# FlyMC: Highly Scalable Testing of Complex Interleavings in Distributed Systems

Jeffrey F. Lukman, Huan Ke, Cesar A. Stuardo
University of Chicago

Riza O. Suminto, Daniar H. Kurniawan
University of Chicago

Dikaimin Simon
Surya University

Satria Priambada
Bandung Institute of Technology

Chen Tian, Feng Ye
Huawei US R&D Center

Tanakorn Leesatapornwongsa
Samsung Research America

Aarti Gupta
Princeton University

Shan Lu
University of Chicago

Haryadi S. Gunawi
University of Chicago

## Abstract

We present a fast and scalable testing approach for datacenter/cloud systems such as Cassandra, Hadoop, Spark, and ZooKeeper. The uniqueness of our approach is in its ability to overcome the path/state-space explosion problem in testing workloads with complex interleavings of messages and faults. We introduce three powerful algorithms: state symmetry, event independence, and parallel flips, which collectively makes our approach on average 16× (up to 78×) faster than other state-of-the-art solutions. We have integrated our techniques with 8 popular datacenter systems, successfully reproduced 12 old bugs, and found 10 new bugs — all were done without random walks or manual checkpoints.

***CCS Concepts*** • **Computer systems organization → Cloud computing**; *Distributed architectures*; *Dependable and fault-tolerant systems and networks*; *Reliability*;

***Keywords*** Reliability, Availability, Distributed Systems, Software Model Checking, Distributed Concurrency Bugs

**ACM Reference Format:**
Jeffrey F. Lukman, Huan Ke, Cesar A. Stuardo, Riza O. Suminto, Daniar H. Kurniawan, Dikaimin Simon, Satria Priambada, Chen Tian, Feng Ye, Tanakorn Leesatapornwongsa, Aarti Gupta, Shan Lu, and Haryadi S. Gunawi. 2019. **FlyMC: Highly Scalable Testing of, Complex Interleavings in Distributed Systems**. In *Fourteenth EuroSys Conference 2019 (EuroSys '19), March 25–28, 2019, Dresden, Germany.* ACM, New York, NY, USA, 16 pages. https://doi.org/10.1145/3302424.3303986

## 1 Introduction

Datacenter systems such as distributed key-value stores, scalable file systems, data-parallel computing frameworks, and distributed synchronization services, are the backbone engines of modern clouds, but their complexities and intricacies make them hard to get right. Among all types of issues in such systems, complex interleavings of messages, crashes, and reboots are among the most troublesome [39, 50, 61, 62, 79]. Such a non-deterministic order of events across multiple nodes cause "*distributed concurrency*" bugs to surface (or "**DC** bugs" for short). Developers deal with DC issues on a monthly basis [45, 48], or worse on a weekly basis for newly developed protocols [6]. They are hard to reproduce and diagnose (take weeks to months to fix the majority) and lead to harmful consequences such as whole-cluster unavailability, data loss/inconsistency, and failed operations [59].

Ideally, bugs should be unearthed in testing, not in deployment [35]. One systematic testing technique that fits the bill is stateless/software model checking that runs directly on implementation-level distributed systems [46, 49, 55, 58, 73, 80, 81]. These software model *checkers*[1] attempt to exercise many possible interleavings of non-deterministic events such as messages and fault timings, hereby pushing the target system into unexplored states and potentially revealing hard-to-find bugs.

One nemesis of checkers is the *path explosion problem*. As an illustration, suppose there are 10 concurrent messages (*events*) $\{a, b, .., j\}$, a naive checker such as depth-first search (DFS) has to exercise 10! (factorial) unique execution paths

[1]In this paper, **"checkers"** specifically represent the distributed system software model checkers, as cited above, *not* including "local" thread-scheduling checkers [22, 66] or the classical model checkers [37, 42].

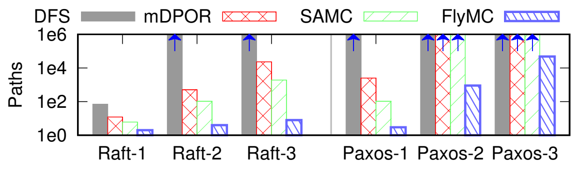


**Figure 1. Checkers[1] scalability.** *The x-axis represents the tested protocol (Raft or Paxos) with 1 to 3 concurrent updates. The log-scaled y-axis represents the number of paths to exhaust the search space (i.e., the path explosion). Compared to our checker,* FlyMC*, current checkers do not scale well under more complex workloads.* **"↑"** *indicates incomplete path exploration.*

(*ab..ij*, *ab..ji*, and so on). Figure 1 illustrates further this explosion problem. The gray "DFS" bar shows almost 100 paths to explore (in *y*-axis) under a *simple* workload such as an instantiation of a Raft update protocol ("`Raft-1`") [67].

To tame this problem, checkers employ path *reduction algorithms*. For example, MoDist [81] and some others [73, 80] adapted the popular concept of Dynamic Partial Order Reduction (DPOR) [38, 41], for example "a message to be processed by a given node is *independent* of other concurrent messages destined to other nodes [hence, need *not* to be interleaved]." SAMC [58] also extended DPOR further. As a result, reductions significantly improve upon a naive DFS method, as shown by the "mDPOR" and "SAMC" bars on `Raft-1` in Figure 1.

Despite these early successes, we found that the path explosion problem remains untamed under more *complex* workloads. For example, under two or three concurrent Raft updates (`Raft-2` and `-3` workloads in Figure 1), the number of paths to explore still increases significantly in MoDist and SAMC. Not to mention a much more complex workload such as Paxos [57] where the path explosion is larger (*e.g.*, `Paxos-1` to `-3` workloads in Figure 1).

To sum up, existing checkers fail to scale under more complex distributed workloads. Yet in reality, some real-world bugs are still hidden behind complex interleavings (§7). For example, the Paxos bug in Cassandra in Figure 2 can only surface under a workload with three concurrent updates with 54 events in total. These kinds of bugs will take weeks to surface with existing checkers, wasting testing compute resources and delaying bug finding and fixes. For all the reasons above, to find DC bugs, some checkers mix their algorithms with *random* walks [81] or *manual* checkpoints [49], hoping to faster reach "interesting" interleavings that would lead to DC bugs. However, this approach becomes unsystematic – the random and manual approaches lead to poorer coverage than a systematic coverage of all states relevant to observable events.

We present FlyMC, a fast, scalable, and systematic software/stateless model checker that covers all states relevant to observable events for testing distributed systems implementations. FlyMC achieves scalability by leveraging the internal properties of distributed systems as we illustrate below with three FlyMC's algorithms.

*(1) Communication and state symmetry:* Common in cloud systems, many nodes have the same role (*e.g.*, follower nodes, data nodes). The state transitions of such symmetrical nodes usually depend solely on the order and content of messages, irrespective of the node IDs/addresses. Thus, FlyMC reduces different paths that represent the same symmetrical communication or state transition into a single path.

*(2) Event independence:* While state symmetry significantly omits symmetrical paths, many events must still be permuted within the non-symmetrical paths. FlyMC is able to identify a large number of event independencies that can be leveraged to alleviate a wasteful reordering. For example, FlyMC automatically marks concurrent messages that update disjoint sets of variables as independent. FlyMC can also find independence among crash-related events.

*(3) Parallel flips:* While the prior methods reduce message interleavings to every node, in aggregate many flips (reordering of events) must still be done across all the nodes. The problem is that in existing checkers, only one pair of events is flipped (reordered) at a time. To speed this up, parallel flips perform simultaneous reorderings of concurrent messages across different nodes to quickly reach hard-to-reach corner cases.

Finally, not only path reduction but wall-clock speed also matters. Existing checkers must wait a non-negligible amount of time in between every pair of enabled events for some correctness and functionality purposes. The wait time is reasonable under simple workloads, but it significantly hurts the aggregate testing time of complex workloads. FlyMC optimizes this design with local ordering enforcement and state transition caching which will be explained later (§5).

Collectively, the algorithms make FlyMC on average 16× (up to 78×) faster than other state-of-the-art systematic and random-based approaches, and the design optimizations improve it to 28× (up to 158×). FlyMC is integrated with 8 widely-used systems, the largest number of integration that we are aware of. We model checked 10 protocol implementations (Paxos, Raft, etc.), successfully reproduced 12 old bugs, and found 10 new DC bugs, all confirmed by the developers and all were done in a systematic way *without* random walks or manual checkpoints. Some of these bugs cannot be reached by prior checkers within a reasonable time. We have released our FlyMC publicly [20].

The following sections detail our four contributions:

1. Highly scalable checker algorithms that provide systematic state coverage for given workloads. (§3).
2. A checker design that is backed with static analysis help developers extract information from the target system and use it to write the system-specific parts of the algorithms (§4).

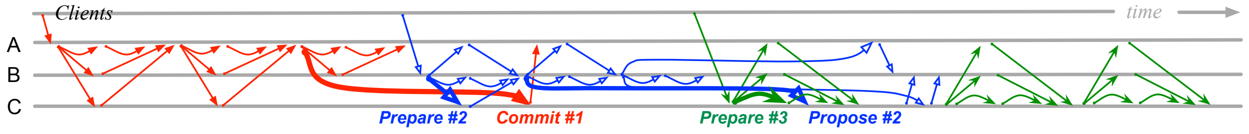


**Figure 2. A complex DC bug in Cassandra Paxos (`CASS-1`).** *This bug which we label as "`CASS-1`" [4] requires three Paxos updates and only surfaces with the two flips (the prepare message with ballot 2 must be enabled before the commit with ballot 1 and the prepare with ballot 3 before the propose with ballot 2) happening within all the possible flips of the 54 events, resulting in data inconsistency.*

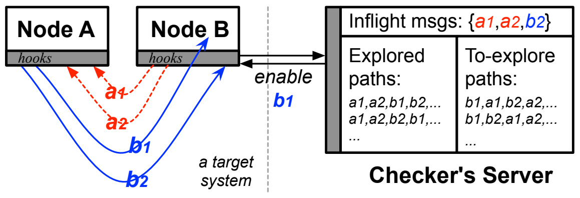


**Figure 3. A checker architecture.** *As explained in Section 2.*

3. Additional optimizations that improve the checker's wall-clock speed in exploring paths (§5).
4. A comprehensive integration with challenging applications, and detailed evaluations that demonstrate the checker's effectiveness. (§6-7).

For interested readers, we provide an in-depth technical report [21].

## 2 Background

• **Checker architecture:** The concept of checkers and how they work in detail can be found in existing checker literature [58, §2.1][81, §2] [73, §3][21, §2]. This section briefly discusses the important components and terms.

As shown in Figure 3, a checker runs the target workload (*e.g.*, in nodes *A* and *B*) and intercepts all the in-flight messages (*e.g.*, the concurrent messages $a_1$, $a_2$, $b_1$, and $b_2$ intercepted by the gray "hooks") to control their timings. The checker's server then *enables* one message *event* at a time (*e.g.*, enable $b_1$). The checker's hooks wait for the target system to quiesce (after $b_1$ is processed) and the node to pass the new resulting global state (*e.g.*, $S_1$) to the checker's server which records it as the *state-event history* (*e.g.*, $S_0+b_1\rightarrow S_1$). The developers decide which global state variables to check (*e.g.*, role, leader, ballot number). The server then runs assertions to find any safety violation in the new state.

New events generated by every enabled event will be intercepted again by the checker (*e.g.*, $a_3$ generated in response to $b_1$, not shown in the figure). This whole process repeats ($S_0+b_1\rightarrow S_1$, $S_1+b_2\rightarrow S_2$, ...$+a_3\rightarrow$...) until it reaches a *termination point* – when a specification is violated or the workload ends without any violation (*e.g.*, no more messages observed). This forms an *explored path* (*e.g.*, $b_1b_2...a_3$). A path implies a unique total ordering of events; it is also known as "trace" or "execution sequence" [44, 54, 81].

Given a previously exercised path, the checker will permute the possible interleavings (to-explore paths) and restart

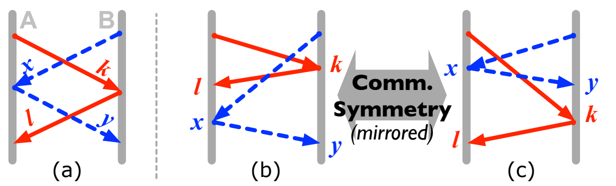


**Figure 4. Communication symmetry.** *The figure is explained in the "Problem" part of Section 3.1.*

the workload. For example, in the next run, it will *flip* $b_2$ before $b_1$, hence exercising a new path $b_2b_1$... within the same workload. Paths can also contain crash/reboot events; for example, a path $b_1\cancel{B}B^{\uparrow}b_2$... implies a crash $\cancel{B}$ and a reboot $B^{\uparrow}$ on node *B* are injected after $b_1$ is processed but before $b_2$ arrives. The whole test *completes* (exhausts the state space) if there are no more paths left to explore.

## 3 FlyMC Algorithms

By considering the properties of distributed systems, we equip FlyMC with two reduction algorithms: communication and state symmetry (§3.1) and event independence (§3.2); and one prioritization algorithm: parallel flips (§3.3). The two reduction algorithms reduce unnecessary interleavings (redundant paths) that would lead to the same states already explored before. While the prioritization algorithm prioritizes interleavings that would reach corner cases faster.

Throughout this section, we describe each of the algorithms in the following format: (a) the specific path explosion issue being addressed, (b) the intuition for the reduction or prioritization, (c) the algorithm in a high-level description, and (d) a comparison to existing solutions. Later in Section 4, we discuss the intricacies of implementing these algorithms correctly and how our static analyses support can help developers in this regard.

### 3.1 Communication and State Symmetry

• **Problem:** Let us imagine a simple communication in Figure 4a where message *k* triggers *l*, *x* triggers *y*, and *k* and *x* are messages of the same type (*e.g.*, a write request). Figures 4b and 4c show two possible reordered paths *klxy* and *xykl*. While these paths seem to be different, their communication structures in Figures 4b-c hint at a possibility for symmetrical reduction.

A method to implement the symmetrical reduction in local concurrency literature is to *abstract* the system property [32, 33, 75]. Applying this to distributed systems, we initially attempted to abstract only the communication structure, specifically by abstracting the sender and destination node IDs (*e.g.*, IP addresses) to a canonical receiving order; for example in Figure 4b, as node $B$ is the first to receive, its node ID is abstracted to node "1" (*e.g.*, $k_{A\to B}$ becomes $k_{2\to 1}$). Similarly in Figure 4c, as node $A$ is the first to receive, its node ID is abstracted to node "1" (*e.g.*, $x_{B\to A}$ becomes $x_{2\to 1}$), hence the two figures exhibit a communication symmetry as $k$ and $x$ are messages of the same type from node "2" to "1".

Unfortunately, this approach is not always effective because most messages carry a unique content. For example, in Paxos, messages $k$ and $x$ carry different ballot numbers, hence cannot be treated the same. Thus, while the communication structures (the arrows) in Figures 4b and 4c look symmetrical, abstracting only the messages does *not* lead to a massive reduction.

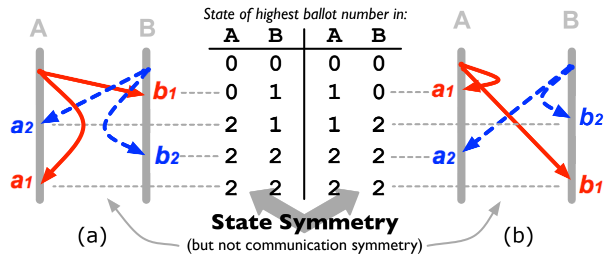
• **INTUITION:** Fortunately, in many cloud systems, many nodes have the same role (*e.g.*, follower nodes, data nodes) although their node IDs are different. Furthermore, the state transitions of such symmetrical nodes usually depend solely on the order and content of the messages, irrespective of the sending/receiving node IDs.

To illustrate this, let us consider the two communication structures in Figures 5a-b, which represent the first phase of a (much simplified) Paxos implementation with two concurrent updates (solid and dashed lines). Node $A$ broadcasts its prepare messages (the solid lines), $a_1$ to itself and $b_1$ to node $B$, with "$_1$" representing a ballot number 1. Similarly, node $B$ broadcasts $b_2$ to itself and $a_2$ to node $A$ with ballot number 2 (dashed lines).

If we compare the two communication structures in Figures 5a-b, they are *not* symmetrical, unlike the previous example in Figure 4. But let's analyze the state transition of every node, such as the highest ballot number the node has received, as shown in the middle table of Figure 5. In this Paxos example, every node only accepts a higher ballot and discards a new lower one, hence the node prepare status monotonically increases. In the left ordering, $b_1a_2b_2a_1$ in Figure 5a, node $A$'s state transition is `00222` and $B$'s is `01122`. In the ordering on the right, $a_1b_2a_2b_1$, the *state transition is symmetrical* (mirrored), `01122` in $A$ and `00222` in $B$.

To sum up, while the two paths do not exhibit communication symmetry (Figures 5a-b), their *state transitions are symmetrical* (the middle table). Thus, *state symmetry* can be effective for path pruning (*e.g.*, if $b_1a_2b_2a_1$ is already explored, then $a_1b_2a_2b_1$ is redundant).

• **ALGORITHM:** To implement symmetry, first, we keep a history of state-event transitions (§2) that have been exercised in the past, in the following format: `Si`+$e_j$⟶`Sj` where "S" denotes the global state (*i.e.*, collection of per-node states)


A
B
a2
a1
b1
b2
(a)
State of highest ballot number in:
State Symmetry
(but not communication symmetry)
A
B
a1
b2
a2
b1
(b)

| A | B | A | B |
|---|---|---|---|
| 0 | 0 | 0 | 0 |
| 0 | 1 | 1 | 0 |
| 2 | 1 | 1 | 2 |
| 2 | 2 | 2 | 2 |
| 2 | 2 | 2 | 2 |

**Figure 5. State symmetry.** *The figure is explained in the "Intuition" part of Section 3.1.*

and $e_j$ is the next enabled event. So, when $e_j$ is enabled, the global state transitions from state `Si` to `Sj`.

In addition, we keep a history of {`absState`+*absEv*} transitions where `absState` denotes the abstracted global state (in alphabetical order) that excludes the node IDs for symmetrical nodes such as datanodes (and similarly *absEv* for events). Using the example in Figure 5a, the first event will generate {`00`+*1*} where `00` represents the abstracted state of datanodes $A$ and $B$ (with just the highest ballot numbers, excluding the node IDs) and *1* represent[illegible] abstracted $a_1$ message. Subsequently, we record {`01`+*2*}, {`12`+*2*}, and {`22`+*1*} to the history. Important to note that state `12` is from the alphabetically ordered state `21`; that is, symmetry implementation requires alphabetical/numerical sorting.

With this history, the second ordering $a_1b_2a_2b_1$ in Figure 5b will be marked symmetrical; when $a_1$ is to be enabled (abstracted to +*1*) when the system is at state `00`, a historical match {`00`+*1*} will be found. Similarly, for $b_2$ (abstracted to +*2*) when the system is at state `01`, a match {`01`+*2*} will be found. One caveat is that state symmetry works less effective in earlier paths as the history is still being built up, but after a few initial paths, the "cache hit rate" increases significantly (more in §5).

• **COMPARISON:** In classical (stateful) model checking, symmetry is commonly used, *e.g.*, for symmetrical processors [32, 75]. In distributed checkers, we found none that employs symmetry [46, 49, 55, 58, 73, 80, 81], except SAMC [58]. However, SAMC only uses symmetry for reducing unnecessary crash timings, but not for concurrent messages. FLYMC's symmetry is more powerful as it also generalizes for crash timings. More specifically, a crash is abstracted as a crash event targeted to a particular node; for example, {`12`+$\cancel{2}$} implies a crash injected at the node with ballot number 2 (regardless of the datanode IDs).

## 3.2 Event Independence

• **PROBLEM:** While state symmetry omits symmetrical paths, within the non-symmetrical paths, there are many other events to reorder. For example, if four messages $a_1 \ldots a_4$ of different types are concurrent to node $A$, the permutation will lead to 4! times more paths. As some concurrent messages to every node must still be reordered, more reduction is needed.

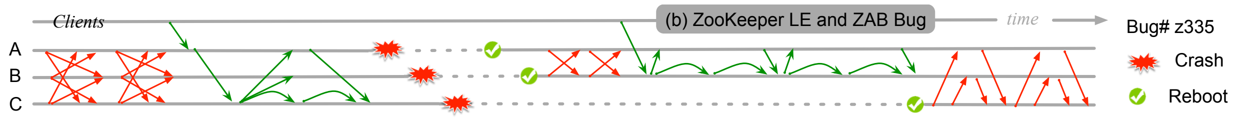


**Figure 6. A ZooKeeper bug with complex timings of multiple crashes (ZOOK-1).** *The bug is referenced in §3.2 and §7.1. This bug labeled ZOOK-1 [13] requires 46 events including 3 crash and 3 reboot events, along with two incoming transactions, a complex concurrency between the ZooKeeper atomic broadcast (ZAB) and leader election (LE) protocols.*

• **INTUITION:** In this context FLYMC adapts the concept of DPOR's "independence" (aka. commutativity) as mentioned in the introduction. In DPOR, two events $e_1$ and $e_2$ are independent if $S_i$+$e_1$+$e_2$→$S_j$ and $S_i$+$e_2$+$e_1$→$S_j$. That is, if $e_1e_2$ or $e_2e_1$ result in the same global state transition from $S_i$ to $S_j$, the pair of events $e_1$ and $e_2$ do not have to be flipped when the system is at $S_i$, hence reducing the number of paths to explore. An example of independence in distributed systems is when many concurrent messages (to a destination node) update different variables. For example, in some distributed systems such as ZooKeeper, the atomic broadcast protocol might be running concurrently with the leader election protocol (because of a crashed node), but some of the messages in these two protocols do not update the same variables (when the system is at a specific state $S_i$), hence it is not necessary to flip them.

• **ALGORITHM:** While the concept of DPOR/independence arose from stateful model checkers (with known state transitions) [29, 38, 41, 69], adapting it to stateless distributed checkers is not straightforward – how can a checker have *prior* knowledge that $S_i$+$e_1e_2$ and +$e_2e_1$ would lead to the same future state $S_j$ *before* exercising the events? For this, FLYMC helps developers identify *disjoint updates* ahead of time with the static analyses (more details in §4.1).

Essentially, for every message $n_i$ to a node $N$, our static analyses builds the live `readSet` and `updateSet`, a set of to-be-read and -updated variables, within the flow of processing $n_i$ at $N$'s current state. That is, our approach incorporates the fact that $n_i$'s read and update sets can change as node $N$ transitions across different states. Therefore, two messages $n_i$ and $n_j$ to a node $N$ are marked independent if $n_i$'s `readSet` and `updateSet` do not overlap with $n_j$'s `updateSet` at the current state $S_i$, and vice versa. In addition, if the `updateSets` of two messages intersect completely and all the variables in the sets are in/decremented by one (*e.g.*, a common acknowledgment increment "`ack++`" in distributed systems), then the two messages are marked independent/commutative.

Beyond reducing unnecessary message interleavings, a scalable checker must reduce unnecessary crash injections at different timings. 50% of DC bugs can only surface with at least one crash injection and 12% require at least two crash events at specific timings [59] (*e.g.*, the complex ZooKeeper bug in Figure 6), which exacerbates further the path explosion problem (imagine different fault timings such as ..$a_1a_2\cancel{A}$.., ..$a_1\cancel{A}$.., ..$a_2\cancel{A}$.., where "$\cancel{A}$" denotes crashing of node $A$). Thus, another uniqueness of FLYMC's adaptation of independence is building the sets above for crash events. For example, if a follower node is crashed ($\cancel{B}$) and the leader node $A$ reacts by reducing the live-nodes count (*e.g.*, `liveNodes-`), then $\cancel{B}$'s `updateSet` will include $A$'s `liveNodes` variable.

• **COMPARISON:** Prior checkers adopted DPOR's independence, but only to a limited extent, hence are not scalable under complex interleavings. For example, MODIST [81, §3.6], CrystalBall [80, §2.2] and dBug [73, §2] only adopted DPOR with the following rule: "a message to be processed by a given node is independent of other concurrent messages destined to other nodes". But because they are *black-box* checkers that do not analyze the target source code, they cannot find more independencies. On the other hand, being a *white-box* checker, FLYMC exploits access to source code in today's DevOps-based cloud development where developers are testers and vice versa [60].

SAMC is another example of a white-box checker, but developers need to manually analyze their target system code and follow the SAMC simple principles. Hence, SAMC only introduces cautious and rigid reduction algorithms which are less powerful than FLYMC's (note that in FLYMC, the content of the sets mentioned above will be automatically constructed through the static analysis support). For example, FLYMC generalizes a discarded message ([58, §3.3.1]) as an empty `updateSet`, such a message automatically does not conflict with any other messages, hence not need to be reordered. As another example, a crash that does not lead to new messages (*e.g.*, a quorum is still maintained after crashing a follower node $\cancel{B}$) will not be interleaved with all the outstanding messages [58, §3.3.2] as FLYMC automatically identifies that the crash event $\cancel{B}$'s `updateSet` (*e.g.*, `liveNodes` in the leader node) does not conflict with `updateSets` of in-flight messages.

## 3.3 Parallel Flips

• **PROBLEM:** While our previous methods reduce messages reordering to every node, in aggregate many flips must still be done across all the nodes. The problem is that in existing checkers, to create a new reordered path, only one pair of events is flipped at a time. For example, in Figure 7a, two concurrent messages $a_1$ and $a_2$ are in transit to node $A$ and four messages $b_1...b_4$ to node $B$. Figure 7b illustrates how existing approaches flip only one non-independent pair of events at a time; for example, after path #1 $a_1a_2b_1b_2b_3b_4$, the next path #2 is created by sliding $b_4$ before $b_3$, then a subsequent path #3 with $b_4$ before $b_2$, and so on. Now, let us

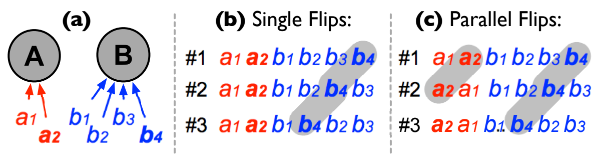

(a)
A
B
$a_1$
$a_2$
$b_1$
$b_2$
$b_3$
$b_4$
(b) Single Flips:
#1 $a_1$ $a_2$ $b_1$ $b_2$ $b_3$ $b_4$
#2 $a_1$ $a_2$ $b_1$ $b_2$ $b_4$ $b_3$
#3 $a_1$ $a_2$ $b_1$ $b_4$ $b_2$ $b_3$
(c) Parallel Flips:
#1 $a_1$ $a_2$ $b_1$ $b_2$ $b_3$ $b_4$
#2 $a_2$ $a_1$ $b_1$ $b_2$ $b_4$ $b_3$
#3 $a_2$ $a_1$ $b_1$ $b_4$ $b_2$ $b_3$

**Figure 7. Parallel flips.** *Figures (a+b) and (c) are explained in the "Problem" and "Algorithm" segments of §3.3, respectively.*

suppose that a bug is induced by the $a_2a_1$ ordering (*i.e.*, $a_2$ must be enabled before $a_1$). In the standard approach above, it will take 4! reorderings (of the four messages to $B$) before we have the chance to flip $a_2$ before $a_1$.

• **Intuition:** We observed such patterns when analyzing our bug benchmarks. For example, to hit the Paxos bug in Figure 2, node $C$ must receive the `Prepare#2` message before the `Commit#1`, but there are 8 earlier in-flight messages to other nodes that must be reordered. Even worse, after that, `Prepare#3` message must arrive before `Propose#2`, but there are 5 earlier messages to flip. Thus, the bug-inducing flips are not exercised early.

This problem motivates us to introduce *parallel flips*. That is, rather than making one flip at a time, parallel flips of pairs of events are allowed. Parallel flips also bode well with a typical developers' view that mature cloud systems are generally robust in the "first order" (under common interleavings) [27] but simultaneous "uncommon" interleavings across all the nodes may find bugs faster.

• **Algorithm:** For the next to-explore path, we flip a pair of two messages in *every* node, hence $N$ simultaneous flips *across* all the $N$ nodes (but we do not perform multiple flips within a node). For example, in Figure 7c, after executing path #1 $a_1a_2b_1...b_4$, in path #2 we make *both* $a_2a_1$ and $b_4b_3$ flips. This is permissible because the in-flight messages to node $A$ are independent of those to node $B$ (per our DPOR adoption in §3.2). If no parallel flips are possible, we revert back to single flips (*e.g.*, only $b_4b_2$ flip in path #3).

We emphasize that parallel flips is a prioritization algorithm rather than a reduction algorithm. That is, this algorithm helps developers to unearth bugs faster but does not reduce the state space. Thus, in the implementation, FlyMC retains the single flips paths prior to the parallel flips into a set of low-priority to-explore paths so that FlyMC stays systematic. Later when evaluating coverage completeness (§7.3), parallel flips are not included.

• **Comparison:** We are not aware of any distributed checkers that employ an algorithm such as parallel flips. However, in the software testing literature [31, 44], we found that our approach is in spirit similar to "branch flipping" where multiple branch constraints are flipped simultaneously to cover more corner cases faster.

## 4 FlyMC Static Analyses and Design Challenges

There are several challenges in applying FlyMC algorithms correctly in the context of distributed systems. First, we describe FlyMC static analyses that automatically extract the knowledge about the target system (§4.1). Next, we describe the challenges in applying the FlyMC algorithms (§4.2). Additional correctness sketches and pseudo-code are available in an anoymized technical report [1].[2]

### 4.1 Static Analyses Support

While FlyMC's algorithms are generic, the details (*e.g.*, the `if-else` predicates for reduction) are specific to a target system. Furthermore, the required predicates can become quite complex, which makes it harder for developers to derive them manually. For this reason, we provide static analyses support in FlyMC, which automatically builds the required predicates from simple annotations provided by the developers. For example, the static analyses automatically build `readSet`, `updateSet`, `sendSet` and `diskSet` (§3, §4.2) containing variable names specific to the target system implementation. Below we describe the input and output formats.

• **Input (annotation):** To use FlyMC's static analyses, developers only need to annotate a few data structures: (a) node states, (b) messages, and (c) crash handling paths. Annotating node states that matter (*e.g.*, ballot, key, value) is a common practice [68, 81], for example:

```
public class Commit {
  ...
  @FlyMCNodeState
  public final UUID ballot;
  ...
}
```

Annotating message class declarations such as "`MessageIn`" in Cassandra is relatively simple (note that we only need to annotate the class declarations, but not every instantiation, hence a light annotation). Crash handling paths are typically in the `catch` blocks of failed network IOs, for example:

```
try{
    ...
    binaryOutput.writeRecord(quorumPacket,...);
    ...
} catch { @crashHandlingPath ... }
```

In addition, our static analyses also maintains a dictionary of disk IO library calls. On average, the annotation is only 19 LOC per target system that we have studied.

• **Output:** The output of the analysis is all the variable sets mentioned above, along with the symbolic paths. For example, for Cassandra, the analysis outputs are as follows:

[2] In Section 3, we have described the algorithms in a way that is easy to understand. For correctness details, we apologize that we cannot fit the entire discussion in Section 4. We hope that our technical report addresses related questions that might arise.

```
(A) if (m.type == "PROP" && m.ballot > n.ballot)
      updateSet = n.key, n.value, n.ballot
      readSet   = n.ballot
(B) if (m.type == "PROP_RESP" && m.resp == true &&
      n.proposeCounter < majority)
     updateSet = n.proposeCounter
     readSet   = --
(C) ...
```

With this output, we can track the relationship of every two concurrent messages $n_i$ to $n_j$ to node $N$. For example, if both messages are type `A`, they conflict with each other and must be reordered. However, if $n_i$ is of type `A` while $n_j$ is of type `B`, they exhibit disjoint updates and therefore, do not need to be reordered (but they are independent only at specific states that satisfy the `if`-predicates above).

To create such an output given the input annotation, our static analyses performs basic data- and control-flow analyses. The detailed steps and pseudo-code are presented in [21, §4.2]. Our static analyses do not cover multi-variable correlation and pointer/heap analysis (as not needed in our target cloud systems so far; *e.g.*, a message simply arrives, gets processed, and then is deallocated).

## 4.2 Design Challenges

• **State symmetry:** In reality, not only one variable (*e.g.*, ballot number) is included in the abstracted state, which then raises the question of which variables should be included/excluded in the abstracted information. For example, if the protocol processes the sender IDs (node addresses) of the messages, then excluding sender IDs from the abstracted event is not safe, as this can incorrectly skip unique event reorderings. Thus, for state symmetry, our static analyses outputs a list of message variables that state transitions depend on, hence cannot be abstracted (excluded). For example, for Cassandra Paxos, neither the sender nor destination datanode IDs are used by the protocol, hence can be safely excluded from the abstracted information.

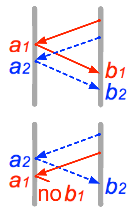
• **Event independence:** We address two challenges in implementing event independence.

First, as we target storage-backed distributed systems, two messages, $n_i$ and $n_j$ to node $N$, might modify two different variables that perhaps will eventually be logged to the same on-disk file. It is not safe to consider them independent as the same file is updated but potentially in different orders. Thus, the two disjoint messages are truly independent only if they are not logged to the same file, which our static analyses tracks (§4.1).

The second challenge is similar but more subtle. In distributed settings, reordering of messages to one node cannot be seen as a local impact only, as an arriving message can trigger *new* messages. This non-local impact must be put into consideration. For example, let us consider two messages $a_1$ and $a_2$ concurrently arrive at node $A$ whose local state is `{x=0,y=0}`. Now, let us suppose $a_1$ makes `x=1` and $a_2$ makes `y=2`. Here, the two messages seem to be disjoint. However, if after processing each message, node $A$ *sends* its state `{x,y}` to other nodes (*e.g.*, $B$), then the two messages are actually *not* independent. Making them independent would lead to an unsafe reduction. Let us consider the following sequence:

1) $A$'s state is `x=0,y=0` 4) $A$ receives $a_2$, hence `y=2`
2) $A$ receives $a_1$, so `x=1` 5) $A$ sends `x=1,y=2` to $B$
3) $A$ sends `x=1,y=0` to $B$

The example scenario shows $a_1$ is enabled before $a_2$, (2) before (4). If we (incorrectly) declare them as independent, $a_2a_1$ ordering will be skipped, therefore we will *never* see `{y=2,x=0}` sent to $B$. If node $B$ has a logic such as "`if (y==2 && x==0) panic()`", then we will *miss* this $a_2a_1$-induced bug. For this reason, in addition to `readSet` and `updateSet`, we keep track of the `sendSet` (§4.1), the variables that are sent out after a message is processed. In the example, because $a_1$'s and $a_2$'s `sendSets` overlap with their `updateSets` (*i.e.*, `x,y`), $a_1$ and $a_2$ are not independent.



• **Parallel flips:** We only allow parallel flips if none of the events within the flips are causally-dependent on one another (*i.e.*, exhibit a happens-before relationship). For example, let us consider $a_1a_2b_1b_2$ in the first case on the right figure, where $b_1$ is causally-dependent on (happens after) $a_1$, and $b_2$ on $a_2$. If we carelessly make the two flips to $a_2a_1b_2b_1$, it is possible that $b_1$ will *never* happen (as shown in the lower figure) because the new ordering $a_2a_1$ that node $A$ receives does not generate $b_1$. In this case, this new path will make FlyMC *hang*. Thus for correctness, FlyMC's parallel flips are backed with happens-before analysis via vector clocks [21, §6.1].

We would like to emphasize that we provide sketches for the correctness claims of our reduction algorithms based on symmetry and independence [21, §4.1]. However, parallel flips do not provide a sound reduction of state space in general, and it is tricky to identify conditions where they might, as also described in [21, §4.1.3]. Thus, we treat parallel flips as a prioritization heuristic to reach buggy states earlier, but it is based on a well-grounded intuition (§3.3) as opposed to randomness or manual checkpoints.

# 5 FlyMC Design Optimizations

In wall-clock time, an execution of *one* path can take 8-40 seconds [58, 73]. Since one of the checker's goals is to quickly unearth bugs, thus, per-path wall-clock speed matters. Below we describe our solutions to the bottlenecks.

• **Local ordering enforcement:** In a path execution, stand-alone checkers that intercept events at the application layer with "hooks" (*e.g.*, dBug [73], SAMC [58], FlyMC) must wait a non-negligible amount of time before enabling the next event, for two purposes: to prevent concurrency issues within itself and to wait for new updated state from the target system.

To illustrate the former, consider two concurrent incoming messages $a_1$ and $a_2$ to node $A$, and the checker's server decides to enable $a_1$ then $a_2$. If the wait time is removed between the two actions, the probability that node $A$ *accidentally* processes $a_2$ before $a_1$ increases. This is because `enable(a1)` and `enable(a2)` actions themselves are *concurrent* messages from the checker's server to node $A$ whose timings are not controlled. This wait time is too expensive for such rare cases. To remove it, we enhance FLYMC's interposition mechanism at the target system side to enforce local action ordering; for example, enabling $a_2$ includes information about the previous enabled event, $a_1$, such that at node $A$'s side, $a_2$ waits for $a_1$, if needed.

**STATE-EVENT CACHING:** Although the wait time has been removed, FLYMC must perform "history tracking" for collecting past state-event transitions `Si`+$e_j \rightarrow$`Sj`. Here, after enabling $e_j$ and before enabling the next event $e_k$, FLYMC must collect `Sj` from the target system, another expensive round-trip time. To optimize this, we use the state-event history as a cache. That is, if $e_j$ is to be enabled at `Si` and the state transition `Si`+$e_j$ already exists in the history, then no wait is needed between enabling $e_j$ and $e_k$. In this case, FLYMC will automatically change its view state of the target system to `Sj`. This strategy is highly effective; the "cache hit rate" reaches 90% quickly after 35 paths explored.

In summary, a checker itself is a complex system with many opportunities for optimization. Our optimizations have delivered further speed-ups to quickly find DC bugs (§7.1). For interested readers, in [21, §5], we describe further explanation regarding the latency analysis of various types of checkers (OS-supported, runtime-supported, and stand-alone checkers).

## 6 Implementation and Integration

FLYMC is implemented in around 10 KLOC which includes the fault injection, deterministic replay, interposition hooks, path execution/history management, state caching/snapshotting, etc., as illustrated earlier in Figure 3. The four core algorithms described throughout Section 3 are however only 2420 LOC and the hooks to a target system are only 147 LOC on average. The static analyses support is written in 1799 LOC in Eclipse AST parser for Java programs [17], which covers many of our target systems including Cassandra, ZooKeeper, and Hadoop. For LogCabin Raft and Kudu Raft (in C++) and Spark (in Scala), we manually build the sets (§4.1). We leave porting to other language front-end parsers as future work.

FLYMC has been integrated with 8 popular systems: Cassandra [56], Ethereum Blockchain [19], Hadoop [1], Kudu [24], Raft LogCabin [25, 67], Spark [83], ZooKeeper [51], and a 2-year old production system "*X*" of a large company (to the best of our knowledge, the largest checker integration compared to prior works). Within these systems, we model checked 10 unique protocol implementations, such as Cassandra Paxos, ZooKeeper leader election and atomic broadcast, Hadoop task management, Kudu Raft, LogCabin Raft leader election and snapshot, Spark core, Ethereum fast synchronization, and "*X*" leader election.

For reproducibility, FLYMC and some integrated systems are open-sourced [20].

| BugName | Issue# | #Ev | #Cr | #Rb | Protocols |
|---|---|---|---|---|---|
| CASS-1 [4] | 6023 | 54 | – | – | Paxos |
| CASS-2 [3] | 6013 | 30 | – | – | Paxos |
| CASS-3 [2] | 5925 | 15 | – | – | Paxos |
| ZOOK-1 [13] | 335 | 46 | 3 | 3 | LE, AB |
| ZOOK-2 [14] | 790 | 39 | 1 | 1 | LE |
| ZOOK-3 [11] | 1419 | 41 | 3 | 3 | LE |
| ZOOK-4 [12] | 1492 | 24 | 1 | – | LE |
| SPRK-1 [10] | 19623 | 42 | – | – | Spark Core |
| SPRK-2 [9] | 15262 | 23 | – | – | Spark Core |
| MAPR-1 [8] | 5505 | 36 | 1 | 1 | TA |
| RAFT-1 [7] | 174 | 21 | 2 | 2 | LE, Snapshot |
| ETHM-1 [5] | 15138 | 12 | 1 | 1 | Fast Sync |

**Table 1. Bug benchmarks (complex DC bugs).** *The table lists DC bugs used to benchmark checkers scalability. In the first column: "*`CASS`*" represents Cassandra, "*`ZOOK`*" ZooKeeper, "*`SPRK`*" Spark, "*`MAPR`*" Hadoop MapReduce, "*`RAFT`*" Raft LogCabin, and "*`ETHM`*" Ethereum BlockChain. For the Protocols column: "LE" stands for leader election, "AB" atomic broadcast, and "TA" Task Assignment. "#Ev", "#Cr" and "#Rb" stands for #Events, #Crashes and #Reboots that interleave to reach the bugs.*

## 7 Evaluation

We now evaluate FLYMC in terms of speed in reproducing DC bugs (§7.1), scalability (§7.2), coverage completeness (§7.3), and effectiveness in finding new bugs (§7.5).

**BUG BENCHMARKS:** A popular way to evaluate a checker is how fast it can reproduce (reach) a DC bug given the corresponding workload. Table 1 shows the bug benchmarks that we use, including the number of events needed to hit the bugs (*i.e.*, the bug "depth"). Most papers did not report bug depths [55, 73, 81], but it is important to pick deep real-world DC bugs for scalability evaluation. Interested readers can find the detailed bug descriptions in our technical report. [21, §7.1].

**TECHNIQUES COMPARED:** We have exhaustively compared FLYMC against six existing solutions as listed in Table 2,: a purely random technique (`Rand`), two systematic techniques (`m-DP` and `SAMC`), and three hybrid systematic+random +bounded techniques (`b-DP`, `r-DP`, `br-DP`). The last category highlights how current approaches incorporate random and bounded flips to reach bugs faster.

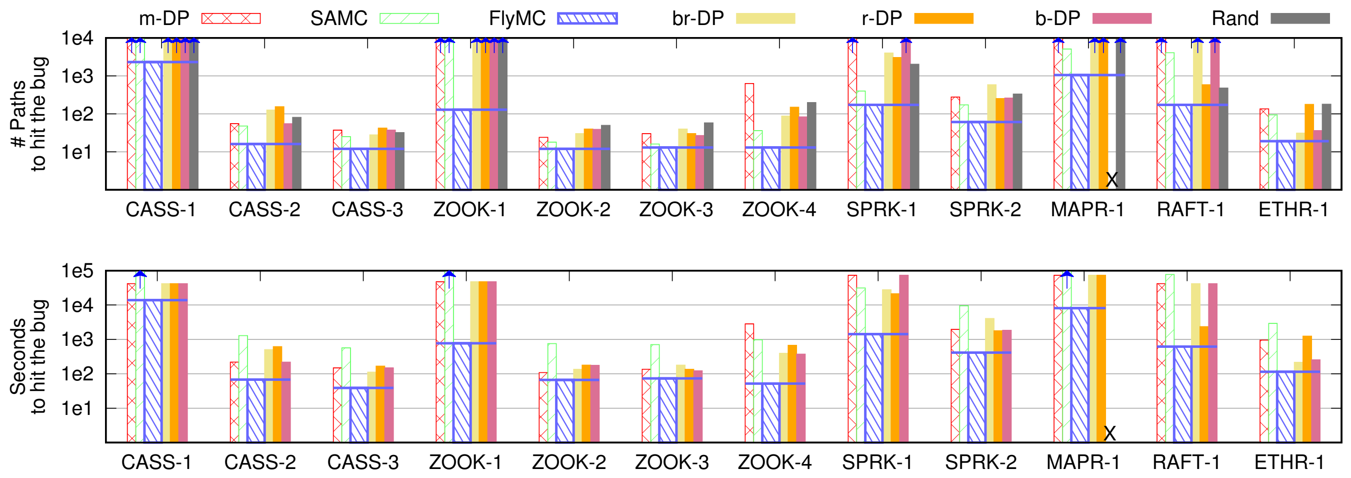


**Figure 8. FlyMC speed.** *The top and bottom figures show the number of paths to explore (in log scale) and the wall-clock time, respectively, to find the buggy paths that make the bugs surface, as explained in Section 7.1. For the legend labels, please see Table 2.* "↑" *implies that the bug is not reached after 10,000 paths.* `Rand` *numbers are averaged from five tries.*

| Label | Technique Description |
|---|---|
| | *Systematic exploration techniques:* |
| `m-DP` | MoDist' systematic DPOR reduction rule [81, §3.6] as discussed in §1 and §3 (comparison segments). Note that this reduction is also used in other checkers such as dBug [73, §2] and CrystalBall [80, §2.2]. |
| `SAMC` | SAMC reduction algorithms [58, §3.3] as discussed in the comparison segments of §3. |
| | *Hybrid systematic/random/bounded techniques:* |
| `b-DP` | MoDist' bounded+DPOR rule [81, §3.6] – run DPOR evaluation up until certain depth (*i.e.*, #events). |
| `r-DP` | MoDist's random+DPOR rule [81, §4.5] – execute random path on every 50 paths and then use DPOR to evaluate the path. |
| `br-DP` | Combination of the last two approaches above (bounded+random+DPOR). |
| | *Random techniques:* |
| `Rand` | A purely random exploration. |

**Table 2. Techniques comparison.** *The table lists all the techniques compared against* FlyMC.

We do not compare with DeMeter [49] and LMC [46] as they mainly reduce thread (local) interleavings in the context of reducing global interleavings (§8). We also do not show the results of depth-first-search (as used in MaceMC [81]) as DFS is extremely unscalable [81, Fig. 9].

**Performance metrics:** The primary metrics of our evaluation are the numbers of **(1)** explored paths to hit a bug, **(2)** total wall-clock time to hit a bug, **(3)** explored paths to exhaust the entire state space of a given workload, and lastly, **(4)** unique global states covered over time.

**Evaluation scale:** Our extensive evaluation exercised over 200,000 paths (across all compared techniques) and used more than 130 machine days. We use Emulab "d430" machines [18] and Chameleon "compute_haswell" machines [16].

## 7.1 Speed

Figure 8a (in log scale) shows the *number of paths* explored to hit each of the bugs in Table 1 across different methods listed in Table 2. Figure 8b shows the *wall-clock time*. For readability, in each bar group, we put FlyMC bar in the middle (striped blue), systematic approaches on the left (`m-DP` and `SAMC` in patterned bars), hybrid and random on the right (`br-DP`, `r-DP`, `b-DP`, and `Rand` in solid colors). The horizontal blue markers are the height of FlyMC bars.

This evaluation method reflects a checker's speed in helping developers to reproduce hidden DC bugs. So, suppose the users supply a workload that non-deterministically (occasionally) fails, the checker then should find the buggy interleaving(s) such that the developers can easily (and deterministically) replay them. Note that some methods fail to find the buggy paths after exploring 10,000 paths (marked with ↑ in Figure 8a). We stop at 10,000 paths to prioritize other evaluations. From the figure, we make the following observations:

**(a)** Within the systematic group, MoDist' DPOR (`m-DP`) is not effective for 5 of the bugs (`CASS-1`, `ZOOK-1`, `SPRK-1`, `MAPR-1`, and `RAFT-1`), which is due to the limitations of black-box methods in pruning redundant paths.

**(b)** `SAMC` is faster than `m-DP` up to 25×. However, for two of the bugs (`CASS-1` and `ZOOK-1`) SAMC cannot reach them within 10,000 paths and for the other two cases (`MAPR-1` and `RAFT-1`) `SAMC` is relatively slow. Again, this happens because `SAMC` does not have any static analysis support. Instead, developers need to manually analyze and implement their own reduction algorithms by following the SAMC principles. Therefore, in practice, SAMC might miss some potential reductions. Furthermore, it mainly focuses on reducing unnecessary crash timings, hence does not scale for workloads with many concurrent messages.

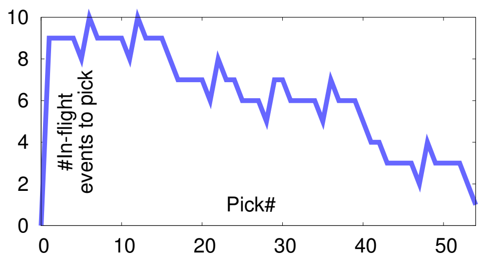


**Figure 9. Many choices make random techniques ineffective.** *For model checking complex protocols such as Paxos* CASS-1*, the figure shows how many inflight messages (y-axis) that can be chosen for every to-enable event (x-axis) within a path execution. For example, for pick #10 (x=10), there are 9 events to choose from (y=9). The figure shows that there are up to 10 choices when making a pick, hence random techniques are not effective for finding bugs in "deep" complex protocols and workloads.*

**(c)** Random is random. `Rand` is the slowest method for 3 of the bugs, but it is faster than `m-DP` and `SAMC` in 4 and 1 other cases, respectively. In the latter cases, the degree of concurrency is low (*e.g.*, to enable an event, random only needs to pick 1 out of 3 outstanding events), hence the probability that the "interesting" event is picked is high. However, in the former cases (more complex concurrency), random is not effective as there are too many choices and it blindly reorders non-interesting interleavings. For example, for CASS-1, Figure 9 shows how many inflight messages (y-axis) that can be picked (up to 10 choices) for every to-enable event (*i.e.*, for every pick) within a path execution (x-axis). This highlights how complex workloads/interleavings make random-hybrid techniques (`r-DP` and `br-DP`) not fast enough.

**(d)** Bounded DPOR (`b-DP`) approximately has the same speed as random-hybrid ones. Interestingly, for bug MAPR-1, the exploration completes, *but* the bug was not found ("**X**" in the figure). This shows a weakness of bounding the number of events to flip. Note that with bounded+random (`br-DP`) the randomness might shuffle the critical events first.

**(e)** Finally, FLYMC is the fastest among all methods. In our bug benchmark, we have not found any other checker that wins over FLYMC. For the most complex bug, CASS-1, FLYMC can find the buggy path in less than 2500 paths. In overall, FLYMC is faster *at least* by 16× on average and up to 78× ("at least" because of the non-finished explorations, labeled with "↑" in Figure 8a). Sometimes "significant state-space reduction does not automatically translate to proportional increases in bug-finding effectiveness" [49, §5.3], however, we believe our results show that it is possible to stay systematic and increase bug-finding effectiveness with more advanced reduction and prioritization strategies.

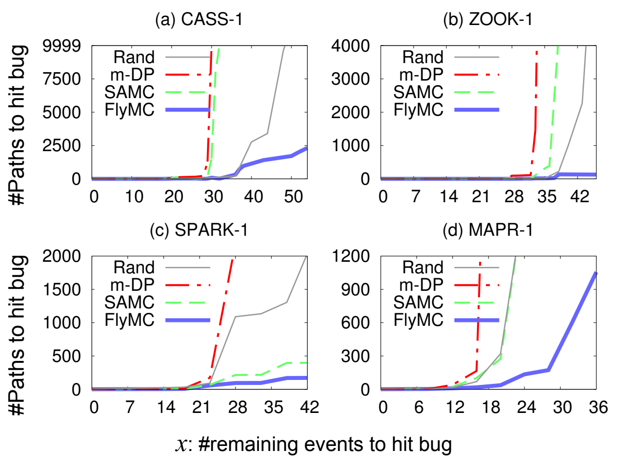


**Figure 10. FLYMC scalability.** *(As explained in §7.2).*

Now we discuss the wall-clock speed in Figure 8b. As discussed in Section 5, for example in CASS-1, the per-path execution time is around 40 seconds in SAMC, 6 seconds in total in FLYMC, and 2 seconds (plus initialization time) in MODIST. Overall, per our design optimizations (§5), FLYMC is now 28× faster on average (up to 158×) compared to all methods. We do not show `Rand` in Figure 8b because we are comparing specific design implementations.

## 7.2 Scalability

To analyze why non-FLYMC algorithms cannot or are slow to hit some of the deep bugs above, we plot a different type of graph in Figure 10. Here, the *x-axis* represents the number of *remaining events* to hit the bug. For this, we control the "*path prefix*," *i.e.*, an initial subset of the buggy path. The *maximum* value in the $x$-axis represents the *total* number of events to hit the bug without any prefix (as in the "#E" column in Table 1). For example, for reproducing CASS-1 (Figure 10a), the workload generates a total of 54 events. Controlling path prefix means that the checker executes in deterministic order some of the earlier events (the prefix) and let the rest be reordered. For example, in Figure 10a, with $x$=30, we first enable the first 24 initial events and then let the checker reorder the remaining 30 events.

The *y-axis* shows the number of paths explored until the bug is reached given the remaining events. For instance, in Figure 10a, at $x$=26, MODIST's `m-DP` must explore 163 paths to hit the bug, but `SAMC` and FLYMC are able to hit the bug in 55 and 27 paths respectively. With more remaining events to reorder (higher $x$), then more paths need to-be explored (higher $y$), *i.e.*, the larger the path explosion problem will be.

Essentially, the graphs in the figure show how FLYMC is more scalable than other approaches. For example, in CASS-1 (Figure 10a), at $x$=32, `SAMC` already explodes to more than 10,000 paths. On the other hand, FLYMC can find the buggy path in 2318 paths without any prefix (at $x$=54).

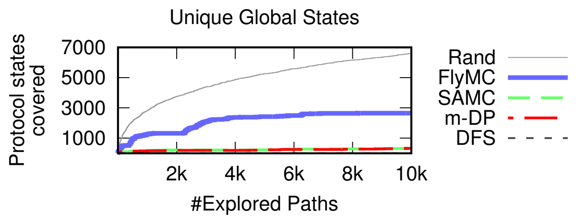


**Figure 11. State coverage.** *The figure shows the number of protocol states (y-axis) covered over explored paths (x-axis), as explained in §7.3a. A unique protocol state is stored as a hash value of a global state S (S is described in §3.1).*

For ZOOK-1, our SAMC exploration results are different compared to the one reported in the SAMC's paper [58]. Upon our conversation with the SAMC developers, there are two reasons for this difference. First, SAMC includes all the initialization events to reach the initial state $S_0$ (*e.g.*, initial leader election to reach stable cluster), which FLYMC ignored. Second, in our checker, we implemented a proper vector clock, while SAMC did not, which causes our checker to detect more concurrent chain of events. Therefore, in our experiment, SAMC is no longer able to hit the bug under 10,000 paths. However, it does not take away SAMC's conclusion that SAMC is still an order magnitude faster than MODIST's DPOR algorithm.

## 7.3 Coverage

For this evaluation, parallel flips algorithm is disabled because it is a prioritization algorithm. Hence, it does not affect all of the coverage evaluation.

**(a) State coverage:** We have mainly measured FLYMC's speed in finding buggy paths in prior sections. Another form of evaluation is the speed to cover unique protocol states over the explored paths. Figure 11 (similar to the format of Figure 10 in [81]) shows the Cassandra Paxos protocol states covered (in $y$-axis) under a 3-update Paxos workload in CASS-1 within the first 10,000 explored paths (in $x$-axis). We make the following observations.

First, DFS is the worst among all (flat line). SAMC and mDPOR are faster but the growth rate is small. Random is the fastest, and for this reason, checkers sometimes mix their algorithms with random walks (see [81, Figure 10]), but unfortunately reduce their systematicity. So, random is fast in state coverage, but its non-systematic nature does not guarantee a buggy path to be found (*e.g.*, random fails to reach three bugs in Figure 8a).

Second, on the other hand, FLYMC does not sacrifice systematicity and is only 3× slower than random. Being *both* fast and systematic is feasible. The figure also shows that coverage growth rate reduces over time (*i.e.*, more paths to explore but they do not always lead to new unseen states).

**(b) Complete coverage:** Another question is whether the entire state space in a given workload can be covered, *i.e.*, there are no more new unique states to explore. We performed this experiment for Cassandra Paxos and Kudu Raft workloads as shown earlier in Figure 1 on page 2, which we now elaborate.

FLYMC *successfully exhausts* the state space for all the workloads, with one to three concurrent key-value updates in Kudu Raft and Cassandra Paxos (`Raft-1` to `-3` and `Paxos-1` to `-3`) within a reasonable time budget, as shown in Figure 1. The most complex one, `Paxos-3`, requires FLYMC to exhaust around 50,000 paths (1 machine week). `Raft-3` is a much simpler case than Paxos as Raft only allows one leader node (per table/partition) to coordinate concurrent updates; for example, three coordinators *A*, *B*, *C* in Figure 2 (on page 3) updating the same key/partition is not allowed in Kudu Raft. Given this simplicity, Raft only needs two rounds, unlike Paxos' three rounds. For this reason, Raft search space is much smaller than Paxos.

MODIST's DPOR and SAMC cannot finish the exploration under 10,000 paths. They do not scale well under these workloads for the following reasons.

MODIST's *inter*-node-independence DPOR algorithm focuses on taming the *N*-induced explosion (*e.g.*, checking 3 nodes will not explode much compared to 2 nodes). However, under a more complex workload where the number of concurrent messages to *each* node increases, this inter-node-independence DPOR algorithm does not scale (for example, `Raft/Paxos-2/3` in Figure 1). What is needed is the *intra*-node message independence.

SAMC implements such an intra-node message independence. For example, in a single Paxos update (`Paxos-1`), the `ack++` received by the coordinator in each round of the Paxos three stages are considered commutative/independent. Hence, SAMC is more scalable than MODIST. However, SAMC's other algorithms such as crash independence and symmetry do not work in no-crash workloads.

Under two concurrent updates ("`Paxos-2`" in Figure 1), the path exploration explodes significantly in all the checkers. This is because in a single update, the three Paxos rounds (prepare, propose, commit) are serialized, but under two updates, each round of the first update can interleave with any round of the second update.

**(c) Systematic coverage:** We use the same sense of "systematic" that is used with concurrent programs [42, 77], where it refers to exploring the state spaces of concurrent processes. Our FLYMC reduction algorithms are systematic in that they cover all states relevant to observable events, *i.e.*, the intercepted messages in distributed systems. These algorithms do not skip any interleavings that would lead to new unique states (more correctness sketches in [21, §4.1]). We want to emphasize that this systematic property follows in principle from correct identification of communication and state symmetry and event independence, which is supported by

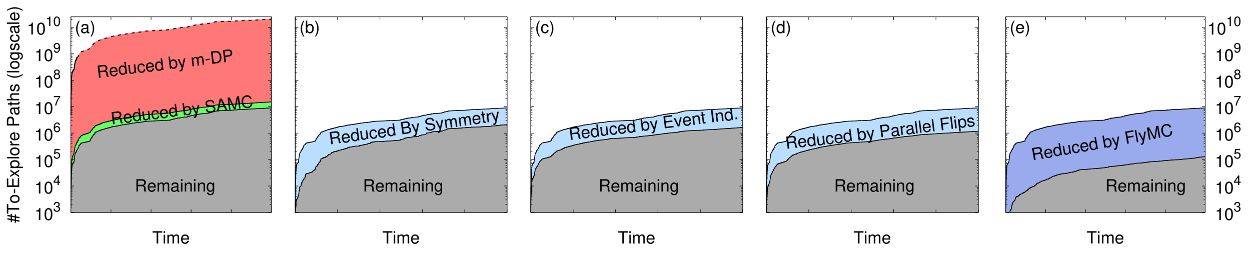


**Figure 12. Path explosion and reduction.** *The figure is explained in §7.4a. The y-axis represents the to-explore paths over time. Figure (e) shows that* FlyMC *reduces the path explosion problem by two orders of magnitude from* ModiSt*'s DPOR and SAMC.*

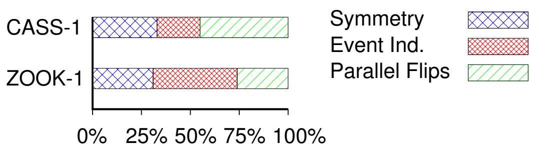


**Figure 13. % of removed and deprioritized paths by each algorithm.** *The symmetry and event independence areas represent % of reduced paths, while the parallel-flips are represents % of deprioritized paths. The figure is explained further in Section 7.4b.*

FLYMC's static analyses (which we assume are correct). As experimental evidence, we collected all unique global states (compressed to hash values) explored by depth-first search (DFS) and MODIST's DPOR for `Raft-1`, `-2`, and `Paxos-1` examples. When compared with the explored states in FLYMC, we found that FLYMC had not missed any unique states. Note that we could not compare more complex workloads since the non-FLYMC techniques take too long to complete.

### 7.4 Per-Algorithm Effectiveness

In this section, we evaluate the effectiveness of each individual algorithm by showing the reduced paths over time and the ratio of reduced paths per algorithm.

**(a) Reduced paths over time:** Figure 12 highlights the combined power of FLYMC algorithms, using `CASS-1` as a specific example. Figure 12a (in log scale) depicts the number of to-explore paths over time. The path explosion in the beginning, just after $x$=0, shows the many possible interleavings generated after the first path is exercised. Let us imagine that the first path contains 14 all concurrent events, a DFS checker would generate 14! new paths. However, not all of them need to be exercised, because they are removed by the individual reduction algorithms.

The highest line in Figure 12a reflects the number of generated paths by a naive depth-first-search (DFS) algorithm without any reduction algorithm. The top region in Figure 12a depicts the number of paths reduced by MODIST's DPOR algorithm, roughly 3 orders of magnitude reduction from DFS, hence its popular usage in other checkers [73, 80]. Next, the middle region shows that SAMC slightly reduces the explosion (SAMC is not highly effective for this bug, as explained in §7.1-7.2).

Figures 12b-d depict the individual reductions by state symmetry, event independence, and parallel flips, each reduces the explosion by almost an order of magnitude. Ultimately, Figure 12e shows that all FLYMC algorithms *collectively* provide two orders of magnitude of reduction in the `CASS-1` Paxos workload.

**(b) Ratio of reduced paths per algorithm:** We plot Figure 13 to show the effectiveness of the individual FLYMC algorithms. Here, the $x$-axis represents the ratio of paths removed (by symmetry and event independence) and deprioritized (by parallel flips) from all the paths. This figure focuses on displaying two bugs from our benchmark with the most complex workloads. The graph essentially shows how all FLYMC algorithms successfully complement each other. We can also see that for different workloads, certain algorithms are more effective than the others.

For example, parallel flips are effective for `CASS-1` (45%) because this workload (three Paxos updates) generates a high degree of concurrency (*e.g.*, up to 9 outstanding events at a given time) and the important flips are far from the end of the queue, which parallel flips address (as illustrated earlier in Figure 7). Symmetry also works best in `CASS-1` (33%) as the workload exercises replication-based protocols involving multiple worker/follower nodes, which are automatically considered symmetrical in FLYMC. Our event independence algorithm is effective in `ZOOK-1` (43%) as the messages in this workload update different sets of variables (*e.g.*, leader election messages and snapshot messages that touch different sets of variables) and, as this bug requires three crashes to surface, reducing unnecessary crashes is effective.

### 7.5 New Bugs

Finally, our last evaluation tests whether FLYMC can find new bugs. For this, we integrated FLYMC with (1) a recent stable version of Cassandra and (2) ZooKeeper. (3) a 2-year old proprietary system; the proprietary system is a production system that supports five other cloud services within the company (akin to how ZooKeeper supports HBase, Yarn, and

CASS-5 **:** (1) A client submits Paxos *Write-1 (W1)* to node A with a column in key K's row. (2) Node A sends W1's prepare messages and propose messages, accepted by all nodes A, B, and C. (3) Node A sends W1's commit messages. (4) *Node C crashes before* accepting the commit message. (5) Nodes A and B accepts the W1's commit messages. At this point, A and B have stored W1 locally. (6) *Node C reboots*. (7) Another client submits Paxos *Write-2 (W2)* to A, updating another column in key K's row. (8) Node A sends W2's prepare messages (then propose and commit messages), accepted by all the nodes. At this point, Paxos nodes incorrectly have *inconsistent data*; A and B store W1-2, but C only stores W2 locally. The read repair did not happen during W2's preparation. Thus, if a client reads K from C, she would get an inconsistent data (missing W1's update).

**Figure 14. Another DC Bug in Cassandra Paxos.** *The list above summarizes (simplified) the total order of 48 messages including one crash and one reboot at specific timings. A longer list is presented in our technical report.*

other cloud systems). We found 10 new bugs in total, all confirmed by the developers. The detailed descriptions of all the new bugs can be found in our extended report [21, §7.5].

For Cassandra, we successfully discovered 2 new bugs that require 2 and 3 concurrent Paxos updates. One of the bugs also requires a crash and a reboot to be injected. Figure 14 summarizes the complex interleavings (total ordering of events) needed to hit this bug. We have communicated these two bugs to the developers and they have confirmed that those two bugs are real issues which will be fixed.

For ZooKeeper, we model check its "reconfiguration" feature, which allows ZooKeeper cluster to elastically grow and shrink while serving foreground requests without any downtime, hence a complex feature. FLYMC successfully discovered 3 new bugs. The first bug reveals that the developers' prior fix to an old DC bug was not robust enough, that there is another interleaving that makes the old bug surface. The second bug was reported to appear once every 500 unit test cycles. With FLYMC, we help the developers pinpoint the exact buggy path to reproduce the bug deterministically. The third bug is about two threads in a single node entered a deadlock due to a specific incoming message timing and a local thread operation that was managing the node quorum.

For the proprietary system, FLYMC successfully discovered 5 new critical bugs that have significant impacts including unavailability (*e.g.*, no leader is chosen) and data inconsistency. The bug depths range from 9 to 30 events.

## 8 Related Work

We now discuss the many efforts by the systems community in making distributed systems more reliable.

**MODEL CHECKING:** The main issue that these checkers try to overcome is the state-space explosion challenge. Table 3 summarizes the difference between many state-of-the-art checkers. First, MACEMC [55] combines DFS and random walk biased with weighted (prioritized) events manually labeled by testers ("Ran"✓ in Table 3).

| | ■ | □ | **Ran** | **Ind** | **Sym** | **Prio** | $\not{N}$ |
|---|---|---|---|---|---|---|---|
| MACEMC[55] | ✓ | | ✓ | | | | |
| CrystalBall [80] | ✓ | | | ✓ | | | |
| dBug [73] | ✓ | | | ✓ | | | |
| MODIST [81] | ✓ | | ✓ | ✓ | | | 1 |
| SAMC [58] | | ✓ | | ✓ | ✓ | | $\leq 3$ |
| FLYMC | | $\checkmark_S$ | | $\checkmark_+$ | $\checkmark_+$ | ✓ | $\leq 3$ |

**Table 3. State-of-the-art DC checkers.** *The table is described in §8. "■" denotes a black-box approach; "□" a white-box approach; "Ran" random; "Ind" independence; "Sym" symmetry; "Prio" prioritization; "$\not{N}$+$N^{\uparrow}$" number of crashes and reboots injected; "$\checkmark_S$" static analyses support; and "$\checkmark_+$" more powerful.*

Subsequent works, CrystalBall [80], MODIST [81], and dBug [73], began to adopt DPOR independence [38] in a black-box manner without domain-specific knowledge ("■"✓ and "Ind"✓), hence do not scale well for complex workloads. The $\not{N}$ column in Table 3 shows that prior checkers did not interleave crash timings.

SAMC [58] enhances DPOR's independence by exploiting white-box information and employs symmetry-based reduction ("□"✓ and "Sym"✓). However, SAMC has three weaknesses. First, the domain-specific algorithms are written manually without any static analysis support, hence SAMC only introduces cautious reduction so that it does not accidentally skip interleavings that would lead to unexplored states. Second, SAMC primarily reduces crash interleavings, hence do not scale for complex messages (*e.g.*, 3 concurrent Paxos updates). Third, SAMC does not consider any prioritization strategy.

Compared to the others, FLYMC employs more advanced and powerful ("$\checkmark_+$") independence- and symmetry-based reductions and a well-grounded prioritization strategy ("$\checkmark_P$"), backed by static analyses support ("$\checkmark_S$"). Hence, FLYMC scales for complex workloads including multiple crashes.

There are other checkers such as DIR [49] and LMC [46] but they mainly address the decoupling of local and global explorations (orthogonal to FLYMC). Hence, they are not shown in Table 3 because none of the bugs in our benchmarks require local thread interleavings. Other practical checkers, such as Jepsen [23] and Namazu [26], do not introduce new reduction algorithm. Instead, they mainly depend on random-walk and randomly injecting network partition or failures to detect bugs. Finally, others suggested parallelizing DPOR by distributing the path executions across many worker nodes [74, 82]. This can be engineered into FLYMC.

Techniques in distributed checkers above are similar to those in "local" concurrency checking, *e.g.*, symmetry [32, 75], disjoint-update independence [34, 42], property-driven pruning [76], and multiple branch flips [44], but the details are vastly different.

Lastly, one limitation that stateless distributed model checking has is that this technique only provides correctness confidence over the tested workloads that are specified by the developers.

**VERIFICATION AND TESTING:** There is a growing body of work on new verifiable programming frameworks for distributed systems (*e.g.*, IronFleet [50], PLang [36], Verdi [79]). Such methods are more formal than checkers, but the developers must write proofs that are typically in the thousands of lines. Compared to verification and testing [47, 52, 53] or bug-finding tools [61, 62], stateless model checking is often considered to be in "between" [30, 43]; for example, checkers deliver higher coverage than testing/bug-finding tools but lower than verification, but the development cost is cheaper than verification but higher than testing.

**POST-MORTEM DIAGNOSIS:** Post-mortem methods such as record-and-replay [40, 63, 64] and flow reconstruction [71, 84] are popular methods to reverse engineer failures. However, tracing is often done in a coarse-grained way [65, 70, 72], thus not all DC bugs can be reconstructed easily in post-mortem analysis. ZooKeeper developers shared with us that occasionally more than ten of iterations of log changes over a long period of time is required to replay DC-related failures at customer sites.

## 9 Conclusion

For model checking complex distributed concurrency, FLYMC shows that it is possible to be fast and scalable while staying systematic. This makes stateless distributed model checking a more practical approach. More exciting challenges are on the horizon as no checkers to date completely control the timings of *all* non-deterministic events such as messages, crashes, timeouts, local thread schedules, as well as disk IOs [59]. We hope FLYMC motivates more advancements in this research space.

## 10 Acknowledgments

We thank Peter Druschel, our shepherd, and the anonymous reviewers for their tremendous feedback and helpful comments. This material was supported by funding from the NSF (grant Nos. CNS-1350499, CNS-1526304, CNS-1405959, CNS-1563956) as well as generous donations from Huawei, Dell EMC, Google Faculty Research Award, NetApp Faculty Fellowship, and CERES Center for Unstoppable Computing. The experiments in this paper were performed in the Utah Emulab[1] [78], the University of Chicago River [28] and Chameleon [15] testbeds.

Any opinions, findings, and conclusions, or recommendations expressed herein are those of the authors and do not necessarily reflect the views of the NSF or other institutions.

[1]http://www.emulab.net

## References

[1] Apache Hadoop. http://hadoop.apache.org.
[2] BUG: CASSANDRA-5925: Race condition in update lightweight transaction. https://issues.apache.org/jira/browse/CASSANDRA-5925.
[3] BUG: CASSANDRA-6013: CAS may return false but still commit the insert. https://issues.apache.org/jira/browse/CASSANDRA-6013,.
[4] BUG: CASSANDRA-6023: CAS should distinguish promised and accepted ballots. https://issues.apache.org/jira/browse/CASSANDRA-6023.
[5] BUG: ETHEREUM-15138: eth/downloader: track peer drops and deassign state sync tasks. https://github.com/ethereum/go-ethereum/issues/15138.
[6] BUG: HBASE-4397: -ROOT-, .META. tables stay offline for too long in recovery phase after all RSs are shutdown at the same time. https://issues.apache.org/jira/browse/HBASE-4397.
[7] BUG: LOGCABIN-174: resiliency in InstallSnapshot. https://github.com/logcabin/logcabin/issues/174.
[8] BUG: MAPREDUCE-5505: Clients should be notified job finished only after job successfully unregistered. https://issues.apache.org/jira/browse/MAPREDUCE-5505.
[9] BUG: SPARK-15262: race condition in killing an executor and reregistering an executor. https://issues.apache.org/jira/browse/SPARK-15262.
[10] BUG: SPARK-19623: DAGScheduler should avoid sending conflicting task set. https://issues.apache.org/jira/browse/SPARK-19263.
[11] BUG: ZOOKEEPER-1419: Leader election never settles for a 5-node cluster. https://issues.apache.org/jira/browse/ZOOKEEPER-1419.
[12] BUG: ZOOKEEPER-1492: leader cannot switch to LOOKING state when lost the majority. https://issues.apache.org/jira/browse/ZOOKEEPER-1492.
[13] BUG: ZOOKEEPER-335: zookeeper servers should commit the new leader txn to their logs. https://issues.apache.org/jira/browse/ZOOKEEPER-335.
[14] BUG: ZOOKEEPER-790: Last processed zxid set prematurely while establishing leadership. https://issues.apache.org/jira/browse/ZOOKEEPER-790.
[15] Chameleon. https://www.chameleoncloud.org.
[16] Chameleon Haswell Website. https://bit.ly/2KrnE4L.
[17] Eclipse Abstract Syntaxt Tree (AST). http://www.eclipse.org/articles/article.php?file=Article-JavaCodeManipulation_AST/index.html.
[18] Emulab d430 Website. https://wiki.emulab.net/wiki/d430.
[19] Ethereum. https://www.ethereum.org.
[20] FlyMC Open-Sourced Code. http://ucare.cs.uchicago.edu/projects/FlyMC/.
[21] FlyMC Technical Report (includes correctness sketch, pseudo-code, implementation details, etc.). https://tinyurl.com/flymc-technical-report.
[22] Java Path Finder. https://babelfish.arc.nasa.gov/trac/jpf.
[23] Jepsen. http://jepsen.io/.
[24] Kudu. https://kudu.apache.org/.
[25] Logcabin. https://github.com/logcabin/logcabin.
[26] Namazu. http://osrg.github.io/namazu/.
[27] Personal Communication with ZooKeeper Developers (Michael Han, Patrick Hunt, and Alex Shraer).
[28] RIVER: A Research Infrastructure to Explore Volatility, Energy-Efficiency, and Resilience. http://river.cs.uchicago.edu.
[29] Parosh Abdulla, Stavros Aronis, Bengt Jonsson, and Konstantinos Sagonas. Optimal Dynamic Partial Order Reduction. In *Proceedings of the 41st ACM SIGPLAN-SIGACT Symposium on Principles of*

*Programming Languages (POPL)*, 2014.

[30] Ivan Beschastnikh, Patty Wang, Yuriy Brun, and Michael D. Ernst. Debugging Distributed Systems: Challenges and Options for Validation and Debugging. In *Communications of the ACM (CACM)*, 2016.

[31] Ella Bounimova, Patrice Godefroid, and David Molnar. Billions and Billions of Constraints: Whitebox Fuzz Testing in Production. In *Proceedings of the 35th International Conference on Software Engineering (ICSE)*, 2013.

[32] Edmund M. Clarke, E. Allen Emerson, Somesh Jha, and A. Prasad Sistla. Symmetry reductions in model checking. In *10th International Conference on Computer Aided Verification (CAV)*, 1998.

[33] Edmund M. Clarke, Orna Grumberg, and David E. Long. Model Checking and Abstraction. *ACM Transactions on Programming Languages and Systems*, 1994.

[34] Katherine E. Coons, Sebastian Burckhardt, and Madanlal Musuvathi. GAMBIT: Effective Unit Testing for Concurrency Libraries. In *Proceedings of the 15th ACM SIGPLAN Symposium on Principles and Practice of Parallel Programming (PPoPP)*, 2010.

[35] Pantazis Deligiannis, Matt McCutchen, Paul Thomson, Shuo Chen, Alastair F. Donaldson, John Erickson, Cheng Huang, Akash Lal, Rashmi Mudduluru, Shaz Qadeer, and Wolfram Schulte. Uncovering Bugs in Distributed Storage Systems during Testing (Not in Production!). In *Proceedings of the 14th USENIX Symposium on File and Storage Technologies (FAST)*, 2016.

[36] Ankush Desai, Vivek Gupta, Ethan Jackson, Shaz Qadeer, Sriram Rajamani, and Damien Zufferey. P: Safe Asynchronous Event-Driven Programming. In *Proceedings of the ACM SIGPLAN 2013 Conference on Programming Language Design and Implementation (PLDI)*, 2013.

[37] Ernest Allen Emerson. *The Beginning of Model Checking: A Personal Perspective*. Springer-Verlag, 2008.

[38] Cormac Flanagan and Patrice Godefroid. Dynamic Partial-Order Reduction for Model Checking Software. In *Proceedings of the 33rd ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages (POPL)*, 2005.

[39] Pedro Fonseca, Kaiyuan Zhang, Xi Wang, and Arvind Krishnamurthy. An Empirical Study on the Correctness of Formally Verified Distributed Systems. In *Proceedings of the 2017 EuroSys Conference (EuroSys)*, 2017.

[40] Dennis Geels, Gautam Altekar, Petros Maniatis, Timothy Roscoe, and Ion Stoica. Friday: Global Comprehension for Distributed Replay. In *Proceedings of the 4th Symposium on Networked Systems Design and Implementation (NSDI)*, 2007.

[41] Patrice Godefroid. Partial-Order Methods for the Verification of Concurrent Systems: An Approach to the State-Explosion Problem. volume 1032, 1996.

[42] Patrice Godefroid. Model checking for programming languages using verisoft. In *Proceedings of the 24th ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages (POPL)*, 1997.

[43] Patrice Godefroid. Between Testing and Verification: Software Model Checking via Systematic Testing (Talk). In *Haifa Verification Conference (HVC)*, 2015.

[44] Patrice Godefroid, Michael Y. Levin, and David Molnar. SAGE: Whitebox Fuzzing for Security Testing. In *Communications of the ACM (CACM)*, 2012.

[45] Patrice Godefroid and Nachiappan Nagappan. Concurrency At Microsoft - An Exploratory Study. Technical report, Microsoft Research, 2008.

[46] Rachid Guerraoui and Maysam Yabandeh. Model Checking a Networked System Without the Network. In *Proceedings of the 8th Symposium on Networked Systems Design and Implementation (NSDI)*, 2011.

[47] Haryadi S. Gunawi, Thanh Do, Pallavi Joshi, Peter Alvaro, Joseph M. Hellerstein, Andrea C. Arpaci-Dusseau, Remzi H. Arpaci-Dusseau, Koushik Sen, and Dhruba Borthakur. FATE and DESTINI: A Framework for Cloud Recovery Testing. In *Proceedings of the 8th Symposium on Networked Systems Design and Implementation (NSDI)*, 2011.

[48] Haryadi S. Gunawi, Mingzhe Hao, Tanakorn Leesatapornwongsa, Tiratat Patana-anake, Thanh Do, Jeffry Adityatama, Kurnia J. Eliazar, Agung Laksono, Jeffrey F. Lukman, Vincentius Martin, and Anang D. Satria. What Bugs Live in the Cloud? A Study of 3000+ Issues in Cloud Systems. In *Proceedings of the 5th ACM Symposium on Cloud Computing (SoCC)*, 2014.

[49] Huayang Guo, Ming Wu, Lidong Zhou, Gang Hu, Junfeng Yang, and Lintao Zhang. Practical Software Model Checking via Dynamic Interface Reduction. In *Proceedings of the 23rd ACM Symposium on Operating Systems Principles (SOSP)*, 2011.

[50] Chris Hawblitzel, Jon Howell, Manos Kapritsos, Jacob R. Lorch, Bryan Parno, Michael L. Roberts, Srinath Setty, and Brian Zill. IronFleet: Proving Practical Distributed Systems Correct. In *Proceedings of the 25th ACM Symposium on Operating Systems Principles (SOSP)*, 2015.

[51] Patrick Hunt, Mahadev Konar, Flavio P. Junqueira, and Benjamin Reed. ZooKeeper: Wait-free coordination for Internet-scale systems. In *Proceedings of the 2010 USENIX Annual Technical Conference (ATC)*, 2010.

[52] Pallavi Joshi, Malay Ganai, Gogul Balakrishnan, Aarti Gupta, and Nadia Papakonstantinou. SETSUDO : Perturbation-based Testing Framework for Scalable Distributed Systems. In *Conference on Timely Results in Operating Systems (TRIOS)*, 2013.

[53] Xiaoen Ju, Livio Soares, Kang G. Shin, Kyung Dong Ryu, and Dilma Da Silva. On Fault Resilience of OpenStack. In *Proceedings of the 4th ACM Symposium on Cloud Computing (SoCC)*, 2013.

[54] Vineet Kahlon, Chao Wang, and Aarti Gupta. Monotonic Partial Order Reduction: An Optimal Symbolic Partial Order Reduction Technique. In *21st International Conference on Computer Aided Verification (CAV)*, 2009.

[55] Charles Killian, James W. Anderson, Ranjit Jhala, and Amin Vahdat. Life, Death, and the Critical Transition: Finding Liveness Bugs in Systems Code. In *Proceedings of the 4th Symposium on Networked Systems Design and Implementation (NSDI)*, 2007.

[56] Avinash Lakshman and Prashant Malik. Cassandra - A Decentralized Structured Storage System. In *The 3rd ACM SIGOPS International Workshop on Large Scale Distributed Systems and Middleware (LADIS)*, 2009.

[57] Leslie Lamport. The part-time parliament (paxos). *ACM Transactions on Computer Systems*, 16(2), May 1998.

[58] Tanakorn Leesatapornwongsa, Mingzhe Hao, Pallavi Joshi, Jeffrey F. Lukman, and Haryadi S. Gunawi. SAMC: Semantic-Aware Model Checking for Fast Discovery of Deep Bugs in Cloud Systems. In *Proceedings of the 11th Symposium on Operating Systems Design and Implementation (OSDI)*, 2014.

[59] Tanakorn Leesatapornwongsa, Jeffrey F. Lukman, Shan Lu, and Haryadi S. Gunawi. TaxDC: A Taxonomy of Non-Deterministic Concurrency Bugs in Datacenter Distributed Systems. In *Proceedings of the 21st International Conference on Architectural Support for Programming Languages and Operating Systems (ASPLOS)*, 2016.

[60] Thomas A. Limoncelli and Doug Hughe. LISA '11 Theme – DevOps: New Challenges, Proven Values. *USENIX ;login: Magazine*, 36(4), August 2011.

[61] Haopeng Liu, Guangpu Li, Jeffrey F. Lukman, Jiaxin Li, Shan Lu, Haryadi S. Gunawi, and Chen Tian. DCatch: Automatically Detecting Distributed Concurrency Bugs in Cloud Systems. In *Proceedings of the 22nd International Conference on Architectural Support for Programming Languages and Operating Systems (ASPLOS)*, 2017.

[62] Haopeng Liu, Xu Wang, Guangpu Li, Shan Lu, Feng Ye, and Chen Tian. FCatch: Automatically Detecting Time-of-fault Bugs in Cloud Systems. In *Proceedings of the 23rd International Conference on*

*Architectural Support for Programming Languages and Operating Systems (ASPLOS)*, 2018.

[63] Xuezheng Liu, Zhenyu Guo, Xi Wang, Feibo Chen, Xiaochen Lian, Jian Tang, Ming Wu, M. Frans Kaashoek, and Zheng Zhang. D3S: Debugging Deployed Distributed Systems. In *Proceedings of the 5th Symposium on Networked Systems Design and Implementation (NSDI)*, 2008.

[64] Xuezheng Liu, Wei Lin, Aimin Pan, and Zheng Zhang. WiDS Checker: Combating Bugs in Distributed Systems. In *Proceedings of the 4th Symposium on Networked Systems Design and Implementation (NSDI)*, 2007.

[65] Jonathan Mace, Ryan Roelke, and Rodrigo Fonseca. Pivot Tracing: Dynamic Causal Monitoring for Distributed Systems. In *Proceedings of the 25th ACM Symposium on Operating Systems Principles (SOSP)*, 2015.

[66] Madanlal Musuvathi, Shaz Qadeer, Tom Ball, Gerard Basler, Piramanayakam Arumuga Nainar, and Iulian Neamtiu. Finding and Reproducing Heisenbugs in Concurrent Programs. In *Proceedings of the 8th Symposium on Operating Systems Design and Implementation (OSDI)*, 2008.

[67] Diego Ongaro and John Ousterhout. In Search of an Understandable Consensus Algorithm. In *Proceedings of the 2014 USENIX Annual Technical Conference (ATC)*, 2014.

[68] Patrick Reynolds, Charles Killian, Janet L. Wiener, Jeffrey C. Mogul, Mehul A. Shah, and Amin Vahdat. Pip: Detecting the Unexpected in Distributed Systems. In *Proceedings of the 3rd Symposium on Networked Systems Design and Implementation (NSDI)*, 2006.

[69] Cesar Rodriguez, Marcelo Sousa, Subodh Sharma, and Daniel Kroening. Unfolding-based Partial Order Reduction. In *Proceedings of the 26th International Conference on Concurrency Theory (CONCUR'15)*, 2015.

[70] Raja R. Sambasivan, Ilari Shafer, Jonathan Mace, Benjamin H. Sigelman, Rodrigo Fonseca, and Gregory R. Ganger. Principled workflow-centric tracing of distributed systems. In *Proceedings of the 7th ACM Symposium on Cloud Computing (SoCC)*, 2016.

[71] Colin Scott, Vjekoslav Brajkovic, George Necula, Arvind Krishnamurthy, and Scott Shenker. Minimizing Faulty Executions of Distributed Systems. In *Proceedings of the 13th Symposium on Networked Systems Design and Implementation (NSDI)*, 2016.

[72] Benjamin H. Sigelman, Luiz AndrÃľ Barroso, Mike Burrows, Pat Stephenson, Manoj Plakal, Donald Beaver, Saul Jaspan, and Chandan Shanbhag. Dapper, a Large-Scale Distributed Systems Tracing Infrastructure. Technical report, Google, Inc., 2010.

[73] Jiri Simsa, Randy Bryant, and Garth Gibson. dBug: Systematic Evaluation of Distributed Systems. In *5th International Workshop on Systems Software Verification (SSV)*, 2010.

[74] Jiri Simsa, Randy Bryant, Garth A. Gibson, and Jason Hickey. Scalable Dynamic Partial Order Reduction. In *The 3rd International Conference on Runtime Verification (RV)*, 2012.

[75] A. Prasad Sistla, Viktor Gyuris, and E. Allen Emerson. SMC: a symmetry-based model checker for verification of safety and liveness properties. *ACM Transactions on Software Engineering and Methodology*, 2010.

[76] Chao Wang, Swarat Chaudhuri, Aarti Gupta, and Yu Yang. Symbolic Pruning of Concurrent Program Executions. In *Proceedings of the 17th ACM SIGSOFT International Symposium on Foundations of Software Engineering (FSE)*, 2009.

[77] Chao Wang, Mahmoud Said, and Aarti Gupta. Coverage guided systematic concurrency testing. In *Proceedings of the 33rd International Conference on Software Engineering (ICSE)*, 2011.

[78] Brian White, Jay Lepreau, Leigh Stoller, Robert Ricci, Shashi Guruprasad, Mac Newbold, Mike Hibler, Chad Barb, and Abhijeet Joglekar. An Integrated Experimental Environment for Distributed Systems and Networks. In *Proceedings of the 5th Symposium on Operating Systems Design and Implementation (OSDI)*, 2002.

[79] James R. Wilcox, Doug Woos, Pavel Panchekha, Zachary Tatlock, Xi Wang, Michael D. Ernst, and Tom Anderson. Verdi: A framework for formally verifying distributed system implementations. In *Proceedings of the 36th ACM SIGPLAN Conference on Programming Language Design and Implementation (PLDI)*, 2015.

[80] Maysam Yabandeh, Nikola Knezevic, Dejan Kostic, and Viktor Kuncak. CrystalBall: Predicting and Preventing Inconsistencies in Deployed Distributed Systems. In *Proceedings of the 6th Symposium on Networked Systems Design and Implementation (NSDI)*, 2009.

[81] Junfeng Yang, Tisheng Chen, Ming Wu, Zhilei Xu, Xuezheng Liu, Haoxiang Lin, Mao Yang, Fan Long, Lintao Zhang, and Lidong Zhou. MODIST: Transparent Model Checking of Unmodified Distributed Systems. In *Proceedings of the 6th Symposium on Networked Systems Design and Implementation (NSDI)*, 2009.

[82] Yu Yang, Xiaofang Chen, Ganesh Gopalakrishnan, and Robert M. Kirby. Distributed Dynamic Partial Order Reduction Based Verification of Threaded Software*. In *International SPIN Workshop on Model Checking of Software (SPIN)*, 2007.

[83] Matei Zaharia, Mosharaf Chowdhury, Michael J. Franklin, Scott Shenker, and Ion Stoica. Spark: Cluster Computing with Working Sets. In *The 2nd Workshop on Hot Topics in Cloud Computing (HotCloud)*, 2010.

[84] Yongle Zhang, Serguei Makarov, Xiang Ren, David Lion, and Ding Yuan. Pensieve: Non-Intrusive Failure Reproduction of Distributed Systems using the Event Chaining Approach. In *Proceedings of the 26th ACM Symposium on Operating Systems Principles (SOSP)*, 2017.