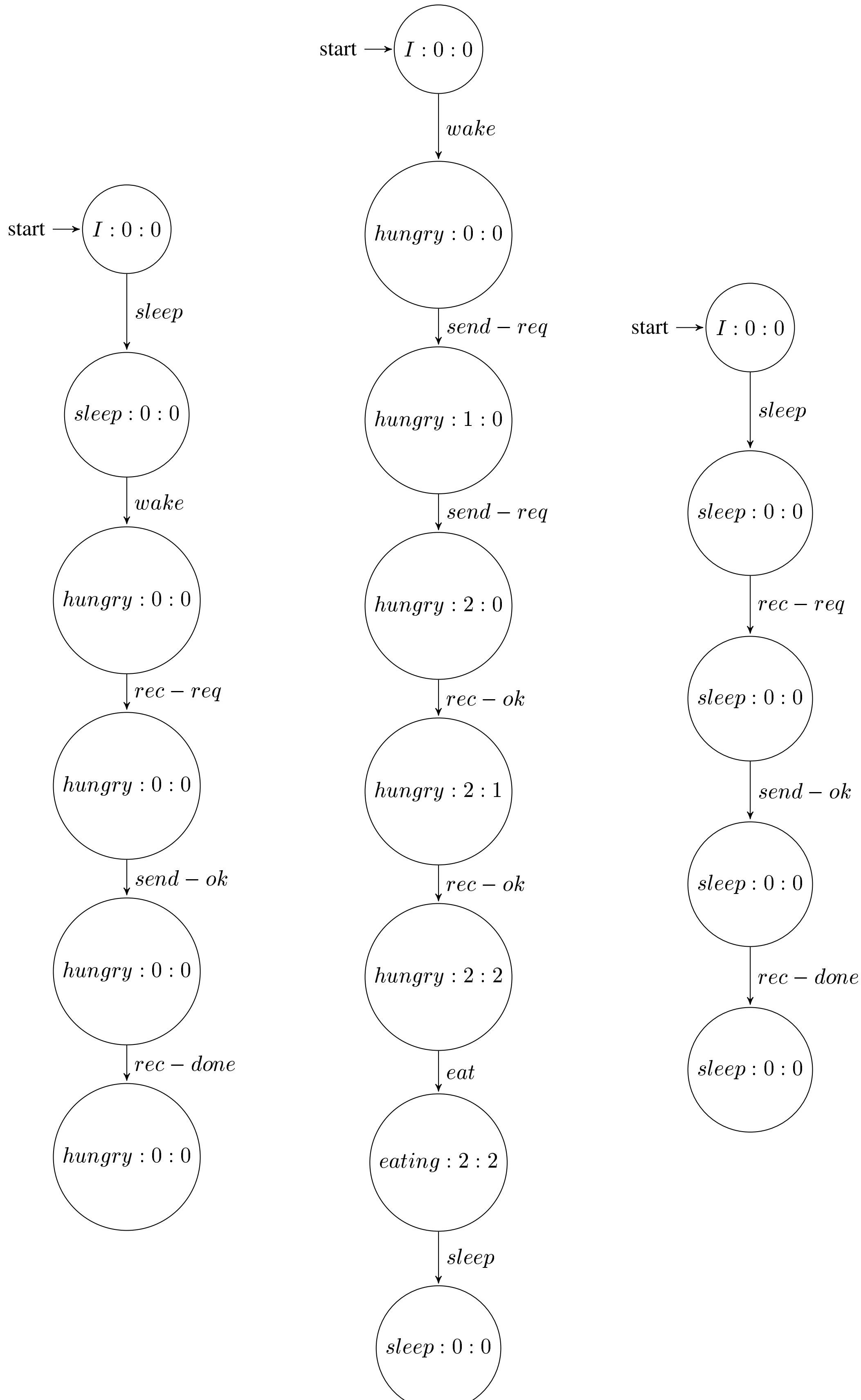


Figure 1: Dining philosopher traces. Each process maintians 3 state variables, [$currentState$,$OustandingRequests$,$AcksReceived$]. When hungry a philosopher requests to eat from its neighbour, each request increases outstandingRequets. A philosopher can eat after receiving two acks.

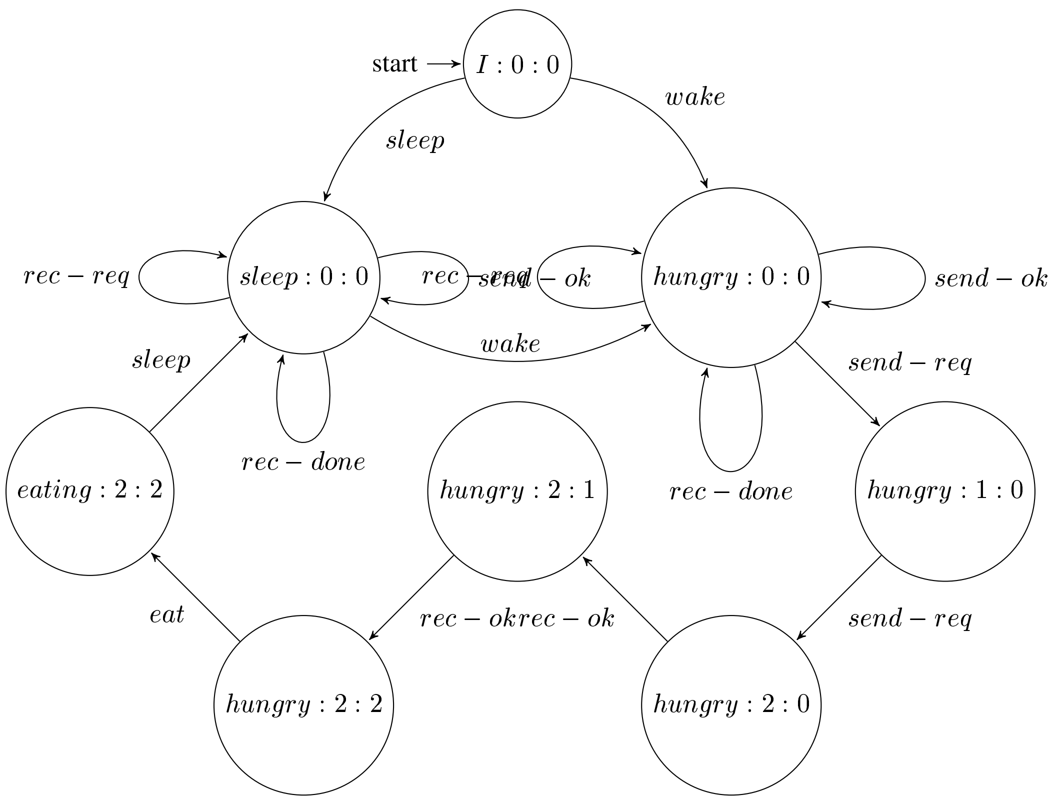
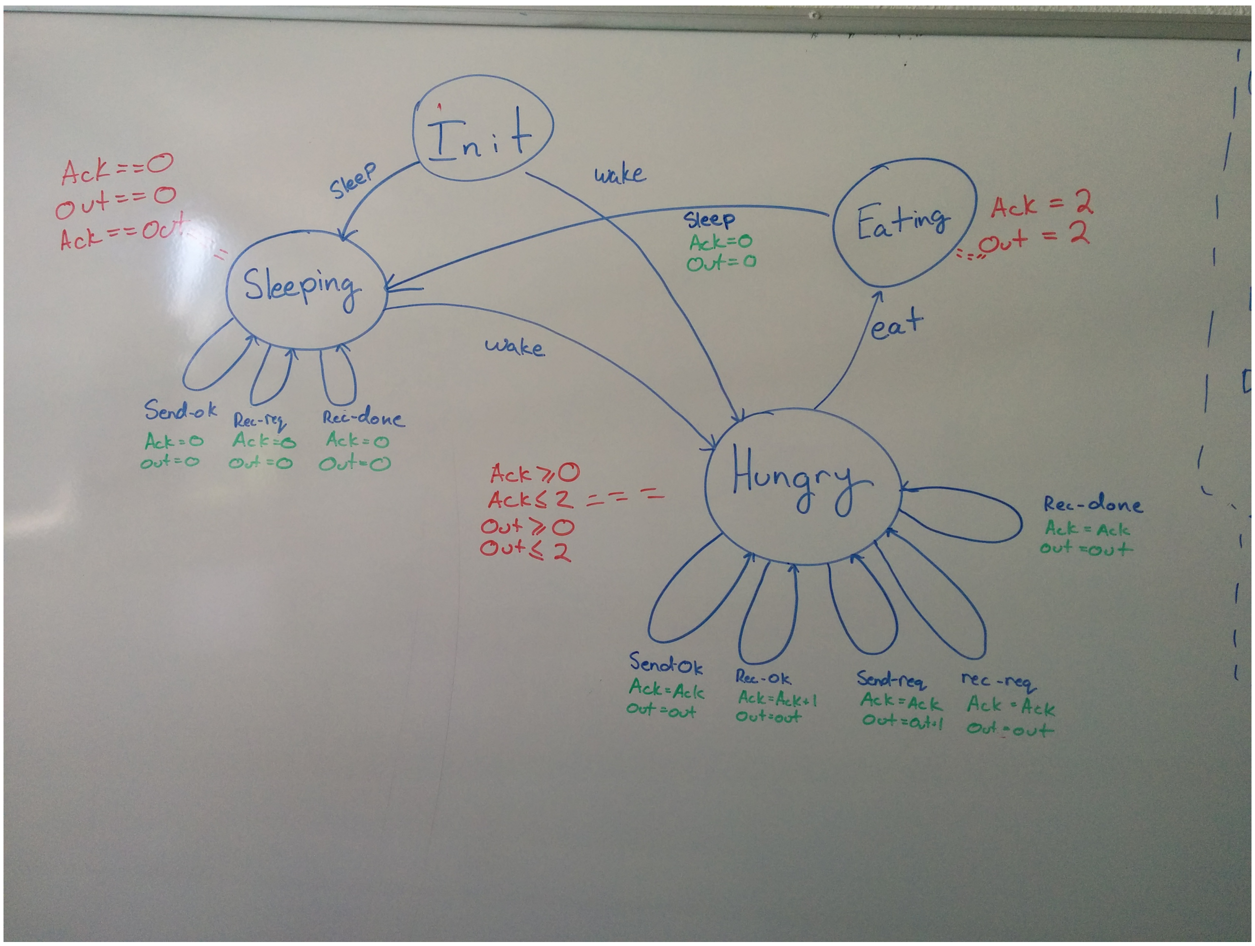


Figure 2: Aggregate state machine from 3 traces, using exact state matching


Init
Sleep
wake
Ack==0
Out==0
Ack==Out
Sleeping
Sleep
Ack=0
Out=0
Eating
Ack = 2
Out = 2
eat
wake
Send-ok
Ack=0
out=0
Rec-req
Ack=0
Out=0
Rec-done
Ack=0
Out=0
Ack≥0
Ack≤2
Out≥0
Out≤2
Hungry
Rec-done
Ack = Ack
out = out
Send-Ok
Ack=Ack
Out=out
Rec-Ok
Ack=Ack+1
Out=out
Send-req
Ack=Ack
Out=Out+1
rec-req
Ack = Ack
Out = out

Messages are consumed by only a single node. As our search is performed systematically, all permutations of message delivery are eventually explored.

While executing a trace of variables is maintained. Variables are updated during each state transition. If the state transitioned into is exactly matched, runtime variables are assigned the value of the state. Otherwise the operations determined by constraint solving are applied to the variables.

The runtime environment has a holistic view of the system, and is therefore able to check safety predicates at all times. Predicates defined by a user specification, such as only one machine may enter the critical section at a time, or at least one node has a token, are checked on a per variable basis.

Liveness conditions are checked using techniques developed by [10]. If a periodic pattern is found in a distributed execution, ie if at two points in an execution, the state of the system is exactly the same, the events between the two states can periodically execute forever (given non random liveness guarantees). If exact states are revisited during runtime, and a liveness condition is not met over the interval between matching states, a liveness violation is reported.

4.4 Violations & false positive reduction

The result of simulating is a set of traces on which a safety or liveness violation occurred. Traces contain vector time stamps for simulated events, which are formatted to be visualized by ShiViz, to aid in debugging [1]. Traces generated using **State Matching** and **Event Matching** are guarantees bugs, the traces of which can be traversed to identify the root cause of the bug.

Traces generated using **Relaxed State Matching** and **Relaxed Event Matching** may be false positives. These traces are approximately ordered by their likelihood to be false positives. Each simulated trace (containing simulated variable values at runtime) is analyzed by Daikon. Using Daikons Invariant Difference tool the count of invariant violations generated by the simulated execution can be determined. Traces which violate the minimum count of invariants are reported to the user first, as they are least likely to have diverged from the systems real behavior.

5 evaluation

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6 Timeline

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