TardisTM: Incremental Repair for Transactional Memory

Daming D. Chen
Carnegie Mellon University
ddchen@cs.cmu.edu

Phillip B. Gibbons
Carnegie Mellon University
gibbons@cs.cmu.edu

Todd C. Mowry
Carnegie Mellon University
tcm@cs.cmu.edu

Abstract

Transactional memory (TM) provides developers with a *transaction* primitive for concurrent code execution that transparently checks for concurrency conflicts. When such a conflict is detected, the system recovers by *aborting* and restarting the transaction. Although correct, this behavior wastes work and inhibits forward progress.

In this paper, we present TardisTM, a software TM system that supports *repairing* concurrency conflicts while preserving unaffected computation. Our key insight is that existing conflict detection mechanisms can be extended to perform incremental transaction repair, when augmented with additional runtime information. To do so, we design a mechanism for localizing conflicts back to transactional program points, define the semantics for optional *repair handler* annotations, and extend the conflict detection algorithm to ensure all repairs are completed. To evaluate our system, we characterize the benefit of repair on a set of benchmark programs; we measure up to 2.95x speedup over mutual exclusion, and 93% abort reduction over a baseline software TM system that does not support repair.

CCS Concepts. • **Computing methodologies → Concurrent computing methodologies**; • **Computer systems organization → Multicore architectures**.

Keywords. software transactional memory, program repair, incremental computation

ACM Reference Format:
Daming D. Chen, Phillip B. Gibbons, and Todd C. Mowry. 2020. TardisTM: Incremental Repair for Transactional Memory. In *The 11th International Workshop on Programming Models and Applications for Multicores and Manycores (PMAM'20), February 22, 2020, San Diego, CA, USA.* ACM, New York, NY, USA, 10 pages. https://doi.org/10.1145/3380536.3380538

PMAM'20, February 22, 2020, San Diego, CA, USA

ACM ISBN 978-1-4503-7522-1/20/02.
https://doi.org/10.1145/3380536.3380538

1 Introduction

Transactional memory (TM) provides developers with first-class transactional regions that guarantee atomicity, consistency, and isolation, avoiding the drawbacks of low-level concurrency control primitives [21]. These guarantees are ensured by the transactional runtime, which upon detecting a concurrency conflict, will abort, roll back, and restart a transaction. However, this behavior discards *all* work already performed within a transaction, which impedes forward progress and decreases performance. Transactions that are more likely to encounter conflicts, such as those that are *high-contention* or *long-running*, are particularly affected.

Prior Work Helps But Still Aborts/Restarts: Prior work has developed various orthogonal strategies to mitigate this problem; namely, *contention management*, *transaction scheduling*, *abort impact reduction*, and *conflict reduction*. *Nested transactions* [29] reduce the scope of aborts to that of the innermost encapsulating transaction, but require strict nesting and are frequently flattened when unsupported. *Early release* [20], *abstract locking* [31], and *transactional boosting* [19] reduce conflicts by bridging the *semantic gap* between abstract datatypes and concrete implementations, where multiple implementation-defined memory states can correspond to the same abstract state (e.g., multiple lists of elements with different ordering can represent the same unordered set). Taken further, *semantic commutativity* [48] observes that certain *abstract operations* can be reordered; e.g. insertion into a linked list, increment of an integer counter, etc. However, these strategies only mitigate certain transaction conflicts, at the cost of a completely different TM runtime. Both *transactional boosting* and *abstract locking* require abstract datatypes to inform the runtime of inverse abstract operations, or to implement custom locking, which obviates much of the benefits of TM. All these prior approaches still rely on aborting and restarting.

Our Approach: Incremental Repair: In contrast, we propose TardisTM, a software TM system that supports *incremental repair* of conflicting transactions. Using repair annotations, TardisTM can safely resume transaction execution, ensuring forward progress and reducing wasted work. As an example, consider the simplified array-based microbenchmark shown in Listing 1, in which two concurrent transactions can conflict when one commits after incrementing the stored array value, and the other has read the now-stale previous value.

```
1 void work(data_t d) {
2   for (int i = 0; i < d.tx_per_thread; ++i) {
3     transaction {
4       for (int j = 0; j < d.ops_per_tx; ++j) {
5         unsigned idx = RAND_UNIFORM(0, d.array_size);
6         int val = d.array[idx];
7         if (!d.ops[j].read_only)
8           d.array[idx] = val + RAND_UNIFORM(0, 100);
9       } for (int k = 0; k < d.spin; ++k) { } // spin
10    }
11  }
12 }
```

Listing 1. A simplified array-based microbenchmark. A random shared array value is read (lines 5–6), and randomly incremented if the operation is read-write (lines 7–8). Some emulated local work is performed (line 9). This is repeated for some number of operations per transaction (line 4) and transactions per thread (line 2).

Instead of aborting, TardisTM can repair the stale read by fetching the new value, re-incrementing it if the operation was read-write, and resuming execution (this is shown later in Listing 2). Similarly, a long-running transaction that may append to a linked list can be repaired after conflict, by re-appending to the new list, among many other examples.

Our key insight is that, in conjunction with certain additional runtime information, conflict detection can be extended to perform incremental transaction repair using optional repair handlers, which maintains compatibility with existing transactional programs written for word-based systems (§2). Our main contributions are:

- We develop a repair mechanism for localizing transaction conflicts back to program points (§3.3), define the semantics for optional *repair handler* annotations (§3.5), and augment the conflict detection algorithm to identify additional *temporal conflicts* (§3.4) introduced by incremental repair (§3.6).
- We implement this design (§4) in TardisTM[1], a software-based transactional memory system.
- We provide repair annotations[2] for a library of data structures and benchmark programs. With repair enabled, we measure up to 93% abort reduction over a baseline system that does not support repair, and 2.95x speedup over mutual exclusion. This also exceeds the performance of compiler-based software-only and hybrid hardware TM designs (§5).

2 Background: Software-based TM

We design our repair mechanism as an extension of existing software TM [42]. In this section, we provide a brief overview, and show a commit-time write-back design in Figure 1.

Conflict Detection: Time-based designs (e.g., TL2 [9]) increment a global timestamp counter when a transaction successfully completes (commits). A timestamp is associated with every global memory address, which records when its value was last updated. Each transaction stores the observed timestamp for each global memory read in a local *read set*. During *read validation*, the read set is checked for stale timestamps, and if one is detected, then a *data conflict* occurs.

Timestamp Extension [14, 36]: To minimize validation frequency, each transaction tracks a local *validity threshold* (Figure 1), which is initialized to the global timestamp counter when the transaction starts. Read validation is performed only if a transactional read observes a newer timestamp, or attempts to commit with a stale validity threshold. If successful, the transaction can update its validity threshold to the validation-time global timestamp counter.

Memory Locking: Transaction atomicity is ensured by two-phase locking [13], which uses an additional global lock array. A predefined surjective function maps memory addresses to locks, which can also store the corresponding timestamps. In a word-based design, multiple memory words may map to the same lock, resulting in *lock aliasing* and allowing *spurious conflicts* (e.g., TinySTM [14], SwissTM [12], McRT-STM [40]). These locks can be acquired eagerly as memory is accessed (*encounter-time*), or lazily when a transaction attempts to commit (*commit-time*). If a lock is already held by another transaction, then a *lock conflict* occurs.

Transactional Writes: A local *write set* is used to track transactional writes. Under eager *write-through*, writes are performed immediately, and the write set is used as an *undo log* in case the transaction aborts. Conversely, under lazy *write-back*, writes are delayed until successful commit, and the write set is used as a *redo log*. This also requires reads to check for pending writes in the write set.

Dynamically-Allocated Memory: Transactional semantics can be implemented using an epoch-based *garbage collector*. Memory is queued for deallocation if it is allocated but the transaction aborts, or if it is deallocated and the transaction commits. To avoid a *use-after-free* violation by other ongoing transactions, conflicts are forced by incrementing all corresponding lock timestamps, and deallocation is delayed until all concurrent transactions have finished.

3 Design: TardisTM

We first discuss the design principles of TardisTM in §3.1, before summarizing our design in §3.2, and detailing our contributions in §3.3 - §3.7.

3.1 Principles

Precision: We want to preserve transaction progress without discarding non-conflicting computation, which requires finer-grained tracking to identify data and control-flow dependencies involving stale reads. We achieve this with first-class *abstract operations* and read set *origin tracking*, which resemble lightweight dynamic *program slicing* [49].

[1] https://github.com/ddcc/tardisTM
[2] https://github.com/ddcc/stamp

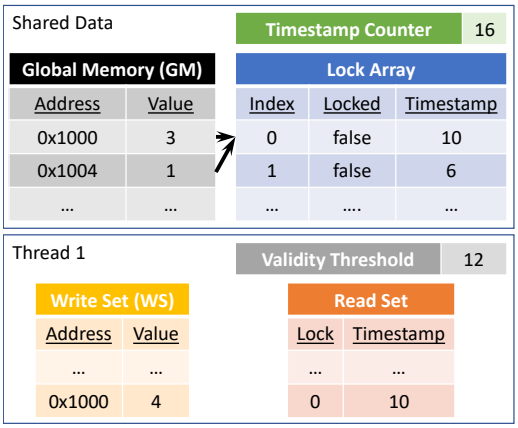


Figure 1. A time-based write-back commit-time locking TM. Observe that thread 1 read the value 3 from global memory location `0x1000` (lock 0) with timestamp 10, and then wrote the value 4 to that location (Listing 1). Because it has a stale validity threshold (12 vs. 16), timestamp extension is needed before commit.

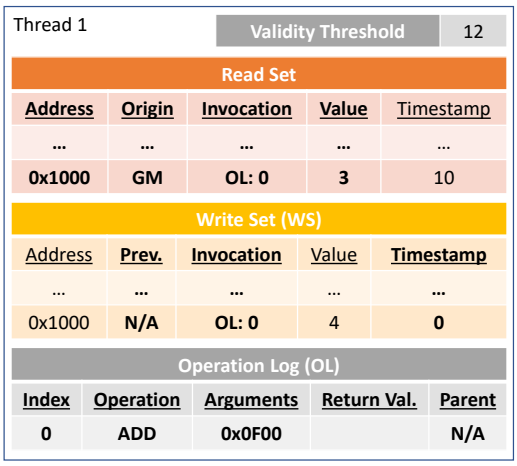


Figure 2. Thread-local state of TardisTM at the same program point as Figure 1, with changes **bolded**. Observe the additional read set fields (abstract operation invocation, address, origin, and value), as well as the additional write set fields (abstract operation invocation, previous, and timestamp). The operation log shows an ongoing invocation of an abstract operation annotated as `ADD` (which is implemented by the transaction from Listing 1), and was called with data pointer `0x0F00`.

Isolation: We want to avoid interacting with other concurrent transactions, in order to ensure consistency and avoid additional synchronization. Each transaction repairs its local conflicts with respect to global memory, much like the *rebase* operation in distributed version control systems such as `git` [46], which requires a write-back design (§2). This also prevents cyclic dependencies from occurring. A fully-repaired transaction thus appears as if it had instantaneously executed to the same program point.

Efficiency: To minimize overhead, we want to perform repair as infrequently as possible. This favors a commit-time locking design (§2), which we found to be much simpler than an early prototype that used encounter-time locking.

Compatibility: Since repair annotations are optional, we want to compose with existing transactions that abort.

3.2 Overview

We build TardisTM as an extension of a word-based software TM with time-based conflict detection and commit-time locking, which we denote the *baseline* system. At a high-level, our approach is as follows:

1. Annotations for first-class *abstract operations* and *repair handlers* are added to existing transactional code.
2. Inside a *repairable* transaction (§4.3), whenever an abstract operation is executed (invoked), it is tracked in a local *operation log*, and its corresponding read/write set entries are tagged (§3.3). Also, the source of each read set entry (*origin tracking*), and the chronology of each write set entry (*write history*) are recorded (§3.4).
3. When a conflict is detected, incremental repair (§3.5) is performed by executing any *repair handlers* attached to the corresponding abstract operation. Various *repair policies* are available, including a *replay repair* that automatically rolls back and re-executes the operation invocation.
4. After a successful repair, conflict detection resumes. To ensure correctness, any additional *temporal conflicts* (§3.6) caused by repair must also be identified and repaired.

3.3 Conflict Localization: Abstract Operations

Recall the simplified array-based microbenchmark shown in Listing 1. Observe that under the baseline system (shown in Figure 1), when a data conflict occurs on lock #0, multiple memory addresses may correspond to the same lock (e.g. `0x1000` and `0x1004`), preventing localization to a specific program point. We make a number of changes in TardisTM to resolve this, discussed below and shown in Figure 2.

First, we store observed values and memory addresses in the read set, which generally correspond to language-level variables while in scope.[3] Next, we define first-class typed abstract operations, which annotate arbitrary code sequences. Each execution (invocation) is recorded in a local *operation log*, including its input arguments, return value, and parent invocation (every transaction is initialized with a dummy root). Furthermore, every read/write set entry is tagged with its corresponding invocation.

Taken together, these changes record the execution history of each transaction, ensuring that when a conflict occurs, the *repair handler* (§3.5) can lift memory addresses back to language-level variables at a specific point in time.

[3]Because variables are identified by memory address, any that are modified during repair must be address-taken and thus memory-backed. We also define an optional user-defined tag field (omitted for clarity), which can be used to disambiguate between sum types (e.g., unions in C), record the base address of a product type (e.g., structs in C), or store other implementation-defined repair information.

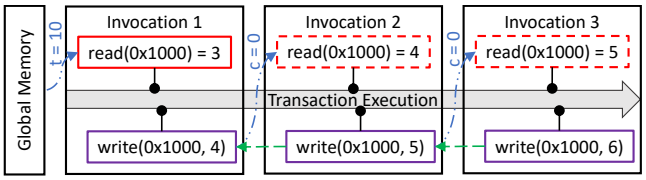


Figure 3. A simulated transaction that executes the same abstract operation thrice, with each incrementing a variable at address 0x1000. Reads are depicted in red boxes, and writes in purple boxes. Dashed red lines denote reads of local writes not tracked by the baseline system, dashed blue arrows denote our origin tracking mechanism, and dashed green arrows denote our write history mechanism. Observe that reads of global memory record the lock timestamp, whereas reads of local writes record the per-entry counter (in this case $c = 0$ because the writes are in separate invocations).

3.4 Dependency Resolution: Origin Tracking

Likewise, under the baseline system, reads of local writes are not tracked in the read set, and existing entries in the write set are overwritten when subsequent writes occur at the same address. This inhibits repair, because intermediate write-read dependence edges are lost, preventing detection of these stale computations. To address this problem, we perform *origin tracking*, which includes a mechanism for storing *write history*, shown in Figures 2 and 3.

First, we create an entry in the read set for each read of a local write. To disambiguate between reads of global memory and the write set, we introduce an "origin" field in the read set that specifies the source (**GM** or **WS**). As an optimization, we enable deduplication of read set entries to avoid storing multiple copies of the same read (e.g., if executed in a loop).

Next, to determine if a write set entry has been changed since it was last read (e.g., by repair), we introduce a per-entry last update timestamp for the write set that is analogous to the last update timestamp for global memory.[4] Thus, the "timestamp" field of each read set is interpreted based on its origin, either with respect to a local write set entry or to a shared lock array entry. These changes affect conflict detection, which we discuss subsequently in §3.6.

Finally, instead of immediately overwriting existing write set entries, we implement a lightweight history mechanism that tracks the chronology of past writes at the same address. Since each write set entry is already associated with an abstract operation invocation (§3.3), we identify past entries by their address and abstract operation invocation. This means that an existing entry is overwritten only if both fields match, and otherwise a new entry is created and the old entry is recorded as its "previous" entry.[5]

[4] An alternative approach could compare observed values instead, but would suffer from value aliasing.

[5] This is simplified for the sake of brevity, because abstract operation invocations can nest. In certain situations, such as a *straddle write* where two writes in a parent (outer invocation) span at least one write in a child (inner invocation), we may create additional entries to maintain a consistent linear timeline in the event that some are reverted during repair.

```
1  tardistm_repair_t repair(tardistm_conflict_t c) {
2    int idx = c.addr - d.array;
3    assert (!c.recursive && idx < d.size);
4    tardistm_read_t r = c.conflict;
5    int old_read = TARDISTM_READ_VALUE(r);
6    int new_read = TARDISTM_READ_UPDATE(r);
7    tardistm_write_t w = TARDISTM_WRITE_QUERY(d.array[idx]);
8    if (old_read == new_read || !TARDISTM_VALID_WRITE(w))
9      return TARDISTM_REPAIR_OK;
10   int old_write = TARDISTM_WRITE_VALUE(w);
11   TARDISTM_WRITE_UPDATE(w, new_read + (old_write -
     ↪  old_read));
12   return TARDISTM_REPAIR_OK;
13 }
```

Listing 2. A simplified manual delayed repair for Listing 1, involving a stale read at some array index. As outlined in §1, the value of the stale read is fetched (line 4–5) and updated (line 6). If a write occurred (line 8), the stale write is updated (lines 10–11).

3.5 Incremental Repair

3.5.1 Overview. When attempting incremental repair, we look up the appropriate *repair handler* for the conflicting abstract operation invocation. We distinguish between *just-in-time* and *delayed* repair handlers, which have different capabilities depending on whether the conflicting invocation is still executing (and thus on the stack). The former are lexical closures, which can directly modify the execution context, and complete using a continuation that allows execution to resume at any program point within the same abstract operation. In contrast, the latter must utilize a different interface, described below in §3.5.2.

Next, each repair handler must select from one of two different *repair policies*: *replay* or *manual*. Under a replay repair, the repair handler delegates the repair to TardisTM, which will automatically revert all effects of the conflicting invocation on the local transaction, and re-executes it at that point in time with the same arguments. This requires that an abstract operation corresponds to an implementation function of the same type.

Subsequently, our conflict detection algorithm (§3.6) will identify any orphan or stale dependent computations as *temporal conflicts* that must also be repaired to avoid transaction abort. Changes to non memory-backed dependents, such as return value, constitute a *recursive conflict* that precipitates repair at the parent invocation, effectively recursing up the execution stack recorded in the operation log.[6]

3.5.2 Manual Repair. During a manual repair, the repair handler is provided with the conflict context, and given an opportunity to perform repair. We show examples of a delayed repair in Listing 2, and a just-in-time repair in Listing 3.

[6] By default, detection of a recursive conflict is triggered by a change in value, but repair handlers can use a special flag to force a conflict in the event that, for example, a change is written non-transactionally through an input argument or return value.

Transaction State	Repair Operation			
	Query	*Update*	*Create*	*Revert*
Read Set	Value	Value	Entry	Entry
Write Set	Value	Value	Entry	Entry
Operation Log	Input Args., Return Value	Return Value	Invocation	Invocation
Dynamically-Allocated Memory	Allocate, Free	N/A	Allocate, Free	Allocate, Free

Table 1. Interface for operating on transaction state during repair, discussed in §3.5.2 and for dynamically-allocated memory, §3.7.

The conflict context always includes the memory address and corresponding abstract operation invocation of the conflict. Depending on the conflict type, it may also include a reference to the stale read set entry (data conflict), or the values of the previous and current return values (recursive conflict). Each repair handler must indicate if it succeeded, and may provide a new return value. Should it fail, the transaction may have become inconsistent and must abort.

We provide repair handlers with a special interface for querying and modifying the internal state of TardisTM, including the read set, write set, and operation log. These operations, summarized in Table 1, are temporally scoped such that the affected transaction observes the current global memory without the effects of its subsequent transactions. This ensures that queries cannot retrieve its future state, and modifications cannot affect its past state–paradoxes that would violate *temporal consistency*.

New writes that are created by the repair handler must be carefully handled, because the origin of subsequent reads at the same address should now point to this write. In the event that the conflicting invocation has already performed a write at this address, we simply abort the repair because their chronology cannot be automatically resolved.[7] After eagerly correcting the "origin" field of subsequent reads, we deliberately invalidate their observed timestamp to ensure subsequent identification by conflict detection (§3.6).

Note that bugs or unsafe behavior within repair handlers can violate transaction consistency. For example, non-transactional reads and writes will evade the temporal scoping provided by our design. Likewise, failure to update a stale write will prevent detection of its subsequent stale reads.

3.6 Temporal Conflict Detection

To ensure the correctness and convergence of incremental repair, we need to perform each individual repair in their original execution order. Because repair occurs whenever a conflict is detected, this means that a particular ordering of conflict detection is needed. In contrast, the baseline system aborts and restarts when any conflict is detected.

We resolve this by imposing chronological ordering on the read set, and limiting conflict detection to read validation, which iterates sequentially through the read set. During normal execution, entries are appended to the read set, and when a new read occurs during repair, it is inserted at the correct position. After completing each repair, conflict detection resumes at the next entry, and if invalid, the first read set entry from the current abstract operation invocation. These changes ensure that repairs respect dependency ordering.

As mentioned previously (§3.4), our read set tracks reads of both the global memory and the local write set. The conflict criterion for the former remains unchanged; a data conflict occurs when the observed timestamp does not match the lock's last update timestamp (§2). In contrast, a temporal conflict occurs when the originating write set entry has been reverted (§3.5.2), or the observed timestamp does not match the write's last update counter (§3.4).

Additionally, care must be taken to avoid executions that would be impossible in the baseline system. If conflicts with multiple committed transactions are detected during incremental repair, the transaction must abort, because it might be partially repaired with respect to an older version of global memory that has been overwritten. Similarly, if a new read occurs during repair while the current transaction is attempting to commit, and the corresponding lock is held by another concurrent transaction, it must abort to avoid deadlock due to circular waiting. Finally, if a new write occurs during repair while the current transaction is attempting to commit, it must re-attempt commit because it may not own the corresponding lock, which would violate two-phase locking.

3.7 Dynamically-Allocated Memory

Transactional operations on dynamically-allocated memory may also need to be repaired. To support this, we tag queued memory operations (§2) with their corresponding abstract operation invocation, and extend the repair handler interface to include these operations (Table 1). Thus, deallocations can be reverted by simply removing the queued request. But, allocations cannot be reverted by deallocating immediately, because they could be reused by the memory allocator and alias with an existing unrepaired read/write set entry. Instead, reverted allocations must be queued for the garbage collector.

4 Implementation

We implement TardisTM on top of TinySTM [14], an existing software TM written in the C programming language. Our changes amount to approximately an additional 5.7 kloc, computed using `cloc` [8].

4.1 Abstract Operations

Abstract operations are dynamically registered with TardisTM at startup using a function with the `constructor` attribute, a compiler extension supported by both the GNU C Compiler (GCC) and Clang. A macro is used to generate the body of this function for all abstract operations defined in the current compilation unit. Manual calls are inserted to record input arguments and return value for each abstract operation.

[7] Automated replay repairs do not suffer from this problem, because the entire abstract operation invocation is reverted and re-executed.

4.2 Just-in-Time Repair

Just-in-time repair handlers (§3.5.1) are implemented using *nested functions*, a GCC-specific feature for lexical closures [3]. Because these are generated as executable stack trampolines, we ensure that the corresponding invocation is still executing by recording and subsequently invalidating the address of the nested function in the operation log. To perform automatic replay, we record the implementation function for each abstract operation and invoke it using the `libffi` [15] library, which can dynamically generate typed function calls for the platform-specific calling convention.

Continuations are implemented using another GCC-specific extension, *local labels*, which allow nested functions to immediately return from any intermediate stack frames and `goto` the code at the label. Just-in-time repair handlers must first call a special cleanup function to fix-up the internal state of TardisTM before doing so; e.g. locks may need to be released if the transaction was committing.

4.3 Adaptive Execution

To reduce overhead, we proactively check whether the current abstract operation invocation is *repairable*. If not, we disable operation logging (§3.3), as well as origin tracking and write history (§3.4).

5 Evaluation

To demonstrate the effectiveness of transaction repair, we evaluate TardisTM on a set of benchmark programs: `array` (Listing 1), and the Stanford Transactional Applications for Multi-Processing [28] (STAMP).[8] We manually developed repair annotations for various operations on linked lists, hashtables, queues, and red-black trees, as well as program-specific logic and data structures. Most of these were for STAMP's internal data structure library, which are used by multiple individual benchmarks.

We compare against TinySTM, baseline TardisTM without all repair-related functionality[9] (TardisTM-None), lock-based mutual exclusion (Mutex), as well as GCC's compiler-based software system (GCC) and compiler-based hybrid [7] (GCC-RTM), which utilizes hardware Intel Restricted Transactional Memory [17] (RTM).

Our benchmarks were performed on a system with a Samsung 850 EVO 500 GB SSD, 64 GB DDR4 ECC RAM per socket, and 2x Intel Xeon E5-2683v4 CPUs at 2.6 GHz, running Debian 10 with Linux kernel 4.12.6-1 and GCC 8.3.0-6.[10] All experiments were averaged over 10 runs, with speedup error bars set to one standard deviation.

Category	High/High	Mixed
Benchmark(s)	`array`	`bayes`, `genome`
Abort Rate	$\geq$ 60%	20% to 60%
Avg. Wasted Work	$\geq$ 6	$\geq$ 5
Speedup vs Mutex	up to 1.62x	up to 2.95x
Abort Reduction vs TardisTM-None	61% to 78%	34% to 93%
Speedup vs TardisTM-None	up to 2.78x	up to 1.26x

Table 2. Benchmarks, characteristics, and TardisTM improvements by category.

5.1 Benchmark Characterization

We characterize the repair potential for these benchmarks by measuring transaction cycles (using `rdtscp`) under TardisTM-None, and computing the following metrics:

$$\text{Average Wasted Work} = \log_{10}\left(\sum_{\text{Threads}} \frac{\text{Aborted TX Cycles}}{\text{\# Aborts}}\right)$$

$$\text{Abort Rate} = \sum_{\text{Threads}} \frac{\text{\# Aborts}}{\text{\# Aborts} + \text{\# Commits}}$$

We show the results in Figures 4a and 4b, respectively, which we use to roughly categorize our benchmarks as follows: *High/High*, where we expect significant speedups (§5.2), *Mixed*, where we expect moderate speedups (§5.3), and *Low/Low* (omitted), which are summarized in Table 2. Observe that for each benchmark, higher thread count increases both metrics, due to an increased probability of conflict.

5.2 Case #1: High Wasted Work, High Abort Rate

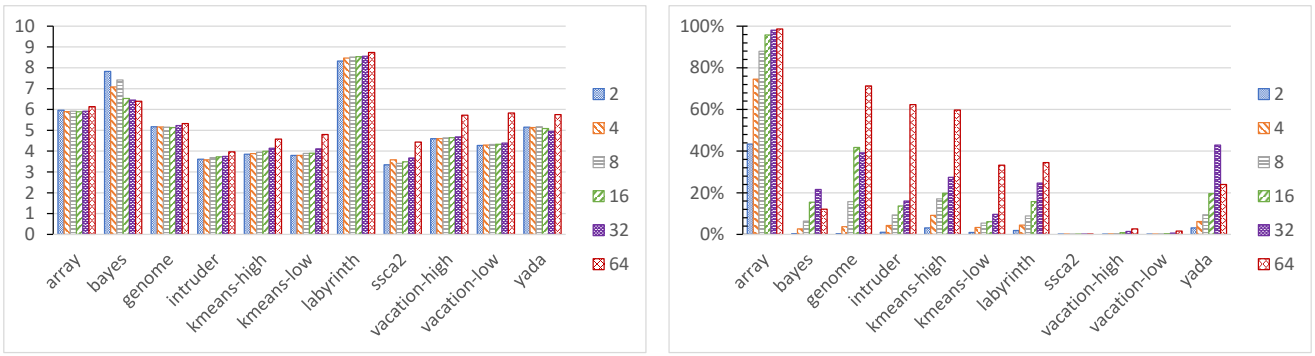
Our `array` benchmark (Listing 1) falls into this category. Conflicts in `array` occur when concurrent transactions access and modify values at the same array index. Instead of aborting, TardisTM uses a manual delayed repair handler to perform incremental repair, shown earlier in Listing 2.

As shown in Figure 5a, TardisTM achieves a speedup of up to 1.62x compared to Mutex, and is consistently the fastest among the compared systems on `array`. Surprisingly, TardisTM-None, GCC, and TinySTM almost always performed worse than Mutex, likely due to frequent aborts.

[8] We made some changes to the STAMP benchmarks; namely, modernizing the code using C11 standard library atomics, and padding 32-bit floating-point variables to avoid word aliasing on 64-bit systems. We also fixed numerous resource leakage and correctness bugs (§5.5), some of which were identified by previous work [23, 37]. Where necessary, we moved local variable declarations to be within repair handlers, and adjusted control-flow into single-entry single-exit regions for ease of annotation.

[9] This includes the operation log, origin tracking, write history, etc.

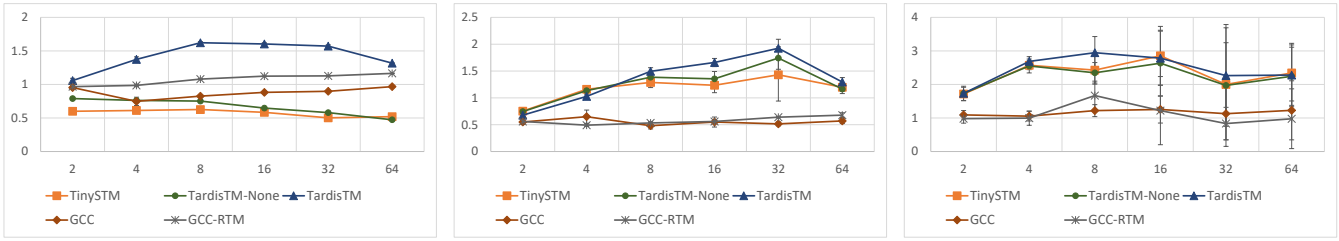
[10] For the STAMP benchmarks, we used the '++' configuration, and for `genome`, we also increased the batching factor from 12 to 100 hashtable insertions per transaction. For `array`, we used an array of size 1024, with 10000 transactions per thread, 1000 operations per transactions, 25% read-only operations, and a spin value of 1000.



(a) Average wasted work (defined in §5.1).

(b) Abort rate (defined in §5.1).

Figure 4. Average wasted work and abort rate on TardisTM-None, for each of the benchmarks, with 2 to 64 threads.

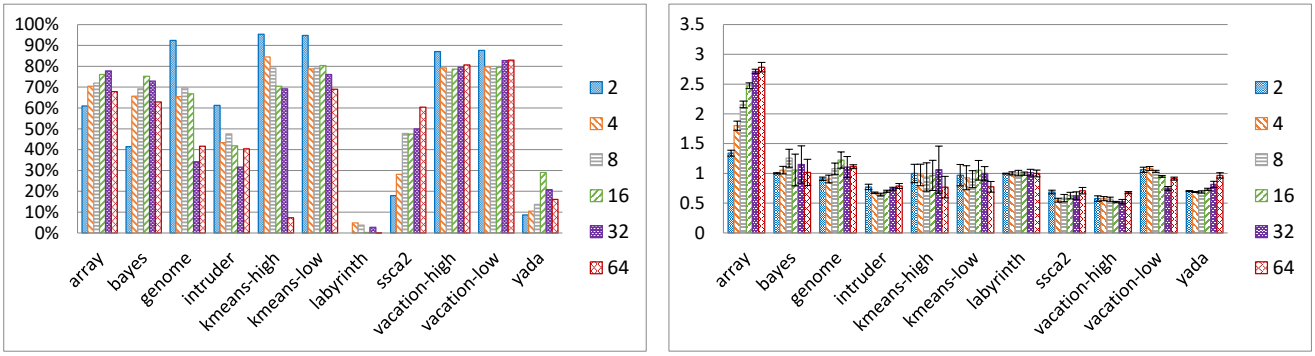


(a) array.

(b) genome.

(c) bayes.

Figure 5. Speedups of each TM system relative to Mutex, as a function of thread count, for array, bayes, and genome.



(a) Abort reduction.

(b) Speedup.

Figure 6. Abort reduction and speedup of TardisTM over TardisTM-None, for each of the benchmarks, with 2 to 64 threads.

Compared with TardisTM-None, TardisTM achieves an abort reduction of between 61% and 78% (Figure 6a) and a speedup of up to 2.78x (Figure 6b).

5.3 Case #2: Mixed Wasted Work and Abort Rate

Two benchmarks, genome and bayes, fall into this category.

genome: This program performs batched reassembly of textual DNA segments for genome sequencing. Fragments are inserted into a fixed-size hashtable, which is equivalent to a membership check on the bucket linked-list, followed by insertion if not present. Because the return value of the hashtable insertion is never checked, repair can be fully delegated to the underlying annotation, shown in Listing 3.

Conflicts during linked-list insertion can occur at three different positions: (1) within the operation to find the predecessor, (2) when reading the predecessor, or (3) when incrementing the list size. All can be repaired by updating the predecessor if changed (line 6), reverting all reads/writes from the current invocation (line 7), and re-inserting (line 9).

As shown in Figure 5b, TardisTM achieves a speedup, starting at 8 threads, of up to 1.92x compared to Mutex. In contrast, GCC and GCC-RTM perform worse than Mutex, whereas TinySTM and TardisTM-None perform better, but still worse than TardisTM. Compared with TardisTM-None, TardisTM achieves an abort reduction of between 34% and 93% (Figure 6a) and a speedup of up to 1.22x (Figure 6b).

```
1 void list_insert(list_t *listPtr, void *dataPtr) {
2   node_t *prevPtr = NULL, *nodePtr = NULL;
3
4   tardistm_repair_t repair(tardistm_conflict_t c) {
5     if (c.recursive && TARDISTM_OP_ID(c.prev_op) ==
      ↪  LIST_PREVIOUS)
6       prevPtr = c.conflict.rv.ptr;
7     TARDISTM_REVERT_RW(c.current_op);
8     TARDISTM_FINISH_REPAIR();
9     goto insert;
10  }
11
12  prevPtr = LIST_PREV(listPtr, dataPtr); // (1)
13  nodePtr = LIST_ALLOC_NODE(dataPtr);
14 insert:
15  nodePtr->nextPtr = prevPtr->nextPtr; // (2)
16  prevPtr->nextPtr = nodePtr; // (2)
17  listPtr->size += 1; // (3)
18 }
```

Listing 3. Implementation and just-in-time repair for a simplified linked-list insertion (`LIST_INSERT`) abstract operation.

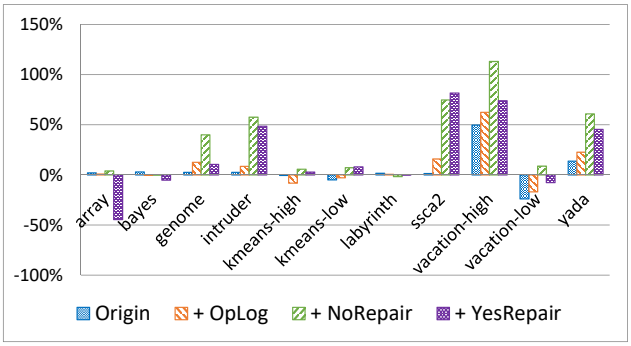


Figure 7. Cumulative overhead at 4 threads of TardisTM over TardisTM-None as runtime tracking features (and finally actual repair) are enabled, for each of the benchmarks.

bayes: This program performs bayesian inference by searching for the edge between variables that maximizes prediction log-likelihood [5]. The search is transactional, and may conflict when log-likelihood estimates are concurrently updated. However, because these values always increase monotonically, conflicts do not affect the best edge unless the baseline increases to make it invalid. Thus, repair typically only needs to increment the final score by the improvement.

As shown in Figure 5c, TardisTM achieves a speedup of up to 2.95x compared to Mutex. These speedups are occasionally matched by TinySTM and TardisTM-None, whereas both GCC and GCC-RTM barely perform better than Mutex.

Compared with TardisTM-None, TardisTM achieves an abort reduction of between 41% and 76% (Figure 6a) and a speedup of up to 1.26x (Figure 6b). However, these results should be taken cautiously, given the high variance and nondeterministic behavior of `bayes` observed by past work [37].

5.4 Overhead

Runtime tracking is required for repair, which imposes overhead on all transactions regardless of whether they abort or commit. To measure this, we show performance while cumulatively enabling tracking in Figure 7, using 4 threads. The results show that incremental repair improves performance when enabled (`YesRepair`) compared to when not enabled (`NoRepair`), across all but `kmeans-low`, `labyrinth`, and `ssca2`. However, this improvement does not necessarily exceed the overhead of origin tracking (`Origin`), operation logging (`OpLog`), and other repair-related code (`NoRepair`) at 4 threads. Although we do expect absolute speedups to increase with greater thread count, based on our previous figures, we observe that overall repair effectiveness is affected by a variety of factors, including repair cost, number of repairs, and the repair success rate, as all repairs must complete successfully for a transaction to avoid aborting.

5.5 Discussion

As shown in Figure 6a, TardisTM achieves significant reductions in abort rates across benchmarks and thread counts, compared to TardisTM-None (Figure 4b). However, this large reduction often does not result in any speedups (Figure 6b), due to repair overhead (§5.4).[11] We do not expect speedups on the remaining benchmarks (`kmeans`, `intruder`, `ssca2`, `vacation`, and `yada`), due to low abort rate or low wasted work. Some are dominated by small transactions (e.g. `kmeans`, `ssca2`), where repair overhead exceeds abort cost, whereas others (e.g. `intruder`, `yada`) contain data structures that are impractical to repair incrementally, despite our automated replay repair. For example, insertion/deletion on a red-black tree can involve recursive rebalancing, which may affect all subsequent operations.

Another contributing factor is that the STAMP benchmarks have been restructured for TM. For example, `intruder` has been split into two transactions that pass data non-transactionally: one solely dequeues an element, whereas the other performs packet reassembly on it. Others perform non-transactional operations within transactions, which is unsupported by transactional compilers like GCC[12], and resulted in many correctness bugs that we fixed. These include memory leaks and use-after-free bugs involving non-transactional dynamically-allocated memory operations, as well as non-transactional writes that are unobservable within transactions, or irreversible when the transaction aborts. Nevertheless, some of the programming models and data structures used by the STAMP benchmarks are suboptimal, which adversely affects scaling with increased thread count [30].

[11] `labyrinth` relies entirely on privatization and manual aborts [47], which bypasses both transactional conflict detection and our repair mechanism.
[12] Under GCC and GCC-RTM, all operations in transactions were executed transactionally.

Program	array	bayes	genome	intruder	kmeans
Repair loc	47	189	61	232	130
Program	**labyrinth**	**lib**	**ssca2**	**vacation**	**yada**
Repair loc	N/A	1780	56	438	368

Table 3. Repair size upper bounds, in lines of code (loc).

5.6 Repair Annotations

We implemented 76 repair annotations total, of which 69 were manual repairs. Estimated sizes are shown in Table 3, with STAMP's internal data structure library listed as `lib`. This includes debug code and disabled annotations that were difficult to automatically exclude; for example, the core repair for `array` from Listing 2 amounts to 13 loc, instead of 47 loc.

6 Related Work

We provide an overview of related work on transactional conflicts, which we categorize as follows. As mentioned previously in §1, these are orthogonal to TardisTM, because none support general transaction repair.

Contention Management: A contention manager dynamically handles conflicts. Policies include waiting with exponential backoff [20], based on work performed [41], aborting based on work performed [41], and prioritizing based on earliest original start time [16].

Transaction Scheduling: A scheduling mechanism determines when transactions start or commit. Decisions can be made based on contention [50] or commit ordering [1, 35, 38].

Abort Impact Reduction: Transactions are structured to minimize abort effects. *Transactional checkpoints* [24] partially abort to user-defined rollback points, whereas *hardware pre-abort handlers* [33] partially commit and fall back to software. *Nested transactions* [29] scope aborts to that of the innermost affected transaction. *Open nesting* and *closed nesting* differ in the visibility of committed child transactions, whereas *abstract nesting* [18] may delay restart of aborted child transactions.

Conflict Reduction: The conflict detection algorithm can avoid certain conflict types. *Value-based conflict detection* [6, 11, 32] is impervious to timestamp conflicts from lock aliasing. Subsequent work [39] adds first-class comparison and increment primitives that support semantic-aware recomputation. *RetCon* [2] performs hardware symbolic recomputation using program slicing, but is limited by complex expressions or control-flow changes. *Multi-version memory* [10, 27, 34] allows concurrent transactions with different memory versions, but may ultimately need reconciliation.

Semantic commutativity [48] can avoid conflicts that semantically commute. These include an approach using open nesting [31], a model [25] for coarse-grained transactions, a *commutativity lattice* [26] for reasoning about *commutativity conditions*, a method [4] for retrofitting abstract locks, hardware support [51] for commutative operations, a compositional transactional data structure library [44], and datatype-level transactional semantics [22].

Alternatively, *parameterized atomic blocks* [45] allow hardware to ignore certain conflicts on a per-transaction basis, and *early release* [20] allows manual removal of read set entries, which can be useful for linear data structures [43].

7 Conclusion

In this paper, we introduced TardisTM, a software TM that supports incremental repair. We find that repair is especially useful for workloads with high abort rate and wasted work, achieving up to 1.62x speedup over mutual exclusion and 78% abort reduction over baseline, on `array`. Repair is also useful for workloads with mixed abort rates and wasted work, reaching up to 2.95x speedup over mutual exclusion and 93% abort reduction over baseline on the STAMP benchmarks.

Given the trade-offs between runtime overhead and repair capability, we are interested in exploring improvements as future work. For example, a hardware-based repair mechanism would significantly reduce the overhead of our current approach. In addition, statically pre-computed repairs using program slicing could eliminate user-defined repair handlers and runtime dependency tracking.

Acknowledgments

This work was supported in part by the National Science Foundation, and by the Department of Defense through the National Defense Science & Engineering Graduate Fellowship Program. Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect those of the sponsors.

We would like to thank Chris Fallin and Pratik Fegade for their suggestions, as well as the Parallel Data Lab, Guy Blelloch, Sol Boucher, Thomas Kim, and Dave Andersen, for access to additional computational resources.

References

[1] Utku Aydonat and Tarek S. Abdelrahman. 2008. Serializability of Transactions in Software Transactional Memory. In *TRANSACT '08*. ACM.

[2] Colin Blundell, Arun Raghavan, and Milo M.K. Martin. 2010. RETCON: Transactional Repair Without Replay. In *ISCA '10*. ACM, 258–269.

[3] Thomas M. Breuel. 1988. Lexical Closures for C++. In *C++ Conference*. USENIX, 293–304.

[4] Nathan G. Bronson, Jared Casper, Hassan Chafi, and Kunle Olukotun. 2010. Transactional Predication: High-Performance Concurrent Sets and Maps for STM. In *PODC '10*. ACM, 6–15.

[5] David Maxwell Chickering, David Heckerman, and Christopher Meek. 1997. A Bayesian Approach to Learning Bayesian Networks with Local Structure. In *UAI '97*. AUAI, 80–89.

[6] Luke Dalessandro, Michael F. Spear, and Michael L. Scott. 2010. NOrec: Streamlining STM by Abolishing Ownership Records. In *PPoPP '10*. ACM, 67–78.

[7] Peter Damron, Alexandra Fedorova, Yossi Lev, Victor Luchangco, Mark Moir, and Daniel Nussbaum. 2006. Hybrid Transactional Memory. In *ACM Sigplan Notices*, Vol. 41. ACM, 336–346.

[8] Al Danial. [n.d.]. cloc. https://github.com/AlDanial/cloc

[9] Dave Dice, Ori Shalev, and Nir Shavit. 2006. Transactional Locking II. In *Distributed Computing*, David Hutchison, Takeo Kanade, Josef Kittler, Jon M. Kleinberg, Friedemann Mattern, John C. Mitchell, Moni Naor, Oscar Nierstrasz, C. Pandu Rangan, Bernhard Steffen, Madhu Sudan, Demetri Terzopoulos, Dough Tygar, Moshe Y. Vardi, Gerhard Weikum, and Shlomi Dolev (Eds.). Vol. 4167. Springer Berlin Heidelberg, 194–208.

[10] Nuno Diegues and Paolo Romano. 2014. Time-Warp: Lightweight Abort Minimization in Transactional Memory. In *PPoPP '14*. ACM, 167–178.

[11] Chen Ding, Xipeng Shen, Kirk Kelsey, Chris Tice, Ruke Huang, and Chengliang Zhang. 2007. Software Behavior Oriented Parallelization. In *PLDI '07*. ACM, 223–234.

[12] Aleksandar Dragojević, Rachid Guerraoui, and Michal Kapalka. 2009. Stretching Transactional Memory. In *PLDI '09*. ACM, 155–165.

[13] K. P. Eswaran, J. N. Gray, R. A. Lorie, and I. L. Traiger. 1976. The Notions of Consistency and Predicate Locks in a Database System. *Commun. ACM* 19, 11 (Nov. 1976), 624–633.

[14] P. Felber, C. Fetzer, P. Marlier, and T. Riegel. 2010. Time-Based Software Transactional Memory. *IEEE Transactions on Parallel and Distributed Systems* 21, 12 (Dec. 2010), 1793–1807.

[15] Anthony Green. [n.d.]. Libffi. https://sourceware.org/libffi/

[16] Rachid Guerraoui, Maurice Herlihy, and Bastian Pochon. 2005. Toward a Theory of Transactional Contention Managers. In *PODC '05*. ACM, 258–264.

[17] P. Hammarlund, A. J. Martinez, A. A. Bajwa, D. L. Hill, E. Hallnor, H. Jiang, M. Dixon, M. Derr, M. Hunsaker, R. Kumar, R. B. Osborne, R. Rajwar, R. Singhal, R. D'Sa, R. Chappell, S. Kaushik, S. Chennupaty, S. Jourdan, S. Gunther, T. Piazza, and T. Burton. 2014. Haswell: The Fourth-Generation Intel Core Processor. *IEEE Micro* 34, 2 (March 2014), 6–20.

[18] Tim Harris. 2007. Abstract Nested Transactions. In *TRANSACT '04*. ACM, 10.

[19] Maurice Herlihy and Eric Koskinen. 2008. Transactional Boosting: A Methodology for Highly-Concurrent Transactional Objects. In *PPoPP '08*. ACM, 207.

[20] Maurice Herlihy, Victor Luchangco, Mark Moir, and William N. Scherer, III. 2003. Software Transactional Memory for Dynamic-Sized Data Structures. In *PODC'03*. ACM, 92–101.

[21] Maurice Herlihy and J. Eliot B. Moss. 1993. Transactional Memory: Architectural Support for Lock-Free Data Structures. In *ISCA '93*. ACM, 289–300.

[22] Nathaniel Herman, Jeevana Priya Inala, Yihe Huang, Lillian Tsai, Eddie Kohler, Barbara Liskov, and Liuba Shrira. 2016. Type-Aware Transactions for Faster Concurrent Code. In *EuroSys '16*. ACM, 31:1–31:16.

[23] Gokcen Kestor, Osman S. Unsal, Adrian Cristal, and Serdar Tasiran. 2014. T-Rex: A Dynamic Race Detection Tool for C/C++ Transactional Memory Applications. In *EuroSys '14*. ACM, 20:1–20:12.

[24] Eric Koskinen and Maurice Herlihy. 2008. Checkpoints and Continuations Instead of Nested Transactions. In *SPAA '08*. ACM, 160–168.

[25] Eric Koskinen, Matthew Parkinson, and Maurice Herlihy. 2010. Coarse-Grained Transactions. In *POPL '10*. ACM, 19–30.

[26] Milind Kulkarni, Donald Nguyen, Dimitrios Prountzos, Xin Sui, and Keshav Pingali. 2011. Exploiting the Commutativity Lattice. In *ACM SIGPLAN Notices*, Vol. 46. ACM, 542–555.

[27] Heiner Litz, David Cheriton, Amin Firoozshahian, Omid Azizi, and John P. Stevenson. 2014. SI-TM: Reducing Transactional Memory Abort Rates through Snapshot Isolation. In *ASPLOS'14*. ACM, 383–398.

[28] Chi Cao Minh, JaeWoong Chung, C. Kozyrakis, and K. Olukotun. 2008. STAMP: Stanford Transactional Applications for Multi-Processing. In *IISWC '08*. IEEE, 35–46.

[29] J. E.B. Moss. 1985. *Nested Transactions: An Approach to Reliable Distributed Computing*. Massachusetts Institute of Technology.

[30] Donald Nguyen and Keshav Pingali. 2017. What Scalable Programs Need from Transactional Memory. In *ASPLOS'17*. ACM, 105–118.

[31] Yang Ni, Vijay S. Menon, Ali-Reza Adl-Tabatabai, Antony L. Hosking, Richard L. Hudson, J. Eliot B. Moss, Bratin Saha, and Tatiana Shpeisman. 2007. Open Nesting in Software Transactional Memory. In *PPoPP '07*. ACM, 68–78.

[32] Marek Olszewski, Jeremy Cutler, and J. Gregory Steffan. 2007. JudoSTM: A Dynamic Binary-Rewriting Approach to Software Transactional Memory. In *PACT '07*. IEEE, 365–375.

[33] Sunjae Park, Christopher J. Hughes, and Milos Prvulovic. 2018. Transactional Pre-Abort Handlers in Hardware Transactional Memory. In *PACT '18*. ACM, 33:1–33:11.

[34] Dmitri Perelman, Rui Fan, and Idit Keidar. 2010. On Maintaining Multiple Versions in STM. In *PODC '10*. ACM, 16–25.

[35] Hany E. Ramadan, Indrajit Roy, Maurice Herlihy, and Emmett Witchel. 2009. Committing Conflicting Transactions in an STM. In *PPoPP '09*. ACM, 163–172.

[36] Torvald Riegel, Pascal Felber, and Christof Fetzer. 2006. A Lazy Snapshot Algorithm with Eager Validation. In *DISC'06*. Springer-Verlag, 284–298.

[37] Wenjia Ruan, Yujie Liu, and Michael Spear. 2014. STAMP Need Not Be Considered Harmful. In *TRANSACT'14*. ACM.

[38] Mohamed M. Saad, Masoomeh Javidi Kishi, Shihao Jing, Sandeep Hans, and Roberto Palmieri. 2019. Processing Transactions in a Predefined Order. In *PPoPP '19*. ACM, 120–132.

[39] Mohamed M. Saad, Roberto Palmieri, Ahmed Hassan, and Binoy Ravindran. 2016. Extending TM Primitives Using Low Level Semantics. In *SPAA '16*. ACM, 109–120.

[40] Bratin Saha, Ali-Reza Adl-Tabatabai, Richard L. Hudson, Chi Cao Minh, and Benjamin Hertzberg. 2006. McRT-STM: A High Performance Software Transactional Memory System for a Multi-Core Runtime. In *PPoPP '06*. ACM, 187–197.

[41] William N. Scherer, III and Michael L. Scott. 2005. Advanced Contention Management for Dynamic Software Transactional Memory. In *PODC '05*. ACM, 240–248.

[42] Nir Shavit and Dan Touitou. 1995. Software Transactional Memory. In *PODC '95*. ACM, 204–213.

[43] Travis Skare and Christos Kozyrakis. 2006. Early Release: Friend or Foe?. In *WTW '06*. ACM.

[44] Alexander Spiegelman, Guy Golan-Gueta, and Idit Keidar. 2016. Transactional Data Structure Libraries. In *PLDI'16*. ACM, 682–696.

[45] Ruben Titos-Gil, Manuel E. Acacio, Jose M. Garcia, Tim Harris, Adrian Cristal, Osman Unsal, Ibrahim Hur, and Mateo Valero. 2012. Hardware Transactional Memory with Software-Defined Conflicts. *ACM Trans. Archit. Code Optim.* 8, 4 (Jan. 2012), 31:1–31:20.

[46] Linus Torvalds. [n.d.]. Git. https://git-scm.com

[47] I. Watson, C. Kirkham, and M. Lujan. 2007. A Study of a Transactional Parallel Routing Algorithm. In *PACT '07*. IEEE, 388–400.

[48] W. E. Weihl. 1988. Commutativity-Based Concurrency Control for Abstract Data Types. *IEEE Trans. Comput.* 37, 12 (Dec. 1988), 1488–1505.

[49] Mark Weiser. 1981. Program Slicing. In *ICSE '81*. IEEE, 439–449.

[50] Richard M. Yoo and Hsien-Hsin S. Lee. 2008. Adaptive Transaction Scheduling for Transactional Memory Systems. In *SPAA '08*. ACM, 169–178.

[51] G. Zhang, V. Chiu, and D. Sanchez. 2016. Exploiting Semantic Commutativity in Hardware Speculation. In *MICRO '16*. IEEE, 1–12.